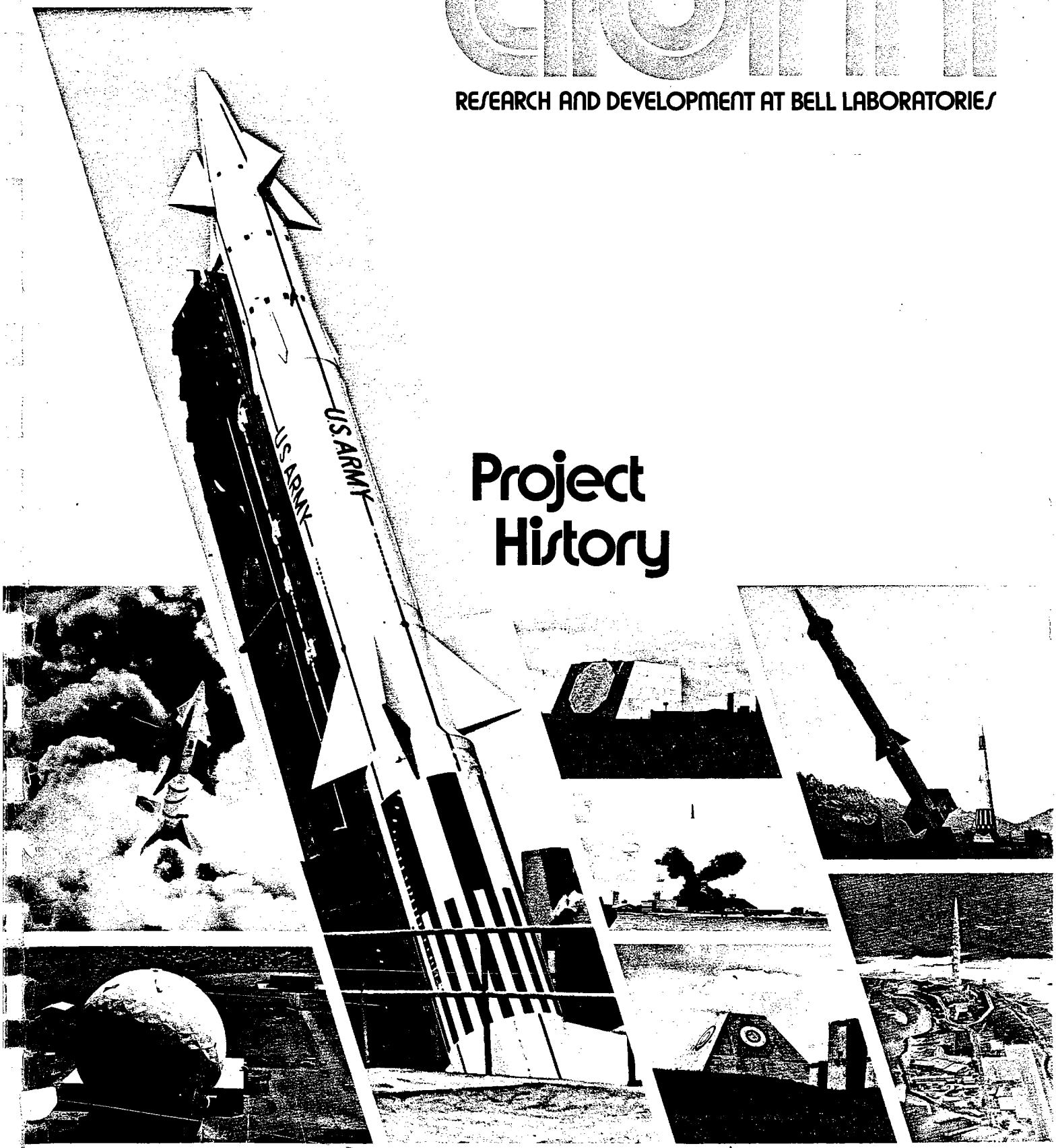
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RESEARCH AND DEVELOPMENT AT BELL LABORATORIES

Project History





RESEARCH AND DEVELOPMENT AT BELL LABORATORIES

Project History

October 1975

prepared by Bell Laboratories
on behalf of Western Electric
Whippany Road, Whippany, N. J. 07981
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under Contract DAHC60-71-C-0005

PREFACE

In March 1955, Col. M. B. Chatfield of the Army Ordnance Missile Defense Command at Redstone Arsenal asked Bell Laboratories to carry out an 18-month study of defense against future air threats including Intercontinental Ballistic Missiles (ICBMs), then in early development in the United States. This history begins with that study and highlights the evolution of ABM defense during the ensuing twenty years that led to a tactical operating ABM defense system at Grand Forks, North Dakota.

It covers the important decisions, changing requirements, and major innovative development steps taken to meet the changing threat. The research and development programs associated with each major ABM system are discussed together with the principal radar, missile, and computer subsystems. The report concludes with a summary of lessons learned with respect to managing such programs in the future and includes a comprehensive bibliography of supporting reference material.

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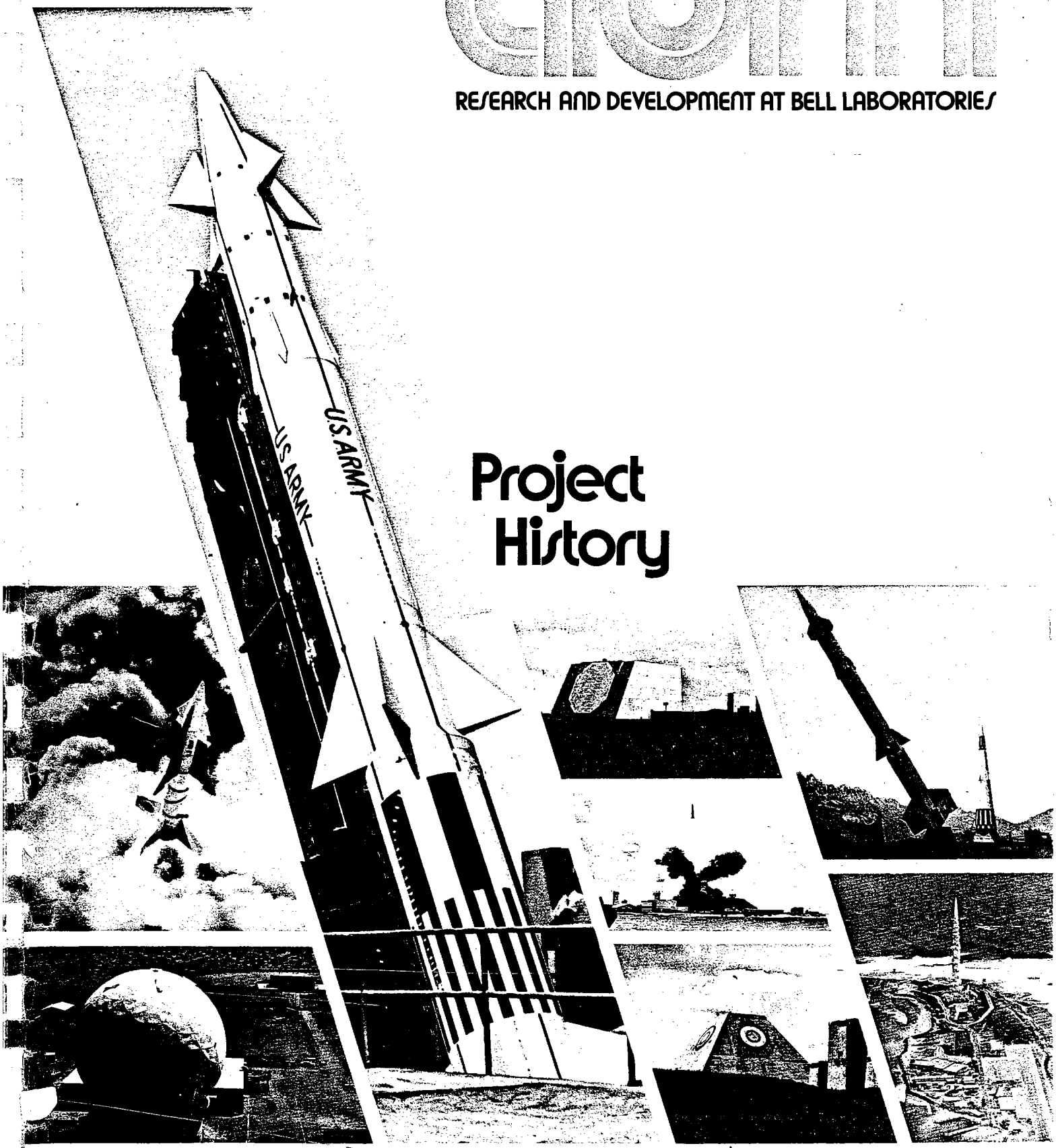
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RESEARCH AND DEVELOPMENT AT BELL LABORATORIES

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Project History

October 1975

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Whippany Road, Whippany, N. J. 07981
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under Contract DAHC60-71-C-0005

PREFACE

In March 1955, Col. M. B. Chatfield of the Army Ordnance Missile Defense Command at Redstone Arsenal asked Bell Laboratories to carry out an 18-month study of defense against future air threats including Intercontinental Ballistic Missiles (ICBMs), then in early development in the United States. This history begins with that study and highlights the evolution of ABM defense during the ensuing twenty years that led to a tactical operating ABM defense system at Grand Forks, North Dakota.

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Part I.

HISTORY OF ABM DEVELOPMENT

Part I.

HISTORY OF ABM DEVELOPMENT

In March 1955, a small Bell Laboratories military system development group working with a team from Douglas Aircraft Company (now McDonnell-Douglas), had just completed a study of a single-stage, solid-propellant missile for possible air defense. When Army Ordnance asked Bell Laboratories to start an 18-month study of a new forward-looking, anti-aircraft defense system for the Zone of the Interior to defend against future target threats in the 1960-1970 time period, a system team already was available.

The initial thought was to place primary emphasis on the super air-breathing-type target while also keeping in mind ballistic targets and the desire to defend against the extremely difficult Intercontinental Ballistic Missile (ICBM) with a reasonable extension of current radar and missile technology. In other words, the system originally to be designated as NIKE II was not to be considered as a solution to the ICBM defense problem, but rather as a step toward its ultimate solution. However, discussions with the Army in June 1955 brought to light the increasing concern over the possibility of an ICBM threat, and Bell Laboratories was asked to place primary emphasis in this area. Consequently, the NIKE II Study would focus on ICBM defense, but still include the full spectrum of future target threats.

NIKE II STUDY

The relatively small study team available to carry out the NIKE II work was actually a well-coordinated task group of Bell Laboratories and Douglas Aircraft Company people who met at regular intervals to review completed tasks and outline future objectives. Messrs. C. A. Warren and J. W. Schaefer coordinated the overall systems work supported by Bell Laboratories' Mathematical Research Department, whose efforts were coordinated by Messrs. D. P. Ling and R. C. Prim. At the Douglas Aircraft Company, Mr. J. L. Bromberg was responsible for the project coordination, supported by Messrs. R. L. Johnson, M. Hunter, N. Weiler, and J. Tschirgi.

Initially, the objective was to explore the possibility of a common anti-aircraft defense system to cover all future high-altitude threats without substantially compromising the overall defense. It was felt that any anti-aircraft defense designed for the extreme ICBM targets would overlap on a system capable of handling the future air-breathing, high-performance targets. Consequently, by adding certain specialized elements of one to the other, there was the attractive possibility of having an anti-aircraft system capable of attacking any future air target.

The spectrum of possible future target threats (1960-1970 time period) considered for the Army study is shown in Figure I-1. It covered a wide area of performance capability from the maximum speed of the air-breathing ramjet out to ICBM speed of 24,000 ft/sec, and at altitudes far beyond 100,000 feet. For the ballistic targets, the short-range, 150-mile, 5000-ft/sec rocket of the V2-type set the lower boundary.

The Army authorized funding of $1.65 million on Army Ordnance Contract DA-30-069-ORD-1082 for the 18-month study effort. This funding was to cover not only the system study effort, but also exploratory hardware development in those areas of radar and missile technology that could be defined as critical to successful development of a NIKE II System. A year later, an additional $1.8 million was added for expediting exploratory hardware work.

ABM Defense Requirements

The first full status report on the NIKE II System Study was presented to Army Ordnance at Redstone Arsenal December 2, 1955, about seven months after beginning the study. It is interesting to note here how many solutions proposed in this preliminary report, after only one third of the study was completed, remain basic even today to any ICBM defense. Some highlights presented at this status review follow.

To handle the full range of threat, a common data-gathering system was proposed using a defensive missile with interchangeable noses as shown in Figure I-2. One nose, for use in long-range intercepts of the future air-breathing targets, would contain an active seeker. The second nose would have no seeker, but would contain

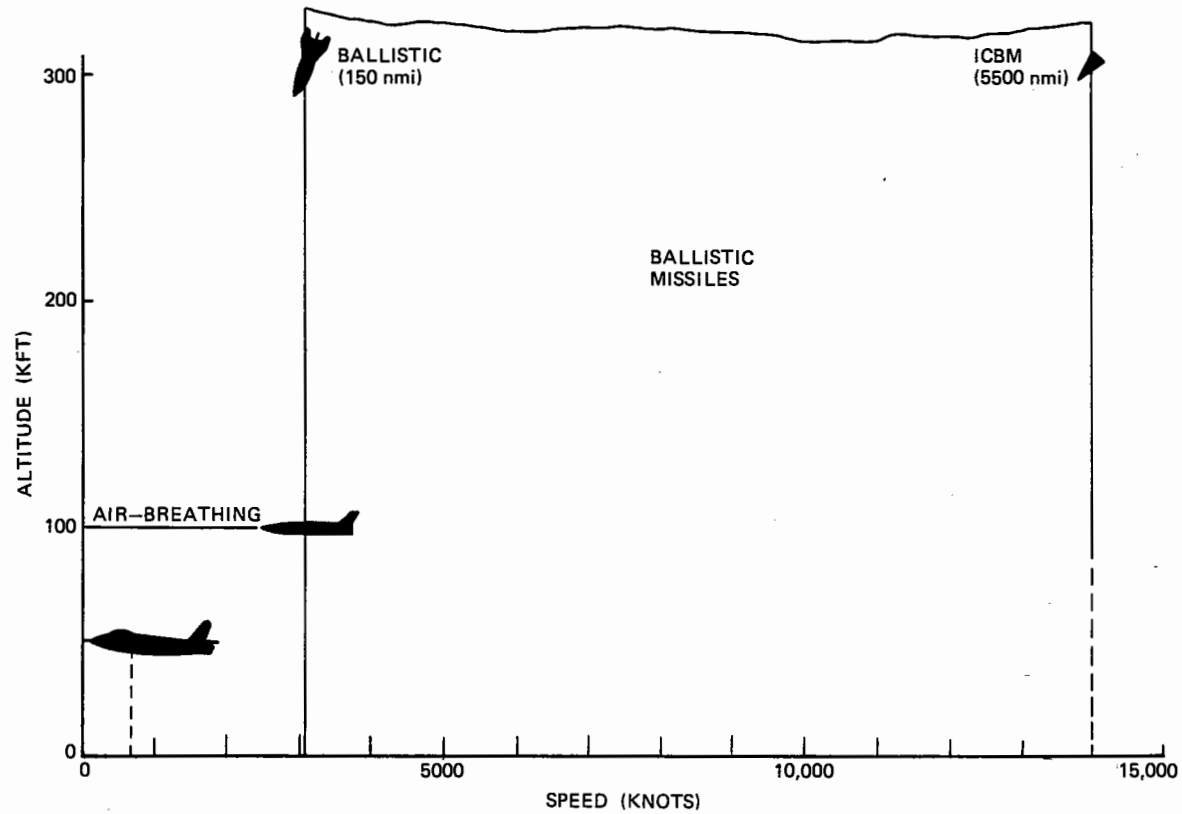


Figure I-1. Spectrum of Target Threats

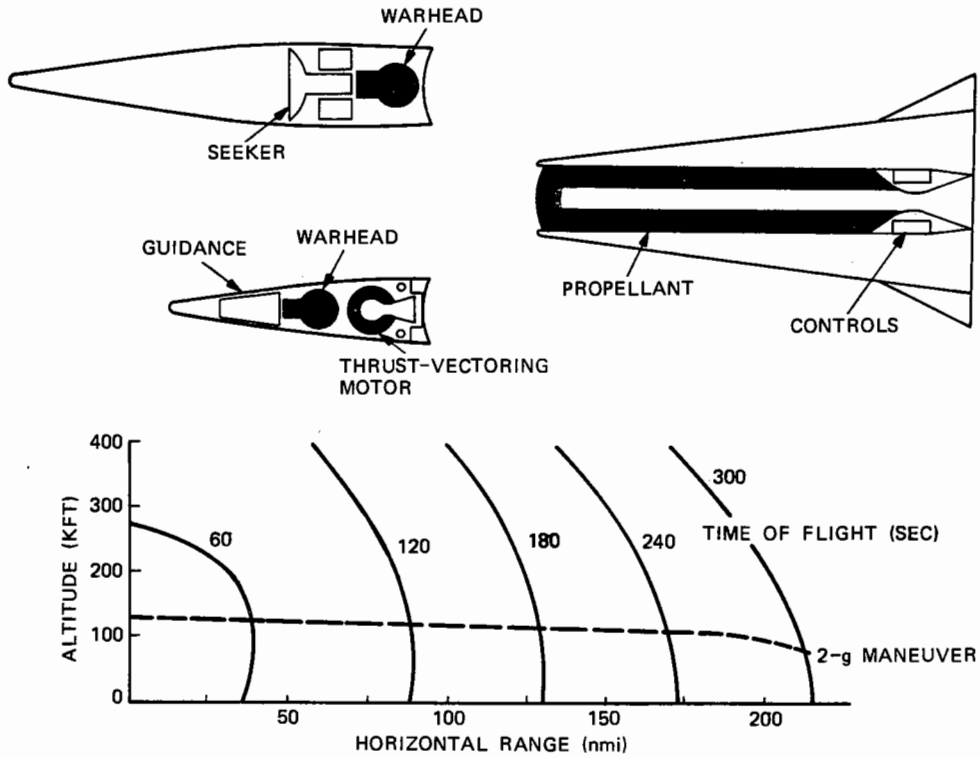


Figure I-2. Defensive Missile with Interchangeable Noses

a jet-control mechanism to provide maneuverability at altitudes above 120,000 feet. This nose would be used when engaging ballistic targets.

By comparison to World War II air defense objectives, where a 10- to 15-percent attrition rate was acceptable, the nuclear-warhead threat required defense levels of 95- to 100-percent attrition against a tough-to-kill reentry target. Studies showed that using a 50-kiloton nuclear warhead in the defensive missile required relatively small miss distances to kill the enemy warhead. The use of a high-yield warhead did not relax the need for a guidance system of high accuracy.

One of the first questions in the initial study concerned the point in the offensive missile's trajectory where intercept should take place. Consideration was given to making the intercept near the middle of the trajectory. However, not only would this necessitate a defensive missile as formidable as the offensive weapon, but it would require gathering information on the offensive missile almost at its point of launch. With the obvious advantage of choice of launch time belonging to the offense, it did not appear feasible or economical to attempt mid-course intercepts. Consequently, we proposed that the intercepts be much closer to the point of impact. (See Figure I-3 for ICBM trajectory.)

Further studies indicated that the most attractive guidance method was a command system based on extension of the NIKE-AJAX/HERCULES Systems. The use of homing seemed precluded by the extremely high closing rate of over 5

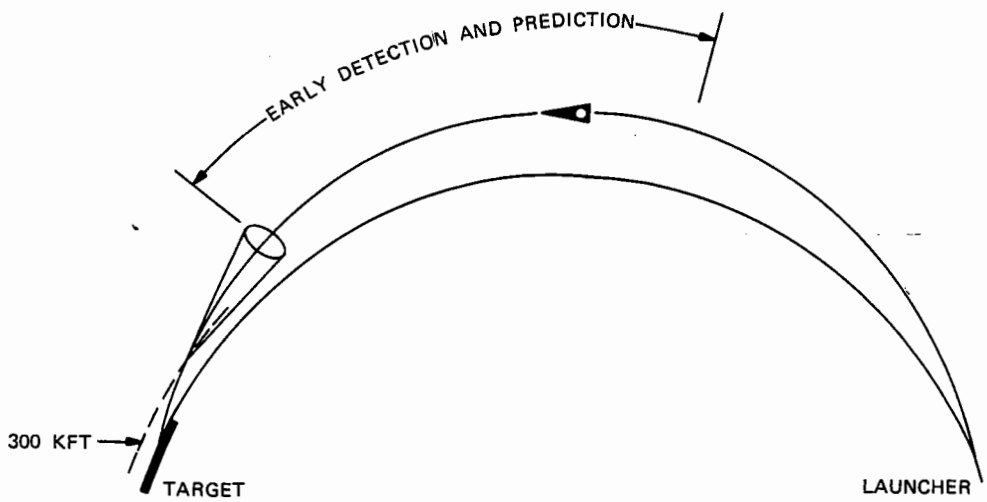


Figure I-3. ICBM Trajectory

miles per second, necessitating homing ranges that did not appear attainable on so small a target as a ballistic reentry body (only one one-thousandth the radar size of an aircraft). The terminal nature of the defense also made command guidance feasible and attractive.

Ballistic missiles entering the atmosphere would suffer deceleration of up to 60 g's at altitudes dependent on the shape of the reentry nose. A comparison of ballistic target characteristics is given in Figure I-4. The guidance problem and related missile maneuverability requirements could be eased, as proposed by Bell Laboratories' Mathematical Department, through the use of analytical prediction of ICBM deceleration, well in advance of the actual high-g deceleration.

An extensive communications network, data processing, computation, and tactical control would be necessary to the functioning of the ABM defense system. Local radars in the vicinity of the defended area and forward radars for initial detection would require integration with an extensive network of communications. The importance and complexity of fast response were emphasized strongly with speeds so high and reaction times so short that all operations would have to be

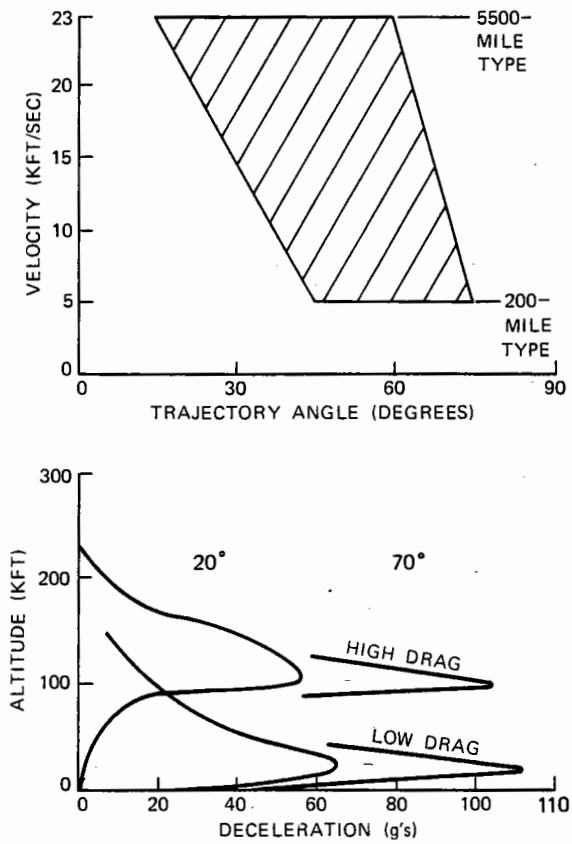


Figure I-4. Ballistic Target Characteristics

automatic with only the power of veto exercised by man. Dependence on a 10- to 15-minute early warning could be relatively loose and flexible, but once a target was acquired, all system elements would have to function as an integrated whole to successfully meet mission objectives.

A major concern pointed out in this first report was the problem of separating radar decoys from warheads. Chaff or balloon decoys having high drag-to-mass ratios would be held back by the atmosphere and separated, but rods or jacks cut to the defensive radar frequency might be made to have approximately the same drag-to-mass ratio as the warheads. Rate of arrival of ICBMs over a target area and unresolved decoys could present high traffic levels requiring a target tracking and guidance system capable of engaging up to 20 targets per minute.

On December 28, 1955, Lt. Gen. J. M. Gavin, Army Deputy Chief of Staff for Research and Development (R&D), visited Whippany for a review of all the NIKE programs. A somewhat shortened version of the NIKE II status report was presented. General Gavin was impressed with the study to date and gave it top priority, particularly for defense capability against ICBMs. Messrs. F. R. Lack, Vice President of Western Electric, and J. B. Fisk, Bell Laboratories Executive Vice President, W. C. Tinus, R. R. Hough, L. W. Morrison, and C. A. Warren were among those present at this meeting.

Additional Defense Considerations

On January 4, 1956, a similar NIKE II briefing was given by Mr. R. R. Hough of Bell Laboratories to the Army Policy Council. At this briefing, Mr. Hough responded to an Army request for information concerning what could be done to provide an interim solution to the intermediate and long-range ballistic missile defense problem. It was pointed out that regardless of the approach taken, information gathering was the difficult part of the problem. Furthermore, a high level of defense was essential and a marginal interim capability might not be worth extensive effort. Also, any interim solution should be directed along lines that would lead to the final solution.

A long-range, high-data-rate acquisition radar was essential to any ballistic missile defense solution, and if development could start immediately on this critical element, a possible interim ICBM defense might be possible with the NIKE B missile and system. Mr. Hough reported that Bell Laboratories was currently studying the problem of ICBM interim capability with NIKE B and would report back to the Army within the next two months on this defense possibility. A comparison of early Antiballistic Missile (ABM) sizes is given in Figure I-5.

The Air Force was also interested in ABM defense, and in the fall of 1955, an ARDC-TR-56-11 technical request was made to industry for a 12-month ABM defense study. In this period, the roles and mission of the Army were defined as "terminal" defense and those of the Air Force as "area" defense. Since the ABM concept covered both roles,* Bell Laboratories recognized that any successful ABM system would have to combine area and terminal defense within one

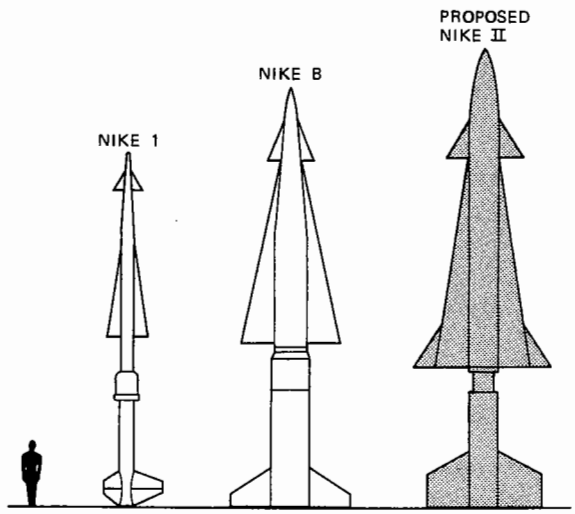


Figure I-5. Comparative Sizes of Early ABM Missiles

*Area defense involved the long-range acquisition radars tied together by a communications network, while terminal defense involved the missiles, local tracking radars, and computers.

integrated system approach. We therefore bid on the Air Force's 12-month study on the basis that the additional effort for the Air Force would be concentrated on the Forward Acquisition Radars (FARs) and the communications network. However, the results of the complete ABM study would be made available to both the Army and the Air Force.

The Air Force study effort was for about $0.5 million in comparison to more than $3.0 million for the Army, which also covered exploratory development. Air Force Contract AF33(616)-3285 with Western Electric was authorized on November 15, 1955, and was directed specifically to Anti-ICBM (AICBM) defense only. Two other defense contractors, Boeing and Lockheed, were among those selected in this Air Force competitive study.

As the NIKE II study and the complementary Air Force study proceeded through the first six months of 1956, Bell Laboratories and Douglas were requested to make a number of presentations, not only to the Army and Air Force, but to a number of high-level Department of Defense (DOD) and special defense panels as well. These briefings included:

NIKE II and Study of Early Solution to ICBM Defense	— Briefing for Dr. C. C. Furnas, Assistant Secretary of Defense Research and Development, March 30, 1956.
Air Force AICBM Weapon Study First Status Report	— Air Force Scientific Advisory Board, May 2, 1956.
NIKE II	— Presentation before Dr. Murphree's Anti-Missile DOD Defense Committee, September 17, 1956.

Proposed ABM System

The defense problem and the early system proposed as a solution against future threats, including the ICBM, as presented to the Assistant Secretary of Defense for R&D on March 30, 1956, involved a number of significant features. The defensive missile with the interchangeable noses for the air threat (seeker) or ICBM threat (thrust-vectoring motor for outside atmosphere) was proposed. (See Figure I-2.) Early acquisition of the ICBMs would be obtained by a series of Forward Acquisition Radars with fan beams well north of the defended areas, as shown in Figure I-6. The overall system is illustrated in Figure I-7. The local high-data-rate acquisition radar shown pictorially in Figure I-8 was based on the Luneberg lens antenna principle (Figure I-9). The possible characteristics of this radar are given in Table I-1.

Table I-1
AICBM Radar Characteristics

Coverage	120° azimuth x 60° elevation
Data Interval	1 sec
Repetition Rate	120 pps
Radio Frequency	500 MHz
Power	
Peak	5000 kW
Average	300 kW (each of two)
Transmit Antenna	
Aperture	2 ft x 120 ft
Beam	60° x 1°
Gain	27 dB
Receive Antenna	
Aperture	120 ft diameter
Beam	1° x 1°
Gain	43 dB
Range of ICBM	600 nautical miles

At this same meeting, at the request of the Army and DOD, a possible Interim AICBM Study using the NIKE B missile and system was presented. The system and guidance plan proposed is illustrated in Figures I-10 through I-16.

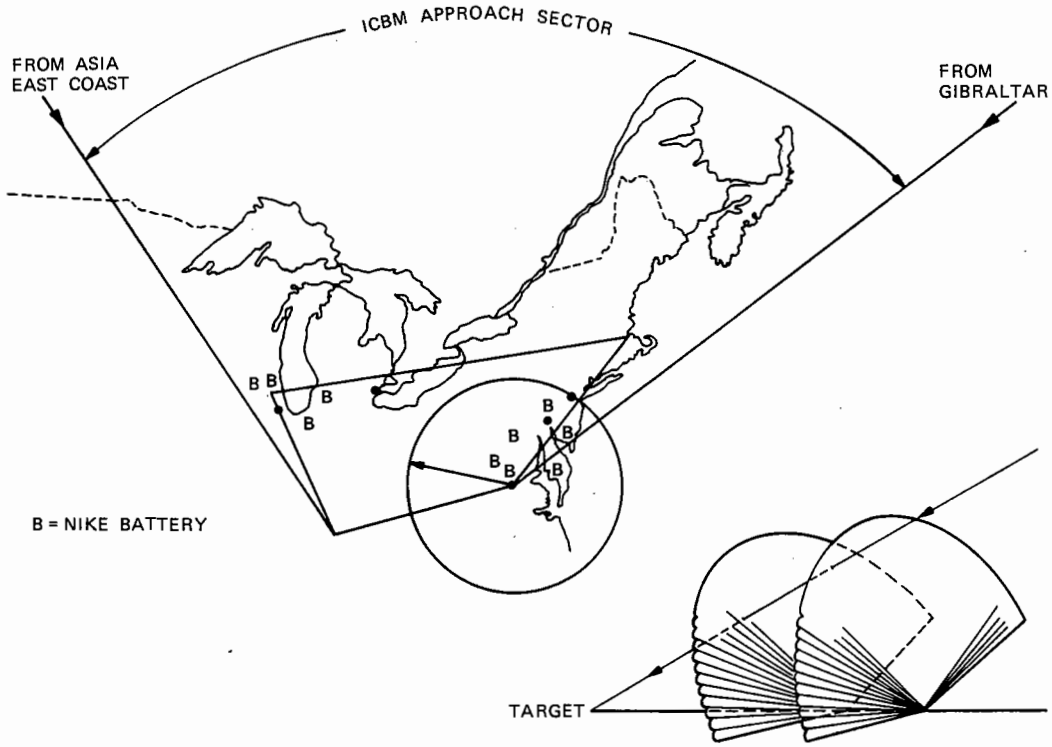


Figure I-6. Deployment for ICBM Defense

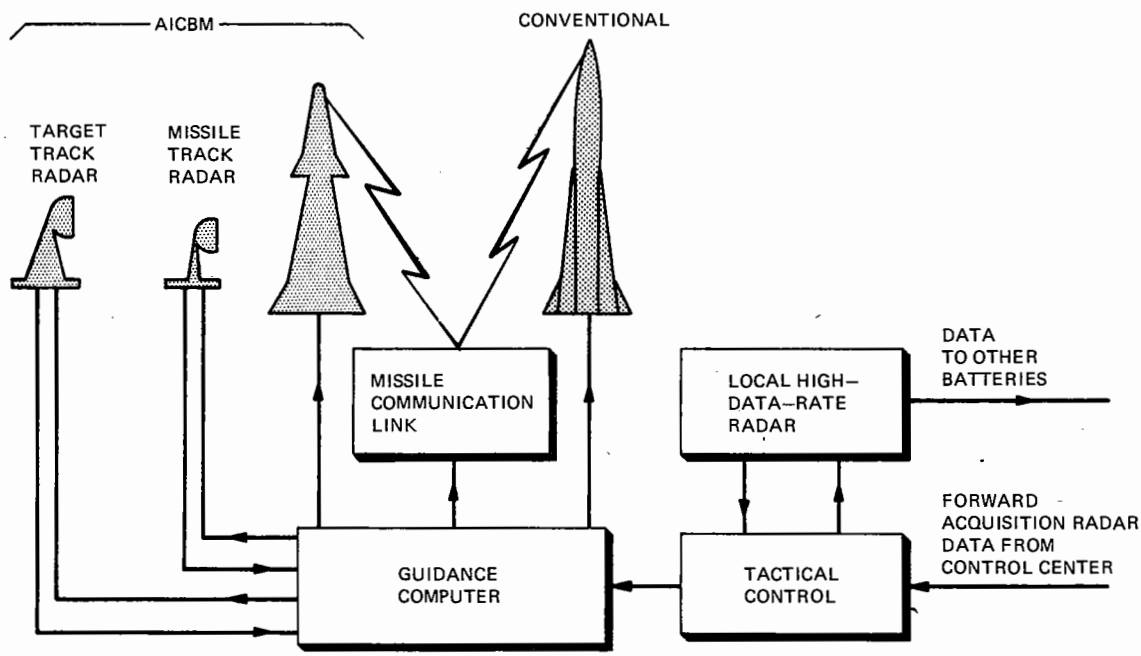


Figure I-7. ABM Battery

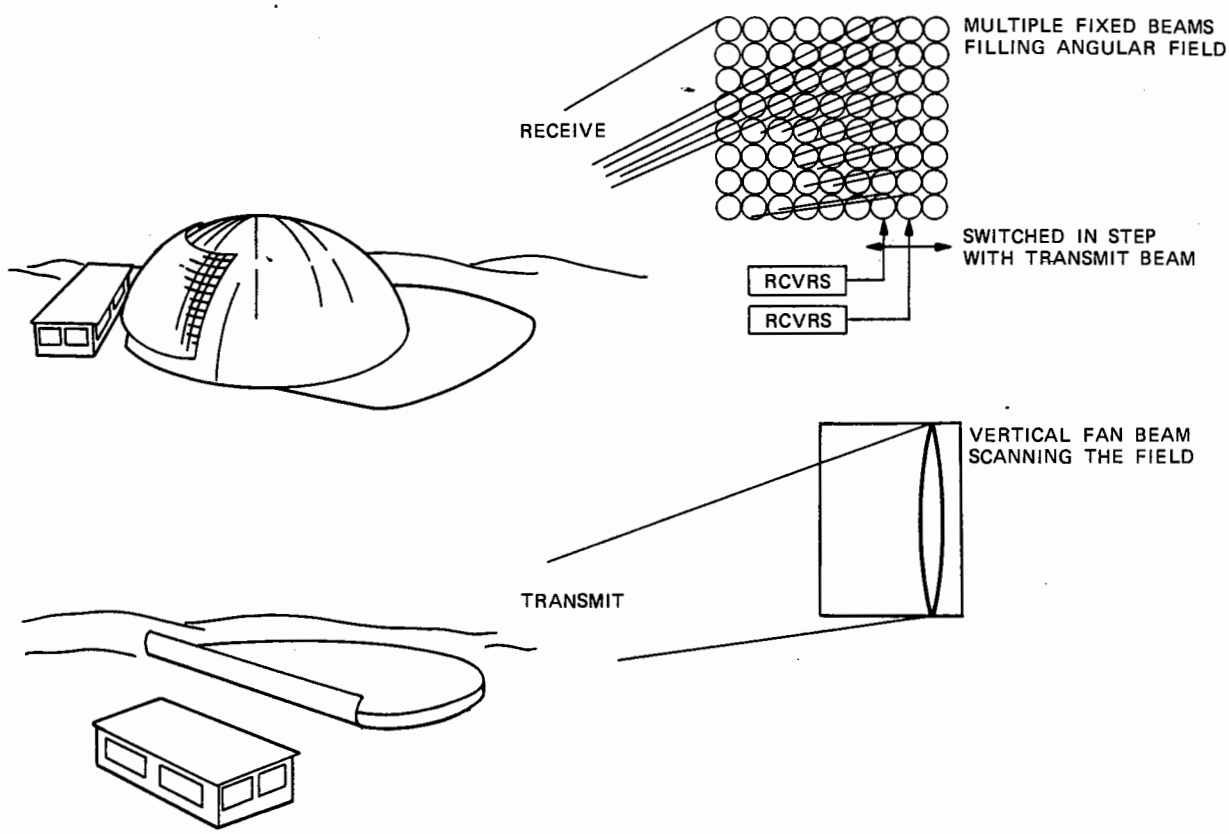


Figure I-8. AICBM Acquisition Radar

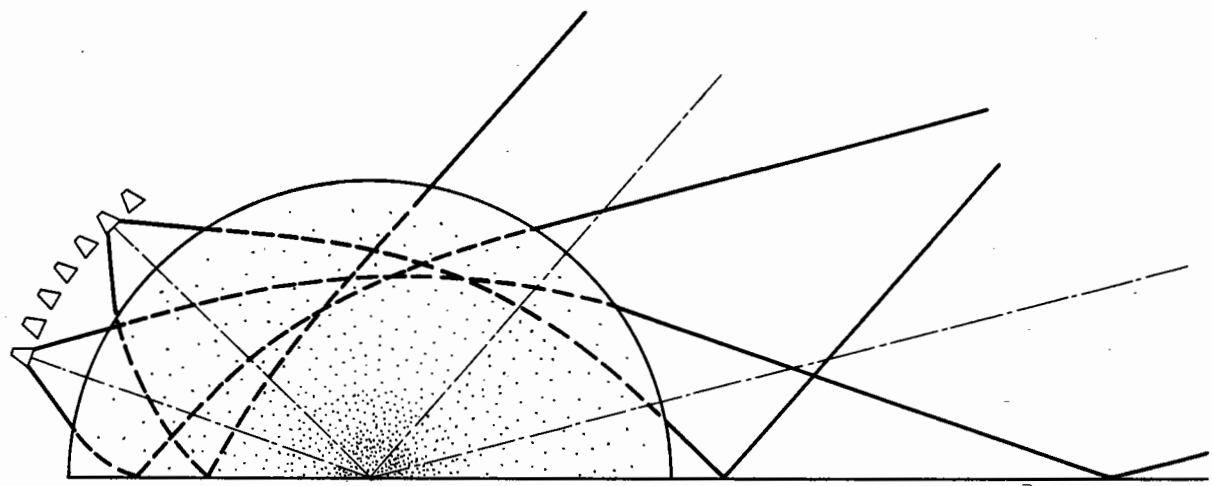


Figure I-9. Luneberg Lens Antenna

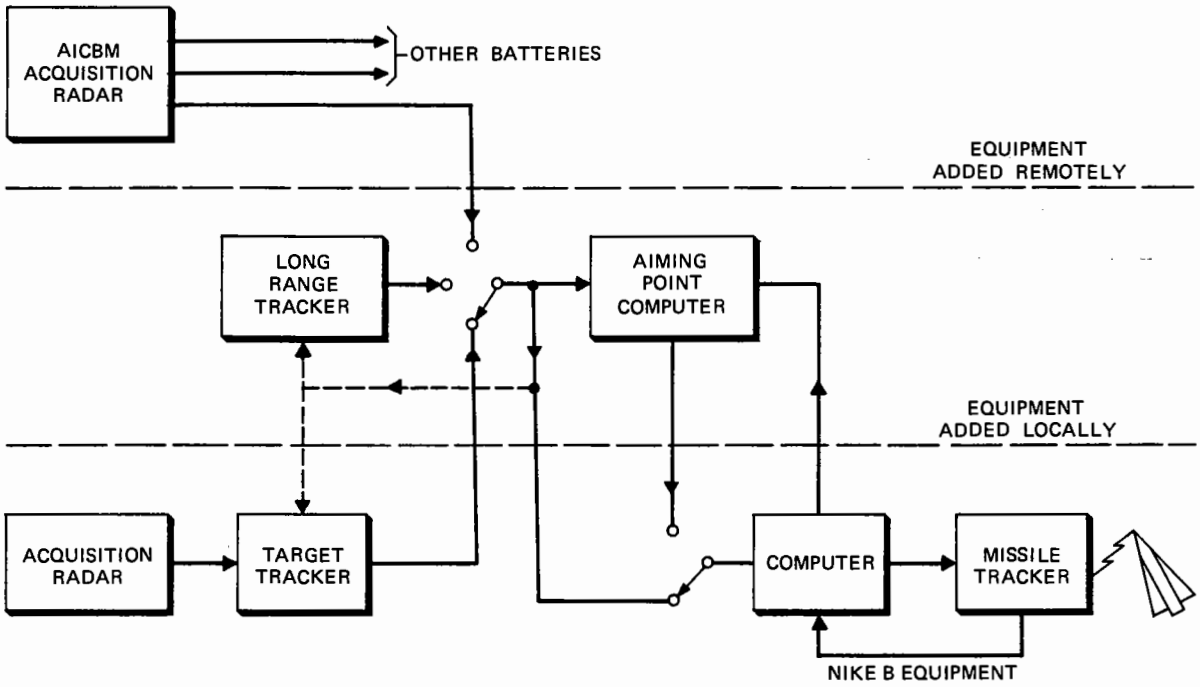


Figure I-10. NIKE B System

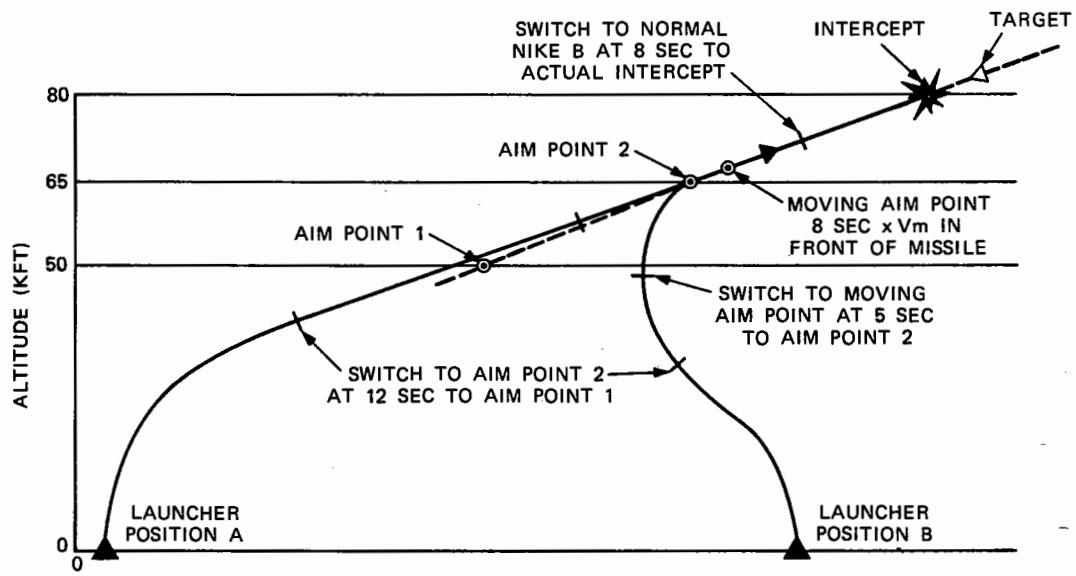


Figure I-11. Mechanization of Parallel Approach for ICBM Targets

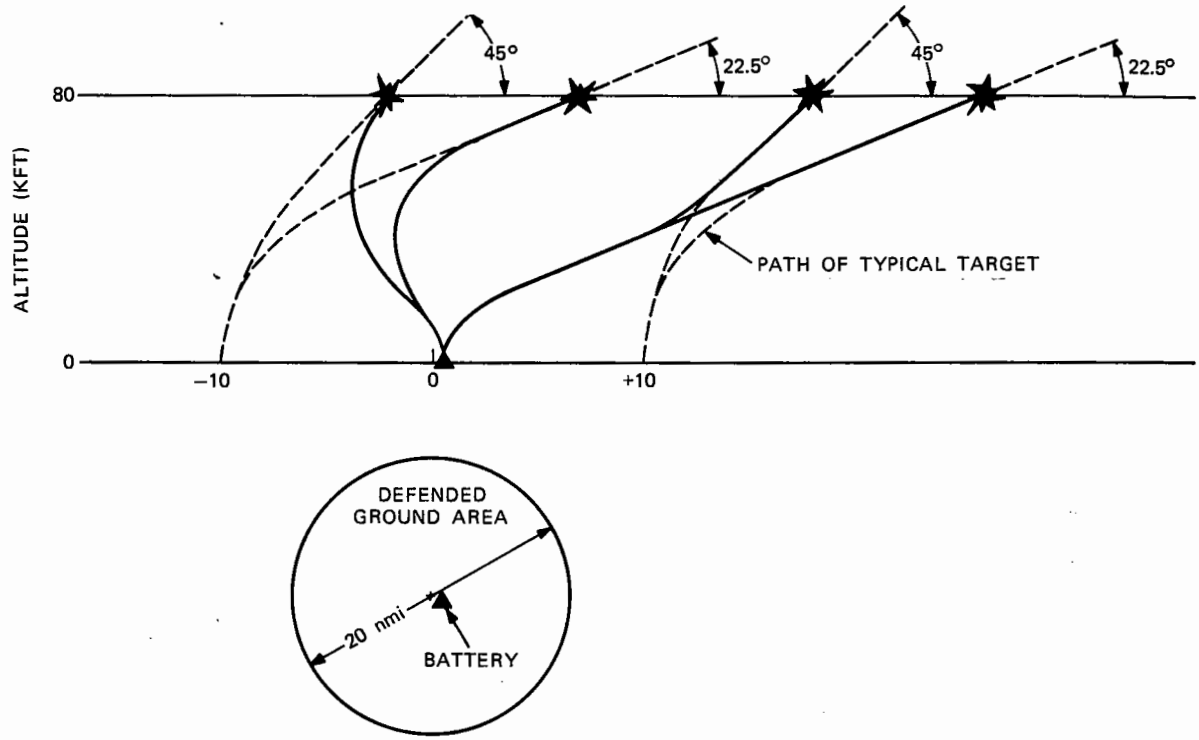


Figure I-12. Battery Capability vs. Target Angle

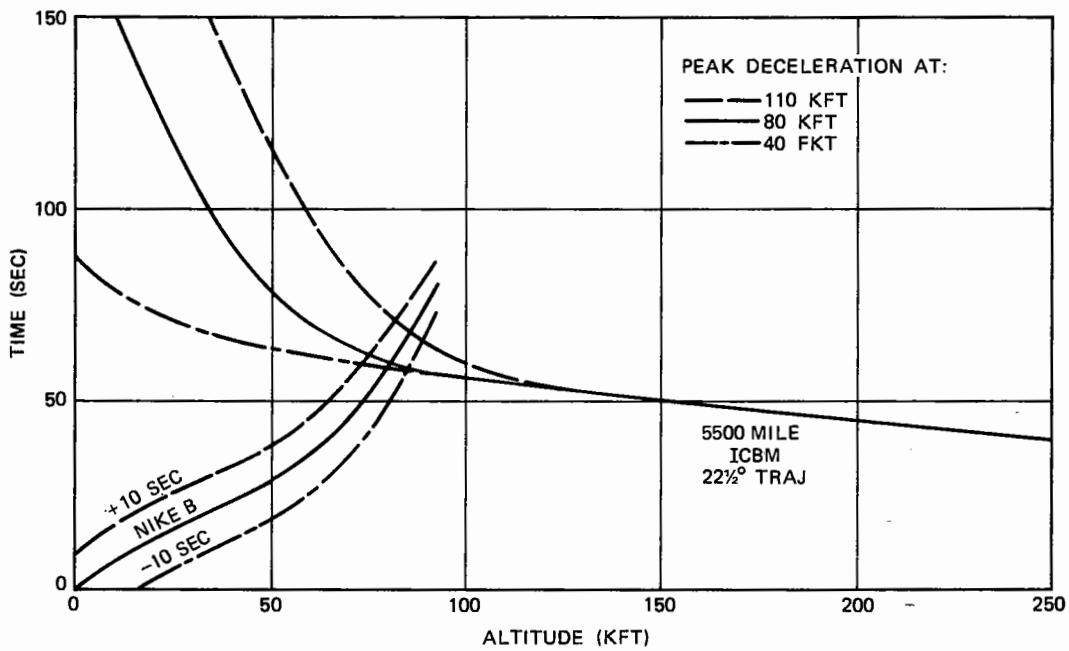


Figure I-13. Variation from Nominal Intercept

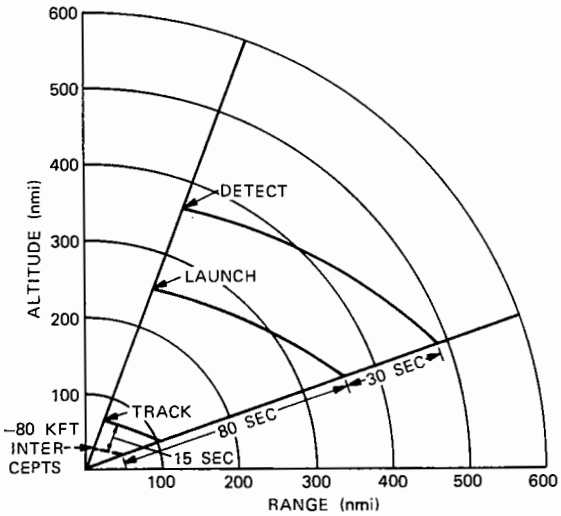


Figure I-14. Radar Range Requirements

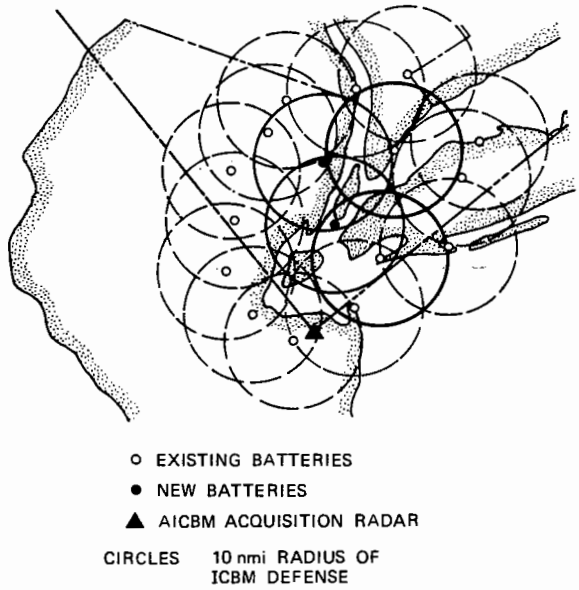


Figure I-15. ICBM Coverage in New York Area

CHARACTERISTICS

FREQUENCY	4500 MHz ± 250
PEAK POWER	3000 kW
PULSE WIDTH	3.0 μSEC
RECEIVER NF	7.0 dB
ANTENNA GAIN	47 dB
ANTENNA SIZE	20 FT DIAMETER PARABOLIC DISH
TRACKING ACCURACY	SAME AS NIKE B TRACK

ESTIMATED RANGE PERFORMANCE

RADAR CROSS SECTION (m^2)	RANGE (nmi)
16	800
1	400
0.1	220
0.01	125

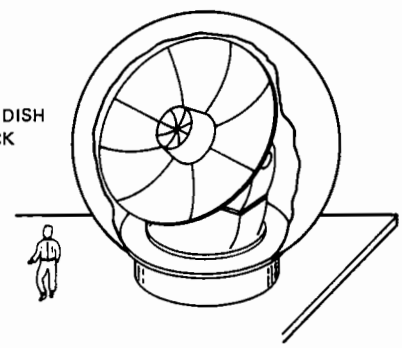


Figure I-16. Long-Range Track Radar

During the period of this NIKE II and Air Force AICBM study, there were many scientists in the various government agencies and in universities who believed it was impossible to intercept a target going 24,000 ft/second, comparing it to "hitting a bullet with a bullet." Recognizing that guidance of a defensive missile to accurately intercept ICBMs was a challenge, an analog simulation room used in testing the NIKE-AJAX and HERCULES Systems at Bell Laboratories in Whippany was modified to handle ICBM intercepts. After some 50,000 intercept runs under varying threat parameters and intercept altitudes, it was convincingly demonstrated that ICBMs could be accurately intercepted when the guidance was properly scaled to the high-speed target. Furthermore, through the use of analytical prediction tested in these simulations, the 60-g slowdown of the ICBM could be adequately handled by a defensive missile of much lower steering capability. Following a series of visits to Bell Laboratories by DOD and military groups to witness these simulations, the question of being able to accurately intercept an ICBM was no longer seriously challenged — although it was not until six years later that full-scale intercepts of actual ICBM targets were confirmed in tests at Kwajalein Island in the Pacific.

Results of NIKE II Study

In October 1956, the results of the NIKE II 18-month study were presented in the Pentagon to Lt. Gen. J. M. Gavin and the Army General Staff. The final written report on NIKE II* was published March 1, 1957. The report included both the defense against air-breathing targets with a seeker-nose missile and the defense against ICBMs with a separable thrust-vectoring nose for intercepts outside the atmosphere. In this final report, the Luneberg lens-type of acquisition radar was fully refined and proposed for two applications. It would be used for both the forward acquisition coverage called FAR and for a high-data-rate (2 seconds) Local Acquisition Radar (LAR) within the defended area to provide hemispheric coverage and multi-tracking of 50 to 100 targets. The plan of integration is shown in Figure I-17. Artist views of the acquisition radars as proposed are shown in Figures I-18 and I-19 and the weapon battery in Figure I-20. The ICBM defensive missile shown in Figure I-21 would carry a 400-pound nuclear warhead and provide 10-g maneuverability at 100,000 feet. The thrust-vectoring nose would be required for end-game steering at altitudes above 80,000 feet.

*System Study, NIKE-ZEUS Guided Missile System, Bell Laboratories Report, Vol 1 Requirements and Vol 2 Appendices, March 1, 1957, (SECRET).

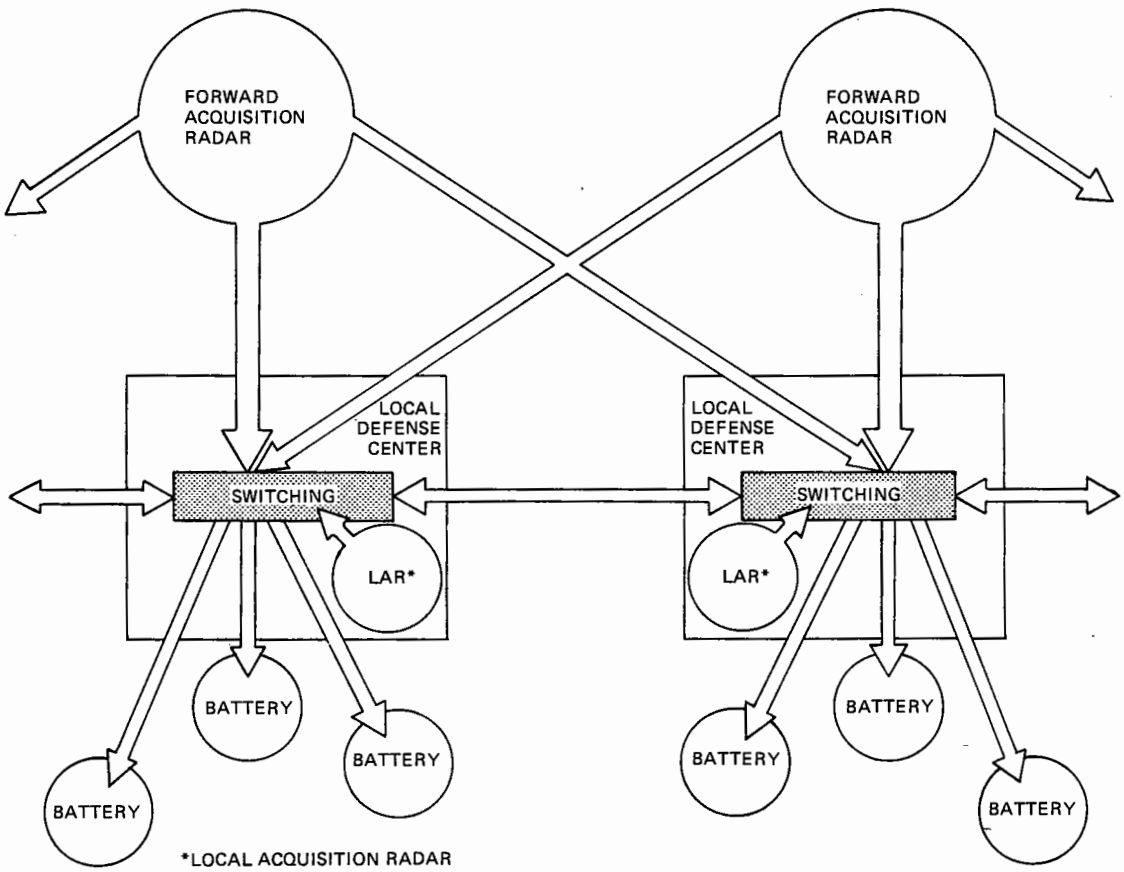


Figure I-17. NIKE II Plan of Integration

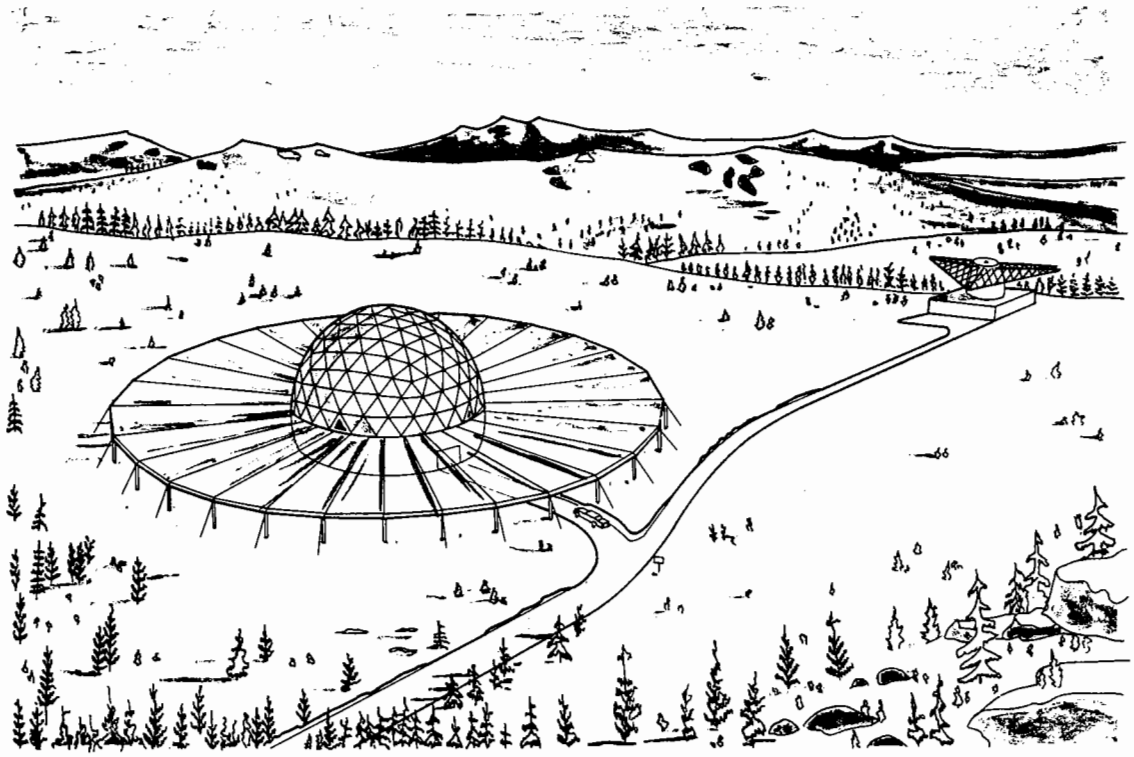


Figure I-18. Proposed Forward Acquisition Radar

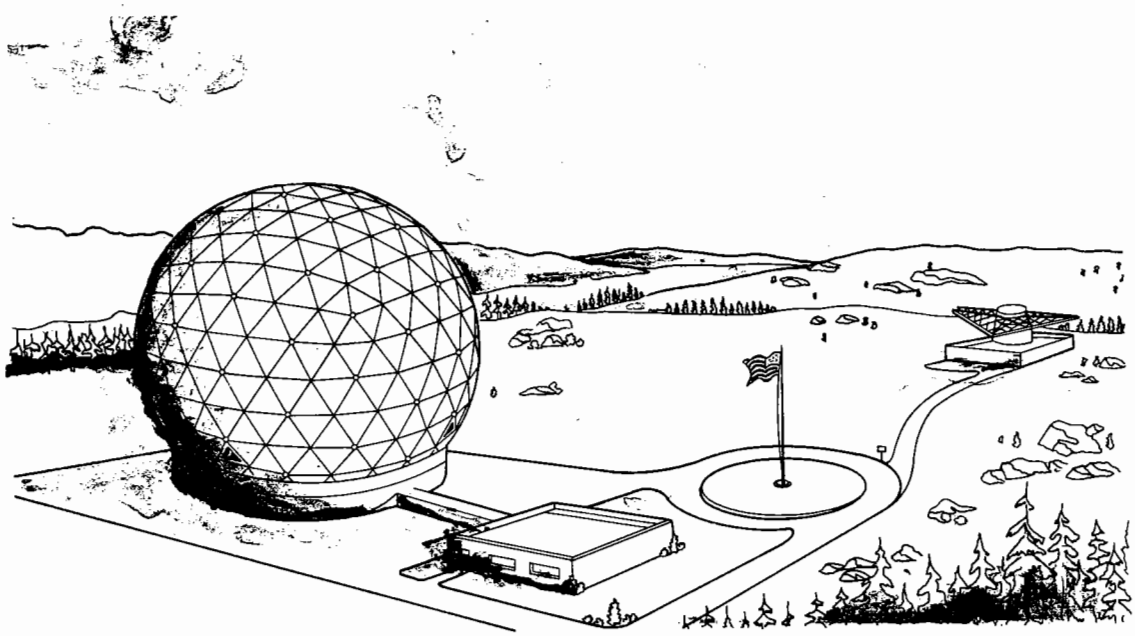


Figure I-19. Proposed Local Acquisition Radar

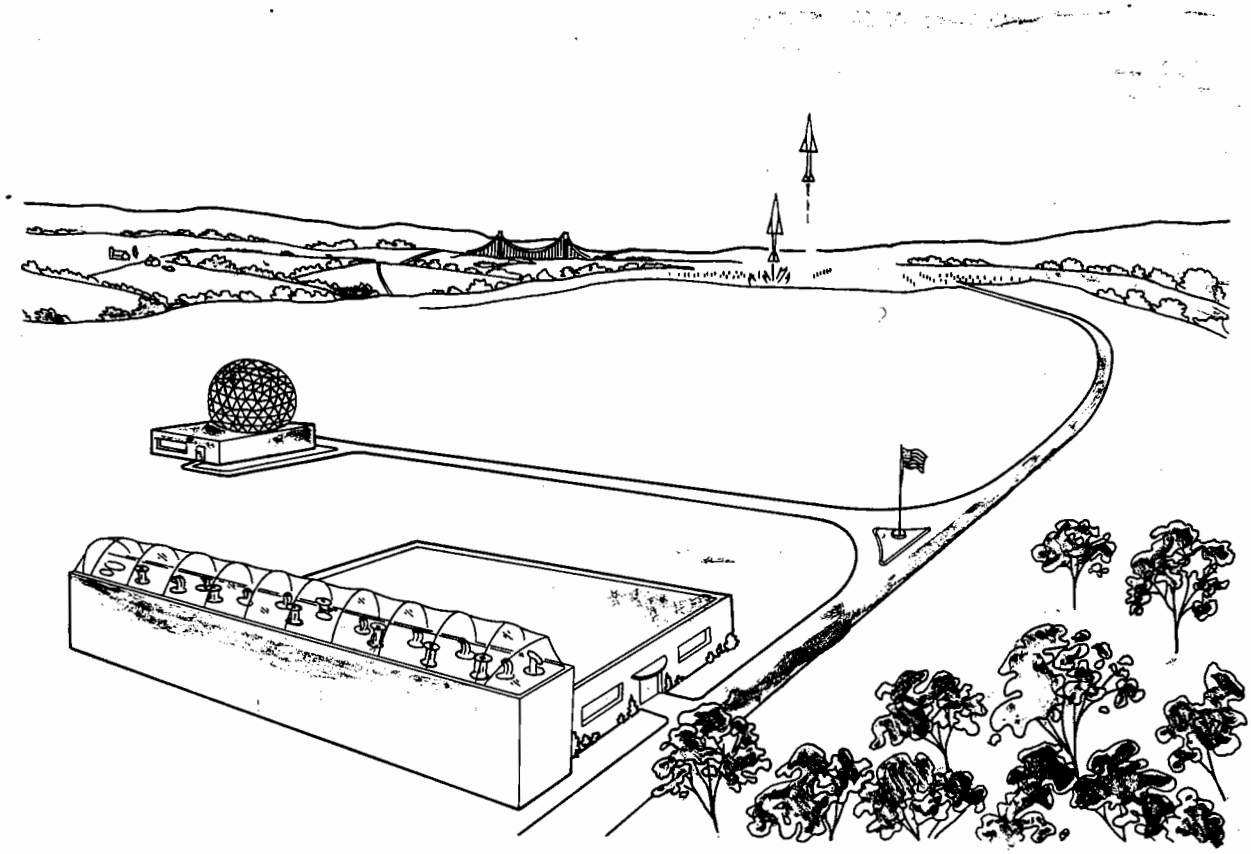


Figure I-20. Weapon Battery Installation

In late 1956, a report on the same system was given to the Air Force upon completion of the year's study. As mentioned earlier, the additional effort for the Air Force was applied to studies of the forward data gathering and on the communications network required for connection to local defense elements.

In reporting on an ABM communications system for both the Air Force and Army final March 1957 studies, the following general features were proposed:

- The system should be completely automatic with all elements electronic and capable of operating at high speed. A communications message-numbering plan should be used, based on the destination of the data (FAR to specific battery).
- The system should use intermediate switching to reduce the number of channels required for a full Continental United States (CONUS) defense network.
- Multi-alternate routing should be used to provide reliability.
- Error checking should be incorporated to ensure accuracy in transmission.
- Each message should be acknowledged to increase reliability.
- Voice-bandwidth channels should be used universally. (A proposed communication route was presented for defense of the northeastern United States.)

As part of the final March 1957 report, a complete Development Test Plan for the proposed system was included, covering a six-year period from initial development to system demonstration tests against real ICBM targets at a remote testing range.

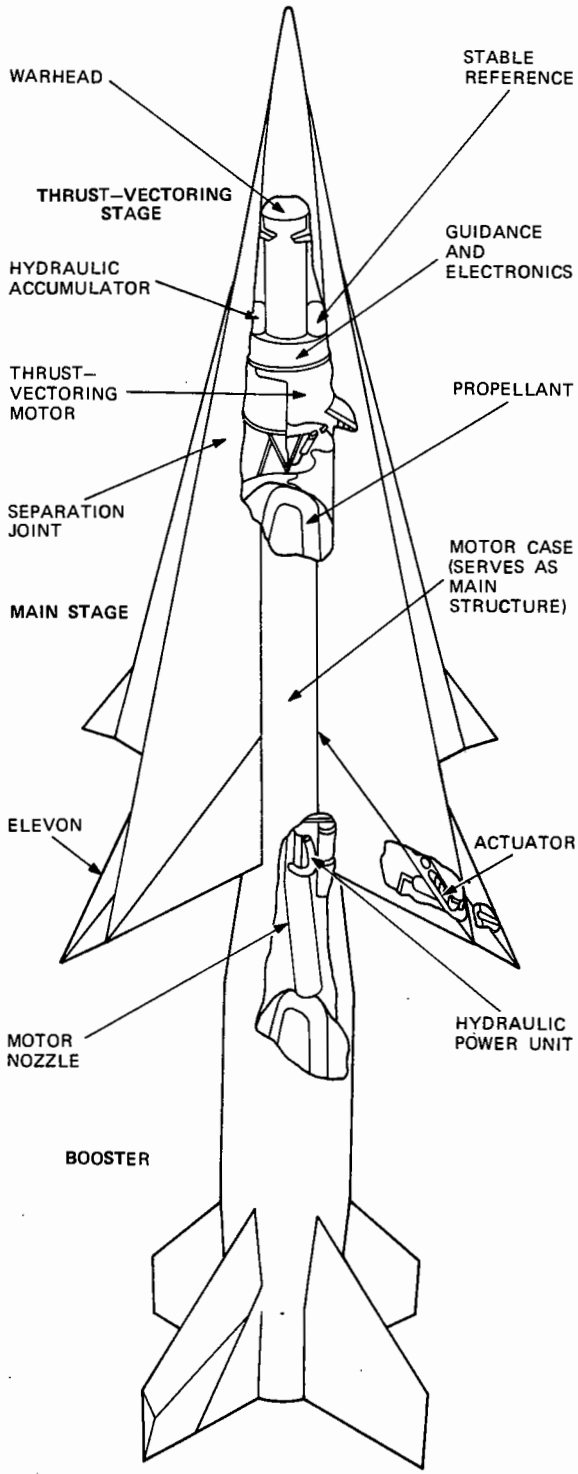


Figure I-21. The Defensive Missile

AICBM Report

During the period of these studies, there was intense rivalry between the Army and the Air Force for the mission of ICBM defense. Our work at Bell Laboratories resulted in one system concept, with the additional Air Force effort affording an opportunity to study the overall communications network, including problems of data processing and data transmission. General Hertford of the Army had no objections to including appropriate parts of the results of the NIKE II study in our study report to the Air Force. In actual practice, the combined study effort proved somewhat embarrassing since, in presentations to top DOD and special antimissile committees, the same Bell Laboratories/McDonnell-Douglas system concept was presented by both the Army and the Air Force.

After the AICBM report was made to the Air Force, they established a task group to review the Bell Laboratories/McDonnell-Douglas system and those of the other two contractors. The Air Force Air Research and Development Command (ARDC) Report of January 1957 informally indicated that they would like Bell Laboratories to continue their contract for another six months at a level of about $200,000 to cover further analysis of decoy work. Since a major effort on AICBM was continuing for the Army, the actual supplementary extended study for the Air Force was for only $90,000 directed specifically to decoy discrimination. (Roles were subsequently redefined giving responsibility for AICBM effort to the Army.)

AICBM DEVELOPMENT CONTRACT — NIKE II/NIKE-ZEUS

In February 1957, the Army awarded Western Electric/Bell Laboratories prime contractor system responsibility for development of an AICBM defense system and changed its name from NIKE II to NIKE-ZEUS. With the growing concern for the ICBM threat, Bell Laboratories

concentrated solely on the ICBM defensive missile, hence terminating work on the seeker nose for air-breathing targets. The level of research and development effort for the first year was to be about $12 million, including subcontract work by McDonnell-Douglas on the missile, RCA on the transmitter, and Goodyear Aircraft Company on the antenna structure.

Major changes were made in certain elements of the NIKE-ZEUS System from that described in the March 1957 report during the early development phase.

Discrimination Radar

One of the major research and development problems mentioned in both AICBM reports to the Army and Air Force was the task of separating the reentry body from the various decoys and junk that might accompany it. Consequently, research and systems work continued on this high-priority problem as development work on the overall system was initiated. The Target Track Radars (TTRs) in the proposed NIKE-ZEUS System would have to see all the objects in a cloud assigned to them by the Acquisition Radar and track one of the objects (preferably one near the center of the cloud). At the same time, the radar would have to systematically examine all received signals from the cloud of objects at a high data rate to permit a wideband frequency analysis of the radar return signals. The implementation for scanning would be such that once the reentry body was identified, precise automatic position and velocity tracking of the target would have to be established in a few seconds by the TTR.

Note that at this particular time, radar measurements of incoming ICBMs were not available, since the first successful ICBMs were not flown until the 1959-1960 time period. Consequently, such discrimination possibilities as scintillation, radar size, and slowdown were proposed among other methods whose success might depend on the ability of the TTRs to obtain the high data rate mentioned. Thus, three methods were considered to increase the angular field of radar coverage for examining an incoming cloud: (1) scanning the TTR beam, (2) increasing the TTR beamwidth, and (3) providing additional receiver beams in the same TTR focusing structure. The first method was dropped, because the intermittent data would seriously limit radar data rate and would present a problem in tracking one of the objects while scanning the cloud. The second method of a larger beam was not practical because of the serious loss in radar range and accuracy. The third method was then proposed as a modification to the TTR, and was named the "Fly's Eye" Antenna.

The principle of the Fly's Eye Antenna is shown in Figure I-22, where an array of antenna feedhorns is clustered about the monopulse horns which would be used for accurately tracking the target after discrimination. The center monopulse horns would transmit and receive in the conventional manner. The cluster of horns located on the main reflector would act as range-only receivers and provide a field of view of about 4-1/2 by 4-1/2 degrees, as shown in Figures I-23 and I-24. A separate transmitting antenna slaved to the large TTR mount would provide the illumination for the range-only receivers. To avoid the losses caused by the hole in the main reflector, a grating of vertical wires would be stretched across the horn openings and the secondary reflector would be designed to shift the polarization from horizontal to vertical.

With these changes, and with pulse-collapsing chirp techniques for fine range resolution together with multiple range-tracking circuits, high-data-rate signature outputs on objects in a cloud would be provided for radar signature and aerodynamic discrimination. These discrimination circuits would accept the individual gated signals from the multiple range-tracking equipment and perform tests based on differences in amplitude, frequency spectrum, radar frequency sensitivity, ionization, aerodynamic-slowdown characteristics, etc.

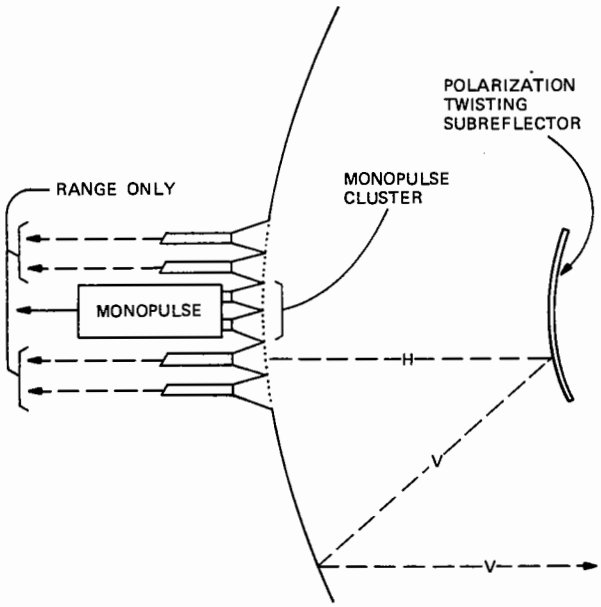


Figure I-22. Fly's Eye Antenna

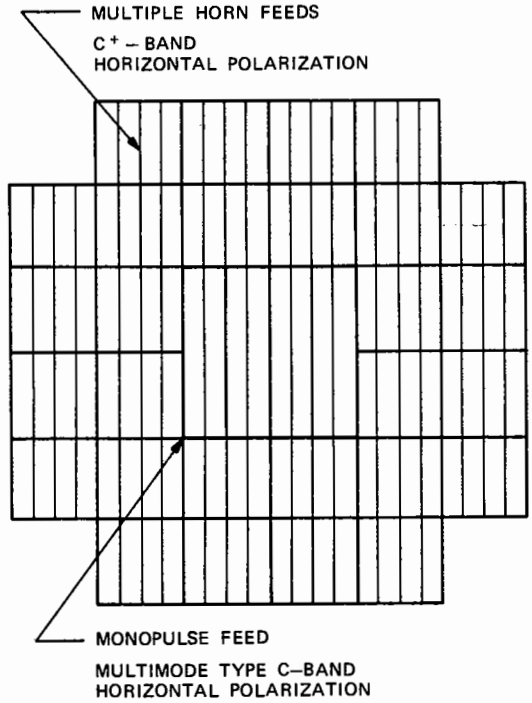


Figure I-23. Fly's Eye Antenna Feedhorn Structure

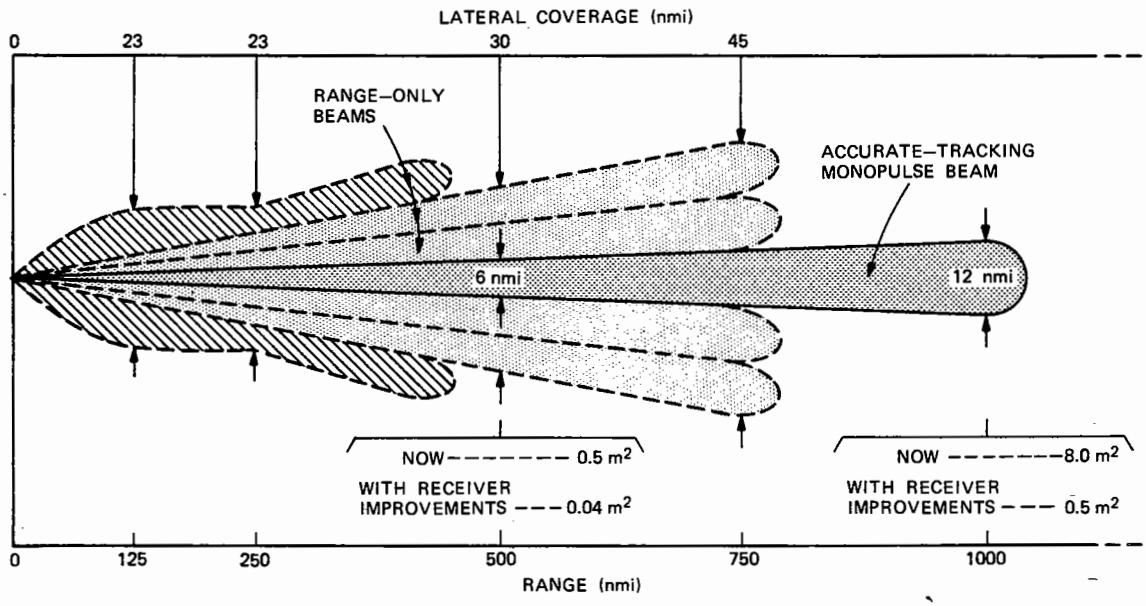


Figure I-24. Fly's Eye Antenna Coverage

On further study of various threat possibilities, the Fly's Eye TTR concept had the major drawback of having a multi-function requirement in a mechanical dish-type radar. Where more than one Reentry Vehicle (RV) was in a cloud of objects, the discrimination function would have to be terminated once the first RV was acquired and precision-tracked for intercept. Furthermore, off-angle data on objects would not be sufficiently accurate for fast acquisition of an RV once it was selected for intercept. The decision therefore was made to have a completely separate Discrimination Radar (DR) and time-share the TTRs to provide precision track of designated targets 6 to 10 seconds before intercept.

The DR became the ZEUS System's instrument to select attacking warheads from debris and accompanying decoys. (For a full description of this radar, see the NIKE-ZEUS System description in Chapter 1 of Part II.) To perform the discrimination functions, the DR would examine a threatening cloud of objects designated by the Acquisition Radar. Radar returns would be processed by an associated DR data processor. The unique feature of this radar was a Cassegrainian-type antenna with a movable subreflector that permitted the radar to continuously widen its antenna beam and maintain cloud coverage as the range decreased. The radar could also provide angle information on all objects off the beam, so that defensive missiles could be launched using this data and, prior to intercept, the data could be transferred to a precision TTR for automatic acquisition of the designated target. The radar was to be designed for operation in the L-band with 40 megawatts of peak power from a low-noise maser RF amplifier. The beamwidth was to be continuously variable from 2 to 20 degrees. A cutaway view of the DR antenna together with its range and angle coverage is shown in Figure I-25.

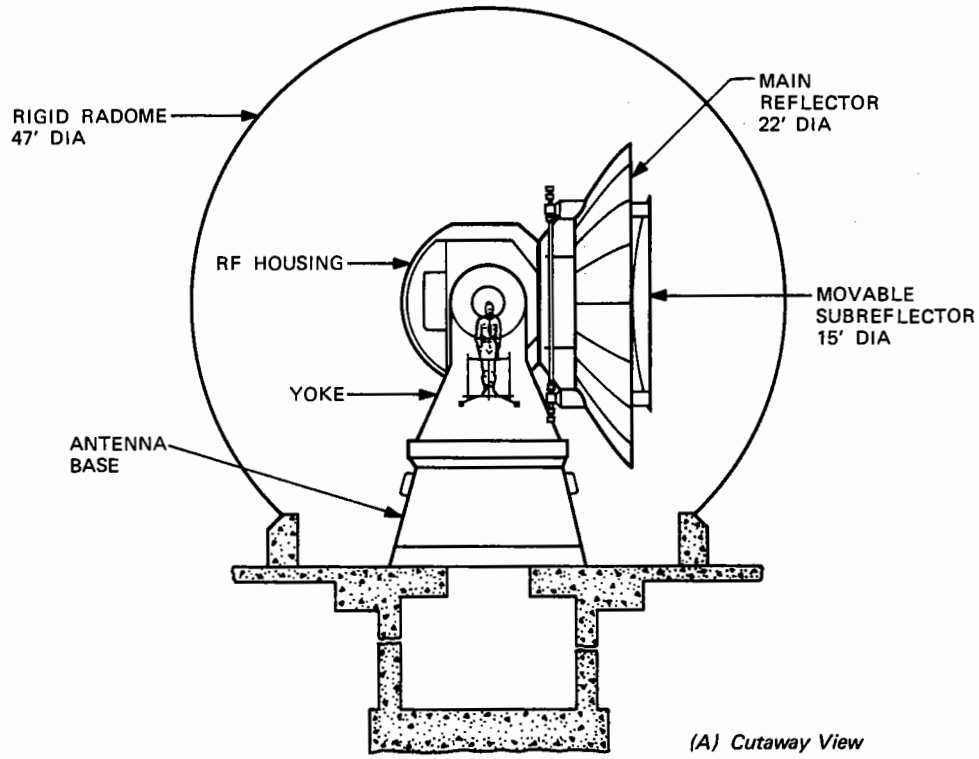
As proposed, the characteristics of the DR returns would be compared with the reentry body radar characteristics stored in the DR data processor. Velocity data obtained by tracking individual objects would also be used by the data processor to measure the slowdown and determine the ballistic coefficient of the objects. Requirements were established for range-tracking up to 100 tracks with three-coordinate data on 10 tracks. Later system studies of threat scenarios indicated a need for 3 DRs, 6 TTRs, and 12 Missile Track Radars (MTRs) in a firing battery.

Acquisition Radar

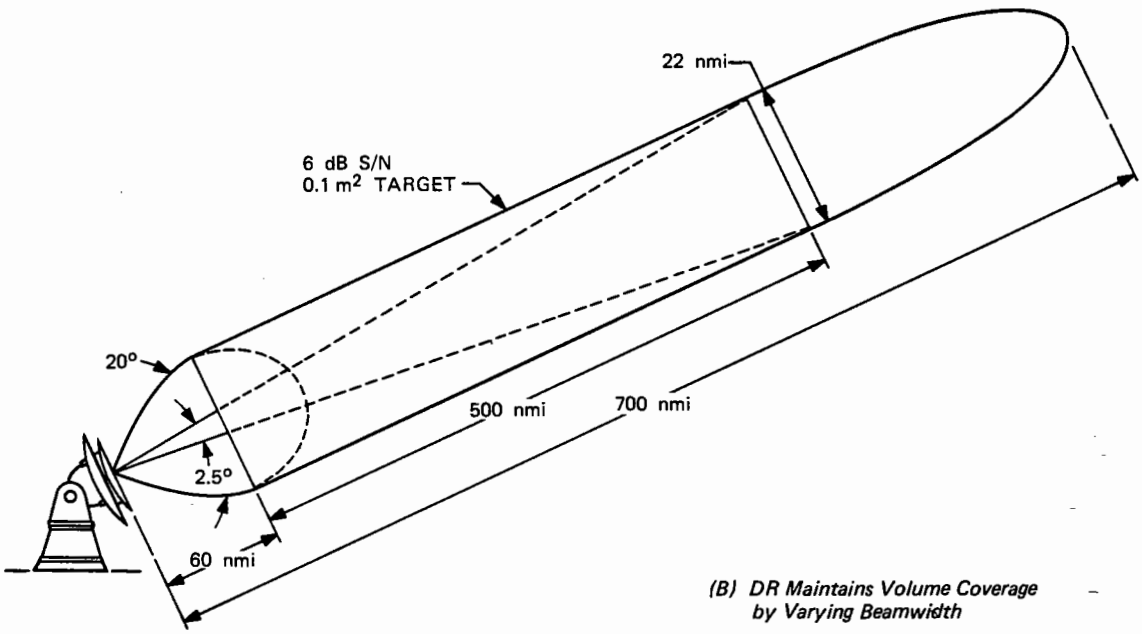
The ZEUS System Study Report included a Forward Acquisition Radar (FAR) and a Local Acquisition Radar (LAR) near the firing battery. Further system studies, however, raised serious questions about the defense of the FARs. Systems people raised the question that if the few FARS were integrated and were important elements of the ICBM defense, then each should be defended n times as well as any of the single batteries associated with it (where n is the number of batteries integrated with a single FAR). With the FARs located primarily in Canada, serious questions were raised on just how essential the FAR installations were to the defense. As a result of these studies, the FARs were eliminated and all search and acquisition functions were assigned to the LARs at each battery. The LAR design, however, was changed from a spherical design to a hemispherical Luneberg lens, as proposed for the FAR, since the hemispheric lens could be made less sensitive to nuclear weapon overpressure effects.

In establishing the 500-MHz frequency of the ZEUS Acquisition Radar (ZAR) during the 18-month study, all important radar parameters known at that time and their sensitivity to frequency were taken into account. However, the effect from nuclear burst at very high altitude was not yet known. The existence of this threat was later shown theoretically and partially verified by the high-altitude nuclear test program at Johnston Island.

It became clear through further study that radar-signal attenuation due to nuclear burst



(A) Cutaway View



(B) DR Maintains Volume Coverage by Varying Beamwidth

Figure I-25. Discrimination Radar

effects is reduced by the square of the radar frequency. This new factor was taken into account in balancing the optimum frequency of the ZAR. The tactical design chosen was modified for 1000 MHz, although all prototype radars underway for White Sands Missile Range (WSMR) and Kwajalein were left in the 450-MHz range. While a tactical design radar was never constructed at 1000 MHz, design effort and manufacturing plans for the Luneberg lens dielectric material, receivers, and transmitters were changed to the higher frequency.

ZEUS Missile

The missile design proposed in the 18-month study was to have a jethead-type nose for ballistic missile defense and an active-seeker nose for future air threats. With the new emphasis concentrated on ballistic defense, the seeker development was dropped as mentioned before. The antimissile missile as originally proposed had the aerodynamic control system packaged around the second-stage nozzle for controlling elevons on the main fins entirely separate from the control system for the jetavator motor in the nose section. It soon became apparent that substantial simplification could be achieved by changing to forward aerodynamic canard control combined with thrust-vectoring control. With such a change, two control systems were reduced to one, and all electronic controls would be in the nose section — a major simplification.

This change, however, required that thrust control be obtained by exhausting the thrust motor's hot gases through the aerodynamic control fins. Although the change greatly simplified the electronics and hydraulic control system, the problem was transferred to the mechanical designers who had to design 180-degree reversal exhaust systems through the fins capable of withstanding extreme temperatures for the 12-second operation of the thrust motor. Many failures resulted in the step-by-step solution to this problem, which involved complex surfaces of tungsten and carbon materials. In the end, a highly reliable system resulted, but not without pain to the McDonnell-Douglas engineers.

Further Meetings on NIKE-ZEUS System

A complete summary of all the presentations made to high-level personnel in the government during the development years of NIKE-ZEUS would fill many pages. A sample of presentations in 1959 is given below.

- A NIKE-ZEUS meeting at Bell Laboratories, Whippany, in March 1959. The following people attended:

  W. A. Holaday — DOD Missile Director

  Dr. H. Skifter — DOD

  Maj. General D. E. Beach — Dept. of Army

  Maj. General W. W. Dick — Dept. of Army

  Brig. General A. J. Pierce — North American Air Defense Command (NORAD)

  Representatives from AT&T, Western Electric, Bell Laboratories, and McDonnell-Douglas.
- Briefing for Dr. Herbert York and his DOD staff on April 15, 1959, in Washington, D. C. covering possible degradation of system capabilities in the presence of various countermeasures.
- Similar meeting with presidential advisor Dr. James Killian's staff on April 24, 1959, in Washington.
- Army Policy Committee briefing by Army and Bell Laboratories representatives on May 6, 1959, in the Pentagon.
- Lt. Gen. C. E. Hart, Commander-in-Chief of the Army Air Defense Command (ARADCOM) briefed on May 19, 1959; General E. E. Partridge, Commander-in-Chief of NORAD and Air Marshal Sleman, Deputy Commander of NORAD briefed on May 20, 1959.

FIELD TESTING THE NIKE-ZEUS SYSTEM

Suitable locations for field testing the high-performance subsystems of ZEUS and for testing the overall NIKE-ZEUS System represented major new challenges to DOD, the Army Missile Command, and the system prime contractor. Some of the background in arriving at these worldwide test locations is briefly covered here.

Early testing of the ZEUS missile in the fall of 1959 was necessary to establish the extent of the aerodynamic heating problem in such a

high-velocity missile. White Sands Missile Range was selected for these critical tests using a modified HERCULES missile radar for tracking. However, the test flights had to be limited to aerodynamic control below 100,000 feet to keep within the 100-mile limit of the range. Of particular concern was the very long carry range of heavy missile parts in case of missile failure when testing outside the atmosphere with the jethead thrust control.

Many presentations were made to top DOD R&D officials by the Army and Bell Laboratories showing the very low probability of any missile parts landing in a populated area. Some consideration was given to clearing a 25-mile extension of the range, but even this would not permit full altitude testing of the missile. A decision was therefore made to provide a second missile test site at the Naval Test Range at Pt. Mugu, California. A ZEUS missile track radar, guidance computer, launching equipment, etc., had to be installed at Pt. Mugu to permit testing the ZEUS missile at high altitude outside the atmosphere. As it developed, Pt. Mugu proved to be a poor missile test site for ZEUS because of the severe range-safety restrictions imposed by the Navy resulting in fail-safe delays of only a fraction of a second. This led to a number of good missiles being destroyed early in flight without obtaining any useful data.

The importance of R&D effort and continued field testing for ICBM defense were given top priority in August 1957, when the USSR announced that it had successfully tested an ICBM shortly after placing Sputnik I into orbit. It became increasingly important to ready the ZEUS System for tracking our own incoming ICBMs as soon as they became operational in the Atlantic Test Range. We had to learn if we could successfully track a reentry body through slowdown and, in addition, what discrimination possibilities might be realized. These were questions critical to the success of the ZEUS System. Top priority was given to the installation of a ZEUS Target Track Radar (TTR) on Ascension Island, the target area planned for ICBM launches from Cape Canaveral, Florida. At Whippany, a similar TTR installation was built simultaneously to provide a local prototype for correcting design problems.

In addition, a full-scale program was begun at White Sands Missile Range. This involved ZEUS missile firings and the installation of major components of the ZEUS System — the large spherical acquisition radar, the associated missile and track radars, and the ground guidance computer — to prove in the designs.

Still to be found, though, was a location where the entire NIKE-ZEUS System could be installed and eventually tested against real offensive targets. Since this one key site had yet to be selected, it was temporarily referred to as "Site X." In January 1958, Bell Laboratories, Western Electric, and Army planners began shopping for a suitable location. The logical place to look was the Atlantic Range area, where Antigua, Barbuda, and Ascension were the first locations considered. These islands, however, were not U.S. possessions and their potential use for missile firings was considered too sensitive. Another location had to be found. General E. Dooley of the Army Rocket and Guided Missile Agency (ARGMA) was the prime mover in arriving at a suitable test site.

Attention then shifted to the Pacific area. Planners pored over maps and studied data and photography of a dozen Pacific islands and atolls. As the study progressed, Kwajalein Atoll in the Marshall Islands began to look more and more attractive, for a number of reasons.

Kwajalein was not owned by the U.S., but it had been under American stewardship continuously since 1944. Kwajalein was once a Navy base, but appeared headed for phaseout. Although it was remote, Kwajalein was still within a day's flying time of Hawaii; Johnston Island, another possible test site, lay almost directly enroute. Most desirable of all, however, were Kwajalein's existing facilities and its geographic location. Kwajalein already had an airstrip, a harbor, housing areas, schools, a hospital, merchandising facilities, and more. In addition, Kwajalein was roughly 4800 miles from the West Coast, a range nearly ideal for testing NIKE-ZEUS against ICBM targets of opportunity to be launched from Vandenberg Air Force Base.

On February 12, 1959, on recommendation of ARGMA, supported by Bell Laboratories and Western Electric, DOD approved a test program for NIKE-ZEUS with Kwajalein as the down-range test site. The sponsoring Army organization would become a tenant on the naval base. Plans called for a Kwajalein-Johnston Island testing complex, with Jupiter Intermediate Range Ballistic Missiles (IRBMs) fired from Johnston Island toward Kwajalein. A year later, however, Dr. Herbert York (then Assistant Secretary of Defense for R&D) ruled that only Air Force Atlas ICBMs launched from Vandenberg would be used as target vehicles for NIKE-ZEUS. Thus, work on Johnston Island was halted. With the beginning of operations at Kwajalein, and for a number of years thereafter until Ascension Island closed, the NIKE-ZEUS System development and test activities were 12,000 miles apart on opposite sides of the globe.

With selection of Kwajalein, project managers, anxious to inspect the new site, chartered a Pan American DC-7 which touched down on Kwajalein on August 4, 1959. The 41 passengers aboard represented various Army agencies, Bell Laboratories, Western Electric, McDonnell-Douglas, and other subcontractors.

The initial work at Kwajalein belonged to the Army Corps of Engineers and their subcontractor, the Pacific Martin Zachry Company, who was responsible for the NIKE-ZEUS technical building and launch facilities. They were followed later by Western Electric equipment engineers and installers responsible for the NIKE-ZEUS installation. On October 1, 1960, Bell Laboratories announced the establishment of the Kwajalein Field Station, and four days later, Mr. R. W. Benfer of Bell Laboratories arrived as its first director.

HIGHLIGHTS OF NIKE-ZEUS R&D TEST RESULTS

ZEUS Missile Tests

The NIKE-ZEUS System Test Program required solution of numerous problems before successful intercept of live ICBM targets could be accomplished. The ZEUS missile, operating in the lower altitude region with a peak velocity three times that of NIKE-HERCULES, presented aerodynamic heating problems even greater than an ICBM reentry body. During the 18-month initial study and exploratory development effort, McDonnell-Douglas aerodynamic engineers carried out wind tunnel tests at high-supersonic velocities and heat-tested various ablative coatings such as teflon and fiberglass to protect the missile structure. However, the extent of the problem was not fully appreciated until the early ZEUS missiles were flown at the White Sands Missile Range.

Catastrophic failure of these early flights occurred within a few seconds of the missile's reaching peak velocity, and ground cameras recorded what appeared to be a fire aboard the missile prior to its failure. A hydraulic oil fire was suspected and steps were taken to provide heat shields around the hydraulic power system for future missile flights. However, after these changes, fire was still observed in the nose section and missile failure occurred as before. It was not until missile pieces were recovered from the desert range and partially reassembled that the real problem was discovered.

It was clear from examining the four control fins that their large-diameter hardened-steel shafts were sliced off by aerodynamic heating which resulted in loss of control and missile destruction. The control fins were purposely shaped to have wide separation from the missile skin based on aerodynamic wind-tunnel data. After returning to the wind tunnel with much finer measurements of pressures under the fin surface, high pressure points were discovered that resulted in concentrated heat levels. On redesign, a teflon ramp was provided under the control fin giving close spacing. In addition, circular traps were provided to protect the control shaft, much like a radar engineer would design to protect the ball bearings in a shaft from RF power. With these changes, the major aerodynamic problem was solved, opening the way to successful ZEUS missile firings. This ramp design and close

spacing for the control fins was adopted by Martin designers for the SPRINT missile some six years later. As a result, even though SPRINT's velocity was higher at lower altitudes, with much greater aerodynamic heating, the same basic design was successful in protecting its control fins.

The other major step forward in missile design was providing aerodynamic and thrust control from the same control fins. The problem of handling the hot gases of the third-stage motor through a manifold system into the control fins was solved by extensive ground testing with many configurations of tungsten and carbon materials. As a result, relatively few failures of the jet control system occurred in early flights at high altitudes from the Pt. Mugu range.

One important lesson learned from the ZEUS development firings, and reaffirmed years later with SPRINT, is that there is no substitute for missile testing over a ground range where the pieces can be recovered and the cause of failure found. This is especially true where the state of missile art is being advanced significantly and where there is a limit to the number of missile-borne sensors capable of detecting the cause of failures. A summary of these early ZEUS missile firings is given in Table I-2.

TTR-Whippany/Ascension

The first attempt of the TTR at Ascension Island to track an ICBM (Titan) fired from Cape Canaveral took place on March 29, 1961. This attempt failed because the TTR computer did not properly translate trajectory data from Cape Canaveral to position the antenna needle beam. However, on May 28, 1961, an ICBM from Cape Canaveral was tracked along its trajectory down the Atlantic Missile Range. These initial tracking tests were not perfect, but for the first time they did permit analysis of target characteristics and measured our ability to track such high-speed targets.

Concurrently, a similar TTR at Bell Laboratories, Whippany, was used to investigate these early automatic tracking problems. On May 6, 1961, the Whippany TTR successfully tracked the Echo satellite at distances up to 1400 miles. Later in the year, four ICBMs (two Atlas and two Titan) were successfully tracked by the Ascension TTR with continuous tracks of up to 100 seconds. In the last tracking, the Atlas had a nose cone designed for NIKE-ZEUS tests at Kwajalein. The nose cone had the same radar

Table I-2
Summary of Early ZEUS Firings

	No Test	Failures	Partial Success	Full Success	Total
	Development Firings				
WSMR	-	15	7	34	56
PT. MUGU	-	5	4	10	19
KWAJALEIN	-	2	1	1	4
				Total	79
	Missile Performance in System Tests				
WSMR	2	3	0	11	16
KWAJALEIN	5	12	7	28	52
				Total	68
				Total Firings	147

cross section as a regular Atlas nose, but it also had special shaping to reduce the plasma-sheath effect on radio signal propagation. This was required for a radio doppler miss-distance indicator to be used later in system tests at Kwajalein.

White Sands Missile Range Tests

Initial operation of the ZEUS Acquisition Radar (ZAR) as a system was accomplished at WSMR in June 1961. Typical targets were automatically acquired and tracked in three dimensions. The targets included balloons, aircraft, parachutes deployed from Highball missiles, and HERCULES missiles. These three-dimension tracks were transferred to Battery Control, where they were automatically acquired by the TTR subsystem.

Such tests were historic in that the ZAR was the first track-while-scan radar system to successfully cover the entire hemisphere surrounding a radar position, detect the objects in that space, remember their past positions, and predict where the objects would next be in three dimensions — all automatically, beginning with initial detection. Even today, considering the advances with phased-array radar systems, the ZAR represents the most efficient wired-logic system for detection, report sorting, track initiation, and track processing ever developed. Its stacked-array receivers on three rotating arms also provided the highest data rate (measured for full hemispheric coverage) yet achieved, and is not mached even by today's phased-array systems.

The TTR radar at WSMR was made operational without difficulty, based on previous testing with a similar design at Whippany and Ascension. The other major subsystem was the Battery Control Building, which contained two Missile Track Radars, the Target Intercept Computer, and data communication equipments. The ZEUS missile had been under development at WSMR for the previous two years, using modified HERCULES equipment for ground guidance.

All elements of NIKE-ZEUS were checked out and system demonstrations begun in November 1961. On December 14, 1961, a major ABM system milepost was passed with the successful interception by a ZEUS missile of a NIKE-HERCULES target missile. A second successful ZEUS system test against a HERCULES missile was carried out in March 1962. Major attention then shifted to the forthcoming system tests at Kwajalein against ICBM targets.

NIKE-ZEUS System Tests at Kwajalein

The entire NIKE-ZEUS System, consisting of the hemispheric ZEUS Acquisition Radar (ZAR), two Target Track Radars (TTRs), one Discrimination Radar (DR), three Missile Track Radars (MTRs), and Battery Control Equipment with Target Intercept Computer and four ZEUS launch cells, was installed on Kwajalein and ready for the first test of intercepting an ICBM on June 26, 1962. The photographs in Figures I-26 and I-27 show this installation.

In the first attempt (probably in the world) to intercept an ICBM fired 4500 miles down range from Vandenberg Air Force Base, the ZAR started tracking the tank at 446 nautical miles and immediately transferred the track to a TTR. The TTR transferred from the tank to the nose cone (the RV) at 131 nautical miles. When the tank began to break up, a clutter mode of operation was initiated in which any significant departure of the RV from a predicted trajectory would indicate that debris had taken over the tracking gate. The radar would then use extrapolated data to "coast" the range gate so as to reacquire the RV after it passed through the tank clutter. Unfortunately, in this first test, the clutter mode did not properly indicate when tracking of the RV was lost. However, the ZEUS missile would not have achieved intercept because of malfunction.

Although this first system test was a failure, it did emphasize the need for sound logic and reliable circuitry to properly track RVs through severe tank clutter. This early lesson carried through to the current tactical SAFEGUARD System tests at Meck Island, where tracking through



Figure I-26. NIKE-ZEUS System Installation at Kwajalein, Looking Toward Lagoon

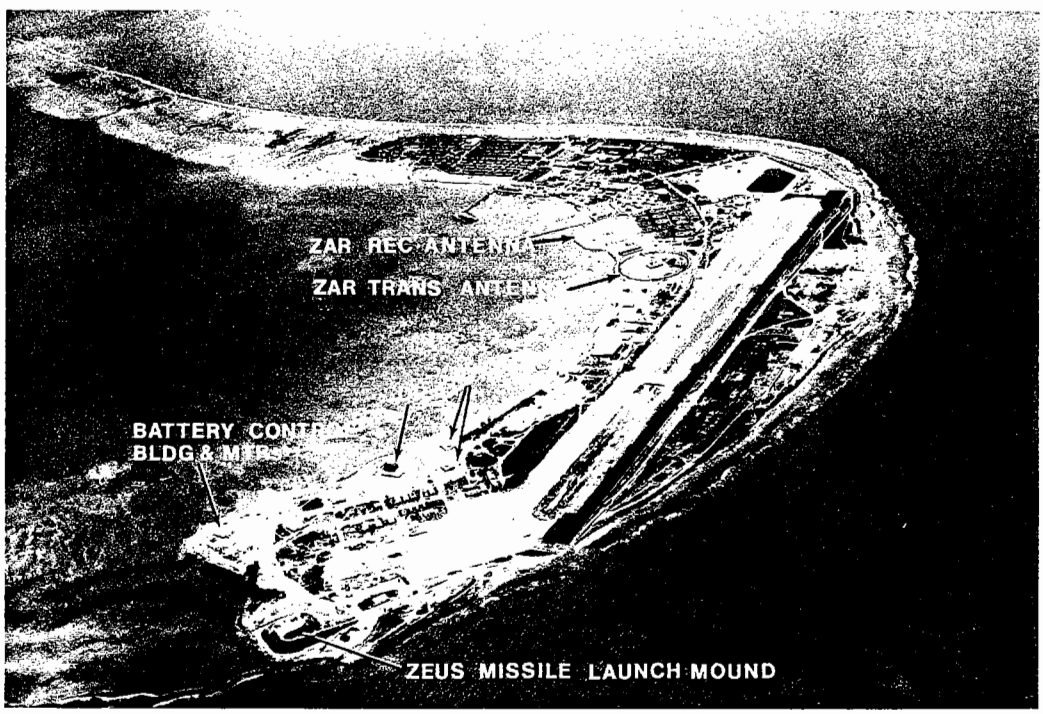


Figure I-27. NIKE-ZEUS System Installation at Kwajalein, Aerial View

clutter has been satisfactorily demonstrated under even more stringent conditions.

The first partially successful intercept of an Atlas D ICBM occurred on July 19, 1962, with the ZEUS missile coming within 2 kilometers of the target vehicle at intercept. The large miss distance resulted from the ZEUS missile losing hydraulic power due to excessive roll during the last 10 seconds before intercept. The second ICBM intercept — this one fully successful — took place on December 12, 1962, with a miss distance well within acceptable limits. A two-missile salvo was planned for the first time with this test, but the second missile failed because of an instrument failure.

Another two-missile salvo intercept of an ICBM was attempted on December 22, 1962. In this test, the first missile missed the target by 200 meters at a range of 55 nautical miles. Again, dual interception did not occur because of a failure with the second missile.

A summary of the live-intercept system tests of ZEUS, extending through November 1963, is given in Table I-3. Of 13 system tests, nine were successful, three were partially successful, and only the first failed. Photographs of some of these intercepts are shown in Figures I-28 through I-31.

With completion of the above live-target system tests and the decision not to deploy the NIKE-ZEUS System, no further live ICBM target tests were carried out. However, further tests under the Satellite Test Program and system tests against taped live targets or simulated ICBMs continued at Kwajalein for another year and a half until June 1965.

Miss-Distance Indicator for ZEUS Tests

Miss distance between target and defensive missile at the instant of commanded warhead burst is the principal measure of performance of an AICBM system. To avoid suspicion of any self-generated miss distance within the ZEUS System, considerable effort was directed at finding an independent miss-distance recorder for the ZEUS System Tests at Kwajalein. One method pursued involved a radioactive source in the ICBM nose cone and a detection system in the ZEUS missile. This work was carried out starting in April 1961 on subcontract with the Giannini Control Corporation. However, a simpler radio-doppler, Miss-Distance Indicator (MDI) was adopted

Table I-3
Summary of Live Target Systems Tests

Mission Number	Date	Target	Remarks
K1	6-26-62	Atlas D	Failure
K2	7-19-62	Atlas D	Partial success
K6	12-12-62	Atlas D	Success (first missile in salvo)
K7	12-22-62	Atlas D	Success (first missile in salvo)
K8	2-13-63	Atlas D	Partial success
K10	2-28-63	Atlas D	Partial success
K17	3-30-63	Titan I	Success
K21	4-13-63	Titan I	Success
K15	6-12-63	Atlas D	Success
K23	7-4-63	Atlas E	Success
K26	8-15-63	Titan I	Success
K28	8-24-63	Atlas E	Success
K24	11-14-63	Titan I	Success

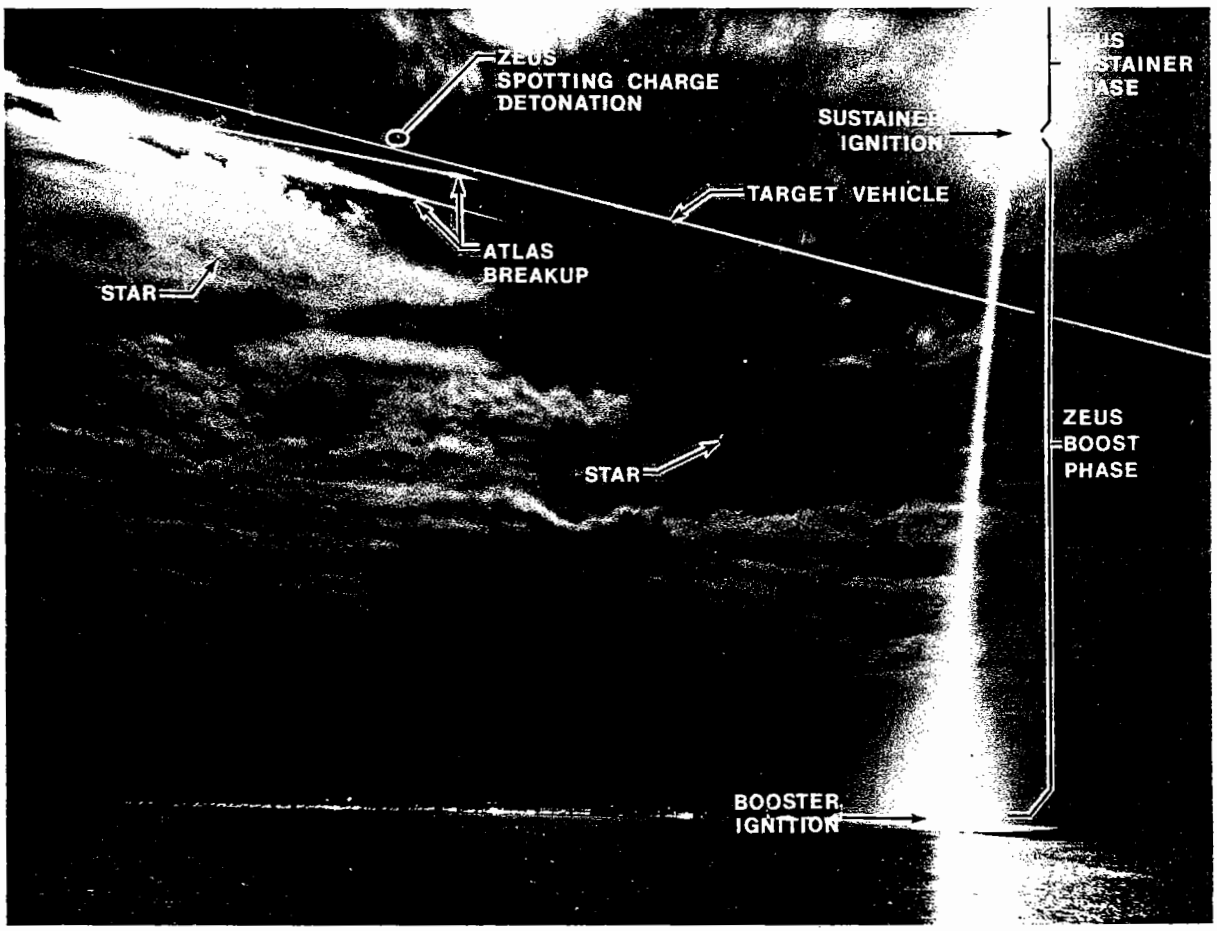


Figure I-28. A 75-second time exposure of the K-2 Atlas D intercept at Kwajalein on July 19, 1962. Picture was taken from Carlson Island (5 miles northwest of Kwajalein).

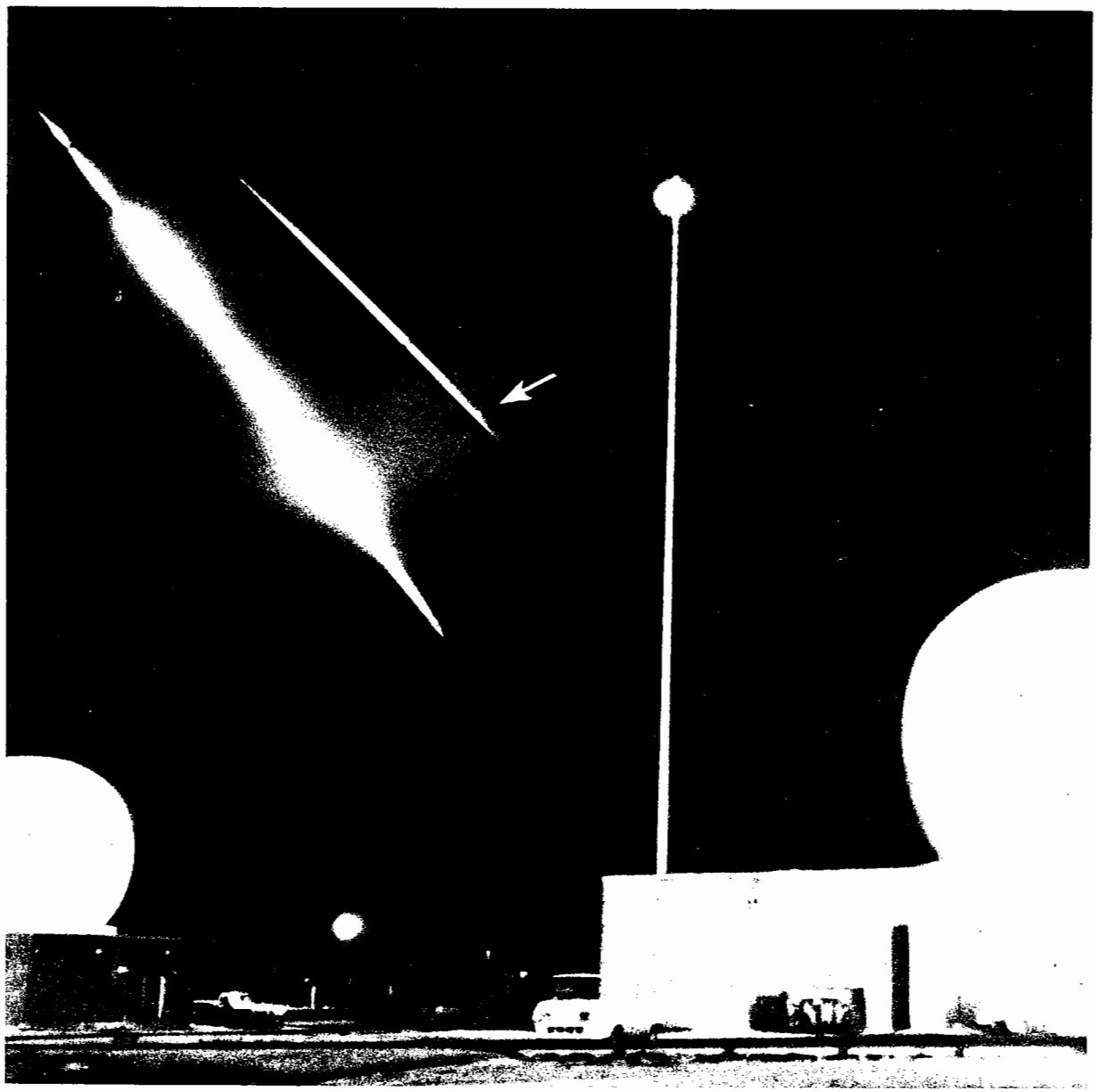


Figure I-29. View of the August 15, 1963, K-26 Titan I intercept test at Kwajalein. The ZEUS thrust-vector motor trail and spotting detonation (arrow) mark the successful intercept.

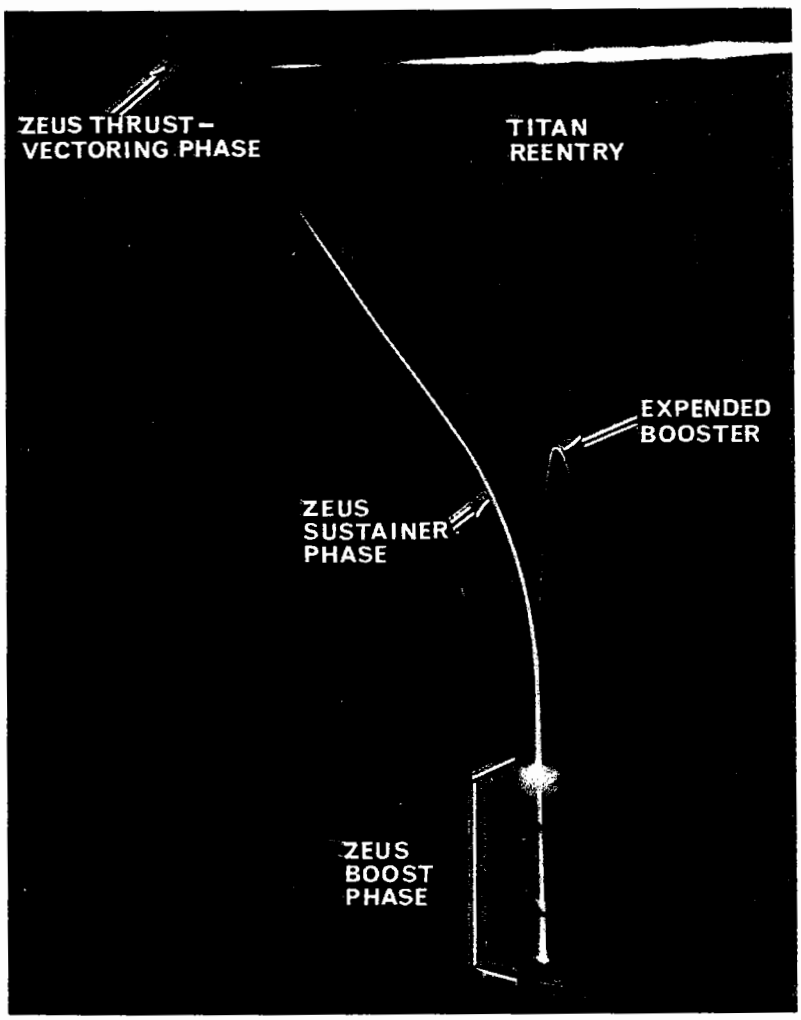


Figure I-30. A 120-second time exposure of the March 30, 1963, K-17 intercept test at Kwajalein. This was the first intercept test to be conducted against a Titan I-boosted target vehicle.

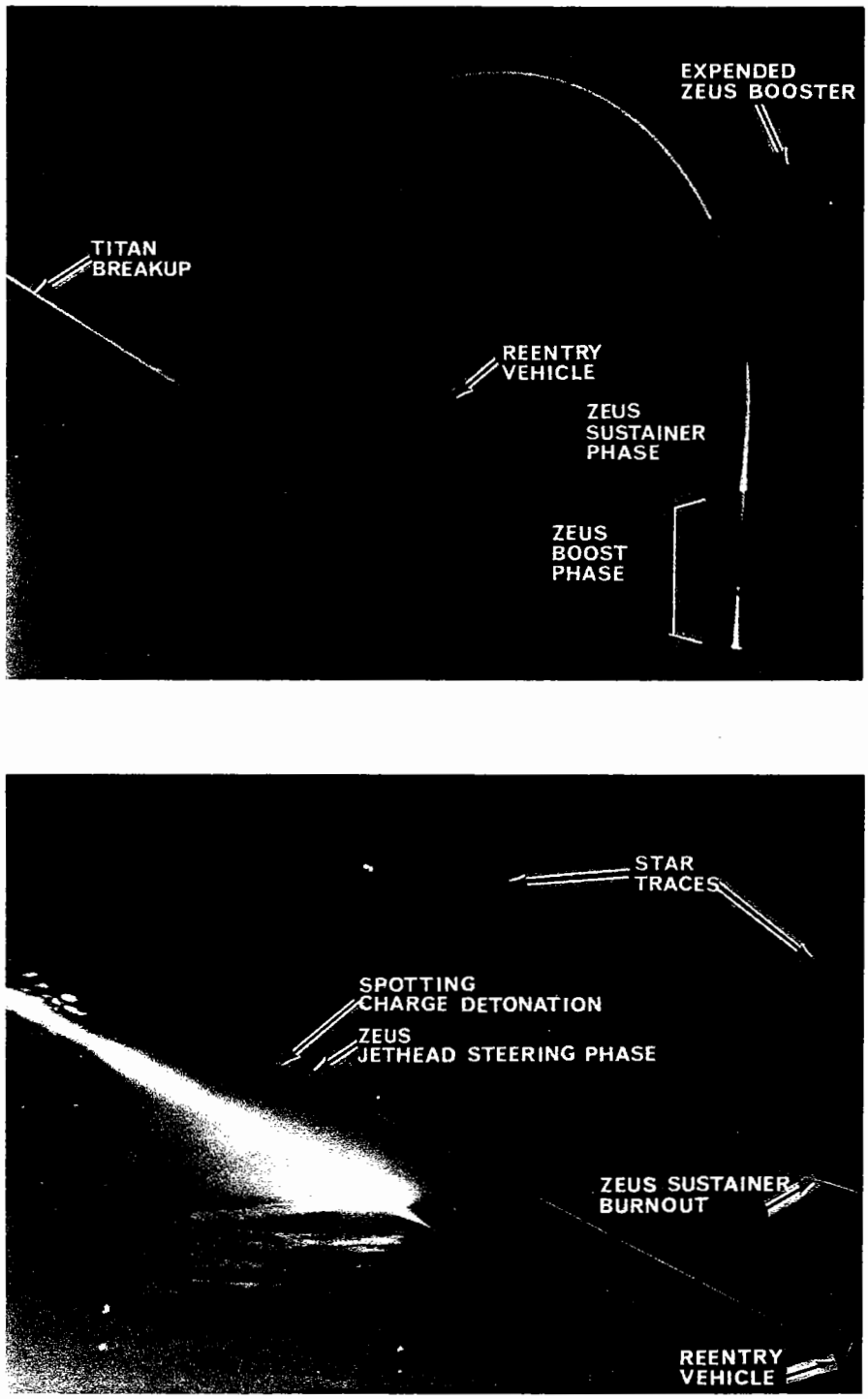


Figure I-31. Two 120-second time exposures of intercept test K-21 conducted April 13, 1963.
Top: Overall view of test taken from Enubuj (Carlson) Island.
Bottom: View showing successful intercept (spotting charge detonation) taken from Ennylabegan (Carlos) Island.

after its successful development by the Physical Science Laboratory (PSL) of New Mexico State University.

Well in advance of the ZEUS System Tests in 1960, PSL was contracted to adapt a Navy AN/US Q-11 radio-doppler, miss-distance measuring set to the environment of Highball and Speedball test-rocket targets being developed for ZEUS tests, and to extend this adaption to the ICBM target environment. The success of this system was dependent on tests carried out in December 1961, in the Atlantic Missile Range, which proved that a signal from a UHF radio transmitter in a reentering ICBM nose cone could penetrate the surrounding plasma sheath. The miss-distance instrumentation planned required such a transmitter in the ICBM and a compatible receiver in the ZEUS missile. The resultant shape of the doppler signal telemetered to ground during intercept, when correlated to the burst-command time, provided an independent measurement of miss distance. This system was made ready for the ZEUS Systems Tests at Kwajalein for live ICBM targets and provided quite accurate measurements matching reasonably well with self-generated miss-distance numbers within the ZEUS equipment.

Consideration was given to adapting the same MDI System for the SAFEGUARD System Tests on Meck. However, the cost of converting the signals to the new telemetry S-band, adapting the system to the much tougher SPRINT environment, and a new requirement for encrypting signals from missile to ground led the Army to cancel this effort. Independent miss distances in the SAFEGUARD tests were obtained from ZEUS TTR tracks of target and missile, combined with optical measurements.

SATELLITE TEST PROGRAM

At request of the Secretary of Defense, the Army was asked in early 1962 to prepare the ZEUS System on Kwajalein for the eventuality of having to intercept and destroy satellites. Bell Laboratories advised the Army that the ZEUS System could be readied for a satellite-intercept demonstration at Kwajalein by May 1963.

Toward this goal, the first DM-15B series ZEUS missile, modified for satellite-intercept tests, was fired at White Sands Missile Range December 17, 1962. The missile successfully intercepted a designated stationary space point at an altitude of 100 nautical miles. This missile reached the highest altitude of any missile launched at White Sands to that date. The DM-15S series was modified for this high-altitude, long-range application to include a two-stage (instead of a single-stage) hydraulic pumping unit, a high-performance Polybutadiene Acrylic Acid (PBAA) booster propellant, and a 5-minute (instead of the normal 2-minute) battery capability. A second DM-15S series missile was fired at WSMR February 15, 1963. In this flight, intercept of space point occurred at an altitude of 151 nautical miles.

The third DM-15S, the first to be tested at Kwajalein, was fired March 21, 1963 to intercept a simulated satellite target at an altitude of 112 nautical miles. The flight was unsuccessful because the MTR failed to properly track the missile. A second missile was fired from Kwajalein April 19, 1963 to intercept a simulated satellite at 160 nautical miles. In this case, loss of beacon return 30 seconds before intercept prevented proper mission completion.

The first successful satellite intercept test and demonstration occurred May 24, 1963, at Kwajalein against a real target. The target was a special "Agena D" stage of the Air Force 162A series. This target was instrumented with the NIKE-ZEUS single-path doppler, miss-distance measuring equipment discussed earlier, and a Luneberg lens for radar augmentation. The TTR first acquired the satellite at long range, and the missile was launched after a period of precision tracking. A close intercept was achieved, well within what was expected to be the lethal range of the ZEUS nuclear warhead.

From this time on through 1964, satellite-intercept missiles were maintained at Kwajalein with one always checked out and in a state of readiness. Arrangements were made by the Army to make a ZEUS nuclear warhead available if called upon for a real satellite mission. (Army personnel on Kwajalein would be responsible for launching the missile in a real defensive operation.) Bell Laboratories and McDonnell-Douglas personnel went through many test runs to minimize the time required to launch such a missile. In addition, successful test intercepts were carried out against simulated satellites and booster space targets in 1964 as part of the training of Kwajalein test personnel. Fortunately, intercept and destruction of an enemy satellite were never ordered. After 1964, we were relieved of this "ready" requirement and were once more able to concentrate fully on the normal R&D test program.

DISCRIMINATION AND SUPPORTING RESEARCH ON ZEUS PROGRAM

As the ZEUS R&D program moved forward, continuing and expanded effort was carried out on the major problem of discrimination. To supplement its own internal effort, Bell Laboratories established subcontracts with Cornell Aeronautical Laboratories (now Calspan Corporation) and Avco Everett Research Laboratories. The principal types of discrimination under investigation in the early 1960's were aerodynamic slowdown, scintillation, polarization, frequency diversity, short pulse, and infrared/optical. Other supporting research was concerned with blast tests to determine the hardness of ZEUS ground facilities, atmospheric effects of nuclear bursts, plasma studies of reentry bodies, and warhead requirements.

The Avco Everett investigation concentrated on infrared, visual, and ultraviolet reentry effects and was carried out with the aid of the NIKE-ZEUS TTR on Ascension Island. Phase I, which began in early 1961, determined discrimination criteria with simple instrumentation in a DC-6 aircraft operating out of Ascension. Optical/infrared data, particularly on wake spectra, were obtained on 14 of 17 ICBMs fired toward Ascension Island in 1961. Phase II started in early 1962, with more sophisticated instrumentation in the aircraft and on the ground. This permitted target designation between the TTR and the optical tracker in the aircraft so that the same object tracked by the TTR could be correlated with optical/infrared data. A HERCULES missile track radar installed on Ascension Island tracked the beacon in a new WV-2 aircraft equipped with a stable reference platform. Positional data on incoming objects could then be transmitted in both directions between aircraft and TTR. Later on, the same aircraft was used at Kwajalein to obtain additional data.

Although useful optical/infrared data were obtained in these tests, no solid discrimination criteria were uncovered to warrant adding optical airborne trackers to the ZEUS system. Furthermore, in attempting to correlate radar and airborne optical data, these tests forcefully demonstrated the practical problems of trying to incorporate such an airborne platform into a tactical system.

In 1961, Bell Laboratories carried out analysis of the effects of plasma on radar observation. It was hoped that the plasma (ionic layer) sheath caused by aerodynamic heating might provide additional means of discrimination against decoys. Other work at Bell Laboratories in this time period showed that extremely short pulses could determine the length of a target and thus provide a possible discriminant.

Major effort at Cornell Laboratories in 1961 and 1962 was directed at testing various radar signatures in the laboratory. These signatures included scintillation, polarization, and frequency diversity. Both Bell Laboratories and Cornell examined methods of incorporating a number of radar signatures into a combined "likelihood" number that would reveal if a given object was a warhead, since no one signature had proved powerful

enough to do this by itself. Other work at Cornell Laboratories, in cooperation with the Ballistic Research Laboratory, involved a study of Atlas booster fragmentation with high-speed cameras.

The discrimination studies and supporting research carried out during this period of the early 1960's provided the basis for continued effort in the years ahead. The lessons learned from the ZEUS program proved valuable in the on-going R&D work for future ABM systems.

ZEUS R&D TEAM

The ZEUS R&D program was a team effort directed by Bell Laboratories with 24 major subcontractors and 89 other subcontractors located in many areas of the country. There were also hundreds of additional suppliers who provided components directly to Western Electric and Bell Laboratories or their subcontractors. In addition to having overall system responsibility, Bell Laboratories designed many of the major system elements. The Western Electric Company in North Carolina manufactured the R&D models of system elements designed by Bell Laboratories and installed, tested, and operated the R&D models at all test sites.

Douglas Aircraft Company (now McDonnell-Douglas) was responsible for the design and development of the missile (less the Bell Laboratories guidance unit), the launcher, and associated ground handling equipment. The major subcontractors and their areas of activity are listed in Table I-4.

ZEUS MULTIFUNCTION ARRAY RADAR — MAR-I

In 1960, Bell Laboratories conducted fundamental investigations of phase-controlled scanning antenna arrays for possible application to the ZEUS System. The potential advantages of radars using such antennas as seen at that time were: (1) increased blast resistance capability, (2) greater power handling capability, (3) flexibility of beam adjustment, and (4) capability of combining several functions in one radar. As discussed further under NIKE-X in Chapter 2 of Part II, phased arrays with their inertialess beams would provide greater capability against the high-traffic-level threat. This consideration became one of the principal technical reasons advanced in 1963 for not proceeding with tactical deployment of the original NIKE-ZEUS System. (There were, of course, many other reasons apart from strictly technical considerations in the 1962-1964 time period for not deploying an ABM system.)

In these forward-looking studies supported by the ZEUS Program, phased-array scanning was analyzed with respect to such factors as (1) element pattern directivity, (2) array pattern deterioration with scanning, (3) pointing-accuracy degradation with scan angle, and (4) frequency. The major steps involved in an engagement from acquisition of the target through intercept were quantitatively evaluated in terms of phased-array radar characteristics and the necessary data processing.

On November 18, 1960, at Redstone Arsenal, Bell Laboratories representatives gave a presentation to ARGMA on the subject of phased arrays in a terminal defense. The purpose of the meeting was to report on the study work performed to date and to provide a basis for a proposal to do exploratory phased-array work.

Authorization to proceed with the design of a prototype model of a phased array, based on the Bell Laboratories study, was granted June 1961. Western Electric had the prime contract and Bell Laboratories was responsible for supervising the design. Sylvania was selected as the major subcontractor for detailed design of the prototype model and fabrication of the model to be installed at WSMR. Sperry Rand Univac was given the responsibility for a Phase II digital computer as well as the programming for the prototype radar. Bell Laboratories was also responsible for major system elements including the large number of solid-state RF amplifiers.

Table I-4

Major NIKE-ZEUS Subcontractors

Company	Location	Area of Activity
Goodyear Aircraft Corporation	Akron, Ohio	ZAR Receiving and Transmitting Antennas DR Antenna Mount and MTR Reflector
Armstrong Cork Company Dow Chemical Company	Lancaster, Pa. Midland, Mich.	ZAR Lens Media
Continental Electronics Mfg. Co.	Dallas, Tex.	ZAR Transmitter
Texas Instruments, Inc.	Dallas, Tex.	Tactical Displays
Sperry Gyroscope Company	Great Neck, N. Y.	DR and TTR Transmitters
Vickers, Inc.	Waterbury, Conn.	DR and TTR Antenna Hydraulic Drives
Narmco Mfg. Co.	La Mesa, Cal.	DR and TTR Antenna Reflectors
Continental Can Co.	Chicago, Ill.	TTR Antenna Mount
Allis Chalmers	Akron, Ohio	Steel Weldments for TTR Antenna Mount
Steel Products Engineering Co.	Springfield, Ohio	MTR Antenna Mount
Sperry Rand Univac	St. Paul, Minn.	Target Intercept Computer
Douglas Aircraft Company	Santa Monica, Cal.	Missile, Launcher, and Missile Handling Equipment
Thiokol Chemical Co.	Huntsville, Ala.	Booster and Sustainer
AiResearch Mfg. Co.	Beverly Hills, Cal.	Missile Hydraulic Power Unit
Epsco West	Anaheim, Cal.	Test Equipment
Stromberg-Carlson	Rochester, N. Y.	Test Equipment
Lear Inc.	Grand Rapids, Mich.	Stable Platform
Burns and Roe, Inc.	New York, N. Y.	Architectural Engineering for the R & D program
New Mexico State University	University Park, N.M.	Test Targets
Airborne Instruments Laboratories	Mineola, N. Y.	ZAR Antenna Measurements
Cornell Aeronautical Laboratories	Buffalo, N. Y.	Decoy Discrimination Studies
Avco Everett Research Laboratory	Everett, Mass.	Infrared Decoy Discrimination Studies
Varian Associates	Palo Alto, Calif.	High-Power Klystrons for ZAR Transmitter

Originally, the prototype radar was named the ZEUS Multifunction Array Radar (ZMAR). Although not part of the ZEUS System at that time, it was considered exploratory effort that might be phased into the ZEUS System at a later date. Later, the radar was referred to as MAR-I. The basic concept was to employ four installations to provide 360 degrees in azimuth; however, only one hardened installation was installed at WSMR for evaluation. Ground breaking for the MAR-I technical facility took place at WSMR in March 1963. Construction of these facilities was the responsibility of the Army Corps of Engineers and their contractors. An aerial view of the installation is shown in Figure I-32.

One of the important lessons learned from the hardware installation and test of the MAR-I radar sensor was the need to thoroughly test in the laboratory all the elements duplicated in large numbers in an array radar. A number of design faults resulting in poor reliability were uncovered in such elements as the Traveling Wave Tube (TWT) and its associated filament transformer. This resulted in an expensive redesign and replacement program because of the large number of such elements involved. With this background of experience, designers of the later phased-array radars, MSR and PAR, were required to run exhaustive laboratory performance and reliability tests on elements that were to be duplicated thousands of times in the full radar. Reference should be made to Chapter 8 of Part II on PAR, for discussion of the Limited Engineering Development Model (LEDM) set up for this specific purpose at General Electric.



Figure I-32. Aerial View of MAR-I at White Sands Missile Range

The testing of the MAR-I at WSMR demonstrated the feasibility of using a phased-array radar for a multiplicity of simultaneous functions, and verified the analytical predictability of array performance in a multifunction role. Among the important test results in these demonstrations were:

- Extensive external antenna pattern measurements of single beams and multiple-beam clusters which closely matched both the internal antenna pattern measurements (using the element alignment network) and the patterns calculated from basic phase and amplitude data of the individual receive and transmit antenna elements
- Stability and repeatability of these antenna patterns over extended time periods
- The ability to form and steer various search, track, and discrimination beam clusters with desired precision
- Dynamic tracking accuracy of airborne and ballistic targets and satellites
- Absolute tracking accuracy from precision tracking of solar microwave radiation.

The system demonstrated the inherent broad frequency-bandwidth capability of arrays using time-delay steering in both the transmit and receive modes. It demonstrated the ability of microsecond switching in time and the use of multiple frequencies for separation of simultaneous radar functions using various beam-cluster arrangements. An important demonstration was the use of a centralized digital computer to control all radar functions and execute large-scale, real-time data processing. This included generation and execution of all the beam forming and tracking functions, full automatic system control with provision for manual intervention, search detection and verification, precision tracking in range and angle, fault monitoring, display, and numerous other simultaneous and sequential system operations. In general, these tests verified on a full-scale basis the satisfactory performance of a multifunction array radar in a real target environment. Further information on MAR-I characteristics is given in Chapter 2 on NIKE-X.

NIKE-X R&D SYSTEM

The Secretary of Defense on January 5, 1963 directed the priority development of an ABM defense system incorporating the most advanced components and techniques available. This new system was temporarily designated NIKE-X, pending selection of a more appropriate name. The Army NIKE-ZEUS Project Manager was assigned the task of implementing the new program. Bell Laboratories, as the system's development director on behalf of Western Electric Company, the prime contractor, was called upon to redefine the system taking full advantage of the latest technical state-of-the-art, moderated by economic restraints of production costs and time restraints of deployment schedules.

System Objectives

In carrying out this system responsibility, Bell Laboratories was to conduct studies and R&D work directed to this forward-looking anti-missile defense system which would include a combination of the high-performance SPRINT type missiles and a phased-array radar. The R&D Field Tests at Kwajalein, WSMR, and Ascension, as previously described, were to continue essentially as planned to provide fundamental information needed for the new system. The technical reasons for continuing development at this time, rather than deployment, involved a concern that the USSR could soon develop (by the early 1970's) the ability to mount a high-traffic threat with decoys and chaff that could only be discriminated endoatmospherically. However, there were many sensitive political reasons in the decision not to deploy the NIKE-ZEUS System in 1963. Among these were (1) the high cost of a complete defense for the country, (2) ABM defense would be de-stabilizing, and (3) the defense would provide only for principal cities and industrial regions, leaving major areas of the country undefended.

The basic plans for phased-array radar tests at WSMR to prove whether a single radar could perform acquisition, discrimination, and track

of targets and defensive missiles were underway in 1963. Furthermore, an advanced ABM study group at Bell Laboratories had shown the advantages of a high-acceleration, short-range SPRINT-type missile to defend a limited area when discrimination of the RV was delayed until it reached low altitude. Actually, by 1963, the basic concept of the NIKE-X System was well underway at Bell Laboratories with the objective of terminal defense of the larger U. S. cities against the sophisticated USSR attack postulated for the mid-1970's.

Already under study for NIKE-X was a much more powerful multifunction array radar than the MAR-I planned for WSMR tests. This radar, referred to as MAR-II, was assigned the role of search, track, and discrimination and was considered the centerpiece for city defense. A second smaller radar, called the Missile Site Radar or MSR, was proposed to provide multiple tracking of defensive missiles and short-range target tracking. Later on, as a result of further study involving the economics of ABM defense for smaller cities, the MSR role was increased to provide search, acquisition, and track of incoming targets and thus provide autonomous operation in the defense of smaller cities. The long-range NIKE-ZEUS missile was carried over to the NIKE-X System concept* to supplement the short-range SPRINT missile. Further information on the NIKE-X System and the threat postulated is given in Chapter 2.

SPRINT Missile Development

On October 1, 1962, three contractors were given study contracts by Bell Laboratories for the proposed new SPRINT-type missile. When their proposal arrived on February 1, 1963, seven technical subcommittees composed of representatives from Bell Laboratories, Western Electric, and the Army Missile Command were appointed to examine the proposals and select the successful contractor for SPRINT development. On March 18, 1963, the Army announced the selection of Martin Marietta as the development contractor for the SPRINT missile. Development work was to be carried out in the Martin plant at Orlando, Florida; with initial testing of the missile at WSMR and subsequent system firings at Kwajalein.

What followed through the next twelve years was the successful development and test firing of a most challenging missile, when viewed from the state of missile technology in the early 1960's. The SPRINT missile, with its acceleration to high velocity within the dense atmosphere at low altitudes, produced such high aerodynamic heating that its skin surface could be cooled with an oxy-acetelyne torch! There were several years of pure agony to the Martin and Bell Laboratories engineers in overcoming the many problems of the early flight program. However, in the end, these problems were overcome and a highly reliable SPRINT missile was available for the SAFEGUARD System Tests at Kwajalein. For a discussion of the characteristics and flight history of this development, refer to Chapter 9 on the SPRINT Missile Subsystem.

Missile Site Radar — MSR

Various configurations and parameters for the MSR were studied at Bell Laboratories. The agreed upon concept was an S-band, phased-array radar with a single transmitter or receiver time sharing a single phase-controlled antenna face. The ability to change direction of the beam very rapidly was established as a requirement to provide high traffic-handling capability. After competitive proposals were received from seven companies, the Raytheon Company, Wayland, Mass., was awarded a contract for development in December 1963. The initial Phase I effort combined engineering

*Principal features of the NIKE-X System concept were summarized in a paper, "NIKE-X, Design Approach and Preliminary Description" which was presented at the Anti-Missile Research and Advisory Council (AMRAC) Symposium, April 15, 1963, in Monterey, California.

personnel from Bell Laboratories and Raytheon to define the MSR in detail and highlight areas requiring maximum effort to meet development schedules. Varian Associates was selected to provide the high-power transmitter output tubes.

In early 1965, a decision was made to provide the MSR with its own data processing and command and control equipment to permit autonomous operation independent of a Defense Center in smaller city defense. Higher performance requirements were established for the MSR to carry out search, acquisition, and longer-range target tracking. The major change was a five-fold increase in average transmitter power. These changes were formulated with Raytheon in June 1965. Once this was done, the schedule for power-on of a two-face MSR (the tactical version would have up to four faces) on Meck Island in the Kwajalein Atoll was set for May 1968. An artist's view of the proposed tactical installation is shown in Figure I-33.

The digital beam-forming and steering logic for the MSR was the responsibility of Raytheon. However, in the interest of standardization, the same type of hardware designed for the Bell Laboratories data processing equipment was supplied by Western Electric to meet Raytheon's logic requirements. Full details of the MSR development and performance are covered in Chapter 7.

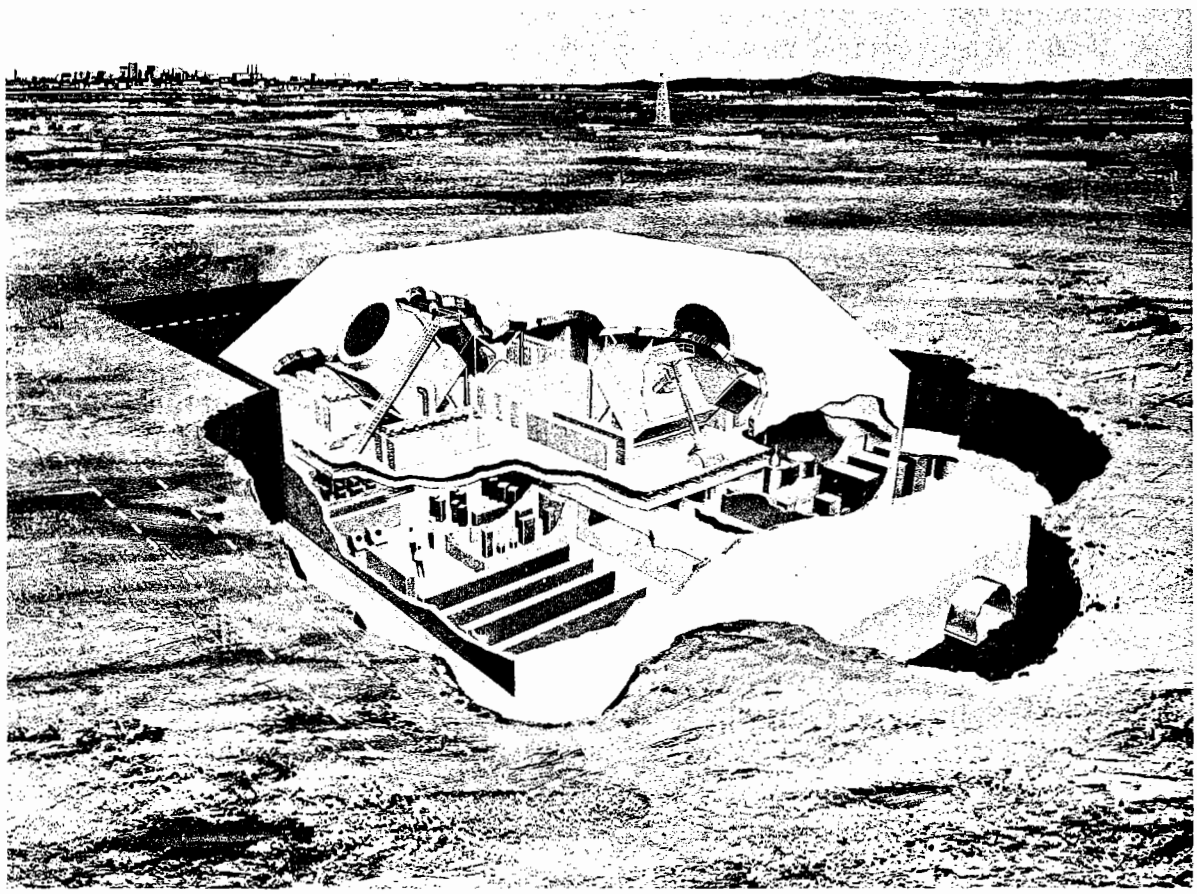


Figure I-33. Proposed Tactical MSR

Multifunction Array Radar — MAR-II

The L-band MAR-II of the NIKE-X System was specially designed for long-range search and acquisition and high-data-rate coverage for discrimination. Plans were established for installing a prototype model on Kwajalein (see artist's view in Figure I-34), while the MSR was to be located on Meck Island some 25 miles away. The high-power requirements for MAR (100 MW peak and 2 to 3 MW average per transmitter face) dictated separate transmitter and receiver array faces. Two transmitter and receiver array faces were planned to provide 180-degree coverage. From the start, two possible implementations of receiver beam-steering configurations were pursued in scale laboratory tests to determine which method would provide the optimum performance, consistent with high reliability and lowest cost. One method involved time delay (actually phase delay, a Board-Steered System — BSS) and the other was a Modulation Scan Array Radar (MOSAR) technique developed by General Electric, Syracuse, New York as part of an R&D contract with Bell Laboratories.

Raytheon was awarded the contract for the development of the high-power transmitter. A key requirement of the transmitter was the need for a long-life, broad-band TWT used in large numbers to meet the high-power requirements. A team of tube engineers from Bell Laboratories' Murray Hill Laboratory with experience in building long-life TWT gun structures joined with Raytheon tube engineers in the development of the TWT with a goal of 50,000 hours of life. Although the L-band TWT was

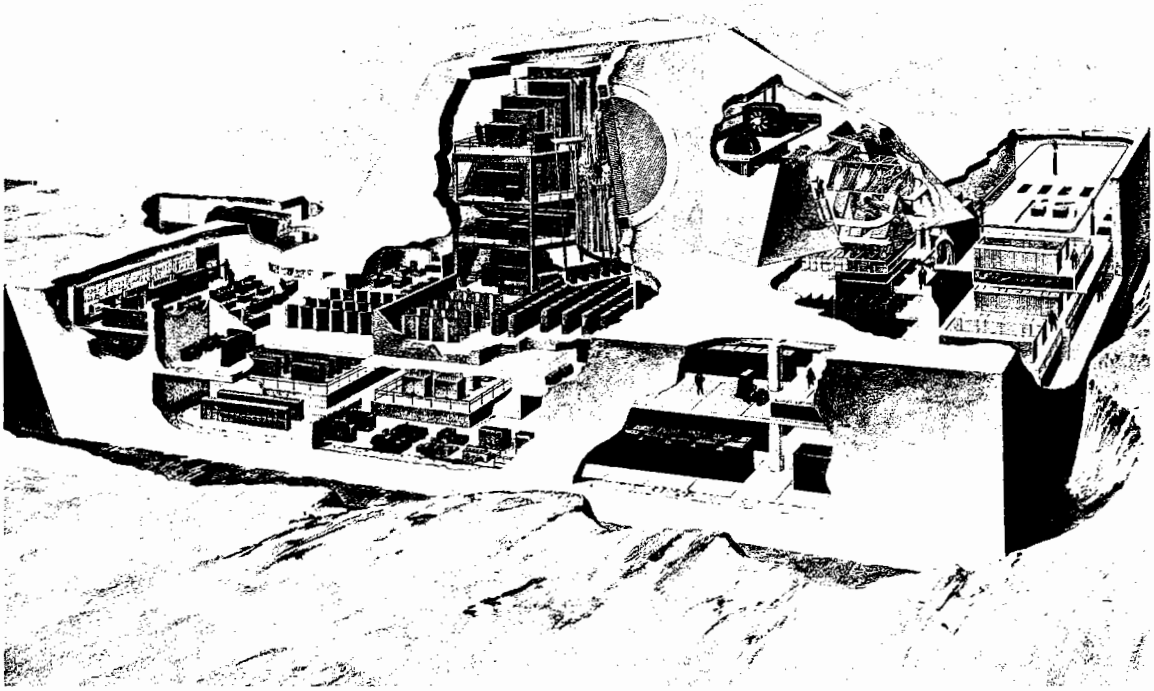


Figure I-34. MAR-II Planned for Kwajalein

not deployed because of the later cancellation of the MAR-II, Raytheon later scaled the tube down to the PAR UHF band and supplied it to General Electric. As deployed in the PAR today, the tube is indicating a life of 50,000 hours or more.

One of the features planned for the MAR-II was the ability to form multiple independent beams for search and, simultaneously, form separate clusters directed to different incoming clouds for discrimination. The transmitter beam width would be adjusted to match the receiver beam-cluster size.

The plans for time-delay steering (the board-steered system — BSS) employed phase delay in contrast to the MAR-I real-time delay steering. It was the BSS system that was compared to the MOSAR system from General Electric, resulting in a recommendation to the Army NIKE-X Project Office in March 1967 to drop further development of MOSAR and use the BSS for MAR-II. The final decision was based on the straightforward approach of BSS and a real concern for the complexity and cost of a full implementation of MOSAR. However, much credit should go to the General Electric engineers who developed an innovative steering system and made it work successfully in the laboratory reduced-scale tests.

The MAR-II system costs, because of the high-power requirements and complexity, were so high that even the deployment of an R&D prototype on Kwajalein had to be delayed in schedule and finally scaled down in January 1968. The scaled down model, referred to as TACMAR, was to initially leave out some of the transmitter and receiver modules, although these could be added later. However, by this time the original requirements for ABM defense had changed, as discussed below, and a less expensive Perimeter Acquisition Radar (PAR) was substituted for MAR/TACMAR in tactical deployment plans. In May 1968, the TACMAR prototype objectives for installation on Kwajalein were changed from a tactical design to an R&D field-site radar referred to as CAMAR (and later GUARDIAN) to provide basic field data on discrimination. Further information on the GUARDIAN/CAMAR objectives is given in Chapter 2 on NIKE-X. However, the project then supported by the Advanced Ballistic Missile Defense Agency (ABMDA), was cancelled in August 1969.

Data Processing System

Early in 1963, studies were in progress on the requirements for the NIKE-X Data Processing System. What was clear from the start was the need for high-speed calculations (up to 30 million per second) that could be provided in modular equipment giving stepped capability for future growth. Equally important was the need for equipment having reliability an order of magnitude better than any commercial computer then available or planned. In reviewing the status of computing equipment designs with manufacturers, it became clear that the NIKE-X data processing requirements dictated a challenging new design approach.

Bell Laboratories enlisted the help of UNIVAC and formed a joint team in the spring of 1963 to establish design requirements and specifications for the NIKE-X Data Processing System. Studies were made in the areas of basic hardware and logic, computer organization, switching and control, displays, recording, programming, and fault location. Out of these studies came the decision that performance capability in a stepped-module structure and high system reliability could only be met by a multiprocessor design. Also, the basic logic integrated-circuit package had to meet reliability goals of 8 fits (8 failures in a billion hours). The Bell Laboratories Device Organization accepted the challenge of providing the integrated circuit to meet this reliability. More detailed discussion of the data processing equipment is given in Chapter 11 on the SAFEGUARD Data Processing Hardware.

Many experts during the late 1960's, including a special committee of the American Academy of Science, reported to the Army that, in their opinion,

a multiprocessor could not be made to meet the expected calculations per second (MIPS) predicted by Bell Laboratories. In final test measurements on SAFEGUARD, MIPS were plotted versus processors in parallel. The curve followed an essentially linear line through eight processors and met or exceeded the performance predicted early in the design. The integrated-circuit package developed for NIKE-X, and manufactured by Western Electric and three subcontractors for the SAFEGUARD program, has now accumulated many millions of device hours and shows results of reliability approaching the 8-fit goal.

REENTRY MEASUREMENTS PROGRAM

In the earlier discussion of discrimination, reference was made to the initial studies and laboratory work that included initial radar and optical observations at Ascension Island carried out during the early ZEUS program. By 1962, the ZEUS radar sensors were now deployed and operational at Ascension, WSMR, and Kwajalein, and an organized reentry measurements program was established (referred to as RMP A, B, and C) as part of NIKE-X R&D to cover the period from 1962 to 1970. The objectives of the program were to develop general discriminants for conical reentry vehicles based on radar observable characteristics as a function of vehicle size, shape, and ablator material. Optical and infrared sensors were also provided as part of these measurements.

The Measurements Program at WSMR starting in 1963 included the use of the ZEUS elements, ZAR, TTR, and DR, as well as an infrared radiometer installed on a HERCULES mount. By June 1964, the WSMR was taking data on the first successful Athena test missile fired from Utah into WSMR. The major portion of the RMP tests was comprised of full-scale reentry flights principally into the Kwajalein Test Range. Special unique targets were provided by the NIKE-X Program, with other targets furnished by the Air Force, Advanced Ballistic Reentry Systems (ABRES), Strategic Air Command (SAC) Evaluation Missions, and the Navy Polaris Program.

The NIKE sensors, TTR and DR, went through major modifications at the end of the ZEUS System Tests at Kwajalein to adapt them to the sensor data-gathering requirements of RMP. For example, TTR No. 4 was changed from a 22- to a 40-foot antenna dish and a wideband 60-MHz coherent system. (See Figure I-35.) In addition, an X-band receiver system was added to provide telemetry reception from NIKE-X supported RVs equipped with special on-board instrumentation. Similarly, the DR at Kwajalein was modified to include a Coherent Signal Processing System (CSPS) developed at General Electric as well as wideband recording equipment.

In January 1964, a reentry physics panel was organized at Bell Laboratories with specialists in electromagnetic theory, plasma physics, gas chemistry, aerodynamics, and hydrodynamic stability to help guide the reentry field-measurements program and represent Bell Laboratories in contacts with outside organizations having related interests. Further information on the RMP work is covered in Chapter 2 on NIKE-X.

Nth COUNTRY THREAT

In February 1965, at the request of the Army, an intensive investigation was started on possible modifications of the NIKE-X System and hardware concept to reflect the heightened national concern about the "Nth country" threat. Special emphasis was to be given to the evaluation of alternate techniques for achieving effective high-altitude defense against relatively unsophisticated attacks with deployment growth to meet sophisticated threats. In particular, other options were to be considered leading to a lower cost MAR-II. As part of this system study, the usefulness of

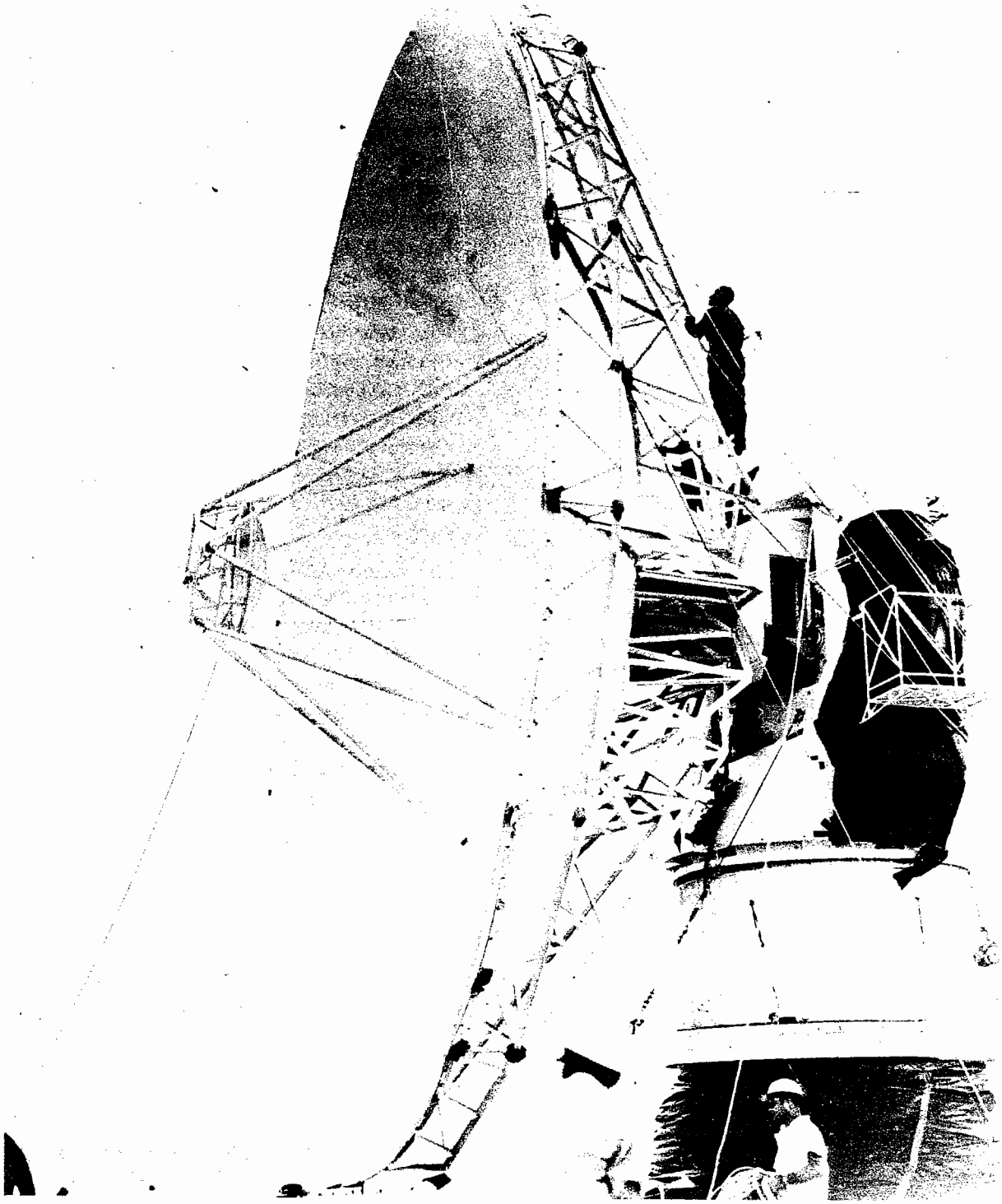


Figure I-35. TTR 4 Antenna, showing 40-foot reflector with subreflector being readied for use in RMP B

VHF radars as supplementary sensors for acquisition, discrimination, or designation in defense against light, unsophisticated attacks, was investigated at Bell Laboratories. Included in this study was the blackout problem in the VHF band.

On April 23, 1965, the major conclusions of this study were orally presented to Dr. Harold Brown, Assistant Secretary of Defense for R&D. A variety of radar design approaches was summarized in terms of performance, cost, and growth potential. The radars proposed were a MINI-MAR — a lower cost, reduced-performance array radar with potential for growth to a full-sized MAR — supplemented by a companion radar at VHF for long-range detection of sneak attacks that could be met by the ZEUS missile. The MSR was the choice for missile guidance, although S-band missile tracking radars of lower cost could be used. For close-in defense, SPRINT and MSR remained the choices. In May 1965, following this presentation, Bell Laboratories was authorized to reorient the NIKE-X System requirements to include certain modifications aimed at providing a more cost-effective defense against a possible Nth country threat, in addition to the more sophisticated Soviet-type threats on which past NIKE-X design had been based.

This was in line with Secretary of Defense McNamara's rising concern early in 1965 over the nation's vulnerability to the kind of attack that some less advanced country might launch. For this reason, it was urgent to determine whether NIKE-X was the most cost-effective way to provide an early defense against such a threat, or if there were less expensive ways.

As a result of these studies, the NIKE-X concept was expanded to provide capability for a broad general defense of the whole continental United States against the full threat spectrum. This change was made possible by increased confidence that large nuclear warheads borne by two or more modified (for greater payload and range) ZEUS missiles in a barrage mode could provide large volume kill capability — leading to the possible concept of an umbrella coverage of the entire country. (Only as threat sophistication increased to extremely hard, i.e., radiation-resistant warheads and RVs, would the short-range terminal defense be required.) As visualized at that time by the Director of Defense Research and Engineering (DDR&E), the VHF radar would be a straightforward development (essentially off the shelf), and thus actual development effort would not have to begin until production was authorized.

In October 1965, in response to a request from DDR&E, a quick examination of minimum NIKE-X hardware was made to assess a defense against simple first-generation Nth country ICBMs. This hardware consisted of 4 VHF radars and 12 MSR sites, with 20 modified ZEUS missiles at each site. Although good coverage against this particular threat was demonstrated in principle, the many limitations of such a defense concept were pointed out by Bell Laboratories.

In November 1965, a new study of active defense for hardened sites was initiated by DDR&E. Three teams — Air Force, Advanced Research Projects Agency (ARPA), and NIKE-X Project — were to study defense systems to meet the threats and defense objectives defined by DDR&E. This initial study and many more that followed associated with Hardsite Defense are covered in Chapter 2 on NIKE-X. It is sufficient to note here, that while studies were going on directed to light area Nth country defense, Bell Laboratories was being asked to carry out studies of high-traffic terminal defense of our offensive weapons. It was during these studies that the concept of pitch-and-catch for the missile-launch phase was seriously considered. Up to this time, in all of our NIKE System developments, the requirement to be completely locked on the missile prior to launch was considered inviolate. However, with the MSR inertialess tracking beam, it was found that SPRINT could be acquired after launch with separations of up to 20 nautical miles.

To provide a suitable missile element for the Nth country barrage-type defense, authorization was received in January 1966 to start development work at McDonnell-Douglas on a modified ZEUS DM-15C missile for this role. The missile payload would be increased to 2900 pounds for the high-yield nuclear warhead, necessitating larger first- and second-stage motors. The decision was made to use the modified DM-15C booster design for both the 5-second first stage and the 19-second second stage. The new three-stage ZEUS missile was expected to have a peak velocity of 9000 ft/sec and a range of about 300 nautical miles. The first firing was scheduled for Kwajalein Island in March 1968. For a discussion of the evolution of this missile into its successor, SPARTAN, refer to Chapter 10 on the SPARTAN Missile Subsystem.

As mentioned earlier, a VHF radar was being studied as a complementary long-range search and acquisition radar for Nth country defense. In December 1966, General Electric at Syracuse, New York was selected to start Phase I study work on this radar under contract to Bell Laboratories. Called the Perimeter Acquisition Radar (PAR), this new development presented the General Electric and Bell Laboratories team with the initial important system consideration of deciding on the operating frequency, VHF or UHF. A schedule for completing design definition by July 1, 1967 was established.

An important consideration in this study was whether a UHF design matching the VHF performance could be realized without a substantial increase in cost. Cost comparisons were made for a UHF radar that matched the VHF performance, -3 dB down and -6 dB down. Bell Laboratories had agreed with an Institute of Defense Analysis (IDA) summer study in 1966 that the radar blackout from offensive and defensive warhead burst would seriously degrade a VHF radar; thus UHF was recommended. By April 1967, Bell Laboratories and General Electric had completed a cost comparison of VHF and UHF for presentation to the Army and DOD. The decision was made to proceed with the planning for a PAR operating at UHF, but arranged so that initial deployment would be -6 dB down to minimize initial cost. However, the design should permit later growth to 0 dB performance for smaller future targets. This next phase, called Phase 1B, was limited to defining the system and developing critical components until such time as a deployment was authorized. A full story of the PAR as finally developed and deployed for SAFEGUARD is given in Chapter 8.

I-67 STUDIES LEADING TO SENTINEL SYSTEM

In December 1966, the Army AMC-NIKE-X Project Office and DOD asked Western Electric and Bell Laboratories to study a deployment model for NIKE-X designed to combine area defense with hardsite defense capabilities. This model, approved by DOD for production planning purposes, was officialy designated as "Plan I-67 Area/Hardsite Defense." The major objectives of the deployment were defense against a deliberate Chinese People's Republic (CPR) industrial/urban attack (countervalue) and defense against a deliberate high-level ICBM attack from the USSR (counterforce) aimed at U. S. strategic forces. In making this request, Secretary of Defense McNamara invited top executives of the Bell System to Washington on December 9, 1966 to ask their support and experience in finding ways to minimize the cost of an ABM deployment, while providing a system of high reliability. This meeting was followed by another on December 13, 1966 involving executives of Western Electric and Bell Laboratories and Dr. John S. Foster, Deputy Director for Research and Engineering (R&E) with his staff in the Pentagon, together with General A. W. Betts and members of his Army staff. This meeting again emphasized that cost was a most important parameter in making the I-67 study.

As a result of this request, Bell Laboratories and Western Electric initiated a six-month study

on January 16, 1967 to evaluate the "I-67" plan. The most important aspect of this study was to optimize system elements with the objective of selecting the option with the greatest cost-effectiveness. A three-month status report of this study was presented by Bell Laboratories to Generals I. Drewry and A. W. Betts on March 2, 1967, and again on March 4, 1967 to Dr. John S. Foster, Deputy Director for R&E, DOD. A status report at the end of the six-month study of the I-67 deployment model was presented to Secretary of Defense McNamara on July 5, 1967 at the Pentagon. Bell Laboratories made the primary presentation while AMC-NXPO presented possible growth options for the I-67 deployment model. Secretary McNamara was pleased with results of the study but asked for further investigation of specific questions dealing with growth aspects of the CPR threat and corresponding growth of the I-67 deployment model. A total report of the Bell Laboratories study was issued on July 5, 1967.

The results of the study were strongly influenced by three conditions: (1) specific design threat, (2) total investment cost not to exceed 5 billion dollars, and (3) initial operating capability (IOC) within 54 months of a deployment decision, thereby limiting choice of equipment to NIKE-X elements. The deployment recommended in the I-67 study consisted of 6 PARs, one of which would be in Alaska, 17 MSRs, including one in Alaska and one on Hawaii, 480 SPARTAN (the new name for a modified ZEUS DM-15C with large payload) interceptors, and 455 SPRINT interceptors of which 325 would be for defense of Minuteman sites. Other studies, directed by the Secretary of Defense, were carried out by the Office of Director of Defense Research and Engineering (ODDR&E) and the NIKE-X Systems Office with threats and constraints changed from the Bell Laboratories study.

On August 1 and 2, 1967 at Los Angeles, California, Mr. D. P. Ling of Bell Laboratories made a presentation on the I-67 deployment to the Defense Science Board of DOD.

On September 18, 1967, Secretary of Defense McNamara announced that production of a "light defense" NIKE-X System would begin before the end of 1967. The "light defense" deployment was to include PAR, MSR, SPRINT, and SPARTAN. This modified system, derived from the I-67 study, was limited in its initial role to a complete area defense against a CPR industrial/urban attack on CONUS, with a growth option for defense of certain U. S. ICBM bases against a USSR attack. With this decision, plans were set for completing the deferred development effort (referred to as objective budget) required to support the I-67 type deployment. This development work included design and manufacture of the PAR prototype, tactical test equipment, a tactical software control center, tactical ground support equipment for SPRINT and SPARTAN, and completion of design documentation.

On November 1, 1967, the Department of Defense announced the locations of the first ten SENTINEL sites, which included Boston, Chicago, Grand Forks and other cities as shown in Figure 3-1 of Chapter 3. Initial SENTINEL deployment was to consist of 6 PARs, 17 MSRs, 480 SPARTANs, and 220 SPRINTs. This deployment could later grow to provide Minuteman defense by the addition of 208 SPRINTs, and modification of the hardware and software located near the Minuteman bases. For further details on the I-67 Study and the SENTINEL System refer to Chapter 3.

SAFEGUARD SYSTEM

Construction contracts were awarded by the Army Corps of Engineers and construction started for the first SENTINEL Site (PAR) at Boston late in 1968. Strong opposition developed, however, over the construction of such sites, and against the deployment of missiles with nuclear warheads for ABM defense. The old question faced with earlier NIKE deployments was now present to a much greater extent; that is, "put it in someone else's back yard." In view of this strong opposition, the acquisition and construction of other sites

were suspended on February 6, 1969, pending a review of the SENTINEL System by President Nixon. On March 14, 1969, President Nixon announced that the SENTINEL System would be "substantially modified" in the form of a new deployment called SAFEGUARD with the following new defense objectives:

- First priority would be protection of our land-based retaliatory forces against a direct attack by the USSR; the complement of equipment was to be modified in accordance with this initial objective.
- A growth option to provide defense of the U. S. against the kind of attack the CPR would likely be capable of launching within the decade.
- Protection against the possibility of accidental attacks from any source.

The SAFEGUARD deployment plan reduced the number of sites to 12, as shown in Figure I-36, and deleted most large city sites. The initial deployment was to proceed in two phases, the first to protect part of the Minuteman force, and the second to complete the coverage of Minuteman sites and cope with more sophisticated threats.

Between the start of SAFEGUARD in March 1969, and the signing of the Strategic Arms Limitation Treaty (SALT I) with the USSR in May 1972, the authorized deployment went through a series of changes. In 1970, approval was given to start work on two Phase I sites, one near Grand Forks AFB, North Dakota, and one near Malmstrom AFB, Montana. Advanced preparation of five additional sites (Phase II) was also authorized; this was later reduced to advanced preparation at only two of these sites, for a total of four sites. The four-site plan was the one authorized through most of this period until the signing of the SALT I Agreement.

The SALT I Agreement permitted the deployment of one ABM defense site for offensive forces and one for the National Command

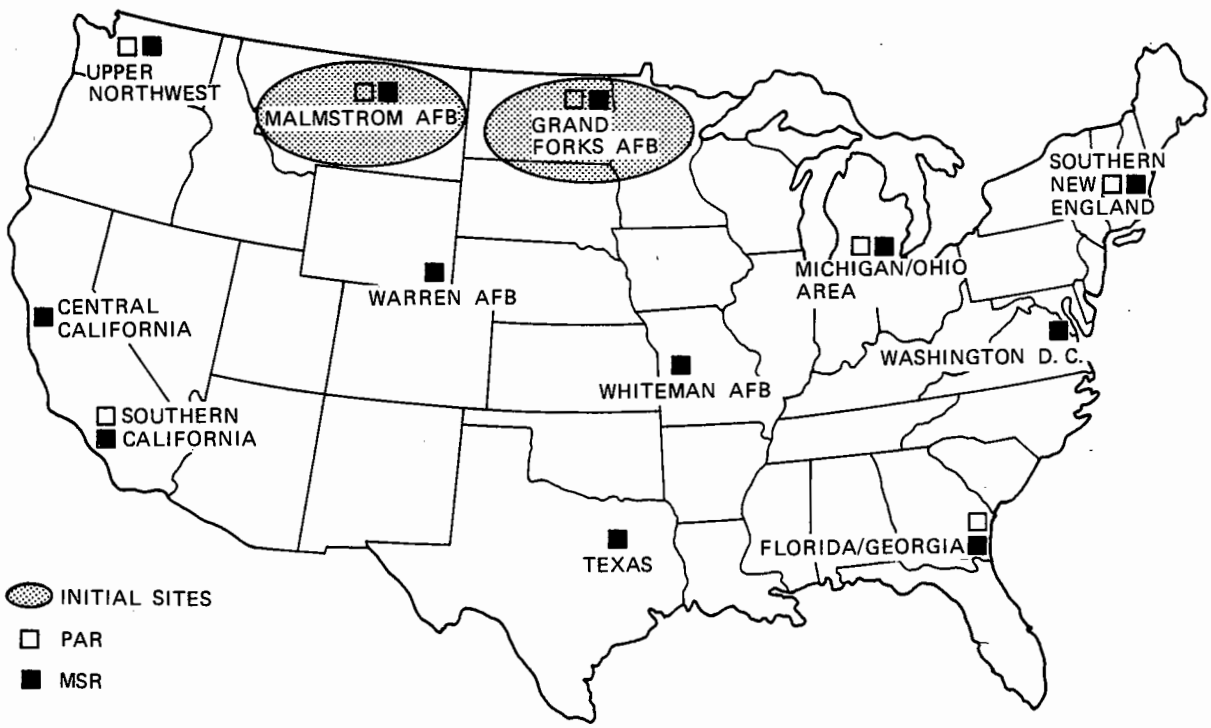


Figure I-36. SAFEGUARD Deployment Plan, March 1969

Authority around Washington, D. C. With this agreement, the second Minuteman site at Malmstrom AFB in Montana, then under full construction, had to be terminated leaving only the site near Grand Forks to continue. Later, the government decided not to proceed with the SAFEGUARD defense of Washington, D. C.

In accordance with the terms of SALT I in May 1972, and the subsequent Congressional decision not to authorize the deployment around Washington, D. C., the SAFEGUARD System consisted of the PAR and a Missile Direction Center (MDC), which included the MSR together with local and remote missile launch farms in the Grand Forks, North Dakota area. The system was under control of the Ballistic Missile Defense Center (BMDC) in Colorado. Under the SALT I Agreement, only 100 defensive missiles were permitted. Both SPARTAN and SPRINT missiles were collocated with the MDC, while additional SPRINT missiles were located at four remote missile farms. See Chapter 4 for more information on the SAFEGUARD System.

Fortunately, the changes in deployment objectives in going from SENTINEL to SAFEGUARD did not require major changes in the test plans for Meck Island. Most important was the proving in of the prototype MSR with its associated software as an operational phased-array radar. Continued development firings were also required for the SPRINT and SPARTAN missiles. Finally, to integrate these elements, a full series of system tests was carried out to progressively stress system capability against live ICBM and IRBM targets. Software packages, which were built up in complexity to match the system test objectives (called the M-test series), were introduced until the final software package (the part to be tested through live ICBM tracking or intercepts) matched the tactical software installed in the Grand Forks tactical system. The field testing at Meck complemented the more exhaustive testing of SAFEGUARD software at the Bell Laboratories Tactical Software Control Site (TSCS) in Madison, N. J. Here, threat inputs were introduced to match the design threat levels not attainable in field testing. Actual tracking data from the Meck tests were used in forming the test input tapes for the TSCS evaluations. Full details of the field tests at Meck and those carried out at the TSCS are given in Chapter 5 on SAFEGUARD System Evaluation.

During the SENTINEL and SAFEGUARD period, much thought was given to the installation of a PAR prototype on Kwajalein or Meck. Time schedules (with PAR development awaiting a production decision) and costs, dictated that the PAR prototype should be evaluated at the first tactical site and then turned over for tactical use after completion of R&D tests. Technically, a much more complete evaluation of the system could have been achieved with an installation on Kwajalein. However, it was also technically true that better evaluation of the PAR from a radar standpoint could be obtained from an installation in the northern hemisphere, where aurora effects, ground clutter with abnormal propagation, and low-angle atmospheric tracking errors could be determined. In discussions with the Army and DOD, it was agreed that simulation of PAR outputs for the Kwajalein system tests would be acceptable, although a larger deployment of SAFEGUARD would certainly have dictated a PAR installation on Kwajalein later in the program.

Some of the key dates in the Kwajalein/Meck buildup of testing are given below:

Mar. 2, 1968 — First SPARTAN development firing at Kwajalein.

May 18, 1968 — Power-on achieved for Meck MSR.

Oct. 8, 1968 — First software data transfer accomplished on satellite data link between Whippany and Meck.

Apr. 18, 1969 — Multiprocessor system demonstrated in Whippany SAFEGUARD Data Processing Laboratory in support of Meck tests.

Dec. 11, 1969 — First MSR track of ICBM.

Apr. 14, 1970 — M-1 Test Series starts at Meck.

Aug. 28, 1970 — First successful intercept of ICBM with SPARTAN.

Dec. 23, 1970 — First live target intercept by SPRINT.

Jan. 11, 1971 — First SPARTAN Salvo.

Mar. 17, 1971 — First SPRINT Salvo.

Aug. 27, 1971 — First M-2 mission.

Mar. 16, 1972 — First remote launch of SPRINT from Illeginni (about 20 miles from Meck) to test "toss and catch."

May 1973 — Revision 19 of software delivered to Meck for final M-2 Series Tests.

Aug. 1974 — Final M-2 System Tests.

Apr. 1975 — Final warhead and production missiles fired from Meck — 2 SPARTANs and 1 SPRINT.

A capsule summary of the M Series of system tests is given below. The M-1 Series was to prove in the basic concept of the system elements working together, while the M-2 series evaluated the system against increasingly stringent target and system conditions.

	M-1 — Concept Verification	M-2 — Final System Evaluation
Success	12	46
Failure	5 (includes one due to target)	7 (includes three due to target)

The TSCS test facility at Bell Laboratories in Madison, N. J. contained the full PAR and MDC data processing equipment and all portions of the analog hardware that interfaced with the missiles and radars at site. This facility accurately reproduced the software in its tactical operational environment and was indispensible in developing software relatively free of errors when introduced at site. A system exerciser for tests at TSCS and at site provided the means of introducing sufficient traffic capability and related attack parameters to test the tactical hardware and software at the required SAFEGUARD design threat level. These evaluation tests, carried out during 1974 and up to April 1975 at the TSCS, supplemented by the M-2 live-target tests at Meck, provided full verification that the SAFEGUARD System deployed at Grand Forks met its performance requirements.

The Equipment Readiness Data (ERD) for the Grand Forks site was met several days before October 1, 1974 — the scheduled date set almost four years earlier. Initial Operational Capability (IOC) was achieved shortly after the April 1, 1975 scheduled date, with operational missiles installed in their cells and full system operation underway, 24 hours a day and 7 days a week.

ABM R&D SUMMARY

The major development milestones in the 20-year evolution of ABM defense, beginning with the early studies in March 1955 and leading to a tactical SAFEGUARD System near Grand Forks, North Dakota, are shown in Figure I-37. These developments trace the history of the step-by-step advance in technology that kept the United States well in the forefront of ABM defense and led eventually to the SALT I Agreement with the USSR. From the initial NIKE-ZEUS System, which extended earlier air defense technology (designed to protect against the bomber) to meet the extreme ICBM threat of very high speed and small radar size, to the more advanced systems designed later to protect against highly sophisticated threats, a large number of truly innovative developments were required. These began with the ZEUS System, whose Acquisition Radar with Luneberg lens and three-dimensional automatic detection and tracking, together with a high-performance missile combining aerodynamic and jet control, made possible the first successful intercept of an ICBM in 1962 at Kwajalein, after earlier testing at Ascension, WSMR, and Pt. Mugu.

With the decision not to deploy the NIKE-ZEUS System, a period of four years followed from January 1963 to September 1967 (referred to as NIKE-X) in which major steps forward were made in ballistic missile defense technology

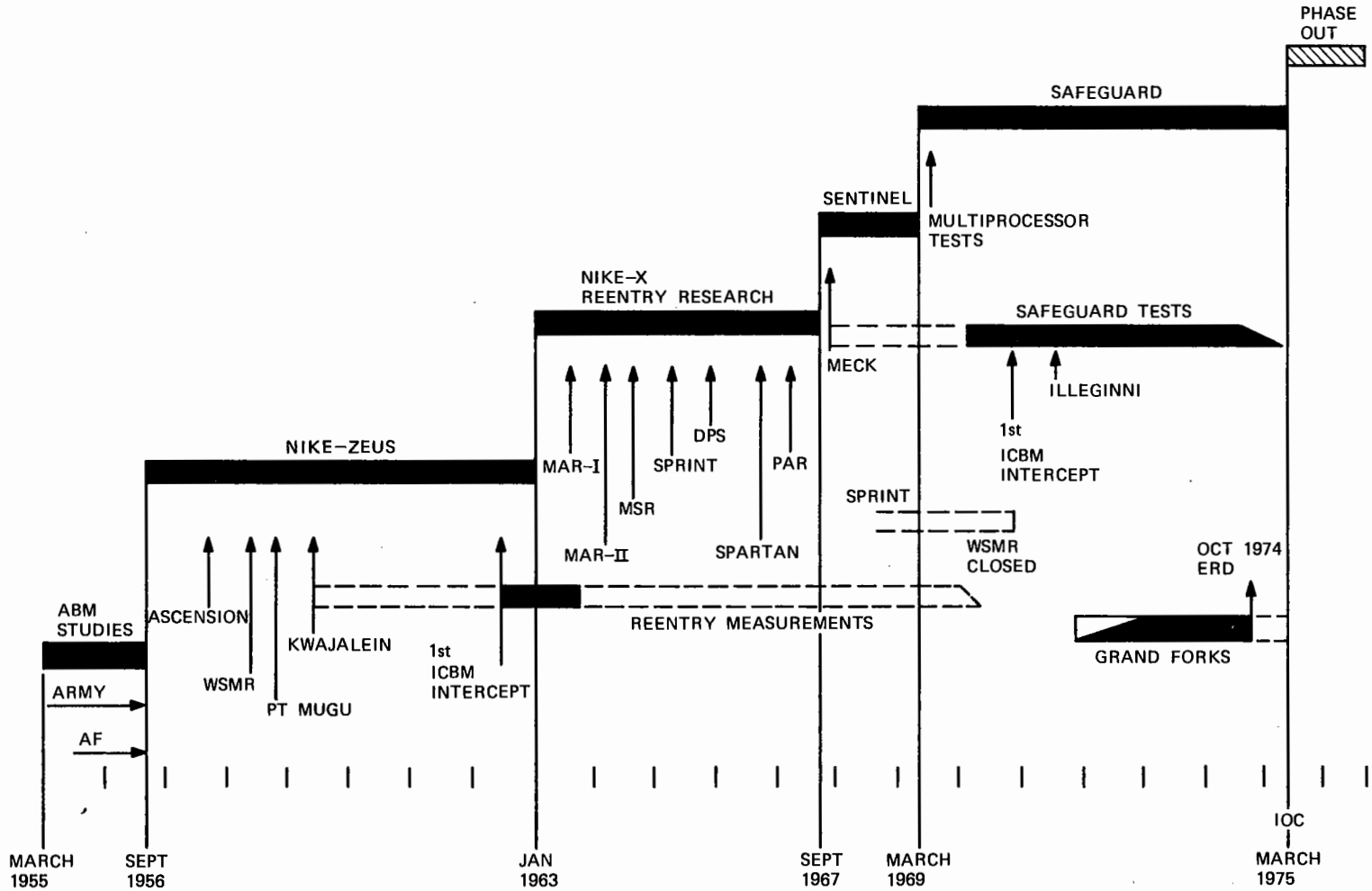


Figure I-37. Summary of Major ABM Developments, 1955 through 1975

to counter the increasing complexity of the ICBM threat. An exhaustive program of reentry research was carried out using the ZEUS radars at the three test sites as sensors for data gathering. Electronic phased-array radars, which compared to the ZEUS mechanically-steered radars had inertialess antenna beams, were developed for multifunction applications in the MAR I, MAR II, and MSR Subsystems. These radars were the major step required to successfully meet the high-traffic threat.

A super-accelerating missile called SPRINT was developed to permit delayed, low-altitude discrimination for close-in terminal defense. This missile represented another major step in technology, since it required high-impulse, short-burning motors and the ability to handle skin temperatures about three times those of the ZEUS missile. The requirements for data processing meant yet another major advance in computing technology to meet the need for high-speed calculations (up to 30 million per second), multiprocessor organization, and an order-of-magnitude improvement in reliability of the basic logic circuits. Closely related to these advances in hardware technology and work on discrimination was a continuing systems engineering activity to determine the optimum subsystem arrangements and deployments to meet various defense objectives of the Army and the Department of Defense.

The new technologies and systems approaches carried out in the NIKE-X period between 1963 and 1967 were "on the shoulders" of the R&D ABM advances made during NIKE-ZEUS System development. When the Secretary of Defense made the decision in September 1967 to deploy an ABM system called SENTINEL, the major elements required were available from NIKE-X development, except for the Perimeter Acquisition Radar (PAR), which was then under study. Later, in March 1969, when this deployment was changed to provide Minuteman defense under the SAFEGUARD Program, these same elements — then under test at WSMR and Meck Island — again met the defense requirements.

One of the major contributions in the last seven years of the R&D program was the successful development of one of the most complicated real-time software systems ever conceived. Critics of ABM defense in the late 1960's concentrated on the software problem as being too complex to provide the reliability needed. However, the high reliability currently attained with the tactical system at the Grand Forks site, 24 hours a day, 7 days a week, is a convincing answer to such critics. Furthermore, the software R&D effort on SAFEGUARD produced a solid background of experience and knowledge that will be helpful in building new defense systems in the future.

Another major contribution of the ABM R&D effort, extending from the first installation of a ZEUS track radar on Ascension Island in 1968 to the present time, has been support of offensive weapons programs. During this period of time, hundreds of data packages obtained from reentry missions have been supplied to the Air Force and other DOD agencies as a byproduct of having the most versatile and accurate radars available at the test ranges. For example, during the last three years of operation of the MSR Subsystem on Meck Island, some sixty data packages were supplied to other agencies concerned with offensive technology. Thus, the ABM program not only advanced its own defense technology, but made important contributions to offensive technology as well.

Each of these developments throughout the 20-year history of ABM activity contributed valuable experience and brought new insights to the challenge of meeting an increasingly sophisticated threat. The details of each of these programs and the lessons learned are discussed in the remainder of this report.

Part II.

MAJOR SYSTEMS AND SUBSYSTEMS

Part II.

MAJOR SYSTEMS AND SUBSYSTEMS

In the evolution of ABM defense from the early NIKE II studies to the present-day SAFEGUARD System, a number of major systems were conceived and developed to meet the ever-changing threat. These systems are discussed in this part of the report and include NIKE-ZEUS, NIKE-X, SENTINEL, and SAFEGUARD. In addition, each principal subsystem used in the SAFEGUARD deployment is described here from its initial research and development to current configuration.

A list of supporting reference documents is provided in Part IV. Additional information detailing SAFEGUARD System performance is given in a Classified Supplement to this report.

The subject areas by chapter are:

1. NIKE-ZEUS System
2. NIKE-X System
3. SENTINEL System
4. SAFEGUARD System
5. SAFEGUARD System Evaluation
6. Nuclear Vulnerability and Hardening
7. Missile Site Radar
8. Perimeter Acquisition Radar
9. SPRINT Missile Subsystem
10. SPARTAN Missile Subsystem
11. Data Processing System
12. Ballistic Missile Defense Center

Chapter 1.

NIKE-ZEUS SYSTEM



Chapter 1.

NIKE-ZEUS SYSTEM

The NIKE-ZEUS System was designed to provide a flexible, high-level defense against the complete spectrum of contemporary ballistic missile threats, and to be deployed to defend prime areas.[1-3] The defense at each area was to be completely self-contained and able to function without external data or control. This capability, together with a modular-type design, allowed the defense to be tailored in accordance with the importance of the defended area. The ZEUS concept also permitted an orderly system growth that could take into account changes in the offensive or defensive situation. While the NIKE-ZEUS System was capable of independent operation, there were provisions for the North American Air Defense Command (NORAD) to exercise overall control and for ZEUS to transmit battle summary information to NORAD during an attack. In addition, ZEUS was designed to receive early warning data from the Ballistic Missile Early Warning System (BMEWS) and other sources.

Radar tracking data and command guidance were used to direct a high-performance defensive missile with sufficient accuracy to intercept and destroy an incoming warhead. Various elements of the system were so balanced that targets could be intercepted successfully at altitudes up to 500,000 feet and at ground ranges out to 75 nautical miles (this represented a nominal range for targets of a particular size, specifically 0.1 square meter, traveling at ICBM speeds).

The NIKE-ZEUS System was never deployed tactically because, by 1963, the rapid evolution of the ballistic missile threat made it necessary to redirect development to the more advanced NIKE-X System. Rapid changes during the ZEUS development period led to divergence between the installed research and development (R&D) equipment and the tactical NIKE-ZEUS System envisioned at the end of that period. The NIKE-ZEUS System described here is this envisioned tactical system; much of the equipment discussed thus never existed in the form described. Most of the R&D models used as examples in the text and shown in illustrations, however, were sufficiently representative so that, allowing for known differences, their appearance affords a clear picture of the tactical system planned at that time.

THE NIKE-ZEUS INSTALLATION

The envisioned tactical system would have appeared as shown in Figure 1-1. The planned tactical ZEUS installation, as shown in Figure 1-2,

consisted of a Defense Center and at least one Battery, both to be located within the defended area.

Defense Center

The NIKE-ZEUS Defense Center, that part of the system shown in the right-hand portion of Figure 1-1, provided tactical control and acquisition data for as many as five Batteries associated with it in the defense of a local area. Its mission was to supply multichannel track-coordinate data on ballistic targets or decoy formations, and to select and transmit the necessary data and commands to the appropriate Battery.

The ZEUS Acquisition Radar (ZAR) was the major element in the Defense Center. The ZAR was a highly accurate, three-dimensional radar with substantial range against small targets. It had separate transmitting and receiving systems, and was able to scan 100 million cubic miles of space per second.[4]

The signal processing equipment at the Defense Center received the ZAR output and used it to determine trajectories of detected objects. These trajectories were examined to decide whether the objects were threatening the defended area. Those judged to be a threat were automatically designated for engagement by appropriate Batteries.

Although each Defense Center could operate independently, there were provisions enabling neighboring centers to act in concert. This

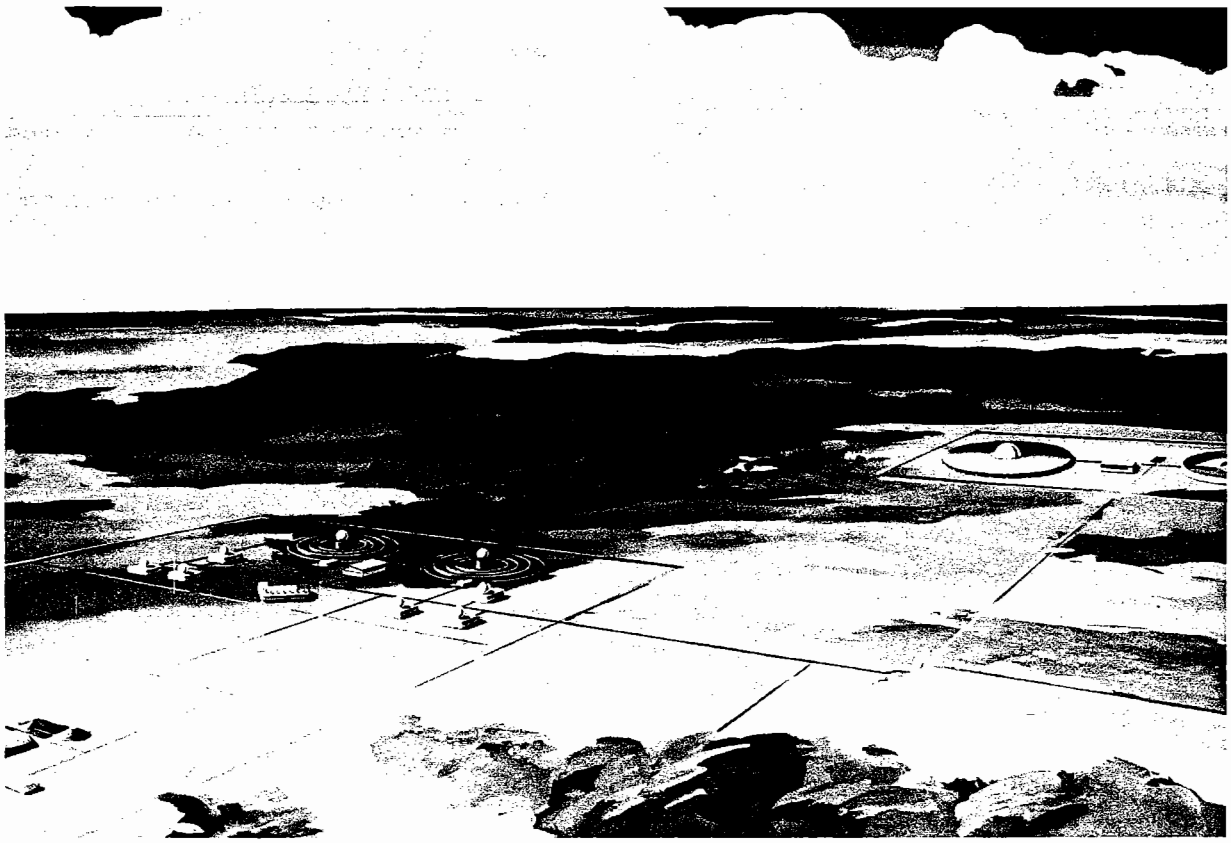


Figure 1-1. The NIKE-ZEUS Installation, Artist's Conception

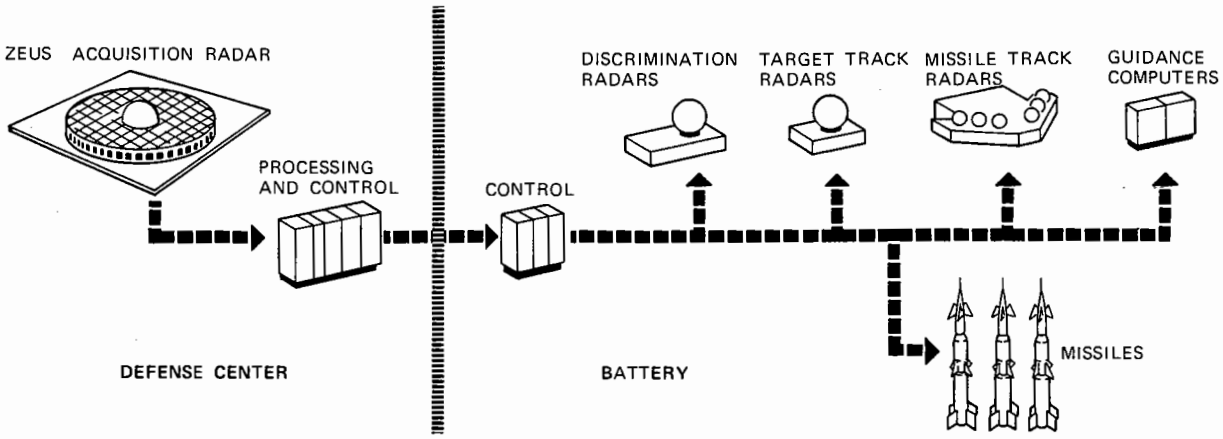


Figure 1-2. The NIKE-ZEUS Installation, Symbolic Block Diagram

capability would have been particularly advantageous if two or more centers had been needed to defend an area. In such a case, communication channels would have been provided for coordinating weapon assignment functions so that, if necessary, any one Defense Center could assume control of all area Batteries.

Communications also would have been established between centers defending nearby areas so that the ZAR at one center could provide data for the Batteries at another should the ZAR at the latter site be put out of action.

Battery

The NIKE-ZEUS Battery, in the left-hand portion of Figure 1-1, comprised all the elements required for carrying out the engagement of an assigned target.[5] Specifically, this included radars for tracking and discrimination, defensive missiles, and computers for all the calculations needed to accomplish a successful intercept.

As indicated in Figure 1-3, the Battery was flexible, being composed of modular units so that it could be increased in size and capability when used to defend areas of greater importance. The number of missiles, radars, and computers for a given site could be tailored to a specific defense mission.

Each Battery had at least one Discrimination Radar (DR) able to track simultaneously individual objects within a specific grouping, or cloud of objects, and select the threatening ones for intercept. There also were Target Track Radars (TTRs) for highly precise, long-range tracking of small, high-speed objects to provide the data necessary for accurate terminal guidance of the defensive missile. Missile Track Radars (MTRs), also part of the Battery, were mounted on towers at the Battery Control Building (left center portion of the Battery in Figure 1-1). They tracked the defensive missiles and transmitted steering orders to them by means of a discrete multipulse code.[4]

In the Battery Control Building, defensive-missile steering orders were generated by the Target Intercept Computers (TICs) from target and missile position data supplied by the tracking radars. These orders directed each missile along an efficient trajectory toward the continually corrected predicted intercept and caused it to burst at the optimum point. Each computer was able to handle three separate target-missile combinations simultaneously.

The Battery also contained tactical control and monitoring equipment to provide automatic assignment of appropriate guidance equipment

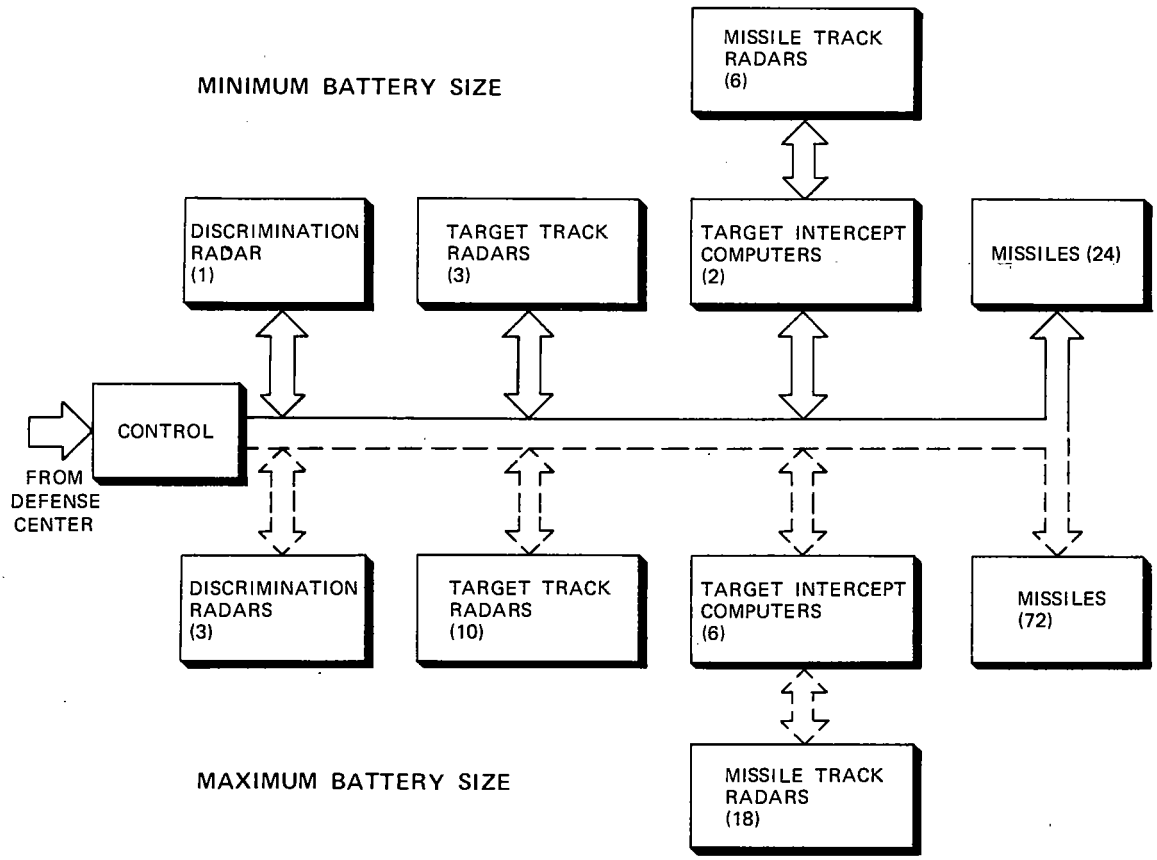


Figure 1-3. Minimum and Maximum Battery Sizes

and missiles. In addition, there were displays to enable operators to monitor the automatic operations of the Battery with provision for manual intervention if required.

As has been noted, the makeup of a particular Battery would depend upon its assignment. The practical minimum complement of equipment at a site was one Discrimination Radar (DR), three Target Track Radars (TTRs), two Target Intercept Computers (TICs), and six Missile Track Radars (MTRs). Twenty-four missiles were considered a normal complement for this minimum Battery.

Generally, the ratios of the number of different elements would not change as the Battery grew in size; however, the equipment's flexibility was such that this was not mandatory, and other Battery compositions could be tailored to the ever-changing threat. Figure 1-3 shows the effective maximum size of the NIKE-ZEUS Battery. Such a maximum did not represent an engineering limitation but rather a practical limit consistent with efficient operation. When a defense assignment required more equipment, additional Batteries could be used to achieve the desired level of defense.

ZEUS ACQUISITION RADAR

The surveillance function for the NIKE-ZEUS System was to be performed by the ZEUS Acquisition Radar (ZAR) (Figure 1-4), a high-performance, track-while-scan radar which could search for targets throughout a large volume of space. The

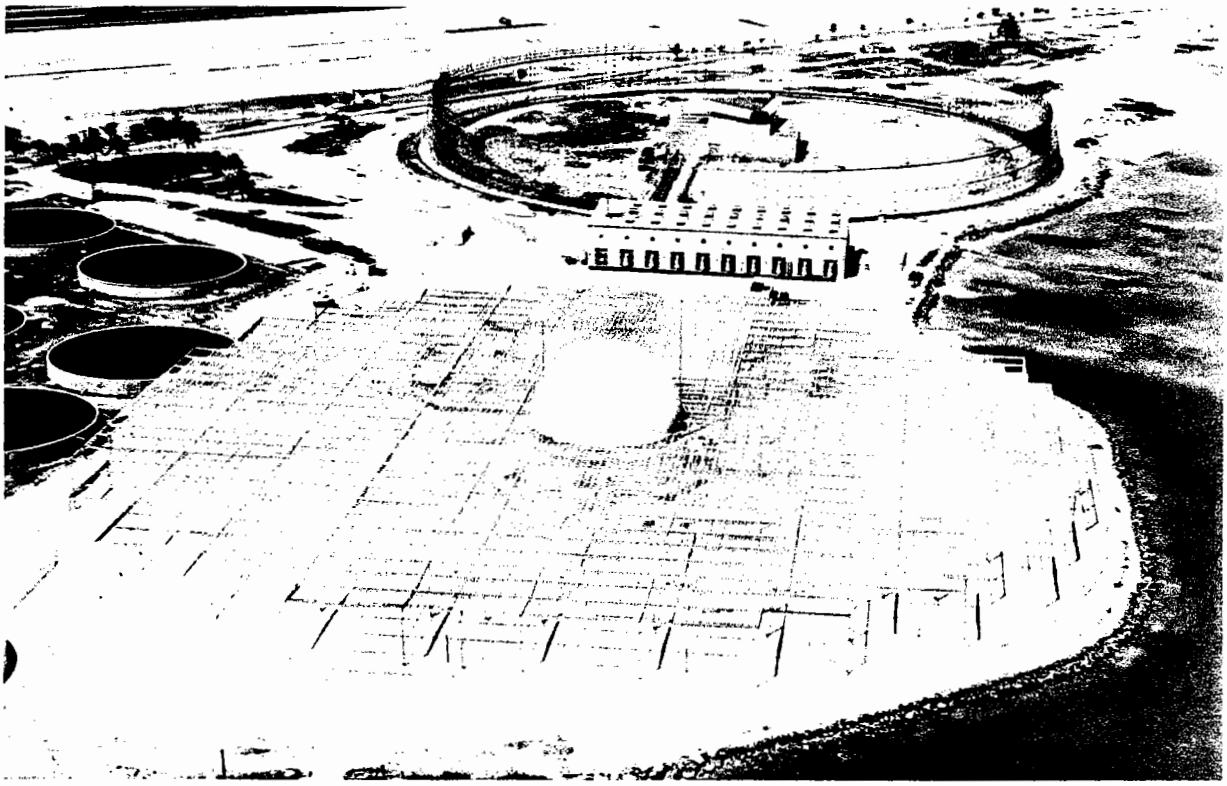


Figure 1-4. R&D Model of ZEUS Acquisition Radar (Kwajalein)

ZAR's primary function was to detect any object — whether alone or accompanied by others in a cloud — that was approaching the particular defended area, and then to provide the data required for determining whether this object was threatening. The ZAR employed separate transmitting and receiving antennas which continually rotated in synchronism about vertical axes to provide full 360-degree azimuth coverages. The three vertical fan-beams generated by these antennas provided elevation coverage from 0 to 70 degrees. The structures had a rotational rate of 3-1/3 revolutions per minute so that the three beams provided new data on each object within the ZAR's essentially hemispherical coverage every 6 seconds. The characteristics of the ZAR are listed in Table 1-1.

Transmitting System

Each section of the transmitting antenna (Figure 1-5) had a pillbox configuration to achieve a vertical fan-beam of coverage. Three sections were arranged 120 degrees apart in azimuth on a common rotating structure to provide the high data rate. Each antenna section was fed by a separate transmitter, with a 600-kilowatt average power output, located in the building below the antenna.

The three transmitters could operate at different frequencies within the L-band. Each transmitter employed two wideband klystron tubes in parallel to obtain the required power. Chirp pulse techniques were used to collapse the long pulse employed for maximum range performance to a much shorter pulse for the required range resolution.

Table 1-1
ZEUS Acquisition Radar Characteristics

Transmitter (three per radar)	
Peak Power	10 MW*
Average power	600 kW*
Pulse rate	97.7 pps
Pulse duration	650 μsec
Duty factor	0.06
Frequency	
Carrier	Ten or fewer preselected frequencies between 870 and 960 MHz
Frequency shift	Carrier shifts on successive pulses among the preselected frequencies
Chirp	Instantaneous output frequency changes linearly 400 kHz during each pulse
Transmitting Antenna	
Type	Triangular three-pillbox array
Gain	28 dB
Aperture	80 ft by 2 ft, 6 in. (each of three)
Beamwidth	0.9° azimuth by 70° elevation
Angular coverage	Continuous in azimuth, 0° to 70° in elevation
Diameter of fence	660 ft
Height of fence above pillbox aperture	15 ft ± 6 in.
Receiving Antenna	
Type	Rotating hemispherical Luneberg lens with three receiver horn tower assemblies and stationary ground plane
Gain	41 dB
Aperture	80-ft diameter lens
Beamwidth	0.9° azimuth and elevation per feed cluster
Number of beams	Three sets of vertical beams spaced 120° with 77 beams in each vertical stack†
Angular coverage	Continuous in azimuth, 0° to 70° in elevation
Ground plane	600 ft in diameter
Receiver	
Noise figure	3.5 dB (T = 720°K)
Number of receivers	231 for 70° elevation coverage
Collapsed pulse width	4.5 μsec at 3 dB
Angle determination	Azimuth: pulse-count technique Elevation: beam splitting (comparison of adjacent receivers)
Overall Characteristics	
Antenna rotation rate	3-1/3 rpm
Data interval	6 sec
Hits per beam pass	Minimum of four (increases with elevation angle)
Range performance	600 nmi for 90% probability of generating a target report per scan (on a 0.1 sq m target)
Range accuracy	250 yd (1σ)
Angular accuracy	8 mils, elevation 4 mils, azimuth

*Waveguide loss between transmitter and antenna is less than 0.2 dB, therefore, essentially full power is radiated.

†Based on an elevation coverage of 70°.

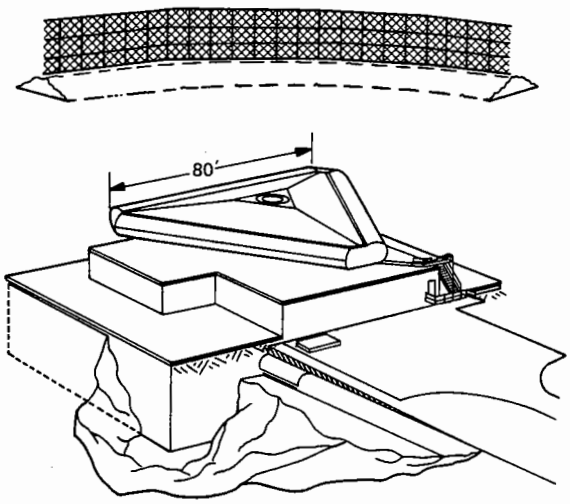


Figure 1-5. ZAR Transmitting System

Receiving System

The receiving system (Figure 1-6) used a Luneberg lens with an associated reflecting ground plane. The solid, hemispherical lens was constructed of thousands of polyfoam blocks, containing tiny metal slivers, to obtain the necessary variation in dielectric constant through the lens media.[6] The symmetry of the lens permitted the formation of beams in all directions, while its entire structure was used as an aperture. An array of vertically stacked receiving beams (Figure 1-7) permitted simultaneous coverage in elevation. Three of these arrays were spaced 120 degrees in azimuth. The feed horns and associated RF receiver equipment required for these arrays were embedded in the periphery of the lens. This, in turn, rotated in synchronism with the transmitting antenna. The remainder of the receiving equipment was located in the receiver building under the ground plane.

A simplified cutaway view of the lens media, horn trusses, ground plane, and drive mechanism is shown in Figure 1-8. The feed horns, each with its own complement of receiver front-end circuits, were mounted along each of the three horn trusses. Received signals, focused by the Luneberg lens and reflected by the ground plane, were picked up by one or more of the horns, depending upon the azimuth and elevation of the signal. The fan-type transmitting beam and the fan of receiving beams combined into a composite beam structure as illustrated in Figure 1-7.

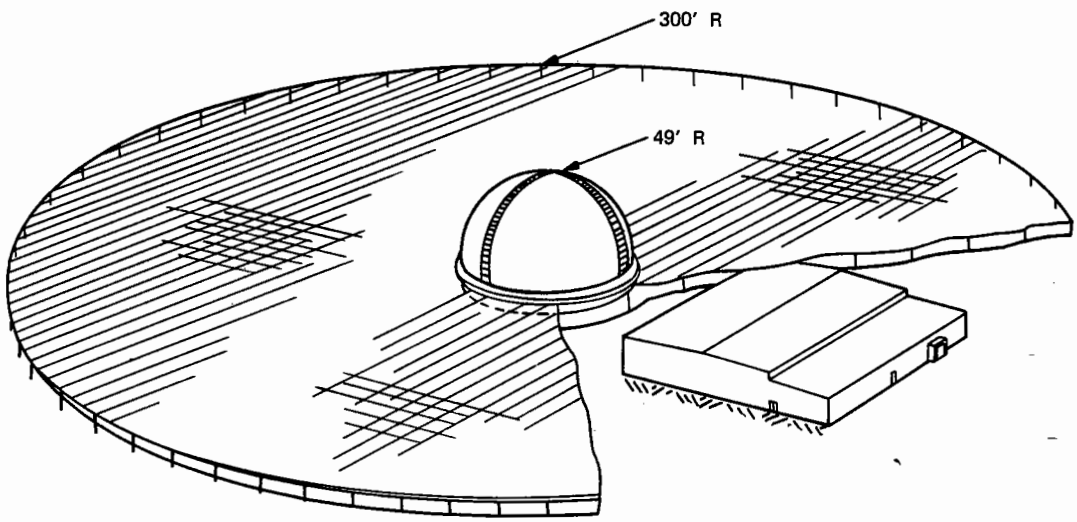


Figure 1-6. ZAR Receiving System

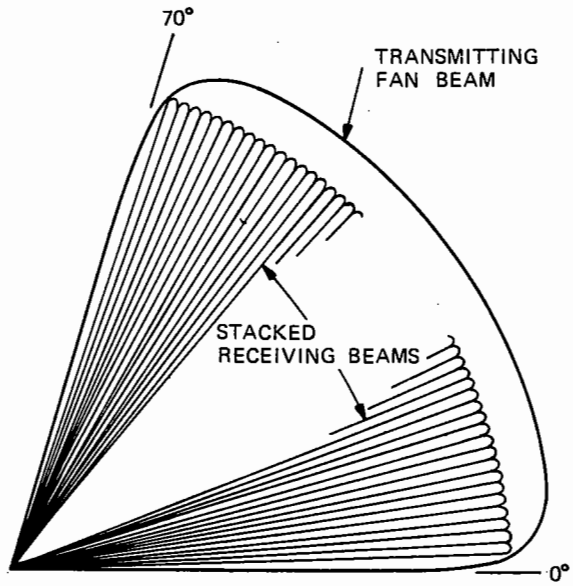


Figure 1-7. Multiple Receiving Beams Formed by Luneberg Lens

Target position information was obtained for elevation using monopulse, and for azimuth using a pulse-count technique.

Signal Processing Equipment

Since it was anticipated that hundreds of objects — perhaps as in a massed decoy attack — would be within the ZAR's field of view, a special type of signal processing equipment was associated with the ZAR. This track-while-scan equipment not only had high-speed capabilities for processing many targets simultaneously, but also had special provisions for reducing its susceptibility to saturation. The primary functions of the ZAR signal processing equipment (Figure 1-9) were: (1) detection and consolidation of the radar returns, (2) initiation of tracks on new objects, (3) maintenance of tracks on each object by comparing new position with expected position

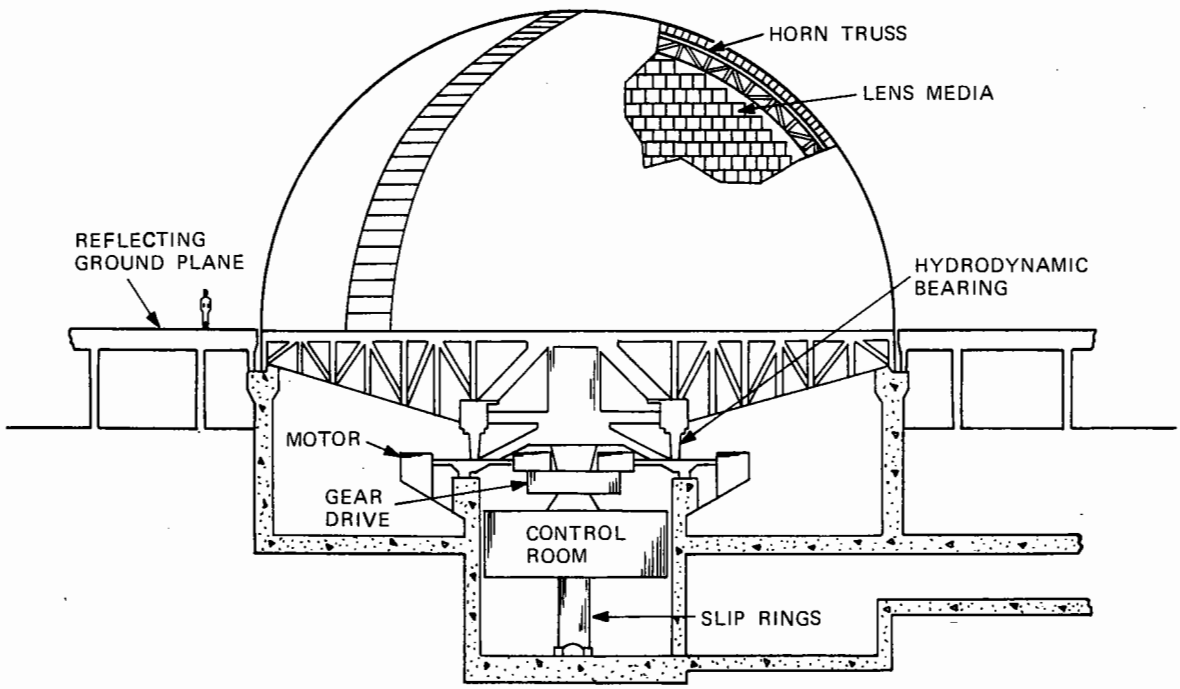


Figure 1-8. ZAR Receiving Antenna, Cutaway View

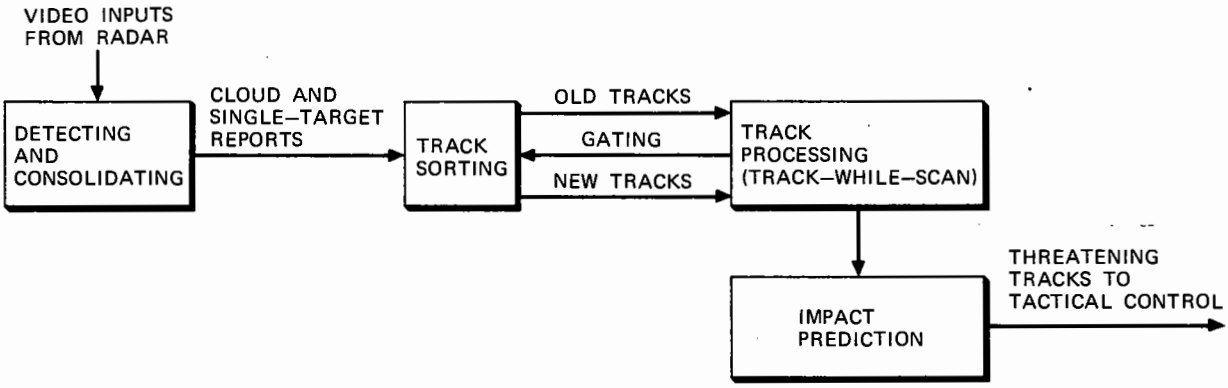


Figure 1-9. ZAR Signal Processing Equipment, Functional Block Diagram

based on previous data, and (4) prediction of impact point, the parameter used to determine which objects were threatening. All of these functions were performed completely automatically.[7,8]

The Target Data Consolidator used all the outputs from the individual receivers on the three horn trusses of the ZAR receiving antenna to detect targets and determine their positions. This was done by noting the truss and receiver at which a radar return was received, time at which the signal was received, and azimuth information (from a magnetic drum mounted below the Luneberg lens on the rotating portion of the antenna structure). Target elevation was derived by combining the signal-amplitude data from three adjacent receivers with stored data indicating the fixed elevation angle associated with each receiver. The range, azimuth, elevation, and time items were arranged into a "report" which comprised the output signal of the Target Data Consolidator.

DISCRIMINATION RADAR

The design of the NIKE-ZEUS System was such that when the Defense Center assigned a cloud of threatening objects to a Battery, a point within the cloud would be designated for use by a Discrimination Radar (DR) in tracking the entire cloud. The function of this radar was to provide sufficient information on all of the objects in the cloud so that non-lethal objects could be filtered out and true targets identified. The DR that was installed at Kwajalein is shown in Figure 1-10.

The DR was designed to cover clouds with diameters up to about 22 nautical miles. To maintain this coverage as the cloud approached, the antenna beamwidth was varied, according to range, from 2.5 degrees at 500 nautical miles to 20 degrees at 60 nautical miles. This beamwidth variation was accomplished through use of a movable subreflector mounted in front of the main antenna reflector [see (A) of Figure 1-11]. The spacing between the subreflector and main reflector was varied to produce an adjustable degree of defocus, and thus width, of the beam. The characteristics of the transmitted beam are shown in (B) of Figure 1-11.

The DR transmitted long-duration, extremely high-power pulses because it had to track targets dispersed over a large area and begin its

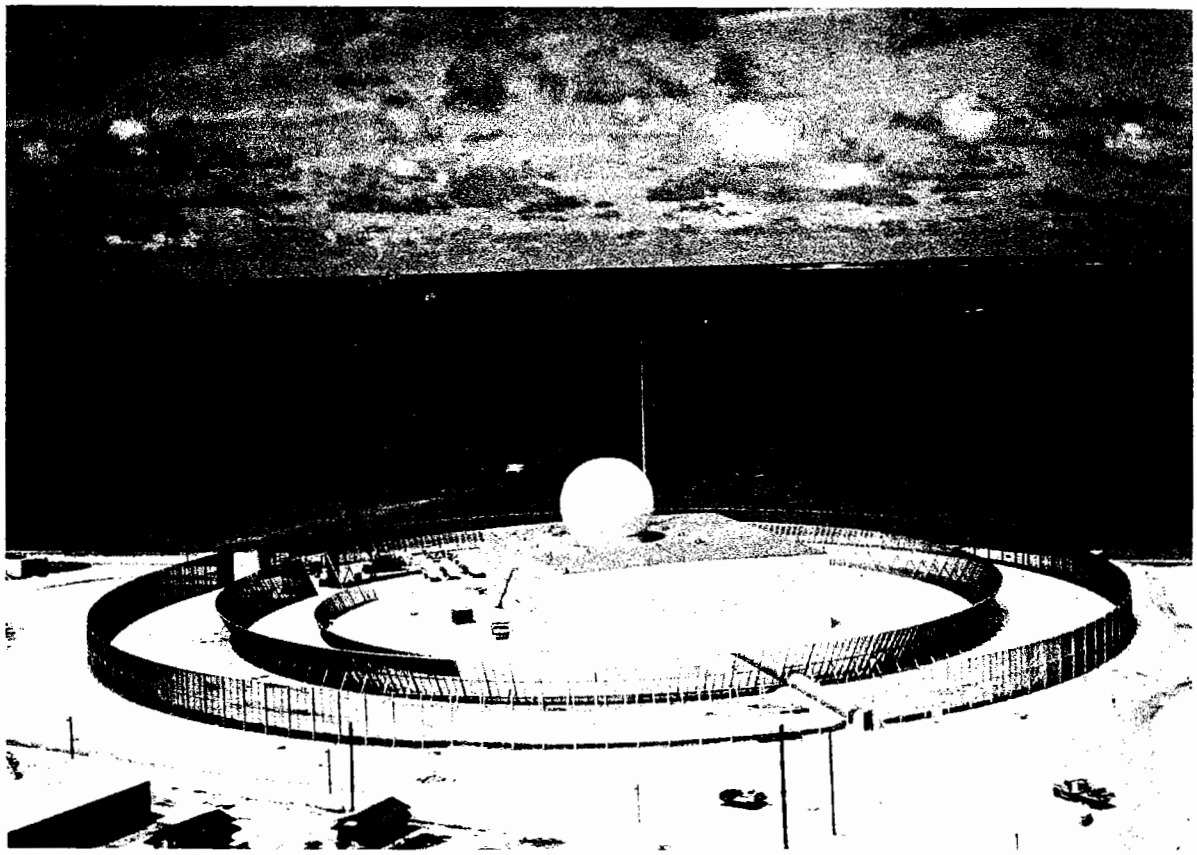


Figure 1-10. R&D Model of Discrimination Radar (Kwajalein)

tracking at long ranges. To carry out the discrimination function, however, extremely high resolution of many objects was required. This was accomplished by compressing the long transmitted pulse in the receiver to provide fine range resolution and accuracy. Also designed into the DR was a system of multiple narrow tracking gates. These features made possible the separation of signal returns from the individual objects within the cloud for subsequent discrete analysis by data processing equipment associated with the DR.

The Discrimination Radar (with its signal processing equipment) had to be able to designate a target, which it had selected for engagement, to a TTR with sufficient accuracy for prompt and unambiguous transfer. To accomplish this, the DR generated three-dimensional position information on the objects it designated. A monopulse receiving system provided azimuth and elevation position signals for the object in the narrow range gate. These signals gave target position with respect to the beam axis. In addition, the transmitted pulses of the DR and the TTR were synchronized to facilitate target transfer. The return signals in both radars were collapsed to 0.25 microsecond to ensure that they would receive exactly the same signal from the selected object. These measures enabled transfer of an object from the DR to a TTR (when it was pointed in the general direction of the eloud) within 2 seconds.

The characteristics of the DR are listed in Table 1-2.

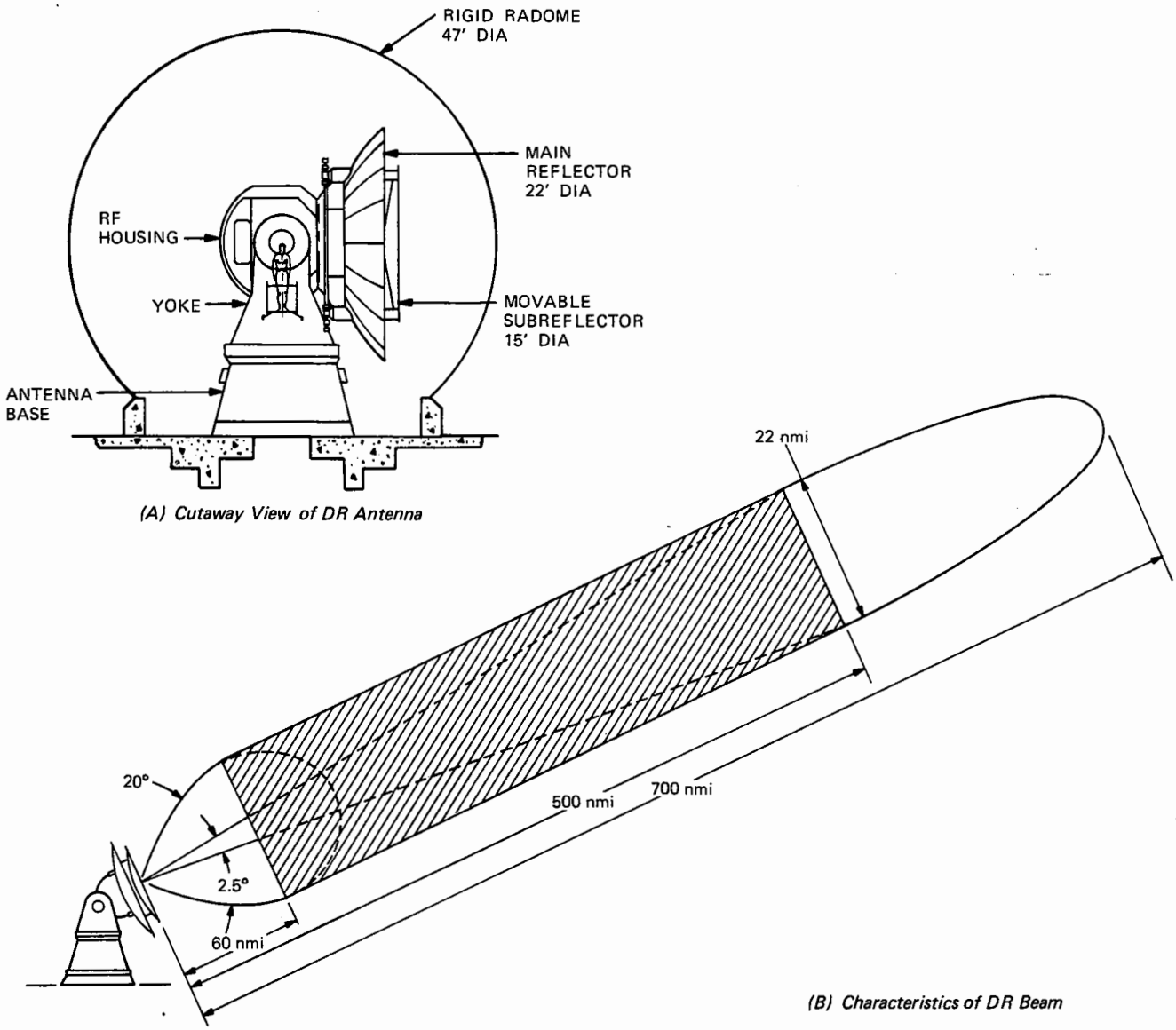


Figure 1-11. Discrimination Radar

Transmitter

The DR transmitter generated chirp pulses of high peak power. This power output was delivered from two special high-powered klystrons in the final RF amplifier.[9] Transmitter operation was within the L-band with the output signal generated in 13 preselected frequency channels over the entire operating range. It was planned that, in tactical operation, these channels would be used randomly, on a pulse-to-pulse basis, to provide frequency diversity. Each channel was crystal-controlled for frequency stability.[10]

Antenna

The DR antenna [see (A) of Figure 1-11] was a parabolic reflector-subreflector structure employing a multimode monopulse feed and supported on a two-axis mount. The main reflector was a metallic paraboloid with an added overlay of metal wires which acted as a polarization twister. The subreflector was a nonmetallic hyperboloid, embedded with horizontal metal wires, capable of being moved continuously for 18 inches with respect to the main reflector. This motion defocused the beam and

Table 1-2
Discrimination Radar Characteristics

Transmitter	
Peak Power	40 MW*
Average power	78 kW*
Pulse rate	97.7 pps
Pulse duration	20 μsec
Duty factor	0.00195
Frequency	
Carrier	1270 to 1400 MHz
Diversity	Random pulse-to-pulse shift among 13 preselected frequencies over entire band
Chirp	Instantaneous output frequency varies linearly over 10-MHz range during pulse
Antenna	
Type	Cassegrainian
Diameter	22 ft
Beamwidth	Variable from 2.5° to 20°
Gain	Varies from 36 dB at 2.5° beamwidth to 18 dB at 20° beamwidth
Angular coverage	Continuous in azimuth and 190° (-5° to +185°) in elevation
Radome	Rigid, 47 ft in diameter
Receiver	
RF amplifier	Maser
Equivalent noise temperature (overall)	120°K
Intermediate frequency	30 MHz
Collapsed pulse width	0.25 μsec at 3-dB points
Angle determination	Monopulse
Range Capability†	
At maximum beamwidth (20°)	85 nmi at center beam 60 nmi at 3-dB points of beam (22-nmi diameter cloud coverage)
At minimum beamwidth (2.5°)	700 nmi at center beam 500 nmi at 3-dB points of beam (22-nmi diameter cloud coverage)
Target Position Accuracy‡	
Range	5 yd
Angular	10% of off-axis angle (0.4 mil minimum)

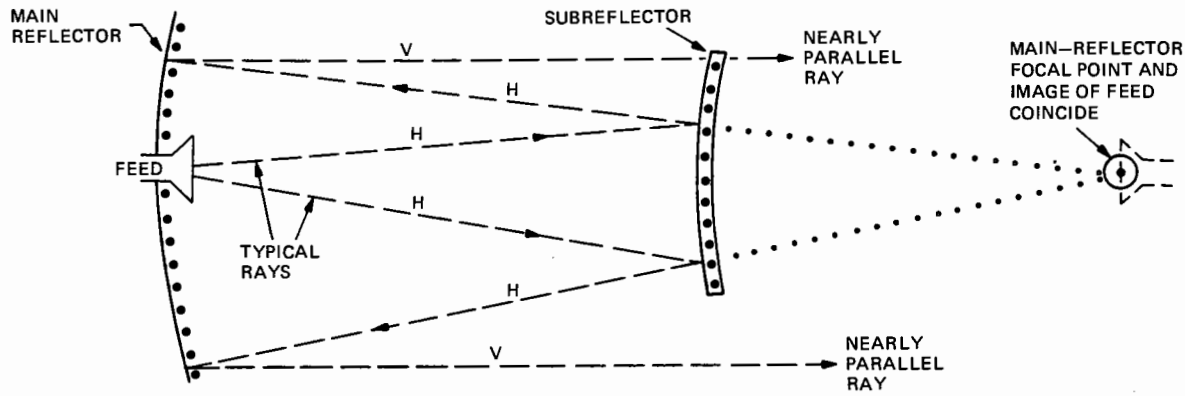
*At the two output klystrons; losses in the guide, etc., are approximately 2.0 dB.

†With 0.1 sq m target.

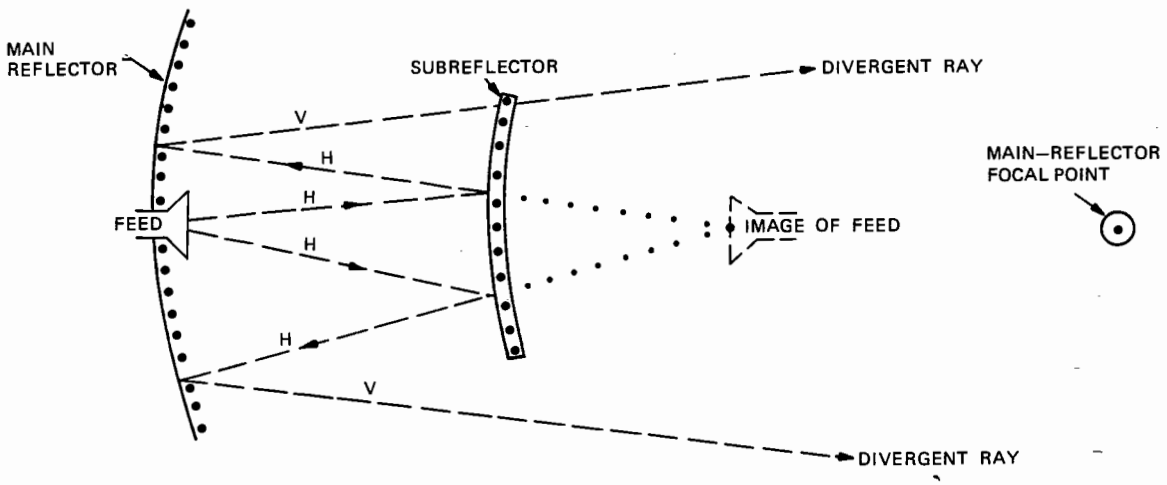
‡6 dB S/N (at half-power points of beam).

caused the beamwidth to change. The design of the focusing/defocusing system is illustrated in Figure 1-12.

To obtain a narrow beam (2.5 degrees) for tracking at long ranges, the subreflector was positioned at the point where the image of the feed was at the focal point of the main reflector. In this condition, the rays were made nearly parallel by the main reflector and produced a narrow beam. Then, as target range decreased and the subreflector was moved in toward the main reflector, the image of the feed moved away from the focal point of the main reflector, causing the antenna to be defocused. When this occurred, the rays from the main reflector were divergent, and the beam was widened (up to a total width of 20 degrees).



(A) Antenna Focused – Narrow Conical Beam



(B) Antenna Defocused – Widened Conical Beam

Figure 1-12. Focusing/Defocusing System of DR Antenna

Receiver

The DR used an extremely sensitive receiver to provide highly accurate position information on small objects in the target-decoy cloud. Maser RF amplifiers, operating at 2.5 degrees Kelvin, achieved a very low noise level. The receiver's monopulse design enabled it to provide simultaneous off-axis angle information on many objects,[11] and its chirp circuits compressed (dechirped) the long transmitted pulse to 0.25 microsecond to provide satisfactory range resolution.

Data Processing Equipment

A major portion of the data processing equipment of the NIKE-ZEUS System was associated with the Discrimination Radar. The function of this equipment was to analyze tracked objects and perform tests on them to determine which targets were threatening. These targets then were arranged in a list according to their "likelihood" of being warheads. The DR data processing equipment comprised the All-Target Processor and the Discrimination and Control Computer. (See the section on Data Processing Equipment later in this chapter.)

TARGET TRACK RADAR

The Target Track Radar (TTR), shown in Figure 1-13, was a precise, long-range, narrow-beam tracking radar which gathered highly accurate, continuous position data on very small, high-speed targets during the terminal phase of an engagement.[12] A supercooled, super-low-noise, solid-state maser RF amplifier was used in conjunction with a high-gain Cassegrainian antenna to receive and amplify signal returns as low as 110 dB below 1 milliwatt.

The tactical TTR did not have a computer of its own, but was being designed to operate in conjunction with the Target Intercept Computer (TIC). However, because of testing requirements, each of the R&D models of the TTR had its own computing equipment which accomplished some of the functions that in a tactical deployment would have been done by the data processing equipment associated with the Discrimination Radar. In the tactical environment, the TTR would have made no decisions about targets, but would have been assigned a specific target (one at a time) by the TIC, based on the information that computer received from the Discrimination and Control Computer. Characteristics of the TTR are listed in Table 1-3.

Transmitter

The TTR transmitter provided a narrow chirp pulse with 10 megawatts peak power. The transmitter consisted of a chirp generator and synchronizer, a low-level section, and a high-level section.[13]

A stabilized local oscillator in the low-level section generated a signal at the transmitter carrier frequency from low-frequency crystal oscillators. This local-oscillator signal was mixed with a chirped signal for good range resolution even though long, high-energy pulses were transmitted.

The high-level section of the transmitter provided final amplification of the pulses to be transmitted. This amplification was accomplished by two 5-megawatt klystrons whose outputs were combined. Figure 1-14 shows the klystron amplifier section, with the two output klystrons installed in their insulating-oil tanks.

Antenna

The TTR antenna (see Figure 1-13) was a 22-foot-diameter parabolic reflector-subreflector arrangement supported on a three-axis (elevation, traverse, azimuth) mount. A three-axis mount (instead of the more usual two-axis type) was chosen to allow the tracking of extremely high-speed ballistic missile targets directly overhead, where the required axial velocities and accelerations would be prohibitive for the two-axis type.[14] Under these conditions, such targets

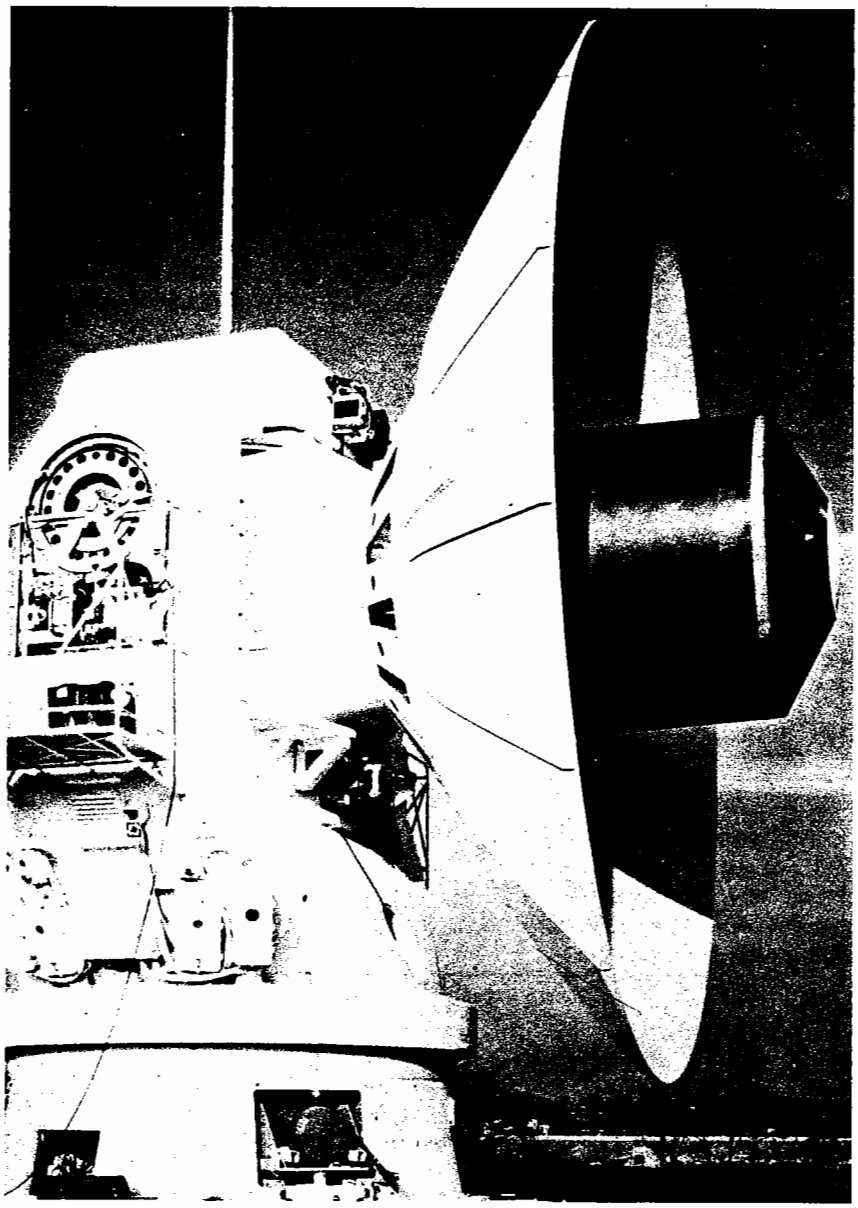


Figure 1-13. R&D Model of Target Track Radar Antenna (Whippany)

Table 1-3
Target Track Radar Characteristics

Transmitter	
Peak power	10 MW*
Average power	5 kW*
Pulse rate	97.7 pps
Pulse duration	5 μsec
Duty factor	0.0005
Frequency	
Carrier	5500 ± 250 MHz
Diversity	Random discrete changes among 50 frequencies in 500-MHz range
Chirp	Instantaneous output frequency varies linearly over 10-MHz range during pulse
Antenna	
Type	Cassegrainian
Diameter	22 ft
Beamwidth	0.6°
Gain	48.5 dB
Angular coverage	Continuous in azimuth, 190° (-5° to +185°) in elevation, and ±25° about a zero reference in traverse
Radome	Rigid, 47 ft in diameter
Receiver	
RF amplifier	Maser followed by Traveling Wave Tube
Intermediate frequencies	First IF: 1280 MHz Second IF: 30 MHz
Collapsed pulse width	0.25 μsec at 3-dB points
Angle Determination	Monopulse
Equivalent Noise Temperatures at Antenna	
Antenna	40°K
Duplexer and waveguide	99°K
Maser amplifier	13°K
Circuit following maser	45°K
Total radar system	197°K
Range Capability — 6 dB S/N†	
Target cross section	
0.1 sq m	580 nmi
0.01 sq m	325 nmi
Tracking Accuracy — 18 dB S/N‡	
Angular (overall)	0.18 mil
Tracking jitter	0.10 mil
Boresight	0.10 mil
Mechanical error	0.10 mil
Data takeoff	0.05 mil
Range	
Tracking jitter	2 yd
Zero set	2 yd

*At the two output klystrons; losses in the guide, etc., are approximately 2.7 dB.

†0.1 angular mil thermal tracking jitter occurs at about one half these ranges.

‡Standard deviation tracking errors.

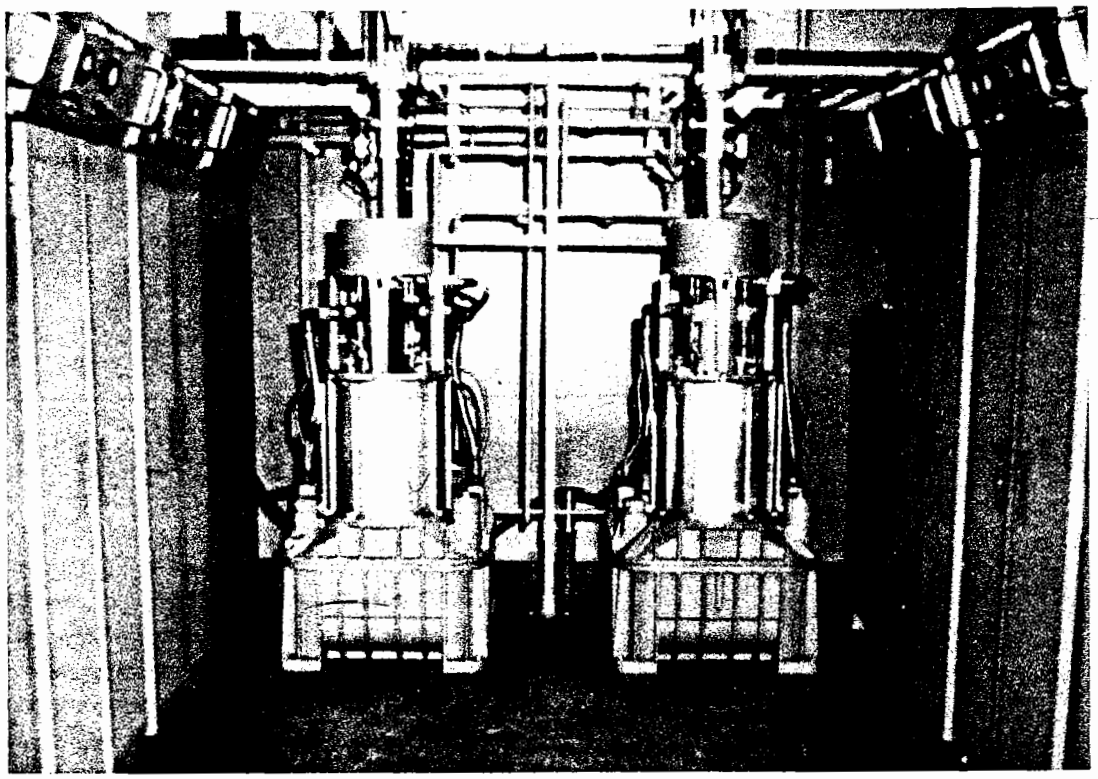


Figure 1-14. TTR Klystron Amplifier Section

could be tracked to altitudes as low as 50,000 feet; ballistic missiles not passing through the zenith could, of course, be tracked to lower altitudes.

The TTR antenna mount weighed about 150,000 pounds and was positioned by hydraulic motors operating in pairs on each axis. These hydraulic drives provided a maximum slew rate in azimuth and elevation of 1.25 radians per second, and in traverse of 0.5 radian per second.

Receiver

The TTR receiver used a super-low-noise, solid-state maser for the first RF amplifier, followed by a Traveling Wave Tube (TWT) for final amplification. The equivalent noise temperature of the RF amplifier, the most critical source of noise in the receiver, thereby was reduced enormously. In previous radar receivers, a receiver noise temperature of 3000 degrees Kelvin was not unusual. (Figure 1-15 compares graphically the performance of the maser receiver with other types of receivers.) The overall TTR system noise temperature was 197 degrees Kelvin.[15]

Data Processing Equipment

As previously stated, the tactical TTR was not to have any data processing equipment of its own. However, those R&D models built and operated during the test program were equipped with data processing equipment to meet the test objectives. Each such TTR was equipped with a Target Intercept Computer as well as with peripheral equipment to provide the necessary interface with the computer.

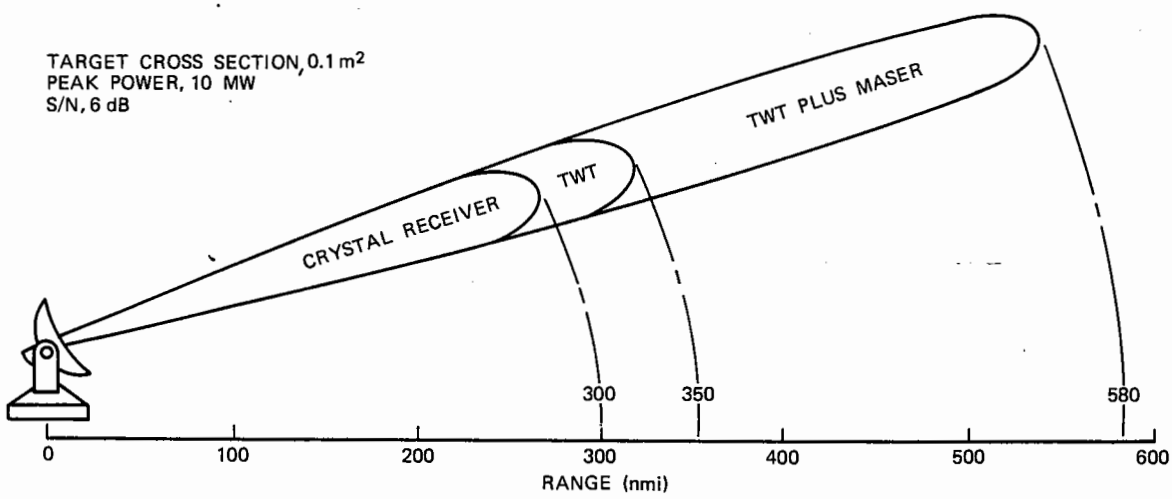


Figure 1-15. Comparison of Range Obtained with Maser Receiver and Other Receivers

MISSILE TRACK RADAR

The Missile Track Radar (MTR) provided position data on the defensive missile to the Target Intercept Computer (TIC). It also transmitted steering, burst, and other orders from the TIC to the defensive missile via the radar beam. This radar could track the beacon-equipped ZEUS missile to a range of 75 nautical miles with an overall angular accuracy of 0.2 mil. A combination of different pulse codes and frequencies permitted a particular MTR to communicate with a defensive missile without interfering with other missile-radar combinations. As many as 450 missiles could be under control in a defense area without mutual interference. The characteristics of the MTR are listed in Table 1-4. The MTR antennas of a Battery were mounted on towers that were part of the Battery Control Building (Figure 1-16) which also housed the radar equipment and the Target Intercept Computers.

Transmitter

The MTR transmitter provided a peak power output of 300 kilowatts. It consisted of a hardtube modulator driving a magnetron that was automatically tuned to any one of nine fixed frequencies spaced at 50-MHz intervals. The transmitter could be switched to any of these nine separate ZEUS missile receiver frequencies quickly and accurately. An automatic frequency control unit referenced the transmitter signal to the X-band harmonic outputs of a transistorized, crystal-controlled frequency standard.[16]

The MTR transmitter was installed below the antenna in the Battery Control Building, rather than in the rotating structure, to keep the size of the rotating portion of the antenna mount to a minimum. RF power was fed to the antenna via X-band waveguide and two rotary joints, one in the azimuth axis and the other in the elevation axis. The waveguide was pressurized to 35 pounds per square inch absolute to prevent breakdown and thus ensure full power output.

Antenna

A 4-foot-diameter Cassegrainian antenna (Figure 1-17), on a two-axis mount, provided a gain of 38 dB. The mount could rotate continuously in azimuth and track in elevation from 11.5 degrees below the horizon through the zenith to 11.5 degrees below the horizon on the opposite side. The slew rate in each axis was about 2 radians per second. Only 5 seconds was required from the end of an engagement for the radar to lock on to the next missile.

Table 1-4
Missile Track Radar Characteristics

Transmitter	
Peak power	300 kW*
Average power	108 W*
Pulse rate	Normal: 162.8 groups per sec (9 pulses in each group) Burst: 488.4 groups per sec (4 pulses in each group)
Pulse duration	0.25 μsec
Duty factor	0.00036
Frequency	8525 to 8925 MHz
Antenna	
Type	Cassegrainian
Diameter	4 ft
Beamwidth	2°
Gain	38 dB
Angular coverage	Continuous in azimuth and 203° (-11.5° to +191.5°) in elevation
Receiver	
Frequency	8960 to 9600 MHz
Noise figure	9 dB
Intermediate frequency	25 MHz
Angle determination	Monopulse
Tracking Accuracy — 26 dB S/N	
Angular (per coordinate)	
Tracking jitter	0.10 mil†
Boresight	0.10 mil†
Mechanical error	0.10 mil†
Data takeoff	0.05 mil†
Angular (overall)	0.18 mil
Range	
Tracking jitter	2 yd‡
Zero set	2 yd‡

*At magnetron; losses in the guide, etc., are approximately 2 dB.
†Nominal value obtained at maximum design range.
‡Standard deviation tracking accuracy.

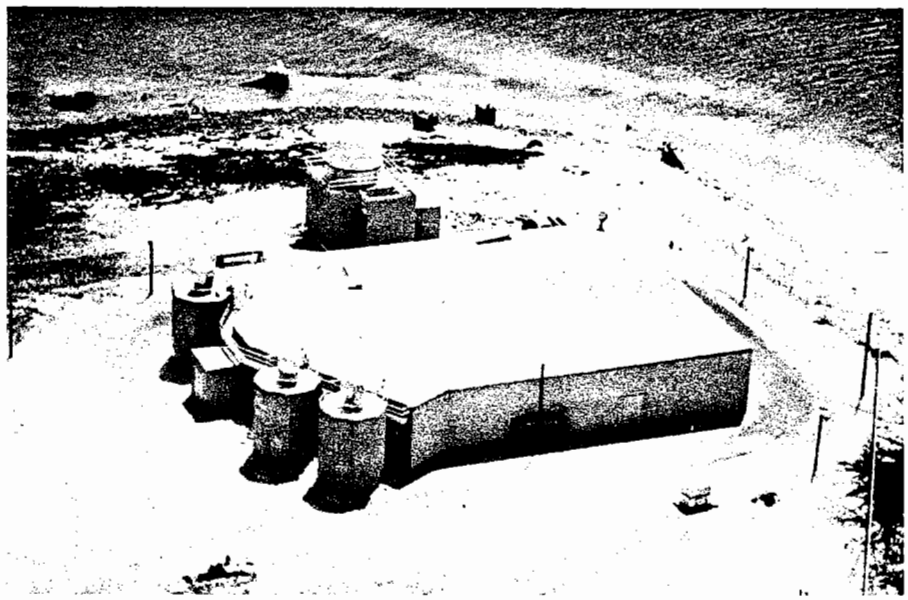


Figure 1-16. Battery Control Building with Missile Track Radar Antennas

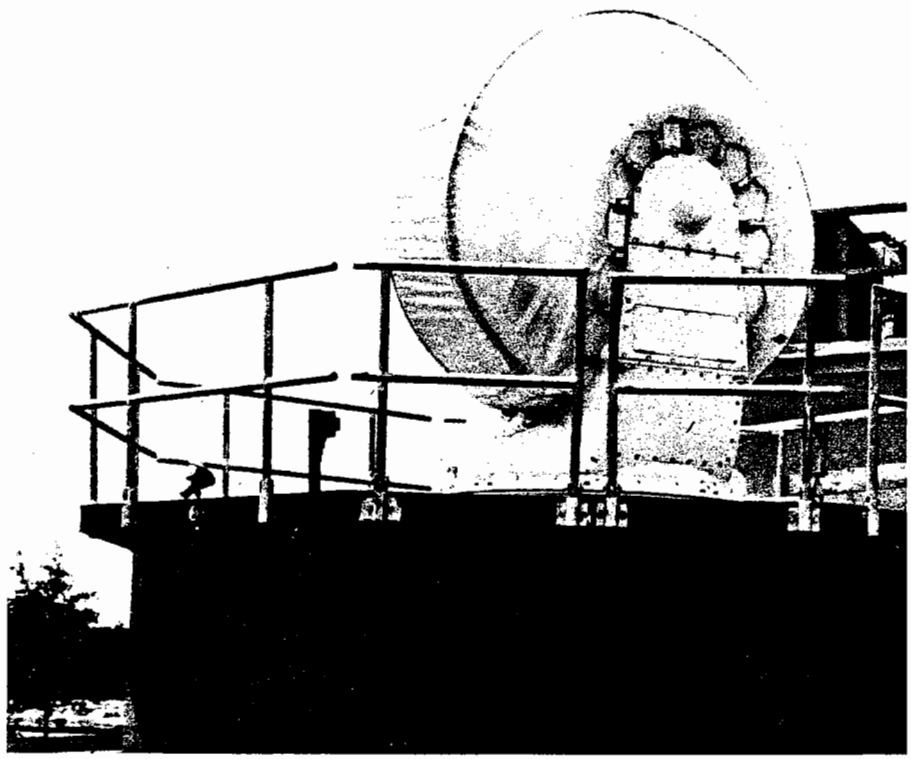


Figure 1-17. R&D Model of MTR Antenna (Whippany)

Receiver

The MTR's monopulse receiver had a noise figure of 9 dB and a bandwidth of 10 MHz. It could be automatically tuned to any one of the nine fixed frequency channels used by ZEUS missile transmitters; these channels were spaced at 80-MHz intervals.

The signals from the missile transmitter, intercepted by the MTR antenna, were fed to a comparator which converted the horn inputs to azimuth, elevation, and sum signals. These in turn were fed to a converter assembly, where they were mixed with the local oscillator output to produce IF signals. The local oscillator was a klystron, the frequency of which was controlled to within ±3 MHz by an automatic frequency control system, thus locking the receiver to the signals from the missile.

The gains of the sum, azimuth, and elevation channels of the receiver always had to be kept equal to preserve interchannel balance, even though the received signals may have had amplitudes varying over a range of 94.5 dB. This automatic gain control was achieved through the use of transistorized digital-amplifier and attenuator-switching circuits, which could adjust gain in 1.5-dB steps. The range unit in the receiver also employed transistorized circuits and digital techniques in furnishing data to the Target Intercept Computer. Azimuth and elevation angle data were derived from precison resolvers on the two antenna axes and were encoded for transmission to the computer.

MISSILE

The NIKE-ZEUS missile (Figure 1-18) had three major sections — the booster or first stage,

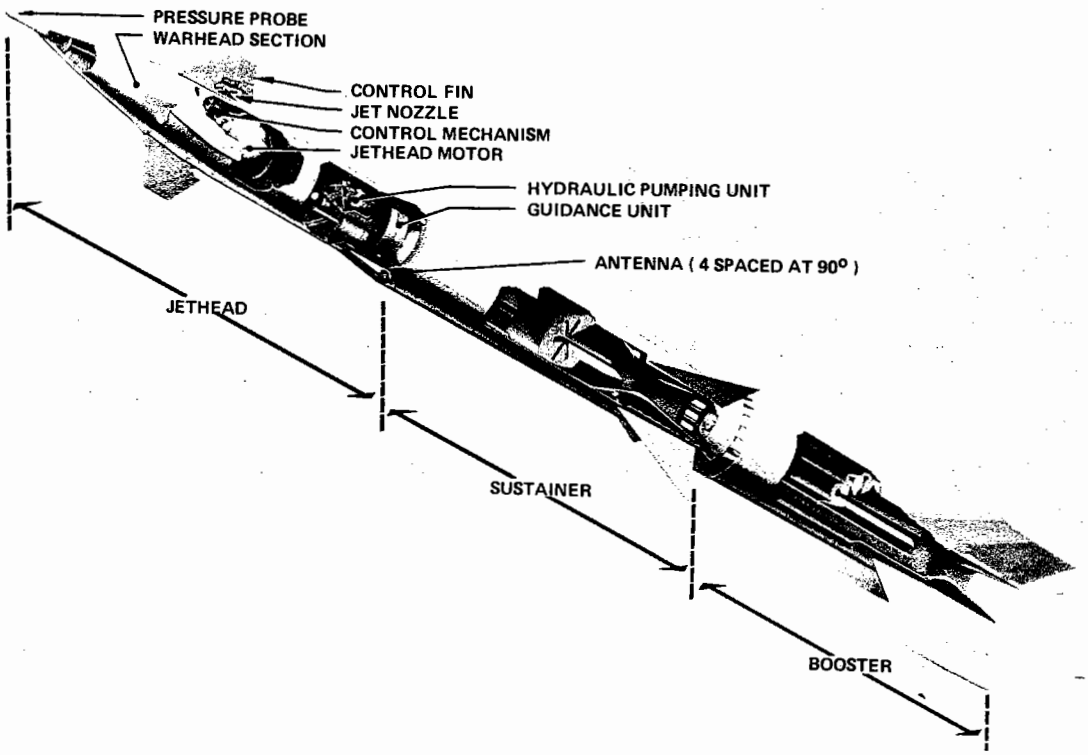


Figure 1-18. NIKE-ZEUS Missile, Cutaway View

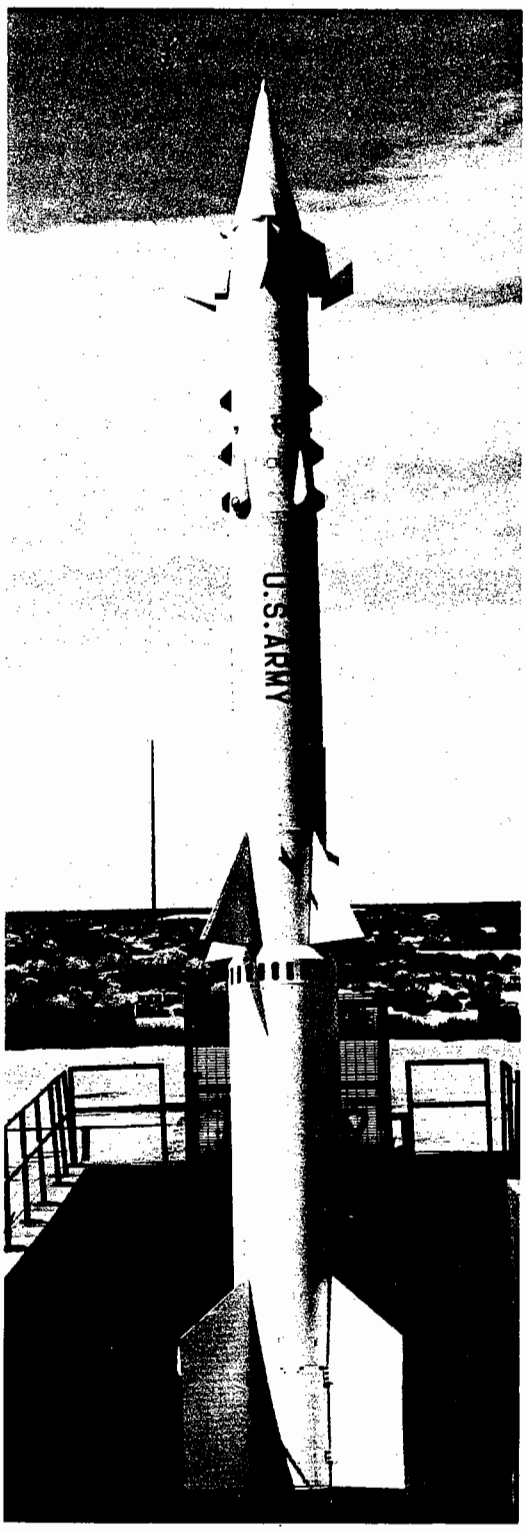


Figure 1-19. NIKE-ZEUS Missile in Launch Pit

the sustainer or second stage (also called the mainstage), and the nose section or jethead.[17] To avoid additional complexity, the same missile-borne guidance and control equipment was used to position the missile's control surfaces both inside and outside of the atmosphere. Within the atmosphere, roll control and steering were accomplished by aerodynamic forces acting on four control fins. Outside the atmosphere, reaction control was used, with the gases expelled through jet nozzles in the same control surfaces. Figure 1-19 shows the NIKE-ZEUS missile ready to launch. Missile characteristics are given in Table 1-5.

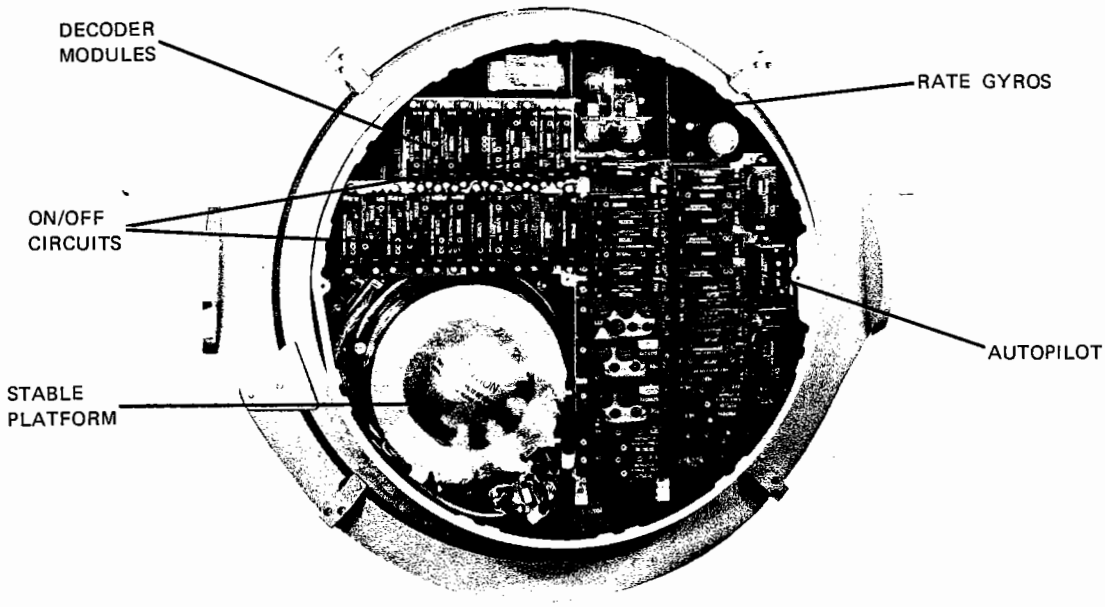
The missile-borne guidance unit, shown in Figure 1-20, received and decoded the steering orders and certain commands, such as arm and burst, relayed to it by the MTR.[18] These coded instructions were received as groups of pulses modulating a carrier whose frequency was in the range from 8525 to 8925 MHz. The guidance unit comprised a transmitter, a receiver, a decoder, a stable platform, part of the missile's autopilot, and several on/off circuits. There were four identical antennas spaced at 90-degree intervals on the outer housing of the guidance unit and enclosed in strakes (see Figures 1-18 and 1-19). Each antenna was a cylindrical waveguide terminated in a diverging lens to give hemispherical coverage. Two of the antennas were used for transmitting and all four were used for receiving.

To prevent interference among the MTR-missile combinations in a Battery, a different combination of carrier frequency and pulse code was used for each missile. The missile's receiver had a dual Traveling Wave Tube RF amplifier and a dual crystal detector, each channel being used for the signals from two of the missile's antennas.

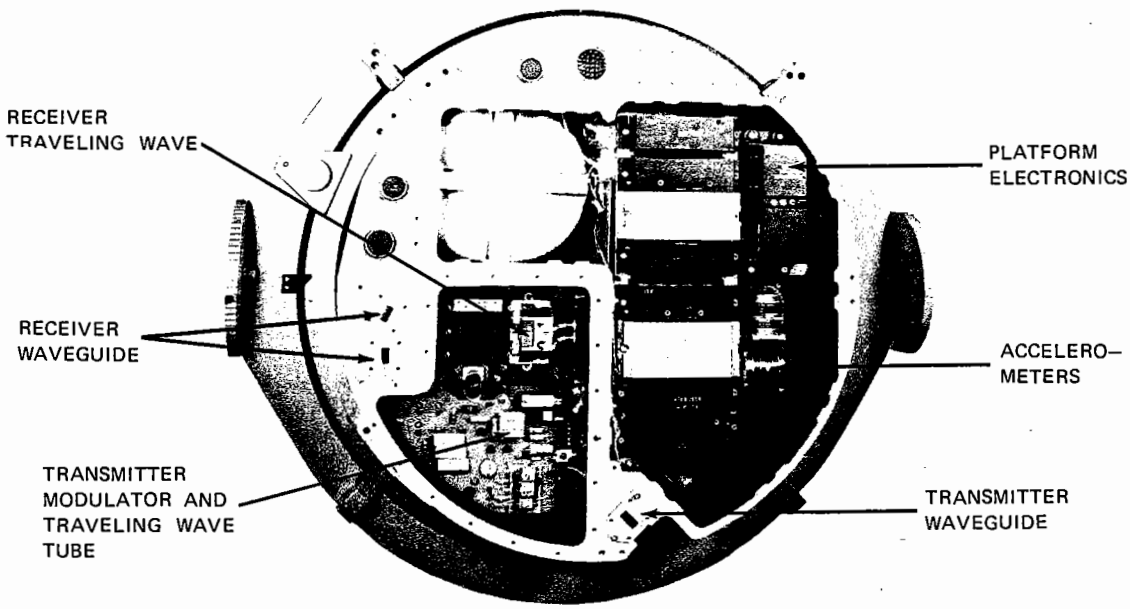
Table 1-5

NIKE-ZEUS Missile Characteristics

Overall	
Length (including booster)	50 ft, 2 in
Gross Weight	24,200 lb
Payload	468 lb
Booster	
Length	17 ft, 6 in
Diameter	34 in
Gross weight	12,900 lb
Solid propellant	Polybutadiene acrylic acid (PBAA)
Sustainer	
Length	15 ft, 2 in
Diameter	36 in
Gross weight	8,250 lb
Solid propellant	PBAA
Ablative covering	Phenolic nylon skin
Maximum skin temperature	600°F
Maximum operating altitude	84,570 ft
Jethead	
Length (including probe)	17 ft, 6 in
Diameter (maximum)	36 in
Gross weight	3050 lb
Solid propellant (jethead motor)	PBAA
Ablative covering	Phenolic nylon skin
Steering and roll control:	
Within atmosphere	4 control fins
Outside atmosphere	Motor exhausting through fin nozzles
Warhead section:	
Tactical missile	Warhead and arming
R&D missile	Telemetry



(A) Interior View from Forward



(B) Interior View from Aft

Figure 1-20. ZEUS Missile-Borne Guidance Unit

DATA PROCESSING EQUIPMENT

Functional Organization

Data processing equipment in the NIKE-ZEUS System was concerned with processing position information from the radars, planning and controlling system operations (tactical control), and accomplishing target selection and decoy discrimination. These functions were implemented by six major computing equipments, as illustrated in Figure 1-21, plus associated peripheral equipment.[19]

The Target Data Consolidator detected targets and determined their positions.[20] The ZAR Data Processor evaluated the threat and provided data on threatening objects to the Batteries, where appropriate Battery elements would be assigned to engage each target. This target information also was to be used by the Batteries to determine (1) when to fire defensive missiles and (2) what command-guidance orders should be given during the early stages of missile flight. The ZAR Data Processor was to have a capacity of several hundred tracks depending upon the size of the NIKE-ZEUS installation.

The All-Target Processor was a special-purpose digital computer which could process data on as many as 625 objects in a target-decoy cloud. These data were received from the Discrimination Radar in analog (video) form and were encoded into digital form by the processor. The All-Target Processor then used the slowdown, scintillation, and cross-section characteristics of the objects to eliminate obvious decoys. Data on the remaining objects were passed to the Discrimination and Control Computer, where additional and more rigorous discrimination tests were performed.

The Discrimination and Control Computer could accept data on as many as 50 targets from the All-Target Processor. This computer also used the slowdown, scintillation, and cross-section characteristics of the objects to eliminate those that had the characteristics of decoys. The computer then generated a composite likelihood

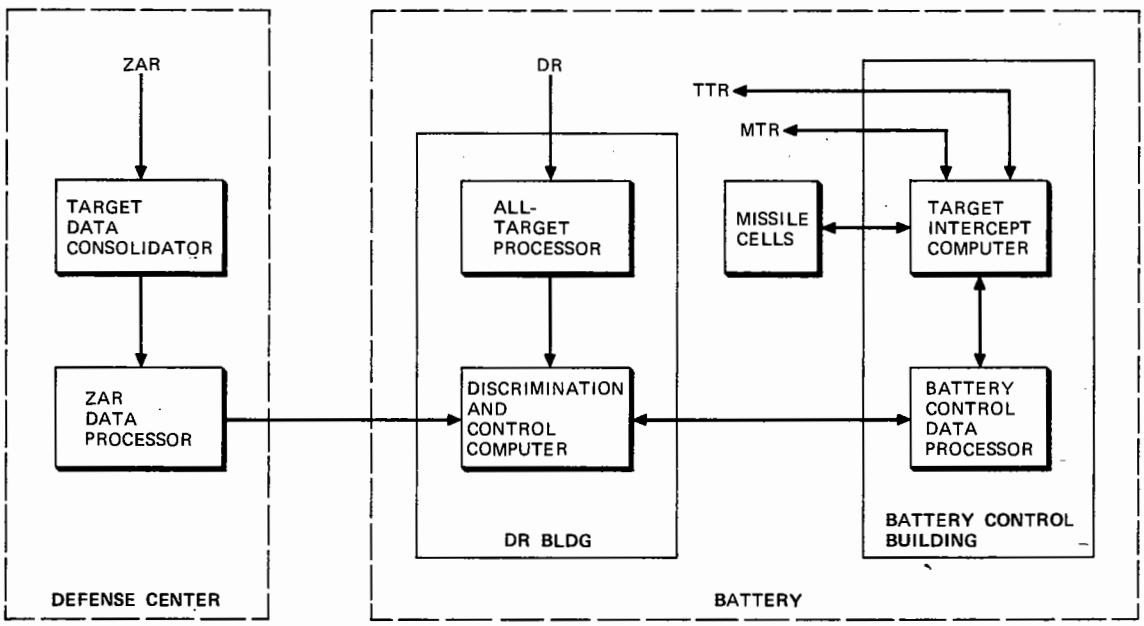


Figure 1-21. Major Computing Equipments of NIKE-ZEUS, Simplified Block Diagram

ratio for each remaining object.[21] The likelihood ratios, along with acceleration, velocity, and position data on all the remaining objects, were sent to the Battery Control Data Processor where the final determination for engagement was made.

Signal flow at the Battery is shown on Figure 1-22. Selections of Missile Track Radars and Target Track Radars for a given engagement were made by the Battery Control Switching System, at the direction of the Target Intercept Computer. The timing for all Battery units was provided by the Battery Timing Generator and communication with the Defense Center was via the Communications Terminal. The Battery Assignment Monitor and Console Displays provided the required man/machine interface.

The Battery Control Data Processor was designed to perform the tactical control operations required by the Battery primarily in an engagement involving decoys. Its functions were to include engagement planning (that is, how many missiles to launch, on what trajectories, and at what time) and engagement execution (that is, which object or objects to intercept). This equipment received position and target-likelihood data from the Discrimination and Control Computer and provided target-designation, engagement, and equipment-request signals to the Target Intercept Computers.

The Target Intercept Computer made all the computations required to determine the guidance orders enabling the defensive missile to intercept a hostile target. Each Target Intercept Computer handled the computations required for six separate concurrent engagements by time-multiplexing in one circuit path. The computing cycle was divided into six equal periods, each handling all computations for an engagement. The Target Intercept Computer utilized Missile Track Radar information on the position of the ZEUS missile; it also received target position information from the ZEUS Acquisition Radar, the Discrimination Radar, or the Target Track Radar. From this information, it computed and generated coded acceleration orders for the Missile Track Radar to transmit to the defensive missile. During a normal interception, it generated a "jet ignite" command to start the jethead motor and a "burst" command when the ZEUS missile reached the point on its trajectory which produced the maximum kill probability. Besides generating guidance orders, the Target Intercept Computer's functions included (1) performing certain computations needed by the Target Track Radar and (2) furnishing engagement data and status information to the Battery Control Data Processor. Figure 1-23 shows the Target Intercept Computer; its characteristics are given in Table 1-6.

Modular Structure

In the NIKE-ZEUS System (as in the successor systems) it was planned that the data processing equipment be completely modular. The equipment was constructed of a hierarchy of "building blocks," used in the numbers and combinations required to accomplish specific functions.

The largest building block was the NIKE-ZEUS High-Speed Digital Computer (Figure 1-24). Each of the major computing equipments shown in Figure 1-21 used at least one of these computers. Next below the level of the digital computer was the D-unit (Figure 1-25), the unit of replacement for field maintenance. D-units were slide-mounted in special racks. Each D-unit was composed of flat, chassis-like assemblies called C-planes (Figure 1-26). C-planes were stacked vertically (up to a maximum of six) to form a D-unit.

The lowest-unit building blocks were the A- and B-modules. The basic A-module (Figure 1-27) contained four transistor inverters, which could be connected externally to form double inverters, flip-flops, and other logic elements. A-modules were arranged in an array seven modules wide by ten modules long on the C-plane. Special packages, in multiples of the A-module size, were referred to as B-modules.

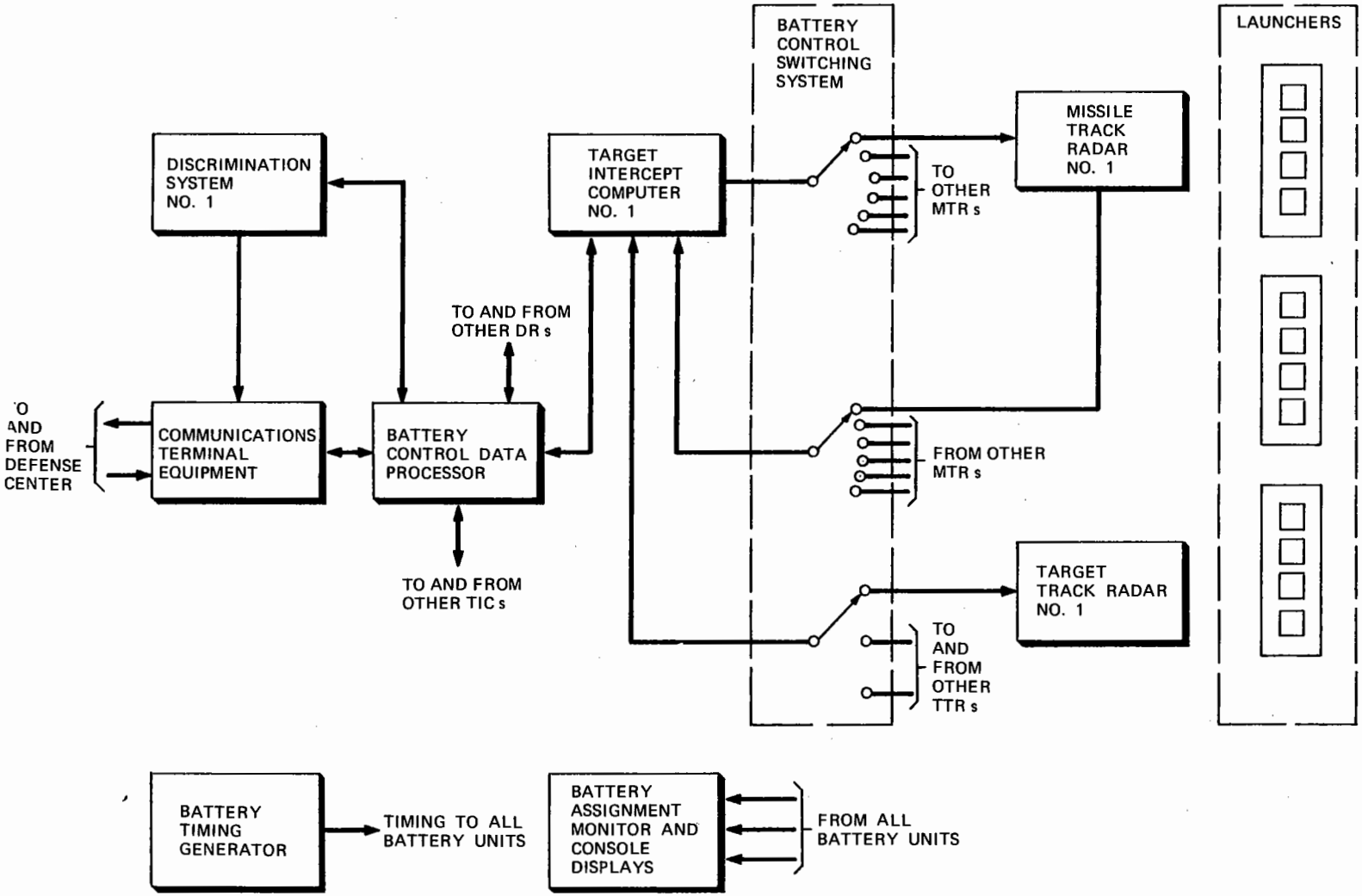


Figure 1-22. Signal Flow at Battery, Simplified Block Diagram

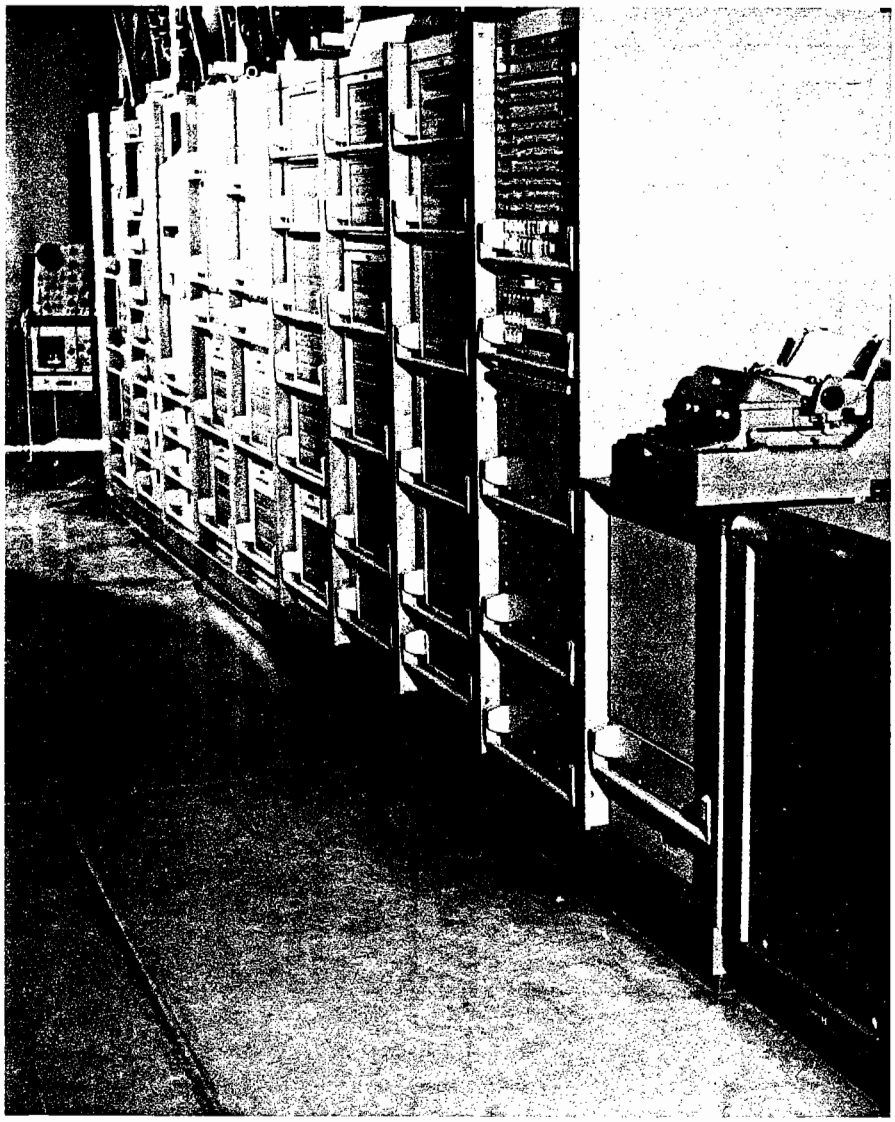


Figure 1-23. Target Intercept Computer

Table 1-6

Target Intercept Computer Characteristics

Type of logic	Resistance-coupled transistor logic
Type of arithmetic	Two's complement
Type of operation	Parallel
Word length	25 bits including sign and parity
Number representation	Fractional
Instruction repertoire	54 instructions
Modes of operation	Assigned, ready, and off-line
Arithmetic Unit	
A-register	24-bit double rank
Q-register	24-bit double rank
N-register	24-bit single rank
Speed of operation	
Addition and subtraction	2.5 μsec
Multiplication	7.5 μsec
Division	15.0 μsec
Square root	27.5 μsec
Storage	
Permanent memory	
Capacity	24,576 25-bit words
Type of read-out	Nondestruct
Cycle time	2.5 μsec
Variable memory	
Capacity	4,096 25-bit words
Type of read-out	Destruct
Cycle time	2.5 μsec
Reference memory	
Capacity	15 16-bit words
Type of read-out	Destruct
Cycle time	1.25 μsec

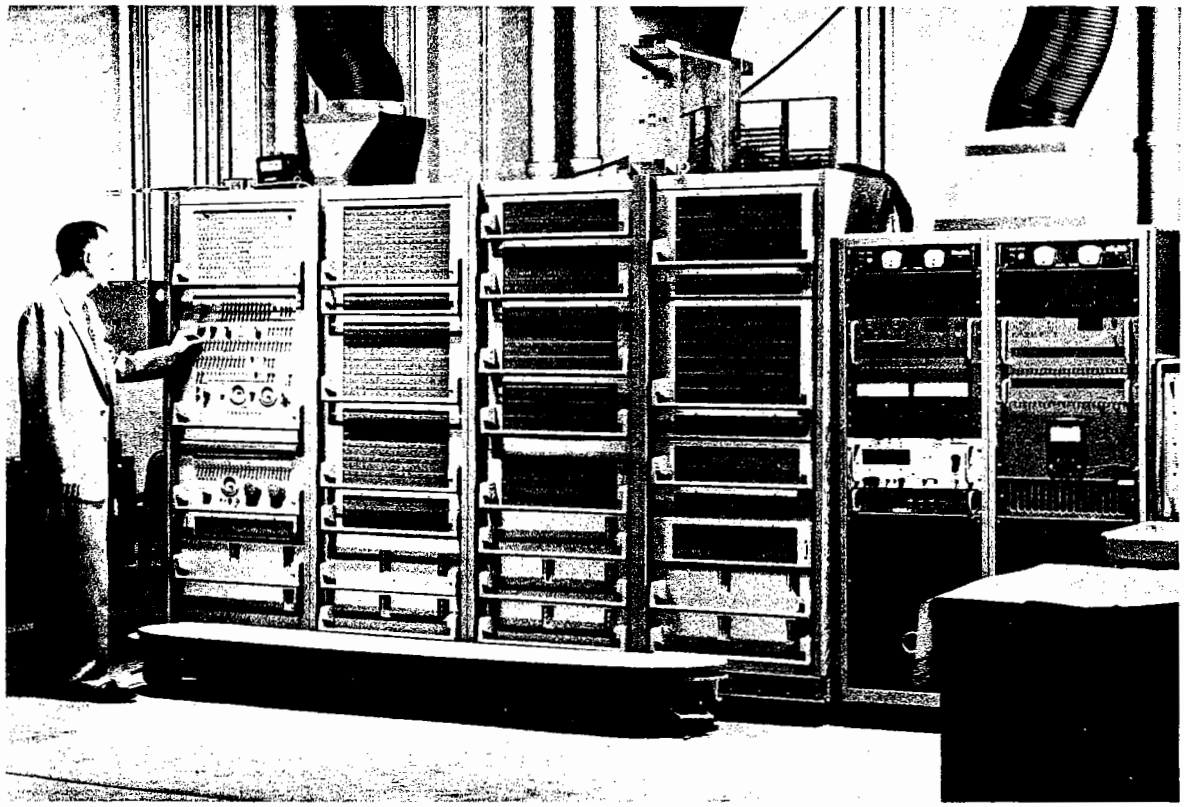


Figure 1-24. NIKE-ZEUS High-Speed Digital Computer

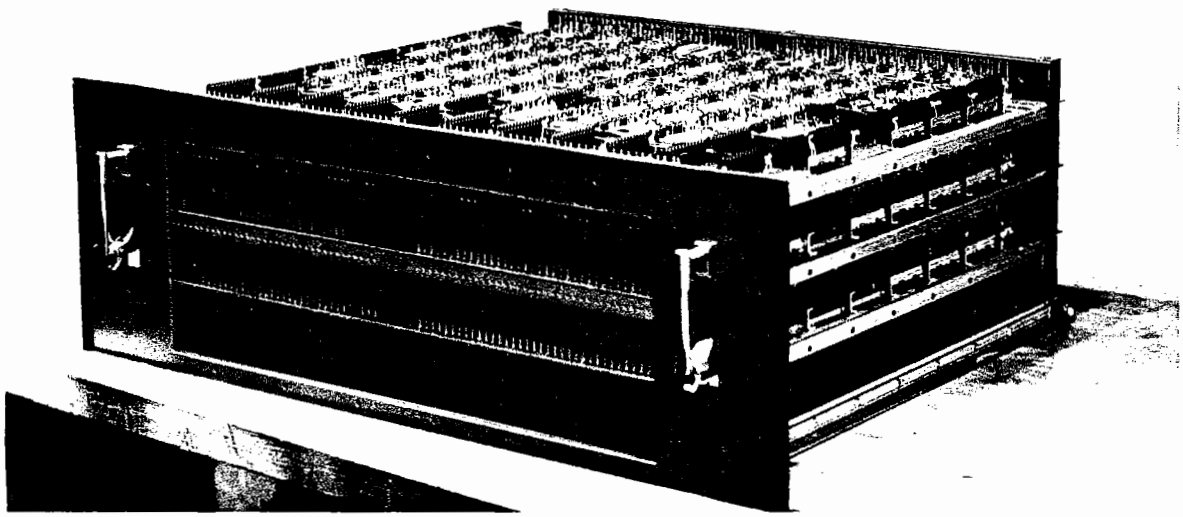


Figure 1-25. D-Unit for NIKE-ZEUS Computer

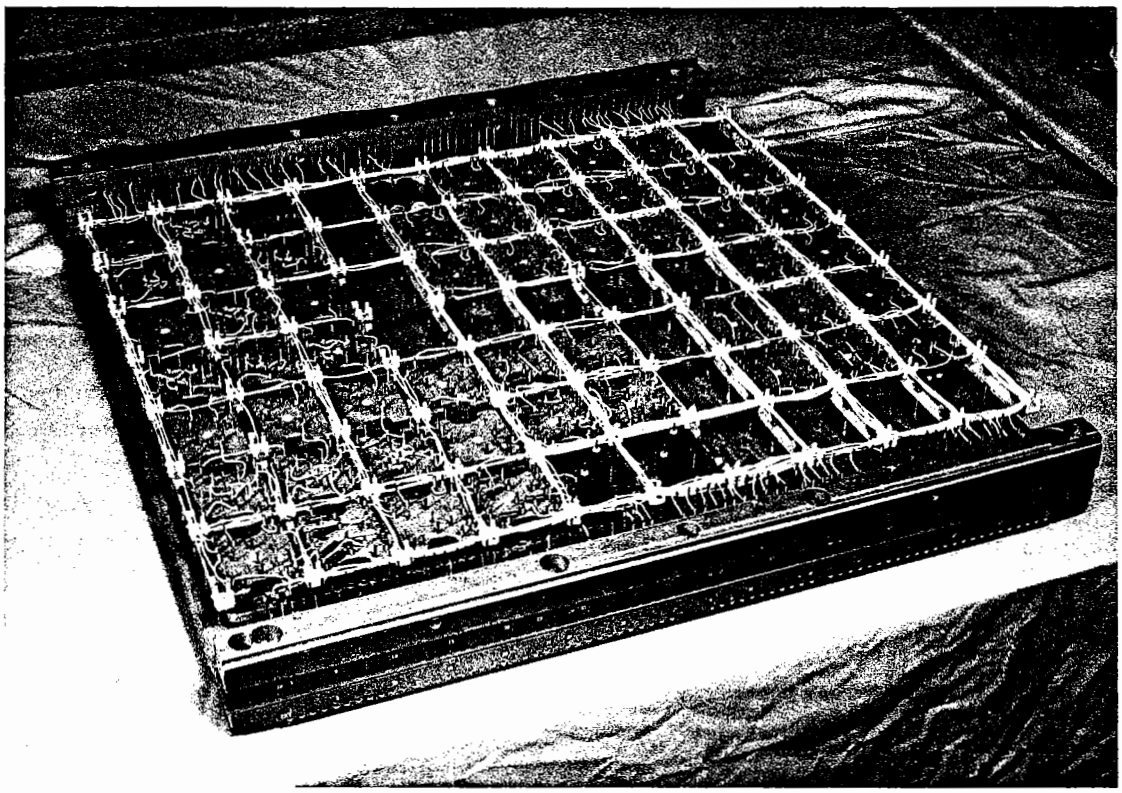


Figure 1-26. C-Plane for NIKE-ZEUS Computer

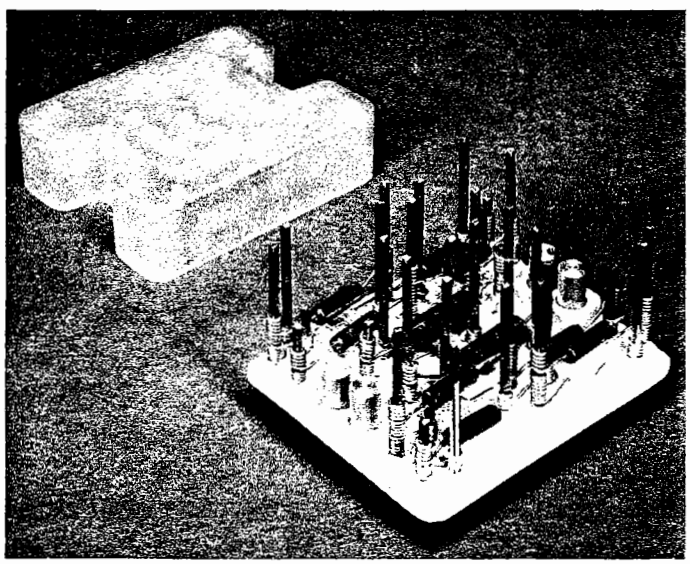


Figure 1-27. Logic A-Module for NIKE-ZEUS Computer

In addition to the standard A-module inverters, some 35 special-purpose circuits were required. Among these circuits, which took up only about 10 percent of the equipment, were sense amplifiers, inhibit generators, current generators, relay drivers, delays, and dummy loads. Wherever possible, these circuits were built into the basic A-module package.

Another important feature of the modular units making up the NIKE-ZEUS data processing equipment was the diffused-base germanium transistor (designated 2N559) used in the logic circuits. This device was developed for NIKE-ZEUS by Bell Laboratories and produced in large numbers by the Western Electric Company. Major emphasis was placed on providing the high degree of reliability needed by the system; a demonstrated reliability of only eight failures in 10^9 hours was achieved.

Stores

Three independent data processing stores were included in the NIKE-ZEUS System: (1) a permanent memory called a program store; (2) a variable memory called operand store; and (3) a reference memory called reference control store. Characteristics of these stores are given in Table 1-6.

The program store consisted of twistor wires and program cards containing a pattern of small vicalloy magnets.[22] As shown in Figure 1-28, a twistor is made up basically of a conductor around which is helically wrapped a strip of

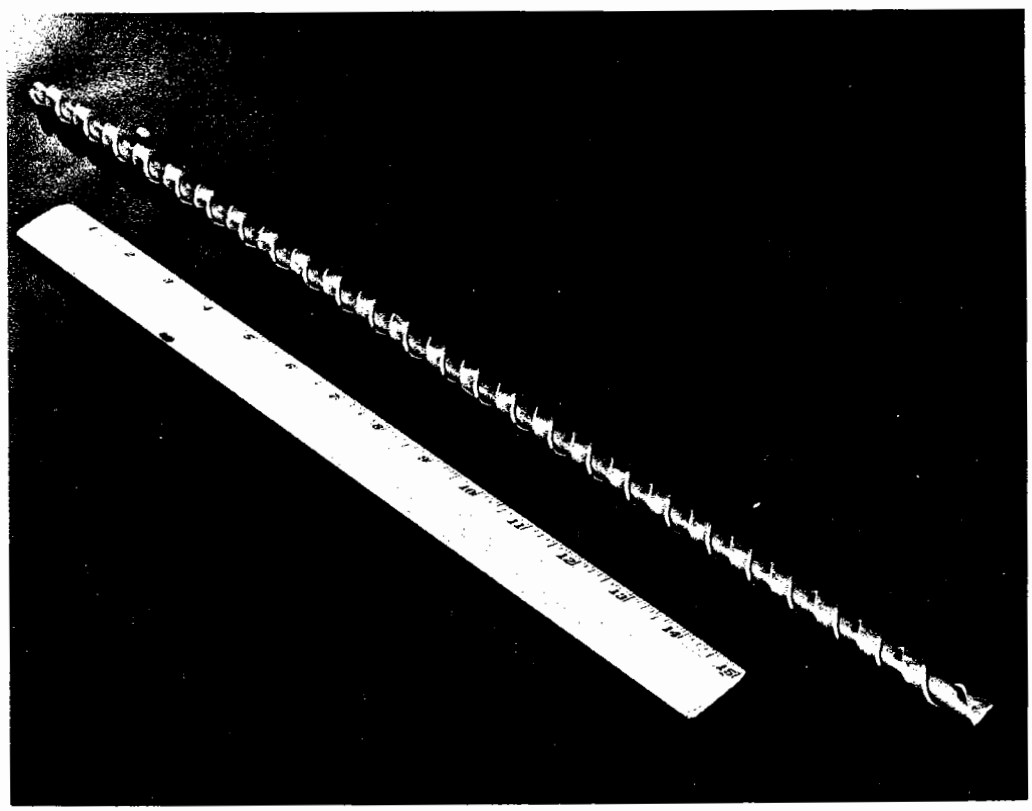


Figure 1-28. Twistor Wire

magnetic material. (The picture shows a greatly enlarged model of a twistor wire.) This material has a square-loop B-H characteristic, and the application of a magnetic field to a twistor element switches it from one magnetic state to another. Such a change of magnetic state induces readout current in the conductor. If a relatively strong external magnetic field is maintained on the twistor element, this element becomes magnetically saturated and readout results in a "zero." Stored programs or constants can be set up in an array of twistors; a "zero" readout is obtained by placing a permanent magnet near each twistor element, and a "one" is obtained without the magnet. A 48-word variation of the program store was called the twistor input switch. Storage slots in this equipment were similar to those in the program store, but the permanent magnets were replaced by direct-current solenoids.

The twistor type of memory (see Figure 1-29) was developed by Bell Laboratories specifically for NIKE-ZEUS computers. It has the advantages of (1) high operating speed, (2) readily changeable programs, and (3) the capability of a high rate of manufacture at low cost. A system of automatic memory-card production was devised; the program was prepared in symbolic form and the program cards were produced by a special machine. Twistor arrays also were used for switching in the NIKE-ZEUS System.

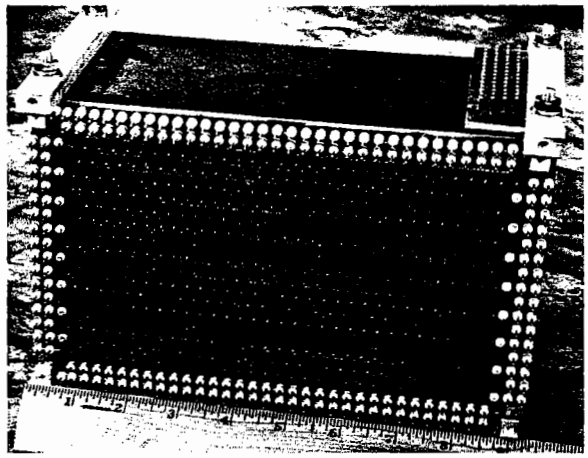


Figure 1-29. Twistor Store

The operand store was used to store data temporarily during calculations. Ferrite cores were used for the storage elements and the store information was changed electronically on command. The reference control store was used for input-output control and as a link register for storing return addresses and subroutine jumps. It also used the words it had in storage to modify the addresses of other words being operated on in the computer. (This step was required in many programs in which the address of the next operation was based on the results of the previous operation.) A high-speed, ferrite-core, word-organized store was developed for this reference memory.

Chapter 2.

NIKE-X SYSTEM



Chapter 2.

NIKE-X SYSTEM

Unlike its predecessor, NIKE-ZEUS, and its successors, SENTINEL and SAFEGUARD, NIKE-X was not a single ABM system concept. Rather, it should be thought of as a collective term to cover a number of studies and exploratory developments aimed at leading from the then outmoded NIKE-ZEUS to the next generation ABM system. Figure 2-1 maps the more significant NIKE-X System Studies and supporting R&D activities discussed in this chapter.

NIKE-X began about 1960, when it became apparent that by the early 1970s the USSR might be able to mount a high-traffic attack against the U.S. By 1963 it was accepted that the USSR had the technological ability and the expressed intention to develop at least a parity in warhead yield with the U.S. The sophistication of USSR mid-70s ICBM offensive systems was not readily predictable; conservative assumptions included chaff, decoys, and Electromagnetic Countermeasures (ECM) as penetration aids.

This escalation of the assumed USSR threat was a breakpoint in the general approach to the NIKE-ZEUS development. Until then the ZEUS system had been based on earlier assumptions of much lower USSR capabilities. The NIKE-ZEUS system had been designed to defend population and industrial centers from a relatively light attack. For example, in tracking targets and missiles, only one target and missile could be tracked at one time by the ZEUS Target Track Radar (TTR) and Missile Track Radar (MTR), respectively. Multiple targets and missiles were handled by multiple pairs of TTRs and MTRs. Adding single target-interceptor tracking subsystems was not a cost-effective response to escalation of the predicted threats; fundamental changes in radar data-gathering techniques were required. Furthermore, the best large-scale computers of the time were not capable of handling the data processing loads associated with the newly expanded threat concepts.

Fortunately, as the threat expanded, solid-state technology evolved enough to make possible two important improvements in ABM system capability. One of these was the development of large electronically steered, phased-array radars capable of tracking many targets simultaneously. The other was the development of high-reliability, very-large-throughput data processors for ABM needs. The combination of escalating threat and expanding technology gave impetus to the NIKE-X high-traffic ABM concepts.

The initial thrust of NIKE-X was to develop a base of knowledge from which the development effort could be started. For example, the

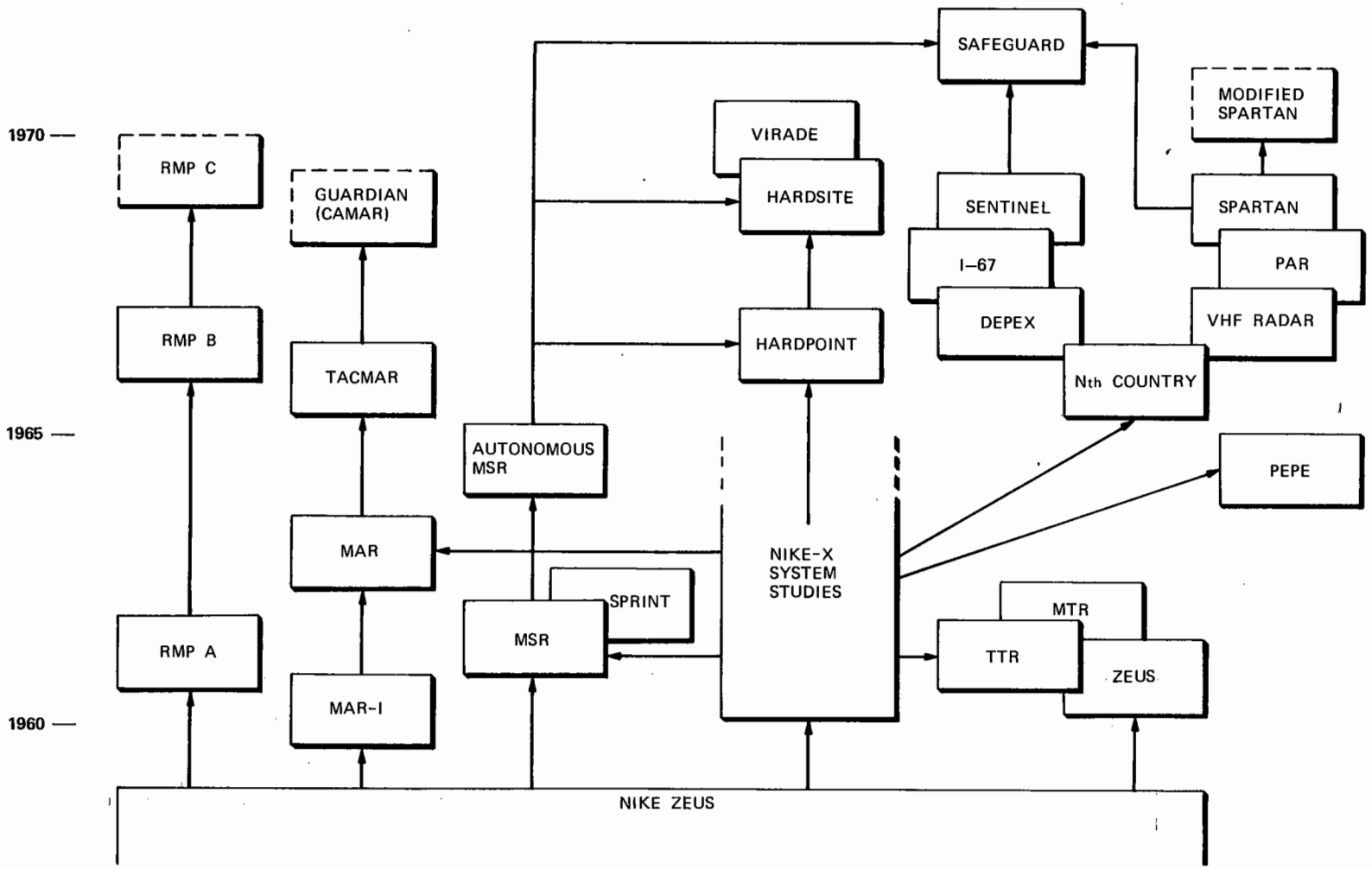


Figure 2-1. Map of the NIKE-X Era

MAR-I at White Sands Missile Range (WSMR) explored array radar designs to develop a firm technical base for NIKE-X. The Reentry Measurements Program (RMP A and B), in which NIKE-X radars observed reentries of IRBMs and ICBMs, was another very large, technically challenging effort that helped to establish the NIKE-X data base. RMP is discussed in detail later in this chapter.

NIKE-X CONCEPT

The first NIKE-X System Study, in 1963, considered a terminal defense for the larger U.S. cities against the sophisticated USSR attack postulated for the mid-1970s. It was unreasonable to make the defense impenetrable; the objective was to mitigate damage and thus deprive the offense of attractive attack opportunities.

In developing concepts to meet these city defense objectives, several major subsystems were defined. The Multifunction Array Radar (MAR), which performed search, track, and discrimination, was the centerpiece of city defense. The Missile Site Radar (MSR) and a high-acceleration, atmospheric interceptor, the SPRINT, formed a team for fast reaction, high-traffic, terminal interception of attacking ICBMs. The MAR, MSR, and SPRINT were also responsible for self-defense of the ABM facilities.

At the beginning of NIKE-X, a number of major elements were carried over from ZEUS: the Target Track Radar (TTR), the Missile Track Radar (MTR), and the ZEUS missile.

After the studies of deployment and system effectiveness, the defense of cities smaller than our 50 largest was studied next. This led to an enhanced role for the MSR — the defense of smaller cities. For cost reasons, the MSR, in addition to interceptor track and guidance, was assigned many roles similar to those of the MAR, such as search, track, and target designation. Where coverage with the reduced resources of the MSR was consistent with the small city requirements, the autonomous MSR served as a cost-effective duplication, on a lesser scale, of the MAR.

By the mid-1960s, system studies concentrated on reducing the cost of defense and improving its cost effectiveness. One approach, designated TACMAR, was a reduced-power variation of the MAR that could, if the need arose, grow to full MAR capability. By 1968, the city defense concepts were reassessed, and the decision was made to shift the defense objective to an area defense against relatively light attacks. The I-67 Study addressed this less costly area defense objective. With this shift in emphasis, ABM moved away from the city defense concept, thus removing the requirement for MAR/TACMAR. As a result, a much different kind of sensor was required; one that could detect, track, and designate targets above the atmosphere at very long ranges. This role was first assigned to a new VHF radar, which, late in the NIKE-X period, became the UHF Perimeter Acquisition Radar (PAR). The interceptor chosen for area defense was an extension of the ZEUS missile, called SPARTAN.

In summary, the light area defense concept was developed through various deployment studies, beginning with NIKE-ZEUS, which was a pure area defense system. The ZEUS area defense concept was partially incorporated into NIKE-X and became a separate concept in the Nth Country and I-67 Studies. The chronological sequence of area defense studies and postulated deployments included NIKE-ZEUS, Nth Country, DEPEX, I-67, SENTINEL, and finally SAFEGUARD. The other variant, point defense, is discussed next.

DEFENSE OF STRATEGIC FORCES— TERMINAL/POINT DEFENSE

By the mid-1960s, the NIKE-X program had two distinct defense objectives:

1. As discussed above, area defense against relatively light threats

2. Defense of strategic offensive forces against high-density, sophisticated threats.

Defense of strategic forces moved toward hardened defensive and offensive sites. The objective was to present significant, obvious uncertainties to the offense planner and hence produce influential deterrence. These terminal defense efforts led to a series of system studies: Hardpoint, Hardsite, and VIRADE. An early study[1] of the defense of U.S. strategic forces took place in 1963-64. For this study, two configurations were considered: one for defending hardened sites near defended urban areas (called HSD-I) and the other for autonomous defense of isolated sites (called HSD-II). The study sought to protect command and communication facilities and the U.S. strategic offensive force, including clusters of ICBMs and SAC bases.

Under joint directorship of the Army and the Air Force, a later study[2] emphasized an active defense dedicated to hardened ICBM silos which hold the Minuteman strike force. The study concentrated on technical tradeoffs between parameters in designing the various subsystems and drew conclusions about the relative effectiveness of tactics, deployments, and required technology.

The VIRADE (Virtual Radar Defense) mobile system was proposed as a way to increase radar attack price by presenting to the attacker a large number of possible locations for each available system. The proposed system is discussed later in this chapter.

BASIC NIKE-X SYSTEM

Threat Description

NIKE-X was designed to counter a high traffic, decoyed attack that included active jammers and low-visibility Reentry Vehicles (RVs).[3] Various threats were postulated to guide the design work and to serve as models for projecting effectiveness. These threat models used USSR ballistic missile characteristics, estimated on the basis of known technology and intelligence information, and were defense conservative.

The RV was assumed to have low radar cross section and high ballistic coefficient.[4] The USSR would use low cross section, in combination with chaff or jammers, to mask the exact RV position. Multiple warheads were considered likely, and an RV that maneuvered evasively in the terminal trajectory phase was considered possible. Assumed yields ranged from several kilotons to many megatons, depending on the mission of the particular RV. Chaff was considered a standard countermeasure to obscure the attack outside the atmosphere. In addition, "fast chaff" was postulated as a number of simple dipoles, with a moderately high ballistic coefficient, serving as traffic decoys at high altitudes. More sophisticated decoys would simulate RVs down to relatively low altitudes. They would match the radar cross section and ballistic coefficient of the RV down to an altitude which could force the defense to engage them as potentially dangerous. Active jammers were also assumed as penetration aids.

System Architecture and Operational Concept

System Elements

During its development, which extended through 1966, NIKE-X and its defense objectives changed several times, which in turn produced major changes in configuration. In its original form, NIKE-X used two types of phased-array radars (MAR and MSR), two defensive missiles (SPRINT and ZEUS), and a modular, multiprocessor data processing system. In addition, the NIKE-ZEUS Target Tracking Radar and Missile Tracking Radar remained parts of NIKE-X until it was verified that the phased-array MAR had the accuracy needed for long-range intercepts.

The L-band MAR was to be installed in densely populated urban/industrial areas (see artist's

view of city defense in Figure 2-2) for (1) the long-range search needed for attack recognition and (2) the quick reaction, high-traffic capability needed for terminal defense. Associated with each MAR was a Defense Center Data Processing System (DCDPS) which controlled the MAR and any MSRs in the same area. With the MAR as its principal sensor, the DCDPS performed all urban defense functions: detecting, tracking, and evaluating threats, planning the battle, and guiding defensive missiles.

For terminal defense, NIKE-X relied on SPRINT, a relatively small, high-acceleration missile, which is described more fully in Chapter 9. SPRINT is aerodynamically guided (except for first-stage boost) and designed for intercepts within the atmosphere. Its warhead

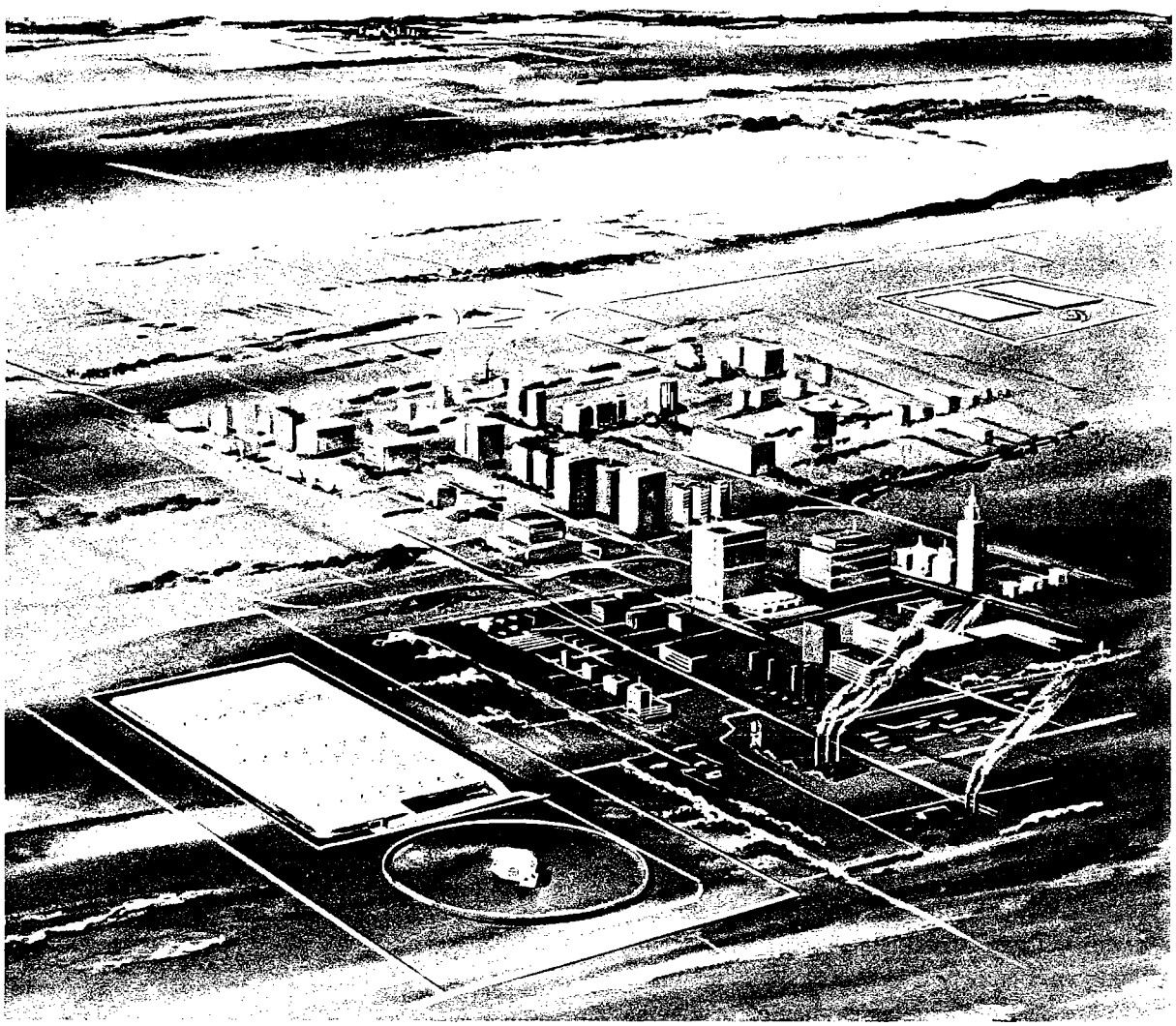


Figure 2-2. City Defense

has maximum lethality at its operational altitudes. For terminal defense of a large area, SPRINT missile farms were emplaced at various points about the defended urban center, particularly forward of the MAR.

The S-band MSR originally had two functions: missile tracking and target tracking at relatively short ranges. A missile tracker was needed at the forward SPRINT farms because the MAR would generally not have a line-of-sight to the SPRINTs at launch. The MSR could launch and guide the SPRINT to intercept, or launch and then transfer control to the MAR when the SPRINT came into the MAR's view. The MSR could track targets at relatively short range and look behind nuclear fireballs that obscured MAR coverage. Also, it could either look behind or permit triangulation on jammers, and generate additional tracks when required by traffic levels.

By mid-1964, a Small City Defense (SCD) concept was firmly established as part of NIKE-X. In this concept, the MSR role was expanded so that it was deployed either singly or in groups to provide a somewhat autonomous defense of small urban areas. The SCD also had a smaller version of the DCDPS, called a Local Data Processor (LDP). In addition to the target and missile tracking functions originally assigned to the MSR, the MSR-LDP combination carried on search, verification, and limited threat evaluation.

The ZEUS missile was included in NIKE-X whenever intercepts were required at extended ranges and high altitude. It was a somewhat modified version of the standard missile developed for NIKE-ZEUS. Although it was conceived that NIKE-X would defend concentrated urban areas and rely on close-in use of the SPRINT missile, several uses were envisioned for the ZEUS missile. Its exoatmospheric capability could "break up" a heavily cluttered attack, particularly if salvos of ZEUS missiles were launched. For attacks simpler than those expected against urban centers, such as submarine-launched missiles aimed at suburban or peripheral targets, the ZEUS missile could extend the effective coverage of a NIKE-X installation. Other potential uses for the ZEUS missile included intercept of a three-quadrant ballistic missile approaching from the south and intercept of low altitude satellites.

Operational Concept

NIKE-X was designed as a defense against a massive, sophisticated ballistic missile attack. All phases of the defense, from surveillance to missile guidance, were controlled by stored programs in the DCDPSs and LDPs. Man's role in the defense was regarded as one of augmenting and modifying system responses, once he had released the defending missiles. Although advantage would be taken of any attack that was simpler than expected (e.g., without decoys or chaff), the operational concept envisioned the decoyed, chaff-obscured attack, possibly also masked by active jammers.

The system's radars — the MAR supplemented by the MSR — would perform constant surveillance against attack from any direction, with emphasis on expected attack corridors. MAR would detect the large, chaff-obscured threat complexes, or "clouds," as they appeared above the radar horizon and start to track them. Depending on attack geometry, a track could be an individual object or a whole threat cloud.

Engagement planning would begin as soon as a threatening target was detected. The first action would be to determine the feasibility of launching ZEUS missiles. They would be launched to disperse chaff, disable jammers, disorganize or destroy decoys, and kill warheads. Any information from adjacent MARs with a side look at the threat cloud would facilitate ZEUS engagement planning. The next step would be to plan the SPRINT response. As the threat cloud entered the atmosphere, a "threat tube" would be defined. This tube would have a circular or elliptical cross section and define

the envelope formed by the reentry trajectories of threatening objects in the cloud.

MAR used a "monosweep" technique to scan threat tubes and track each object separated from the chaff background by atmospheric interactions. In monosweep, a cluster of MAR receiver beams was simultaneously steered in angle and controlled in beamwidth so that the threat tube was "swept" for signal returns after each radar transmission. This technique, which used the flexibility of the Modulation Scan Array Radar (MOSAR) beamforming and steering method, produced receiver beam clusters whose width just matched the threat tube width at each range that yielded a radar return. The signal strength of objects in the threat tube was thus maximized at any given range.

As the reentering objects in the threat tube were resolved, their radar signals would be processed to estimate their weights and ballistic coefficients. SPRINT missiles would be launched to intercept threatening objects as they were identified.

Deployment

The NIKE-X system was modular, and the primary purpose of each module was to defend a single urban area. Defense components would be allocated to limit fatalities during those attacks designed to inflict maximum fatalities. Secondary deployments included locating the MARs to defend small cities and adjacent MAR modules.

Specific deployments analyzed during the NIKE-X development ranged from covering a relatively small number of cities, including no Small City Defense (SCD) modules, to furnishing essentially total city coverage, including a large number of SCD modules of various types. Each deployment could be implemented in phases to achieve the highest level of overall defense at any point in time.

Functional Capabilities of Major Subsystems

This paragraph briefly describes each major subsystem, emphasizing its role and relationship with the whole.[5]

Multifunction Array Radar (MAR)

MAR was an L-band, high-power, phased-array radar that was NIKE-X's principal sensor. It had four functions: (1) search and verification, (2) threat evaluation, (3) target track, and (4) missile track. Its multifunction capability was achieved through electronic beamforming and steering controlled by programmed data processing equipment.

The MAR had separate transmitting and receiving subsystems, with two transmitting and two receiving arrays per radar. Each set of one transmitting and one receiving array was effective over one quadrant of the radar's combined 180-degree azimuthal coverage. Each array consisted of a large number of cylindrical elements whose radiating ends formed a planar face approximately circular in shape.

The MAR could transmit signals of any of 14 different waveforms for its several functions. These waveforms varied from single CW pulses of 1 to 440 microseconds length to chirped pulses and pulse trains. The pulse trains were used for discrimination, with the most sophisticated being a sequence of 32 coherent 6.2-microsecond pulses, 12.4-microseconds apart with a 30-megahertz bandwidth. With its long search pulse, the MAR could detect small objects in a reentry complex as they crossed the radar horizon.

The MAR receiver used a technique of electronic beamforming and steering known as "modulation-scan" or MOSAR, which was described under Operational Concept above.

Missile Site Radar (MSR)

The MSR was an S-band, single beam, phased-array radar that, depending upon its defensive role, could be built with one to four phased-array

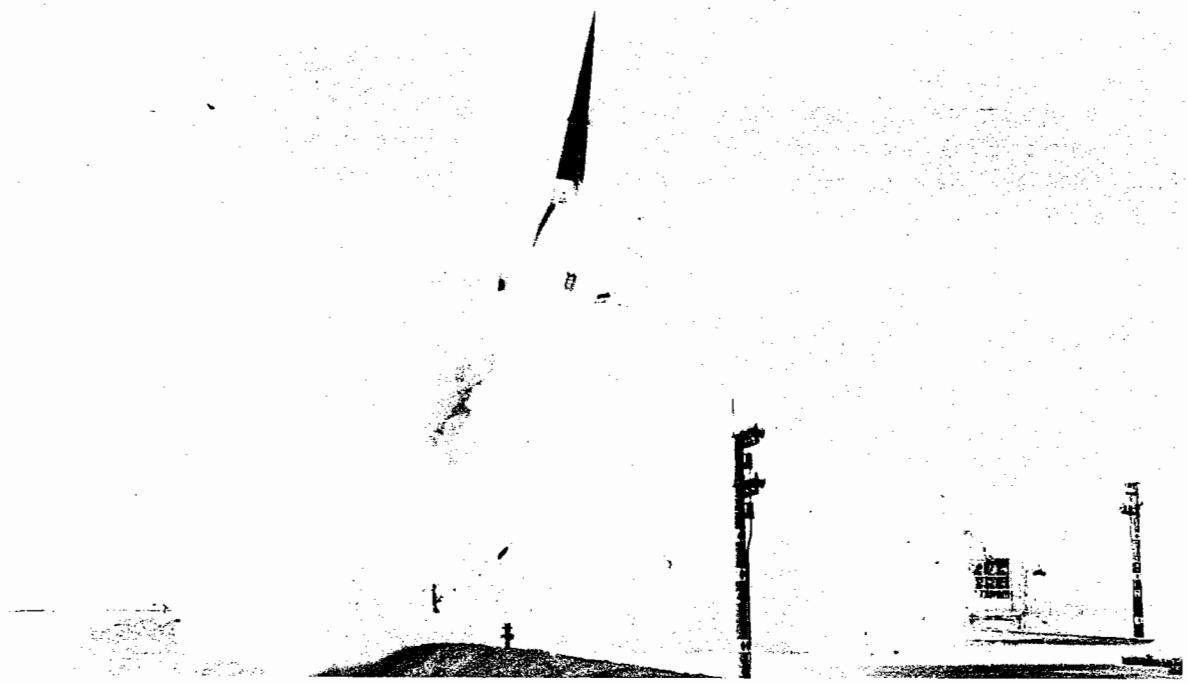


Figure 2-3. SPRINT Missile Firing

lens-type antenna faces. In all configurations, a single transmitter and receiver time-shared the face(s). The MSR could transmit or receive in one direction at a time as opposed to MAR's multifunction operation. The four-faced MSR provided 360-degree azimuthal coverage.

The MSR had four system functions: (1) search and verification, (2) target track, (3) limited threat evaluation, and (4) missile track. In the plan for Small City Defense, the MSR, along with its associated data processor, performed all four of these functions. When it was deployed as part of the MAR defense module, its role would be primarily that of target and missile tracking. The MSR could transmit any of six different waveforms, including short and long CW pulses, a chirped pulse, and a pair of pulses for threat evaluation.

SPRINT Missile

SPRINT was a two-stage, solid propellant missile designed for short-range intercepts inside the atmosphere. (See Figure 2-3.) It was intended to be guided by radio command guidance from either the MAR or MSR, but only the MSR guidance transponder was developed. Its first-stage flight was controlled in pitch and yaw by a thrust vectoring system in which liquid Freon* was injected into the booster exhaust. During second-stage flight the missile was steered by aerodynamic forces acting on air vanes. A pulsed transmitter in the missile served as an S-band or L-band beacon, depending on the ground radar.

*Trademark of E. I. DuPont de Nemours.

The SPRINT missile was ejected vertically from an underground launch station by a gas-powered piston. After it cleared the launch cell, its first-stage motor was ignited; the second-stage motor was ignited after the first stage burned out. SPRINT was a high-acceleration, highly maneuverable missile that could intercept targets between 5 and 100 kilofeet high. A typical intercept would occur at an altitude of 40,000 feet, at a ground range of 10 nautical miles, after about 10 seconds of flight time. See Chapter 9 for a more complete description of this missile.

ZEUS Missile

ZEUS was a three-stage, solid propellant missile designed for long-range intercepts with radio command guidance from either the MAR or MSR. (See Figure 2-4.) In the atmosphere, aerodynamic forces acting on the third-stage control fins controlled steering. Outside the atmosphere, gases expelled through the same fins controlled motion. A pulsed transmitter in the missile was beacon tracked by the ground radar.

The ZEUS missile, launched from an underground station at an angle of 85 degrees from horizontal, was unguided until second-stage ignition. The first and second stages had similar characteristics and accelerated the third stage to peak velocity. The third stage carried the warhead, missile guidance set, autopilot, fin servo system, hydraulic system, and the thrust vector motor. See Chapter 1 for a more complete description of ZEUS, and Chapter 10 for a description of SPARTAN, the successor to the ZEUS missile.

A typical ZEUS missile intercept, which would take place 100 nautical miles above the tangent plane at a tangent range of about 300 nautical miles, would require a flight time of about 300 seconds. For such an intercept, aerodynamic steering would remove trajectory errors before the missile left the atmosphere. The missile would then "coast" without guidance or thrust until third-stage ignition. Controlling the third stage by thrust vector reaction would remove residual trajectory errors just before intercept. For longer range intercepts, the third-stage motor could be ignited earlier and used to increase missile range at the expense of accuracy.



Figure 2-4. ZEUS Missile Firing

Data Processor

There were two general forms of data processor in NIKE-X: the Defense Center Data Processor (DCDP) and the Local Data Processor (LDP). The difference between them was in the number of modules (processors, stores, display consoles, etc.) each contained. Because of its modular design, the data processor could be sized for its particular application at each site. Within each DCDP and LDP, the general

purpose Central Logic and Control (CLC) performed the computation and central processing. Manual command and control was implemented by the Display Subsystem (DSS).

Automatic control was centered in the CLC. Computer programs, stored in program stores, controlled NIKE-X system operations as interpreted and executed by processor units. The processor units obtained input data from variable stores and stored computation results there. Processor units operated in parallel, forming a multiprocessor system in which each processor, as it became idle, was assigned a computational task, or program segment, to execute.

The DCDP used separate report processors for routine initial data processing of MAR radar returns. This wired logic preprocessing relieved the CLC of many repetitive computations on a large amount of data.

Nth COUNTRY DEFENSE STUDIES

Basic to the NIKE-X concept, as it developed during 1963 and 1964, was the idea of defending industrial and suburban centers against heavy USSR attacks during the 1970s.[4] The objective was to minimize overall damage to the country.

The cost of limiting damage against massive and sophisticated attacks was relatively high, and only part of the population was protected. From early 1965 to late 1967, increasing interest in potential "Nth Country" or "light" attacks,[5] as well as developments in nuclear warhead technology,* led to a series of studies and deployment options. The Nth Country or area defense concept evolved from those studies as a defense against light attacks, along with concepts of terminal defense,[7] including defense of strategic forces. This effort culminated in the NIKE-X I-67 deployment concept,[8] the harbinger of the SENTINEL System.

*Applicable to ZEUS or modified ZEUS missiles.

During this time, there were significant changes in equipment concepts: the PAR was conceived and its development commenced, the autonomous MSR came into being, and the ZEUS DM-15C missile was extensively modified to eventually become the SPARTAN missile.

Defense Objectives

The evolution of NIKE-X was naturally shaped by the evolution of defense objectives, which were in turn shaped by prevailing economic, political, and technological factors. Initially, the objective was to blanket the Continental United States (CONUS) with a high-altitude ZEUS-type defense, backed up at urban centers by a close-in SPRINT defense.

By the time of the I-67 deployment study, defense objectives had crystallized into two major roles, with some equipment elements supporting both:

1. By minimizing the probability of penetration, the defense was to deny damage in relatively light attacks. As the attack force grew, the defense was to minimize population fatalities. Also, modularity allowed growth from the original deployments against light attacks to a damage-limiting defense against highly sophisticated threats from any source.
2. The defense was to ensure that a significant number of the Minuteman strategic missile force would survive a USSR attack.

Threat Description

An Nth Country, lacking an extensive industrial base, could only attack the U.S. with a limited number of relatively unsophisticated ICBMs and SLBMs. It was assumed that this limitation would remain quite stable, with the significant variants being the offensive force level, RV vulnerability, and the number of SLBMs.

The NIKE-X I-67 Study assumed that up through 1980 the Chinese Peoples' Republic (CPR) threat would simply be a single large, blunt warhead accompanied by a tank and hardware pieces. Both the warhead and the tank had

large radar cross sections, since no attempt was made to conceal either. After 1980, the CPR RVs would grow moderately in sophistication and significantly in numbers.

Although the later NIKE-X developments basically considered that the USSR threat would be directed against Minuteman forces, NIKE-X nonetheless was a factor in area defense because it had to defend the country against accidental launches of USSR ICBMs. The postulated USSR threat, although more sophisticated than the early threat, determined the eventual NIKE-X response with long-range interceptors.

Operational Concepts

At the beginning of this development period, it was considered that the modified ZEUS missile would support the terminal defense of industrial and urban centers. ZEUS missiles would disrupt "penetration aids" (decoys, chaff, etc.) and allow the MAR to gather data on RVs as early as possible.

By the mid-1960s, the emphasis was to reduce the cost of defense, so new directions for NIKE-X were evolving. At the same time, developments in warhead technology altered the earlier concepts about the modified ZEUS and gave it a significant capability for killing RV/warheads during attacks that included penetration aids. By this time the possibility of light attacks was being considered, although concern about sophisticated attacks remained dominant.

These changes in emphasis eventually led to a less powerful MAR, designated TACMAR, which could search for and track the basic NIKE-X threats at long ranges. It could react early enough for modified ZEUS to intercept threats and protect almost all of CONUS from the unsophisticated threats. Around urban centers ZEUS would be backed by SPRINT, which gave the cities two levels of defense. Because Nth Country threats involved moderate to small RVs without penetration aids, a VHF radar was required for long-range detection of these attackers, thus complementing the TACMAR.

In addition, to defend the U.S. against attacks from any direction and for terminal defense, the proposed typical NIKE-X deployments consisted of TACMARs, VHF radars, and ZEUS/SPRINT/MSR sites. (The MTR-TTR combination of ZEUS intercept was no longer required.)[7]

Next, further evaluation of these basic ideas led to the NIKE-X Deployment Study (DEPEX), which organized the defense against attack from an Nth Country and light attacks from the Soviet Union.[9] The basic objective was still to protect population and industrial centers. Particular attention was given to countering the ballistic missiles the CPR might eventually develop. The defensive deployment was to grow so it could meet the more massive and sophisticated ballistic missile threats arriving from any quarter. The DEPEX concept by and large retained the basic characteristics described above, and added a four-phase deployment sequence. The first phase was about as described in the above deployment options, but more extensive, while in the next three phases the terminal defenses grew in steps.

Increasing interest in very light deployments, at least during the initial stage of deployment, led to the DEPEX "Phase 0," which, for the most part, used modified ZEUS missiles, VHF radars, MSRs, and a few SPRINTs.[9] In addition, system studies showed that somewhat higher frequencies for the long-range search radars would strike the most cost-effective balance between susceptibility to nuclear effects and the long-range detection and track of objects with small radar cross sections. Concurrently, interest in defending the Strategic Offensive Forces became stronger.

This concept embodied the objective of denying damage to an early CPR attack and provided a moderate high-level terminal defense for Minuteman forces.[8] It also allowed for growth to heavy terminal defense.

By this time, the needed long-range characteristics were embodied in a new UHF radar called PAR. The design of the modified ZEUS was stabilized and the missile was renamed SPARTAN.

The I-67 deployment used a few PARs, moderate numbers of MSRs, and many SPARTANs and SPRINTs. The MSR and SPRINT missile system defended the Minuteman bases and were also collocated with each PAR site. The remaining MSRs and SPARTANs were strategically located throughout CONUS.

In this system, PARs carried out long-range surveillance and target tracking. In area defense, SPARTAN served as the primary interceptor, tracked and guided by the MSR. SPRINTs were to be used only to defend PARs, urban areas near the PARs, and Minuteman silos.

Generally, targets would be detected first by the PARs. After they were tracked for some seconds, their trajectories and impact points would be determined and the defense battery would be designated. In SPARTAN engagements, information on target intercept would be continually refined and passed to the Missile Defense Center battery assigned the engagement. This battery would launch and guide interceptors to the appropriate point. The concept was a good cost-effective balance between radars (PAR), radar resources (tracking requirements), and lethal effects from the large-yield SPARTAN warhead.

I-67 deployment concepts represented the first real effort to set up a nationwide ABM command and control system and set forth the functional logic of a defensive engagement. The PAR would operate somewhat independently, with built-in rules governing normal search assignment, detection, verification, and track initialization. The MSR was more closely coordinated (between MSRs) within a Missile Defense Center region. In fact, one facet of NIKE-X at this point was the increasing degree of intersite netting that furnished CONUS-wide coverage with a few search radars.

With minor modifications, the I-67 deployment and its operating concept led directly to SENTINEL and later to SAFEGUARD, as discussed in Chapters 3 and 4, respectively. Many SAFEGUARD features and characteristics had their origin in the I-67 deployment concept of NIKE-X, which marked a fundamental milestone in the evolution of SAFEGUARD.

Modified SPARTAN

Between 1968 and 1971, there were extensive studies of improving the SPARTAN interceptor in its assigned role and in a role against more sophisticated attacks.[10] This effort is mentioned here because it falls into the studies associated with area defense.

The study explored the utility of a high-performance (higher than SPARTAN), long-range, exo- and endoatmospheric interceptor that would significantly reduce the number of MSR/missile sites required to defend CONUS. New tactics and advanced intercept concepts were also studied. However, cost-effectiveness considerations terminated the effort in 1971.

DEFENSE OF STRATEGIC FORCES—TERMINAL HARDSITE DEFENSE

Between 1963 and 1969, Bell Laboratories postulated several systems for defending hardened U.S. ICBM sites. The systems evolved in response to specifications of the threat and trial deployments, and they were examined from the standpoint of cost, component availability, and effectiveness in achieving objectives.

The primary objective of hardsite defense was to deter enemy attacks on the U.S. strategic ICBM offensive force. If deterrence failed, the defense was to save enough Minuteman boosters that the U.S. could carry out its post-attack policy. The defense was to be effective against an advanced-technology threat including penetration aids. Existing technology

and components were to be used in the proposed deployments as fully as possible.

One of the first two hardsite systems proposed was designed to protect sites in urban areas;[1] the other to defend sites at remote locations. A hardened site could be a command and communication facility at a SAC base or a cluster of ICBM silos. In a later study, only hardened silos having the Titan II and Minuteman forces and the hardened defense elements were to be defended.[2] In this work other contractors' schemes were also reviewed. They ranged from area/terminal defenses similar to the Bell Laboratories concept to proposals for the autonomous defense of each silo (called "hardpoint" defense).

The last major Bell Laboratories study of hardsite systems resulted in the proposed movable radar, or Virtual Radar Defense (VIRADE) system, which furnished extended terminal coverage through radar netting.[11] In this approach, the radar antenna and transmitter would be transported by rail and moved frequently among a large number of hardened radar sites. VIRADE was an alternative to fixed radars and was intended to increase the radar attack price. It recognized the practical limits and cost of increasing radar hardness, introducing redundancy, or using decoy radars to force the attacker to increase the "throw weight" of his offensive missiles.

Each hardsite study indicated that MSR technology would be adequate, and each study increased the radar hardness levels. Early in these studies it was recognized that both data processing and hardsite requirements for radar netting and resource allocation would be complex. Computers would have to use faster circuitry and different organizational schemes to achieve the required throughput. The interceptor proposed for each system was the SPRINT. Interceptors with improved performance would counter a more sophisticated attacking vehicle, which could maneuver to increase its chances of penetrating the NIKE-X defenses.[12]

The defense system design took into account uncertainties faced by the attacker. These uncertainties were caused by the disturbed environment created by his warhead bursts, target vulnerability, and the presence of an active defense. Defense parameters that affected system requirements included sure-safe and sure-kill hardness levels for radars and silos, single-shot warhead kill probabilities, peak traffic rates, and the attacker's targeting doctrine. From these considerations and knowledge of the Soviet ICBM force, a threat was specified. The ICBM force was sized, assumptions were made about Multiple Independently Targeted RVs (MIRVs), only high weight-to-drag RVs were included, and trajectory geometries were bounded. The attacker's payload was estimated, his booster availability/reliability was computed, and his warhead yield and vulnerability to interceptor bursts were estimated.

The threat was enhanced by penetration aids which included tank fragments, precursor bursts, chaff clouds, traffic decoys, ECM, and maneuvering RVs. Many possible ways to distinguish warheads from penetration aids were considered, and many were found unsuitable.[13]

PARALLEL ELEMENT PROCESSING ENSEMBLE

As studies of ballistic missile defense systems progressed, the postulated threats expanded greatly in terms of the number of objects arriving simultaneously and the sophistication of the penetration aids. This increase in threat influenced ABM design and especially increased the estimate of throughput needed for ABM data processors.

In response, a new concept of architecture for the ABM data processor was suggested.[14]

Because a large part of the processing associated with radar tracking and discrimination required that the same set of algorithms be repeatedly applied to each object, parallel elements might carry on the processing. In 1964, research began on a content-addressable memory invented by Lee and Paull of Bell Laboratories. This memory offered an approach to the needed parallel processing, and a follow-on development program supported by the Advanced Ballistic Missile Defense Agency (ABMDA) led to the Parallel Element Processing Ensemble (PEPE) concept.

PEPE was a programmable, special-purpose computing machine that augmented conventional sequential computing in ABM data processing. Processing capacity was largely independent of traffic because an independent parallel element was assigned to each object in track. Each parallel element was, in fact, a small digital computer, with an arithmetic unit and memory. In addition, each contained a special-purpose input unit called a "correlator," which associated radar replies with the appropriate track by simultaneously comparing each radar reply with predicted track positions. Most of the control circuitry was in an ensemble control unit, which was connected in turn to a more conventional "host" sequential digital computer. The host computer stored instructions for the parallel ensemble, sequenced through them, and passed them to the ensemble control unit. The host computer also did the processing that could be most effeciently handled by a sequential computer.[15]

By the mid-1960s, a study was under way to adapt PEPE to ABM. The intent was to realistically assess feasibility and cost factors. Several studies were launched, primarily in the areas of software development and testing.

Hardware Feasibility

Using readily available components, a processor with 16 elements was built with integrated circuits and tested with an IBM 360/65 as a host computer. This "IC Model" of PEPE was used in the demonstration tests discussed below. A study which showed the feasibility of using more advanced large-scale integrated circuits in PEPE was completed toward the end of the development project.[16]

Software Development

Since the job to be done by parallel processing elements would be done the same way by a sequential computer, similar programming methods could be used. A parallel version of FORTRAN, P-FOR, became PEPE's basic programming language. P-FOR was supported by a compiler and an assembler to convert programs into machine code. Also, programs could be written for input to the assembler using PAL, the Parallel Assembly Language.

The language and software system were available well before any hardware so that programs could be tested by simulation. The P44 precompiler converted each operation on parallel data in a P-FOR program into a DO loop on an array in a standard FORTRAN program. The FORTRAN program could be readily tested on any machine with FORTRAN capability.

In addition to P44, which tested P-FOR programs at the source level, the Parallel ABM System Simulation (PASS) simulated operation at the machine level. PASS Tests I to IV, each testing a broader system, were planned. PASS I and II demonstrated PEPE's capability for basic ABM processing and were completed. PASS III and IV were replaced by tests defined by ABMDA, as noted below.

Application Studies

To identify problems and evaluate the advantages of PEPE, several specific applications were studied:[17]

- SAFEGUARD. Routines planned for SAFEGUARD as developed in NIKE-X simulations were converted to parallel form in PASS I and II.[18]

- VIRADE. As discussed previously under Defense of Strategic Forces, the VIRADE concept added the problems of changing sites to the basic ABM problems.[19]
- ABMDA defined tests. For a final evaluation of PEPE as part of the Bell Laboratories development program, ABMDA defined two systems: Zero Order Software (ZOS) and Preliminary Hardsite Defense (PHSD). These replaced PASS III and IV. The final PHSD demonstration was against a threat defined by General Research Corporation and transmitted to Bell Laboratories by data link from Santa Barbara, California in interrupted real time. The PEPE system used in this test was the 16-element IC model supplemented by sequential simulation, and it achieved essentially all the test objectives.[20]

Lessons Learned

- The ability of PEPE to carry a large, constantly growing portion of SAFEGUARD data processing was established. The threat level defined for the current SAFEGUARD System did not make PEPE cost effective. Its cost effectiveness would have to be established for a given threat, for a given ABM system, and with the current state of the processor art considered.
- The feasibility of increasing system capability by removing processing from a sequential computer and assigning it to a parallel processor was established.
- The high level language, P-FOR, was found to be a powerful tool in rapidly programming a complex system.

REENTRY MEASUREMENTS PROGRAMS A, B, AND C

The NIKE-X Reentry Measurements Program (RMP), which spanned the interval from 1960 to 1970, had the objective of developing discriminants for conical RVs. The program used a straightforward phenomenological approach, with tabulated comparisons of radar observable characteristics as functions of vehicle size, shape, and ablator material.

To complete the program, a broad spectrum of targets was observed by the radar, optical, and infrared sensors[21] at the Eastern Test Range (ETR), Kwajalein Test Site (KTS),[22,23] and White Sands Missile Range (WSMR).[24] Most of the RMP flights were full-scale reentry tests flown into the Kwajalein Test Range. The NIKE-X program supplied many of the unique targets. Other targets came from the Air Force Advanced Ballistic Reentry Systems (ABRES) Studies, SAC Evaluation Missions, and the Navy Polaris Program.

The RMP general test requirements were coordinated through the Tri-Agency Technical Coordination and Operations Group (TATCOG), an Army, Navy, and Air Force committee that set test objectives and planned coordination. The responsibilities and contributions of the various RMP groups were divided as follows:

1. Bell Laboratories. Specified program objectives, reentry hardware performance requirements, and target delivery (trajectory and deployment) requirements. Operated the NIKE radar sensors and EC121 optical aircraft. Reduced and analyzed collected data.
2. Army. Procured target vehicles and delivery systems through the Air Force. Coordinated test requirements, program objectives, and schedules. Provided the Kwajalein Test Range support. Coordinated interservice data exchanges.
3. Air Force. Provided the reentry hardware, booster systems, and the ETR facilities; i.e., delivered targets to KTS. Exchanged technical data and coordinated their reentry study program, ABRES, to support mutual-interest missions.
4. Navy. Cooperated in providing SLBM targets. Coordinated mission planning and data exchange.
5. Lincoln Laboratory. Supplied technical consultation and coordinated design of reentry experiments and data analysis exchange. Operated additional sensors (data sources) of the PRESS facilities at KTS.

Test Objectives

The RMP was divided into several significant phases. Initially, from 1960 to 1964, the NIKE-X Field Measurement Program (FMP)[22,25,26] developed sensor techniques and discrimination technology. The prime objectives developed then, which were changed very little in the follow-on RMP, were to determine:

- The observables associated with various targets, which would define the sensor techniques for obtaining adequate discrimination measurements
- The relationship between various target types and sensor measurements to define effective discrimination techniques.[27]

From approximately 1964 through 1966, the experiments labeled RMP-A[23,26,28] were concerned with the class of material used in RVs.[22,23] The primary objective was to search for and evaluate discriminants.[29]

The RMP-B program (1966-1970)[23,28] sought to establish basic theoretical understanding of reentry phenomena so that experimental measurements and discrimination techniques could be extrapolated to other possible threat sizes and variations.[30-32] Another area of RMP-B was the qualitative confirmation, through on-board instrumentation,[33] of basic reentry phenomena that could not be measured from the ground.

RMP-C was to consider advanced RVs. Before the target requirements were specified, the program was terminated about 1970.

Target Vehicle Summary

The RMP used a series of reentry measurements vehicles, tactical offensive weapons with penetration aids, and vehicles developed for future offensive weapons.[34] The Reentry Measurements Vehicles (RMVs) were uniquely developed for the RMP.

Missions and Data Reports

Bell Laboratories issued a Target Measurements Report (TMR) on each reentry measurement mission. These documents briefly summarized the operation and outlined pertinent factual information. Data available for continued analysis were listed, and plots, photographs, and available reentry identification information were included. The TMR data reports are available at the Reentry Data Facility at Calspan Corporation, Buffalo, N. Y., a data repository maintained by the Army.

MULTIFUNCTION ARRAY RADARS

The MAR-I Program

In the early stages of NIKE-X, 1963-1964, the Multifunction Array Radar (MAR) was foremost among the relatively new radar concepts. This radar was to be the major NIKE-X sensor, able to perform in many operational modes in a high-traffic environment and to carry out endo- and exoatmospheric engagements. The MAR's principal task was to form and steer the multibeam clusters that would perform the radar missions of search, track, discrimination, and guidance.[35]

By that time, studies of phased array radars had progressed to the point where the fundamentals of their antennas and beamforming were well understood. A number of arrays had been built to demonstrate some of their basic capabilities. Prior to MAR, however, these sensors had been designed for a single function, principally that of target acquisition and tracking.

By 1963 the NIKE-X program had reaped substantial benefits from two experimental linear arrays, one employing the time delay steering proposed by Sylvania, the other using a novel modulation scanning technique developed by the General Electric Company.[36] Early tests of these two arrays formed a technical base from which a complete array radar feasibility effort was launched. This radar complex was identified as MAR-I. The design, construction, installation, and testing of MAR-I took place in the 1961-65 time period. A close-up view of the installation at WSMR is shown in Figure 2-5.

Development tests of the radar, scheduled into 1965, determined how well the equipment met design objectives and furnished data for design improvements to the NIKE-X tactical model (MAR-II) planned for installation at Kwajalein. The development program included extensive antenna pattern measurements and beam stability checks to evaluate the

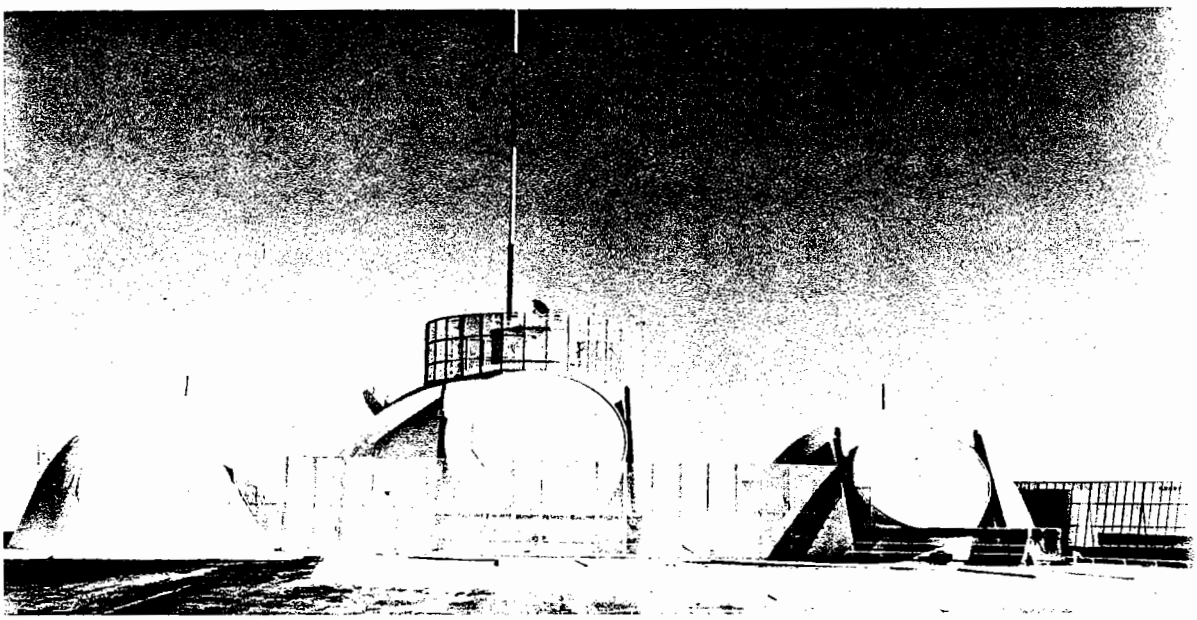


Figure 2-5. Close-up View of MAR-I at White Sands Missile Range

beamforming and steering concepts. Dynamic tracking accuracy and multiple beam operation tests were also included.

Major contractors and their responsibilities were:

1. Western Electric. Acted as prime contractor for the MAR-I project under contract DA-30-069-AMC-333(Y).
2. Bell Laboratories. Held overall responsibility for project management, including design, development, building construction, test site operation, and system evaluation.
3. Sylvania Electronic Systems, East Waltham, Mass. Developed a multifunction array radar by designing, constructing, installing, and testing MAR-I electronic equipment.
4. Sperry Rand Univac, St. Paul, Minn. Designed the MAR-I Phase II digital computer, the associated Control Switch and Buffer (CSB), and the computer programming.

Western Electric and Bell Laboratories also designed and constructed some of the MAR-I equipment.

Functional Capabilities

The MAR-I at White Sands was designed to perform the functions shown in Figure 2-6 and to demonstrate fully automatic operation.[35] Manual override and a full manual capability were included to allow flexibility in testing. A tactical system would operate in two modes: surveillance (the normal mode) and engagement (which began after a target had been detected and classified as a threat to the defended area). The automatic elimination of targets as non-threatening, based on impact predictions or discrimination, was never implemented in this radar.

In the surveillance mode, the system performed two functions: search (and detection) and verification tracking. In the engagement mode, the system performed four functions: search (and detection), verification tracking, precision tracking, and discrimination sensing. Except when restricted by the operator, MAR-I automatically carried out verification tracking assignments on all targets detected in the search beam.

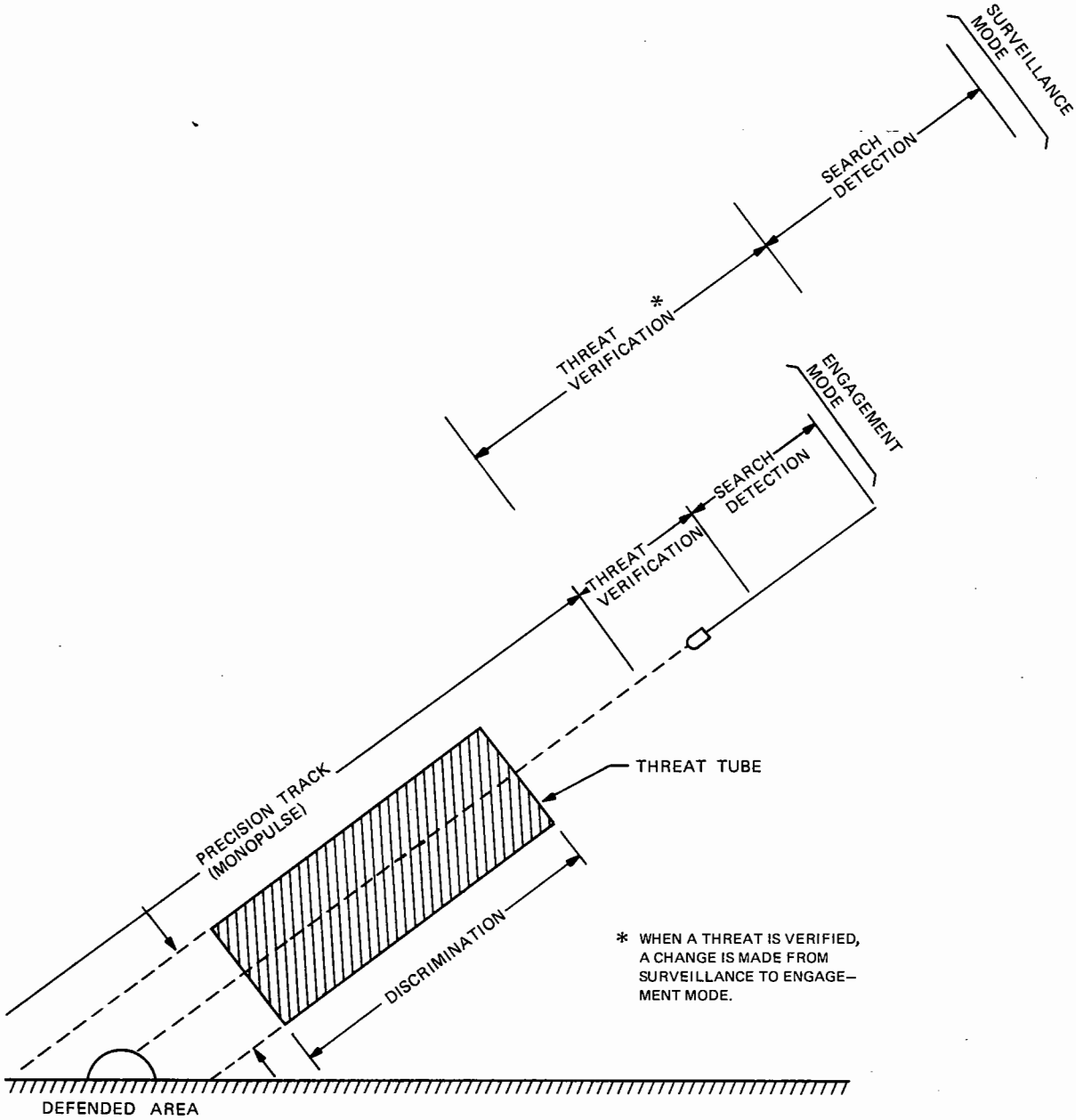


Figure 2-6. MAR Functional Capabilities

After verification, a precision tracker was assigned to threats and used the target position estimates generated by the verification tracker. Except for a coded pulse that increased range resolution, precision tracking was essentially the same as verification tracking. A sub-beam cluster, positioned either automatically or manually to cover a threat tube, obtained discrimination data. Threat tubes were cylindrical volumes whose axes were parallel to the velocity vector of the target. A Coherent Signal Processing System (CSPS) for acquiring discrimination data was developed but never installed in MAR-I. It was added to the Discrimination Radar (DR) at Kwajalein to support the Reentry Measurements Program (RMP).

System Description

Operational Concept

MAR-I operations reflected the two modes, surveillance and engagement, in which a tactical system would function.[35] In the surveillance mode, the radar beam scanned the total coverage volume in less than 20 seconds. When a target was detected, the radar returns were examined automatically to extract target position and range rate (radial velocity) data. A verification track on the target began when the range rate and position predictions satisfied preselected criteria for range velocity and track initiation volume. Search scanning continued independently of the other functions.

An operator could overrule the automatic function to initiate verification tracking manually on a target of his choice. In either case, the successful verification of a threat changed the mode from surveillance to engagement. In the engagement mode, search and verification tracking continued at a faster search scan rate. In addition, the precision tracking and discrimination functions became available.

Discrimination data were obtained by either manually or automatically positioning the radar coverage of a threat tube. Each threat tube was divided into subtubes, each formed by a separate radar beam. The widths and center-to-center spacings of the beams were controlled as functions of range to provide constant-volume coverage independent of range. The discrimination transmitter beam was a single beam broadened to illuminate the entire threat tube.

A precision tracker was assigned and given target position estimates from the verification tracker. Verification tracking was thus a prerequisite for precision tracking and terminated after the precision tracker locked on the target. Except for a pulse-compression waveform that increased range resolution, the two track processes were essentially the same.

MAR-I was divided into ten major subsystems, as shown in Figure 2-7. They are briefly described below.[36]

Transmitter Antenna

The transmitter antenna consisted of active elements forming a circular planar array, with elements arranged as the vertices of equilateral triangles. Each element was fed by an individual power amplifier in the transmitter. The transmitter array was housed in a concrete dome structure so that the array normal was elevated 38.5 degrees above horizontal. MAR-I had one transmitter array.

Receiver Antenna

The receiver antenna consisted of elements in a circular array, each element followed by a low noise preamplifier which was part of the receiver. MAR-I had one receiver array.

Transmitter

The final power amplifiers were specially-designed high-gain traveling-wave tubes. Delay matrices consisting of switching diodes and strip lines performed beamforming and steering. Search, track, and discrimination pulses at different frequencies were transmitted in a single pulse chain.

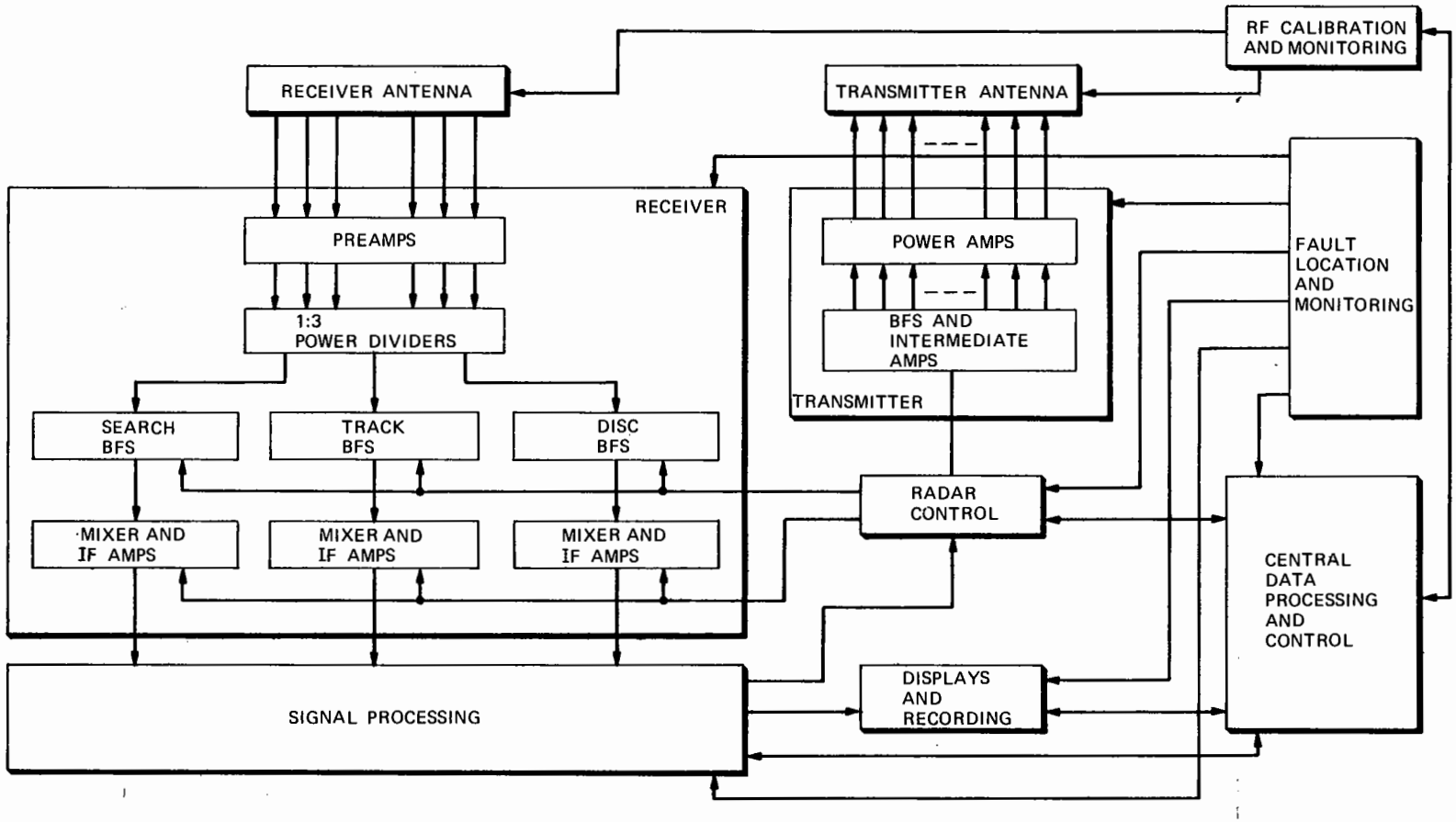


Figure 2-7. MAR-I Functional Block Diagram

Receiver

The receiver operated on three separate channels, one each for the search, track, and discrimination functions. Each channel had its own beamforming and steering circuits and its own unique beam and cluster configuration. The incoming signals from the antenna elements were fed through individual preamplifiers to power dividers which provided signals to the three channels. After beamforming and steering, the three mixing circuits (search, track, and discrimination) converted the RF signals to IF signals at different frequencies. These signals were then amplified in the IF amplifiers and sent to signal processing.

Signal Processing

Signals were processed in two basic units: the Search Signal Processor (SSP) and the Video Pulse Converter (VPC). The SSP indicated initial target detection and determined range, range rate (by doppler shift), and angular position. These parameters were fed to displays, recorders, and central data processing and control.

The VPC processed the outputs of the receiver track detectors and video amplifiers, converted the desired information to digital form, and converted search and discrimination video to digital form for test purposes. The pulse-compression networks for the precision track and discrimination functions were part of the signal processing subsystem.

Radar Control

Radar control, under instructions from central data processing and control, coordinated and controlled some of the activities of MAR-I. It generated and selected local oscillator frequencies and modulation parameters and controlled the beamforming and steering networks.

Displays and Recording

Operators at display consoles monitored system operations and performed some MAR-I functions which would have been automatic in a tactical MAR. The MAR-I display and recording subsystem had four operator positions, which monitored and reported on system status, controlled search and track assignments, positioned the discrimination cluster for sub-beam selection, and controlled recording.

Fault Location and Monitoring

MAR-I used a Fault Location and Monitoring (FLAM) subsystem for more efficient maintenance and to minimize down time. The subsystem monitored the system to detect faults, indicated the existence and rack location of each detected fault, and automatically recorded fault occurrences.

RF Calibration and Monitoring

The RF calibration and monitoring subsystem measured the overall amplitude and phase transfer characteristics of individual channels in the phased array. Various routines were measured for all combinations of input channels and beam outputs, and faulty components were located by these measurements. In most cases measurements did not interfere with normal operations. In the transmitter, the transmitted search pulses were used for monitoring; in the receiver, a calibration pulse was inserted during ranging dead time just before the next transmitted pulse.

Central Data Processing and Control

The Central Data Processing (CDP) and Control Subsystem had three basic units: Control Switch and Buffer (CSB), Tape Buffer System (TBS), and General Purpose Digital Computer (GPDC). The CDP sorted and routed all data flowing between the GPDC and the other units of MAR-I and also performed system timing.

The TBS served as a buffer memory between the GPDC and input/output devices. Output devices were magnetic tape units, flexwriters, and a high-speed line printer. The former two units were also used as input devices.

The GPDC processed large quantities of real-time data, and the computer operated in the fixed-point parallel binary mode with a 24-bit word format. Instructions were single address with a minimum execution time of 2.5 microseconds.

Multifunction Array Radar (MAR-II)

As discussed earlier in this chapter, NIKE-X was to be an autonomous system capable of fully-automatic, instantaneous, and effective response to a wide variety of offensive tactics and intensities of ballistic missile attack. Its main radar was to be the MAR. The MAR combined search, verification track, discrimination, precision track, and defensive missile track and guidance into a single phased array operating at L-band.

By mid-1967, the ABM defense objectives of NIKE-X were directed to defending CONUS against light attacks. This shift from local defense against high-traffic, sophisticated penetration-aided attacks culminated in a decision to concentrate on the lower cost autonomous MSR as the primary terminal defense sensor. On this decision the development of MAR and its Kwajalein prototype (MAR-II) was terminated.

Initially, it was planned that NIKE-X would be tested at the Kwajalein Missile Range and involve two phased-array radars: the MSR and the MAR.[37] The latter was to have reduced capability, but could be retrofitted to full MAR capability later. The Kwajalein version of the MAR, designated MAR-II, was to be a single-faced (single transmitting antenna array and single receiving antenna array) radar.

To retrofit MAR-II with minimum down time, all of its transmitter and receiver elements and associated cabling would be installed initially. To reach full MAR capability, the additional transmitting and receiving hardware, waveform generation equipment, signal processors, etc., would be installed, checked, and then connected to the antenna elements.

TACMAR

Originally, two versions of the MAR were to be used in NIKE-X. The MAR was to be a higher powered radar, with a full complement of transmitting and receiving antenna elements. The second version, TACMAR,[5,38] had only half as many active antenna elements as MAR for both transmitting and receiving. TACMAR thus had approximately half the power output, lower receiver performance, and a proportionately lower range. It could produce fewer waveforms and therefore had a reduced discrimination capability. This radar was designed to be cost effective in the less demanding defense against an early, relatively unsophisticated threat. It was to be used for high-confidence, early detection of ensemble attacks, for detecting RVs with small radar cross sections at intermediate ranges, and for supporting ZEUS area defense and SPRINT local defense.[9] If the need developed, TACMAR could be augmented to full MAR capability.

MAR/TACMAR Subsystems

MAR and TACMAR were divided into six major subsystems, as shown in Figure 2-8. They are briefly described below.[5,38]

Antennas

In TACMAR, each of the two transmitting antenna arrays contained active elements arranged in a concentric hexagonal configuration with one element in the center. In addition, passive elements were mounted in the array face so that TACMAR could later be augmented to a full MAR.

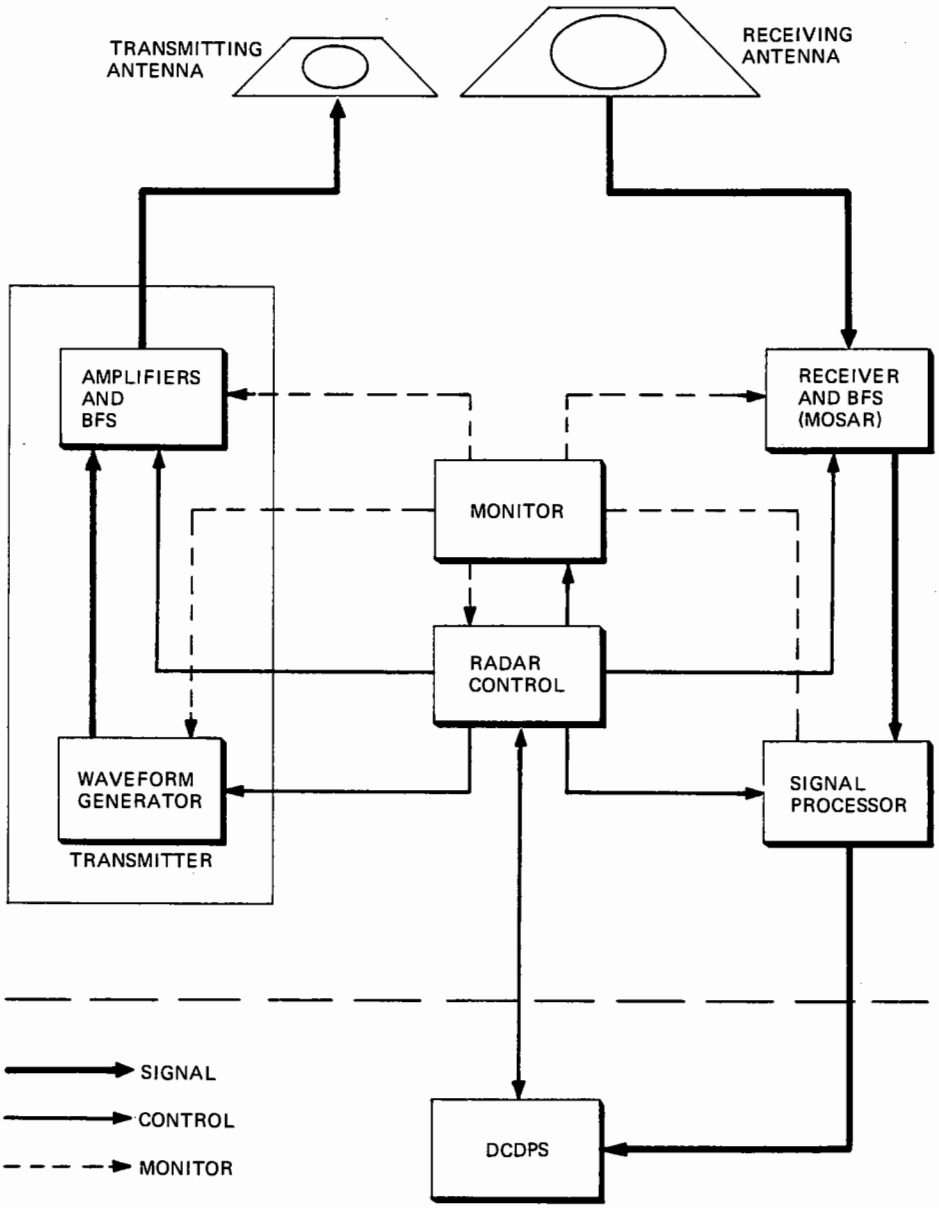


Figure 2-8. TACMAR Block Diagram

Transmitter

The transmitter chain generated and radiated high-power pulses and pulse trains with the correct waveforms for various radar functions. Real-time delay boards, with diode bit switches directed by radar control, formed and steered beams. After high-power amplification by traveling wave tubes, the signal went to the transmitting elements through an RF face selection switch.

Receiver

The output of each element of the receiving antenna array was connected to a preamplifier module. The module had a transistor amplifier, level control attenuators, a second transistor amplifier stage, and a phase equalizer unit. The output of the module was connected to the Beamforming and Steering (BFS) equipment which was of the fan-multiplex MOSAR type. The BFS circuits steered the multiple beams formed by the receiver. These circuits had an output for each of the 40 discrimination beams (nine of which formed the search cluster) and the three monopulse track beams. Digital inputs from radar control controlled the BFS equipment. The local oscillator signals, which were used in the mixers to reduce the received L-band signals to intermediate frequency, were formed in the exciter-stalo.

The input module of the BFS section included the face switch directed by radar control to switch receiver operation to either antenna-preamplifier face. The received signal output from the BFS section went to the signal processor.

Signal Processor

The signal processor accepted outputs from the receiver and converted them to forms for the radar function that the Defense Center Data Processing System (DCDPS) was analyzing. The signal processor also accepted pulses from the missile beacon and identified or rejected spurious signals introduced by noise, countermeasures, or sidelobes.

Radar Control

Radar control provided communications between the MAR and DCDPS. It executed DCDPS's Central Logic and Control (CLC) orders concerning pulse selection, transmitter and receiver BFS equipment, frequency selection, and power levels. Radar control furnished timing information to the subsystem elements and accepted fault location information, which it relayed to the monitor.

Monitor

The monitor detected system degradation, calibration drifts, or failures that required replacement of a unit. Also, if the failed unit was a critical item, the monitor took corrective action by switching in a redundant unit. System degradation was reported via displays and printouts. The monitor had two major parts: RF Calibration and Monitoring (RFCM) and Fault Location and Recording (FLAR).

Conclusion

By mid-1967, the ABM defense objectives of NIKE-X were directed to the area defense of CONUS against light attacks. This shift from local defense against high-traffic, sophisticated penetration-aided attacks culminated in a decision to concentrate on the lower cost, autonomous MSR as the primary radar for terminal defense. Hence, the development efforts on MAR, the Kwajalein prototype (MAR-II), and TACMAR were terminated.

As stated earlier, the fundamentals of phased-array antennas and beamforming were well understood when MAR-I was conceived, and the only real question concerned the application of phased arrays to a multiplicity of simultaneous functions. Thus, the paramount lesson learned from MAR-I was that the program verified the analytical predictability of array performance in a multifunction role.

Of equal, if not greater, importance was identifying the significant problems that re-

sulted from attempting to verify hardware and software on site, with an operational system, without the support of either a hardware or software testbed. This was especially apparent with the array hardware. Unit level tests of either single elements or a small sampling of elements with their associated hardware appeared to be trouble-free. However, when these tests were integrated into the complete system consisting of thousands of elements with their associated signal and power cabling, adverse interactions occurred. A hardware testbed for simulating the physical and electrical characteristics of a full array might have averted the problem. Software testing presented a similar problem, since development and test were done by computer simulations of the expected data processor-radar hardware interface. A software testbed that duplicated the interfaces would no doubt have uncovered most of the problems with the on-site software installation. Partly because of this MAR-I experience, the Tactical Software Control Site (TSCS) concept was adopted for SAFEGUARD. TSCS called for the development, integration, and evaluation of tactical software in a testbed that duplicated the on-site data processors and radar interface hardware.

GUARDIAN (FORMERLY CAMAR) PROGRAM

During the mid-1960s, measurements taken by field radars on reentering bodies had shown an enormous growth in both quantity and sophistication. This information strongly stimulated research in discrimination techniques. Despite vigorous efforts to develop a better theoretical understanding of the fundamental phenomena involved in reentry, the physics of it remained largely an empirical science. By 1968 the success of discrimination research created the need to construct a real-time discrimination capability and to demonstrate its effectiveness in a realistic traffic environment. To demonstrate discrimination capability required a radar and data-processing facility that could perform a variety of interactive functions. It was not sufficient merely to implement, in real time, the simple target-oriented discrimination techniques that were successful in post-flight data analyses, because a credible ABM discrimination depends on a sequence of interrelated events, such as,

- Determining the bounds of the threatening complex to predict the bounds and location of threat tubes to be searched for RVs
- The automatic techniques which acquire and track objects as they emerge from tank breakup clutter or chaff clouds
- The ability to cope with large numbers of traffic decoys and deployment hardware, so that the more likely RV objects can be identified and scheduled for sophisticated discrimination processing
- The ability to maintain track reliability in the presence of crossing targets and nuclear perturbations
- Applying the sophisticated discrimination waveforms and associated signal processing to finally discriminate the RVs
- Real-time management of site resources (radar, data processing, and missile stockpile) to effectively allocate them in the presence of traffic overloads.

A program (initially labeled CAMAR, for Common Aperture Multifunction Array Radar, and renamed GUARDIAN) was started to identify the needs of the ABM community and significantly advance understanding in these areas of the discrimination system problem.

Program Objectives

The intent of the GUARDIAN (CAMAR) program was to produce the technological base and experience from which an urban terminal or hardsite defense system could be developed. The program involved the development and implementation of a system testbed facility at Bell Laboratories, Whippany, and a radar and data processor at Kwajalein that could search, track, discriminate, and intercept actual penetration-aided threats.

GUARDIAN's basic thesis was that the various ABM system functions could not be developed outside the context of the integrated system.

Furthermore, because of their complicated interdependence, these functions, taken as a whole, could not be developed, integrated, and evaluated through the usual approach of a prototype field site demonstration. Therefore, to develop and evaluate the hardware/software forming the integrated system, it was planned that a high-fidelity testbed be built at Bell Laboratories in Whippany, N. J. All low-level radar subsystems and a complete Data Processing and Control Computer (DPCC) were to be incorporated in the testbed. To drive the testbed, an extensive radar simulator and threat generator were to be developed.

Thus, the GUARDIAN proposition was (1) that the exploratory development planned for GUARDIAN could only be accomplished with a flexible, high fidelity testbed and (2) that the field site pseudo-prototype would have two roles: to measure the environment and characterize radar performance in supporting the testbed development, and to "certify" testbed results through demonstration exercises.

With these objectives, two distinct phases were planned for the Kwajalein experience. The first was the Measurement and Recording (MR) role and the second the Discrimination Demonstration (DD) role. The MR role, primarily a real-time recording activity, was to supply supporting data for developing the testbed and discrimination algorithms. The DD roles were primarily concerned with demonstrating, in real time, functions developed with the aid of the testbed.

Development Progress

By early 1968 the requirements for the testbed and its target and radar environment driver had been established, and the testbed was under development. This involved planning the interconnection of the data processor, the low-level radar subsystems, and the radar target/environment simulator. Target threats and specific target environments were defined early in the program. The time-phased sequence of missions to exercise and evaluate the system had also been planned.

As a consequence of the NIKE-X I-67 (SENTINEL) decision, the very high traffic, regional coverage capability of the MAR was no longer needed. Therefore, in April 1968, the MAR/TACMAR development and the MAR-H prototype work at Kwajalein were redirected to the GUARDIAN program. MAR's basic elements were used in designing CAMAR, the field site radar of the GUARDIAN program.[39] The major subsystems of CAMAR were:

- Array Subsystem. This used a common aperture that functioned as both transmitter and receiver. A beam steering translator controlled the phase shifters and converted steering orders from the Data Processing Control Computer.
- Transmitter Subsystem. The waveform generator, exciter, and stalo were controlled by the data processor. The radar control processor selected from among six waveforms and associated signal processors.
- Receiver Subsystem. The receiver input was a low-noise parametric amplifier. The receiver was to form a three-beam cluster for search and designation and a four-beam monopulse cluster that could be broadened for track.
- Signal and Report Processor. Individual processors were provided for the six waveforms.

Development Plan

GUARDIAN's MR role was scheduled for early 1972 and the DD role by late 1973.[40,41] The test and evaluation phase was to consist of two parts:

1. Testing the radar to ensure that it met requirements
2. Evaluating the entire radar-computer system to establish that it performed the DD role as intended.

Demise of the GUARDIAN Program

By early 1969 the program received the name GUARDIAN; its radar continued to be designated as CAMAR. During this period serious consideration was given to modifying the testbed objectives to directly support

deployment of advanced hardsite defense systems.[42] This implied a possible change in the GUARDIAN radar. Therefore, design of hardware and software sensitive to the choice of radar frequency was curtailed from mid-June onward.[43] This was essentially the end of the GUARDIAN program. Shortly thereafter the Army decided that design of a terminal ABM would proceed in directions different from the GUARDIAN program in two significant ways:

1. A prototype of a site-defense system would be developed.
2. Recognizing the inadequacy of the technological and phenomenological data base of the discrimination and bulk filter functions, the Lincoln Laboratories discrimination development and demonstration effort, employing the Kiernan Reentry Measurement Site (KREMS) at Roi-Namur, was to be accelerated.

With this redirection toward a directly deployable system design, the GUARDIAN exploratory program was set aside.

Chapter 3.

SENTINEL SYSTEM



Chapter 3.

SENTINEL SYSTEM

The SENTINEL System was formulated to defend against the potential ICBM threat from both the Chinese People's Republic (CPR) and the USSR during the 1970s. The deployment decision limited its initial role to a complete area defense against a CPR industrial/urban attack on the Continental United States (CONUS), and contained a growth option for defending certain U.S. ICBM bases against USSR attack. Damage prevention was the defense objective against a credible CPR attack while damage limitation was the defense objective against a future expanded CPR threat and against a USSR counterforce attack on major Minuteman installations.

The SENTINEL System evolved from the NIKE-X program, specifically the I-67 System Study.[1-3] The objectives of this study were to:

- Devise a defense against a countervalue attack with ICBMs from the CPR
- Provide for defense against a counterforce attack with ICBMs and SLBMs from the USSR
- Hold total system investment costs to $5 billion
- Meet an Initial Operational Capability (IOC) date within 54 months of a deployment decision. (This requirement limiting the choice of system elements to NIKE-X equipment.)

The study concluded that a system consisting of modified NIKE-X subsystems deployed at installations within CONUS and on Hawaii would meet these objectives.

In September 1967, the decision was made to proceed with the development, production, and installation of this system — given the project name SENTINEL. Further studies led to relatively minor modifications of the components and deployment called for in the I-67 System Study. It was also decided to give first priorities to the installations necessary for an area defense against a CPR attack. This deployment would then be augmented later to defend Minuteman sites against a USSR attack.

SYSTEM DESCRIPTION

The SENTINEL System consisted of the following major subsystems:

- Perimeter Acquisition Radar (PAR) and associated PAR Data Processor (PARDP) for long-range surveillance and tracking of attacking ICBMs
- Missile Site Radar (MSR) and associated Missile Site Data Processor (MSDP) for close-in target surveillance and tracking, and for command guidance of defensive missiles
- SPARTAN missiles with high-yield nuclear warheads for long-range intercepts
- SPRINT missiles with low-yield nuclear warheads for close-in, fast response intercepts

- A Command and Control structure linking these elements.

Deployment

The initial SENTINEL deployment, to provide an area countervalue defense of CONUS and Alaska, was to consist of 6 PARs, 16 MSRs, 480 SPARTANs, and 192 SPRINTs. An additional MSR and 28 SPRINTs were to be provided for Hawaiian defense. The PARs would have their single arrays generally faced to the north. The MSRs would have one, two, or four array faces depending on their location and role in the defense. This initial deployment could grow to include defense of strategic missile bases by the addition of 208 SPRINTs and modification of the data processing hardware and software at the sites located near Minuteman bases.

This system was to be closely netted and would have the ability to modify its response to specific attacks. Overall command and control, administration, and status of the system was to be effected through netting of local and area defense centers and, these in turn, with the Continental Air Defense Command (CONAD). This deployment is depicted in Figure 3-1.

Area Coverage

The area defense provided by the SENTINEL deployment involved nearly complete coverage of the contiguous United States, as well as parts of Alaska and Hawaii, against the defined CPR threat.[4]

The defensive coverage planned for each SPARTAN firing site is depicted in Figure 3-2.

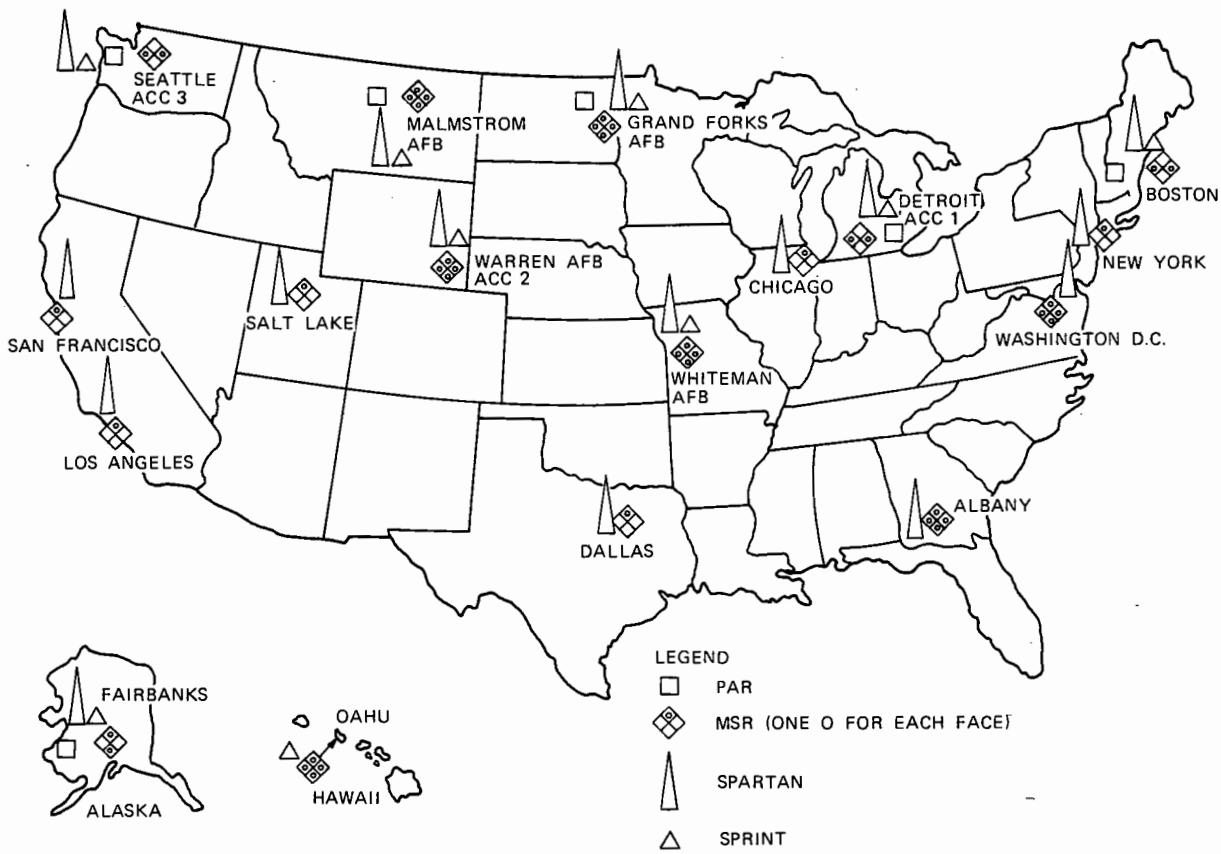


Figure 3-1. Locations of Sites for SENTINEL Deployment

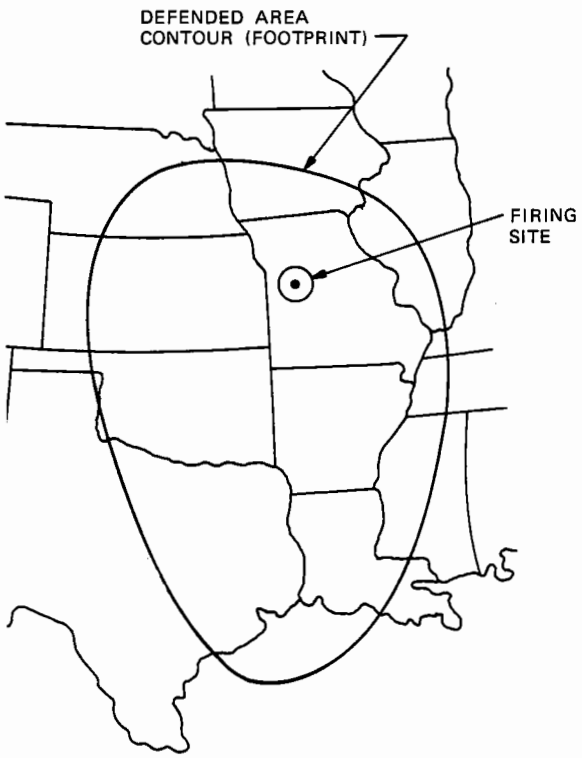


Figure 3-2. Ground Impact Area Coverage

The contour shown encloses the impact points of attacking ICBMs which could be intercepted above the atmosphere by a SPARTAN launched from that site. In general, the coverage (sometimes called a "footprint") was limited in the forward direction by the PAR detection range, and to the side and rear by a combination of missile capability and MSR scan limits.[5]

Achieving an effective area defense depends on the ability to search and detect objects at ranges that provide sufficient time to launch an interceptor at the attacking ICBM. This function of long-range search and detection would be performed by the Perimeter Acquisition Radar. Five PAR installations were to be located along the northern periphery of the United States, with one additional installation in Alaska.[6,7] The PARs would also have a verification and tracking capability to provide trajectory information to the missile firing sites and to command and control centers.

The SPARTAN missile firing sites, each with an MSR, were located in such a manner that their defended area footprints encompassed the entire CONUS. The SPARTAN firing site in Alaska provided a defense for most of the population there, while a SPRINT firing site on Hawaii provided almost complete area coverage of Oahu.

Collocated with each of the six PARs was a missile firing site using SPRINT to provide a high-confidence, terminal-intercept capability for the defense of these forward radars.

Minuteman Defense Coverage

The SENTINEL deployment called for growth to provide a terminal (SPRINT) defense of Minuteman squadrons at five bases.[8,9] The deployment objective was the maximization of silo coverage and survival against a large USSR attack.

The defense coverage to be provided, as contrasted with area defense, was strongly dependent on the characteristics of the threat, the actual site locations, and the level of deployment. Of particular importance was the target commit altitude, i.e., the altitude of the target at the time of launching a defensive missile. The commit altitude was determined by radar coverage, system response against a specified threat, and defensive missile fly-out time.

Remote launch of SPRINT was specified for the Minuteman defense sites to minimize fly-out time. These remote missile farms were located near the Minuteman silos at distances of about 25 miles from the MSR.

The SPARTAN missile, in addition to its area defense role, provided additional protection of Minuteman bases.

Command and Control

Of importance to the system operation and response was the concept that Command and Control should be designed to allow appropriate authority to reside at the lowest level in the command hierarchy, consistent with the level at which available data would support system functions and decisions.[10]

The SENTINEL Command and Control is illustrated in Figure 3-3. The system was to operate under a three-level hierarchy of Command and Control headed by the Ballistic Missile Defense Center (BMDC) which was the interface point between SENTINEL and CONAD. The BMDC was to be the command point through which the Commanding General of the Army Air Defense Command (ARADCOM) would exercise command and technical supervision over the SENTINEL System.[11] The BMDC was charged with defense of the entire United States through coordination with three Area Control Centers (ACCs) under its command.[12] The ACC responsibilities included PAR command and control,[13] MSR command,[14] and SPARTAN command. Missile Direction Centers (MDCs) were grouped on an area basis with five or six MDCs under the control of an ACC. The MDC was responsible for MSR control, SPRINT command and control, and/or SPARTAN control.[10]

The three ACCs were collectively responsible for three areas of CONUS. The boundaries between areas were drawn to minimize SPARTAN coverage overlays and to provide necessary coordination. Each primary ACC had an alternate as shown in Figure 3-4 which illustrates the MDCs and PARs included in the command and control structure of ACC No. 2. Here, the primary ACC was located at Warren AFB and the alternate was located at Whiteman. A failure at Warren resulted in a preplanned, progressive sequencing of control to Whiteman.

Communication circuits were to be provided, for both voice and data, with two geographically

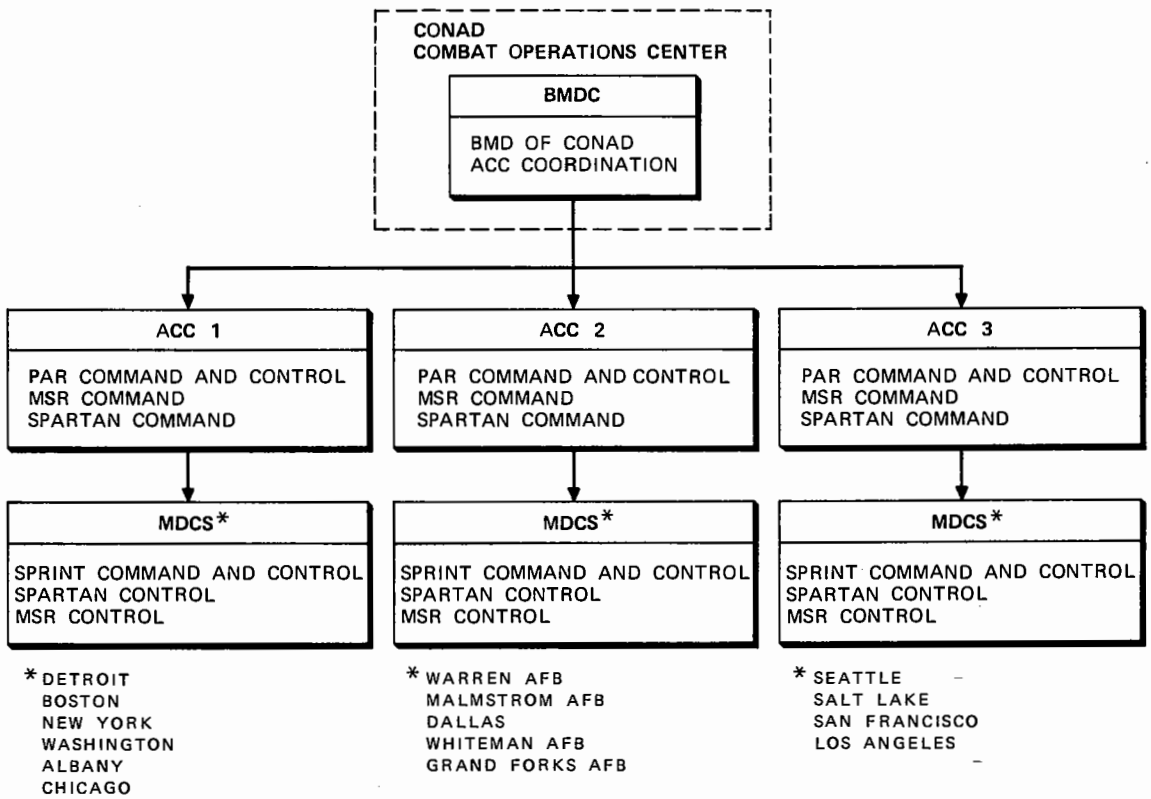


Figure 3-3. SENTINEL Command and Control Structure

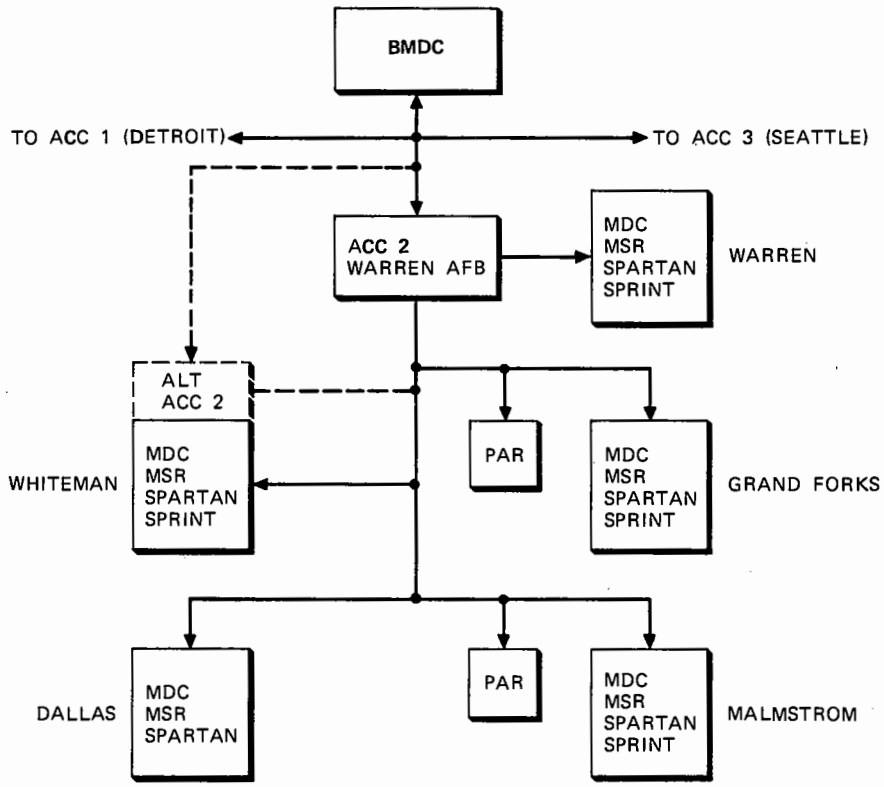


Figure 3-4. Area Control Center Number 2

separate paths required for all links. Inter-area communications were to be provided only between ACCs, with PAR data being sent to the BMDC via the ACC; MSR data were to be sent to the controlling ACC for inter-area MSR coordination and threat evaluation.

System Operation and Response

Long-range surveillance and target tracking in the SENTINEL System were to be provided by the PAR. For urban defense, the SPARTAN was the primary interceptor and was tracked and guided by MSRs. Minuteman defense would be accomplished largely as a terminal defense with SPRINT, supplemented by SPARTANs, contributing where they could be effectively brought to bear.

Generally, targets would be detected first by the PARs and, after a few seconds of tracking, trajectories and impact points would be determined and an MDC designated. For SPARTAN intercepts, target information relative to interception would be continually refined and passed to the appropriate point. The MSR, in some instances, would acquire and track the target prior to SPARTAN burst and thus reduce the intercept error.

For SPRINT engagements, the PAR data would be passed to the assigned MDC for subsequent action once the local MSR had established track. For terminal defense, the MDC could act autonomously with the MSR providing target surveillance and acquisition, as well as target and missile track.

For area defense, the SPARTAN engagement would be planned at the ACC and take into account blackout and fratricide constraints, defensive missile stockpile balance, and other restrictions.

The ACC would determine effectiveness against possible follow-on attackers. Allocation thresholds would be set and the stockpile balance among SPARTAN firing sites adjusted accordingly. The intercept would be planned specifying the place, the time, and how many SPARTANs were to be used in meeting effectiveness criteria. Continuous evaluation of the engagement plan would be provided to ensure its adequacy. The BMDC would coordinate the roles of the ACCs and provide information on estimated future attack size and defense objectives. Implementation of the SPARTAN engagement plan would be performed by the MDC, including post-intercept evaluation for use at the ACC.

For Minuteman defense, the BMDC would provide information to the ACC as in area defense, together with any Minuteman silo coverage constraints on the defense. The ACC would determine the division of the total attack for SPARTAN and/or SPRINT engagement assignments. These assignments would be sent to the designated MDCs where engagement plans would be completed. Any conflicts involving fratricide or blackout between SPARTAN and SPRINT would be resolved by the MDC. The MDC would also select the SPRINT farm to be used and plan the engagement to achieve the effectiveness level specified by system objectives, including preferential defense of Minuteman and the SENTINEL complex.

System Readiness Verification

The SENTINEL System design was strongly influenced by stringent availability/reliability objectives, that is, requirements for high probability that the system would be available if an attack should occur, coupled with requirements for high reliability during an attack.[15-19] The design intent was to provide a built-in capability for comprehensive testing of all system elements to provide continuous confidence in the system's readiness to perform its mission. This led to requirements for developing a large array of subsystem, functional, and hardware tests. In addition, a system exerciser would test the fully-integrated system, partially by simulation. The collection of hardware and software required to provide this built-in test capability was referred to as System Readiness Verification (SRV).[20]

The SRV tests were oriented toward providing:

- Verification that critical system performance parameters were within specified limits
- Detection, isolation, and indication of hardware faults
- Verification that the dynamic response of individual and collective sites (including hardware, software, and personnel) to design-level attacks was correct and that predetermined results were obtained.

In the PAR and MSR, fault detection tests were designed to run cyclically during the radar pulse-cycle dead-time while the system was performing its major role. If test results did not meet specified limits, spare groups of equipment would be automatically switched in while monitors indicated the faulty equipment. Additional fault detection and isolation tests were provided for the off-line equipment.

Data Processing System (DPS) hardware was checked by periodically scheduling units (processors, memories, etc.) off-line for testing by the Maintenance and Diagnostic Subsystem. A fixed set of tests was applied to each unit, results analyzed, and, in most cases, the fault identified.

For SPRINT and SPARTAN, special test programs were periodically run in the DPS to exercise missile subsystem hardware via normal interface channels. Monitors would indicate if the tests were unsuccessful and additional tests would be run to isolate the fault.

A System Exerciser provided the means for additional testing of system hardware as well as for exercising the tactical software (known as the weapons system process). This was accomplished by partitioning the DPS equipment at each site into two separate data processors — one to simulate a specified threat and the other to respond as during a real engagement. During an

exercise, the simulator would generate radar returns representing the preselected attack for injection into the radar receivers. The system would respond in a normal manner except that simulated defensive missiles would be launched and guided under control of the weapons system process. The results of the exercise would be checked to make certain that the engagement proceeded as expected.

The System Exerciser concept also provided the means for developing and testing software in the SENTINEL Data Processing Laboratory (SDPL) at Whippany, where site equipment was either duplicated or simulated. Similarly, the System Exerciser would provide the major tool for integrating and testing software at tactical sites.

SYSTEM REQUIREMENTS AND DEVELOPMENT

Documentation

The basic requirements for the SENTINEL System and its major components were developed during the initial system studies (e.g., I-67 System Study) and refined during the first phase of system development following the deployment decision. These requirements evolved into a hierarchy of performance/design specifications which were to be prepared by Bell Laboratories and approved and placed under configuration-management control by the Army.[21] The functional organization and objective of these specifications were:

- SENTINEL System Specification — included threat parameters, overall performance requirements, deployment plan, radar and missile types and locations, and a list of sub-specifications.
- Hardware Oriented Specifications — one each for the PAR, MSR, BMDC, Data Processor, and SPARTAN and SPRINT with their associated equipment; performance requirements and design characteristics were included in each document.
- Specifications for Maintenance Facilities — stipulated requirements for Test Equipment, Maintenance Data System, and System Readiness Verification.
- Software Oriented Specifications — one each for the programs in the MSDP, PARDP, BMDC, and System Readiness Verification; requirements for inputs, outputs, operations, and major functions were included in each document.

These specifications were also used in the contractual requirements placed on the major subcontractors for the radars and missiles.

System Engineering

System engineering activities were primarily concerned with definition, documentation, and specification of the SENTINEL System operational requirements. Simulations were developed for evaluating tactical concepts and system effectiveness.[22] A mathematical model was prepared to simulate, in a computer, the proposed SENTINEL deployment to evaluate the complete system design and interaction among its various parts.[23-27] As data from MSR and MSDP tests at Meck Island and from SPRINT and SPARTAN firings became available, they were introduced into the simulation to increase the accuracy of results.

Missile Site Radar

The Missile Site Radar (MSR), an S-band single-beam, phased-array radar, was used with the Missile Site Data Processor (MSDP) to perform surveillance and limited discrimination, track of reentry targets, and track and command guidance of SPRINT and SPARTAN missiles.[28] The Raytheon Company, Bedford, Mass., was the MSR subcontractor with Bell Laboratories providing overall direction, design control, and assistance in critical areas.

The MSR was structurally a part of the Missile Site Control Building which also housed the MSDP. It was designed to have one, two, or four antenna faces inclined 51.5 degrees from the horizontal. Each face was used for both transmitting and receiving, with a single transmitter and a single receiver time-shared among faces. The transmitter (up to the final klystron amplifiers) and the receiver had duplicate equipment and automatic switching for redundancy. The two

final klystron amplifiers were operated in parallel but also could operate alone at reduced power. Face switching and beam forming and steering were computer controlled.

With the change to SENTINEL, the autonomous role of the MSR was expanded, thus necessitating major changes to upgrade its tracking capability. An example of this change was the required five-fold increase in its output average power level. A prototype MSR with two array faces was constructed on Meck Island and tested extensively. This test program provided significant data useful in the design of the follow-on SAFEGUARD System.

Perimeter Acquisition Radar

The Perimeter Acquisition Radar (PAR), a single-beam, phased-array radar, was used with the PAR Data Processor (PARDP) to perform long-range surveillance, target verification, and tracking of attacking ICBMs.[29] The requirements specified a maximum detection range sufficient to allow time for SPARTAN missiles to intercept warheads outside the atmosphere. The PAR initially was planned as an "off the shelf" VHF-band radar, but following a study on the effects of nuclear blackout,[30] the frequency was changed to the UHF band, necessitating an extensive redesign program.

PAR was designed to operate in a hostile environment consisting of false targets (aircraft, satellites, meteors, or aurora), clutter signals (from the ground, chaff, or aurora), and nuclear disturbances (electromagnetic pulses, blast waves, ground shock, thermal radiation, and other radiation from nuclear weapons).

Development of the PAR was divided into three phases as follows:

- Phase I — Performance definition and equipment specification
- Phase II — Design and manufacture of a prototype at a site near Boston
- Phase III — Production and deployment of the remaining five radars.

The General Electric Company, Syracuse, New York, was responsible for PAR development under subcontract to Bell Laboratories. At the time the decision was made to reorient SENTINEL System development to SAFEGUARD objectives, the prototype site near Boston was underway and had to be moved to Cavalier, North Dakota.

SPRINT Missile Subsystem

SPRINT, a two-stage, solid-propellant missile, was the interceptor for terminal defense in the SENTINEL System. It was designed to be extremely fast reacting and capable of delivering a nuclear warhead to an intercept point, at short ranges, within seconds after launch.[31]

Development test firings of SPRINT were first conducted at White Sands Missile Range as part of the NIKE-X program. Later SPRINT launches at Meck and Illeginni Islands were conducted using SENTINEL MSR/MSDP guidance in SAFEGUARD System missions.

The Martin Marietta Corporation, Orlando, Florida, was the subcontractor to Bell Laboratories for development of SPRINT. Missile-borne guidance equipment was developed by Bell Laboratories and manufactured by Western Electric.

SPARTAN Missile Subsystem

The SPARTAN missile, in its primary role, provided long-range, large-payload, intercept capability against exoatmospheric targets.[32] The three-stage missile employed booster and sustainer motors to achieve peak velocity and a third-stage controllable jet motor for final intercept control.

Design and development of SPARTAN was the responsibility of the McDonnell Douglas Corporation, Santa Monica, California, under subcontract to Bell Laboratories. Guidance equipment for SPARTAN was developed by Bell Laboratories and manufactured by Western Electric.

Many of the basic design features of the NIKE-ZEUS DM-15C missile were used in SPARTAN. Design emphasis for use in SENTINEL was concentrated on those areas in which changes had to be made to carry a heavier warhead for the longer range, barrage-type function of SPARTAN.

The SPARTAN missile development flight-test program began at Kwajalein in March 1968 and continued into 1969. Use of SPARTAN in SAFEGUARD system missions began in April 1970.

Data Processing

Each SENTINEL installation included a Data Processing Subsystem which controlled the functioning of its radar (PAR or MSR), analyzed attacks, allocated system resources, and commanded the launch and guidance of interceptor missiles.[33]

Two R&D versions of partial data processing subsystems were installed: the SENTINEL Data Processing Laboratory (SDPL) at Whippany, and a minimum Missile Site Data Processing Subsystem (MSDPS) at Meck. The SDPL was used for equipment evaluation and software program development; the MSDPS was integrated with the MSR and used for MSR testing and performance verification.

The DPS hardware was of modular design to permit sizing to meet requirements of the processing tasks associated with each deployed site. The design was standardized so that any number of processors could be combined with any number of storage units to meet the requirements of a given site.

Most equipment was designed, developed, and manufactured by Bell Laboratories and Western Electric. Lockheed Electronics produced core memory systems for program and variable stores.

Software

The basic tactical functions of the SENTINEL System were embodied in the software programs which would drive the data processors at each site. These tactical functions were to be implemented in three generic weapons processes — one each for the PAR, MSR, and BMDC. Versions of these processes would be used at the various sites, with each version site-unique and capable of operating only in the DPS at the site for which it was designed.[34]

The Weapons Process requirements were specified in Data Processing System Performance Requirements (DPSPRs), prepared as a result of system engineering and analysis of overall system objectives. These documents specified the fundamental concepts, functional requirements, and constraints for SENTINEL System deployment. In addition, requirements for software-driven equipment tests and readiness verification were included.

The plan for development of SENTINEL weapons processes as well as other software required at the tactical sites included development of tactical support software.[35,36] In this category were:

- Program Preparation Facilities — including all tools necessary to assemble, maintain, and construct a process
- Program Execution Facilities — including the basic DPS management facility and the Tactical Operating System
- DPS Test and Maintenance Facilities — including provisions for maintenance of DPS hardware and diagnosis of faults.

Software development also included special installation software packages for use during installation and testing of SENTINEL site hardware. Three types of installation software were to be developed: (1) the DPS Installation Test Facility, (2) the PAR Installation Process, and (3) the MSR Installation Process.

In addition, software processes were developed for the Meck Test System. The initial software provided for Meck was much like the DPS and MSR Installation Processes. A software process, referred to as M-1, was an early prototype for the tactical MSR Weapons Process and provided the method for exercising the MSR, MSDP, and missile subsystems.

Testing

Major testing for the SENTINEL System was conducted with the Meck Test System which consisted of the MSR, MSDP, SPARTAN, and SPRINT subsystems.[37] The purpose of the Meck test program was to:

- Exercise and evaluate all elements of the subsystems installed
- Achieve SPRINT and SPARTAN intercepts against high-performance targets of known and controlled characteristics
- Permit study and evaluation of man's role in augmenting system responses
- Gather data applicable to the continuing design effort.

The test plan was directed toward evaluating those functions related specifically to SENTINEL deployment. This plan involved several phases of system testing at Meck Island. The M-0 phase used sets of comparatively small software packages to facilitate checkout of the radar, data processor, missile subsystems, and the interfaces between subsystems. The M-1 phase provided initial tactical functional capabilities required in the area defense role, including the first MSR-guided SPARTAN and SPRINT intercepts. Subsequent phases were to be designed with the functional capability required to test against the growth threat and to evaluate hard-site defense.

SUMMARY AND CONCLUSIONS

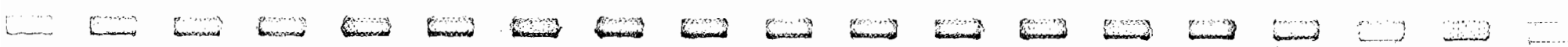
In the total story of ABM development, the SENTINEL System is but one brief chapter. Although not actually deployed, SENTINEL was significant in that it was the first ABM system on which an affirmative decision to deploy was made. This decision initiated development and other related activities not addressed as specifically, or in as much depth, for earlier systems. Not surprisingly, some of these activities turned up important problems that required significant attention and therefore became important conclusions in the planning for SAFEGUARD.

Because the SENTINEL System evolved into the SAFEGUARD System, rather arbitrary judgments were required to identify the conclusions, or lessons learned, from SENTINEL. The following list emphasizes those items which relate only to SENTINEL, or which were clearly highlighted before the transformation to SAFEGUARD.

- It became very clear that development, testing, and integration of the large and complex software programs required for the system seriously affected successful, on-schedule completion of the project. This led to an intensive effort to expedite the software development for SAFEGUARD. The technical and management procedures which resulted are described in Chapter 4, SAFEGUARD System, and Part III, Management and Overall Approach.
- Providing adequate confidence that the system was operational emerged as a difficult task. The design of an extensive built-in System Readiness Verification subsystem therefore became an important part of the system design.
- Specification of requirements for positive nuclear control having a very short reaction time necessitated a complex interface with the various organizations involved.
- A complex Command and Control System was required to internet the elements of the SENTINEL deployment. The unique requirements of SENTINEL made the design of such a system difficult.
- An organization of Configuration Control Boards was established to provide a Configuration Management System to control the requirements for the many elements of the SENTINEL System.

Chapter 4.

SAFEGUARD SYSTEM



Chapter 4.

SAFEGUARD SYSTEM

SAFEGUARD is an ABM system designed to protect U.S. Minuteman ICBM bases from attacks by enemy ballistic missiles. Development of the SAFEGUARD System began with a redirection of the SENTINEL program in March 1969. Its deployment plan called for a number of sites to be constructed primarily in the western part of the United States. As a result of the Strategic Arms Limitation Treaty (SALT) and related program decisions, actual deployment was subsequently limited to a single complex in North Dakota and a system command center in Colorado.

The initial SAFEGUARD plan called for up to twelve sites deployed in two phases. The first phase, for which authorization was originally granted, provided Minuteman defense at Grand Forks Air Force Base (AFB), North Dakota, and at Malmstrom AFB, Montana, together with a Ballistic Missile Defense Center (BMDC) at Cheyenne Mt., Colorado. The second phase would have added Minuteman defense at Whiteman AFB, Missouri, and at Warren AFB, Wyoming, as well as defense of the National Command Authority (NCA) in Washington, D.C. This phase also retained the option to add additional sites to protect Strategic Air Command (SAC) bases and population centers. In March 1971, approval was granted to proceed with the installation at Whiteman and to plan for the Warren site. Whiteman was designated as the Fire Control Center (FCC) and Malmstrom as the Alternate Fire Control Center. The FCC was an intermediate command center reporting to the BMDC. A year later, however, authorization for the Whiteman site was rescinded and Malmstrom was designated as the FCC.

In accordance with the terms of the Strategic Arms Limitation Treaty of June 1972, and a subsequent Congressional decision not to authorize the permitted deployment in the Washington, D.C. area, the SAFEGUARD System was further reduced to provide Minuteman defense only at Grand Forks AFB. Thus, the current deployment consists of a Perimeter Acquisition Radar (PAR) and a Missile Direction Center (MDC) in North Dakota, both under overall command of the BMDC in Colorado. Included in the MDC are a Missile Site Radar (MSR) and associated SPRINT and SPARTAN missile farms. This deployment is depicted in Figure 4-1 and is aimed at providing a number of defense capabilities.[1-8]

The three types of sites in the SAFEGUARD System are interconnected by communications links. The PAR site uses a single-face, phased-array radar to provide early detection and target trajectory data on threatening ICBMs. Functions of this site include long-range surveillance, detection and selection of threatening objects, and

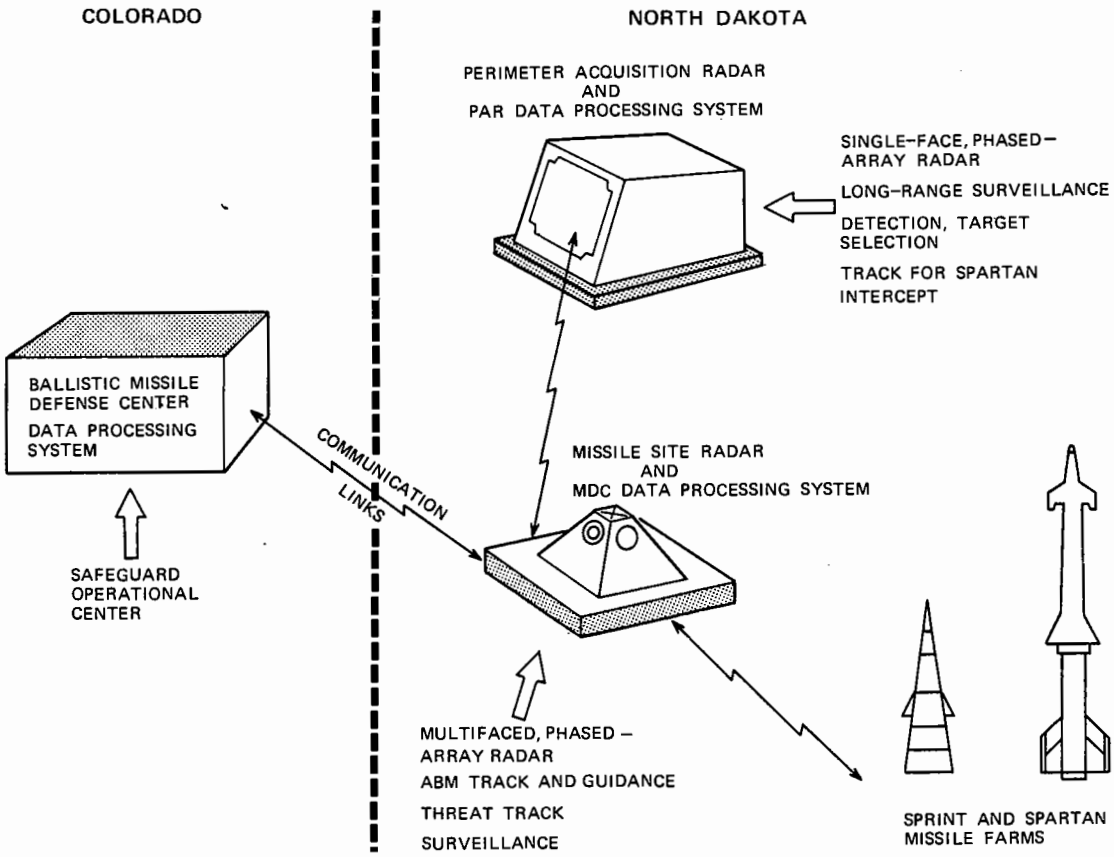


Figure 4-1. SAFEGUARD ABM System

ICBM threat tracking for SPARTAN intercept. This last capability significantly increases the long-range SPARTAN field-of-fire. The PAR site does not perform missile guidance, but instead, transmits trajectory and target classification data over the tactical communication links to the MDC. The MDC uses this information together with data from its own multi-faced, phased-array Missile Site Radar. This site provides additional surveillance and target tracking as well as track and guidance for SPRINT and SPARTAN missiles. Both PAR and MDC sites report to the BMDC, which provides a command interface with other military systems and a means of disseminating command directives and controls.

The PAR and MSR are controlled through digital commands issued by collocated Data Processing Systems (DPSs). These commands are used to manage such radar functions as beam pointing, frequency selection, receiver gating, thresholding, etc. In addition, application programs in the PAR and MSR Data Processors (PARDP and MSRDP) manage the major system functions of surveillance, tracking, target classification, radar testing, intersite communication, and command/control/display. At the MDC, other programs support engagement management and missile guidance. The BMDC DPS primarily performs command, control, and display functions.

MAJOR SAFEGUARD ELEMENTS

Perimeter Acquisition Radar

The Perimeter Acquisition Radar performs long-range surveillance, detection, and tracking of ICBMs for SPARTAN missile intercept.[7,9] As an auxiliary function, it can provide track data on selected satellites of interest. To withstand nuclear blasts,[10] the radar equipment is mounted in a reinforced concrete structure which is shielded against nuclear electromagnetic radiation. The front face of the building supports an array of 6888 antenna elements (see Figure 4-2).

At periodic intervals, the PAR searches the volume of space within a large solid angle in front of the array face. It can detect small targets in a typical ballistic missile complex at large distances with a high probability of detection. The radar operating frequency can be changed and the antenna beam-pointing direction can be switched between points in space and between multiple transmissions in the same radar interval.

The PAR transmitter consists of high-power Traveling Wave Tubes (TWTs) whose combined total peak radiated power is in the multimegawatt range. Target returns are amplified by low-noise transistor amplifiers which are an integral part of the phase-steered corporate-fed array. Further details on the PAR are given in Chapter 8.

Missile Site Radar

The Missile Site Radar is a four-face, single-beam phased-array radar operating in S-band. Its function is to acquire and track incoming ballistic missiles and to launch and guide SPRINT and SPARTAN missiles for intercept.[7,11,12] The MSR can also launch and guide SPARTAN missiles for intercept using PAR target data.

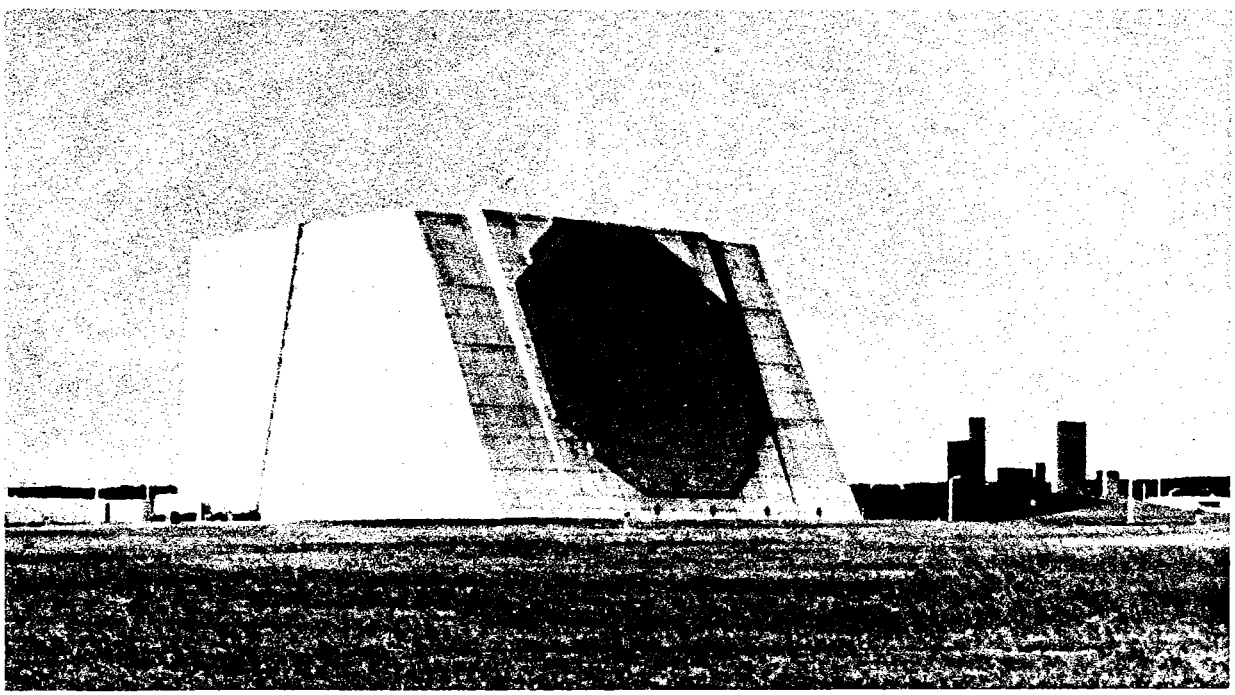


Figure 4-2. PAR Building

To withstand nuclear effects, the radar equipment is housed in a reinforced concrete structure shielded against nuclear electromagnetic radiation.[10] A large portion of the building is below ground with an above-ground turret containing the four phased arrays to provide hemispheric coverage (see Figure 4-3). Each of the four arrays consists of 5001 elements used for both transmission and reception.

The MSR scans the complete hemisphere and can detect targets of small cross section at ranges of several hundred nautical miles.[13,14] The antenna beam pointing direction and operating frequency can be switched between points in space between transmissions. Separate transmit and receive feedhorns are used behind each MSR space-fed array.

The MSR transmitter final amplifier has two high-power klystrons operating in parallel, each with its own power supply. This permits operation at half power, should one unit fail. The transmitter output power is in the megawatt range at high duty cycle. Target returns are amplified by a cooled parametric amplifier before dechirping to achieve the required sensitivity. Further information on the design and performance of the MSR is given in Chapter 7.

SPRINT Subsystem

The SPRINT Subsystem consists of high-performance, ground-radar-controlled, nuclear-armed interceptor missiles and associated support equipment. The missiles are emplaced and ready for launch from underground cells which, together with their support equipment, are deployed in launch areas, or farms, at the MSR collocated site (Figure 4-4) and at farms remote from the MSR.



Figure 4-3. MSR Site

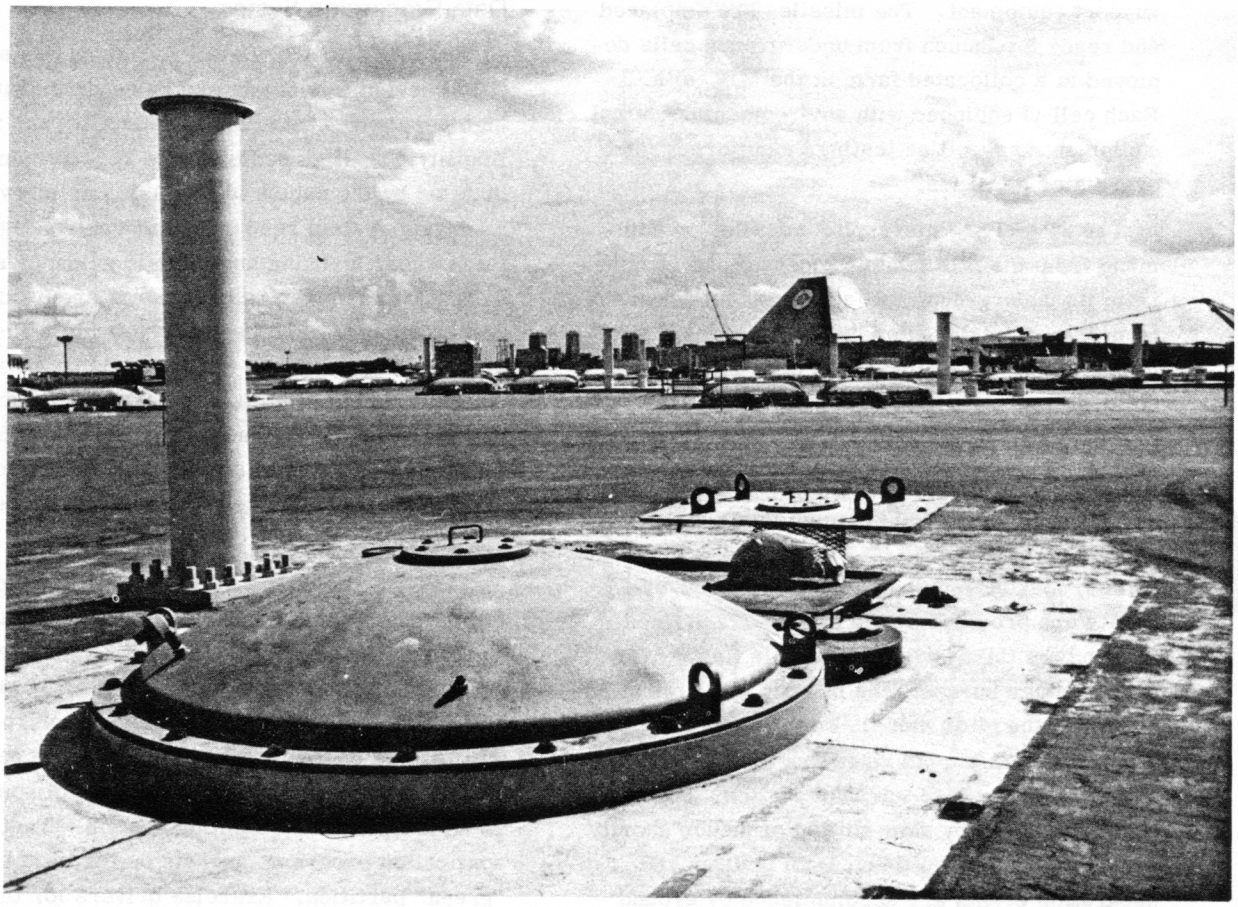


Figure 4-4. SPRINT Cell with MSR in Background

The SPRINT interceptor missile is designed to provide fast reaction-time in reaching endo-atmospheric intercept points.[15] At launch, the missile is ejected from its underground cell and its first stage ignites automatically. A pitchover maneuver is initiated prior to acquisition and track by the MSR. A "missile model" in the computer tells the radar where to look on the planned trajectory so that acquisition can be made as soon as a clear transmission path is available. After first-stage burnout, the second stage is ignited by ground command. The second stage burns for a short interval during which final corrective steering orders are issued and the missile attains the altitude necessary for intercept.

In-flight fratricide related to launch station spacing is a limiting constraint on the rate-of-fire. The launch equipment is capable of accepting launch orders and initiating the launch sequence in a very short interval after receipt of a preparation order. This interval includes the time alloted for tests requested either locally or by radar command and can be reduced somewhat if these tests are not conducted. Refer to Chapter 9 for further details on SPRINT.

SPARTAN Subsystem

The SPARTAN Subsystem consists of high-performance, ground-radar-controlled, nuclear-armed interceptor missiles and associated

support equipment. The missiles are emplaced and ready for launch from underground cells deployed in a collocated farm at the MDC site. Each cell is equipped with environmental control equipment, as well as testing, monitoring, and exercising facilities.

The SPARTAN interceptor missile, on command from the MDC Data Processor, is launched from its underground cell at an angle of 5 degrees from the vertical. After launch, the missile follows a radar-controlled flight plan using three solid-propellant-powered stages and two in-flight separations.

After first-stage boost and burnout, the second stage is ignited automatically and booster separation is achieved by second-stage thrust forces. Second-stage control and maneuverability are provided by the second-stage fixed fins and the third-stage deflectable fins. After second-stage burnout, the missile exits the atmosphere in the glide mode. For intercept to occur, the burned-out second stage must be separated from the third-stage warhead section. Separation is achieved by skin-cutting ordnance shortly after third-stage ignition. Both ignition and separation events are accomplished by ground command and occur in the exoatmosphere region. Third-stage exoatmospheric control is accomplished by directing the exhaust from the third-stage motor through nozzles which are an integral part of the third-stage fins. Finally, the nuclear warhead is spin-stabilized during the latter portion of third-stage burn.

The SPARTAN launch equipment consists of the launch and test equipment and the launch reradiation antenna. The launch equipment provides for testing launch station hardware and missiles under control of the MDC Data Processor. This testing detects any faulty or unsafe condition to ensure that the subsystem is in a battle-ready state permitting missiles to be launched in rapid-fire sequence. Refer to Chapter 10 for further details on SPARTAN.

Data Processing System

The SAFEGUARD Data Processing System (DPS) design was dominated by requirements for high performance and high availability and reliability.[16–18] High performance requirements are dictated by the nature of the DPS's primary job: managing system resources and controlling a large radar tracking and missile guidance system in real time. After radar returns are processed, new commands must be generated and transmitted to the radar every few milliseconds on a fixed schedule. This results in peak processor throughput of 10 million instructions per second and peak transmission rates to service the radar and other peripheral devices of 200 megabits per second.[19–21]

The DPS equipment at a Missile Direction Center is shown in Figure 4-5. The Central Logic and Control (CLC) is the multiprocessing computer used to drive the radar and the other peripherals shown. Under software control, the CLC can be configured into two separate partitions of arbitrary size, each capable of operating as an independent computing system. Tactical application programs execute on the larger or "green" partition. Exercise drivers for the application programs and independent support-activity programs execute on the smaller or "amber" partition, which also provides a reserve of spare equipment.

The CLC can be configured with up to ten processors.[22] Single-processor throughput of about 1.5 million instructions per second is achieved by a combination of design techniques that include instruction execution overlap and use of high-speed arithmetic algorithms.[19,20] Every processor has access to each of several read-only instruction memories called program stores, and several read-write memories called variable stores. These stores have a memory-cycle time of 500 nanoseconds and a double-word size of 64 bits to provide a memory bandwidth in excess of that required for maximum performance

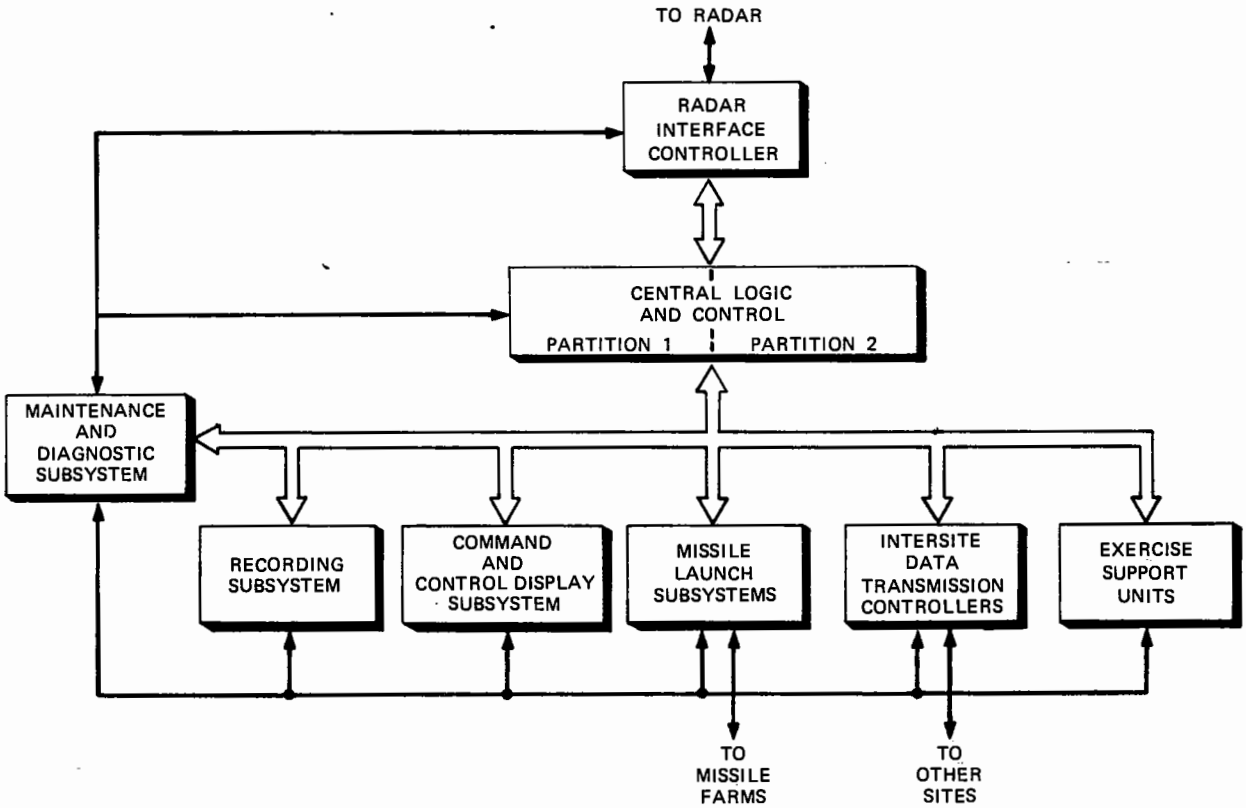


Figure 4-5. Data Processing System Equipment

of a single processor. All data transfers between the CLC and its peripherals are controlled by an Input/Output Controller (IOC), thereby allowing processing and I/O tasks to be accomplished simultaneously.[21]

Table 4-1 shows the CLC configurations, both green and amber, in the SAFEGUARD System.

Several major subsystems peripheral to the CLC are shown in Figure 4-5. These include:

- Radar Interface Controller - provides the primary interface between the IOC and the radar for exchange of control and data words. This unit accepts formatted binary words from the CLC and distributes data to the appropriate radar subsystems.
- Missile Launch Subsystems - convert CLC commands into control signals for the collocated and remote missile farms; this equipment also receives missile status information for encoding and transfer to the CLC.
- Intersite Data Transmission Controllers - provide transfers of digital data via data links between sites.[23-26]
- Exercise Support Units - required in system exercises to provide an interface between the simulated threat running in the amber part of a partitioned DPS and the tactical programs running in the green partition.
- Command and Control Display Subsystem - provides the man-machine interface for monitoring and directing tactical operations through Cathode Ray Tube (CRT) displays, consoles, teletypewriters, and wall displays.[27-31]
- Recording Subsystem - contains the standard computer peripheral devices: magnetic tape transports, disk memory units, line printers, and card reader.
- Maintenance and Diagnostic Subsystem (M&DSS) - provides a centralized facility for testing and maintaining digital hardware to ensure the availability and readiness of the DPS.[32-35] The M&DSS uses unique

Table 4-1
CLC Configurations

Equipment	MDC			PAR			BMDC
	Green	Amber	Total	Green	Amber	Total	
Processor Units	7	3	10	3	2	5	1
Program Stores	9	3	12	4	3	7	3
Variable Stores	10	5	15	10	4	14	3
IOCs	1	1	2	1	1	2	1
Timing & Status	1	1	2	1	1	2	1

dedicated hardware to conduct non-real-time, programmed diagnostic tests on the DPS equipment through an independent data bus connected to each digital unit. The M&DSS also supports initialization of the DPS hardware and assists in automatic reconfiguration and recovery of this hardware should it be necessary during the tactical mission.

For more information on the DPS equipment, refer to Chapter 11.

SOFTWARE DEVELOPMENT

Development Cycle

The SAFEGUARD development benefited substantially from prior work on the R&D prototype called the Meck Test Facility. This effort provided an early demonstration of critical ABM concepts and also collected data needed for subsequent design and evaluation. The many lessons learned were applied directly to the SAFEGUARD program.

The software development cycle involved a number of distinct phases. These phases overlapped, since the general approach used required integration of a basic working system with increasingly more complex capabilities.[36] This integration was performed at a separate test facility, the Tactical Software Control Site (TSCS), using special system exerciser arrangements.

The separate phases of the development cycle were as follows:

- Requirements Generation - initial system requirements were determined, established, negotiated, documented, and rigorously controlled.
- Software Design - in process design, system requirements were translated into a software architecture which defined global structures, tasks, task priorities, and task timing requirements for the data processing environment. In program design, the local data base, algorithms, and control structure for individual tasks were determined.
- Coding and Unit Testing - codes were written, compiled, and checked at the unit or task level using a simulator, drivers, and standard debugging techniques.
- Process and Functional Integration - facilities of TSCS were used to combine blocks of new debugged unit code into processes of increasing functional capability. When the tactical software attained a predefined level of capability, it was sent to site for final integration.

Activities at site were similar to those at the TSCS. However, at site the entire complement of peripheral hardware was available for integration with the system. The final phase of system development involved system testing, in which the PAR, MDC, and BMDC sites were "netted" to achieve coordinated operation of the entire system. After this, formal acceptance tests were run at site.

During all phases of system development, evaluation played a strong role. A separate department was responsible for evaluating system requirements, implementation algorithms, and prototype and system test results. Feedback resulted in frequent changes and refinements in many areas.

In the following paragraphs, the software development activities outlined above are discussed more fully.

Meck Test Facility

The Meck Test Facility consisted of a prototype MSR, SPRINT and SPARTAN missile subsystems, and a DPS. During the R&D phase, ABM system requirements were constantly changing; thus it was decided to implement a series of test processes on Meck, each with increasing complexity and more stressing system objectives.

The first process, M-0, was designed to test the radar and missile hardware subsystems. The next process, M-1, tested both SPRINT and SPARTAN intercept capability in a light-threat environment. The final process, M-2, verified SAFEGUARD tactical algorithms for missile guidance, as well as radar surveillance and tracking functions. This inclued remote launches of SPRINT missiles from Illeginni Island. The testing took place from early 1969 through 1974.

A total of 882,000 program instructions were written for the Meck Test Facility, but only 255,000 instructions were included in the three test processes. The remainder were needed for hardware installation and maintenance programs (137,000 instructions) and support software, such as assemblers, process construction, simulation packages, etc. (490,000 instructions).

In addition to the planned testing and verification, the Meck effort made other contributions to SAFEGUARD. Many of the techniques, procedures, and practices developed were later to be used in the SAFEGUARD software development. These were in many diverse areas, such as operating system and process design, software configuration control, and real-time debugging aids, to name a few.

TSCS and System Exerciser

To develop and test SAFEGUARD software and to support system deployment, the Tactical Software Control Site was established at Madison, New Jersey. This test facility contains the PAR and MDC data processing equipment and portions of the analog hardware that interface with the missiles and radars at site. The TSCS also includes office space for major elements of the software development organization, consisting of designers, programmers, and test teams, as well as many other support personnel.

The basic requirement of the TSCS was to reproduce accurately the software environment found at site. In short, its objectives were to:

- Verify performance of tactical software in its operational environment
- Test software in conjunction with the design organization
- Reduce development time through comprehensive testing prior to shipment to site
- Support deployment activities by providing a centralized facility to aid in solving problems encountered at site.

The TSCS was required to have a representative complement of DPS hardware for both the PAR and the MDC. This meant two distinct DPS configurations, each sized in accordance with tactical requirements (see Figure 4-6). Furthermore, each configuration had to replicate the interfaces between computer and peripherals, and the operation of peripherals to the extent necessary for tactical-like responses. In addition, the capability to net the PAR and MDC was required for system testing.

The tactical equipment at TSCS was used almost exclusively to test and integrate the SAFEGUARD operating system, application software, and installation and maintenance software. The support functions needed to develop, control, and analyze tactical software were relegated to general purpose computers.[37] An IBM System 370 was installed at TSCS and off-premises access to a HIS 635 was provided.

A system exerciser was developed to test tactical software in the SAFEGUARD equipment at TSCS. A separate exerciser was provided for

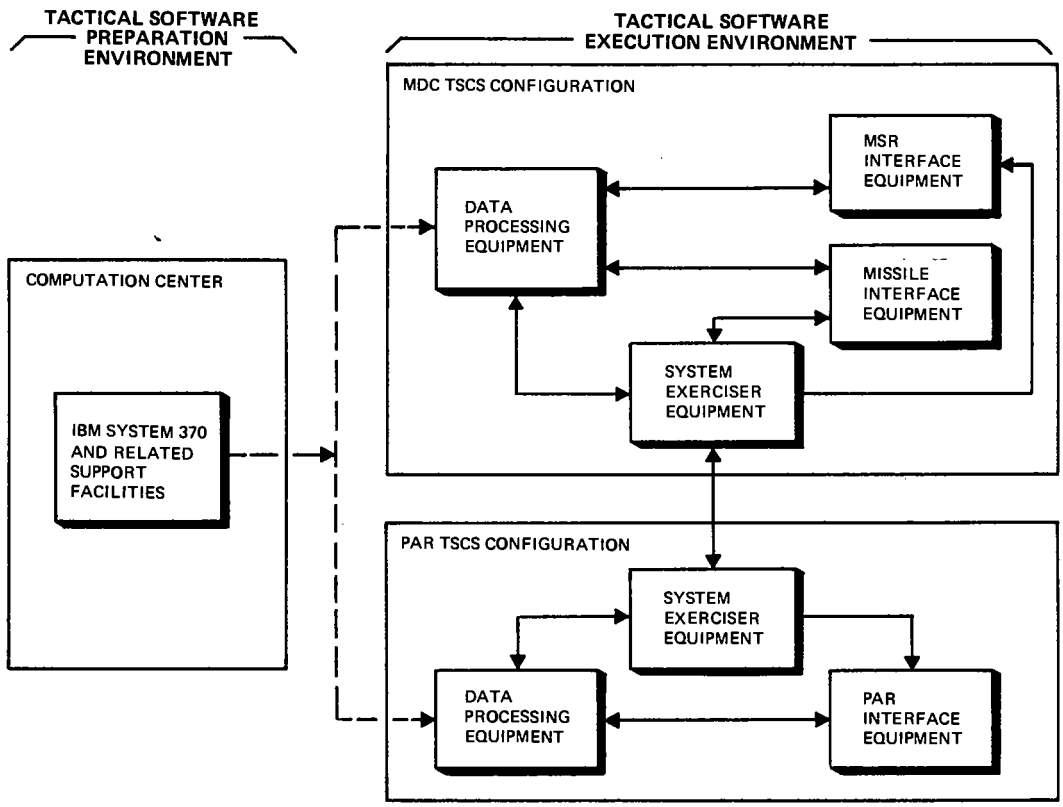


Figure 4-6. Tactical Software Control Site Functions

each configuration (PAR and MDC) for individual testing and for joint testing of the two systems in netted operation.[38,39] These exercisers are used now in the deployed system for site and system readiness verification.

In designing the system exerciser, care was taken to devise a method that would realistically produce an environment similar to the actual tactical conditions found at site. Two special hardware aspects provided this capability. First and most important, the PAR and MDC configurations were each configured into two separate partitions as shown in Figure 4-7. The larger, or green partition, contained the tactical application software as it would be used in an actual engagement; the smaller, or amber partition, contained the system exerciser software. Second, special exercise support hardware was developed: an Exercise Control Unit (ECU) and a Radar Return Generator (RRG).

During a system exercise, the amber partition generates radar returns representing a preselected threat. These returns are sent via the ECU to the RRG for conversion to analog form and injection into the radar receiver of the green partition. The tactical (or green) partition responds as in a real engagement, issuing radar orders, missile commands, and intersite communications. These are sent via the ECU to the amber partition where they control simulated missile responses. The ECU also appropriately routes these responses and intersite communications from the amber partition to the missile ground equipment and tactical communications links in the green partition.

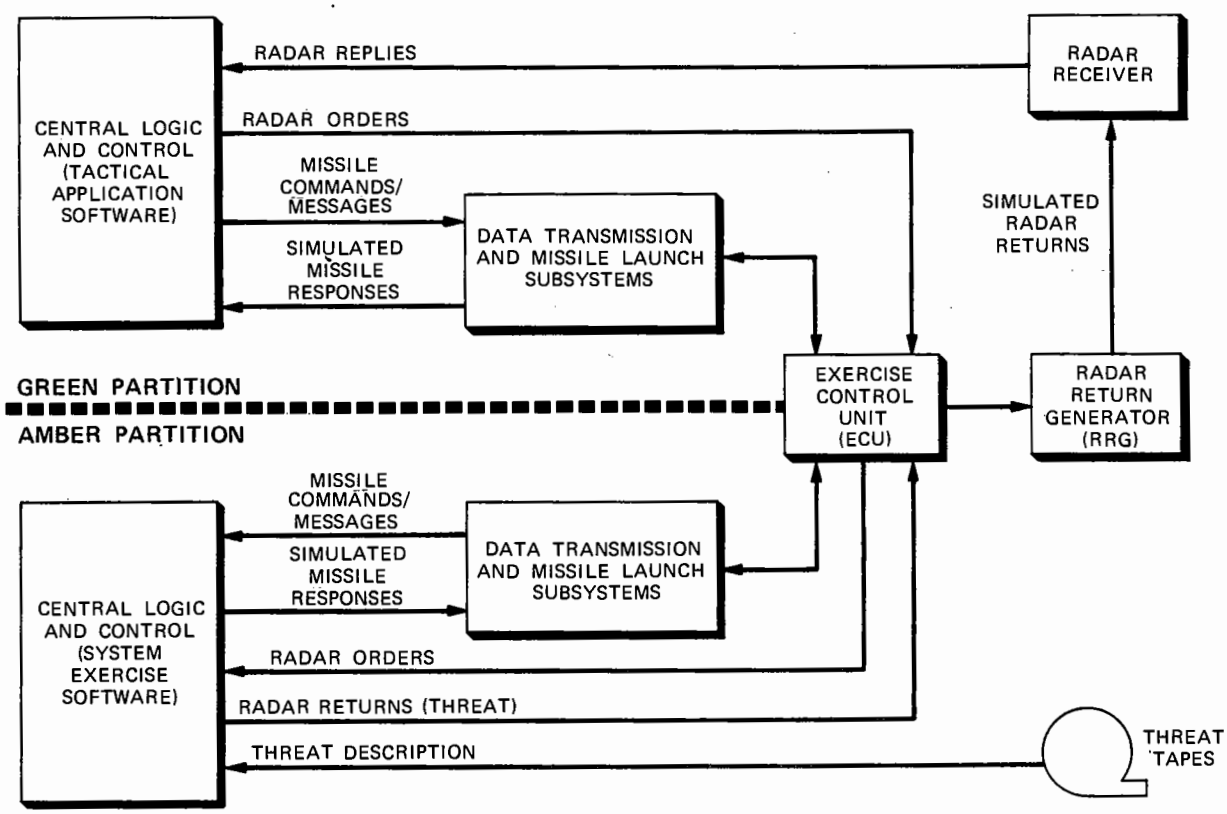


Figure 4-7. Functional Configuration for System Exercise

When the system exerciser is used in the netted mode, the tactical communication between the PAR and MDC is not interrupted for any simulated response, but is allowed to flow normally on one circuit of the split link. The other circuit is used for communication between the PAR and MDC exercisers.

The system exerciser has sufficient traffic capacity to test tactical hardware and software at the required design level. Yet, the amber hardware requirements were kept to a minimum by performing as much simulation as possible prior to conducting a real-time exercise. A program called the SAFEGUARD Threat Action Generator (STAG) was developed to generate target, defensive missile, and intersite message information (for local exercises) in a scenario defined by an input deck. STAG is run in non-real-time on the IBM System 370 and records the simulated threat on tape. These tapes then are used during an exercise by the exerciser software in the amber partition to generate the simulated responses.*

Requirements

The Data Processing System Performance Requirements (DPSPRs) are a set of documents that define the requirements of SAFEGUARD tactical software for the PAR, MDC, BMDC, and system exerciser.[38-40] Requirements were generated by the system engineering organization in accordance with overall system objectives.

*For additional information see SAFEGUARD Data Processing System: Process-System Testing and the System Exerciser, B. P. Donohue III and J. F. McDonald, Bell System Technical Journal - Special Supplement (1975).

The primary objective of the DPSPRs was to specify required functional performance in sufficient detail to permit development of software by the designers, yet not limit design freedom. A second objective was to state functionally how the system was to operate in its different defense modes.

Changes in requirements were made through the course of development as a result of feedback from the software development organization, the SAFEGUARD System Tests conducted at Kwajalein and Grand Forks, system evaluation studies, and from detailed review by the Army SAFEGUARD System Command (SAFSCOM). Later on, formal change-control procedures were instituted on these documents to ensure an up-to-date system definition of SAFEGUARD performance and to control the final software products.

Final system testing and acceptance requirements generated by the system engineering organization were based on the DPSPRs.

Software Design

The collection of application software used to drive the DPS is called the application process and is built from basic computing units, called tasks, which are single routines with or without subroutines. The operating system, considered to be part of the process, schedules tasks from a predetermined, priority-ordered task list for execution on the next available processor.[41,42] Once in execution, a task is not interrupted before completion except for error conditions.[43]

Process design is the definition of overall software structure including task assignment and global data base design. The objective of process design is to meet system requirements with a minimum-cost DPS configuration. This activity was complemented by program design which involved developing the algorithms, internal data base, and control structure necessary to implement the function defined for a task. The software design was documented in process design specifications and process workbooks. Between this detailed level of documentation and the DPSPRs, some application process organizations also produced intermediate-level software functional design requirements.

In many areas, various levels of simulation were used to validate the design. In some cases, a few selected equations were implemented on a time-sharing system for a quick exploration of correctness and adequacy. In others, a subset of the real-time computer program, complete with its interface structures, was simulated. In the PAR development, the intermediate-level functional design requirements, together with radar, threat, and environmental considerations, were modeled and simulated to study expected system performance.

The size of individual programs and the time required for their execution were two major parameters that were carefully controlled. Initial sizing and timing estimates were made early in development based on past experience with similar programs. Throughout the course of further development, sizing and timing estimates were tracked on a monthly basis.

It was found essential to initiate design of the data recording and reduction system early in the development cycle. An attempt was made to define the data to be recorded for each computing function and to design the data base with the ultimate use of the recorded data kept in mind.

Coding and Unit Testing

Most SAFEGUARD software was written in CENTRAN, an extensible intermediate-level language resembling a subset of PL/1.[44] CENTRAN is a macro-based language built on SNX, the assembly language for the CLC. As such, CENTRAN provides many of the advantages of a high-level language but can be interspersed with assembly language statements and system macros as necessary. CENTRAN generates efficient code and was adopted as the project standard.

A project-wide attempt was made to include defensive programming techniques during the

coding period. Particular attention was given to computations that potentially could cause interrupts which, in turn, would result in task termination. Detection and error recovery codes were then added. Another project-wide technique involved enforcing adequate source-code documentation by requiring well-commented program listings. This proved particularly effective later on in isolating programming errors that were detected during the integration phase.

All programming organizations responsible for a functional area of the application software held design reviews for the total project. These reviews not only helped to educate test and integration personnel, but sometimes uncovered subtle design flaws. Some programming groups used structured programming. These techniques led to an orderly top-down approach in the detailed programming design and coding. In such instances, a substantial saving, both in variable store and in computing time, was often achieved.

Once the coding of individual software units was complete, two stages of testing were undertaken. Units assigned to individual programmers - generally entities of code ranging from 100 to approximately 1000 machine instructions - were individually tested. The purpose of this unit testing was to test the logic paths within a unit. To support this activity, a number of special drivers were developed to allow individual units to be interfaced with the data sets needed in their operation. These drivers sequentially initialized the data sets to produce the environment necessary to execute one logic path after another. Element testing was the second stage of testing. Program units comprising a major functional element of the process were tested together using special software "stubs" in place of the other major functions. These tests were primarily functional in nature. A series of tests was defined that would exercise all major functional requirements given in the system requirements and design specifications.

All software preparation and most of the unit and element testing was performed using commercial computers. This was primarily because time on the TSCS test facility was too limited to support such extensive activity. However, a decided advantage accrued from this approach since a number of testing and debugging tools were already available on the commercial machines. Others were developed specifically for SAFEGUARD in high-level languages such as FORTRAN and PL/1. One such tool was the simulator called STACS (SAFEGUARD Tactical Computer Simulator) which provided the primary unit and element testing vehicle.[45] STACS fully simulates, on the IBM System 370, a single CLC processor and most of the conventional CLC peripheral units. It also simulates many of the operating system capabilities designed for the CLC. Special test drivers were designed to interface with STACS, providing universal testbeds. In addition, a variety of debugging aids were included in STACS to allow exhaustive testing of program units. Such debugging aids range from simple snaps and traces to simulation of error response and the ability to modify or patch a unit.

Configuration Management was an important aspect in development of the software product.[46-49] Methods were developed to identify, control, track, and audit the numerous versions of the programming units to be released for process integration. These methods included rigid control of the patches required to correct the coding problems discovered during integration.[48,49] Central to this activity was a disc-based library system which was an IBM proprietary product. This system offered many of the features necessary to sustain a large development effort. For example, it included an editor for changing source lines, a means of temporarily changing source for testing, and a mechanism to facilitate delivery of debugging code. Perhaps its most significant contribution was the procedural discipline it uniformly forced on all SAFEGUARD programmers.

Other procedures were developed to control all patches made to delivered software. Trouble Reports (TRs) were required to document any problems occurring during testing. Corresponding

Correction Reports (CRs) described the approach used in correcting the trouble via a patch or source change. A large number of support software packages were developed to assist in these configuration management procedures, and included programs ranging from the building of patch files for a process to the identification and reporting of status on TRs and CRs.[48,49]

Process and Functional Integration

Following unit and element testing, collections of functions were combined and tested on the PAR and MDC DPS configurations at TSCS. For example, the basic control programs for the MDC were first merged with the operating system, and the ability to load, initialize, and cycle was established. Then, software for the radar loop was added, i.e., radar management, search, and track programs.

Ability to search and track was first established at low traffic levels, while the radar hardware was simulated by software drivers. After basic operation was established for the software, the radar hardware was introduced into the testing loop. In parallel with this activity, application programs supporting intersite communications and command and control were tested in a separate configuration at TSCS. Similarly, both battle planning and missile guidance software were tested in separate software environments. Ultimately, these programs were merged into a single MDC application process and the complexity of the test cases was systematically increased.

This integration was done separately for the PAR and MDC with the effort planned, as seen above, so that a number of parallel activities could be carried out by independent integration teams. Such an incremental approach allowed for integration of increasingly more complex capabilities into the software, building from a simple nucleus of code and culminating in a full application process for each site.

Early in this integration, drivers were developed to assist in the first steps. These early efforts, referred to as process integration, were devoted mainly to software considerations such as basic cycling, sanity, and interface testing between major software blocks. Later, when the system exerciser was available, it was used exclusively to drive and stress the application processes under various conditions and loads. This testing also covered the radar hardware at TSCS and was planned to include specific functions given in the requirements. This functional integration testing culminated in demonstrating satisfactory performance in both the local and netted modes of the large scenarios planned for eventual system testing at site. Literally thousands of individual test cases were documented, including the success criteria, and then run in support of the overall process and functional integration phases.

A number of support software facilities were crucial in building and testing these large application processes. (See Figure 4-8.) CENTRAN and SNX, like most compilers and assemblers, produced relocatable object code. A program was developed to allocate CLC memory, build the control tables needed by the operating system, perform binding functions, structure the overlays, and perform a host of related services. This program, called the Execution Preparation Facility (XPF), operated on the IBM System 370.[50] Similarly, most testing of software units and elements produced by XPF was performed by STACS on the IBM System 370.

Another software package, called DEBUG, provided software debugging aids for the CLC and proved invaluable early in process integration.[51,52] DEBUG's capabilities included many of the same aids provided on the support computers by such facilities as STACS. Although DEBUG contained some multiprocessor capabilities, its design was oriented more toward a single processor, non-real-time environment. Further extension of debugging aids on the CLC resulted in the development of DARTS (Debugging Aids for Real-Time Systems). This software provided full multiprocessor, real-time capabilities with minimum perturbation on the

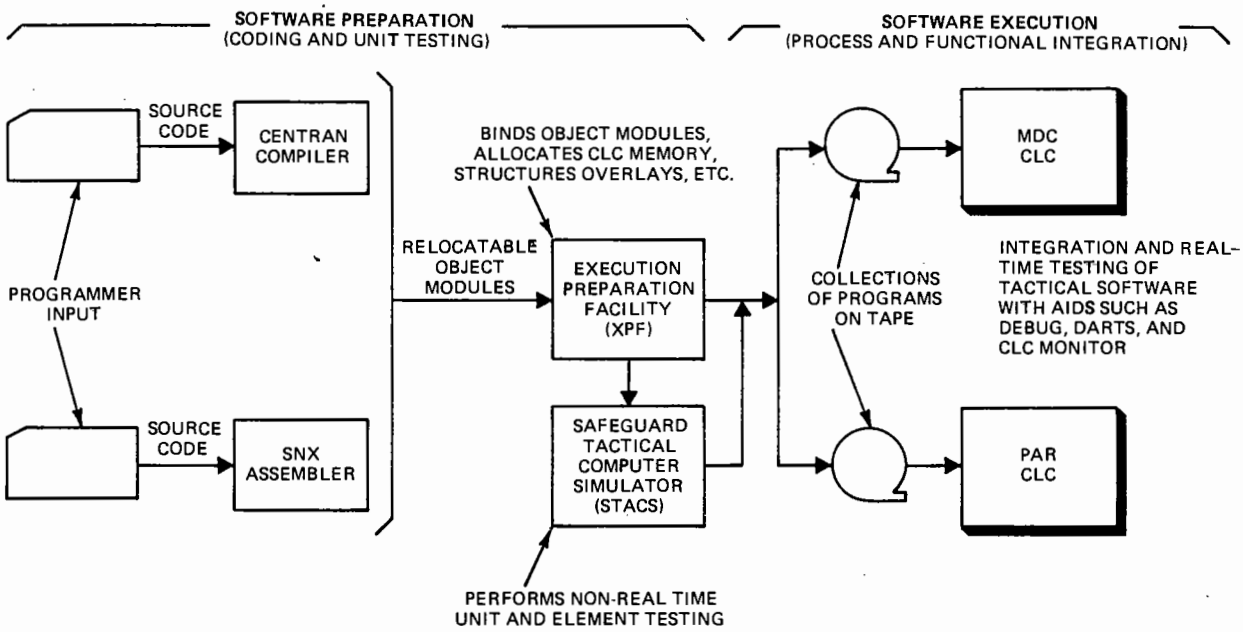


Figure 4-8. Software Preparation and Testing

timing and operation of the application program under test. An array of features was made available, including the ability to simulate manual inputs in real time.

The CLC Monitor was developed to further isolate the effects of running debugging tools on the application process being tested.[53] This monitor is an external hardware monitor which includes its own memory, extensive logic to count and filter data, and two tape units. It was used primarily to validate that process performance was consistent with design. Troubles, such as heavily-loaded time frames and long-running tasks, were analyzed and design changes were made when necessary to provide a more balanced system.

Detailed analysis of functional integration tests was facilitated by designing the real-time recording functions as an integral part of the application and exercise software. Recorded data was reduced and analyzed primarily off-line on the IBM System 370 using the SAFEGUARD Data Reduction System, although summary information was available on-line.[54,55]

Site Integration and System Testing

The TSCS and site integration phases significantly overlapped in time.[56] As tests were completed at TSCS, software updates in the form of patches and data packages relating to performance of the tests were sent to site. These packages included test specifications, exerciser tapes, test results, and reports which itemized any known problems not yet corrected. Site integration then consisted of testing the application software against the full complement of SAFEGUARD hardware using a subset of TSCS tests and special site-oriented tests such as radar-calibration and satellite-tracking tests.

Finally, system testing was carried out at site. This involved a comprehensive series of acceptance tests which demonstrated system capability consistent with requirements and represented the final level of product testing prior to delivery.[57-61] During system testing, it was not possible to exhaustively test all tactical threat environments. Rather, these acceptance tests, or System Technical Verification Tests (STVTs) as they were called, were defined at the design-traffic level

for each of the various system operating modes. A series of tests was designed for each mode, at first simulating all communications with other sites, then netting pairs of sites, and finally netting the entire system.

The stress level was reduced in early testing by selecting subsets of the STVT environments and by running buildup tests at these lower stress levels before increasing the traffic load. Once this was accomplished, the "test chain" was continued by physically internetting the sites in stages until the total system was operating at design-traffic levels. This approach, in which all tests in the chain support the STVTs, greatly simplified the problems of integrating a dynamic system.

SAFEGUARD OPERATION AND MAINTENANCE

Operational Overview

The size and duration of the SAFEGUARD development effort were large indeed. Table 4-2 shows the number of machine instructions for the major software components. Real-time software, consisting of MDC and PAR application programs with their exercisers, the BMDC application program, and the CLC operating system, contained a total of 735,000 instructions.[38-42] Support software, such as compilers and simulators, which executed on commercial computers, amounted to 580,000 statements, some in assembly language and some in PL/1 and FORTRAN. Installation and maintenance software for the data processing system and the radars totalled 830,000 instructions. At least several hundred thousand additional instructions were developed for other purposes such as test drivers and specialized simulations. Together this represents nearly 2.5 million instructions written, tested, and debugged over the six years of SAFEGUARD development.

The massive amount of radar and digital equipment installed at site and at TSCS is visibly even more impressive. The radars on the plains of North Dakota are monuments to modern

Table 4-2
Size of Major Software Components

Real-Time Software Instructions	
MDC Application	300,000
MDC Exerciser	50,000
PAR Application	200,000
PAR Exerciser	25,000
BMDC Application	60,000
CLC Operating System	100,000
Total	735,000
Support Software Source Statements	
CENTRAN, SNX, XPF, STACS, etc.	210,000
System Simulation	50,000
Exerciser Support	30,000
Data Reduction	150,000
Configuration Management Programs	70,000
Fault Logic Simulation	70,000
Total	580,000
Installation and Maintenance Software Instructions	
MDC Radar Installation tests	50,000
PAR Radar Installation Tests	110,000
Real-Time PAR Radar Tests	60,000
M&D Operating System	120,000
Maintenance & Diagnostic Tests	300,000
ITP, DUX, RTE, NPD, etc.	190,000
Total	830,000

technology housing some of the most complex electronics in the world.[1,2] Within these buildings and at the BMDC site in Colorado and the TSCS in New Jersey, hundreds of digital equipment racks were assembled to provide the computing power needed to control and maintain the deployed system and its test facility.

The remainder of this section briefly describes the operational aspects of the system. The Command and Control Display Subsystem provides the facility for monitoring and controlling tactical operations and maintenance.[27]

Tactical operations are basically concerned with integrating the SAFEGUARD weapon system

into the total national defense structure. If an actual threat is detected, the primary tactical function is to provide for the timely release of the system. Maintenance operations are concerned with keeping each element of the SAFEGUARD System at the highest availability level possible.[62-64] This requires monitoring and coordinating maintenance activities for each subsystem consistent with overall tactical demands. Finally, the TSCS test facility takes on a new role during the operational phase of the system — supporting site needs by helping to solve and correct problems as they arise.[65]

Tactical Command and Control

The command and control functions in SAFEGUARD are divided into maintenance and tactical tasks. The maintenance aspects are treated separately in the next section. The tactical functions are designed to be automatic when both feasible and cost effective, with only certain key functions assigned to man. These manual actions complement the automatic system and, except for system release, are not a sequential link in its operation. Hence, man is a controller rather than an operator in the SAFEGUARD System.[27]

The Ballistic Missile Defense Center is the highest echelon of command and control in the SAFEGUARD System. It is collocated with the Commander-in-Chief of the Continental Air Defense Command (CINCONAD) Combat Operations Center (COC) in the Cheyenne Mountain Complex at Colorado Springs, Colorado. CINCONAD exercises operational command of the SAFEGUARD System through the BMDC. The BMDC, in turn, controls and directs the activities of the Perimeter Acquisition Radar and the Missile Direction Center.[40,66]

The COC has special nuclear-employment authority equipment connected directly to the BMDC.[67] In addition, the COC has closed-circuit TV monitors on BMDC displays. These interfaces provide the BMDC with authorization for use of SAFEGUARD nuclear weapons, attack warning and other intelligence data generated external to SAFEGUARD, alert and readiness level coordination with other defense systems, coordination with use of offensive forces, and requests for special intercepts or satellite observations. The BMDC sends SAFEGUARD-generated early warning, attack assessment data, or results of satellite observations to the COC.

Overall manual command and control functions in SAFEGUARD generally relate to implementation of actions associated with this COC-BMDC interface. All such command and control actions at the BMDC, MDC, or PAR require positive feedback to man indicating the application software has recognized the manual input. If a manual action is meaningless or the sequence of actions incorrect, the system indicates this to man. In addition to validity checks on manual inputs, each site performs a validity check on any message it receives from other sites.

A tactical command and control action is classified as either a directive or a control action. A directive is manually initiated by higher authority and requires a corresponding manual action at the PAR or MDC. A control is manually initiated by higher authority and will be automatically effected at the netted PAR or MDC without a local manual action. The Command and Control Display Subsystem includes provision for display of directives (called forced messages) that a tactical officer may implement. The source of each directive accompanies the notification.

System Maintenance

Maintenance is functionally divided into several Maintenance Activity Centers (MACs). The division follows the hardware subsystem division of the site; for example, a DPS MAC, Radar MAC, Missile MAC, etc. The personnel in each MAC are supervised by a Maintenance Director at a maintenance console. From this console, he can request software-controlled subsystem tests that provide current status and fault information. The console also allows him to report his status

to the System Maintenance Director. The System Maintenance Director, together with the Equipment Readiness Officer, man a system monitor console in the Equipment Readiness Center.[68,69] In this way, information on all equipment problems is conveyed to the tactical command, with corrective maintenance controlled and scheduled consistent with the tactical needs of the site.

A number of on-line procedures are available to maintenance personnel. The most useful and general method is to conduct System Readiness Verification (SRV) exercises. The SRV uses the system exerciser discussed previously. Scenarios are available to verify specific functional and hardware aspects of the system. The SRV provides a local or netted system test which stresses not only the CLC hardware and its interfaces but also exercises the application software under simulated inputs representative of the design threat. Other on-line tests periodically used for maintenance are the radar Class A and B tests, the missile subsystem Class B tests, Normal Path Diagnostics (NPDs), and Real-Time Exercisers (RTEs). These tools are part of the application software and are used during normal tactical operation.

The Class A tests are cycled automatically by the application software and measure overall performance to ensure that the system is meeting acceptable operating standards. The Class B tests are run on request and are designed for detailed alignment and performance investigations. Whenever the CLC undergoes a reload operation, the NPDs are run to test all processor units, program stores, and variable stores in the green partition, as well as their interfaces, including those to the input/output controllers. Once the application program is cycling, the Data Processing Officer can request the RTEs be run automatically to test each program and variable store every 5 minutes.[31]

A number of off-line maintenance tests also are used. Generally, these tests are designed to check equipment off-line in the amber partition, although a few tests require the full system configuration. The M&D Subsystem provides a fast procedure to isolate hard faults to a chassis or printed circuit board that can be immediately replaced. These tests usually employ fault-location dictionaries that pinpoint the trouble down to a replaceable level.[32-35]

Digital Unit Exercisers (DUXs) also are used to check individual racks.[70] These are special-purpose equipment exercise and checkout programs designed for each unique type of DPS rack. Each DUX program provides the capability to control the functional operation of a rack on a macroscopic level and to dump the contents of individual registers or groups of related registers within the rack. Strictly speaking, these exercises are not tests but have proved valuable in isolating and solving maintenance problems. Some Installation Test Programs (ITPs) developed for site integration have also proved useful in resolving intermittent timing problems and other non-hard faults.[71] The ITPs are being retained at site.

All of these tests are used for periodic Preventive Maintenance (PM) procedures. Scheduled PM activities are carried out according to procedures contained in the Contractor Maintenance Data System (CMDS). As PM checks become due, maintenance personnel follow the steps listed in the CMDS, reporting any faults that occur to a maintenance director. Corrective repair activity is coordinated with the Equipment Readiness Officer to return the system to a fault-free state. At less frequent intervals, periodic validation of system maintenance is performed using closed-loop tracks taken on test objects, such as satellite and calibration spheres external to the system. These techniques help to achieve a cost-effective level of maintenance and provide assurance that the system is properly calibrated and aligned.

All repair operations are conducted off-line. When a faulty unit is identified, it is removed from the system and replaced with a working spare. The faulty unit is repaired in the Technical Maintenance Repair Center (TMRC). Trained technicians at the TMRC use special test

sets and documentation to repair the unit and return it to a usable spare stock.

TSCS Operational Support

During the operational phase of SAFEGUARD, the primary role of the TSCS is to assist the sites in resolving any problems that arise. The Configuration Management procedures used during the development phase have been expanded to ensure that any changes in the operational weapon system are handled in an orderly and methodical manner.[46,47]

Configuration Management starts with identification of a baselined product. The baseline consists of the software and its high-level requirements as used at site. These software products include the application software and those software tools needed to control, install, test, and validate the application software at site. The documentation includes Performance Design Specifications (PDSs), Data Processing System Performance Requirements (DPSPRs),[8,38-40] User-Oriented Requirements (UORs), and System Design Requirements for Displays and Controls (SDRDC).[27] This baseline was placed under Configuration Management control and was the version used in final testing.

Changes to this software baseline and SAFEGUARD hardware are rigorously controlled by a series of Contractor/Army Review Boards. Any problem or proposed improvement, either hardware or software, is first documented by a Master Problem Report (MPR), which is an outgrowth of the TR/CR forms used during development. These MPRs are referred to the local design organization at the TSCS. Proposed solutions are reviewed by a Change Review Board for technical accuracy and completeness. Technical approval for change is obtained from a Direction Committee comprised of Contractor and Army management. Approved technical changes that affect the baseline are submitted as Engineering Change Proposals (ECPs) to a local Configuration Control Board. If requirements are involved, the ECP also is sent to a System Board for dollar and resource approval. No changes are permitted at site without the necessary approvals.

Before an approved software change can be shipped to site, it must be tested and verified at the TSCS. This testing, called Technical Verification, consists of a selected set of system-level tests. Once the contractor has demonstrated these same tests at site, the Army conducts User Operational Verification tests using tactical procedures and operators. At this point, the old software baseline is replaced for operational use by the modified product.

The status of all changes to the baseline is tracked from inception of the MPR to final incorporation of the ECP in the baseline. Hardware changes are tracked by the On-Site Configuration Activity Reporting System which ensures that the current site configuration is always available. Similarly, software status and various reports are generated by the Status Accounting System.

LESSONS LEARNED

General

It is impossible to document all of the lessons learned on a project the magnitude of SAFEGUARD. Each participant will take with him a wealth of experience gained from years of hard, dedicated work. And each will have his own view as to what is most important. Part III of this report, Management and Overall Approach, deals with a number of fundamental issues, often involving management decision, that relate directly to the material covered in this chapter. In the remaining paragraphs, focus is placed on some of the more technical issues encountered, some of which may seem obvious but can easily be overlooked in the rush to see a large job completed.

Support Computers

Early in SAFEGUARD an effort was initiated to build a Prototype Development Facility (PDF) that would allow program development in a

time-shared environment on the CLC itself, the SAFEGUARD computer. Such an effort seemed admirable since it would have avoided the cost of providing additional computing hardware for unit and element testing. However, it was a mistake. This elegant time-sharing tool competed with demands for CLC time needed to debug the machine itself, to test the SAFEGUARD operating system, and to support early application development, such as installation software. The CLC was being used for testing generic programs and it could not be tied up developing software tools. PDF was abandoned, and very quickly all development tools were concentrated on commercial machines.[37]

Support Software

PDF also erred in trying to be too ambitious. Other efforts followed this same path. A time-sharing system was developed for the GE 635, one of the general-purpose computers available at Bell Laboratories. This system, the GETSS, became operational and supported 20 to 25 users, and in many respects was ahead of its time in providing editing and execution facilities. But it too was misguided. GETSS could not possibly support the hundreds of programmers eventually required, and more importantly, it was developed for the wrong support computer. The project originally was supported by an assembler on the IBM 7094. By decision outside the project, the 7094 was scheduled to be replaced by a GE 635. This led to choosing the GE 635 machine to support the time-sharing development. However, ultimately, SAFEGUARD management adopted the IBM System 370 for project support, leaving GETSS out of the mainstream.

NICOL, the NIKE-X Compiler Language, was an attempt to produce a high-level language compiler, similar to PL/1, for the CLC. It was a very complicated system and went through a number of versions, including one that was to operate on the CLC. The evolution of the project and changing requirements made it a much too complex endeavor. It, like PDF, was abandoned.

There is a message in this experience. Support software goals must be realistic, particularly in the sense that they be attainable at the time they are required. The purpose of support software is, after all, to support the objective of building systems. Building support software using state-of-the-art techniques is laudable, but only if it contributes to the main objective.

Out of these early attempts evolved a system of viable support software for the project. These products were available when needed, flexible enough to react as requirements changed, and reliable. Various methods were used to achieve these objectives. High-level languages were built on a macro assembler to retain flexibility. In fact, flexibility was considered so important that efficiency was sacrificed. Software was borrowed shamelessly and adapted, but with the knowledge that it would have to be maintained. High-risk, state-of-the-art approaches were avoided. Incremental implementations were planned so that programs could be used as quickly as possible. Strict testing and release procedures were adopted to ensure quality. Programs were "frozen" after release and became subject to change-control procedures. Stringent control was placed over the interfaces among the facilities to ensure integrity. All of these techniques helped to build a successful support software system.

System Exerciser

The system exerciser developed for SAFEGUARD was a major innovation.[38,39] This concept can be widely seen in current development on large software systems. The need to provide test signals and data to "drive" any system is clear. As the complexity of the system and its operating environment increases, so does the complexity of the driver. Therefore, it was judged vital to devote considerable resources to the development of a driver on SAFEGUARD, and the effort was started early.

The costs may seem large at the outset of such a development but in the long run they really

are not. They more than repay the effort spent. As much of the hardware should be incorporated in the exercise configuration as is cost effective. The impact of the exerciser on the application system should be kept to a minimum. And then, the exerciser should be tested to create a stable base for system testing.

Patching, Debugging Tools, and Testing

The ability to patch programs in a controlled manner was a major contribution to the SAFEGUARD success. A patch to fix a problem could be delivered within days to the integration team. It eliminated the need for time-consuming source code redeliveries and system reverification except at widely spaced intervals. In addition, patching provided a flexible, easy-to-use tool through which new debugging aids and test tools could be created and readily added to the test configuration.[12]

The importance of unit and module testing cannot be overemphasized. A high percentage of the bugs found in process and functional integration could have been eliminated in the unit testing phase. Therefore, it is highly cost effective to provide extensive unit and module test facilities.

Modularity, Redundancy, and Multiprocessing

In the CLC, the use of well-defined interfaces and modular hardware-building-blocks capable of communicating within the framework of a distributed switching system provide the basis for a dynamic computing complex. This structure incorporating multiprocessing is capable of adding new functional units which offer unique economic or performance advantages. The CLC can be configured in a wide range, from a single-processor to a ten-processor system, and into separate computing facilities to provide an independent exerciser.

This architecture can provide high system availability without the need for costly and complete duplication. An additional computing element (processor, store, IOC, etc.) can be added as a single replacement in the event of failure in that type element. This "n+1" approach has reduced the amount of equipment needed for redundancy and for system exercise to a fraction of that required for a complete standby system.

Multiprocessing did not present the expected conflicts and lock-out problems anticipated. Very few such problems were encountered, possibly because of the single-application nature of SAFEGUARD, as opposed to commercial applications involving an unknown job-mix. But probably more important, care was taken to address process design. The decision to use the task structure, in which each task is a small unit of work, was a good one. These tasks were scheduled by a table-driven operating system rather than being dynamically scheduled. Avoiding the use of interrupts for switching between tasks was very deliberate and was the key to maintaining sanity in a large application with many tasks competing for resources.

It was good design practice to use short-running, low-priority, asynchronous tasks wherever possible. This helped alleviate schedule conflicts that would arise if there were a large number of high-priority synchronous tasks. It guaranteed that high-frequency, high-priority tasks would execute as desired, and aided in distributing the workload over a longer time-frame.

Error Control

The following items are a few key points and recommendations based on the SAFEGUARD experience with error control. The recommendations are generally applicable to any large-scale, real-time control system.

Component redundancy and multiprocessor design are inherently fault-tolerant. Similarly, software architecture is fault-tolerant if it has multiple instances of tasks to do specific functions (e.g., n track functions to update data on any of n objects), if the processing work is divided into many small independent tasks, if the software control is decentralized, if there is emphasis to confine errors locally, and if there are system error responses to reinitialize the system to replace faulty hardware components.

System error control guidelines and structure should be defined early.[43] They are required if the total system is to have a consistent approach to error control. Error logging throughout the system should be the first guideline. The next is to design a structure so that error responses can be easily modified. The logging is an invaluable debugging tool. And as operational experience on error occurrence rate is gained, the response can be appropriately modified.

Finally, manual error control or manual override should be provided even for automatic and self-repairing systems. It is invaluable in "bringing up" a faulty system to isolate a complex problem when the automatic software features have failed to circumvent the trouble.

Maintenance Approach

Experience to date has demonstrated the fundamental power and flexibility inherent in the two primary Maintenance and Diagnostic Subsystem (M&DSS) features. These are the extensive data bus interface with the entire DPS and the general-purpose computing capability of the Maintenance Data Processor.[32-35]

In retrospect, the total range of M&DSS capabilities has yet to be explored fully. For example, because of project schedule constraints, the logic-block partitions originally defined have not been changed. But different partitions, chosen with timing faults in mind, might allow these faults to be handled via the fault dictionary method. (In this case, it also would be necessary to increase the speed of the entire M&DSS which now runs two orders of magnitude slower than many of the internal logic events in the DPS.) Other diagnostic tools, such as the Installation Test Programs, could be restructured with fault isolation more in mind, thus yielding isolation to the chassis level.[71]

Development of Computer Languages

CENTRAN was developed to produce code for the CLC. It is an extensible language whose extensions approximate PL/1 in control structure and FORTRAN in data structure.[44] A number of lessons were learned during its development and use.

The designers, implementers, educators, and users should not be disjcinted groups. The designer should be involved as an implementer to keep in touch with reality. He should also be involved as an educator (if a feature is difficult to explain, maybe there is something wrong with it) and as a user (uniformity in extension is best achieved by knowing how the language is being used.) The implementer should act as both educator and program counselor to get feedback on bugs being "programmed around" and to establish priorities for fixing them.

Several things about the implementer-user relationship should have been learned earlier in CENTRAN development. First, the release cycle should be rigidly controlled as soon as possible, no matter how short the cycle. It does not pay to be a "nice guy" and give "fixes" to bugs informally. Next, old versions of the compiler should not be kept around and certainly not maintained. The maintainers are blamed for bugs that no longer exist, and much time is spent rediscovering causes for problems long since solved.

Notices of new releases must go to everyone, not just supervision. Users often underestimate the impact on schedules of changes due to improvements to the compiler, even though the improvements were requested.

Insofar as the designer-educator-user relationship is concerned, the designers should have been more involved in determining the structure and content of the CENTRAN courses. Frequent symposia (e.g., Advanced Topics in CENTRAN Programming) should have been held, with compulsory attendance.

CENTRAN should have been an expression language. This not only would have aided the production of more efficient, clearer, and more concise code, but would have provided a greater degree of uniformity to the language.

More thought should have been given to data types required for data reduction. Maintenance

of CENTRAN programs (especially patching) should have been given greater priority in the design of CENTRAN.

Several of the CENTRAN design approaches were advantageous. CENTRAN was implemented by a small group of programmers. This approach avoided communication and other problems typically encountered with a large group of programmers.

The register allocation mechanism, subroutine interface primitives, and extensibility mechanism designs worked well, as exhibited by CENTRAN's short development time. The ability to have partial word variables has been found useful. The ability to program at several levels in one language made the language suitable for systems and applications programming. Finally, and most important, the design of the extended language was sufficient for the implementation of SAFEGUARD software, and SAFEGUARD programs have been successfully implemented in CENTRAN. Several studies of the suitability of CENTRAN for SAFEGUARD have been made outside of Bell Laboratories, and all have concluded affirmatively.

System Programming in PL/1

The Execution Preparation Facility (XPF) performs the linkage editor function on the IBM 370 for CLC software.[50] It was decided to develop XPF in PL/1. Throughout the development, many design and implementation decisions concerning the use of PL/1 were made. Some of these proved to be sound and others had unfortunate results.

The extensive use of the PL/1 preprocessor proved to be an excellent control mechanism. The inclusion of macros, entry point declarations, and global variable declarations via preprocessor procedures greatly facilitated intermodule communication. This standardization guaranteed the integrity of interface.

As originally expected, the liberal use of PL/1 debugging aids was an invaluable development tool. The large number of logic errors detected through on-conditions such as SUBSCRIPTRANGE and STRINGRANGE underlines the value of their use.

The use of assembly language subroutines, although dictated by efficiency and necessity, presents some disadvantages. Since parameter definition is compiler-dependent, assembly language subroutines must be coded to meet the parameter-passing standards and conventions of a specific compiler. In PL/1, these proved even more limiting since assembly language subroutines must be coded for a specific version of the compiler. When such subroutines are utilized, this dependency on a particular version of a compiler should be explicitly documented.

One benefit of using PL/1 not considered in the original decision was the ease with which transfer of responsibility was accomplished. Partial turnover of personnel occurred throughout the project. Transfer of code responsibility to new personnel was accomplished very smoothly with no apparent decrease in productivity. Since PL/1 can be largely self-documenting through the use of meaningful variable names and standard operation symbols, it is easy to read and understand. This ease of understanding was the primary reason for the smooth personnel transitions.

Professional Design Review

For part of the application program development, a technique known as "flowchart review" was undertaken. As soon as the flowchart and data set layouts for an area of the program were completed — and before coding began — a review meeting was held. The programmer was required to give a box-by-box explanation of a detailed flowchart for his program to a small group of his colleagues. In as friendly a manner as possible, this review committee was expected to be critical and to question aggressively every assumption that the programmer made.

After such a review, the programmer coded his unit, tested it, and released it to process

integration. Any minor changes due to bugs found during integration had to undergo a second type of review. Each programmer submitting a minor change was required to select a referee from among the senior members of the group. The programmer would discuss with the referee both his proposed change and the procedure to be used in testing the change. The change could not be released until the referee was satisfied with the testing as well as with the code itself. After the referee system was introduced, the problem of bugs in minor changes came to an end.

One lesson learned from these experiments is the extent of the increase in quality and productivity that can be obtained from a disciplined use of professional review. The use of flowchart review:

- Improved and simplified software design.
- Helped detect all major software design errors before code was written.
- Reduced software development time by at least 25 percent.
- Improved quality of delivered software. The referee procedure brought an end to the errors in minor changes turned over to the system integration team. Other forms of professional review have led to similar results.

A second significant lesson can be learned by comparing professional review with some of the other techniques that also have led to improvements in program quality and programmer productivity; e.g., programming teams, modular and top-down design, and structured programming. There is a common denominator to these techniques — the increased structure and discipline that is placed on the process of writing software. Although much remains to be learned about writing software, it is clear that designing and writing software needs to be a much more structured process than it generally is today.

Software Change Control

Two aspects of software change control that were successful in SAFEGUARD were a project-wide library maintenance system to control source and object code and a standard trouble report form. These were not developed over a long period of time, but appeared very early in the project. Because of this stability, software developers grew accustomed to using them. The library maintenance system was available during the first phase (no change control), and the trouble report form was available at the beginning of informal change control. It was recognized that early introduction and acceptance would be beneficial because transition to the later phases would be simplified. Two additional features of the system, change control procedures and software status accounting, proved to be more troublesome to define and implement. Early in the period of informal change control, each process area independently developed its own procedures; thus a certain amount of reexamination and redefinition were required during the transition to formal change control.

Any software change control system is destined to meet with some resistance. Programmers as a rule have very definite ideas about what should be done to their software. This factor, combined with the dynamic nature of software, makes change control a difficult problem, not so much in establishing the mechanisms and procedures, as in dealing with human factors and ensuring adherence to procedures. The first step is to recognize that change control is a necessity that should be addressed early on any large project and, in fact, will be addressed, either early in a systematic manner or later in a less organized but more costly manner. Only the recognition of this need and conscientious addressing of acceptable procedures will guarantee successful change control. These human factor aspects are the more important considerations in successful software change control.

System Constants

The SAFEGUARD application software contains thousands of numerical values or constants to specify site parameters (e.g., radar location), hardware characteristics (e.g., transmitted power), physical modeling (e.g., air density

profiles), etc. Accurate constants were needed by designers in many different areas of each application process. Early in process integration, a group was assigned the task to identify, validate, and control the values of all such system constants. Once this was done, no significant problems caused by improper numerical values occurred during the final integration and testing of the SAFEGUARD software.

While this effort was successful, it is clear that the specification and control of constants should have been considered during the initial design of the software processes. Had it been addressed earlier, undoubtedly it would have resulted in some special design features. These thousands of constants could have been controlled in a less burdensome manner either at process construction time, during process initialization, or during execution, by using special constant data sets. The special features could also encompass easier procedures for verifying and changing values.

Chapter 5.

SAFEGUARD SYSTEM EVALUATION

Chapter 5.

SAFEGUARD SYSTEM EVALUATION

System evaluation attempts to estimate total system performance in order to provide confidence that the overall system objectives will be achieved. Executing this task in the SAFEGUARD program involved two major phases of activity.

The first phase focused attention on the performance and functional requirements specified by the tactical system designers and documented in the performance specification for the hardware and in the Data Processing System Performance Requirements (DPSPRs) [1,2] for the software. The goal of this phase was to verify the viability of the overall system design and to discover and correct any inadequacies in system operation as early as possible. Another objective was to identify critical aspects of system performance to assure that appropriate emphasis was reflected in system requirements and that appropriate test programs and associated test requirements were identified and planned.

The second phase broadened the scope of the evaluation effort to ensure that the design implementation satisfied the design requirements. During this period, system and subsystem models were modified and validated using data collected from field and laboratory tests. Corresponding adjustments were made to estimates of system capability.

Obviously, the SAFEGUARD System evaluation was an evolutionary activity, proceeding from system requirements to system implementation. The objective was to obtain adequate data to permit a confident assessment of system capability in the most cost-effective way. This was accomplished by identifying the appropriate function of each of the available sources of data and establishing how the various simulations, subsystem tests, and system tests would supplement each other.

APPROACH TO SYSTEM EVALUATION

SAFEGUARD System capability was evaluated primarily through simulation, with test data serving to validate the simulation modeling and add confidence to the evaluation results. The hierarchy of simulation tools developed ranged from a total system simulation capable of indicating the response of all system elements during a typical attack to much more detailed simulations of critical system functions such as battle planning, data gathering (target track), and intercept (guidance and missile performance).

Figure 5-1 diagrams the primary interfaces among the design, evaluation, and test activities. Evaluation, primarily an analytic activity, relied

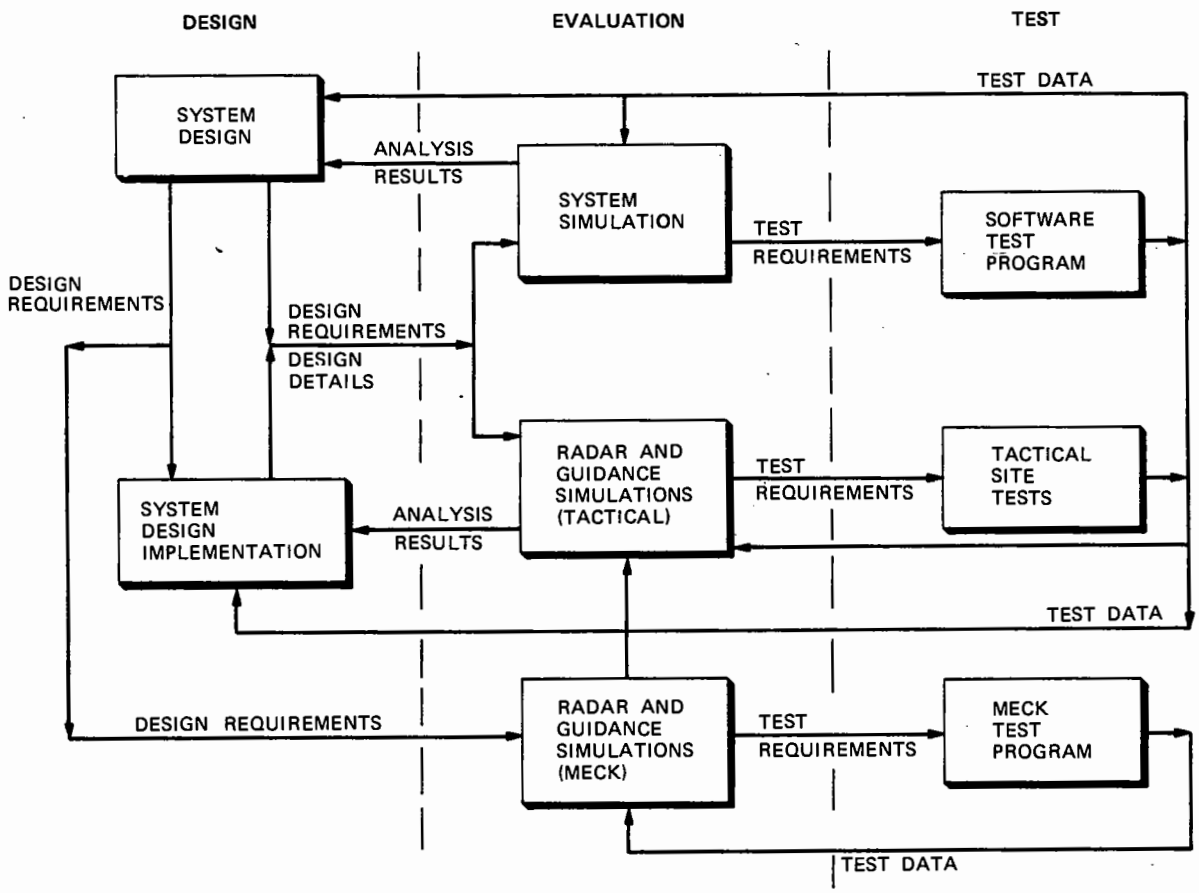


Figure 5-1. Effectiveness Evaluation Procedure

heavily on simulation because of the complex nature of the SAFEGUARD System. Hence, in Figure 5-1, evaluation is represented by the major simulations developed. Three sources of test data were relevant to system evaluation activity and played a major role in simulation validation:

- Meck System Test Program
- Tactical Software Control Site (TSCS), Madison, New Jersey
- Tactical Sites — Grand Forks Air Force Base, North Dakota, and Colorado Springs, Colorado.

For tests at Meck Island, Kwajalein Atoll, "live" ICBM and SLBM targets were available and were tailored to the program requirements and engaged by defensive missiles. Meck data was particularly valuable with respect to the SAFEGUARD target-track and intercept functions and to performance of the Missile Site Radar (MSR) and the SPRINT and SPARTAN missiles. This test site, however, could not provide all required test data nor a complete test of SAFEGUARD System operation for the following reasons:

- Impracticality of providing threat traffic commensurate with the design threat — many aspects of system performance could not be stressed at low traffic levels.
- Absence of nuclear effects — intercept planning, for example, is designed to minimize the effects of self-blackout. The adequacy of this function could not be tested in a blackout-free environment.

- Lack of critical system elements — the Meck test facility did not include a Perimeter Acquisition Radar (PAR) and because of the lack of nuclear effects and high traffic, the data processing software did not include battle-planning functions.
- Expense of live testing — the cost associated with a single live test limited the number and variety of tests that could be conducted.

The Meck System Test Program is discussed more completely later in this chapter.

Tests conducted at TSCS were a major source of data for simulation validation, particularly in those areas not covered by the Meck System Test Program. By using the System Exerciser (SYSEX) to provide high traffic and the nuclear environment, data was available for evaluating several system functions including battle planning and target selection. Because TSCS included both the PAR and MSR data processing systems, data was provided in the netted-system environment not available from the Meck System Test Program.

The Meck test facility did not include a prototype PAR, hence tests conducted at the tactical PAR site provided the necessary PAR performance data. In addition, system tests initially conducted at TSCS were repeated at the tactical sites, supplementing the system performance data gathered at TSCS and utilized in simulation validation.

The remainder of this chapter describes the major simulation tools developed during the evaluation program, the procedures by which these simulations were validated using test data, the key analysis and results obtained with the simulations during the evaluation program, and details of plans and results of system testing at Meck and at Grand Forks. Also included is a description of the system integration and demonstration tests conducted at TSCS and Grand Forks for system certification and customer acceptance.

MAJOR SIMULATIONS

Several simulations were developed to assist in evaluating the system. These simulations proved to be a valuable tool in the overall evaluation program.

System Simulation

The complexity of the SAFEGUARD System and the complex interactions between functions made it difficult to predict the overall system response and effectiveness during a typical attack. The SAFEGUARD System Simulation (SAFSIM/TACSAF), which uses the HIS 635 computer, was developed to evaluate system response and to determine system effectiveness over the spectrum of threat conditions. Two versions of the simulation were developed. The first, SAFSIM, was used early in the evaluation program to evaluate the DPSPRs. SAFSIM consists of models of each of the system functions designed to meet the performance requirements unconstrained by any real-time data processing limitations. A second version of the simulation, TACSAF, has models representing the "as implemented" tactical capability and incorporates knowledge gained from the various test programs, in particular the Meck System Test Program. The major elements of TACSAF are listed in Table 5-1.[3]

The level of detail included in the various functional models varies over a wide range. For example, the MSR track function is not a closed loop as in the MSR Simulation (MSRSIM)[4] discussed next, but uses a statistical error model to represent pulse-by-pulse variations in the track data provided to the track filter. The statistical model was developed using results from MSRSIM and includes Signal-to-Noise Ratio (S/N) effects and the effects of the wake and tank-breakup environments. Similarly, the SPRINT intercept model is greatly simplified because guidance algorithms are not included. SPRINT miss distance is estimated as a statistical combination of target-track and missile-track uncertainties amplified by a factor that depends on intercept geometry. This simplified model was based on extensive simulation of the guidance loop using SES/SIS (see SPRINT Engagement Simulation), which in turn was validated in connection with the Meck System Test Program.

Conversely, the SPRINT Interceptor Response (IR) function essentially duplicates the tactical algorithms, as does the Target Selection

Table 5-1

Major Elements of the SAFEGUARD System Simulation (TACSAF)

TRAJECTORY GENERATOR

- Target Reentry Vehicles (RVs) — Input RV ballistic coefficient history, launch point, impact point, reentry angle, launch or impact time
- Tank, Junk Dispersion — Input ΔVs relative to RV velocity

SURVEILLANCE/DETECTION MODEL

- Threat Characteristics — Radar Cross-Section (RCS) models, vehicle dynamic motions
- MSR Search Sectors

MSR TRACK

- MSR Weapon Process (MW) Data Gathering Logic — Data rates, track priorities, Automatic Gain Control (AGC), waveform switch
- Target Selection
- Discrimination

ENVIRONMENTAL MODELS

- Nuclear Blackout/Attenuation
- Wake Effects
- Tank-Breakup Effects

RESOURCE ALLOCATION/OVERLOAD RESPONSE

- Dynamic Accounting of MSR and Missile Site Data Processor (MSDP) Loads
- MW Logic for Radar and Data Processor (DP) Overload Response

INTERCEPT PLANNING (SPRINT Interceptor Response)

- Farm Selection Logic
- Constraint Resolution
  - Nuclear Models — Blackout, radiation, shock, dust
  - SPRINT Deadzone
  - Wake Avoidance
- SPRINT Capability (flyout, acceleration)

INTERCEPT ASSESSMENT

- Miss Distance Determination (True and Estimated)
- Interceptor Lethality Contours

PENETRATOR EFFECTS

- Facility Damage — Shock, dust
- Nuclear Blackout

Function (TSF). The SPRINT IR and TSF modules can both be exercised as part of the total simulation or can be exercised in a "stand-alone" package for separate response analyses.

To achieve reasonable fidelity, TACSAF is necessarily an extremely large and complex simulation. Some list-handling and dynamic-storage techniques not commonly found in FORTRAN simulations assisted greatly in program organization. Also, TACSAF is event-based to minimize computer resource usage. This means that time is not the independent variable, but rather a time-ordered list of significant events is processed. No computations are performed in between significant events and time is merely updated to correspond to the time of the event under consideration. As an aid to analysis, convenient summaries can be produced by processing the data recorded on magnetic tape during a TACSAF run. A partial list of the summaries currently available in TACSAF includes:

- Overview of Significant Events – Object-by-Object
- Detection Summary
- MSR Target Selection Function
- MSR Discrimination
- Clutter Effects Summary
- SPRINT IR Planning Summary
- SPRINT Engagement Summary
- Resource Allocation Summary - Radar and DP Loads versus Time.

In addition to tabulations of the summary data, plot routines are available for several of the summaries.

TACSAF was used for a wide range of system evaluation activities, including the system traffic-handling capability and overload response and a detailed evaluation of the battle-planning functions. TACSAF also provided an extensive data base of expected results for the set of System Integration and Demonstration tests conducted at both the TSCS and tactical site. The performance criteria and bounds for those tests were developed from the data base.

MSR Simulation

The primary objective of the SAFEGUARD System was to detect, identify, and intercept threatening reentry vehicles. Data from the target-track function, of sufficient quality to support target selection and intercept, was critical to attaining the primary objective. The MSR Simulation (MSRSIM), which runs on the HIS 635 computer, was developed to permit a comprehensive evaluation of the SAFEGUARD target-track functional capability.[4]

The main features of the simulation are detailed models of target characteristics and models of the radar hardware and data processor software, which are included in the tracking loop. MSRSIM consists of two modules of simulation programs, the BED programs that model the radar hardware and threat environment and the LOGIC programs that model the data gathering software.

Features of the threat environment modeled in the BED module are:

- RV radar cross section and sheathing effects
- RV dynamics (trajectory and tumbling)
- Wake parameter histories
- Ballistic coefficient histories
- Tank fragmentation.

The BED hardware models include:

- Main lobe antenna pattern
- Sum-channel video with correlated noise
- Range mark generator
- Monopulse phase detector
- Digital encoder granularities
- T1 and T3 compressed waveforms
- Dispersed pulse measurement.

Modeled features of the data processor algorithms in the LOGIC module are:

- Acquisition and track initiation
- Kalman track filter
- Crossing target logic
- AGC and track-mode selection logic
- Range gate setting and antenna beam pointing
- Tracking status assessment.

Detailed mathematical models of the radar signal processor and high-fidelity signal synthesizers are the heart of MSRSIM. For the MSR, the models digitally synthesize compressed-pulse video and monopulse-angle processor signals and dispersed-pulse integrator signals, including the effects of bandwidth-limited noise. Backscattered signals from waking and/or fragmenting objects, which may be off-axis in the phased-array main beam, are appropriately superimposed to create realistic radar responses. The model accurately represents the interference backscatter from multiple targets by considering their relative ranges from the radar and their off-beam positions. Gain states of the radar, waveforms transmitted, and other factors influencing the phase and amplitude of the interfering returns from targets are also represented.

The time-based simulation is stepped ahead to the time that the next radar pulse is transmitted to the next object in track. After all objects are flown prior to the time of the next radar pulse, their radar cross sections are computed. The objects include reentry vehicles, tanks, and tank fragments, all of which may wake during reentry. Next, the sum-channel video signal is generated and range and amplitude measurements are taken. Simultaneously (to represent the monopulse-angle measurements), sin α and sin β difference-channel signals are generated and combined with predicted sum-channel signals to generate noisy, off-axis sin α and sin β measurements. The range, amplitude, and sin α and sin β measurements are digitally encoded and passed to the data processor software. If the amplitude S/N is above a threshold, the measurements are inserted into the Kalman tracking filter to update the estimated target-state vector and to estimate target position and velocity at the time of the next pulse transmission. Estimated position information is fed to the hardware model to point the antenna beam and set the range tracking gate for the next pulse transmission. Simultaneously, the estimated variances and peak amplitude S/N are sent to the track-logic software to determine the RF gain setting and the track mode.

Different versions of the simulation are available. All use the same BED module, but different LOGIC modules. One version of the simulation, using a LOGIC package consistent with the Meck data processing, was used extensively in defining Meck test requirements, providing premission simulations, and evaluating mission results to validate the simulation. A second LOGIC package was used in developing the tactical tracking algorithms. This version of the simulation was labeled TACMSRSIM.

PAR/SPARTAN SAFSIM

A decision was made in 1972 to develop a separate version of SAFSIM to model the PAR/SPARTAN system response. The development of separate PAR/SPARTAN and MSR/SPRINT versions of SAFSIM was desirable, since the amount of computer storage required by a single simulation would have necessitated sophisticated and expensive disc-to-core program swapping techniques to fit the simulation into the available core storage on the HIS 635 or IBM 370 computers. No analysis capability was lost through this simpler and cheaper approach of developing two separate versions of SAFSIM. Also, a low degree of interaction existed between the PAR/SPARTAN and MSR/SPRINT roles in SAFEGUARD. PAR/SPARTAN SAFSIM (P/Z SAFSIM) was developed on the IBM 370, because the execution speed and core storage advantages were needed for simulating the large number of objects visible to the PAR during a battle. For example, simulation of one of the full system integration test scenarios on P/Z SAFSIM requires 1200 kilobytes of storage and 1- to 1.5-hours execution time on the IBM 370/165.

The attack environment portion of P/Z SAFSIM consists of models of the key attributes of each threat complex type (e.g., RV/tank separation velocities, RCS profiles), trajectory targeting programs, and exoatmospheric nuclear environment models. The satellite environment was not simulated since it was found to have an insignificant effect on system response during an attack.

The PAR surveillance function is approximated in P/Z SAFSIM. Rather than implement a detailed search-raster model, the time for the first surveillance-pulse hit on an object is determined by a random draw from a uniform distribution, with later attempts scheduled deterministically using the scan time of the subsector. The effects of radar resource availability on scan times and of nuclear burst attenuation on detection capability are modeled. The scan-while-track and search-in-range detection mechanisms used by the PAR Weapons Process (PW) are also modeled. PW rules for the traffic-level-dependent switch on maximum search listening range are implemented.

In the tracking area, accurate models are incorporated for track initiation and group clustering, automatic gain control, pulse scheduling, polynomial/Kalman filtering, known object recognition, and low S/N sample pulsing response. Due to excessive execution time and storage requirements, a signal processor model was not included in P/Z SAFSIM. Thus, in unresolved target-track situations, the SAFSIM tracking performance was not an accurate reflection of PAR tracking, and it was necessary to use the detailed radar evaluation simulation (PAR Testbed) in conjunction with P/Z SAFSIM.

The four key subfunctions of PW target selection are modeled in P/Z SAFSIM: determining value structure attacked, determining launch complex type, ranking objects according to estimated probability of being an RV (P_{RV}), and rescaling P_{RV} to support the SPARTAN Interceptor Response (ZIR) missile allocation function.

For battle planning, portions of the simulated models were implemented for defense-mode-dependent SPARTAN allocation, battlespace determination, Minuteman-flyout-corridor avoidance, manual SPARTAN controls (SPARTAN Hold and Hold Fire), and intercept-point selection. Particular attention was given to intercept-point selection due to the complexity and importance of the problem of resolving nuclear effects constraints, such as fratricide and blackout among multiple intercept points. The ZIR models were also configured to run in a stand-alone mode outside the body of P/Z SAFSIM. This facilitated detailed high-fidelity analysis using PW inputs from the PAR Testbed Simulation or TSCS.

Finally, the SPARTAN intercept effectiveness model simulated both controlled and free-intercept guidance modes, using forced or unforced jethead ignition, as appropriate. The primary error sources modeled were atmospheric exit velocity errors, missile state estimation errors at third-stage ignition, third-stage velocity errors, and third-stage spin-stabilization errors.

PAR Testbed

PAR Testbed is a high-fidelity simulation of the threat environment, PW software, and PAR hardware. The threat environment models offer the same capabilities as those described for PAR/SPARTAN SAFSIM. In addition, the Testbed can be driven directly by SAFEGUARD Threat Action Generator (STAG) tapes (see System Integration Testing) for precise simulation of the threat environment encountered in TSCS tests. The satellite and meteor environment is also simulated.

The PW software portion of Testbed includes detailed models of the raster-scan search and verification processing. In the track area, models are provided for track initiation, including range rate histograms, correlation processing, and Known Object Recognition (KOR) checks; Continental United States (CONUS) impact and meteor tests; pulse scheduling rules, including scan-while-track, search-in-range, drop track, sample pulsing, and lost track algorithms; KOR checking throughout track processing; clustering and reclustering logic; and finally, Kalman and polynomial filtering for both null and off-axis tracks. In the target-selection area, models are provided for each of the subfunctions that lead up to determining value structure attacked and launch complex type, ranking objects according to estimated probability of being an RV (P_{RV}),

and rescaling P_{RV} to support the SPARTAN Interceptor Response missile allocation function. Finally, the traffic sensitive switch of search listening range and pulse allocation rules is modeled.

The PAR hardware models include interfering multiple-target effects in range and angle, and correlated noise effects in range. Range marks are generated from simulated noisy range video. Angle measurements are modeled by forming a sum-signal vector and two difference-signal vectors (including noise and jitter effects) and by precisely modeling the characteristics of the monopulse detectors. Simulated signal levels and noise levels are impacted by the pulse-by-pulse setting of digitally controlled attenuators. Finally, the characteristics of the T1 waveform (beamwidth, sidelobe levels, etc.) have been modeled in detail.

SPRINT Engagement Simulation

Two detailed simulations were used to evaluate SPRINT intercept capability in the SAFEGUARD System. The SPRINT Engagement Simulation (SES) was developed to evaluate the performance requirements applicable to SPRINT capability (primarily guidance) and to support the definition of requirements for the SPRINT intercept portion of the Meck System Test Program. All elements of the SAFEGUARD System necessary to the engagement of a single RV by a single SPRINT missile were modeled in SES. A detailed simulation of the SPRINT missile was provided, including statistical models of all significant performance variations such as pitchover errors, motor thrust and total impulse, autopilot biases, etc. The guidance program implemented in SES contained all of the guidance functions specified in the DPSPRs for SPRINT guidance, but were non-real time in the sense that they were not constrained by real-time data processing considerations. Both the target-prediction and missile-prediction functions provided accuracies not achievable in real time to serve as a base for evaluating tactical implementation.

Models of missile and target track were developed consistent with the MSR performance specifications and results obtained from MSRSIM. As indicated earlier, SES was used initially to identify stressing intercept conditions for use in defining the Meck test requirements.

As the tactical guidance design for SPRINT was developed, the guidance section of SES was replaced with tactical algorithms. Using performance data from the Meck System Test Program, the missile simulator was modified and the target-track model was extended to simulate target-wake effects and other clutter sources, such as tank breakup.

SES was used extensively throughout the SAFEGUARD evaluation program to thoroughly explore SPRINT intercept capability throughout the field of fire and to investigate the sensitivity of intercept capability to guidance design alternatives and variations in environment.

The major studies conducted[5-10] included:

- Determining the linear region of the SPRINT field of fire
- Determining the effect of wake-induced target-track biases on intercept capability
- Characterizing controlled guidance effectiveness in limiting intercept-point shift
- Determining the sensitivity of intercept capability to variations in target- and missile-track rates and guidance rate
- Determining sensitivity to variations in missile performance, air density, target beta histories, and other environment factors including blackout-coast intervals
- Evaluating the tactical algorithm design, including missile and target predictors, intercept-point bias, and capability bias
- Developing an approximate intercept capability model for use in the system simulation.

SPRINT Intercept Simulation

The SPRINT Intercept Simulation (SIS) is a Monte Carlo simulation containing all the elements of the subsystem, with the exception of the target-tracking and -state estimation functions. Target-state estimation information is

supplied to SIS via magnetic tape generated by the MSR simulation, MSRSIM. The prelaunch guidance and missile data processing functions contained in SIS are FORTRAN equivalents of the real-time M-2 software code used for the live missions at Meck. The missile simulator and MSR missile-track error simulator are FORTRAN models of the SPRINT missile and MSR missile track hardware, which contain models of all error sources that significantly contribute to intercept effectiveness.

The overall approach to intercept subsystem evaluation developed during the Meck program consisted of three major phases:[11]

- Analysis and simulation
- Stressing tests
- Reconstruction of test results.

Simulations and analysis techniques were developed to verify system and subsystem requirements, and to characterize system performance to hardware, software environment, and threat parameters. The parameters that drive system performance (e.g., radar noise, unpredictable target accelerations, variations in missile performance) are of a random statistical nature, and the properties of the system are highly interactive and nonlinear; therefore, it is not generally feasible to determine intercept effectiveness by analytical techniques. Consequently, Monte Carlo simulation techniques were required to adequately characterize system performance.

Since the cost of a Monte Carlo live-mission approach to validating system performance at Meck was obviously prohibitive, the approach was to use data gathered from a relatively small number of particularly stressing live missions to validate Monte Carlo simulations. These tests were specifically designed to stress some aspect of missile or software performance and to provide data to validate simulation models and techniques (see SPRINT Performance Characterization).

The live-mission results were constructed by simulation using the data gathered during the live mission. If reconstruction was successful, confidence was developed in the validity of the simulation and, consequently, in the accuracy of the system performance predicted by the simulation. If reconstruction was unsuccessful, deficiencies in modeling or simulation techniques were exposed and corrected.

To use simulation results to characterize SPRINT intercept subsystem effectiveness with a high degree of confidence, the simulation itself had to be a valid model of the subsystem. The SIS verification analysis used premission Monte Carlo simulation, live mission, and post-mission Monte Carlo simulation results. Premission simulation analysis provided nominal guidance- and missile-parameter histories and predicted possible mission outcomes. The final post-mission simulation analysis consisted of reconstructing the flight and matching flight test and simulation results.

The premission Monte Carlo simulations with SIS used MSRSIM tapes of target-state histories. In most cases, the MSRSIM tapes contained 25 Monte Carlo samples of estimated target-state histories representing different random target-track noise and variations in target ballistic coefficient histories. For the premission simulations, all other random system errors that influence intercept effectiveness (missile-track noise, missile performance variations, and atmospheric density) were fully simulated.

During the post-mission analysis, data gathered during the live mission were used to particularize the conditions actually present during the mission and to "tune" the simulation models and consequently reconstruct the flight. Three major classes of data were gathered during each flight:

- Recorded software parameter histories (E-Tape)
- Missile telemetry data
- Optical track data - Recording Automatic Digital Optical Tracker (RADOT).

The E-Tape provided recorded histories of all pertinent guidance, missile-track, and target-track parameters. During the post-mission analysis, the recorded target-state estimates were

used to drive SIS. The missile telemetry data provided missile acceleration histories that were used primarily to validate missile simulator models. The RADOT data provided an accurate independent source of missile-state histories, particularly during the powered-flight phases. On some flights, RADOT provided a valuable independent measure of miss distance.

SPARTAN Intercept Simulation

The SPARTAN Intercept Simulation (SPASIM) is a six-degree-of-freedom simulation of the hardware and software making up the SPARTAN intercept subsystem. SPASIM was typically used in the Monte Carlo mode to predict SPARTAN miss distance and kill-probability performance for given intercept points and PAR target-track error distributions.

High-fidelity simulations of SPARTAN and the portions of MSR relevant to SPARTAN support were provided. The SPARTAN flight dynamics models were extensively validated using Meck test data.[12] All of the significant missile error sources were modeled — specific impulse, burn time, and weight variations for all three missile powered-flight stages; attitude control errors during each phase of the missile flyout profile; and time reference and atmospheric density variations. Similarly, MSR missile tracking hardware models were thoroughly validated using Meck test data, and models were provided for the key error sources such as radar noise, atmospheric refraction, and SPARTAN exhaust-plume effects.

SPASIM incorporates high-fidelity models of the MSR Weapons Process (MW) guidance and missile data processing functions. Guidance function models are provided for both free- and controlled-intercept guidance modes, and for each of the seven major SPARTAN flight phases - boost, dive guidance, aerodynamic steering, exit attitude control, exoatmospheric coast, jethead burn, and post-jethead coast. The missile data processing models incorporate the missile-state estimation and radar beam-pointing command-generation functions. Finally, PAR target-track errors were modeled by three-dimensional Gaussian distributions, where the means and variances could be set to values drawn from PAR Testbed or TSCS analysis, or in the default case, to the DPSPR performance specification values.[2]

ANALYSIS AND KEY RESULTS

The total SAFEGUARD evaluation program consisted of a closely coordinated combination of analyses, simulation studies, and test programs conducted over a period of several years. The areas of investigation covered a wide spectrum, resulting in modifications to the design requirements and/or implementation of virtually every functional area in the SAFEGUARD System. In addition, many other results confirmed that the current design was effective in meeting the system objectives.

Even a brief summary of the total evaluation effort is beyond the scope of this document. The evaluation activities described here are typical of the total program and serve to illustrate the emphasis on simulation and the importance of the test programs to the evaluation effort. Extensive annual reports[13–18] provide the details on most of the evaluation effort.

MSR/SPRINT Performance and Characterization

Many areas of MSR/SPRINT performance were investigated. The following discussions cover some of the more significant investigations.

SPRINT Battlespace Utilization

The SPRINT capability analysis conducted early in the evaluation program identified a sizable region of the SPRINT field of fire where successful SPRINT intercepts would be difficult to achieve and attainable miss distance would be highly sensitive to acceleration uncertainties associated primarily with target prediction. This region of the field of fire, the "poor-geometry" region, results from the crossing angle between the target- and missile-velocity vectors being such as to align the miss-distance direction (i.e., the normal to the relative

velocity vector) along the missile centerline. When this geometry prevails, miss distance can be reduced only by speeding up or slowing down the missile. The poor-geometry region was labeled the "nonlinear" region in contrast to the remainder of the field of fire (the "linear" region) where achievable miss distance could be estimated as a linear function of the missile and target tracking errors. Subsequent simulations with the SPRINT Engagement Simulation (SES) generally confirmed the size and shape of the regions.

Using the system simulation (SAFSIM), investigations of the overall system effectiveness when intercepts were constrained to the linear region of the SPRINT field of fire indicated that system effectiveness was in no sense degraded, but conversely was somewhat enhanced. Since only intercepts with a priori high-kill probability were planned, thereby eliminating potential second shots on the basis of a kill assessment decision, the blackout environment (due to SPRINT bursts) was reduced.

As tactical guidance algorithms were developed and incorporated in SES, further exploration of the linear regions was conducted. As expected, due to necessary guidance approximations in the real-time program, the nonlinear region was slightly expanded. Data generated with SES during the study indicated that the boundary of the deadzone was closely coupled to the missile-target crossing angle. Zero degrees is the "worst case" geometry. Plots of miss distance versus crossing angle obtained from the SES results indicated that miss distance increased rapidly as the crossing angle decreased below a specified minimum. Based on these results, the boundary of the deadzone, as implemented in the tactical version of interceptor response, is defined by this specified minimum crossing angle.

Target-track data gathered in the early portion of the Meck Test Program initially characterized the expected performance of the wake-track algorithms employed in the tactical system. That knowledge was used to develop (based on MSRSIM results) a single-pulse error model to simulate the effect of wake-on-track capability. A concurrent analysis conducted with SAFSIM indicated that most intercepts at Grand Forks would be influenced by wake. Hence, the single-pulse error model was incorporated in the SPRINT Engagement Simulation (SES) to determine the impact of the waking environment on intercept capability.

For each target type, the single-pulse error model used a defined region of heavy wake, where heavy wake is the expected region of unresolved-wake returns. These heavy-wake regions are defined in terms of altitude and look angle. Within the heavy-wake regions, appropriate noise, biases, and transient effects are added to the non-wake-error statistics before the track data is provided to the track filter.

The major effect of heavy wake is the introduction of biases in the filtered target-position data. The biases (both range and angle) can vary as a function of vehicle type and look angle (angle between target-velocity vector and radar line of sight).

The SES study of the effect of these biases on intercept capability led to the conclusion that miss distance was increased when intercepts were conducted within the heavy-wake regions. Therefore, requirements developed for the battle-planning function (SPRINT Interceptor Response) accommodated the wake environment. Investigations, using the system simulation (TACSAF) for a variety of attack conditions, confirmed that adequate battlespace was available for almost all intercepts and that the wake constraint produced no overall loss in system effectiveness.

SPRINT Performance Characterization

The SPRINT intercept simulations described earlier were developed to predict the results of the SPRINT intercept tests at Meck and to provide a tool to characterize intercept capability throughout the field of fire. The Meck flight tests served two objectives:

- Provided data for evaluating SAFEGUARD System performance to determine if the

specifications and design produced the desired results

- Provided data for reconstructing the test with simulations. The reconstruction verified the validity of the simulation and/or indicated deficiencies in the modeling.

The measure of intercept capabilities is attainable miss distance. Miss distance, a statistical quantity, is caused by uncertainties that can be categorized as follows: (1) radar tracking inaccuracies, (2) differences between the available or achieved interceptor acceleration and that required to eliminate predicted miss distance, and (3) unpredictable target accelerations. The dependence of intercept effectiveness on subsystem errors made it desirable in the individual flight tests to subject the guidance-interceptor-radar subsystem to situations where the system uncertainties stress the intercept conditions. More can be learned about the effect of system errors from this type of testing, since excessive interceptor-acceleration capability will not overcome or mask subsystem errors. Consequently, the live SPRINT tests were structured to make demands on the interceptor capability and guidance function. The following intercept conditions were of interest:

- Inadequate acceleration capability in the miss-distance direction caused by low dynamic pressure or stressing engagement geometry
- Target flight path near the tangent to the SPRINT time-of-flight contours
- Intercept shortly after motor burnout
- Long-range, low-altitude intercepts
- Low intercept elevation angles
- Near the vertical missile trajectory.

SPRINT intercept effectiveness (miss distance and intercept-point motion) was demonstrated for a variety of intercept conditions during the M-2 series of flight tests at Meck Island. Data was generated for evaluating SPRINT intercept subsystem performance and validating the SPRINT Intercept Simulation. Integration of subsystem elements was proved, and operational characteristics of subsystem elements were determined.

The following major results and conclusions are based on mission events and SPRINT Intercept Simulation analyses conducted during the Meck Test Program:

- Intercept effectiveness was evaluated, and the SPRINT Intercept Simulation was verified for 17 collocated and remote launch SPRINT Meck test missions.
- Observed intercept-point motion for the controlled-intercept guidance-mode intercept points at Meck was always within the specified value for nonstressing engagement geometry.
- The SPRINT Intercept Simulation was shown to be a highly credible simulation of the SPRINT intercept subsystem.
- Most of the differences between premission-predicted and live-mission intercept effectiveness were due to differences between premission and live-mission target-track characteristics.
- The SPRINT Missile Simulation (MISSIM) used in SIS was significantly updated as a result of observed versus predicted mission performance. The key updates were missile drag, airframe response, and atmospheric models. The final SPRINT missile simulation was verified as an adequate model of SPRINT performance.
- An evaluation of the Missile Site Radar Missile Track Simulation (MTRACK) showed it to be a very good model of MSR tracking accuracy and performance.
- The utility of first-stage guidance was shown by premission simulation analysis of Mission M2-22. First-stage velocity dispersion is greater than the velocity estimation error at the time of command computation.
- The intercept-point bias guidance function was deleted from the tactical guidance design because of the guidance performance stress introduced by the aim-point shift during end-game for Mission M2-7 and the uncertainty in warhead shadowing.
- SIS parametric analysis of capability bias* performance during the M2-48 premission analysis showed that capability bias is effective only when an adequate increase in prelaunch time of flight is included to account for the increased missile flight time to intercept.
- Intercepts occurring during heavy-wake track (M2-18, -38) produced miss distance at least on the order of the target position estimation bias associated with heavy-wake track.
- The sensitivity of miss distance to intercept time after wake quench was determined

*A guidance technique to enhance system performance in poor geometry situations.

during the M2-25 SIS premission analysis. Mission M2-27 and -25 verified that intercepts occurring after wake quench are not significantly affected by the target-state estimation occurring at wake quench.

Target-Track Performance

One of the most, if not the most critical function in the SAFEGUARD System is that of target track. The performances of the target-classification (threatening or not threatening), target-discrimination (RV or non-RV), battle-planning, and intercept functions are all critically dependent upon the quality of data provided on a reentering object by the target-track function (both hardware and software). A major portion of the total evaluation effort was devoted to understanding the sources of target-track error in the MSR, the environmental effects on tracking, and the performance of the software tracking algorithms.

An extensive measurement program was conducted on the MSR at Meck to determine the single-pulse range and angle statistics, and to validate the modeling employed in the various simulations, particularly MSRSIM. Biases observed between various types of metric data were systematically investigated. These included offsets in the data at mode changes, face handovers, frequency-to-frequency, and AGC changes. A previously undetected amplitude-dependent bias was isolated and characterized, and the effect of the bias was minimized by adding a phase commutation technique to the MSR receivers. Position biases between the missile-track and target-track modes were identified by simultaneously tracking SPARTAN missiles in both the missile-track and target-track modes.

As a result of these investigations, bias effects in the MSR were minimized by a combination of hardware changes, software corrections, and radar alignment techniques.

The alignment procedures and measurement techniques developed during the Meck program were applied to the tactical radars at Grand Forks.

Cluttered Environment

Obtaining high quality track data on an object during reentry is made more difficult by two potential sources of clutter within that altitude regime — target wake and tank breakup.[19–25] See the Classified Supplement for further discussion of these clutter sources.

A major part of the Meck test program was devoted to providing the information needed to characterize the clutter environment, develop track algorithms for operation in the clutter environment, and validate the design performance.

The design of wake track was accomplished using the MSRSIM, as was the entry and exit logic which uses a combination of a missed-look test, wake-to-body amplitude, and range-extent measurement. Wake track is basically the use of a dynamic threshold to provide a substitute tracking location on the leading edge of the target/wake range return whenever the clean-target zero-slope is missing. This produces a range measurement error of time-varying magnitude and direction. The target amplitude, wake amplitude, and length all change during reentry; each change is a function of RV type and trajectory parameters. Thus, the resulting range error is a complex function of threshold bias, threat type, and trajectory. The angle measurement is taken at the range of the zero-slope beyond the threshold crossing and is therefore at the range of the first wake peak. The measurement is subject to glint caused by the random multiscatter wake. The resulting increased angle-measurement standard deviation and angle bias in the direction of the wake grow as the trajectory look angle increases and more of the wake enters the affected range resolution cell. (The effects of these errors on intercept capability were investigated using SES and SAFSIM.) For further discussion, see SPRINT Battlespace Utilization.

The on-going Meck test program was modified to provide a series of targets to thoroughly explore the performance of the wake-track algorithms.

Prior to the availability of the wake-track design in the MSR at Meck, digital video recording data were obtained for waking targets and used with MSRSIM to verify the design. Later in the program, premission simulations using MSRSIM were carefully matched against the mission results at Meck to improve the design and to verify the modeling in MSRSIM.

MSR/MSDP Traffic Capacity

Extensive analysis of MSR/MSDP (Missile Site Data Processor) traffic capacity during 1971 culminated in major modifications to the overload response in the MSR Weapons Process (MW) early in 1972. (See the Classified Supplement for additional material on traffic response.) Although test program schedules did not permit full software and system testing of the MW overload response, it is implemented in the software as an untested capability. The key features of the MW overload response and the traffic capacity improvements achieved are summarized in the Classified Supplement. SAFSIM results on SPRINT utilization inefficiencies in the overload response are also discussed there.

Significant traffic performance improvements were achieved by functional modifications in four major areas:

- Reduction of track data rates at the onset of template overload
- Revision of overload coast-management rules to delay coast initiation until adequate data quality is achieved and to provide timely and efficient reacquisition
- Real-time limitation of template pulse transmissions to efficiently stay within the return generation capacity of a three-processor system exerciser
- Provision of an MSDP overload response that gives preference to support of MSR/SPRINT processing over displays, communications, and SPARTAN processing.

PAR/SPARTAN Performance and Characterization

Many areas of PAR/SPARTAN performance were investigated. Some of the more important areas are discussed here.

PAR/SPARTAN — Performance Impact of Unresolved Target Track

Refer to Classified Supplement for this discussion.

PAR Performance Characterization

Data gathered by the PAR while tracking satellites with the PAR Test Process (PT) software was analyzed to evaluate range and angle measurement accuracy, radar sensitivity, and PAR antenna patterns.

The radar sensitivity in the search mode was characterized as the S/N at a given range on a known target at a scan angle of 45 degrees. The results indicate that the PAR S/N is approximately 4 dB better than the hardware specification requires.

The peak value, -3 dB widths, and first sidelobe levels of PAR antenna sum patterns were analyzed. The peak values exhibit a dependence with frequency that agrees with the dependence obtained from the radar sensitivity analysis. The search channel was found to be about 0.5 dB more sensitive than the track channel. Analysis of the -3 dB widths indicates the achievement of the desired beamwidth, which changes slightly (approximately ±1 millisine) as the transmission frequency and scan angle change. The null of the monopulse-difference pattern was analyzed and found to be positioned on the tracked target to within 0.1 millisine.

Analysis of PAR measurements of range and angle resulted in the identification of seven components of the total absolute PAR measurement error: (1) a random component, (2) a bias that depends on the off-axis position of a target, (3) a bias that depends on received-signal amplitude, (4) a bias that depends on transmission frequency, (5) a bias that depends on sine-space location of a target, (6) a bias that depends on face-orientation errors, and (7) a remaining unremovable bias. The random-error component was characterized as a function of S/N and was found to be within the system specifications. A bias in off-axis angle measurements was detected.

It is a complicated function of off-axis position, amplitude, and frequency and was seen to change from mission to mission, which strongly implied alignment and calibration differences. Analysis of the alignment procedures used by site personnel led to an upgrading of off-axis track-bias performance to tolerable levels. A bias in range measurements that depends on the received-signal amplitude was detected and characterized, and could be removed from the data using an algorithm in the system software. No significant system performance impact arises from this bias; thus, the PW change was not made. Similarly, a bias in sin α angle measurements that depends on the location of the target in sine space was detected and characterized, and was removed from the data by a PW modification. A component of the total PAR measurement error was attributed to face-orientation errors. After correcting the data for all known biases, face-orientation angles were estimated so that the total PAR measurement error (compared to true satellite positions) was minimized. When this was done, the total PAR measurement errors were within the system specification.

SPARTAN Performance Characterization

This section summarizes an evaluation of the SPARTAN intercept subsystem performance and a validation of the SPARTAN Intercept Subsystem Simulation (SPASIM), based on ten SAFEGUARD System flight tests that used the SPARTAN interceptor.[12] The missions were flown from Meck Island, Kwajalein Missile Range, during the time from August 1971 to June 1973.

The objectives of the study presented here were threefold:

1. Assess the ability of the SPARTAN intercept subsystem to successfully intercept a reentry vehicle
2. Verify that the SPARTAN Intercept Subsystem Simulation can predict and reconstruct the SPARTAN intercept function to a high degree of confidence
3. Using the validated simulation, assess the intercept effectiveness of the tactical system throughout the tactical field of fire.

Each of these objectives was successfully achieved. Significant conclusions and results obtained during the study included the following:

- Evaluation of intercept effectiveness and simulation verification was completed for ten missions.
- The miss distance observed on each mission was successfully reconstructed. The primary contributor to miss distance was shown to be velocity differences between the actual delivered third-stage incremental velocity for the mission and the average performance assumed by guidance in determining third-stage ignition time. Radar-tracking and telemetered-acceleration data gathered during the mission were used to determine actual delivered velocity.
- Missile performance models were significantly updated as a result of observed versus predicted results for the first six missions (i.e., through Mission M2-34). After update, the simulation (SPASIM) was shown to adequately predict mission results.
- A moderate degradation in kill probability for Mission M2-06 resulted from a 2.2-sigma aim-point miss distance. This was the largest miss distance on any mission and was attributed to the combination of a very long coast period after third-stage burnout, a large turnaround angle, and a missile-state estimation error. Mission M2-06 was a low-altitude, long-range mission — the longest range mission in the test series.
- With the exception of Mission M2-03, the actual exit velocity was significantly lower than that predicted for the first six flight tests (through M2-34), indicating significant inaccuracy in the true missile performance assumed for SPASIM and guidance development. As a result of these findings, substantial updates were made to propulsive, weight-flow, and aerodynamic characteristics of the first- and second-stage models.
- Predictions of third-stage orientation stability after spinup were verified using telemetered-attitude data gathered during several missions.
- The third-stage propulsion characteristics used for initial guidance development were shown to result in significantly lower performance than actually delivered. These findings resulted in an update to the third-stage model.
- Effectiveness of the forced third-stage ignition guidance mode is adequate over the range of incremental velocity requirements. The impact of a forced third-stage ignition on intercept miss is accurately characterized by the increased coast time over which the velocity error due to the initial turnaround maneuver is propagated.

- In addition to the performance model updates indicated above, substantial improvements were made to SPASIM during the study. These included additional Monte Carlo and third-stage incremental velocity printouts to facilitate analysis and model verification, and an exoatmospheric short-coast option to more accurately model turnaround angle for missions where third-stage ignition occurs shortly after exit and the vehicle has not tumbled.
- Characterization of the tactical system performance indicates that aim-point and target-miss distance achieved are well within the requirements for target kill throughout the tactical field of fire.

SYSTEM TESTING AT MECK ISLAND

The primary sources for system evaluation were: the Meck System Test Program, Tactical Software Control Site, and the tactical sites. This section discusses the test program as it was supported by the prototype Meck System, including the planning and structure of the test program and some of the mission results.

The Meck System was emplaced as a prototype installation; more importantly, it provided the data for concept verification and evaluated a number of system functions in a controlled environment. The program was intended to provide answers to critical design problems that could only be obtained in a live-target environment and to validate the software simulations that were essential to the success of the SAFEGUARD effort.

The need for a field test program was recognized in the early phases of development and as a result, the installation at Meck contributed to early decisions regarding the SAFEGUARD System implementation.

Objectives

The overall objectives of the Meck System Test Program were to:

- Provide a near-tactical environment for gathering system performance data to aid in development and evaluation of the SAFEGUARD deployment
- Gather S-band radar data for reentry physics research
- Gather data to evaluate concepts for future defense systems
- Gather data for evaluation of tactical and experimental target systems.

Test Requirements

The System Evaluation Program[13-18] was the major source of test requirements for Meck testing. These test requirements[26] were developed using the tactical threat and the tactical system capability as guidelines. Direct requirements from many other agencies, such as the following, also influenced the structure of the Meck System Test Program.

- SAFEGUARD System Command [now Ballistic Missile Defense Systems Command (BMDSCOM)] — primarily responsible for the development and testing of the SAFEGUARD System
- SAFEGUARD System Evaluation Agency (now TRADOC Systems Analysis Activity) — independent evaluation
- Army Air Defense Command — projected user
- Atomic Energy Commission and Army Materiel Command — test requirements related to warhead section evaluation and demonstration.

In addition, the following agencies indirectly influenced the test program, where possible, to support common goals:

- Advanced Ballistic Missile Defense Agency (ABMDA) [now BMD Advanced Technology Center (BMDATC)]
- Defense Nuclear Agency
- Site Defense Program Office
- Air Force Agencies such as Strategic Air Command (SAC) and Space and Missile Systems Organization (SAMSO).

Meck System versus Tactical System

The capabilities of the Meck System were as near tactical as practicable. To support a test program starting in early 1970, the Meck System designs had to be committed before all of the development work on the various tactical subsystems was completed. Many of these design decisions were made in 1967, during the SENTINEL

time frame. At that time, area defense was the primary mission and a multisite deployment was contemplated. As a result, the test plan for Meck initially emphasized area defense. After the SAFEGUARD decision, testing shifted to the SAFEGUARD mission and was compatible with the tactical deployment schedules.

The Meck System ultimately evolved into a prototype SAFEGUARD Missile Site Radar System, which approximated essential features of the tactical system. However, it differed from the tactical system in several aspects.[27–30]

- A Perimeter Acquisition Radar was not installed at Meck because the benefits to be derived did not appear to warrant the expenditure. Other radars in the Kwajalein Atoll could fulfill the acquisition role, and prototype testing of the PAR could be performed at Grand Forks. The absence of the PAR required that the MSR be used at greater than tactical ranges.
- The targets used in system tests at Meck, to a large extent, emulated those specified in the tactical design threat. However, limited system resources (i.e., only eight precision target-track channels with three data processors installed) and the need to obtain data that was well defined required that the test targets used be accompanied by a minimum of debris. The final sustainer stage was emplaced to ensure that the experiment was conducted in a controlled environment.
- The number of SPRINT and SPARTAN launch cells at Meck was limited to four and two, respectively, as compared to planned tactical complements an order of magnitude greater.
- Only three processors were used during Meck testing compared to ten in tactical. Computer capacity was further restricted by the necessity to perform the nontactical function of real-time flight-safety calculations.
- Only two faces were implemented on the Meck MSR as compared to the four faces on the tactical MSR. The primary threat direction of approach at Grand Forks was essentially centered on the overlap region between two MSR faces. The orientation of the Meck faces was such that targets launched from Vandenberg Air Force Base approached at an angle of about 63 degrees from the bisector of the two faces.
- The Meck installation did not include a system similar to the Ballistic Missile Defense Center (BMDC); therefore, internetting concept testing was not possible.
- Because of hardware, software, and threat environment restrictions, battle-strategy testing was not feasible at Meck. Such testing was left to simulation at the TSCS in Madison.

Test Targets versus Design Threat

One of the major influences on the test requirements was the threat against which the Meck System should be evaluated. This was dictated, in part, by the threats defined for the SAFEGUARD System. The Design Evaluation Threat, as outlined in the Data Processing System (DPS) Performance Requirements for the MW1 process,[1] was a guide for determining the Meck threat parameters. Traffic-related characteristics (i.e., rate of delivery of RVs) were not included, since it was not considered meaningful to overload the Meck System capability with high-performance targets at the expense of obtaining useful, controlled data. Such system stressing was better evaluated by means of simulations.

A comparison of the reentry vehicle characteristics used in the Meck System Test Program with the design threat indicated an excellent match, even though the basic Meck targets were obtained from existing Air Force and Navy inventories. Although a Fractional Orbit Bomb System (FOBS) was considered part of the threat, no FOBS-like targets were presented to the Meck System, leaving this threat to be evaluated via simulations.

SAFEGUARD Hardware Facilities and Functional Capabilities

SAFEGUARD facilities were emplaced on two islands in the Kwajalein Atoll: Meck Island and Illeginni Island. Figures 5-2, 5-3, and 5-4 show the facilities available on these two islands. The Meck Island control building housed the two-faced MSR and MSDP. The launch area on Meck consisted of four SPRINT and two SPARTAN launch cells, the respective missile assembly buildings, and related ground support equipment. Illeginni Island had two SPRINT remote launch cells, which were actively

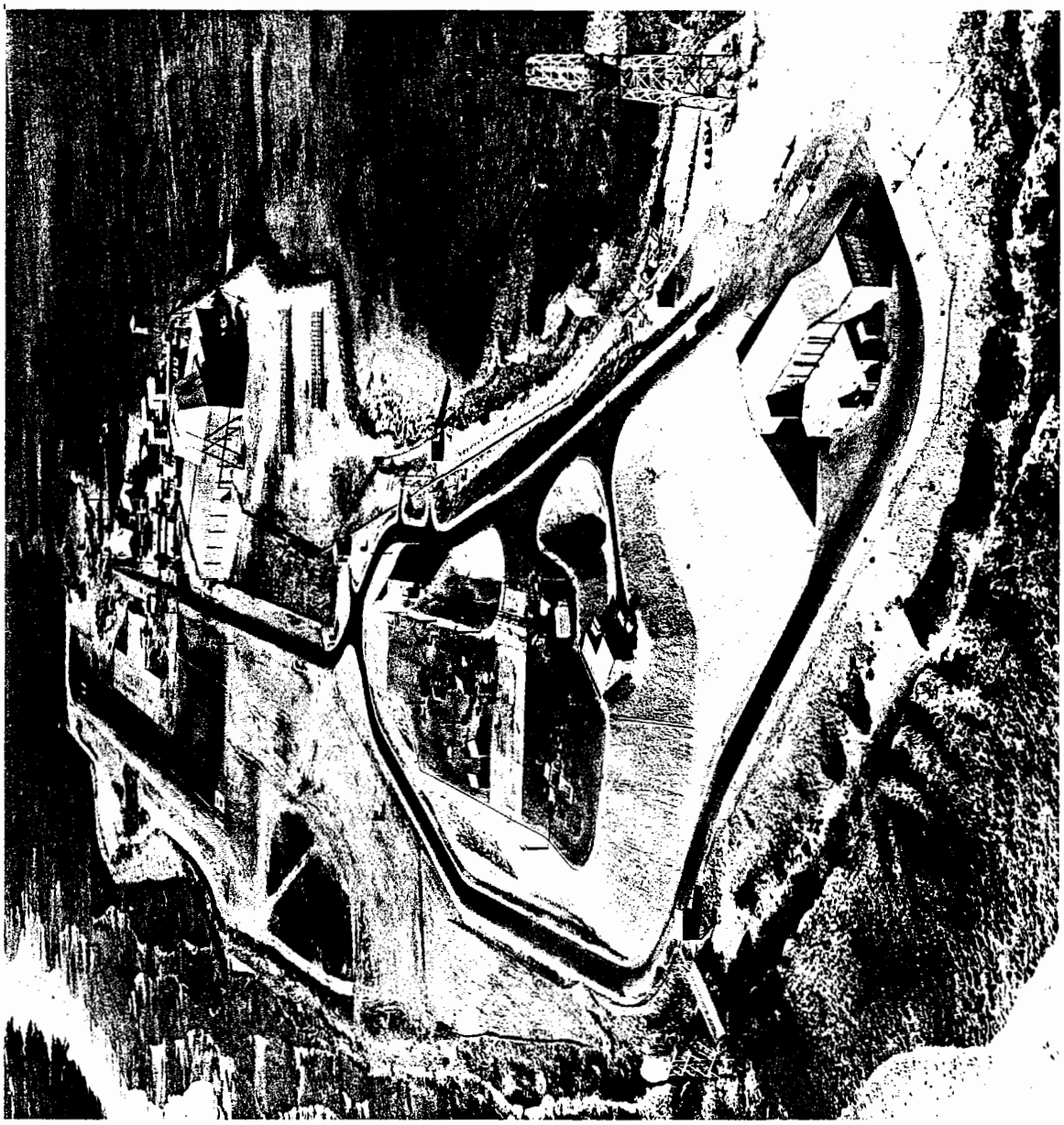
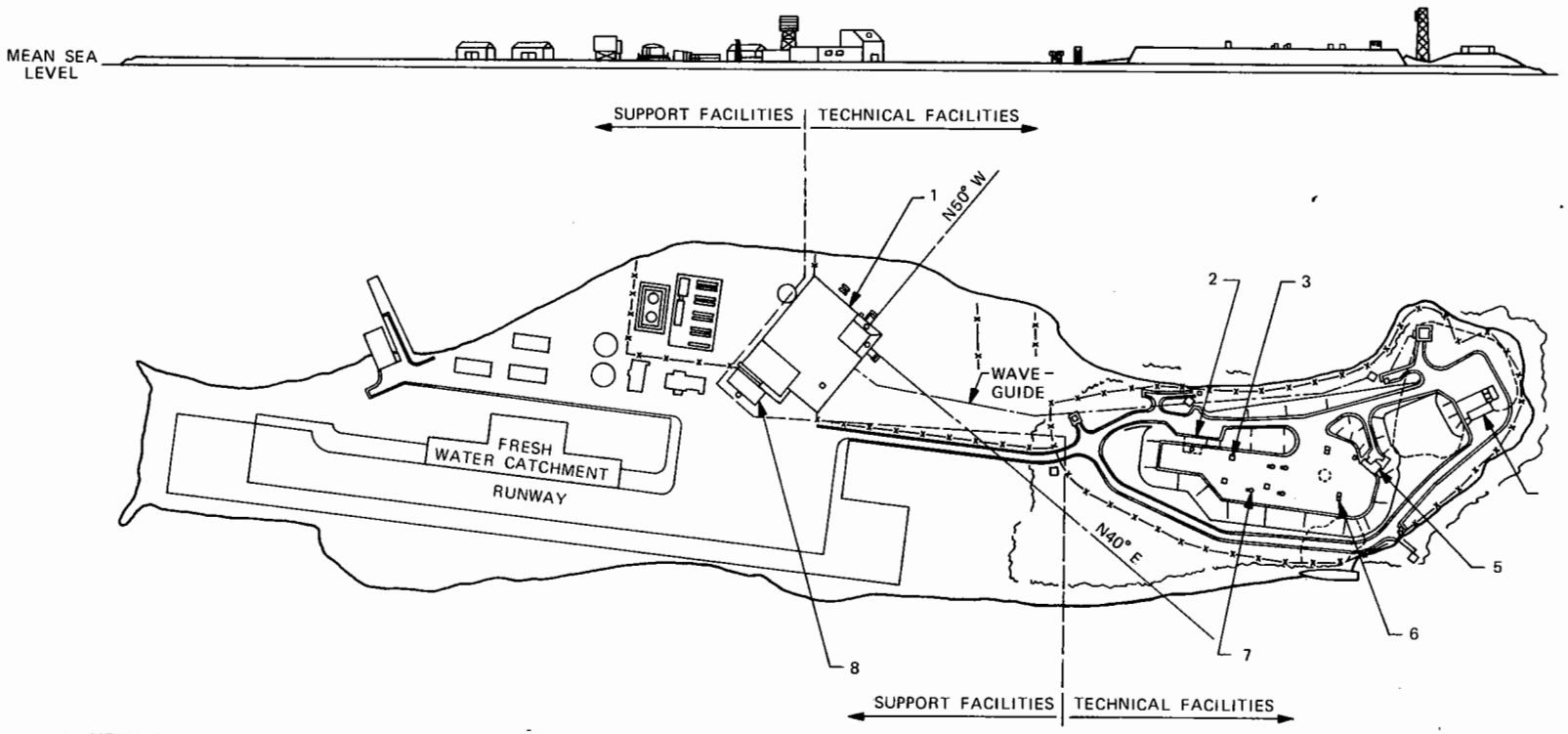


Figure 5-2. Meck Island Installation



1 MECK ISLAND CONTROL BLDG.

2 SPRINT MISSILE ASSEMBLY BLDG.

3 SPRINT LAUNCH AREA ANTENNA (3)

4 SPARTAN MISSILE ASSEMBLY BLDG.

5 SPARTAN LAUNCH EQUIP. ROOM

6 SPARTAN LAUNCH STATION (2)

7 SPRINT LAUNCH STATION (4)

8 LAUNCH OPERATIONS BLDG.

Figure 5-3. Meck Island Facilities

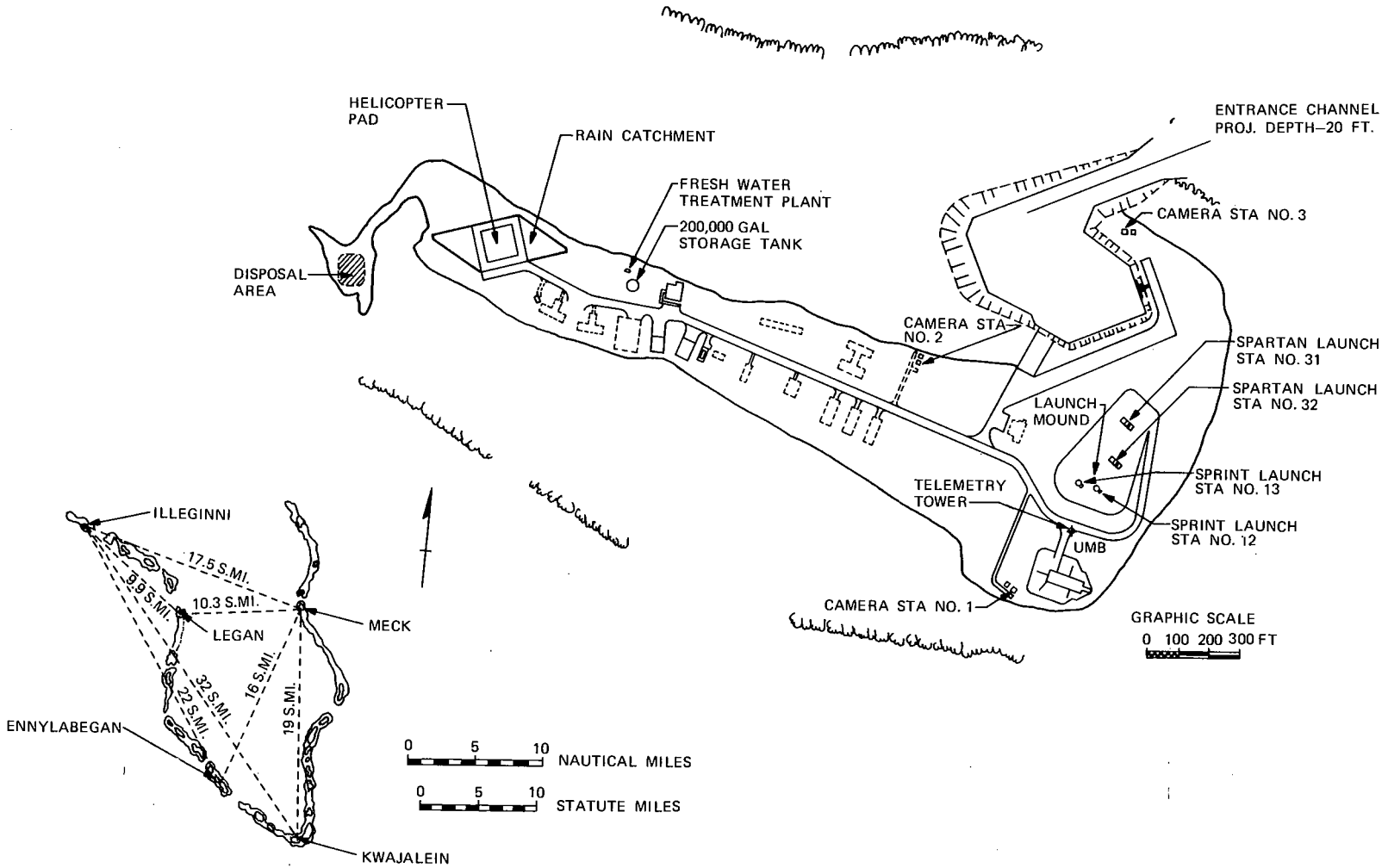


Figure 5-4. Illeginni Island Location and Site Plan

used, and two SPARTAN cells, which were built in anticipation of the possible inclusion of remote launch SPARTANs in the SAFEGUARD deployment. Additional details are contained in the Meck Island System Description.[31]

The functional capability of the Meck System was incrementally developed and was compatible with the planned test program, dictated by the deployment schedule and threat assumption. During the final tests, the Meck System capability was as near tactical as necessary to satisfy the evaluation requirements. As the tactical system design evolved, the Meck System was modified to reflect this refined capability. Table 5-2 summarizes the SAFEGUARD System capability additions for Meck testing.

System testing in support of SAFEGUARD started in 1970. Prior to that time, subsystem checkout and integration was achieved using a software package known as M-0. The M-0 process continued to evolve and was used for subsystem test, calibration, alignment, and maintenance, independent of the M-1 and M-2 processes that followed.

The initial system software capability (M-1), which predated both the SAFEGUARD production decision and the evolution of the tactical designs, allowed relatively early verification of basic concepts and provided preliminary data to support basic evaluation objectives.[32]

The capability of the second version (M-2) reflected the selective refinement and augmentation of M-1 functions in accordance with the SAFEGUARD System tactical performance requirements. The capability additions planned for M-2 were implemented in six revision stages, defined as M2 Revision 17 (M2-R17) through M2 Revision 20 (Revisions R1 through R16 were implemented in M-1). The first of the M-2 revision stages was operational in August 1971 and the last in early 1974. The major functional capabilities introduced in M-2 are listed below.

- M2-R17 — An essentially complete SPARTAN intercept function containing all major tactical SPARTAN functional capabilities, including external-sensor and sequential-state vector inputs to exercise the SPARTAN interceptor capability in the PAR/SPARTAN mode over its complete field of fire. It also included track-function capabilities to provide tactically representative target tracking for SPARTAN engagements.
- M2-R18 — Initial SPRINT intercept, tracking, and target-selection function capabilities for evaluation of SPRINT (collocated or remote launch) engagements over the complete SPRINT free-intercept guidance mode field of fire. It also included tactical endoatmospheric target selection based on target slowdown characteristics.
- M2-R18E — Remaining SPRINT tactical functional capability including the controlled-intercept guidance mode.
- M2-R19 — Expansion of the track functional capability to include tactical track initiation, and resolved-target wake track for aspect angles less than 75 degrees. High-fidelity Digital Target Environment Simulation (DTES) was added to allow accurate simulation of heavily waking single and multiple targets.
- M2-R19E — Expansion of the waking-target functional capability to include resolved target wake track for all aspect angles. Also included target selection using the Gamma filter.
- M2-R20 — Surveillance modifications for tactical detection and acquisition performance in a dense target environment (Tactical TC-3 search). Also contained target-track capability to include unresolved-target wake track, cluster track, and track-through-tank breakup of multiple resolved and unresolved targets at all aspect angles.

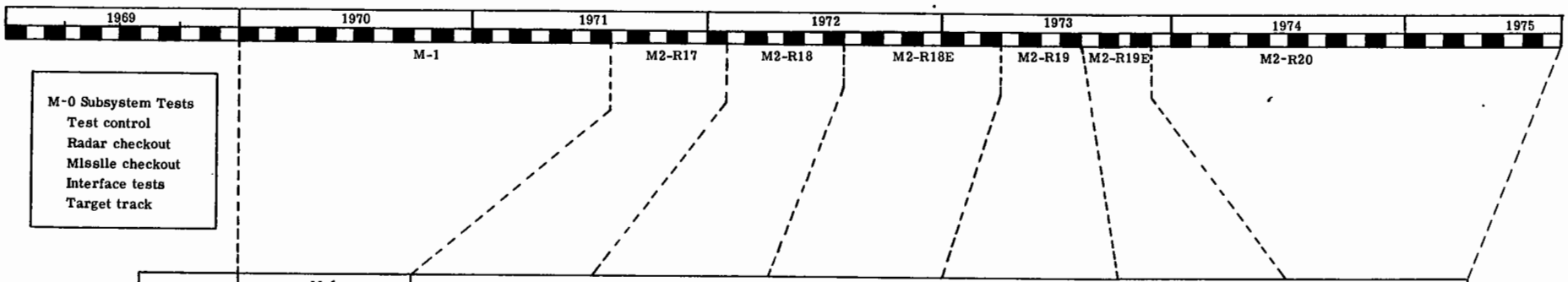
Further explanation of M-2 functional capability is provided in the SAFEGUARD System, M-2 System Functional Requirements and Description.[33]

Data Recording and Reduction Facilities at Meck

Data gathered with the Meck System was recorded on one or more of the following devices: magnetic tape recorder, analog video recorder, digital video recorder, brush strip recorder, line printer, and teletypewriter.

Magnetic tape was used for most of the data including encoded-radar replies, MSR/MSDP interface data, intermediate results of calculations performed within the MSDP, and timing of significant system events. The recording subsystem

Table 5-2
Meck Capability Additions



Function	M-1	M-2					
	M1P-4	M2-R17	M2-R18	M2-R18E	M2-R19	M2-R19E	M2-R20
Surveillance	Sector and special search Target handover from external source	None	Debris mapping special search (D4 Mode)	None	Acquisition I	None	Tactical TC-3 search Detection clustering Doppler mismatch and side lobe rejection filter
Track	Face-to-face handover Eight channels (maximum) Crossing targets Null tracking Coast	Tactical track filter Tactical MSR track/ SPARTAN interface Refraction correction Off-axis data gathering	Tactical automatic, manual data rates True redundant track and external sensor handover Force T3/Inhibit T1 Crossing target track Automatic force coast on slot basis	Extended range T2 mode tracking	Tactical coast, reacquisition, and handover Tactical track initiation Resolved target-wake track for aspect angles < 75° Variable Gate Tracking	Resolved target - wake track for all aspect angles Chi square validity tests	Tactical track initiation Unresolved detection Cluster track Track through tank breakup Extended range search Range resolution search
Target Selection	Average RCS Geometrical position Fine frequency (data gathering only)	Two point external sensor interface with SPARTAN	Endoatmospheric target selection New RCS signatures	None	Dual threshold endo-atmospheric target selection Beta filter	Gamma filter	None
SPARTAN	Minimum-time guidance Salvo Burst delay timer	Tactical third-stage guidance Tactical dive guidance Intercept bias Tactical SPARTAN/MSR track interface SPARTAN redesignation Sequential state vector	SPARTAN 20-Hz track KREMS interface New flight-safety program	SPARTAN/SPRINT salvo capability	Sequential state vector salvo Forced jet-head ignition	None	None
SPRINT	Minimum-time guidance Salvo Burst delay timer	None	Tactical SPRINT guidance and MDP SPRINT remote launch Free-intercept guidance First-stage guidance Extended-range SPRINT	Controlled-intercept guidance Capability bias SPRINT salvo replacement Post-intercept aero test mode Taped-target intercept mode	None	None	None

had ten conventional tape units and two high-performance magnetic tape recorders. Data recorded on the latter was stripped and re-recorded on the conventional units before it could be reduced on the IBM 360 computer.

The analog video recorders consisted of four 16-mm motion picture cameras mounted on four dual-sweep oscilloscopes. Each device could be assigned to display and film either sum-channel or angle-channel video from any of the eight target-track channels or two missile-track channels.

The digital video recorder encoded sum-channel A-scope video over a selectable 6-kft, 30-kft, or 60-kft range interval and recorded it on magnetic tape with digital identifiers. The data could be displayed on a Cathode Ray Tube (CRT) in the MSDP or reduced by the IBM 360 computer to produce various plots and listings. This video recorder could record data from all eight track channels, and recorded data could be reviewed immediately after a mission since no film had to be processed.

The two 120-channel brush strip recorders recorded (1) data gathered while testing interceptor missiles when they were still in the cells, and while sending orders to the in-flight missiles, and (2) the timing of significant system events. These data were available for immediate analysis.

Line printers printed summary data on MSDP performance and certain significant system events upon completion of a test. Hardware malfunctions detected by fault detection programs were printed on teletypewriters.

Since the MSDP was fully utilized while supporting software, hardware, and system testing (even on a three-shift basis), a second computer was used to support data reduction and other non-real-time supported software activities. Thus, most reduction of recorded data performed at Meck was done on an IBM 360 computer with the following output devices: three line printers, one Gould electrostatic plotter, one CALCOMP plotter, and one card punch.

Range Support Facilities

The Kwajalein Missile Range (KMR) range support facilities consisted of equipment and facilities used to obtain data and determine vehicle performance. Telemetry, metric, and signature data were acquired by electronic and optical tracking systems to evaluate environment, control functions, propulsion, airframe, and guidance systems on a vehicle. Figure 5-5 gives the locations of range instrumentation sites in the Kwajalein Atoll.

The following KMR facilities were used in the SAFEGUARD System Test Program:

- Telemetry systems
- Instrumentation transmitters and receivers
- Photo/optical systems
- Meteorological services
- Communications (general)
- Closed-loop television
- Timing
- Target Track Radar (TTR) at Kwajalein
- Radars at Roi-Namur.

The KMR radar facilities at Roi-Namur, operated by Lincoln Laboratories, are of special interest; ALCOR, ALTAIR, and TRADEX radars contributed actively as data sources.

Program Coordination with Other Agencies

The test requirements received from various interested agencies were evaluated and incorporated as appropriate into the Meck System Test Program (MSTP). Figure 5-6 depicts the test planning cycle that followed and shows the various other activities that were included, such as target negotiations, resource procurement, and safety studies. It also shows the documentation, mission certification, and data analysis related to the overall Meck System Test Program.

The Meck System Test Program,[34] prepared by Bell Laboratories, contains a broad summary of the entire test program and basic plans for each mission, and represents the coordinated program of all agencies. Periodic meetings of the System Test Working Group provided a forum

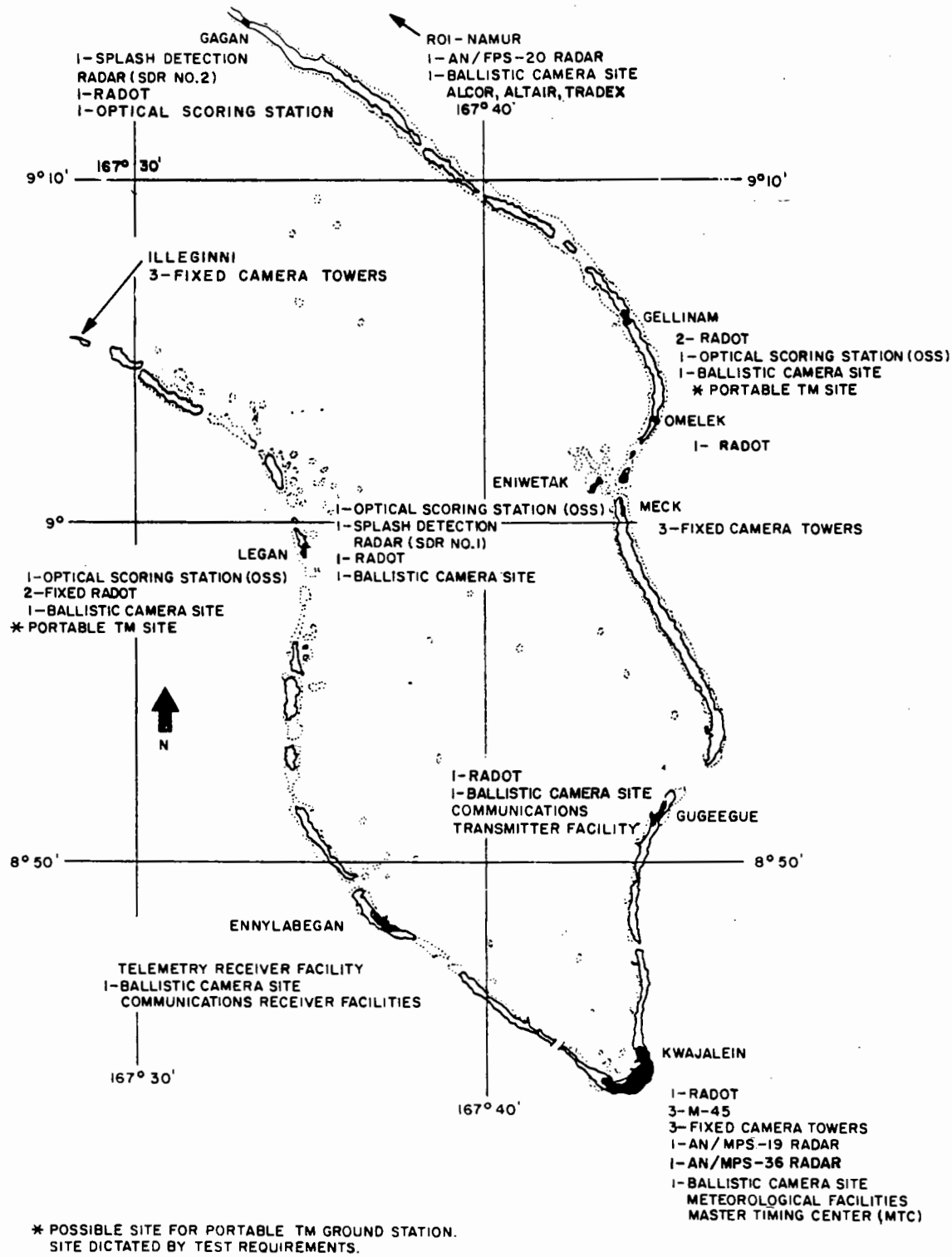


Figure 5-5. Range Instrumentation Sites in Kwajalein Atoll

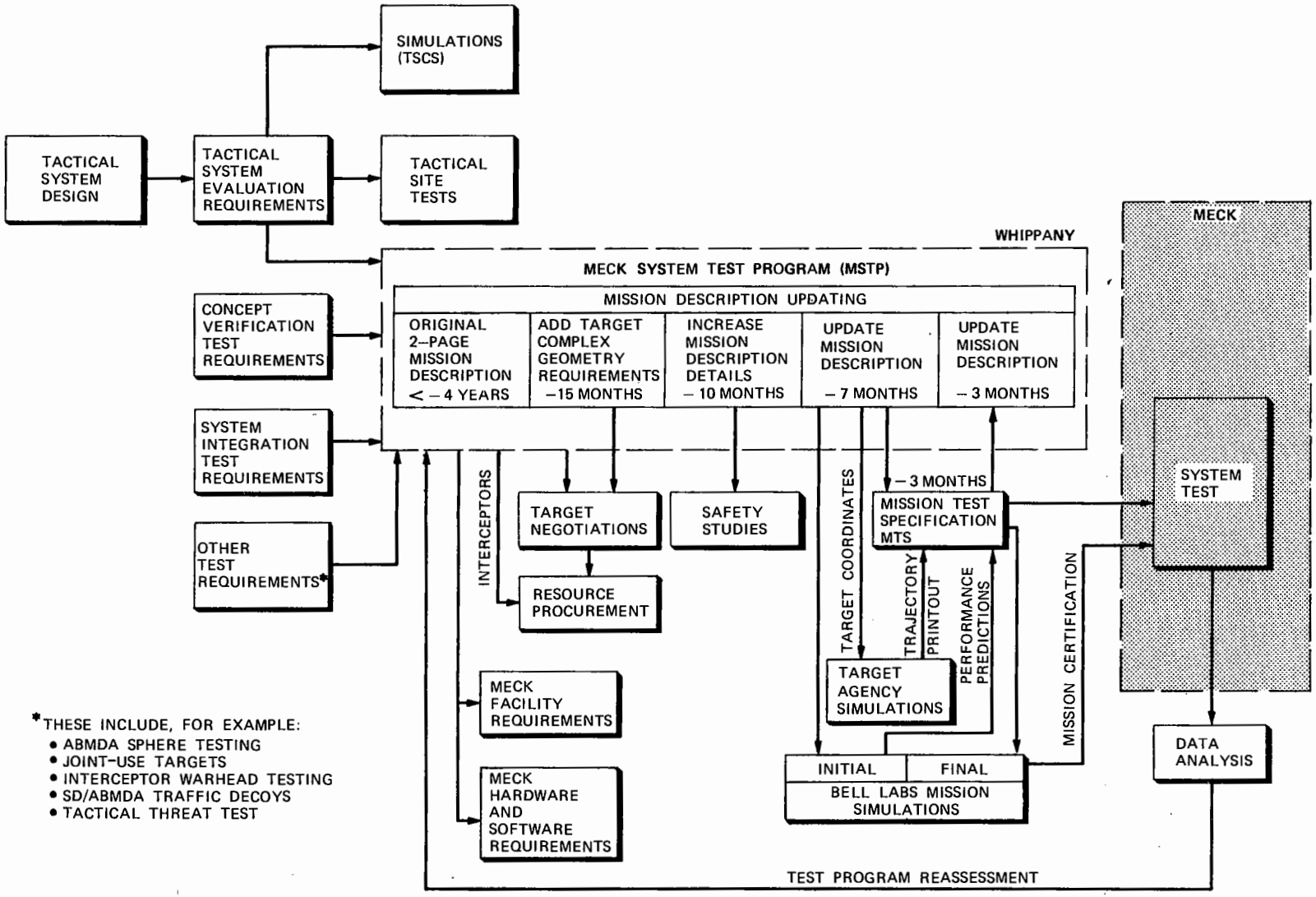


Figure 5-6. Test Planning Cycle

for test-planning discussions among the interested agencies. Likewise, implementation details of each test were discussed at periodic Test Program Review meetings with those agencies specifically responsible for test and target procurement and implementation.

The nominal target procurement cycle (see Figure 5-7) started when the Ballistic Missile Defense Systems Command (BMDSCOM) issued a Scope of Work to the Air Force, for ICBM Minuteman I and Titan II targets, and to the Navy for Intermediate Range Ballistic Missile (IRBM) Polaris missiles.[35] The Air Force and Navy then contracted appropriate studies and the necessary target software/hardware. Initial lead times were two or even three years. Approximately 230 days before the target mission, Bell Laboratories, through either the Army (BMDSCOM) or Navy (SPO), issued a Targeting Requirements Confirmation Report, which officially finalized the desired targeting and missile configuration for a specific mission.

The SPARTAN and SPRINT interceptor missiles used in the Meck System Test Program constituted a potential hazard to the lives and property of inhabitants within the Kwajalein Atoll and up to 350 nautical miles outside the Atoll. The Flight Safety System (FSS) held this hazard probability to an acceptable level. The FSS consisted of (1) a missile-borne Flight Termination System (FTS), a real-time computer program within the MSDP Software System that detects a potentially hazardous trajectory and starts the missile destruction, and (2) the Flight Safety Console (FSC), which provides enough data to an operator to allow detection of a potential hazard and manual initiation of missile destruct. In addition, mission planning for the Meck System

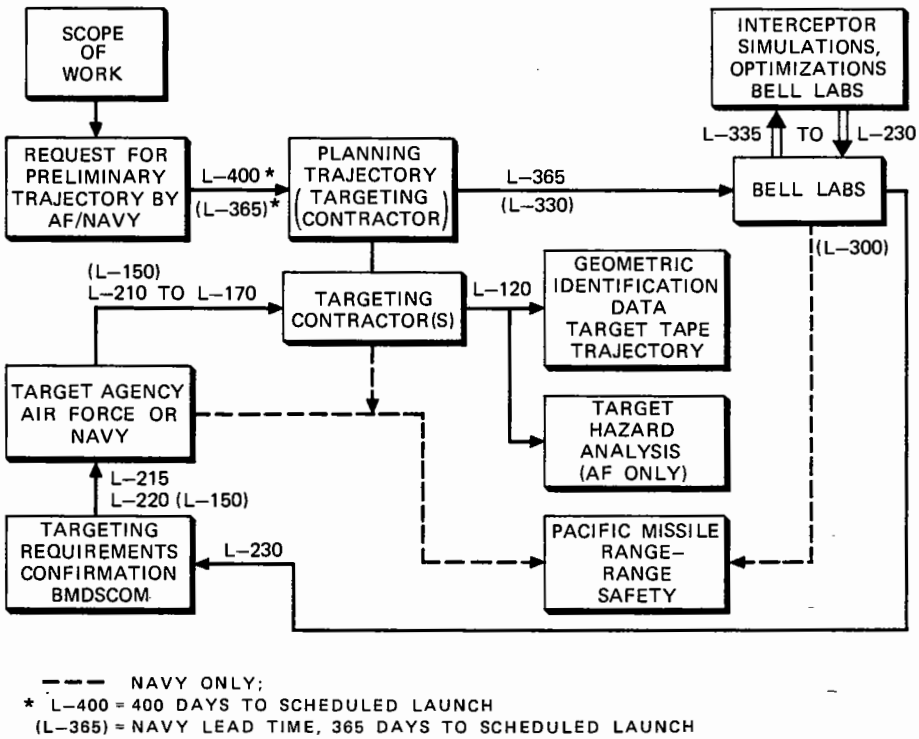


Figure 5-7. Target Procurement Cycle

Test Program excluded interceptor missiles from unsafe portions of their capability volume.

As with interceptor flight safety, target flight safety was directly concerned with the problem of protecting inhabited land masses from target vehicles and/or target debris. Determining applicable constraints was always an in-line function of the test planner in designing system tests.

Program Planning and Mission Design

As Bell Laboratories and other interested agencies supplied test requirements, planning was initiated to incorporate these requirements in the test program. A number of factors had to be considered in developing an efficient and integrated plan. Because the Equipment Readiness Date (ERD) and Initial Operational Capability (IOC) date were fixed, the program completion date was inflexible. As a result, the total number of individual missions that could be undertaken was clearly limited. Interceptor-evaluation requirements were matched to radar-evaluation requirements, and jointly dictated the target characteristics and trajectory geometry. In addition, the state of system development dictated the sequence in which requirements could be fulfilled. A feasible program also had to result in a minimum expenditure of target and interceptor resources.

As shown in Figure 5-6, individual mission designs were documented in the MSTP as early as four years prior to the planned mission date. This early documentation showed the broad objectives of the mission and provided descriptive information, including target type, planned trajectory, interceptor type, and intended intercept location.

As individual mission design progressed, proposals were submitted to the System Test Working Group for support of previously unfulfilled objectives. Until about eight months prior to the mission, more details were added in terms of secondary objectives and, in some cases, tertiary objectives. Concurrent with the assignment of objectives were flight safety considerations and special requirements concerning the geometry of each target complex. Target requirements also included special payload features, such as calibration-reentry spheres.

Extensive simulations (see System Simulation) established that the mission design was compatible with the Meck System and that reasonable assurance of success could be attained. During this detailed planning stage, a Manual Interaction Simulation (MIS) plan was established for the mission. The MIS plan permitted preplanned software control of complex sequences of display console operations in a mission environment, thus exercising the process software in a repeatable fashion. This technique, while developed initially to provide repeatability in the certification environment, was used later during the missions to reduce the number of operator actions that had to be performed in real time.

Finally, three months before the mission, the Mission Test Specification[36] was issued for review and approval by BMDSCOM and all interested agencies. The Meck System Test Program[34] was repeatedly updated to contain a current account of each of these missions as they developed in detail, as well as a current description of the total test program. At one month, Bell Laboratories at Meck published a Mission Test Plan[36] for each mission to define operational details.

Premission and post-mission documents are listed for each mission in Reference 36.

Test Requirements Memorandum

A mechanism, established in 1968, permitted the initiation of subsystem tests on Meck hardware, in addition to the more formally scheduled system test activity. To implement such a test, the requester issued a Test Requirements Memorandum (TRM) describing the test, including data requirements and perhaps an estimate of the man-hours and equipment time period. Bell Laboratories at Whippany, New Jersey, and at

Meck Island coordinated the test into the Meck activity schedule. Test results and data were delivered to the requester; in some cases, a formal report was also issued.[37]

Later in the program, this TRM procedure was expanded to include not only hardware-related tests, but also tests related to specific data-gathering tasks. The intent was to maintain control and coordination over the many tasks that Meck was asked to perform, so that proper scheduling and priorities could be established. Almost 150 TRMs were logged. Table 5-3 lists some of the more significant ones as examples of the type of activity performed under this heading.

Process Verification, Function Integration, and Mission Certification at Whippany and Meck

The complexity of Meck missions and the expense of conducting them (target, interceptor, and range-support costs) dictated that each mission be carefully planned and certified prior to its execution. A procedure established at Whippany and Meck provided reasonable assurance that the mission would be successful. Comprehensive dispersion simulations of both target and interceptor were performed in the Central Logic and Control (CLC) environment.

The Meck System software was verified, integrated, and certified prior to a live mission to establish a high level of confidence in the mission design and performance of the Meck System, exclusive of interceptor hardware. These tasks were undertaken to exercise all portions of the Meck System, both software and hardware, that would be used during SAFEGUARD missions. Live interceptors were not fired during this process.

Figure 5-8 depicts the software development cycle beginning with (tactical) system requirements and culminating with post-mission analysis. Briefly, separate software functional specifications were prepared for each of the major design areas, i.e., Surveillance, Track, SPRINT Guidance, Sensor Control, etc. From these individual specifications, each of the major design areas generated software code essentially independent of the other major design areas. (Inputs to and outputs from each major area, i.e., interfaces, were defined early in the design phase.) Each major area was responsible for testing its own code, i.e., unit testing. When all design areas successfully completed unit testing, the code was delivered to a process construction team that integrated the major blocks into a single software

Table 5-3
Examples of Significant TRMs

TRM-40A,B,C & D	High-power transmitter tests to determine the cause of waveguide breakdown under high duty cycle conditions
TRM-89	Track of TRANSIT satellite by MSR, TTR, and ALCOR radars to determine biases between data collected by each radar
TRM-93	Track targets of opportunity, HK-1 and HK-2, to obtain data on Minuteman I tank breakup and effect of Titan II fuel on breakup phenomenon (HK-2 was also a joint-use mission)
TRM-95[37]	Gather data to determine MSR biases between the two faces
TRM-97	Gather data on SPRINT firing of an aged motor
TRM-104 and TRM-105	Gather additional data on targets of opportunity involving Mark 11 and Mark 12 reentry vehicles
TRM-110	Gather Minuteman tank debris data to determine footprint for target safety consideration
TRM-133	Gather data on SPARTAN flight test of production motors from IMCO

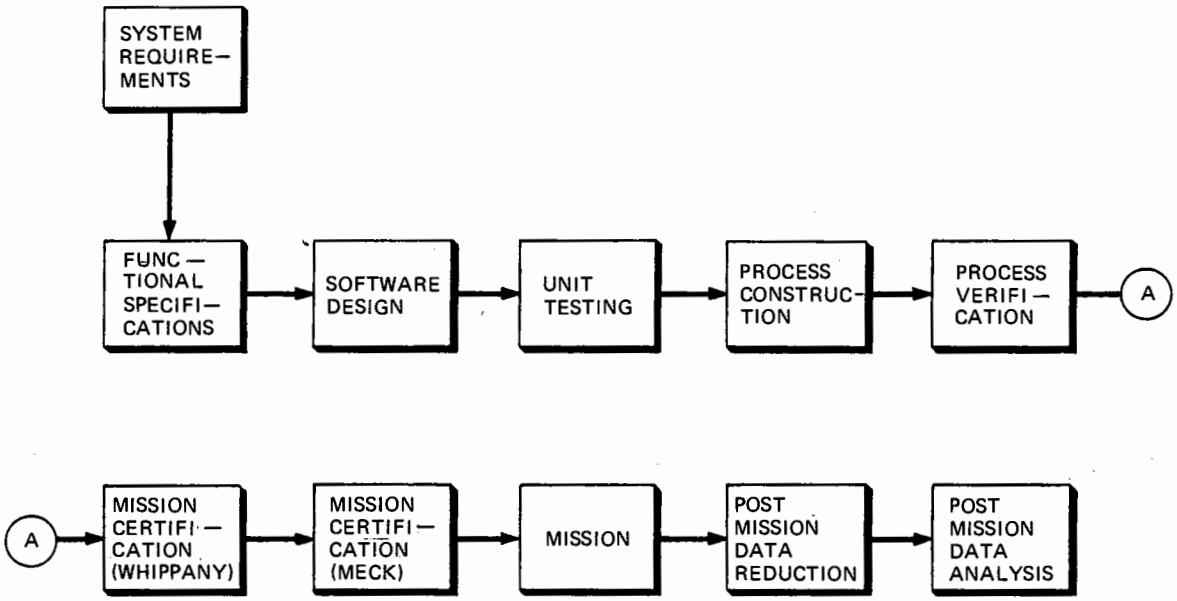


Figure 5-8. Software Development Cycle

package (process) and placed it under configuration control. The process was then verified on the CLC, the computer for which the code was designed, by testing it against a software simulation of the target environment and major subsystems (radar, missiles, etc.). This verification was used to regression test all the capabilities that existed in previous versions of the process and verified proper implementation of any new capability. This procedure terminated with what was basically an acceptance test for the process – a simulation of the most difficult mission anticipated during the life of the process. The verification validated both the major functional blocks and the support software (operating system, data reduction program, etc.). Upon completion of the verification procedure, the process was delivered to Meck Island and design control shifted to the Whippany Certification Group.

At Whippany, a series of "certification" tests tailored to each planned Meck mission was defined to further exercise the software process in a simulated-mission environment. The major difference between process verification and mission certification was that verification was used to check out the new "nominal" performance of the system, while certification was specific with respect to each mission and purposely attempted to stress the system at the most pessimistic extremes of the test in order to expose failure mechanisms or otherwise sensitive areas. To this end, various target and missile anomalies were simulated and the system responses were noted. The certification goal was to establish a high degree of confidence that the software subsystem and mission design would satisfy the mission objectives under a wide variety of adverse conditions.

When Meck received the new process, the process verification tests were repeated using the more complete facility. That is, it was no longer necessary to rely on software simulation of the MSR and its interfaces since an Analog Tactical Environment Simulator (ATES) allowed for actual MSR transmission and provided reply signals to the IF receiver of the radar on up to five discrete targets and two wakes in a beam. The Meck process verification was then followed by mission certification for each mission. This

certification consisted of an ATES rerun of the tests performed at Whippany, plus additional tests designed by the Meck test planners. Again, the ultimate objective was to prepare for each mission in a manner that would give the highest degree of confidence in the ultimate success of the mission. Just prior to each mission, a performance-prediction estimate was prepared delineating the expected performance and outlining the potential problem areas uncovered during the mission-preparation period.

Finally, the mission was conducted, data reduction was accomplished, and the performance analysis was undertaken.

Throughout this verification and certification cycle, functional analysis determined the correct implementation of the system design specification. A comparative analysis technique was used. Independent FORTRAN simulations of the primary functions, tracking and guidance, were developed and used to generate time sequences, order streams, etc., which were then compared with similar parameters generated on the CLC. These parameters were checked for reasonableness and consistency between the two simulations. A large number of mission-reliability runs were performed under the control of the MIS plan (see Program Planning and Mission Design). Without the problem of human response time, the simulations were highly repeatable and performance discrepancies were easily detected. Discrepancies were thoroughly investigated and understood before each mission was conducted.

The verification and certification procedures exposed several design flaws that had to be corrected in the Meck System and in the tactical design. The depth of premission testing was a significant factor in the high degree of success achieved in the test program. Indeed, the actual mission sometimes seemed to be an anticlimax. Each mission, of course, was the vital validation of the preceding simulations.

Premission Radar and Missile Checkout

In addition to the routine day-to-day system checks to assure that the systems and subsystems were operating properly, a series of premission tests was performed that assured readiness to support each mission. In the case of the radar, built-in test equipment and a small computer capable of providing an order stream to the MSR were used for off-line testing. In addition, the M-0 process in the MSDP fed a set of specific orders to the radar hardware causing the radar to react in a predefined manner. This routine checked out the radar, the MSDP interfaces, and data recording. In addition, signals from an antenna on a far-test pole provided off-axis calibration of the radar and location of failed antenna cartridges. Tracking the test pole and calibration-quality spheres provided a calibration constant, which permitted direct readout of target-radar cross section and overall radar system performance analysis. The data collected was used in Post-Mission Data Analysis (POMDA).

A variety of physical radar targets deployed locally by small rockets, aircraft, or balloons was considered for premission and post-mission radar calibration. However, only balloon-lifted spheres were used extensively as SAFEGUARD targets. Most spheres were 12 inches in diameter and were of radar-calibration quality. They were also used to verify system performance and to furnish an accurate amplitude reference for analyzing recorded data. On the average, about 4 spheres were used per week, amounting to roughly 1000 over the entire SAFEGUARD Meck System Test Program.

Premission missile checkout included sending steering and discrete commands to the in-cell missile and noting the response on the telemetry monitors. In addition, during the last few seconds before lift off, the missile underwent go/no-go tests to determine readiness to launch.

Mission Summary Information

SAFEGUARD missions were conducted for a variety of test purposes. Some of the missions were not part of the original evaluation plan but were in response to requests from other agencies. Much of these data were useful to the system evaluation effort.

Post Mission Data Analysis

Bell Laboratories and its subcontractor, Calspan Corporation, expended significant effort in performing timely analysis of mission data to confirm expected performance or, if possible, to permit the identification and correction of any system deficiencies prior to the next mission. The first step handled at Meck provided a preliminary statement of system performance for inclusion in 4-hour and 48-hour reports after each mission. At CONUS, the data was analyzed and presented at a Post Mission Data Analysis (POMDA) meeting within six weeks after the mission. Representatives of all interested design areas attended the meeting. The representatives made note of unexpected performance and quickly set out to understand, explain, and, if necessary correct the problem areas.

Bell Laboratories/Meck completed their summary of post-mission data by publishing a Final Mission Test Report[36] within 90 days after the mission. Calspan Corporation also issued a series of post-mission reports:[36]

- Mission Data Summary Memorandum, which presented MSR data in a series of plots to be used as a tool for mission analysis and function evaluation
- Target Data Summary, which summarized the results of MSR data relating to the target-delivery system performance
- Mission Data Analysis Summary Report, which summarized the results of the primary analysis of MSR performance.

Mission Description and Results

The charts that follow summarize the major characteristics of the system test missions conducted at Meck since early 1970. Table 5-4 summarizes the concept verification phase of the test program during which major SAFEGUARD System firsts were achieved. Successful completion of these milestones permitted the timely commitment of manpower and funds to the development of the SAFEGUARD System as a viable concept.

Table 5-4
Concept Verification

Missile Type	Target Type		Concept Verification Objective
	Simulated Target	ICBM or IRBM	
SPARTAN	M1-1, M1-1A*		First SPARTAN launch at Meck
		M1-4	First live-target intercept
		M1-30	First salvo
		M1-7, M1-7A*	First two-face IRBM intercept
		M2-1	First external data intercept
		M2-3	First in-flight redesignation
SPRINT	M1-9, M1-9A*		First SPRINT launch at Meck
		M1-12	First live-target intercept
		M1-13	First salvo
		M1-8	First two-face IRBM intercept
		M2-7	First remote launch
		M2-7	First remote-launch intercept

*Where two missions are shown, the first attempt was not completely successful.

Mission failures are referred to in several of the summary charts. Note that of the 70 missions conducted, 12 were listed as failures. Of these, four could be attributed to target problems, three to SPRINT missiles, three to SPARTAN missiles, one to data processing hardware, and one to a target-classification error due to a mission-peculiar attribute. Seven of the eight SAFEGUARD-related failures were successful missions in a second attempt. This information is summarized in Table 5-5.

Figure 5-9 presents the broad aspects of each of the Meck missions showing the interceptor type, the target type, the date of the mission, and the software configuration in use at the time. Mission numbers enclosed in rectangles or ovals identify the twelve missions classified as failures.

Figures 5-10 and 5-11 summarize the location of each interceptor flight in the capability volume. Interceptors are classified according to target type and the two pairs of salvos are identified.

Table 5-6 summarizes radar evaluation missions in M-2, highlighting target type versus trajectory geometry.

Table 5-5
Summary of Mission Results

	M1 Series	M2 Series
Missions	13	50
Successes	12	46
Failures	5*	7‡
Missions Repeated	4†	3§
Total Operations	17	53

*M1-1, Data Processing; M1-9, SPRINT; M1-7, Target; M1-14 and M1-14A, SPARTAN W/H.

†M1-1A, M1-9A, M1-7A, M1-14A. (M1-14A counted here, although conducted during M2 Series.)

‡M2-42 and M2-14, SPRINT; M2-20, MSR tank-classification error; M2-44, Target; M2-28, no target deployment; M2-245, SPARTAN; M2-36, Target.

§M2-42A, M2-20A, M2-245A.

Table 5-6
Radar Evaluation with Waking Targets

RV	Trajectory Geometry		
	Radial	Offset	Fly By
MK-6	M2-1 M2-31*	M2-10 M2-14	M2-27
SV-2B	M2-2 M2-7 M2-11 M2-35* M2-135*	M2-15	M2-25 M2-46* M2-146*
SV-3	M2-22	M2-18	M2-38
SV-4C	M2-24	M2-20A	M2-28†

*Primary objective was to gather data to evaluate response to RV flying through active tank breakup.
†No data due to target failure.

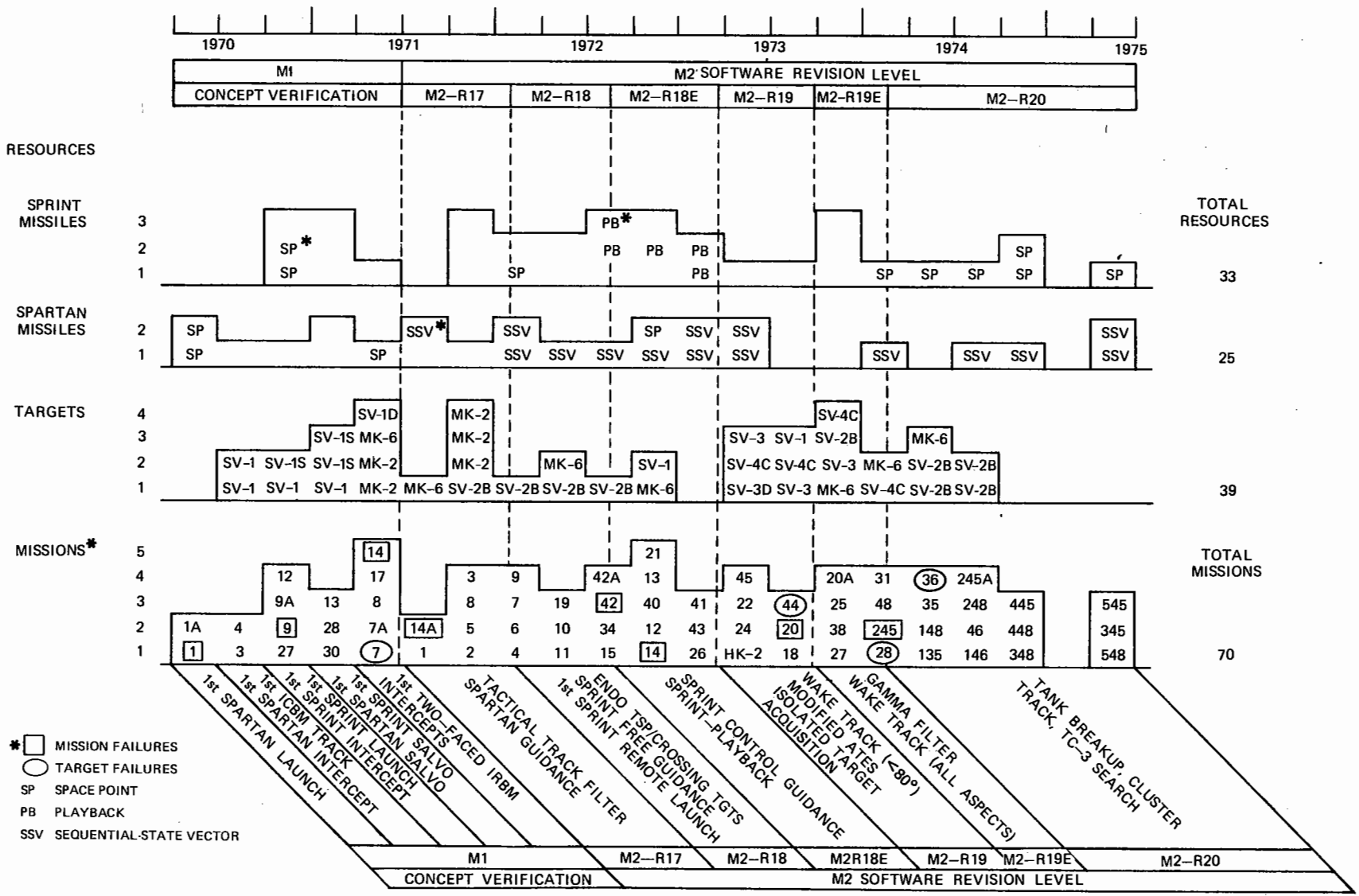


Figure 5-9. Meck Mission Summary

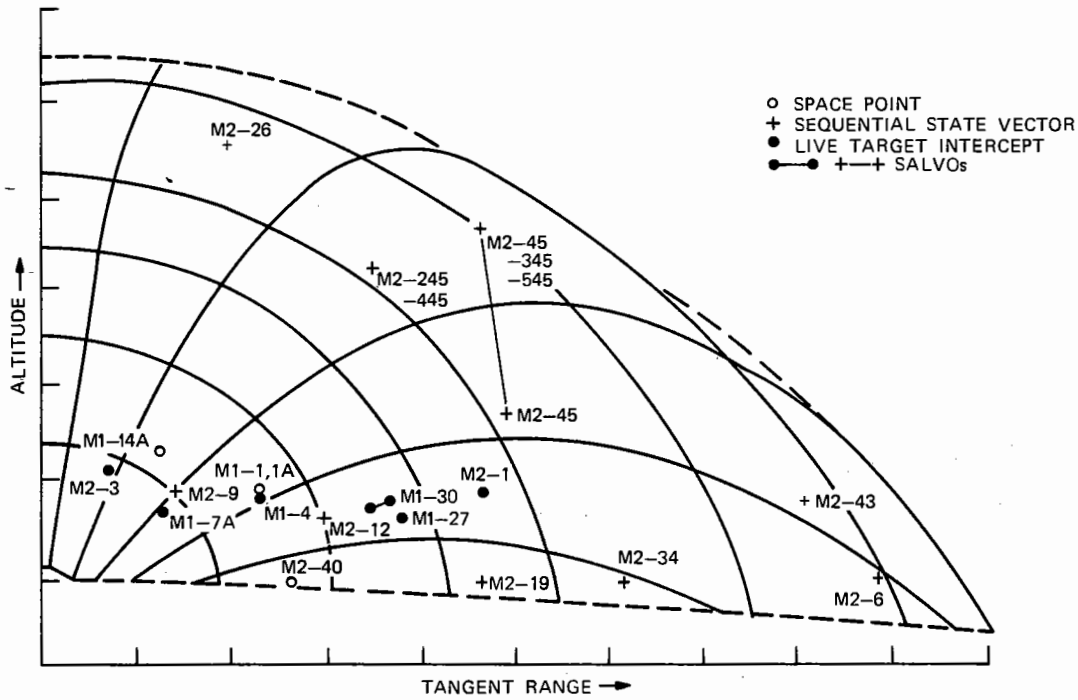


Figure 5-10. Summary of SPARTAN Intercept Locations

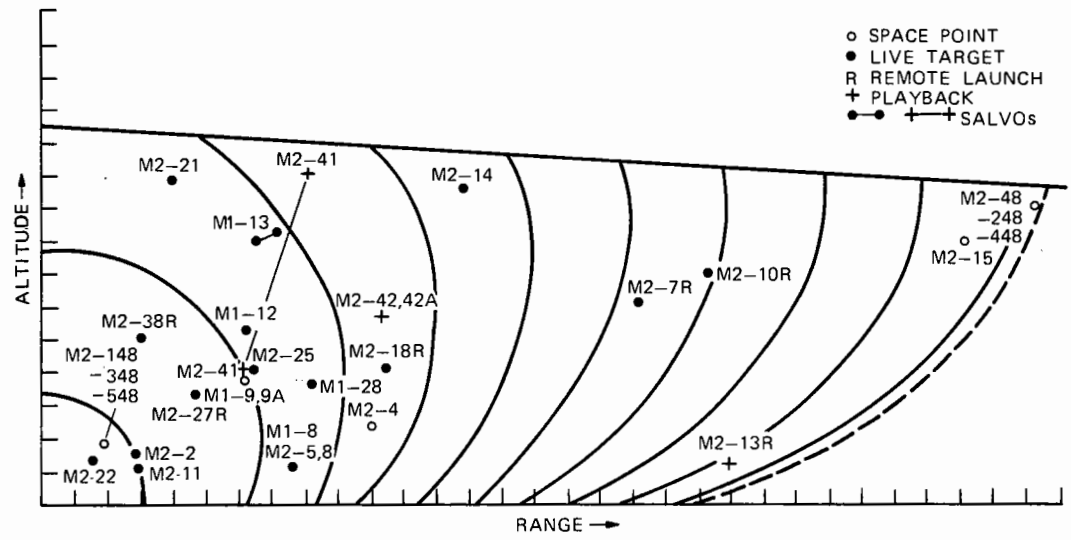


Figure 5-11. Summary of SPRINT Intercept Locations

Targets of Opportunity

The extensive tracking resources of the MSR were attractive to many Air Force programs involving reentry-target complexes targeted into the Kwajalein Atoll area where reentry data could be obtained. These Targets of Opportunity (TOOs) were frequently used as dynamic targets to checkout the SAFEGUARD System at Meck prior to a major system test. In addition, they provided targets to satisfy data requirements related to specific SAFEGUARD engineering tests requested by various design groups. Non-SAFEGUARD agencies (such as BMDATC and the Air Force) also requested MSR data on other targets of opportunity and were generally accommodated on a noninterference basis.

Using Western Test Range (WTR) numbers, Figure 5-12 tabulates the targets of opportunity (TOOs) that Meck tracked. The shading categorizes them according to their status. An "engineering test" status was given to TOOs where some interest was shown in the data and the operation could be conducted on a strict non-interference basis with no hold-status guarantees available on the target launch. "Required" status was reserved for specific TOOs where a strong interest in the data required participation even at the expense of rescheduling other activities. "Mandatory" status was given to only one TOO, which was upgraded to a joint-use target, where the SAFEGUARD project was able to influence payload and trajectory characteristics and obtained guarantees of hold status on the target launch. The TOOs identified with a "none" status were used by Meck personnel for system checkout with no data obligations. Participation in many of the TOOs resulted in useful MSR data packages, which were made available to the Air Force and other agencies. This figure also identifies the TOOs that were used to satisfy Test Requirements Memoranda (TRMs).

System Test Incentive Program Summary

Since 1971, the Bell Laboratories SAFEGUARD contract with BMDSCOM has included System Test Incentives as part of the Scope of Incentive Criteria and Evaluation. From the beginning, an important ground rule was adopted; no "out-of-line" additional effort could be expended on a mission because it was incentivized. Table 5-7 summarizes the major system test events that were incentivized for each fiscal year.

Miss distance, for incentive purposes, is defined as the scalar distance between the interceptor and the intended aimpoint at the time of warhead-command burst. This was considered to be the best yardstick for evaluating total system performance, and therefore, played a major role in the establishment of the System Test Incentive program. Although miss distance could be measured by independent sensors, it was decided that the SAFEGUARD Systems calculation of miss distance using the MSDP would suffice for incentive purposes. A series of documents[36] summarized miss distance obtained on each mission, using independent sensors on most of the live-target intercepts, and tabulated these measurements with the MSDP self-scored miss distance.

Miss Distance Measurement Techniques

The most significant, single indicator of the success level for an intercept-test mission is miss distance. The contract required that miss distance be measured by a means independent of the SAFEGUARD System to verify the quality of the internal measurement.

Significant effort was required to select acceptable methods for obtaining the independent real-time measurements. To be acceptable, the methods had to be of acceptable cost, have timely availability, and produce measurements of adequate accuracy.

Fortunately, a large background of experience was available on which to base the selection of methods. The single-path doppler system, successfully employed in the NIKE-ZEUS era, was initially favored because of its very high accuracy and demonstrated reliability. However, after completing the initial stages of

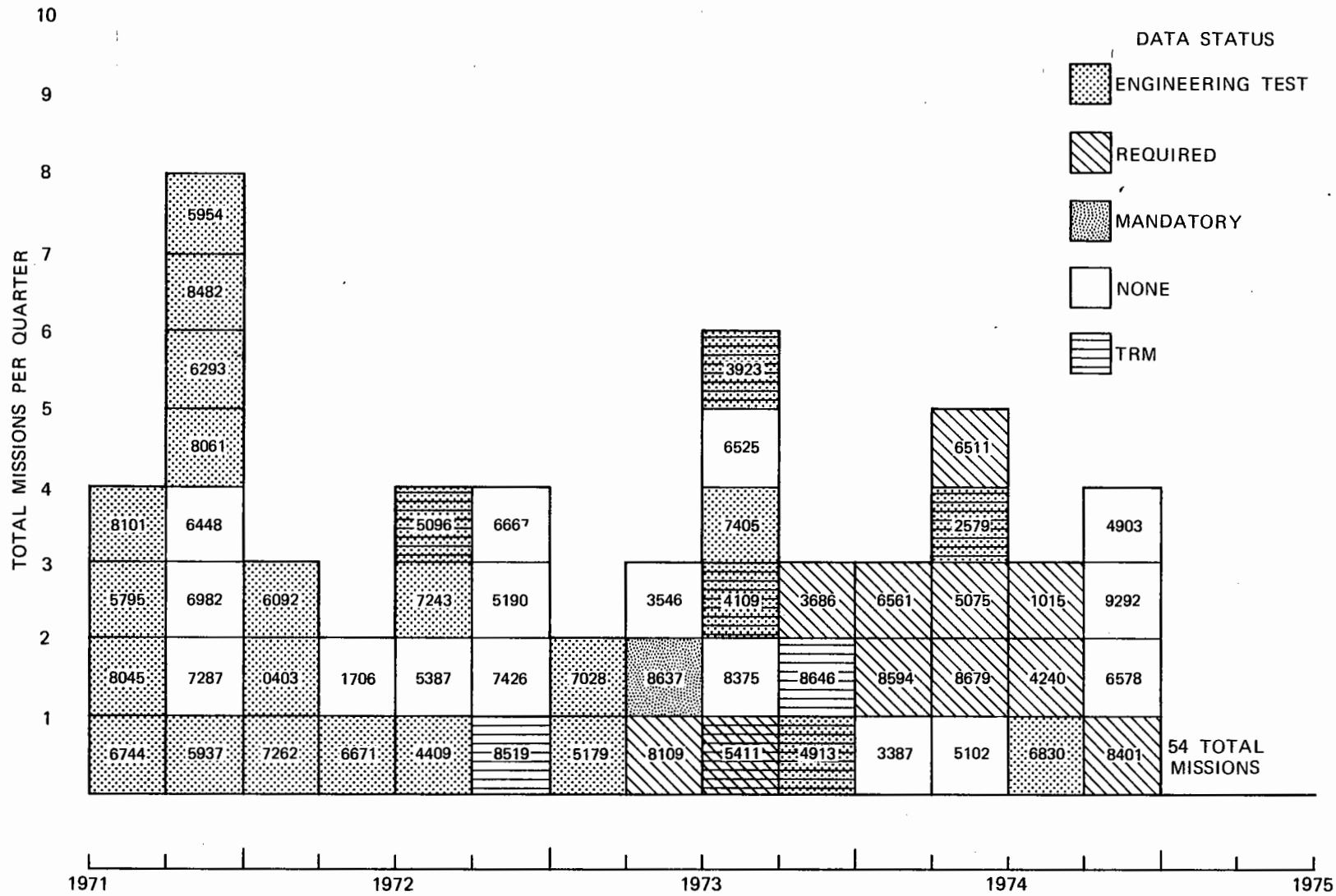


Figure 5-12. Targets of Opportunity Mission Summary

Table 5-7

Summary of System Test Incentives

Fiscal Year	Major System Incentives	Mission Number	Completion Date (GMT)	Contract Points	Points Earned	% of Maximum
1971	First SPARTAN Intercept	M1-4	August 29, 1970	10	10	100
	First SPRINT Firing at Meck	M1-9 M1-9A	October 29, 1970 December 5, 1970	10	6	60
	First SPRINT Intercept	M1-12	December 24, 1970	10	10	100
	First SPARTAN Salvo	M1-30	January 12, 1971	10	10	100
	First SPRINT Salvo	M1-13	March 17, 1971	10	10	100
	Miss Distance		May 7, 1971*	10	8.33	83
1972	First SPARTAN Intercept Using Tactical Guidance	M2-1	August 28, 1971	12	12	100
	First SPRINT Remote Launch	M2-7	March 17, 1972	18	18	100
	Miss Distance		July 16, 1972*	30	24.64	82
1973	Miss Distance		July 21, 1973*	35	22.61	65
1974	Miss Distance		November 30, 1973*	15	15	100
			Total	170	146.58	86

*Date of last mission included in calculation.

adapting this method to the SAFEGUARD environment, the technique was abandoned because of cost. The lesser but acceptable accuracies of other recourses yielded higher cost effectiveness.

Three techniques for independently measuring miss distance[38] were principally employed during the series of SAFEGUARD intercept-test missions.

The TTR/ALCOR* "two-radar solution" was the principal recourse for the relatively long-range SPARTAN intercept missions. In this technique, one of the radars continuously tracked the target while the other tracked the interceptor. Any biases between the radars was powerfully determined by simultaneously tracking the target with both radars until it was necessary to switch one to tracking the interceptor. Backup was provided by processing the data obtained during the interval when both objects were contained in each radar beam.

The TTR or ALCOR "single-radar solution" was the principal recourse for the relatively short-range SPRINT intercept missions. In this technique, the radar tracked the preferred reference object (usually, but not necessarily, the target) throughout the mission, and recorded range data and angle-off-beam-center data for each radar pulse occurring during the interval when the other object was passing through the radar beam.

*TTR = Target Track Radar, ALCOR = a member of the three-radar complex of the PRESS Project at Roi-Namur. Each is a high-performance C-band tracking radar.

The network of Recording Automatic Digital Optical Trackers (RADOTs) served as a major backup for SPRINT intercepts, furnishing photo-optical triangulation whenever at least three of the eight separately-located instruments were not obscured by weather.

For each intercept mission, all available results from primary and backup sources of independent miss-distance measurements were collected into a coordinated report. This facilitated applying the results to the evaluation of miss distance as determined in real time and recorded by the MSDP of the SAFEGUARD System. The independent measurements yielded target-to-missile separation versus time. Evaluation of the SAFEGUARD function required interpretation of success in computing the time-of-burst and in delivering the burst-command signal to the interceptor.

INTEGRATION AND DEMONSTRATION TESTING AT TSCS AND SITE

Early in the SAFEGUARD development cycle, the problems associated with system testing of SAFEGUARD were recognized and planning was initiated for the extensive testing program that would be required following basic function-integration testing of the software processes [MW, PW, and BMDC Weapons Process (BW)] at TSCS and later at the tactical sites.

A SAFEGUARD System Integration and Evaluation Test Plan (SIETP)[39] was developed and documented, which provided detailed plans for accomplishing the following objectives:

1. Integration of the three sites (PAR, MSR, and BMDC) into a smoothly operating system and verification of interfaces
2. Verification of the baseline system-performance capability against the design evaluation threat
3. Determination of the system-performance limits, the limiting subsystems, and functions using extensions of the design evaluation threat
4. Evaluation of the system-overload response and degraded-mode capability.

Objectives 1 and 2 were addressed by a series of approximately 12 basic tests. The initial tests of the series did not include threat traffic but were limited to satellite background, and were designed to thoroughly test the system interfaces and Command and Control (C&C) subsystem, including displays and manual actions. The remaining tests exercised the total system in the three basic system-operating modes (Accidental Launch, Pindown Response, and Minuteman Defense), utilizing nominal threat-traffic levels.

Objectives 3 and 4 were addressed by a series of 25 additional tests designed primarily for system evaluation, which provided increasingly severe system environments (nuclear and clutter) to probe the limits of system capability and provide increased traffic, well into the system-overload regions. These tests, as well as the initial series, were to provide an extensive data base for validating the system simulations, which could then be utilized to extend the evaluation in whatever direction was appropriate, including variations in the offensive threat.

In the spring of 1973, the SAFEGUARD program received significant redirection as a result of the Strategic Arms Limitation Treaty (SALT I) agreements. The limited-defensive capability provided by a single site made an extensive evaluation of system capability less appropriate and the program objective shifted in direction to obtaining operational experience with deployment, operation, and modification of a complex Antiballistic Missile (ABM) or similar system. These factors, as well as significant adjustments in schedules and funding, called for a System Test and Evaluation Program more limited in scope and designed to support additional basic objectives.[40]

In addition to supporting the objectives of initial system integration and verifying the baseline system-performance capability, the revised system test program[40] was structured to meet the following objectives:

- Provide a convenient and satisfactory vehicle by which the installed netted system could be accepted by the Government

- Provide a series of major tests which would serve as a tool in the post-IOC time period for assessing system operability and readiness on a continuing basis [System Readiness Verification (SRV)]
- Provide a limited data base for system simulation validation.

The resulting test program consisted of eight basic tests. As in the previously described program, the first three provided for integrating the three sites and verifying the interfaces and Command and Control subsystem. The remaining tests exercised the netted system in the three basic operational modes at nominal traffic levels and at nominal threat parameters.

System Integration Testing

SAFEGUARD System testing made extensive use of the system exerciser subsystem (hardware and software), which is a part of the tactical configuration at each site, to facilitate assessing operability on a continuing basis. The exercise subsystem simulates the threat environment and responds to tactical-software engagement planning by simulating defensive missiles. An off-line facility, the SAFEGUARD Threat Action Generator (STAG), generates a Site Threat Trajectory File (STTF) tape, which provides offensive trajectories and threat parameters to the system exerciser. (STAG is a software facility that enables simulation of a threat for use by the system exerciser.) In addition to producing the threat tapes, STAG can produce Site Information Tapes (SIT), which simulate intersite communications.

The initial integration tests were performed first at the TSCS with each software process operating in the "local" mode, i.e., unnetted with the rest of the system and with SIT simulating the other sites. Local-mode tests were conducted to establish software sanity and correct any software deficiencies that became visible. Local-mode tests were followed by "netted" tests with real-time intersite communications (no SIT) and STTF tapes synchronized so that each site observed the identical threat. Extensive recording during the test run, together with off-line data reduction, permitted detailed investigation of software problems and analyses of functional performance.

The local and netted tests were run repeatedly over a period of several weeks to establish the reliability of system response and to ensure that most, if not all, software problems had surfaced during the runs and had been corrected. Following satisfactory completion of a test sequence at TSCS, the identical sequence was repeated at the tactical site.

Acceptance Testing

Using the system test program as a vehicle for Government "acceptance" of the installed system imposed a number of specific requirements on the program. The means by which these requirements were implemented are illustrated in Figure 5-13 and described in the following paragraphs.

The planned system acceptance tests, as described in the System Integration and Evaluation Test Plan[40] were reviewed with

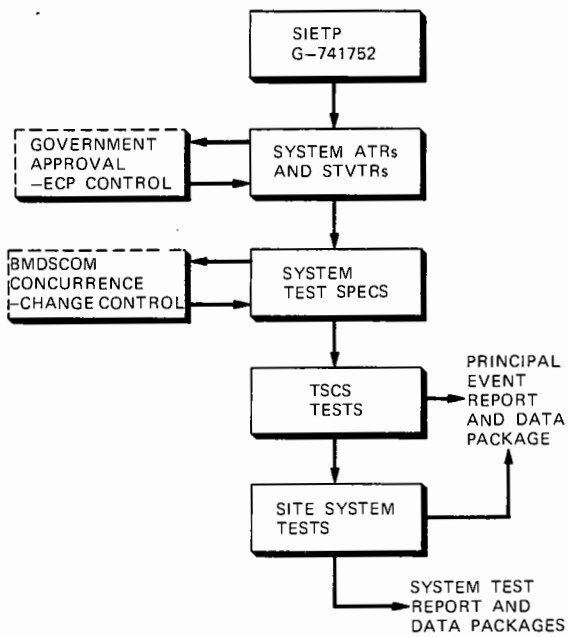


Figure 5-13. SAFEGUARD System Test Program

BMDSCOM. The review was conducted to ensure that the tests adequately covered all basic system operational modes and threat variations. In a number of instances, additions and/or modifications to the tests were made at the request of BMDSCOM.

System performance criteria and specific performance bounds were established for each of the tests. In developing performance criteria, the following guidelines were used:

1. The number of pass/fail criteria were minimized by utilizing system-level criteria rather than detailed functional-performance criteria
2. Performance bounds were established such that a properly operating system should pass a given test on a single run
3. The set of criteria was sufficiently comprehensive that an improperly operating system could not go undetected
4. The pass/fail criteria for each test should permit rapid assessment of test success.

The performance criteria[41-45] [Acceptance Test Requirements (ATRs) and System Technical Verification Test Requirements (STVTRs)] were subject to Government concurrence and approval and were documented along with detailed test descriptions in System Test Specifications (STSs).[46-50] The STS documents were placed under formal change control and required BMDSCOM concurrence prior to modification.

In line with the rapid-assessment guideline (4 above), a system data-reduction program was developed to extract, from the considerable quantity of data recorded, that data relevant to the system performance criteria. The program provided, in a very readable format, the information necessary to verify the pass/fail status.

The acceptance test criteria were applied only to the tests conducted at the tactical site. As each of the tests was concluded at the TSCS, however, a report and data package was provided to BMDSCOM.

System Readiness Verification Tests

As indicated previously, the system exerciser subsystem was part of the tactical configuration at each site to assess system operability and readiness on a continuing basis. The expected variability in overall system response had to be well characterized for any tests to be used for readiness testing. The tests utilized for integration and system acceptance testing met this requirement and, therefore, were used for the System Readiness Verification exercises. The complexity of the SAFEGUARD System and complex interactions between functions were such that, although the ultimate outcome of an exercise in terms of defense level was predictable, the path taken through the system to achieve that result was quite variable and repeatable to only a limited degree. Statistical variations, in not only the threat parameters but in functional performance within the system, produced variations in performance that were totally proper system operation but quite unpredictable.

The system tests were repeated many times at TSCS and at site, in addition to being simulated via the system simulation. Therefore, a large data base was available from which to draw functional performance bounds for SRV exercises.

To avoid the need for off-line data reduction to appraise the results of an exercise, facilities were provided in the tactical software to make the information readily available. During an exercise run, information concerning detection tracking, discrimination, and engagement of a threatening object was output to a high-speed printer. At the conclusion of the exercise, information from the weapons process was combined with system exerciser data, and a "quick look" report on engagement results was provided via the printer.

Evaluation and Simulation Verification

System simulations were used extensively in connection with the system test program. Simulation results were used in the following ways:

1. Design of the test scenarios to ensure that the desired functional capability was being exercised

2. Selection of performance criteria for acceptance tests to be indicative of overall system response and capability
3. Fine tuning of the performance bounds to ensure that a properly operating system would pass and that system deficiencies would be detected with high confidence
4. Predictions of total system response to a particular scenario such that anomalous performance could be quickly identified for further analysis
5. Indications of the expected variability in system response due to relatively low probability occurrences and estimates of the probability of a particular response occurring.

Item 5 in particular was a major time saver with respect to test analysis. The stochastic nature of the system inputs (threat) and performance of system functions frequently produced results that initially appeared to indicate system deficiencies. However, analysis indicated that, in most cases, these results were normal system response to low probability events.

MAJOR CHALLENGES AND INNOVATIONS

Evaluating a test program as complex as the SAFEGUARD System presented many problems. Compounding these was the time frame involved. Many of the innovative techniques proved to be more effective than anticipated.

Cost Effectiveness of System Evaluation

Considerable resources were spent on the system evaluation organization — a department-size effort in-house, augmented by a subcontractor simulation development and test data analysis effort of approximately equal size. This investment led to the development of an in-depth analytical capability that otherwise could not exist with the tight schedules in the design or test organizations. Applying this capability to the analysis of system performance led to identifying and resolving fundamental system problems that required simulation-based analysis owing to their complex and interactive nature (e.g., track and intercept of waking targets in a tank-breakup environment, traffic management, and overload response). Similarly, this detailed understanding of functional performance allowed significant contributions to the quality and efficiency of the key SAFEGUARD test programs — Meck, MSR site, PAR site, and TSCS. System evaluation inputs were particularly useful in defining a relatively small number of test scenarios that stressed all key aspects of functional performance, predicted system test response through simulation, and defined data-recording/data-reduction requirements tailored to expedite the analysis of known performance problems. In summary, the cost of the system evaluation program was well justified by the results — a significantly stronger system design and higher quality test programs.

Multisimulation Approach to System Evaluation

Developing a family of complementary simulations rather than a single, large simulation embodying both broad scope and extremely detailed models proved most effective. Separate simulations were developed for detailed analysis of radar and missile functional problems, in addition to the total system simulation. This approach allowed a great deal of flexibility in the approach to analyzing a particular problem. In particular, the long delays in obtaining analysis results, which are necessarily associated with the use of a single large simulation, were avoided.

Iterative Approach to Analysis of Complex System Problems

It is most efficient to first analyze a given system problem with the simplest model possible, then use the insight gained to build an intermediate-level simulation to probe key areas further, and finally, put the appropriate level of detail into the system simulation. This approach significantly improves the cost effectiveness of system simulation development effort by avoiding a uniform level of detail in the models — too detailed in some areas and not detailed enough in others. Most important, it maximizes the timeliness of the results by allowing insight based on analysis with simple models to be factored into project decision-making sooner than would be possible with the more detailed simulation models.

System Exerciser Evaluation

Insufficient resources were devoted to an evaluation of System Exerciser (STAG, EMX, and EPX) fidelity and flexibility. This led to the relatively late discovery that a few of the key elements of system response (such as unresolved-target track of PAR) could not be accurately exercised with the automatic facility. The resultant crash program of exercise facility modifications and "work arounds," while successful, was an extremely inefficient use of resources. Further information on the System Exerciser is given in Chapter 4.

Requirement for Intermediate Level System Design Documentation

When the focus of the system evaluation effort shifted from analysis of the system design implied in the DPSPRs to analysis of the actual design implementation in MW and PW, it became apparent that a level of documentation falling between the DPSPRs and the process workbooks/coding specifications was required. It was not possible to maintain useful simulation development and modeling schedules when working from coding specifications. The required intermediate level of documentation, which was provided in time to allow the effort to proceed, is best exemplified by the PW Functional Design Requirements.

Evolution of Meck System Test Program

Major challenges to the planning and execution of the Meck System Test Program related primarily to fulfilling the major objectives of the program within economic constraints, which tended to change with varying funding pressures. An adaptive process resulted in which test planners established a carefully considered priority-ordering of the test requirements so that implementation costs could be weighed against value. Examples of challenges and innovations that were necessary are included in this section.

At the time the SAFEGUARD Meck System Test Program was initiated in early 1970, the Meck System test resources (targets and interceptors) planned for use in the test program through June 1974 were somewhat greater than those actually expended. Table 5-8 compares the final program to the February 1970 program. A number of factors contributed to these differences.

The test program was continually scrutinized for efficiencies which could result in economies to the test program. For example, increased emphasis on the use of simulated or taped targets for intercept purposes was justified by experience and subsequently resulted in the elimination of several targets.

Experience with azimuth diversity and exploration of the MSR face-overlap region using IRBM targets demonstrated that these factors were not as troublesome as originally feared. As a result, Bell Laboratories recommended the elimination of several IRBM targets.

The need for target-tracking tests of actual FOBS targets was weighed against development costs of FOBS. On the basis of our demonstrated ability to conduct realistic simulations, it was decided that TSCS exercises against simulated FOBS would be more cost effective.

Table 5-8

Resource Comparison Between Present and 1970 Version of Meck System Test Program

	1970	1975
SPRINT		
Meck	24	26
Remote Launch	6	7
Warhead	(8)*	(11)
SPARTAN		
Meck	26	25
Remote Launch	4	0
Warhead	(6)	(11)
ICBM		
Minuteman	33	26
Titan	7	7
FOBS	4	0
IRBM		
Polaris A2	6	4
Polaris A3	3	1

Note: Contingency resources were not included in this tabulation

*Parentheses indicate the warhead totals were included as part of the Meck or remote launch mission.

The development of the tactical system depended heavily on the evaluation of Meck test data. Timely analysis resulted in a continuing re-evaluation of the test program and provided additional emphasis on data for suspected problem areas. For example, additional target-tracking tests were added to better characterize tank breakup when it was found that a redesign of the system was necessary to perform RV data processing through tank breakup.

Additional economies in the execution of the test program were obtained using the operational concepts of mission pairing and mission coupling. It was found that, by observing reasonable constraints, a missile flight test could be paired with a target-tracking mission and we could achieve significant savings in the mission preparation and operation intervals. This reduced the total required man-hours and permitted maintaining and even increasing the pace of the test program.

The remote launch station on Illeginni Island supported a series of critical tests. The success there permitted it to be closed down after calendar year 1973, approximately 16 months before its planned closing. The cost savings justified this change even though the more tactical-like facilities at Illeginni were preferred for assembling and launching production SPARTAN missiles. The remaining production missiles were rescheduled for launch from Meck cells, with a minor compromise in shipping and handling and a significant saving in program costs.

An exhaustive set of highly repeatable simulations was made possible through the innovation of the Manual Interaction Simulator, which eliminated human response differences from repeated runs of the same mission. These mission reliability runs permitted early detection of non-normal system performance prior to each mission and thereby resulted in high confidence that the mission itself would run as expected.

Chapter 6

NUCLEAR VULNERABILITY AND HARDENING

Chapter 6.

NUCLEAR VULNERABILITY AND HARDENING

When planning the requirements for an ABM system, nuclear vulnerability and hardening are important considerations in establishing system performance objectives. The need for nuclear hardness stems from the system's role of providing a defense against offensive missiles which carry nuclear warheads through use of its own defensive missiles with nuclear warheads. This role requires a careful assessment of nuclear hardness requirements. Consequently, hardness has entered into system design to an increasing degree throughout the history of ABM development.

The need for system hardness was first recognized in NIKE-ZEUS, but it was not until NIKE-X and subsequent systems that challenging hardness requirements were established to provide effective defense of the system's own radars against multiple attackers. Throughout the evolution of NIKE-X, SENTINEL, and SAFEGUARD, hardware designs were carried out with hardness requirements in mind. Over the years these requirements changed and became more detailed, not so much because of changes in basic system objectives and tactics, but more because of a deeper understanding of nuclear phenomena. By 1968, an extensive program was getting underway to assure that hardness requirements were being met in all building facilities and subsystems. That activity continued until the end of the SAFEGUARD development effort.* The nuclear hardness requirements for SAFEGUARD were finally stated in three nuclear environment specifications: one for ground equipment[1] and one for each of the two missiles.[2,3]

ACHIEVING HARDNESS

The primary consideration for ground equipment hardness is the effect of enemy warhead bursts. An artist's view of the principal nuclear effects created is shown in Figure 6-1. Because of these effects, a "protection volume" is

*This chapter concentrates on the vulnerability and hardening effort associated with the SAFEGUARD Weapon System Equipment designed by Bell Laboratories. Over the same time period, other organizations within Bell Laboratories and AT&T Long Lines were studying the effects of Electromagnetic Pulse (EMP) on Long-Haul Communications for other defense applications. Between 1969 and 1974, Bell Laboratories and Long Lines participated in a program established by the SAFEGUARD Communications Agency (SAFCA) to assess the effects of EMP on SAFEGUARD Communications. The conclusion reached was that existing common carrier facilities with relatively modest changes would meet SAFEGUARD requirements in an EMP environment.[4]

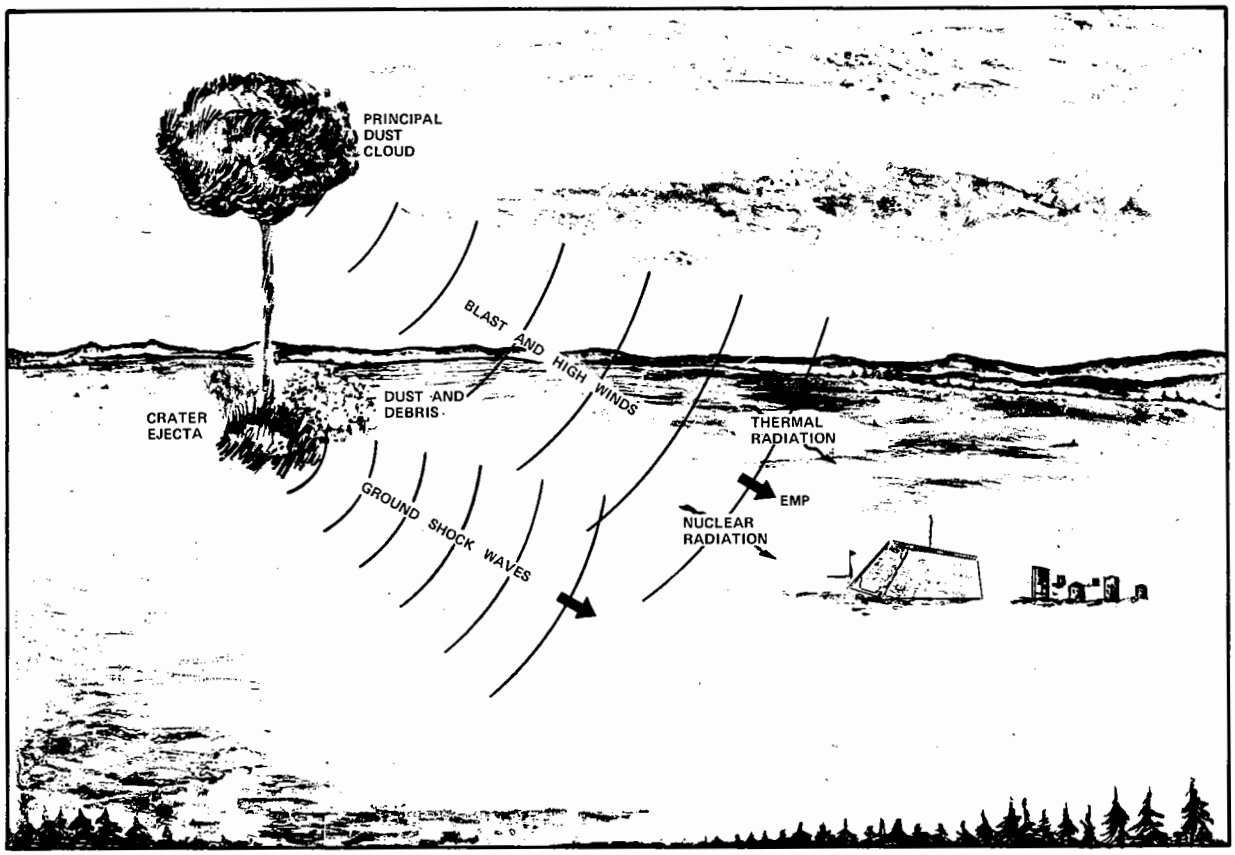


Figure 6-1. Nuclear Weapon Effects on System Facilities

required (see Figure 6-2) within which enemy warheads are not allowed to penetrate because an offensive warhead burst within this volume will "kill" the defensive installation. To maximize the battle space for engaging enemy warheads, the protection volume should be kept as small as possible, although this implies a hard defense installation.

Considerable effort was expended on the choice of a protection volume shape and size that would represent a good balance between battle space and hardness. The size of the volume is very much a function of the hardness of the system elements (radars, launch stations, essential facilities) within the ABM site. The contour finally chosen was governed by thermal and nuclear effects at high altitude, blast effects at intermediate altitudes, and by crater ejecta and debris at low altitude.

For defensive missiles, the dominant hardness requirements are influenced by fratricide, which is the effect of one defensive missile warhead burst on a nearby defensive missile in flight. Improvements in missile hardness permit closer burst spacings and, hence, more effective defense in the form of multiple intercepts on a single warhead or the capability to engage additional warheads.

Direct verification of nuclear hardness through field testing was not possible because nuclear detonations in the atmosphere were prohibited by the Nuclear Test Ban Treaty. Instead, hardness verification was primarily done by judicious combinations of analysis and experiment.

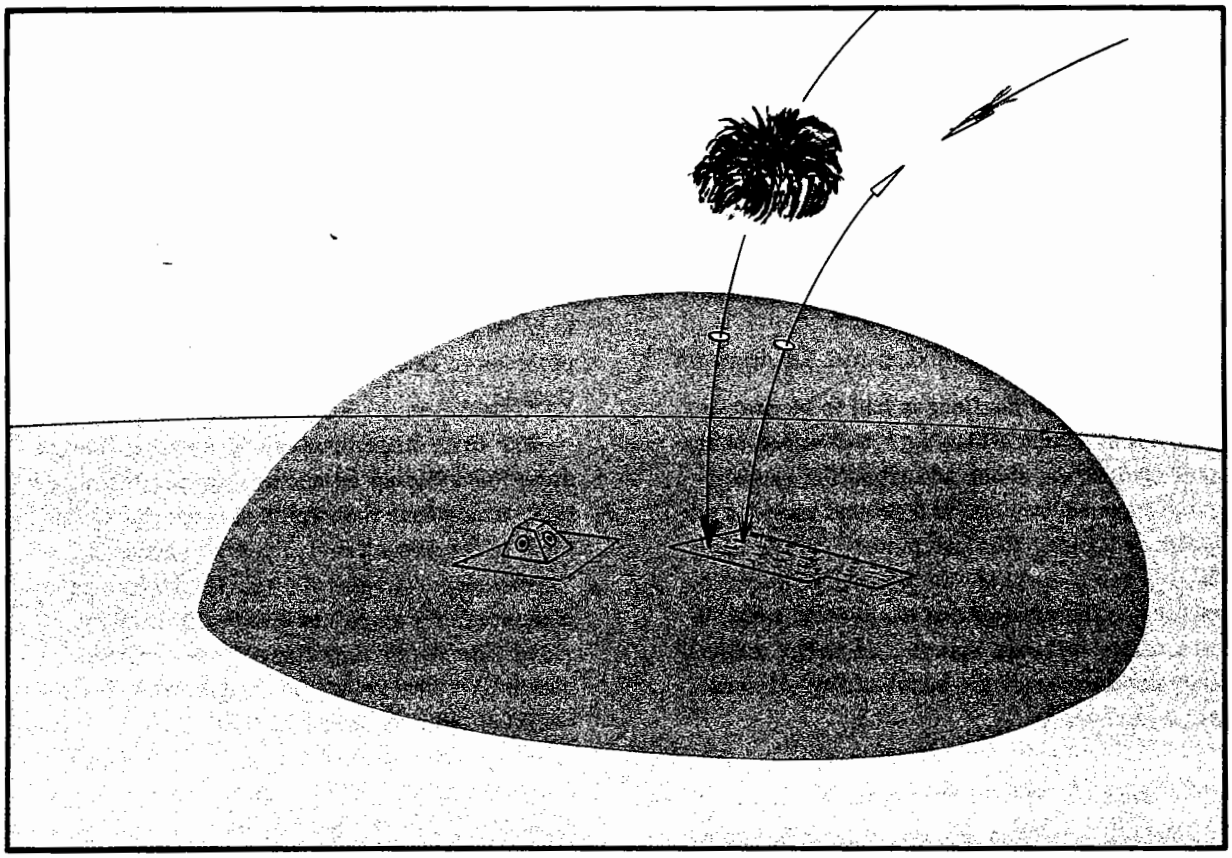


Figure 6-2. ABM Site Protection Volume

Extensive testing was done with shock and vibration simulators, nuclear reactors, flash X-ray facilities, and various EMP simulators. In some instances, where none of these testing methods would suffice, underground tests were conducted with actual nuclear weapons.

Although some testing and analytical verification were carried out in the early years, a significant increase in hardness assessment activity began in 1968, and remained at a high level until the end of the SAFEGUARD development period. Ground equipment was assessed against the following nuclear effects: ground shock and vibration, nuclear radiation, air blast, thermal radiation, dust, crater ejecta, debris, and EMP. The major radar subcontractors, General Electric and Raytheon, participated in these programs together with Bell Laboratories. Similarly, missiles were assessed against the following effects: radiation from neutrons, gamma rays, X-rays, EMP, air blast, dust, and thermal radiation. The missile subcontractors, McDonnell-Douglas and Martin Marietta, participated extensively in these programs.

After the signing of the Strategic Arms Limitation Treaty and the decision to deploy only one site, the final achievement of nuclear hardness became somewhat less important than achieving other major development objectives. Nonetheless, all the hardness assessment programs were carried to completion.

MAJOR CHALLENGES AND INNOVATIONS

In the following sections, a number of representative activities are discussed in which contributions to the technology of hardness assessment were made on particularly difficult problems. These examples were chosen to illustrate the scope of challenging work that characterized the program.

Shock and Vibration in Ground Equipment[5-8]

Three major challenges had to be met to ensure the survivability of ground-based equipment against the shock and vibration environments induced by blast and ground motions on facilities housing this equipment. In each instance, some novel techniques were developed, whether in the area of nuclear effects criteria for a major weapons system, or in the methodology used to verify the survivability of associated equipment.

Environment Definition and Simulation

Initially, ground motion criteria had to be developed, not only in terms of free-field shock spectra, but also in the form of ground motion-time histories suitable for use in subsequent phases of development. The resulting environment was defined in terms of free-field shock spectra for various depths and two types of ground motion-time histories. Two histories were required to adequately represent the different soil conditions likely to be encountered at various potential SAFEGUARD sites.

Next, it was necessary to establish the shock and vibration environments to be expected within the site facilities (e.g., radar buildings and missile silos). This was perhaps the first major weapons system project in which these environments were established through the use of analytical models representing the building structures, together with some analytical representation of the foundation (e.g., soil-structure interaction models), in order to calculate the in-building motions. Much basic work was carried out at Bell Laboratories, followed by joint efforts with the Army Corps of Engineers and their contractors, to incorporate these models into complex software packages that would permit predicting the in-building motion environments. The results of these studies were further verified by exposing scale models of the buildings to blast environments generated by high explosives in Operation DIAL PACK, Alberta, Canada.

The final stage involved translating the predicted in-building environments into laboratory test simulations that would subject the equipment to the actual environments expected. A "synthesized waveform" was developed which consisted of a series of damped sinusoidal vibrations whose simultaneous application yielded a vibration signature that closely resembled the predicted in-building motion-time histories and matched the shock spectrum. Coupled with this effort was the need to implement testing of equipment response to the synthesized waveform. A pilot facility was first developed at the Bell Laboratories Environmental Test Installation in Whippany, N.J. to handle most of the smaller, lighter equipment. For the larger, heavier equipment, a similar facility was implemented at Wyle Laboratories in Huntsville, Alabama.

Verification Methodology and Testing

After developing realistic environments and corresponding laboratory simulations, the next step was to verify the large number of equipment units involved. (In the Perimeter Acquisition Radar alone, there were 68 different designs and a total of 991 units.) Ideally, to achieve adequate verification, all equipment should have been tested. However, by taking advantage of equipment modularity (some cabinet designs were used repeatedly) and similarity, and by careful design of each test, a limited test program was formulated.

In spite of this effort, some radar units required special treatment. These were highly complex assemblies considered to be more vulnerable in the operational mode. Several such assemblies, weighing up to 10,000 pounds and fully powered with up to 40,000 volts (see Figure 6-3 for example), were tested at the Wyle Laboratories facility. In some cases, while the structure of these units was found capable of withstanding the tests, certain operational faults were uncovered (and later corrected) that could only have been found using the high-voltage operational mode.

Blast and Thermal Effects on Exposed Equipment[5,6]

A major milestone was achieved when the Perimeter Acquisition Radar (PAR) antenna element's survivability against the combined threat of blast and thermal effects was established. This work was noteworthy because it was representative of the approach developed to verify the survivability of all exposed equipment. Similar work was performed with the hardened designs of the Missile Site Radar (MSR) antenna element and antenna support structure.

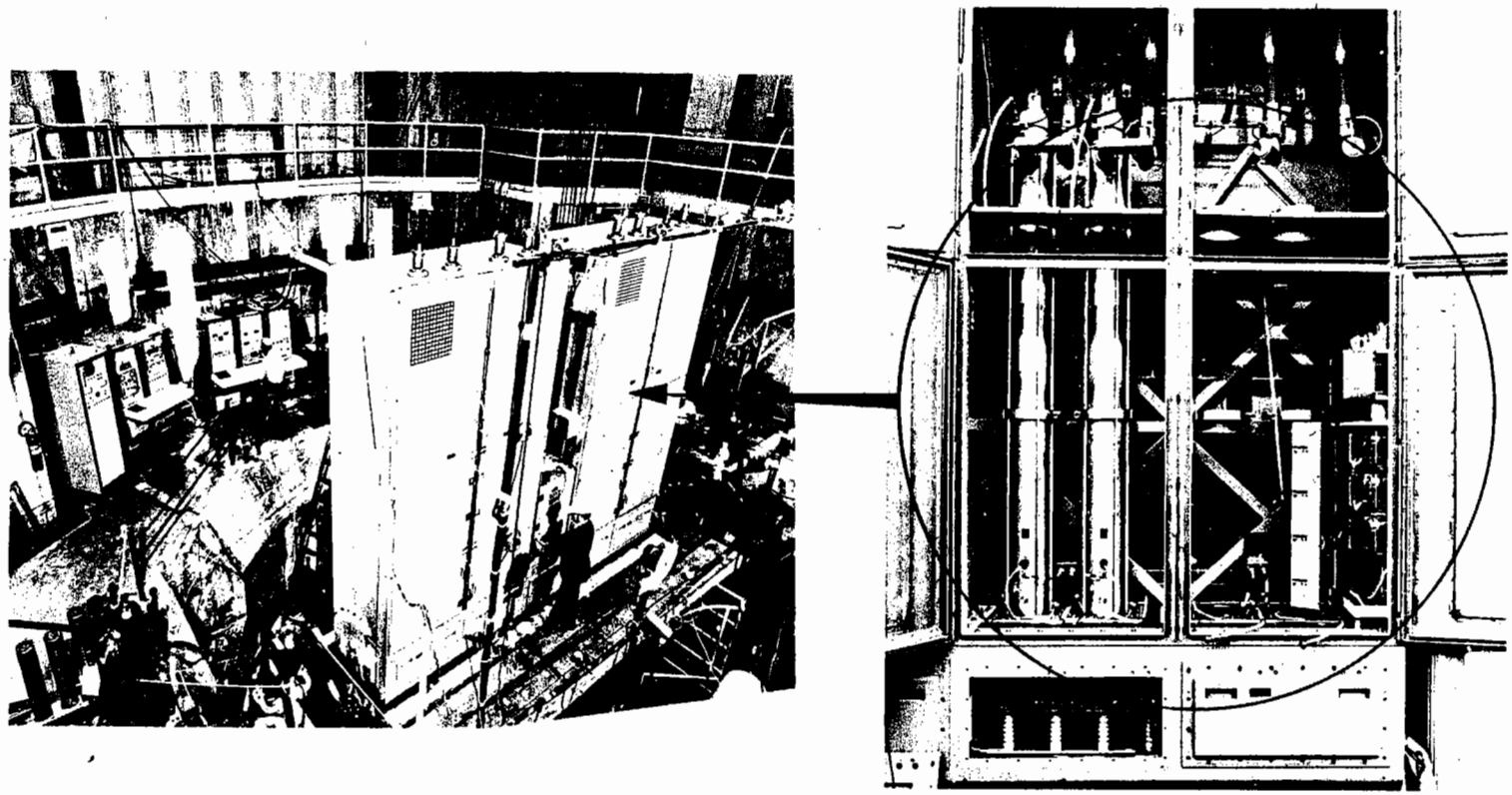
The PAR antenna element protrudes some 9 inches above the ground plane or radar face, and is exposed to a complex blast wave pattern. By the time the blast wave arrives, the antenna element has already been exposed to the thermal pulse from the nuclear weapon. The complexity of this environment posed a major challenge to the engineers who had to simulate exactly the combined blast/thermal effects. They were able to design a combined program of analyses and tests that accurately simulated all the relevant effects produced by the combined blast/thermal environments of the nuclear detonation.

The analytical portion of the verification program revealed that the thermal pulse could produce significant differential expansion of the element's tube structure and even melting of the metal. This led to the choice of a special metal alloy to be used in the tubular structure that forms the element. Another significant conclusion of the thermoelastic analyses was that the weather cover protecting the cross-shaped radiating elements can be severely strained by the differential expansion of the tube structure. This latter effect could only be verified by subjecting the antenna element to a simulated thermal pulse, as was done using the Thermal Pulse Simulation Facility at Sandia Corporation, Albuquerque, N.M., and then subjecting the same element to a blast environment at the DASACON Conical Shock Tube Facility, Dahlgreen, Va. (a half-mile long shock tube using an explosively-generated shock wave).

Understanding the phenomenology of the blast wave interaction with the inclined face of the PAR building led to a definition of the type of blast tests to be performed at the DASACON Facility. Two test configurations were chosen: one consisted of a portion of the inclined antenna face with an array of 40 elements to test the element when subjected to a double shock-wave pattern, and the other involved a simple single shock of higher level which verified the element's survivability against the shock pattern that could develop when the incident shock wave forms a Mach stem sweeping upslope on the inclined face.

The thermal testing results were valuable in the design process in selecting the material for the weather cover or cap used to protect the cross-radiating elements of the antenna. Several materials subjected to the pulse were found inadequate, either because they deteriorated sufficiently to degrade antenna radiating properties, or because they produced undesirable effects in the adjacent metallic ground plane such as increased absorptivity and higher temperature on receipt of the incident thermal energy.

The results of these analyses and tests led not only to selection of appropriate materials for the element metallic structure and the



(A) Amplifier Modulator on Shock and Vibration Test Table

(B) Interior View Showing Traveling Wave Tubes

Figure 6-3. PAR Amplifier Modulator Cabinet

cross-wire weather cover, but also verified that the final design of the element would continue to transmit and receive even when subjected to thermal and blast effects. A similar program was conducted to verify the hardness of other exposed equipment, including the MSR antenna elements, MSR antenna support structure, and PAR ground plane.

EMP Hardness Assessment for Ground Equipment[9]

One of the effects of a nuclear detonation is the generation of an extremely high-intensity Electromagnetic Pulse (EMP). This pulse is capable of inducing currents of thousands of amperes on exposed electrical conductors. An idea of the magnitude of the disturbance can be gained from the fact that EMP from an airburst during the Johnston Island tests was believed to have disrupted telephone service in Honolulu some 600 miles away.

The SAFEGUARD site is subjected to this effect, in varying degrees, from both the detonation of hostile warheads and the detonation of its own missiles.

Very early in the development of SAFEGUARD building facilities, a key decision was made, based on the advice of the EMP Technical Advisory Community, to shield all regions containing sensitive electronic equipment with steel, and to use steel conduit to protect electrical circuits running to the shielded regions.

This decision circumvented the need to design electronic equipment to withstand the free-field EMP levels, but left the more limited task of providing adequate treatment (e.g., use of filters) in the wires, pipes, and apertures which must of necessity pass through the building shields.

The implications of this decision were embodied in the Technical Requirements for Building Construction Specification.* Detailed requirements were included for construction of the shields as well as requirements for attenuation (at most of the frequencies in the free-field EMP spectrum) at each shield penetration from the free-field region.

This specification in itself did not guarantee that the various subsystems would not be upset or damaged by the attenuated EMP-induced transients. Consequently, the SAFEGUARD System Command (SAFSCOM) required each agency to demonstrate by analysis or test that its deployed equipment would operate satisfactorily in the EMP environment.

Approach

In 1968, Bell Laboratories began work on the hardness assessment which involved predicting the behavior of major subsystems under tactical conditions. Of primary importance was the need to characterize the effects of EMP-induced transients in the various configurations of equipment. To provide insight, a number of laboratory tests were conducted. These included:

- Field illumination tests using Parallel Plate Transmission Lines (PPTLs) to induce transients sufficient to cause upset in the circuits of the Whippany Data Processing System (DPS) and the analog and digital control circuits of the MSR on Meck Island
- Investigation of the upset modes
- Tests using PPTLs to determine the coupling loss via DPS coaxial cables from a free field to DPS sensitive circuits
- Determining the attenuation characteristics of filters in the EMP environment
- Tests of specific items of hardware, such as the PAR receiver input circuits, to determine their susceptibility to upset or damage.

Assuming that building shields were continuously welded so that they would be electrically joint free, it was apparent that EMP energy could enter in only one of three modes. These are shown diagrammatically in Figure 6-4 and include:

*Listed in reference number 9.

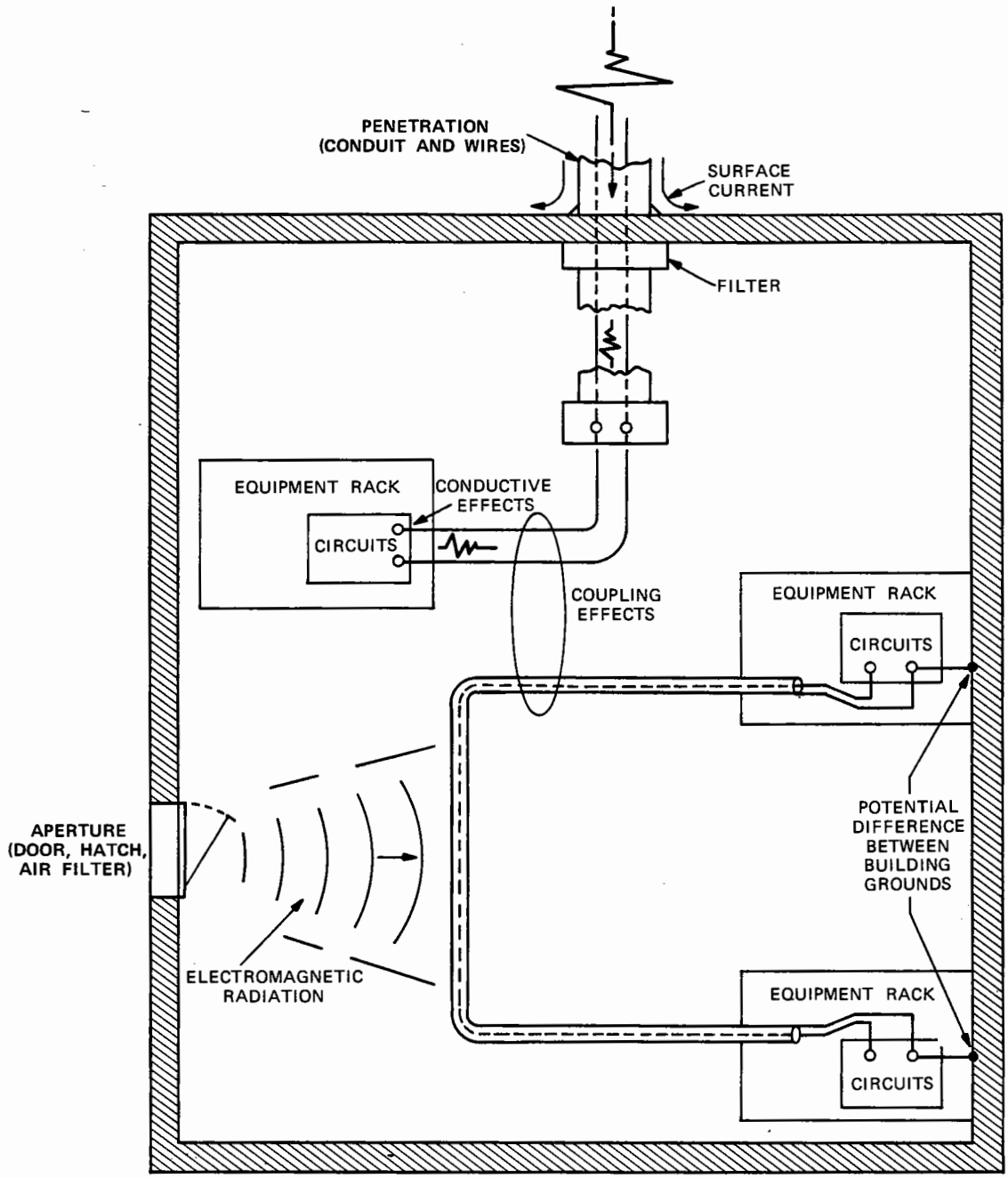


Figure 6-4. Modes of EMP Interaction with Shielded Building

1. Currents on wires and conduits which penetrate the shielded regions
2. Electromagnetic radiation through apertures such as doors and ducts
3. Currents on the shield inner surface induced by large currents on the outer surface. (This process, called diffusion, results in voltage differences between points on the shield inner surface.)

The tests showed (1) that analog equipment was three or more times less susceptible to EMP transients than digital equipment, (2) the significant mode of entry of EMP energy into the hardware systems is by coupling to rack interconnecting cables, and (3) equipment upset in the DPS occurs in the emitter follower Integrated Circuit Packages (ICPs) which terminate the interrack coaxial cables. The characteristic upset level was determined and empirical formulas developed to define the coupling to the coaxial cables. Analysis showed the largest diffusion effect voltage that could reasonably be expected between rack ground points was negligible with respect to ICP upset level.

The hardness assessment of Weapon System Contractor equipment in the SAFEGUARD buildings was a straightforward but laborious process as follows:

- Determine the flow path(s) by which EMP energy can pass from the outside free field to each item of equipment being considered.
- Calculate the magnitude of transient that can be expected from the free field on the associated penetrators and at the apertures. Taking into account transmission and coupling losses, determine the sum total transient to be expected at the equipment inputs.
- By means of careful study (equipment review) determine the upset or damage level of the equipment in response to the sum total transient at its input terminals.
- Calculate the margin between incident transient and upset level.

The intricate path of the cabling and the complexity of the terminal equipment often made it impossible to calculate accurately the EMP transients. The method employed to achieve the desired results was to establish an upper-bound EMP transient that yielded a satisfactory safety margin. An upper bound was established by two procedures.

1. Assume the most detrimental condition (such as an EMP field parallel to a lead exposed to it).
2. Simplify the mathematics at the cost of obtaining an overestimate of the EMP effects (by such means as using a short-circuit current instead of actual load current, neglecting attenuation effects, assuming one-to-one coupling, etc.).

Because of the conservative EMP/RF interference design of the SAFEGUARD System, this methodology made it possible to show quite rapidly that almost all equipment had a satisfactory safety margin. In only a few cases were insufficient safety margins found. Where these occurred, more precise analyses were performed and, if satisfactory results were not obtained, hardware redesigns were undertaken which later demonstrated adequate margins.

Because it was clear that system hardness would be heavily dependent on the effectiveness of the shields, elaborate steps were taken to achieve a practical shield design and to control the quality of construction. Building designs were reviewed and general guidelines for shield application were provided, consistent with the needs of the architects and engineers. Design review meetings were held to answer questions on complicated design problems. Special inspection techniques such as use of magnetic particle inspection (magnaflux) for welds, dye penetrant inspection for brazed seams or welds, and RF testing of all door and hatch closures were instituted. A Western Electric site surveillance team followed the contractor's installation and inspection operations. Many discrepancies were noted by this group, but most were resolved by negotiation.

Others, such as the exothermic welds in the PAR Building and the flexible joints in the Launch Area Utility Tunnel, required special tests to demonstrate acceptability or the need for improved design.

Interagency Intercoupling

In late 1970, SAFSCOM asked Bell Laboratories to form a special group to do preliminary site test planning and to consider two questions: (1) Were there any instances where the penetrations or apertures of one agency could admit EMP-induced transients causing unsatisfactory operation of other agencies' equipment? (2) Were all of the penetrations adequately treated (filtered)?

These two tasks were structured as building-wide hardness assessments. The approach used was similar to that for Weapon System Contractor equipment but with a division of effort. Each agency provided estimates of the transients expected at its penetrations and the upset or damage levels of its sensitive equipment. The interagency group, located at Bell Laboratories in Greensboro, N. C., provided flow path drawings and concentrated on identifying the points of metallic connection between different agencies' equipment and the configurations where detrimental interagency as well as intra-agency coupling could occur.

Bell Laboratories in North Carolina conducted experiments to characterize the coupling between transient-carrying conductors and the coaxial cables which interconnect digital equipment. This group also participated in the Corps of Engineers site test planning, especially with respect to tests that would provide information related to interagency effects. Information from the various agencies was combined with calculations of certain transients and with the known losses at the coupling interfaces. Then, estimates were made of the lowest margin related to the propagation of EMP energy from each of the penetrations by metallic path or by coupling between metallic paths to sensitive equipment within the buildings.

As a result of the building shields, extensive use of conduit, and a strong tendency to segregate conductors by agency, most estimated margins were found to be satisfactory. The majority of those which were unsatisfactory involved intra-agency effects that had already been identified by the responsible agency. Unsatisfactory conditions resulting from certain Weapons System Contractor circuits in SAFCA cables and from SPRINT launch preparation equipment compartment covers removed for maintenance were resolved.

Launch Stations[10,11]

The launch areas differ from the buildings in that they are collections of shielded regions interconnected by long underground conduit runs. The launch cells are open during and after missile launch and the launch preparation equipment chambers can be open when a launch station is undergoing maintenance. Thus, the open launch stations become points of entry for EMP-induced currents which can propagate to the closed launch stations and connected buildings. The magnitude of the currents which enter depend on the missile position as it leaves the cell, as well as the configuration of a launch station when opened for maintenance.

Bell Laboratories subcontractors completed hardness assessments taking into account cross coupling in the signal conduits as well as the various possibilities for transient currents at the launch station openings.

These assessments showed the transient level to be unsatisfactory on signal circuits to the SPRINT Launch Preparation Equipment (LPE) without filter protection. A redesign of the signal circuit shield terminations reduced the effect to an acceptable level. The assessments also predicted that high currents would be injected on the power feeders to a SPRINT launch station undergoing maintenance. A change in the maintenance procedure corrected the problem.

This change resulted from the efforts of Bell Laboratories, N. C., who, while working closely with the Corps of Engineers on Site Acceptance Test No. 5, performed current-injection tests on the power system of Remote Launch Site No. 1. The information gathered was used to characterize the coupling in the power system. From this knowledge it was determined that the transient on the feeders to a ready launch station, due to a neighboring launch station in maintenance mode, would be somewhat higher than the acceptable level for satisfactory LPE operation. Since the exact safety margin was unknown, the maintenance procedure was changed to minimize the offending transient. This change also eliminated the need for refined analyses of equipment at the Remote Launch Operating Building and the Electrical Distribution Center ends of the power feeders.

Large-Scale Threat-Level Testing

In 1969, SAFSCOM, as advised by the EMP Technical Advisory Community, directed the agencies to begin preliminary planning for a SAFEGUARD System EMP Site Test (SEST). A wave launcher was envisioned that would be large enough to illuminate the entire Missile Site Control Building or PAR Building complete with power plant at the design threat level. The basis for the EMP community's advice was prior experience by the Defense Department with weapons systems that failed when they were EMP tested. However, those systems were designed when the effects of EMP were not well understood. Thus, failure resulted from a combination of inadequate shield construction and inadequate design of the shield penetrations.

Preliminary planning for SEST was carried out in parallel with the EMP hardness assessment work for the next two years. In 1971, an in-depth review of the need for SEST was held. By that time, the hardness review of the data processing region of the Missile Site Control Building had been successfully completed, and work on interagency interfaces was well under way. Furthermore, it was now evident that SEST as originally conceived would be elaborate and expensive. As a result of this review, it was decided to drop further planning for SEST and rely on the methodology already developed for EMP hardness assessment in SAFEGUARD.

Conduit Problem[9]

At the time when the launch area conduit system had just been installed, and when cables were first being pulled through the conduits, a number of imperfections were discovered throughout the installation. Evidence of loose and rusty joints was seen, and ground water was leaking into some of the conduit runs. Since both the EMP hardness assessment and the lightning safety analysis depended to some extent on the integrity of the conduit system, there was a pressing need to reevaluate the "as-built" conduit system. Furthermore, there was the fear that water might penetrate the cables and cause electrical problems. In addition, freezing of water-filled conduits could cause physical damage to the cables, thereby degrading electrical performance.

An air-pressure testing technique was rapidly conceived to reveal which conduit runs had the worst flaws. The technique was refined to the point where air-leakage rates for individual joints could be measured. This was done by isolating short lengths of conduit for pressure testing by pulling inflatable bladders into the conduit. Eventually, a large percentage of the entire conduit system was mapped in this way so that air-leakage rates at joints along each run were known. Later, this information was supplemented by visual inspection of joints through the use of a miniature TV camera pulled through the conduits.

Concurrently, laboratory experiments were conducted to determine a correlation between the air-leakage rate of a faulty joint and the EMP leakage to be expected. Other experiments were conducted to determine the breakdown characteristics of faulty joints when struck by lightning. Still other experiments showed that water leakage

and the crushing effect of ice on cables would not present serious problems.

The conclusion reached from these investigations was that minor defects could be tolerated from the standpoint of both EMP and lightning, but that larger flaws had to be corrected. During warm weather in 1973, major flaws in the conduits were repaired on an individual basis to ensure lightning safety and EMP hardness.

Dust and Crater Ejecta Environments[9]

Detonation of nuclear weapons on or near the earth's surface produces considerable airborne geologic material ranging from micron-size dust particles to large boulders. The resulting environments are:

- Dust Cloud - material entrained by the rising fireball
- Crater Ejecta - material essentially thrown free of the hydrodynamic flow field
- Blast-Induced Dust - material scoured from the surface by the outwardly propagating shock front.

In 1968, Bell Laboratories undertook an extensive program to characterize dust and ejecta environments and their potential effects on the SAFEGUARD System. The scientific community was just beginning to concern itself with the impact of these environments on ICBM and ABM systems. Of particular concern were the in-flight hazard to missiles due to erosion and impacts, the degradation of radar signals due to scatter and clutter, and the damage to ground facilities by impacts, entrainment, and accumulation. Characterization of these environments was made difficult by the Nuclear Test Ban Treaty and the fact that none of the previous above-ground nuclear detonations had been instrumented to obtain such data. Particularly lacking was an understanding of early-time (before 5 minutes) dust cloud phenomena and crater ejecta impact environments. On the other hand, the Air Force Weapons Laboratory (AFWL) had done extensive theoretical work on flow fields produced by nuclear bursts. In addition, a number of high-energy explosives and a few low-yield underground nuclear devices had been detonated with the specific objective of understanding cratering and ejecta distribution.

In order to characterize SAFEGUARD dust and ejecta environments, a variety of phenomenologies were studied including weapon-earth energy coupling, crater mass injection, interaction of dust with hydrodynamic flow fields, sweep-up dust sources, and blast-wave dust scouring. This led to the integration of a number of mathematical and computer models describing these phenomena and based on experimental and theoretical studies. In cooperation with the AFWL, extensive computer simulations were run. This work culminated in a description of the nuclear dust cloud for times up to 60 minutes in terms of dimensions, mass, and particle-number density contours. The crater ejecta impact environment was described in terms of impact densities and velocities for various particle-size ranges. Characterizations were also developed for the dust-water cloud, crater ejecta cloud, and blast-induced dust cloud. These environments were ultimately specified in the SAFEGUARD Environmental Criteria which formed the basis for evaluating the effectiveness of the SAFEGUARD System.

Debris Environment[9]

The strong blast wave from a nuclear detonation fragments buildings, vehicles, trees, and similar objects in its path. The resulting debris is transported by the blast wave over a wide area, representing a hazard to tactical facilities. Damage is caused by high-energy impacts and the accumulation of debris on exposed surfaces.

A debris studies program was initiated at Bell Laboratories in 1964 with the primary

objective of investigating and describing the expected debris conditions at ABM sites. Of particular concern was damage to missiles before launch and possible loss of radar elements. At the outset of the program, information on these debris effects was very limited. Some object-travel distances had been measured and a number of photographs taken of structure and object damage in certain blast environments from previous nuclear tests. Unfortunately, no thorough debris data surveys in the blast environments of interest had been made. Moreover, the Nuclear Test Ban Treaty prohibited the direct acquisition of data on this phenomenon during the debris studies program.

To provide data that would properly characterize debris environments at ABM sites, a variety of experiments were conducted and a number of analytical methods introduced. These basically involved:

- Building, automobile, and tree fracturing tests
- Scaled tests and analytical studies on debris transport
- Expected debris condition predictions.

The purpose of the fracturing tests was to determine how buildings, automobiles, and trees broke up in nuclear blasts. Fortunately, fracturing does not depend on weapon yield so this data could be acquired by participating in the high-explosive tests of SNOWBALL, DISTANT PLAIN, PRAIRIE FLAT, and DIAL PACK. Figure 6-5 shows one of the test results from Operation PRAIRIE FLAT.

Because debris transport at a given overpressure is strongly influenced by weapon yield, a mathematical model was developed to simulate debris transport in the Mach region of classical blast waves. The results of scaled debris-transport tests performed in the high-explosive shots compared quite favorably with the debris-transport model predictions, providing some verification of the model. Finally, a procedure was developed that combined the empirical fracturing data of a debris source with the mathematical model to estimate the expected debris conditions of that source.

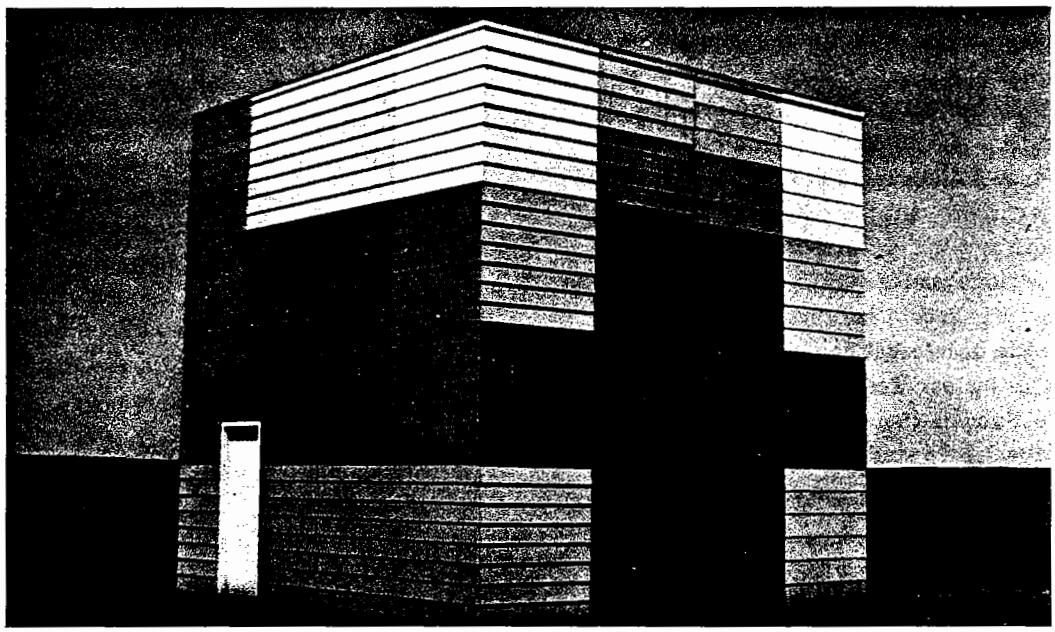
The results of this work were used in the SAFEGUARD Siting Criteria to specify safe distances for potential debris sources from SAFEGUARD missile sites and radars. For debris sources that could not comply with these criteria, system effectiveness studies were conducted to evaluate the extent to which such sources compromised the tactical capability of the SAFEGUARD System. A methodology was developed that can be used to approximate conditions for a variety of debris sources relevant to SAFEGUARD or other hardened systems.

Missile Guidance Set Power Supply Failures[10]

In December 1972 and January 1973, two SPRINT Missile Guidance Sets (MGSs) were tested at the Aurora Flash X-Ray Facility in Beltsville, Md. (See Figure 6-6). The tests were expected to provide final confirmation that the MGSs would operate properly at the full transient radiation level specified for the SPRINT environment. Instead, both MGSs failed catastrophically at half the specified level.

Subsequent investigations revealed that transistors in a power supply inverter circuit had failed due to a breakdown phenomenon. A comprehensive analysis and test program was conducted to explain the cause of the failures and to devise circuit modifications to correct the deficiency. A circuit modification which included changing to another type of transistor was initiated to correct the problem.

Further testing at Aurora confirmed that MGSs with modified power supply circuits were capable of withstanding radiation at the full specification level. As a result of experience with this problem, improved understanding was gained of power-transistor operation in a transient radiation environment.



(A) Preshot View



(B) Postshot View

Figure 6-5. Frame Building Subjected to 15 psi Overpressure, Operation PRAIRIE FLAT



Figure 6-6. SPRINT Missile Guidance Set Being Readied for Gamma Radiation Tests at Aurora Facility

Radiation Effects in Tantalum Capacitors[10]

In the course of laboratory testing of electronic circuits to confirm predictions of radiation-induced transients, it became evident that tantalum capacitors were producing unexpectedly large voltage transients. To obtain a better understanding of the phenomena involved, an experimental program was undertaken at Gulf Radiation Technology in La Jolla, Calif., under Bell Laboratories direction.

The results of the program gave new insights into the radiation-induced transients to be expected from tantalum capacitors, and allowed output transients from electronic circuits to be predicted more accurately. This was of special importance in the SPRINT autopilot, where tantalum capacitors were the dominant source of radiation-induced transients. In addition, an electrical test was developed to screen out tantalum capacitors with abnormal or "maverick" transient outputs before they were installed in circuits.

Internal EMP in Missiles[10,11]

Internal EMP (IEMP) is produced inside a missile as a result of the interaction of gamma rays and X-rays with the missile structure. Absorption of photon energy in the missile structure causes electrons to be ejected from internal surfaces and gives rise to replacement currents in the structure and to a flow of space charge in the internal missile cavities. Both the space current and the missile body replacement currents can cause electrical signals to be induced on interconnecting cables which, in turn, can induce transients into internal electronic assemblies. In simplest terms, even in a missile which is well shielded against normal EMP, gamma rays and X-rays can produce an internal EMP which may lead to failure of electronic circuits.

At the time that hardness assessments on the SPARTAN missile were beginning, IEMP phenomena were poorly understood and no standard techniques were available for

predicting IEMP transients on interconnecting cables within the missile. In fact, it was not until 1969 that the existence of an IEMP effect became accepted in the nuclear community.

The principal problem was to make reasonable predictions of the transients on interconnecting cables. Once these were available, the susceptibility of electronic assemblies could be determined experimentally, although this, too, proved to be a challenging task. Basic physical knowledge was not a serious limitation, but prediction of cavity pressure, then cavity fields, and finally, cable response for actual SPARTAN internal surface materials and cavity shapes was a formidable analytical challenge. Furthermore, there was no way to simulate the threat environment accurately for experimental confirmation of analytical results, even by underground nuclear tests. An underground test with a full SPARTAN warhead and at tactical standoff distance was out of the question, and a scaled-down test with smaller yield and distance would not produce realistic gamma ray and X-ray pulse shapes.

The approach that finally evolved was analytic, with analysis confirmed by a number of specialized experimental techniques. The most useful of these techniques was missile current injection. A full-scale model of the SPARTAN third-stage missile configuration was modified by adding conducting straps within chosen internal cavities, and then cavity currents and replacement currents were made to flow by use of an external pulser (see Figure 6-7). This was used to confirm the analytically predicted relationship between cavity currents and replacement currents and the resulting cable transients.

Confirmation of analytical predictions was also done in an electron beam experiment and in the HERMES Flash X-Ray Facility, Albuquerque, N. M. In addition, some limited experiments were done in underground nuclear tests. In each of these cases, the principal result was confirmation of the ability to use analytical techniques already developed to predict the results obtained in a particular non-threat environment.

This work was carried out by McDonnell-Douglas with close technical direction from Bell Laboratories and with the assistance of several specialized outside consultants. The final result showed that the SPARTAN missile was capable of withstanding IEMP effects produced by the specified gamma ray and X-ray environments.

The SPRINT IEMP hardness assessment began some time after the start of the SPARTAN assessment and profited greatly from insights gained in the SPARTAN work. SPRINT was also shown to be EMP hard.

SPRINT Autopilot Transients[10]

An assessment of neutron and gamma ray hardness of the SPRINT autopilot was begun by Martin Marietta under Bell Laboratories direction in 1969. In the course of the assessment, it became evident that radiation-induced transients in the autopilot could produce transient accelerations of the missile which, when added to normal maneuvers, might cause structural failure of the missile.

After extensive consideration of a number of alternatives, such as circuit hardening, incorporation of circumvention techniques, reduction of order limits, and reduction of specified radiation, a decision was made to follow a dual path: incorporating selected circuit modifications and using more realistic hardness assessment techniques. The circuit changes included:

- Reduction in size of critical capacitors to reduce transients
- Selection of critical zener diodes
- Electrical screening of tantalum capacitors for critical applications to avoid "maverick" response to radiation
- Radiation testing and selection of tantalum capacitors for other critical applications to limit radiation-induced transients.

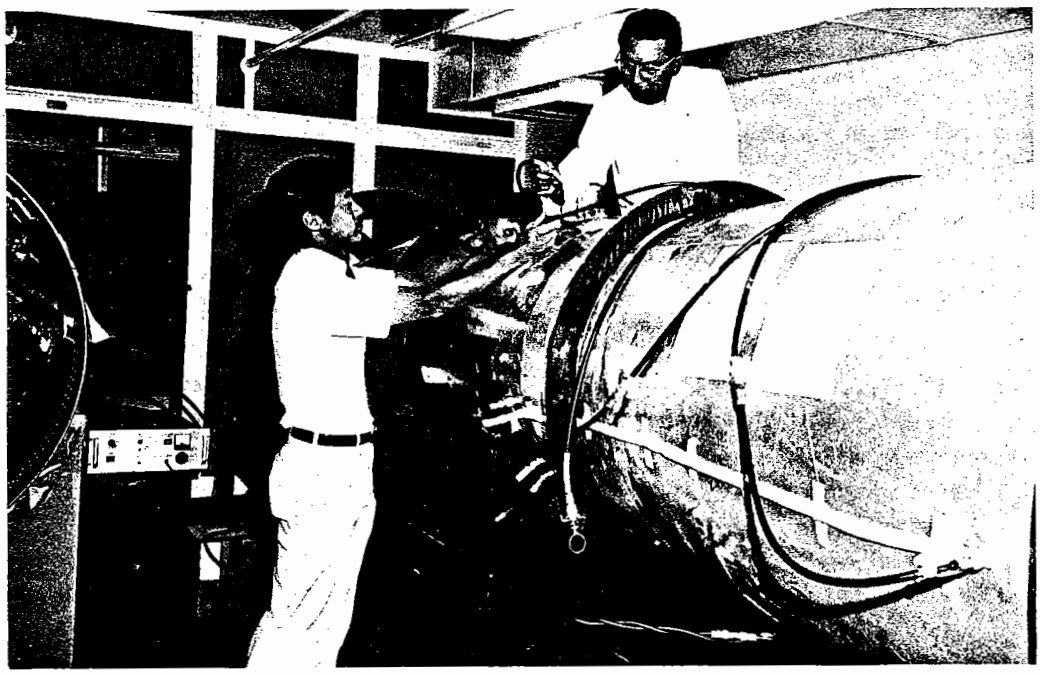


Figure 6-7. Internal EMP Testing of SPARTAN Missile at McDonnell-Douglas Astronautics Company

A more sophisticated hardness assessment analysis procedure was then developed. This procedure could recognize the statistical combination of transients from various sources within the autopilot instead of assuming "worst case" combinations.

Final results from using the statistical analysis on the modified autopilot showed that radiation-induced transients would not exceed structural limits. Thus, both SPRINT and the SAFEGUARD System were able to maintain full effectiveness in the nuclear environment.

Radiation Effects on SPARTAN Missile Structure[11]

The SPARTAN missile in-flight nuclear environment specification requires the missile to survive a stressful radiation environment during third-stage exoatmospheric flight. One important aspect of the SPARTAN hardness evaluation thus became an assessment of the effect of energy absorption from radiation on the missile structure. A number of failure mechanisms had to be considered including shock, spallation, permanent buckling and bending, and fracture of rivets and fasteners. A complicating factor in the assessment was the need to predict the physical state of ablators and other structural materials after the heating and charring of atmospheric flight.

Early in the program, a number of discussions were held with the Atomic Energy Commission (AEC) to determine what degree of structural failure could be tolerated without degradation of warhead effectiveness. After extensive discussion and evaluation of the structural hardness information available at the time, a decision was made in 1968 to make a change in the warhead ballistic case (the outer skin of the warhead section and the supports for the warhead) to meet the hardness requirement.

The structural hardness assessment continued for several years beyond that point. The assessment approach consisted of:

- Laboratory and field tests to characterize materials and determine the adequacy of analytical methods employed.
- Underground tests in simulated fratricide environments. (The most important of these were Mint Leaf in 1970 and Diamond Sculls in 1972.)
- Correlation of laboratory, field, and underground test data with analysis.
- Extrapolation of test and analysis data to the predicted threat environment to determine vulnerability of the missile.

The assessment program was carried out by McDonnell-Douglas under Bell Laboratories direction with the cooperation of the warhead agencies. The result was that SPARTAN, with the redesigned ballistic case, was found capable of withstanding radiation levels considerably above those called for in the nuclear environment specification.

SPRINT Blast Evaluation[10]

An evaluation was performed to assure that SPRINT missiles would survive the specified fratricide blast encounters. The capability of the missile structure was assessed by straightforward analytical and experimental techniques, but assessing the controllability and stability of the missile during a blast wave encounter and the resulting shock effects on missile components required new techniques.

To assess controllability and stability, a special purpose analog computer simulator was assembled that incorporated all of the unique aerodynamic loadings, control system response characteristics, and structural capabilities. The simulator showed the effects of long flight durations in the low density regions within the blast spheres where controllability and stability are most affected, especially if the trajectory requires SPRINT to fly into and then out of a blast sphere. This simulation facility was successful in demonstrating SPRINT's capability during the various segments of flight.

Shock effects on missile components were duplicated by means of large shock tubes at the Naval Weapons Laboratory and at Sandia Laboratories. The Sandia Shock Tube (Thunderpipe) Facility was enlarged to test a completely assembled SPRINT second-stage missile. (See Figure 6-8.) Functional components demonstrated

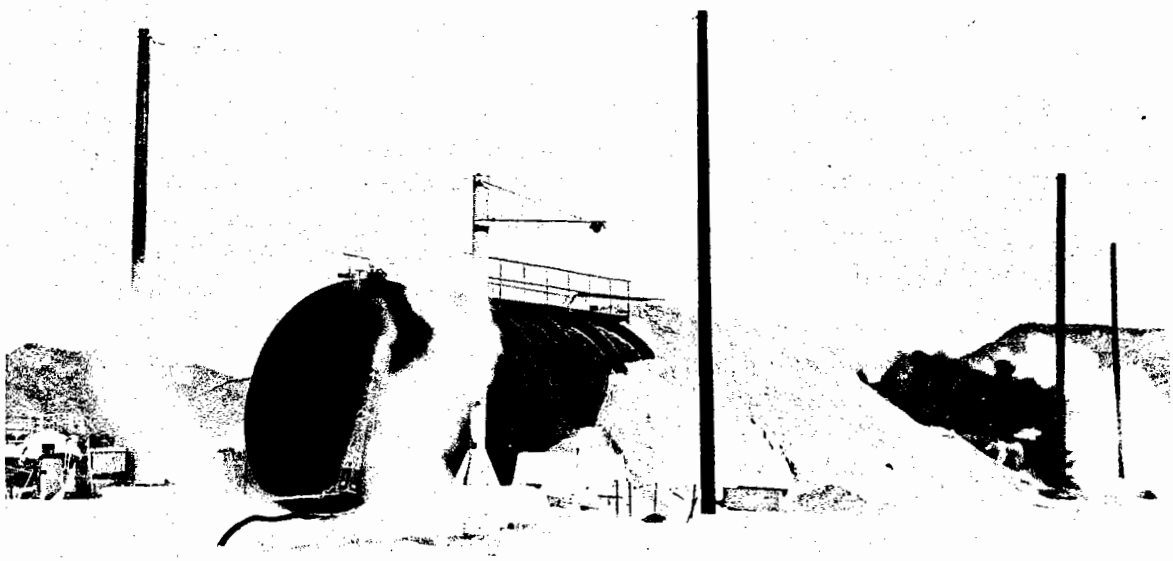


Figure 6-8. SPRINT Missile Undergoing Shock Tests at Sandia Laboratories

their performance under specification-level shock loadings. A principal conclusion drawn from the testing was that locally supplied shock loadings near each functional component can successfully simulate blast loadings on entire missile structures. This allowed high-confidence blast evaluations to be performed at very low cost by making use of readily available shock-loading facilities.

ASSESSMENT RESULTS

All hardness assessment programs were successfully completed. The results of these programs showed that all system elements for which Bell Laboratories had responsibility were capable of meeting the nuclear environments stated in the environment specifications. The results of the assessment programs are outlined in seven Subsystem Hardness Assessment Reports (SHARs).[5-11] These reports also direct the reader to further documentation giving details of the individual assessment programs. In addition to the SHARs, a document was prepared that summarizes the lessons learned in the Nuclear Vulnerability and Hardening Program.[12]

Chapter 7.

MISSILE SITE RADAR

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MISSILE SITE RADAR

The Missile Site Radar (MSR) System was developed in three distinct phases: Prototype (Meck Island Facility - Figure 7-1), Tactical Software Control Site (Madison, New Jersey), and the Tactical Site (Nekoma, North Dakota - Figure 7-2). The three sites were installed over a six-year period. Installation of the prototype system began in late 1967; an MSR receiver and digital equipment group were installed at the Tactical Software Control Site (TSCS), as a software and partial system checkout facility, in 1971; and installation of the tactical MSR site began in 1973. Figures 7-3, 7-4, and 7-5 indicate the schedules for the Prototype MSR, TSCS, and Tactical sites, respectively. The last major milestone occurred on April 1, 1975 [Initial Operational Capability (IOC)], when the tactical system was turned over for military operation.

The MSR, as initially conceived, was a short-range target and missile tracking radar to be used in conjunction with the NIKE-X Multifunction Array Radar (MAR).[1] In this version of NIKE-X, two missile tracking radars were to be deployed near SPRINT missile farms located some distance from the MAR. These two radars were

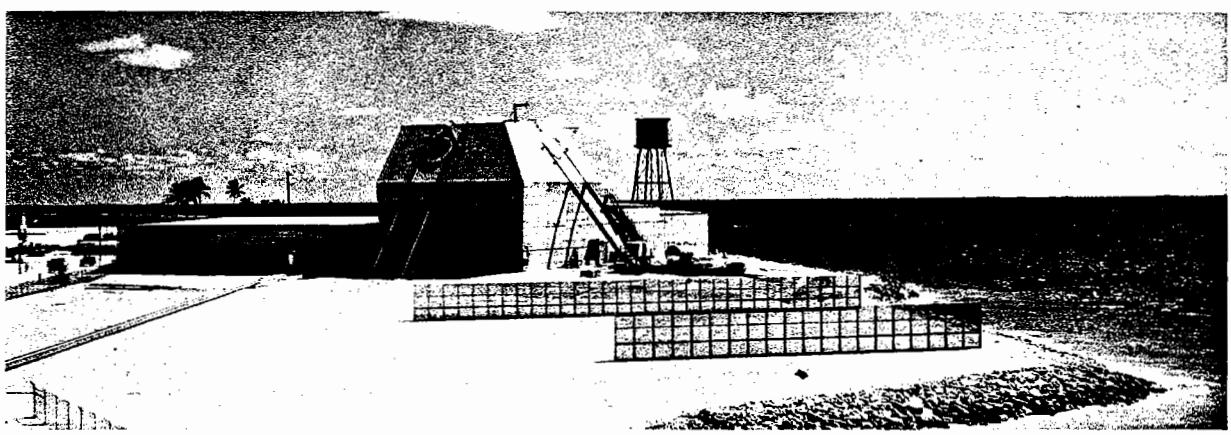


Figure 7-1. Prototype MSR - Meck Island



Figure 7-2. Tactical MSR - North Dakota

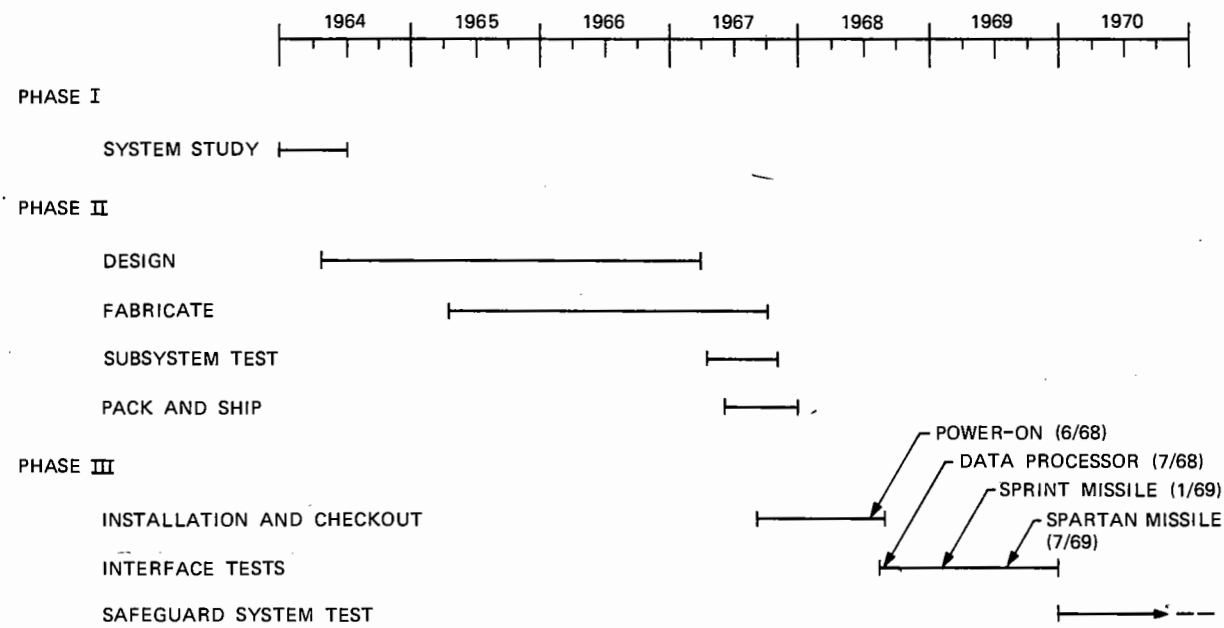


Figure 7-3. Prototype MSR Schedule

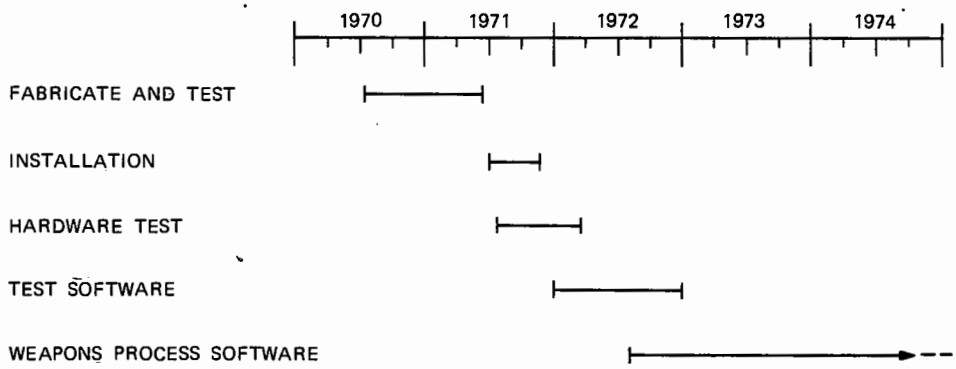


Figure 7-4. MSR TSCS Schedule

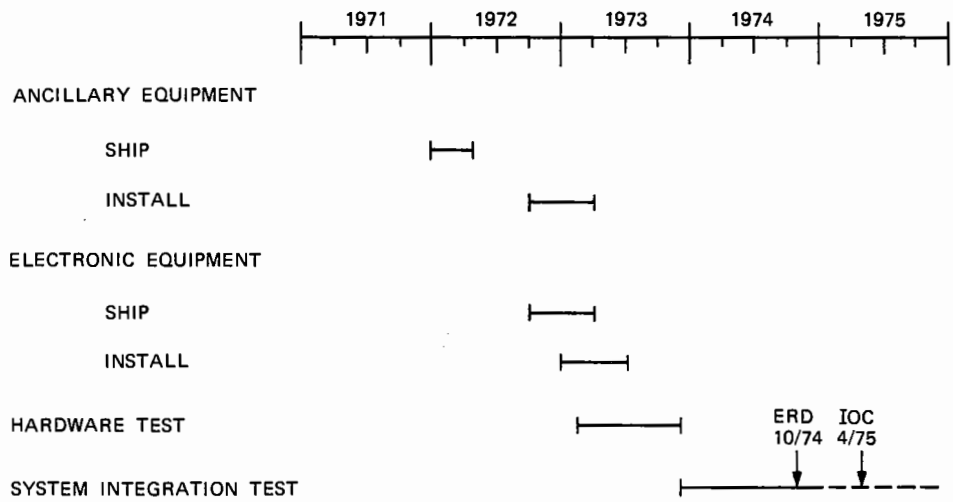


Figure 7-5. Tactical MSR Installation and Test Schedule

to contain a large number of tracking channels for relatively short-range target and missile tracking and, along with the missile tracking capabilities of the MAR, would triangulate the necessary fire power for the proposed NIKE-X System. In this deployment concept, the data processing equipment was to be centrally located at the MAR site.

The requirements of the MSR, as initially conceived, were submitted to prospective contractors during October 1963 in a request for quotation on the study phase of the radar's development program. The proposals were received and evaluated, and the contract was awarded to the Raytheon Company, Wayland, Massachusetts.

Prototype study and definition, Phase I, began in January 1964 and lasted through May 1964.[2] The radar was to be a phased-array type with sufficient power output capability to handle both the size and quantity of planned targets and the large number of missiles in track. To meet this power requirement, a new klystron transmitting tube was designed, which would provide

a combination of bandwidth and output power greater than that of any previously available S-band tube. To meet the high availability/reliability requirements, complete channel redundancy with high-speed switching was designed into the transmitter, receiver, and digital radar control equipment.[3]

The prototype development program, Phase II, had been underway one year when the NIKE-X concept was revised to provide an autonomous MSR with much greater target and missile tracking capacity. The revised MSR design was initiated in May 1965 and, among other changes, required a five-fold increase in average power output. After a brief period for redefinition of this larger radar system, development began with the goals of starting the prototype installation at Meck Island (Phase III) in the latter part of 1967, having "power-on" by June 1968, and testing SPRINT and SPARTAN missiles by June 1969.[4] Development continued under this concept for one year until May 1966 when requirements for additional target handling capabilities were placed on the system. With these additional requirements, it was now possible for the MSR to handle the entire engagement and the MAR system disappeared from the NIKE-X program.[5]

In October 1967, NIKE-X was renamed the SENTINEL System, the MSR prototype design was nearing completion, and design of the production version was initiated.[6] The only major hardware design change at this point, which necessitated a new development phase, was converting the digital radar control from thin-film to core memory. All other subsystems were modified as required for quantity production, and necessary final design work and documentation were begun.

In mid-1971, to facilitate the design and testing of software and system related interfaces, installation of the operating consoles and one channel each of the MSR receiving system and MSR digital control system was undertaken at the TSCS. The MSR equipment design was identical to that of the production equipment and was initially used to evaluate MSR test software. Testing of the tactical weapons system software began in early 1972, with the TSCS continuing to support the system checkout and initial operational phase of the Tactical Site.

During the latter part of 1968, when design of the tactical system was well along, consideration was given to increasing the range of the MSR by increasing the diameter of the antenna face. This proposed redesign, known as the Improved MSR (IMSR), was associated with system capabilities that might be required at some time in the future. Studies were made to define the building modifications and antenna support structure that would be required to retrofit a tactical MSR system to the larger diameter antenna. These studies continued until the early part of 1970.[7] The building was then modified so that the larger antenna could be installed. This redesign incorporated a permanently larger antenna-to-feed horn enclosure which could be used with either size antenna, thus eliminating the need for future retrofit. The smaller antenna, as installed at North Dakota (see Figure 7-2), is actually inside a larger annulus which can be removed if the larger antenna is ever needed.

Construction for the North Dakota tactical site began in the Spring of 1970, installation of equipment began in late 1972, and power-on was achieved for all elements of the system in the beginning of 1973. With testing of the tactical radar and tactical software beginning in 1973, the Equipment Readiness Date (ERD) was achieved on September 27, 1974, with Initial Operational Capability on April 1, 1975.

SYSTEM CAPABILITY[8]

The 430-acre MSR site at the Stanley R. Mickelsen SAFEGUARD complex located near Nekoma, North Dakota, is comprised of an MSR and the SPRINT and SPARTAN missile farms (Figure 7-2). Partially underground, the largest structure at this location is the MSR building — 230 feet square and 123 feet high. The visible

portion of the building holds the four antenna arrays and their associated equipment. Hardened to withstand a nuclear blast and its radioactive effects, the concrete outer walls are 4 feet thick, slope at an angle of 35 degrees, and rise about 80 feet above the ground.[9,10] Each of the four antenna faces is about 13 feet in diameter and contains approximately 5000 phased-array elements.[11]

Operating at a higher average power than any existing radar in its frequency band, the MSR, with the aid of its associated Missile Site Data Processor (MSDP), processes its own autonomous target data as well as data from the Perimeter Acquisition Radar (PAR), discriminates between warheads and other objects, and launches and guides interceptor missiles on appropriate trajectories via an RF command guidance link to the SPARTAN and SPRINT missile farms. Based on a design concept of two-channel redundancy for major subsystems and multiple redundancy within the antenna system, the MSR is a precision sensor designed for continuous use. (Figure 7-6 is a functional block diagram of the MSR.)

Since the MSR is designed for continuous operation, it contains all facilities for maintaining the electronic apparatus. The redundant transmitter, receiver, and digital systems allow maintenance work on the off-line channel while the radar system is functioning normally using the on-line channels. Each of the subsystems can be checked in the off-line position to assure optimum performance when the off-line channel is switched to the on-line position. Facilities built into the MSR provide rapid and frequent checking of all subsystems while the equipment is performing a mission function. When a fault is detected, the channel is switched off-line and with the use of additional test signals, the malfunctioning chassis is located, replaced with a spare, and checked in the off-line position.

The two output klystrons normally operate in parallel. If one of the klystrons malfunctions, it is automatically switched off-line where further tests can be run. This klystron can then be replaced while the other klystron performs mission functions with a 3-dB lower power output. The replacement klystron can be activated in the

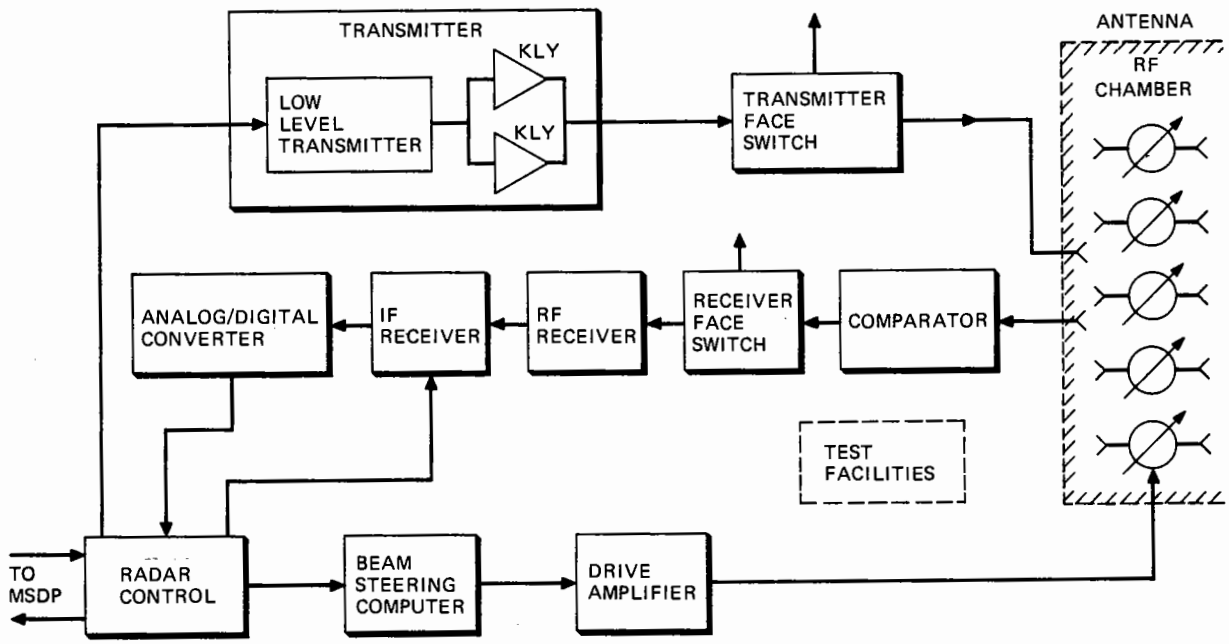


Figure 7-6. MSR Functional Block Diagram

off-line condition, tested for proper operation, and then added in parallel to the transmitting on-line tube.

The 5000 antenna elements in each face are replaced from the outside of the building using an antenna service vehicle designed for this purpose.[12] Very high reliability diodes are used in the phase shifters. This, plus the redundancy inherent in the large number of array elements, results in the need for infrequent maintenance of the arrays. Faulty antenna elements are not changed until a sufficient number have accumulated in each face to warrant removing the system from service and replacing the elements.[13] The replacement operation is quite simple and requires about 2 minutes per antenna element.

A single transmitter supplies power for all four faces by using a high-power face switching network consisting of three high-power waveguide ferrite switches. The switches allow the transmitter energy to be shifted from one face to another in a fraction of a second. (The receiver can be switched from face-to-face considerably faster.) Similarly, to allow maximum use of the large number of track resources that are available for a typical engagement, the antenna beam can be switched in a few microseconds from one position to a newly calculated position.

The MSR provides a variety of radar signals with varying parameters to accomplish the search and tracking functions.[6] Chirp and non-chirp pulses can be transmitted over a wide bandwidth by computer frequency selection. Frequency agility simplifies the separation of the large variety of acquisition and tracking functions, including the frequencies dedicated for communications to SPRINT and SPARTAN missiles.

Operation of the MSR is controlled by the MSDP through the radar control interface.

ANTENNA DESIGN

The antenna subsystem of the tactical MSR provides hemispherical coverage with four 5000-element phased arrays. A single-element Q-channel, located adjacent to each array, rejects signals received on the array sidelobes.[14-16] The MSR arrays are space-fed rather than corporate-fed; each array uses a separate transmit and receive feedhorn located at its focal point. Corporate-feed (as used in MAR) was rejected primarily due to its mechanical complexities in the dimensions inherent in a phased-array antenna at S-band.

Each array element consists of a rear horn, diode phase shifter, and front radiating element containing a beryllia window. As shown in Figure 7-7, the phase shifter and front element can easily be removed from the front of the array for replacement and repair. Development and manufacturing controls of the array components have produced a failure rate of less than 2 antenna elements per day and a PIN diode rate of less than 100 fits (100 failures in 10^9 component-hours).[17] The phase shifter consists of PIN diodes appropriately spaced in a coaxial RF structure to provide the required 4 bits of phase shift in sixteen 22.5-degree segments. The prototype system was designed with 30 diodes[18,19] per phase shifter. The development program[20,21] successfully reduced the number of diodes to 16 for tactical antenna elements.

The Beam Steering Computer (BSC) of the radar control equipment computes the orders for each bit in each of the 5000 phase shifters per array. These orders are processed by drive-amplifier cards, which generate the forward and reverse bias for the phase shifter diodes.

For a space-fed array to be practical, a simple method must be used to test each element in place. To avoid an RF cable connection to each element, a system using the BSC was devised.[22] The antenna is pointed at the test pole, which radiates an RF signal. To test an element, its bits are individually modulated at a 10-kilohertz rate by the BSC. The phase modulated signal from the element under test and the unmodulated signals from all the remaining elements add in the receiving feedhorn and are amplified by the

MSR receiver in the normal way. A sample of the receiver IF signal is fed to an antenna test set, which recovers the 10-kilohertz phase modulation and compares its phase with that of the original BSC 10-kilohertz signal. By proper control of each bit, an actual phase measurement can be made. Six phase measurements are made on each element to test the four bits of each phase shifter.

Measurement of antenna elements, like other test capabilities provided in the MSR, is interleaved with the normal surveillance functions under software control. The antenna element test software computes the value of each bit from the six phase measurements of the element and compares the value against acceptance limits. If out-of-limit, the test is rerun at another frequency; if still out-of-limit, the element number and bit values are "printed out" for use in fault location and repair. The antenna element test software can measure ten elements per second. Measurement of the 5000 elements of one array face typically requires about 20-minutes elapsed time. This antenna element test can be run at any time and is initiated manually. The test is automatically terminated if the system is required for potential battle engagement.

The area behind each array and its feedhorn assembly is enclosed in an RF chamber for personnel protection. The Meck prototype chambers included an RF absorber, which provided very low sidelobe levels. Studies of the clutter levels predicted for the tactical MSR site indicated that under the expected conditions, a higher sidelobe level could be tolerated. As a result, the RF absorber was eliminated from the tactical design. However, provision was made for mounting a high-power absorber material around the periphery of the arrays to improve the far-out sidelobe level by about 6 dB, should it become necessary.[23,24] Figure 7-8 shows the interior of one of the Grand Forks RF chambers.

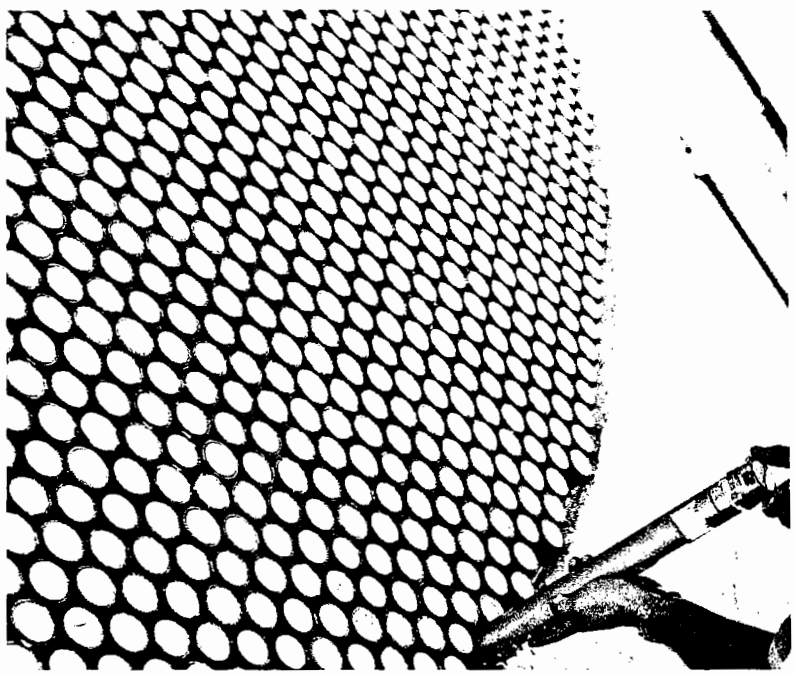
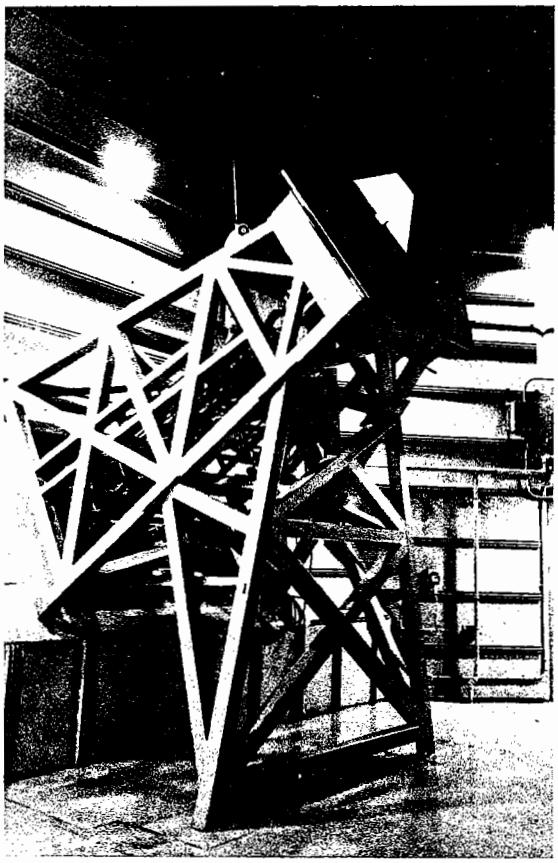
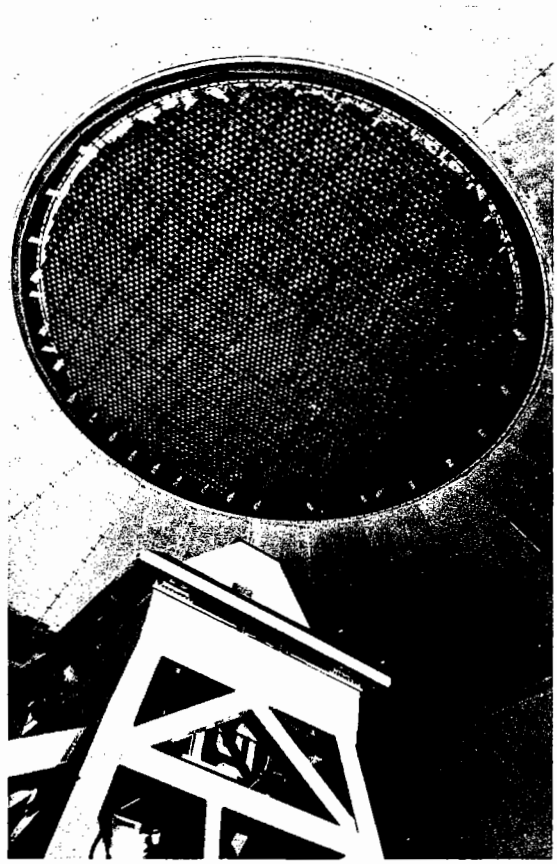


Figure 7-7. MSR Array Element Installation



A. MSR Feedhorn and Chamber



B. MSR Feedhorn and Array

Figure 7-8. MSR RF Chambers

Techniques, such as mechanical and optical array surveys, accurate location of the receive feedhorn on the array normal axis, and use of satellite tracks for final correction, have been developed to accurately "boresight" each array.[25,26] Motion sensors are mounted in the antenna turret to detect any long-term structure motion and derive correction factors to the stored software constants pertaining to array orientation.

RECEIVER DESIGN[6]

The basic concept of the MSR receiver and signal processing stemmed from earlier work done in connection with the NIKE-ZEUS Target Track Radar (TTR) and Discrimination Radar (DR). In many areas, the MSR receiver design was a modification or refinement of the earlier designs. For example, the cooled parametric amplifier uses a closed-cycle helium refrigerator based on an Arthur D. Little design for cooling the ZEUS TTR maser. The 30-megahertz IF limiters and logarithmic amplifiers were based on similar designs in the ZEUS DR. Some of the 30-megahertz IF amplifier module designs in the MSR were unchanged from those in the ZEUS DR.

The MSR receiver consists of two functional groups: RF and IF. The RF portion receives three signals [sum (Σ) channel plus two difference

channels] from the antenna comparator. These signals are amplified by a multichannel cooled parametric amplifier and double-converted to the 30-megahertz intermediate frequency. A fourth channel, the Q channel, is also implemented in the RF and IF receivers to provide antenna sidelobe blanking.[15] Automatic gain control functions are also included in the RF and IF receivers to ensure that the received signal is always within the overall receiver dynamic range.[27,28]

The IF portion continues the four-channel processing of the 30-megahertz signals delivered by the RF receiver. Figure 7-9 shows the IF receiver area. The first portion of the IF group employs the matched-filter concept of signal processing. High-speed electronic switches pass the various waveforms through signal paths that have an optimum response to each waveform. Significant variations of gain and delay (due to the different matched filters) are normalized by including appropriate attenuators and delay sections in each matched filter. Residual relative gain and phase changes [due to changes in operating frequency, Automatic Gain Control (AGC) level, etc.] are automatically compensated with binary controlled amplifiers and phase shifters.[28] After the matched filters, the signals are passed through logarithmic amplifiers, dechirp networks, and equalizers to conventional video signal processors to extract target data. Analog-to-Digital (A/D) conversion is applied to the signals for transfer to the radar control digital circuitry.

Complete MSR redundancy is utilized in the RF and IF receivers to maintain operational capability in the presence of any possible fault environment. Faults in the RF portion of the receiver are detected by amplitude monitoring at the inputs of the IF portion of the receiver. These monitors respond to test pulse signal inputs to the active and redundant channels through directional couplers, which precede the TR tube receiver protectors. The test pulses are gated into the receiver from the RF test set by computer control. Improper amplitude values and other faults will initiate redundancy switching. Other characteristics are displayed on control-monitor panels to allow manual control and to aid in fault isolation and calibration.



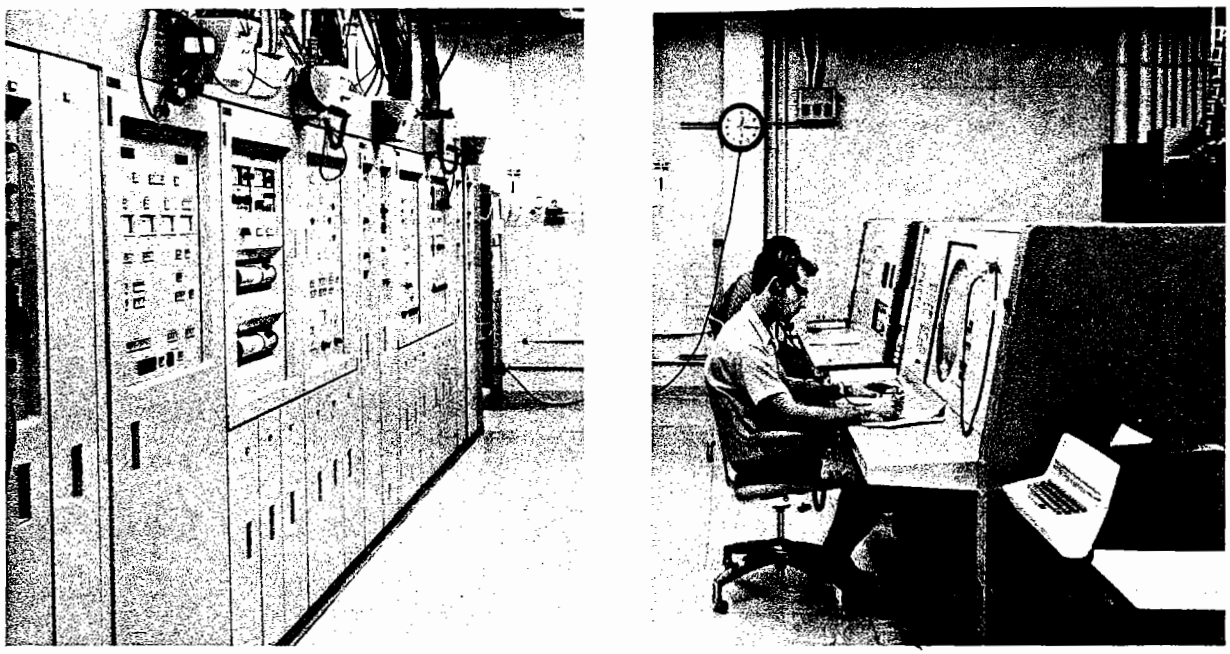
Figure 7-9 IF Receiver

The IF portion includes monitors that respond to these test pulses. The response of the receiver to these test signals is used to determine the IF channel status. Failure in the on-line receiver initiates redundancy switching, after which, off-line maintenance is performed on the faulty equipment, restoring it to normal operation.

TRANSMITTER DESIGN

The MSR transmitter achieves its high power output from two parallel high-power klystrons. The combined output from these tubes is supplied to the space-feed system of the antenna via a microwave waveguide system. A space-feed system powered from a single transmitter source can provide more transmitted power at a lower tube cost than a corporate-feed array using multiple amplifying tubes. Other advantages include fewer total components and the potential of higher reliability.

Four stages comprise the entire transmitter: exciter, buffer, driver, and final. The exciter and buffer are known as the Low Level Transmitter (LLT);[29] the driver and final stages are known as the High Level Transmitter (HLT). The solid state exciter generates the required transmitter frequencies for the HLT, as well as all local oscillator frequencies needed by the receiver. The buffer is a Traveling Wave Tube (TWT), which drives the HLT and also provides the required RF test signals. The LLT is completely under the control of the radar control equipment, changing frequency under computer command.[30] The various waveforms are generated in the IF receiver at 30 megahertz and fed to the LLT for frequency up-conversion to RF. Output power and other monitors are provided in the LLT to initiate an LLT redundancy switch when a failure occurs. The LLT equipment is physically located with the receiver equipment. Figure 7-10 shows the LLT on the left and Radar Monitor and Test Consoles



A. Low Level Transmitter

B. Radar Monitor and Test Consoles

Figure 7-10. MSR Low Level Transmitter and Consoles

on the right. The LLT output is fed by waveguide to the driver stages in the transmitter control room.

The HLT occupies six rooms, comprising a major portion of the equipment space in an MSR building. Two locked rooms contain the high-voltage power supplies. The driver and control equipment occupy a room in which all HLT operation is controlled and monitored. A specially designed room houses the two klystrons mounted in large oil tanks. The remaining area contains the extensive ancillary support equipment for the transmitter, including units involved in the purification, filtering, circulation, and heat exchanging of the high purity water, dielectric oil, and dielectric gas used by the transmitter.

A matrix of waveguide switches and dummy loads provides the redundancy switching capability of the driver stages. Either driver stage can be connected at its input to the LLT output or to the output of built-in test equipment used for alignment and trouble location. The output of either driver stage can be connected to a dummy load or to the final-stage klystron input. Switching is controlled either automatically by built-in fault monitors or manually for test purposes. A specially designed waveguide switch provides millisecond switching times. Fault monitors in each driver stage detect low power output, TWT arcing, low coolant flow, etc. The driver high voltage cabinet is equipped with interlocks for personnel protection. A crowbar, using a vacuum spark gap, fires in case of TWT arcing, interlock operation, or other faults requiring rapid removal of high voltage. Opening the cabinet door operates the mechanical shorting bars to ground high voltage connections.

The 35-kilovolt power supply for each driver occupies a corner of the nearest high-voltage power supply room. These solid state, regulated power supplies are fed by 480-volt three-phase power supplies through conventional switch gear adjacent to the high voltage rooms. Control cabinets adjacent to the driver cabinets operate the driver stages as well as each final amplifier. The built-in test equipment located here includes the RF signal generator, RF power meter, attenuators, etc. needed to align the transmitter and locate faults, as well as power distribution circuit breakers and control switches for all equipment. All logic required for fault indication, crowbar initiation, and system control is in a single cabinet.

Each high power channel includes a Varian Associates VA-144 klystron developed for MSR use. This tube has a wide bandwidth high peak power output, and a high duty cycle and resulting average power output capability. Power varies no more than ±0.7 dB across the band. The tube operates with a 150-kilovolts beam voltage, A modulating anode controls the beam pulse. Physically, the VA-144 is about 8 feet high.[31,32]

As mentioned previously, the klystron is mounted in a tank containing 3500 gallons of high dielectric-strength transformer oil. Two identical tanks are mounted in the klystron room as shown in Figure 7-11. The shock-mounted construction protects the final amplifier equipment from damage in a nuclear battle environment.

All components needed to pulse the modulating anode are immersed in the oil tank. The low level modulators, in cabinets adjacent to each tank, couple to the immersed equipment through a pulse transformer, which provides high voltage isolation between the external equipment at ground potential and the equipment in the tank at -150 kilovolts. The floating-deck modulator uses two Litton L5033 switch tubes, one on the off-deck and one on the on-deck, that are cooled by circulating the tank oil.

The final amplifier room also contains 14 power supplies, seven of which supply focus solenoid current to each klystron. A lead shield weighing about 2-1/2 tons encloses each klystron to protect personnel from X-ray radiation. The room is a high bay area equipped with a crane to handle the lead shield and klystron when tube changes are made. The crane also is used when the modulator on-deck or off-deck needs maintenance or replacement.

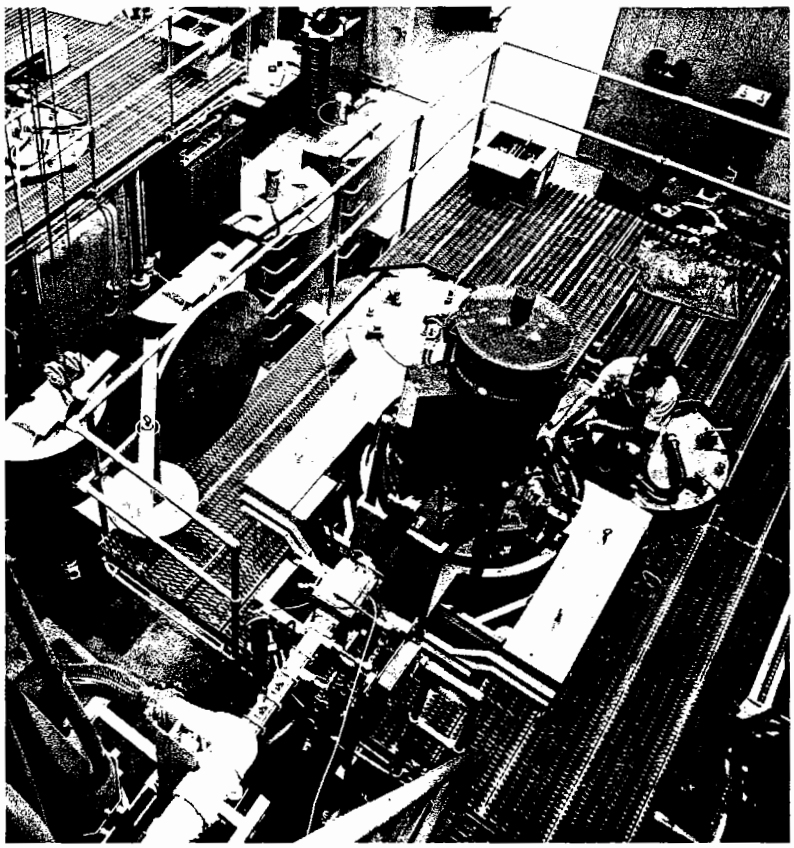


Figure 7-11. Klystron Room

Each klystron output connects through a high power waveguide to a high-power ferrite circulator and then to a high-power waveguide switch matrix to permit control of the output RF power from each klystron. These outputs can be combined and fed to the antenna, the normal condition, or into parallel high-power dummy loads. If a single channel malfunction occurs, the combining hybrid is automatically switched out and the remaining channel is connected directly to the antenna. For test purposes, the matrix can be manually controlled to connect any channel to either its own dummy load or the antenna, or to connect the combined output into either a dummy load or the antenna.

The mechanical waveguide switch used to handle the transmitter full power output is of special design. It is water cooled and operates in less than 100 milliseconds. The high power waveguide also is water cooled. Extensive investigation took place in the laboratory, using a high power resonant ring structure,[33] to determine the mechanism of waveguide RF breakdown, which occurred in the Meck prototype system at high average power levels. In many cases, breakdown occurred at the high power waveguide flange joints. These had been designed for the high RF currents involved but proper assembly was not always achieved. Providing suitable assembly tools and minor changes in flange design resolved this. However, arcing still occurred at random locations in the waveguide. It was noted that the power level at which unstable arcs occurred in the resonant ring

was a function of the physical length of the ring. From these data, it was deduced that the RF pulse duration after an arc forms was the controlling factor. Analytical work showed that, at the long pulse length and high average power levels of the MSR, a random arc would cause the copper waveguide wall to melt.[33] This melting created copper particulate matter, which would be heated by the high average power resulting in more RF breakdown and continuous arcing. The system remedy was to shut off the RF pulse as quickly as possible after an arc formed, preventing the generation of more particulate matter. This technique is known as "early-off."

The early-off circuits also protect the transmitter feed horn window.[34] Air circulates on one side of the window to minimize the deposit of dust particles, which could cause an arc. The early-off operation prevents damage to the ceramic window when an arc does occur. With this addition to the transmitter arc detection logic, stable operation at maximum average power and pulse length was readily achieved.

In the event of particles either in the waveguide or on the transmit feed window, the early-off allows the particles to be vaporized by the arc without creating additional particles. The effect of early-off on the system is similar to that of a missing pulse. As missing pulses regularly occur from target scintillation, etc., early-off has no effect on system performance since the software is designed to bridge gaps in data input.

A bank of three single-pole, double-throw high power RF "face" switches is used to connect the combined output of the final amplifier stage to one of the four antenna faces. One of these face switches is shown in Figure 7-12. These switches are controlled through the radar control equipment and consist of four parallel sets of ferrite phase shifters. These are fed by splitting hybrids that send one-fourth of the power to each set of phase shifters. The outputs are recombined through short slot couplers, which direct the energy to one of two outputs depending on the input phase. Each phase shifter is switched by a suitable modulator connected to its magnet coil. The switch has minimum loss and all microwave parts are water cooled.

Each klystron channel is supplied with the required high voltage from a power supply in an adjacent room. This power supply is completely solid state and uses a three-phase full-wave diode rectifier. It is regulated to within 3 percent by silicon controlled rectifiers in the 4160-volt ac supply line. A total of 250,000 coulombs of energy is stored in the capacitor bank to supply power during the klystron beam pulse.

Elaborate safety precautions are used. A Kirk key system protects personnel against exposure to high voltage components, X-ray radiation, and RF radiation. Fault monitors protect the equipment against klystron arcing, waveguide arcing, low coolant flow, high coolant temperature, out-of-limit solenoid current, etc.

Experience with transmitter operation at the Meck test site indicates all reliability objectives have been met. Tube life data available to the end of 1974 indicate the design objective of 20,000-hours mean life will be achieved for the driver TWT and final amplifier klystron.

After the tactical site transmitter had been in operation about six months, the pressure drop in the VA-144 klystron collector cooling channels increased from a normal 130 psi to as much as 180 psi. This phenomenon had never occurred during the operation at Meck. For seven months, an intensive investigation was conducted.[35] During this interval, site operation was maintained by periodically flushing the collectors with citric acid, which removed the copper oxide deposits and generally restored the pressure drop to near normal. Flushing was needed at intervals varying from a few days to two weeks.

Extensive analysis established that considerable particulate matter existed in the cooling water, although the particles were very small. A set of 0.45-micron absolute filters was installed in the collector cooling line at each klystron tank. These substantially reduced the particulate matter but did not correct the problem.

Small quantities of bacteria were also detected. To prevent possible growth in the collectors, a sterilizing lamp was added to the water purification unit. This also did not change the phenomenon.

Chemical analysis of Grand Forks' high purity water versus samples from Varian, Meck, and the high power test station at Raytheon's Spencer Laboratory (Burlington, Massachusetts) showed no essential differences. Impurities were at extremely low levels (in parts per million). However, only the Grand Forks water showed small traces of sulfides. As these were known to increase copper oxide formation rates, considerable attention was given to a remedy. Sulfide removal was attempted by the temporary use of copper pellet scavengers and sulfide removal resins but had no effect on the pressure increase. An investigation of copper oxide corrosion rate versus sulfide and oxygen concentration showed no significant rates at the concentrations detected at Grand Forks.

Finally, it was possible to disassemble one klystron's collector, which had exhibited the pressure drop change at Grand Forks. This showed a roughening of the copper oxide in the

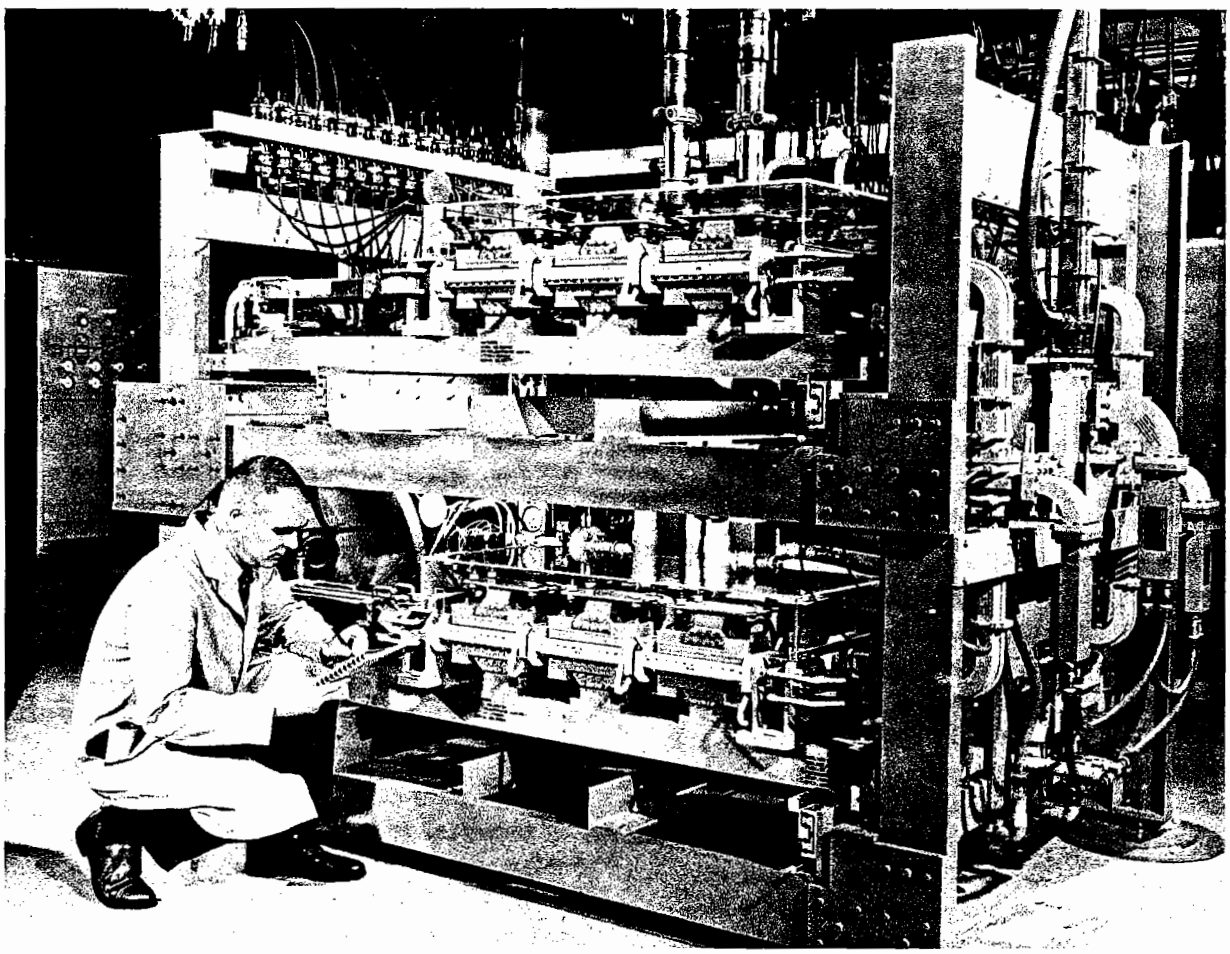


Figure 7-12. Single-Pole, Double-Throw High-Power RF "Face" Switch

conical region. Earlier calculations had shown that such roughening could cause the pressure drop increase. Analysis of the oxide on the Grand Forks collector and on a collector that had operated only at Meck showed no chemical differences. It was postulated that the oxide formed in the normal way but was roughened by hydraulic differences.

Tubes were subsequently flushed at Grand Forks using sulfuric acid to assure more complete removal of oxide. The static pressure on the collector was also increased by throttling on the return line. Since then, no further pressure drop increase has occurred. It is believed that at low pressure, incipient cavitation begins causing rough erosion. Once started, the roughening propagates, causing a pressure drop increase. At a higher static pressure, cavitation does not occur, precluding roughening of the oxide. Meck had always operated at the higher static pressure, hence the phenomenon was never seen there.

RADAR CONTROL DESIGN

The MSR is controlled by the Missile Site Data Processor (MSDP). The MSR Weapons Process (MW) software specifies the mode, frequency, antenna beam direction, transmitter power level, waveform, range gate width, minimum range, type of data needed, etc., for every transmission and every receiving interval.[30,36-41]

The function of the radar control equipment is to accept and store, until called, 68-bit words from the MSDP containing the desired action and the time it is to be taken. At the specified time, the words are decoded and the necessary control signals are generated and sent to the transmitter, receiver, and antenna. The receiver output is transformed from analog to digital signals and sent to the radar control equipment, where it is formatted with related information and stored to be transferred to the MSDP when requested.[8]

The radar control function is implemented by equipment called the Digital Control Group (DCG).[39] Like the receiver and the transmitter, the major portion of the DCG is redundant, with each portion called the Digital Control Unit (DCU). Besides the two DCUs, the DCG includes the Switch Rack and the Beam Steering Computer (BSC).[40] The Switch Rack monitors each DCU output and performs redundancy switching when a fault occurs.

The DCG uses standard SAFEGUARD logic and has eleven logic racks and eleven power supply racks. Some of the DCG logic racks are shown in Figure 7-13. Each DCU has three racks: input, output, and control. The BSC has two control racks and three register racks. The Switch Rack completes the complement.

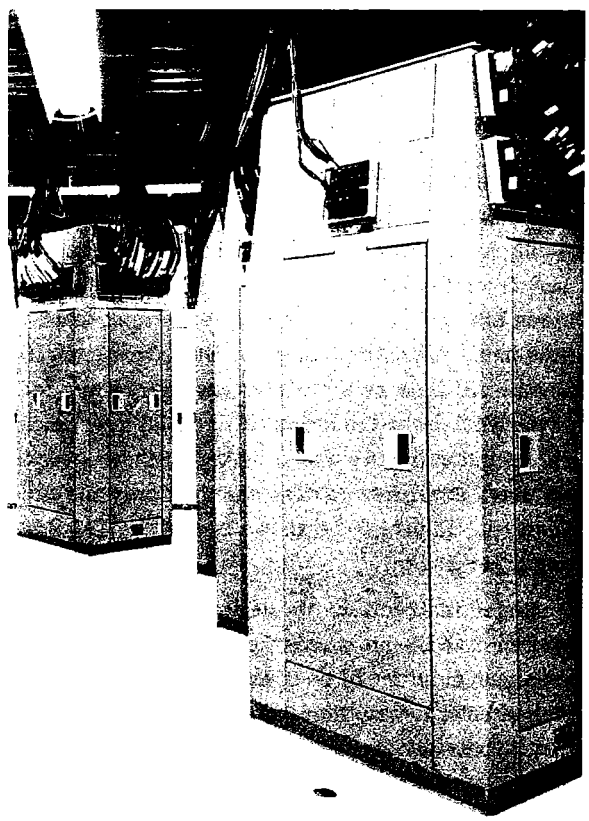


Figure 7-13. Digital Control Group Logic Racks

About 110,000 integrated circuit packages are used in the entire DCG.

To steer the antenna, the phase setting of each phase shifter must be calculated from the steering angle instructions. This is accomplished by the BSC,[40] which has two sets of registers; one holds the array in its last position while the second is being set for the next position. When the beam is to be repointed, the new phase shifter values are "jammed" from the second register to the first one. The beam steering calculation not only determines settings for the desired beam direction, but also corrects for the fact that the wavefront at the array face from the feedhorn is spherical. The constants for this correction are stored in a wired memory, which is part of the BSC. Calculation primarily involves incrementing a fixed phase shift from element to element. This is accomplished in functional logic blocks called accumulators. The element phase values therefore ripple through the registers as they are calculated. At jam time, all values are simultaneously transferred to the output registers.

The phase shifter diodes require 250-volts reverse bias or 150-milliamperes forward current. Each phase shifter has a drive amplifier to convert from the logic level of the registers to the diode bias level. In a four-face system, each face has a full complement of 5000 drive amplifiers. All four sets of drive amplifiers are fed in parallel from the output of the BSC. A face-select indication provided by the BSC fans out to all drive amplifier cards, enabling only the face desired. Figure 7-14 shows one of the 144 drive amplifier racks.

Radar instructions in the form of groups of four or five 68-bit words flow from the MSDP to the input memory of each DCU where they are stored until instruction time. The words are then subdivided by the input controller and fed to the various other controllers. Four controllers convert the digital information into pulses at the proper time to control analog parts of the MSR (i.e., the transmitter, IF receiver, video receiver, and test controllers). The BSC controller sends the instructions in digital form to the BSC for its calculations.

The set of output pulses from each DCU to the other portions of the MSR are continually compared in the Switch Rack. In case of a noncompare, software tests identify the faulty DCU. Redundancy switching takes place as needed.

The data output of the receiver is in digital form from the encoders. Because receiver data must be taken in real time as radar return signals occur, it is loaded into temporary storage (Receiver Data Buffer) for a brief time until it can be transferred in blocks to the output memory. The Output Memory Controller performs

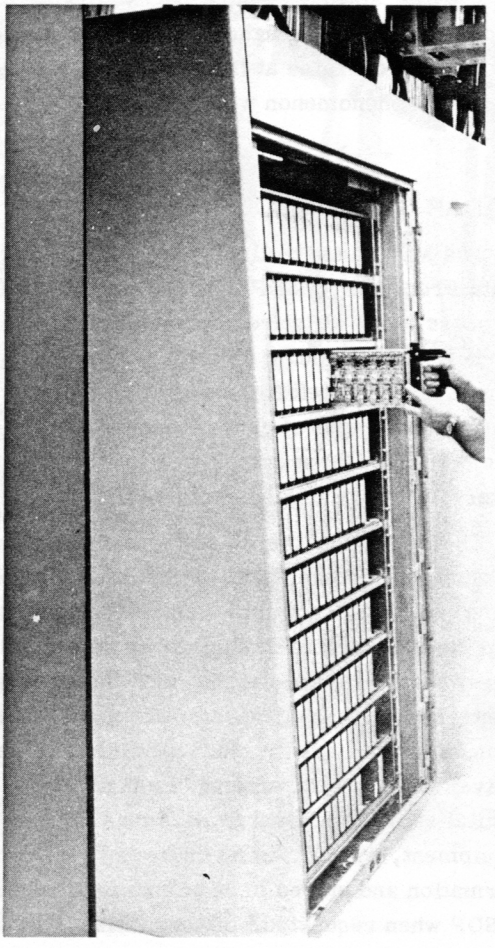


Figure 7-14. Drive Amplifier Racks

this transfer as well as transfer of data from the Output Memory to the MSDP when requested.

The DCG, therefore, is a wired logic decoder for input data and a formatter for output data. There are, of course, a number of important test capabilities. It has parity checking in critical places and also continuously monitors each DCU operation. In summary, the DCG provides the interface between the Data Processor and the analog parts of the radar. It is redundant and automatically switches when a fault occurs. It is maintained by test software via a control console provided for that purpose. This test software also provides monitoring and trouble location for the entire radar equipment.

DCG testing, overall MSR fault indication, and continuous performance checking are accomplished by test software included in the Weapons Process. This software is controlled from the Radar Monitor Console.[42] Three classes of tests are made: Class A, Class B, and Class C.[43,44]

Class A tests create test pulses, which run continuously under all system operating conditions. These cause the hardware monitoring equipment in the receiver to function. The entire signal path, from the Low Level Transmitter to the Receiver A/D encoders, is monitored. The High Level Transmitter is internally monitored exclusive of software. On failure of a Class A test, redundancy switching can occur or man is informed of the trouble. Man then can isolate the difficulty using Class B tests. These run interleaved with the Weapons Process and displace a small number of search channels of the radar template. In the event of a real or simulated engagement, the Class B tests are automatically terminated by software.

The Class B tests provide fault location in the DCG.[44] In most cases, they can isolate failures to within three logic chassis. The Class B tests also provide periodic testing of all antenna elements. The remaining Class B tests permit performance evaluation of the receiver and overall system. Sufficient flexibility is available to permit operator selection of test conditions where appropriate.

To prevent interruption of normal system operation, the flexibility of Class B tests has to be limited. The Class C tests allow complete flexibility under test conditions and perform function tests that can only be accomplished with the entire MSR out of service. Normal MSR operation can be rapidly reestablished from a Class C test condition, however.

COMPARISON OF PERFORMANCE OBJECTIVES AND RESULTS

The performance of both the prototype MSR installed at Meck[4] and the tactical MSR installed in North Dakota,[45] came very close to that specified in the work statement[2,46] prepared at the beginning of the development period. (See the Classified Supplement.) The development of each critical item — the antenna, transmitting klystron, low sidelobe chirp lines, and the like — produced components with performance that equaled or exceeded the specification. The antenna, since this was one of the first phased-array systems, was a distinct challenge. The thoroughness in testing the prototype antenna design ensured achieving the required MSR performance and provided sufficient detailed information to compare the theoretical performance of a phased array with the realized performance of an as-built array. This type of data can be utilized by designers of future arrays to evaluate the need for expensive antenna pattern measurements.[47]

The operation of the prototype system at Meck since mid-1968 has provided a wealth of information concerning the reliability of the radar. Accurate records on component failures have been kept since that time. Following the typical and expected high initial failure rates, the rate of failures in the entire complex quickly reached a level of less than one per day except for the high-usage drive amplifier and phase shifter diodes.[48] These items are replaced periodically

after a sufficient number of failures have occurred to warrant change. The integrated diagnostic system has simplified locating and repairing each malfunction to a degree comparable with much smaller and simpler radars.

The system has demonstrated the ability to run continuously for long periods of time and shows no abnormal wearout in any section of the apparatus. The failure rate of the solid state components, such as transistors and high-power phase shifter diodes, is equal to or better than the design objectives.

The original design did not contemplate an Electromagnetic Pulse (EMP) requirement which subsequently evolved. All elements of the MSR were then designed to meet this requirement and, in many instances, were tested specifically to demonstrate this.[49,50] The results of the antenna hardening, particularly in the beryllia antenna element window, were most encouraging. See Chapter 6 for more information on hardening.

The tactical system in North Dakota afforded an opportunity to observe the installation of this massive amount of electronic equipment. The ease with which the apparatus was installed, wired, and tested confirmed an adequate tactical design. Of particular interest was the simplicity of installing the space-feed antenna systems compared to the usual complex and time consuming corporate transmission system network.

The beneficial capabilities of a phased-array antenna beam have been demonstrated during the prototype firings at Meck Island. The MSR provides data on a very large number of reentry objects over a large area, and the comparison to previous "dish" antenna radar systems is quite dramatic in this regard.

MAJOR CHALLENGES AND INNOVATIONS

One of the major challenges to the MSR system was the development of a space-feed antenna having sufficient beam agility, low loss at S-band, accurate tracking capability, and ease of installation and maintenance. The resulting design has met all of these objectives and has performed well in the very severe environmental requirements at Meck Island and North Dakota.

The very low far-out sidelobes were achieved without resorting to special fabrication techniques requiring high precision. The long life of the high-power phase shifter diodes was achieved after a lengthy development period. This was the first application for diodes in this power range. The performance of the transmit feedhorn window was achieved after a long period of design and testing. Its performance has been proven by both the Meck and North Dakota operations. The low failure rate of the antenna components and the very rapid antenna element checking system reduces the maintenance task on the phased-array antenna to a once-a-month or less often operation. The development of an antenna service vehicle simplifies even this maintenance task. The performance of the beryllia antenna element window both electrically and from the EMP standpoint was a significant achievement resulting from extensive development and testing.

The development of the high-power klystron transmitting tube probably represented as severe a challenge as any item in the entire radar. The very high average power output in S-band, as well as the wide frequency bandwidth, were objectives never before achieved. In fact, the S-band klystrons available at the beginning of the development period provided roughly an order of magnitude less average power output than the subsequent MSR klystron. This development has produced RF power at the S-band frequency at a lower cost per watt of power than that produced at any other frequency. In addition, the requirement of only two tubes produces a transmitter design of high reliability and low maintenance cost.

Utilizing the high power from the klystrons created problems with the power-handling capability of the S-band waveguide transmission system connecting the transmitter to the antenna. These problems required considerable development effort since average power levels of this magnitude had never before been attempted with

S-band waveguide and waveguide components. Final solutions were readily achieved and several years of operation, including operation of the installation in North Dakota, has verified their effectiveness.

The klystron collector cooling channel design was marginally able to cause cavitation-related erosion. This did not appear until the Grand Forks equipment was inadvertently operated at low static pressure.[35] When the roughness was completely removed by a sulfuric acid flush and high static pressure was maintained, no roughening occurred due to erosion. The high pressure apparently prevented the nitrogen entrained in the water from forming bubbles at low pressure points in the collector. Such bubbles led to the rough erosion.

Installation and test of the radar digital control equipment at TSCS permitted early detection and correction of design deficiencies. Tests with system software of increasing complexity turned up logic and timing problems of increasing subtlety. As the DCG is a wired logic computer, the solution of these problems required logic changes. It should be noted that logic design changes could be expeditiously implemented due to the highly automated design process used for SAFEGUARD digital equipment. Solving problems at TSCS resulted in required performance at Grand Forks, showing that reproducibility was easily achieved. However, as TSCS was a partial, nonredundant DCG with only a skeleton Beam Steering Computer, residual problems did occur during Grand Forks testing particularly where DCG redundancy was involved. These problems were corrected on site.

Of particular importance was achieving the availability and reliability objectives for the radar system. With the success of the entire engagement dependent entirely on a single radar complex, attaining these requirements was mandatory. Several years of operation in a firing program at Meck Island has established that the MSR with its redundancy can meet the very stringent availability and reliability requirements. Redundancy switching of receivers, transmitters, and radar control equipment has been demonstrated during engagements, including those with an interceptor missile in flight.

The requirement for very low-range sidelobes in the chirp system used in the MSR was important. The very small target size of the incoming reentry vehicle in relation to its surrounding objects mandated a solution to this problem. The delay lines resulting from the development program did meet these requirements and exhibited such excellent stability that performance could be obtained on a day-to-day basis over a long period.

Chapter 8.

PERIMETER ACQUISITION RADAR

Chapter 8.

PERIMETER ACQUISITION RADAR

Introduced in the Spring of 1965 as an adjunct to a full-scale NIKE-X deployment, the Perimeter Acquisition Radar (PAR) was to be an unhardened, early warning VHF radar. Later in 1965, a limited NIKE-X deployment was proposed with the VHF PAR as one of its major components. This NIKE-X proposal triggered a 12-month "definition and contractor selection" phase for PAR. By October 1966, Bell Laboratories had established the PAR requirements and requested quotes from several major contractors. The proposals were received and evaluated by December 1966, and a contract was awarded for an "initial definition phase"* to General Electric Company (GE), Syracuse, New York. During this initial definition phase, detailed requirements[1] were generated, a configuration was selected, and development of critical components was started.

A new deployment concept evolving from the NIKE-X program was introduced during January 1967 and designated I-67. The I-67 System deployment, later to become the SENTINEL System, consisted of SPRINT and SPARTAN missiles, Missile Site Radars (MSRs), and PARs. In this concept, PAR was redefined from an early warning radar to one that could provide initial target detection, discrimination, and tracking for long-range SPARTAN intercepts. The additional requirements created by the new "area defense concept" redefined the PAR as a VHF radar in the forward portion of the defended area and hardened so that its integrity would be maintained during an attack.

In April 1967, after General Electric completed the Phase I VHF effort,[1] the Phase II portion of PAR was temporarily delayed until a major problem could be solved. With the redirection of its role, PAR was now subject to nuclear blackout from the bursts of SPRINT and SPARTAN missiles. Results of a study on nuclear blackout, conducted the previous summer by the Institute for Defense Analysis, concluded that since the blackout problem was significantly less severe at UHF than at VHF, the PAR frequency band should be changed to UHF. Largely as a result of this study, a joint decision between Bell Laboratories, the Army, and the Department of Defense shifted the PAR operating frequencies to the UHF band. By May 1967, one month after the UHF decision, new detailed requirements for the PAR were established; many major configuration decisions regarding types of transmitters, number of faces,

*A two-phase effort was undertaken in which Phase I was Definition and Phase II Development.

antenna size and type, and waveform types were determined; and the development of critical components was begun.

In September 1967, the decision was made to deploy the system embodied in the I-67 (SENTINEL) proposal. Approval was given to General Electric to begin Phase II — the detailed design and manufacture of the PAR equipment.[2-11] After defining the complete radar system configuration, the detailed design of the PAR building and power plant began in June 1968.

The planned PAR configuration[12,13] in many ways was similar to that of a Multifunction Array Radar (MAR-I — an L-band radar that has been constructed and thoroughly tested at White Sands Missile Range between 1964 and 1966). MAR-I had separate transmit and receive arrays and a one-to-one ratio of receivers and transmitters to antenna elements, but each array was corporate-fed, its transmitter used multiple Traveling Wave Tubes (TWTs), and its receiver used parametric amplifiers similar to those originally planned for PAR. Since the experience gained from MAR-I was directly applicable to PAR and components in the UHF band were thought to be available, much of the PAR design was considered to be "off the shelf." Development of a complete prototype system, therefore, was deemed unnecessary,* and it was decided to construct the first PAR [the Research and Development (R&D) model] at a site where it would become part of the operational system after the R&D phase was completed. In the SENTINEL Area Defense Plan, this site was to be located in the Boston, Massachusetts, area.

In March 1969, the SENTINEL Area Defense System was reoriented to the SAFEGUARD System Minuteman Defense Concept and the first two SAFEGUARD sites were selected in North Dakota and Montana, with North Dakota chosen as the R&D site for the PAR. (See Figure 8-1.) In lieu of an R&D radar for design confirmation, a Limited Engineering Development Model (LEDM)

*As discussed in Part III — Management and Overall Approach — although this decision may have been satisfactory from a hardware standpoint, it led to severe system design penalties in the final ABM effort.

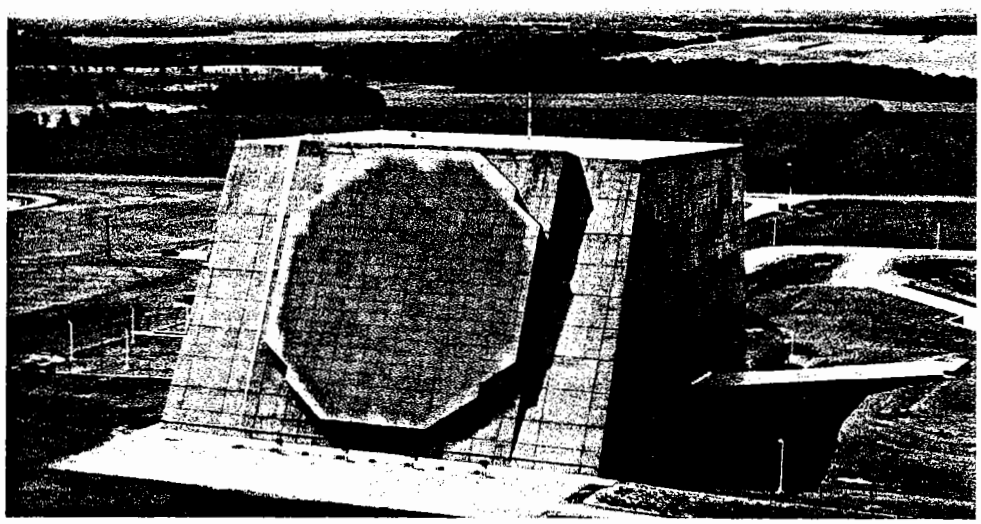


Figure 8-1. PAR Site — North Dakota

was constructed by General Electric. This provided a test bed for prototype models of components used singly in the system (e.g., the signal generator and exciter for the transmitter and the signal and data processor of the receiving chain) and for a significant quantity of each component used in large numbers within the final system (e.g., antenna elements, phase shifters combiners, and transmitter TWTs).

During 1969 and 1970, a major part of the PAR development and test activity involved use of the LEDM at Syracuse, New York. This program continued until May 1971 and verified the design and performance of the high-usage items. It established methods for their test and maintenance (including limited-life testing) and verified their interface with the rest of the system.

The PAR transmitter design (Figure 8-2) was approved in early 1970 and released for manufacture. Qualification testing of the TWTs by Raytheon was completed, the tube design was frozen, and production was started for the LEDM and the first PAR. Several hundred antenna elements and over 120 phase-shifter models were manufactured and tested in the LEDM. The low-noise transistor amplifier was developed, tested in the LEDM, and authorized for use in place of the parametric amplifier.

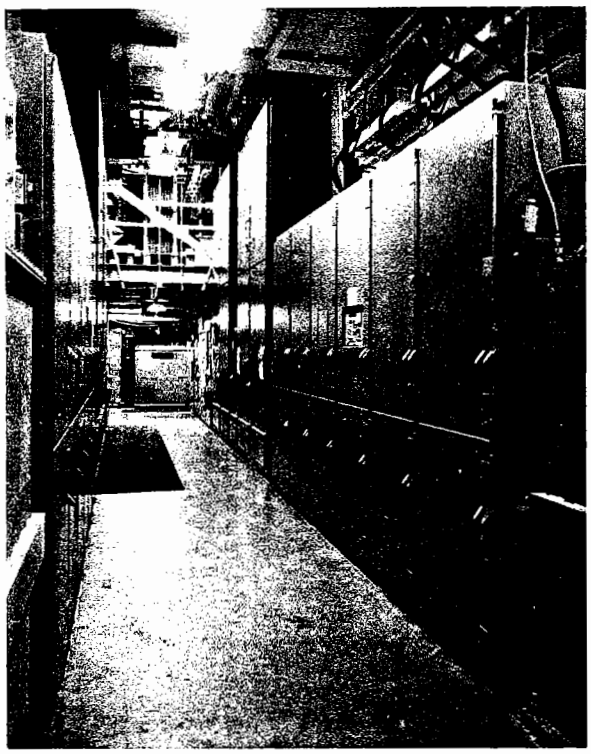


Figure 8-2. PAR Transmitter

A construction contract was awarded for PAR-1 in North Dakota and PAR-2 in Montana in 1970 and actual construction[12,13] began at these sites in April 1970. During the year, Critical Design Reviews (CDRs) were held by the Army resulting in the release of the PAR designs.

Toward the end of 1971, the Army Corps of Engineers installed the heavy duty equipment at the PAR-1 site. Work continued on both sites until August 1972 when, as a result of the Strategic Arms Limitation Treaty (SALT) Agreements, a decision was made to terminate any further work on PAR-2 in Montana. Figure 8-3 summarizes the PAR design history.

During the period from August 21, 1972 [Building Occupancy Date (BOD)] to September 27, 1974 [Equipment Readiness Date (ERD)], an intensive test program to verify system performance was executed.[14] This is detailed in Figure 8-4. The majority of testing was implemented with software (see Chapter 4, SAFEGUARD System) developed at the Tactical Software Control Site (TSCS) at Madison, New Jersey. The success of the test and evaluation activity was largely due to the timely delivery of the many high-quality test software packages to the North Dakota PAR site. The software schedule is shown on Figure 8-5.

The initial alignment of the radar was completed by August 1973. During this month, the first satellite track and the first radio-star track were successfully accomplished.

Work continued past ERD to prove-in the PAR Weapons Process (PW) software for threat conditions exceeding those required at ERD. This

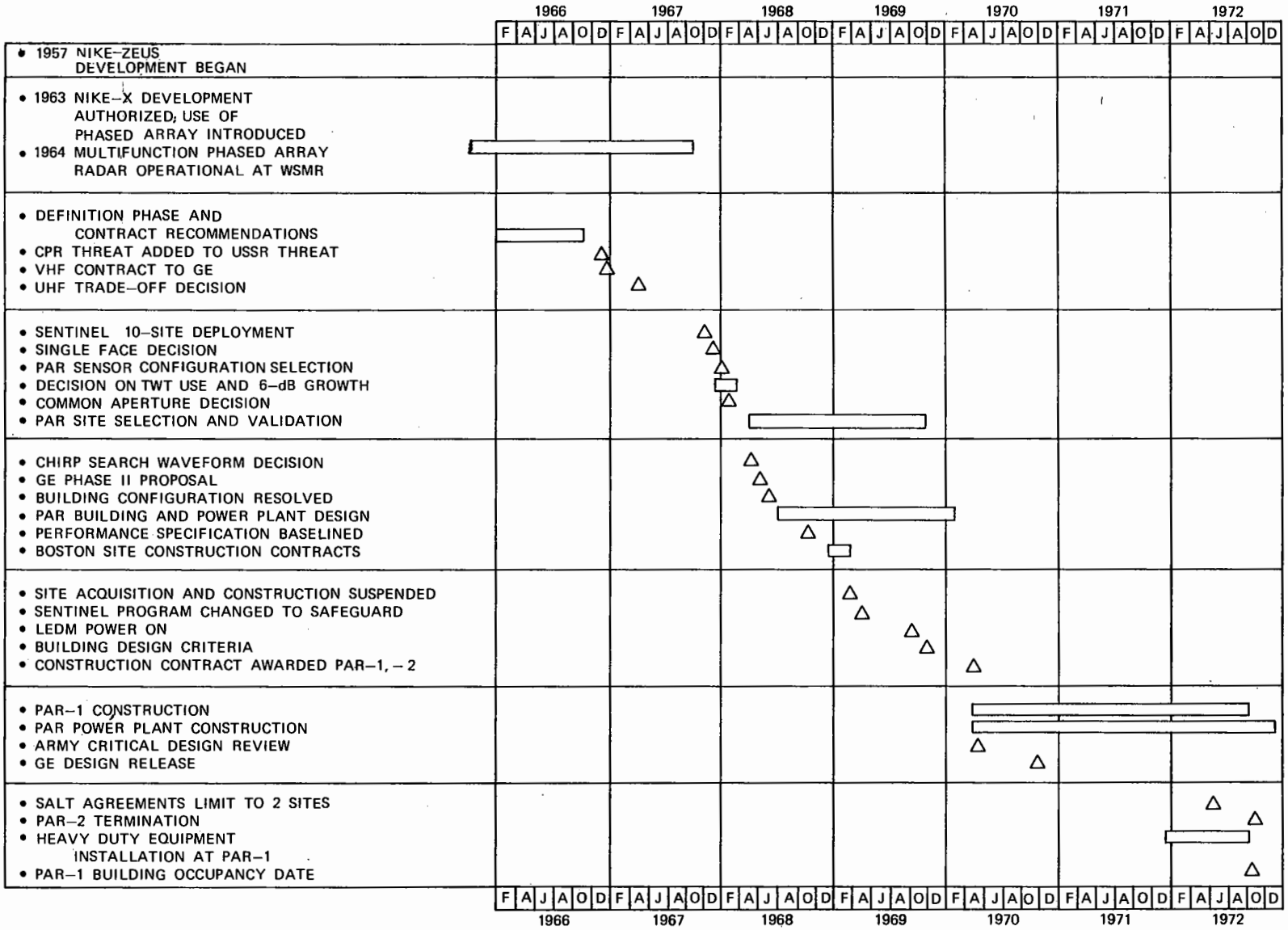


Figure 8-3. PAR Design History

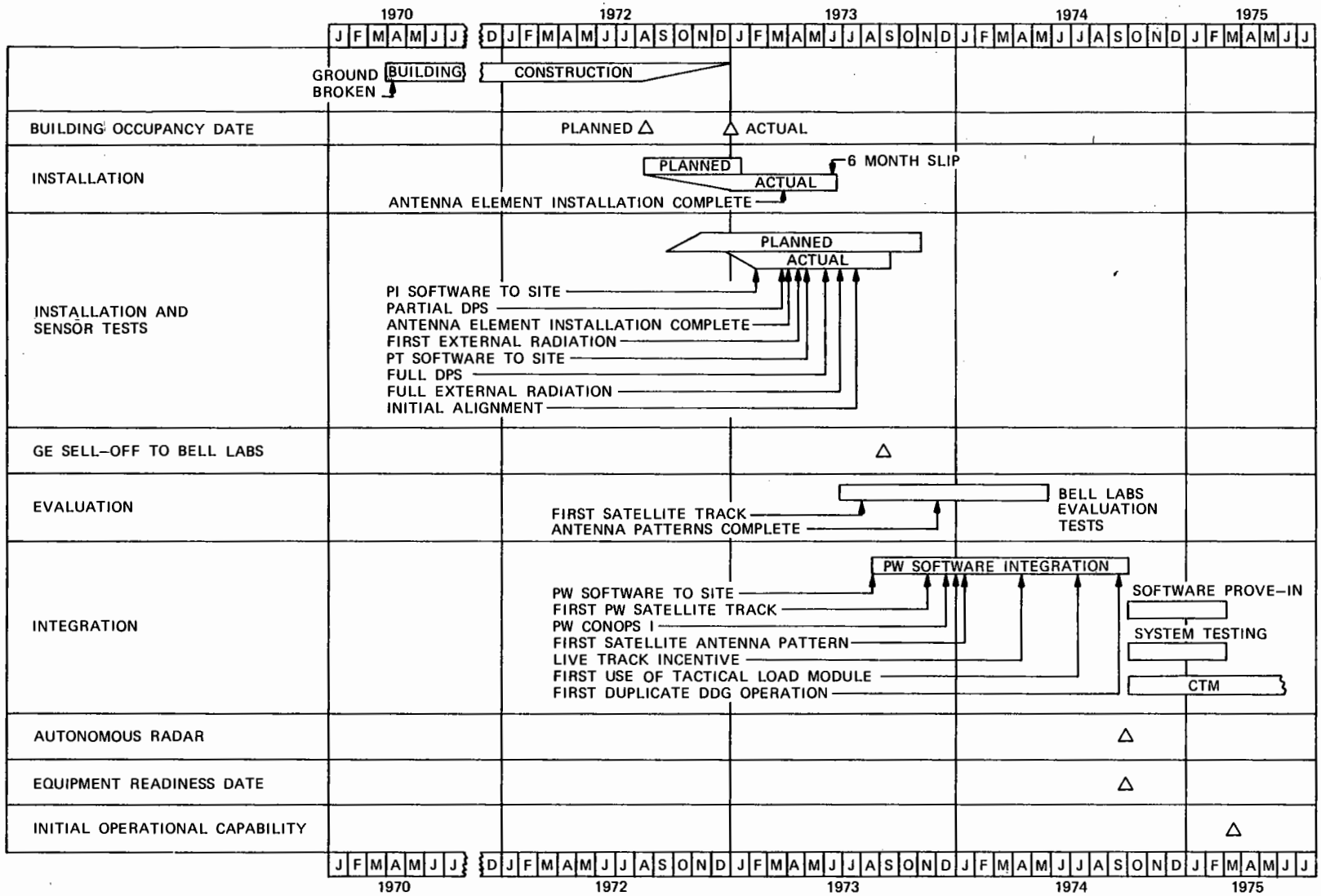


Figure 8-4. PAR-1 Installation and Test Schedule

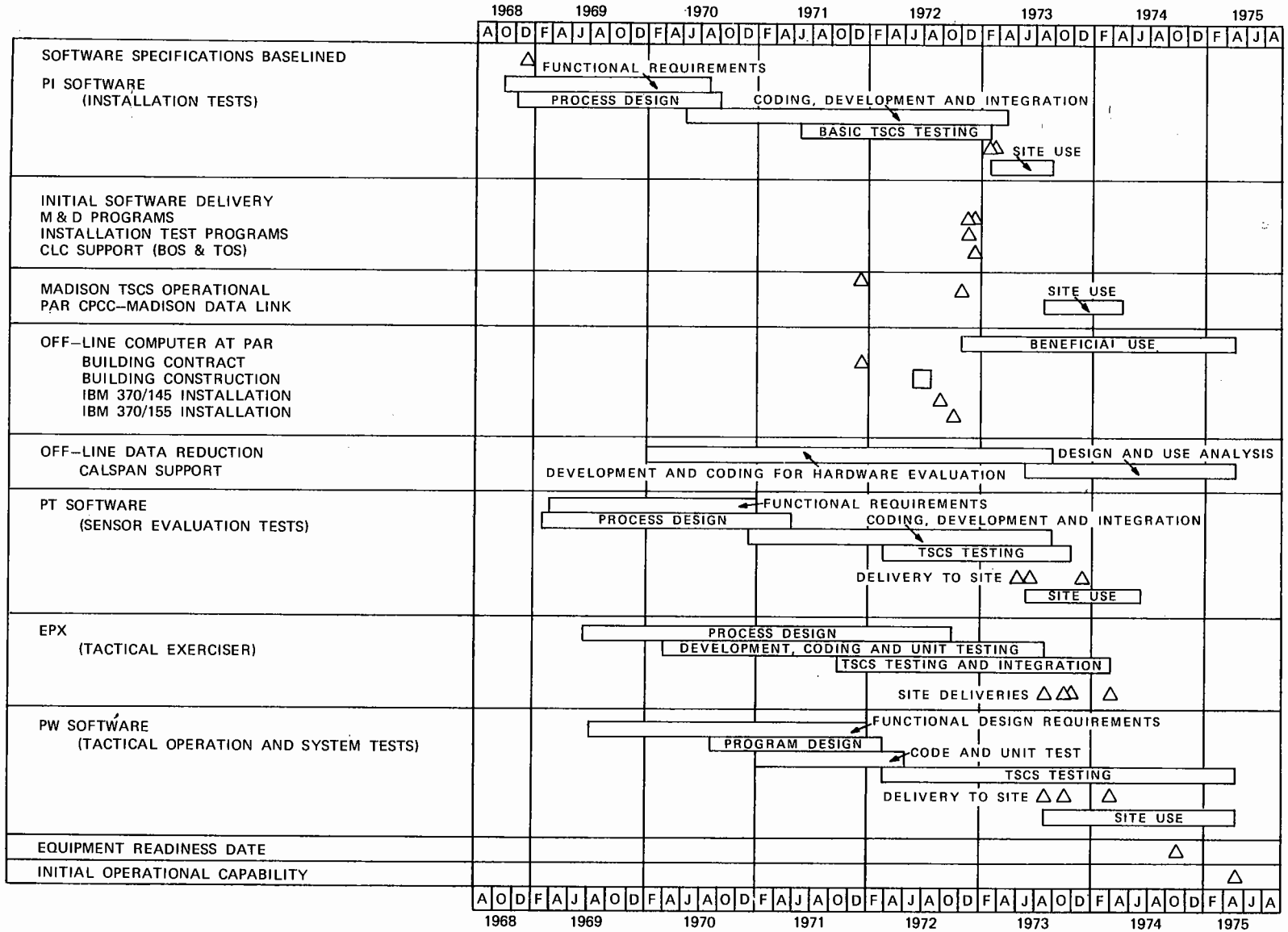


Figure 8-5. PAR Software History

included system testing of the PAR netted with the MSR and the Ballistic Missile Defense Center (BMDC). Additional work was scheduled beyond the Initial Operational Capability (IOC) date in April 1975 and would continue, during a Contractor Technical Maintenance program implemented by Western Electric Company, to final operational capability.

SUBSYSTEM DESCRIPTION

The PAR is a phased-array radar, operating at UHF, which performs long-range surveillance to detect and track enemy ballistic missiles for intercept by the SAFEGUARD missiles. As an auxiliary function, it provides tracking data to North American Air Defense Command (NORAD) on selected satellites. The PAR is designed to perform its mission in an environment that may consist of false targets (aircraft, satellites, aurora, and meteors) and nuclear weapons effects. To withstand nuclear effects, the radar equipment is designed to meet specified environmental criteria.[15] The radar is housed in a 128-foot high hardened reinforced concrete building that provides protection against nuclear thermal radiation and Electromagnetic Pulse (EMP) effects. The front of the building is inclined at a 25-degree angle from vertical, faces almost directly north, and supports a phased-array of 6888 antenna elements[16] (Figure 8-6). The building

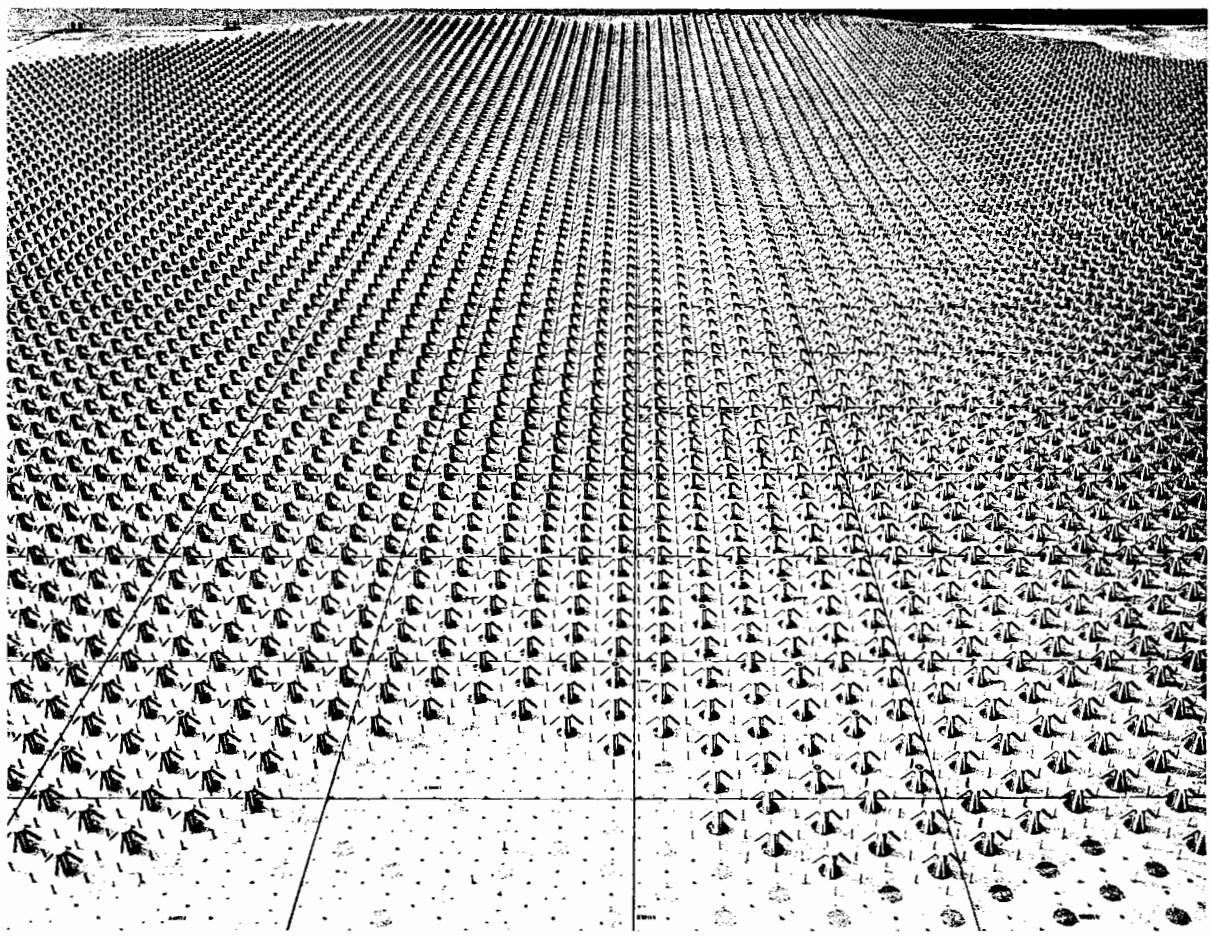


Figure 8-6. PAR Face, Bottom-to-Top View of Phased-Array Antenna Elements

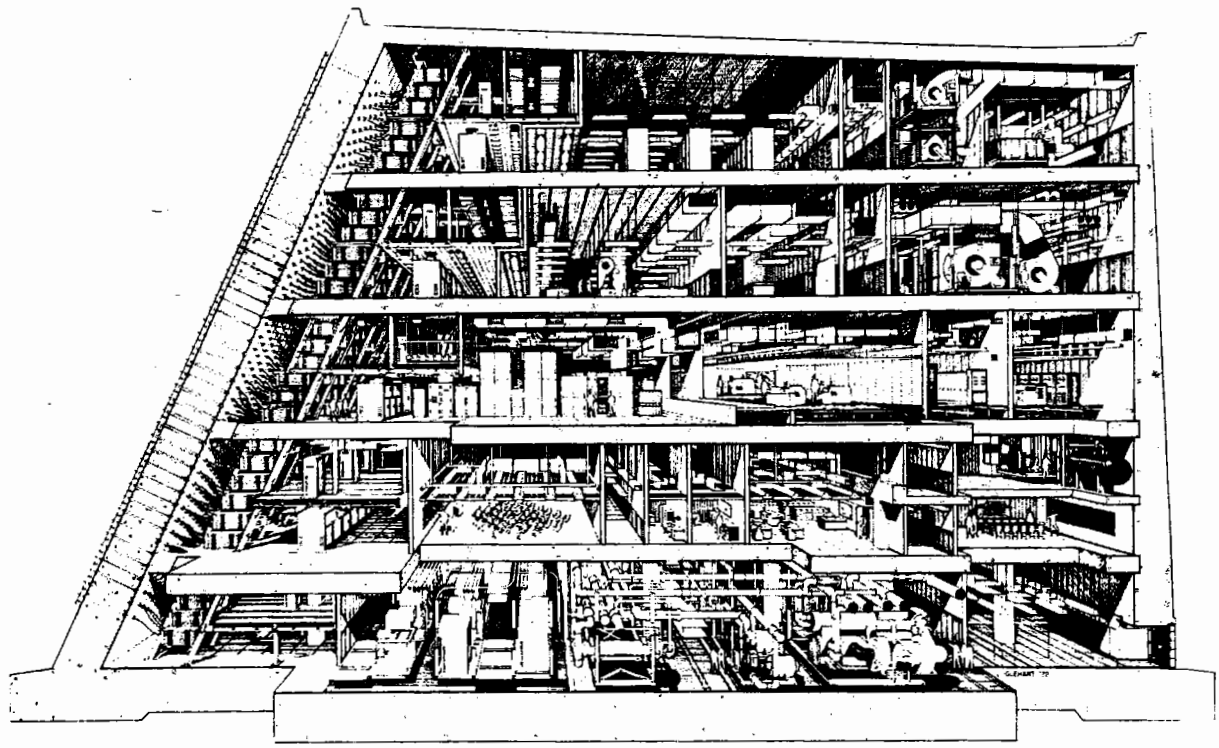


Figure 8-7. PAR Building, Cutaway View

required 17 million pounds of steel reinforcing bars and more than 58,000 cubic yards of concrete. The base of the structure is 200 feet square and 11 feet thick. The PAR face containing the radar elements is 7 feet thick. Adjacent to the PAR is an underground power plant connected by a 130-foot tunnel. A cutaway view of the radar is shown in Figure 8-7.

The PAR searches the volume of space within a large solid angle in front of the array face at regular intervals. It can detect small targets in a typical ballistic missile complex at large distances with a high probability of detection. Both the radar operating frequency and the antenna beam-pointing direction can be varied rapidly. To optimize performance, separate antenna illumination functions are used in the transmit and receive modes. In the transmit mode, an asymmetrical phase taper is applied at low pointing angles to reduce the peak sidelobe power radiated toward the ground and enhance the system's electromagnetic compatibility.[17] In the receive mode, an amplitude taper is used to reduce near-in sidelobes and minimize the effects of interference and jamming.

A block diagram of the radar is shown in Figure 8-8. The PAR transmitter consists of 16 groups of 8 (a total of 128) high-power TWTs, which amplify a chirped waveform generated by a common exciter. The combined total peak radiated power is in the multimegawatt range, and the transmitter operates at an unusually high duty cycle. The energy from each TWT is divided to feed two 24-element subarrays or a total of 48 elements.

Target returns are amplified by 256 low-noise transistor amplifiers, which are an integral part of the phase-steered, corporate-fed array. One transistor amplifier is used for each receive

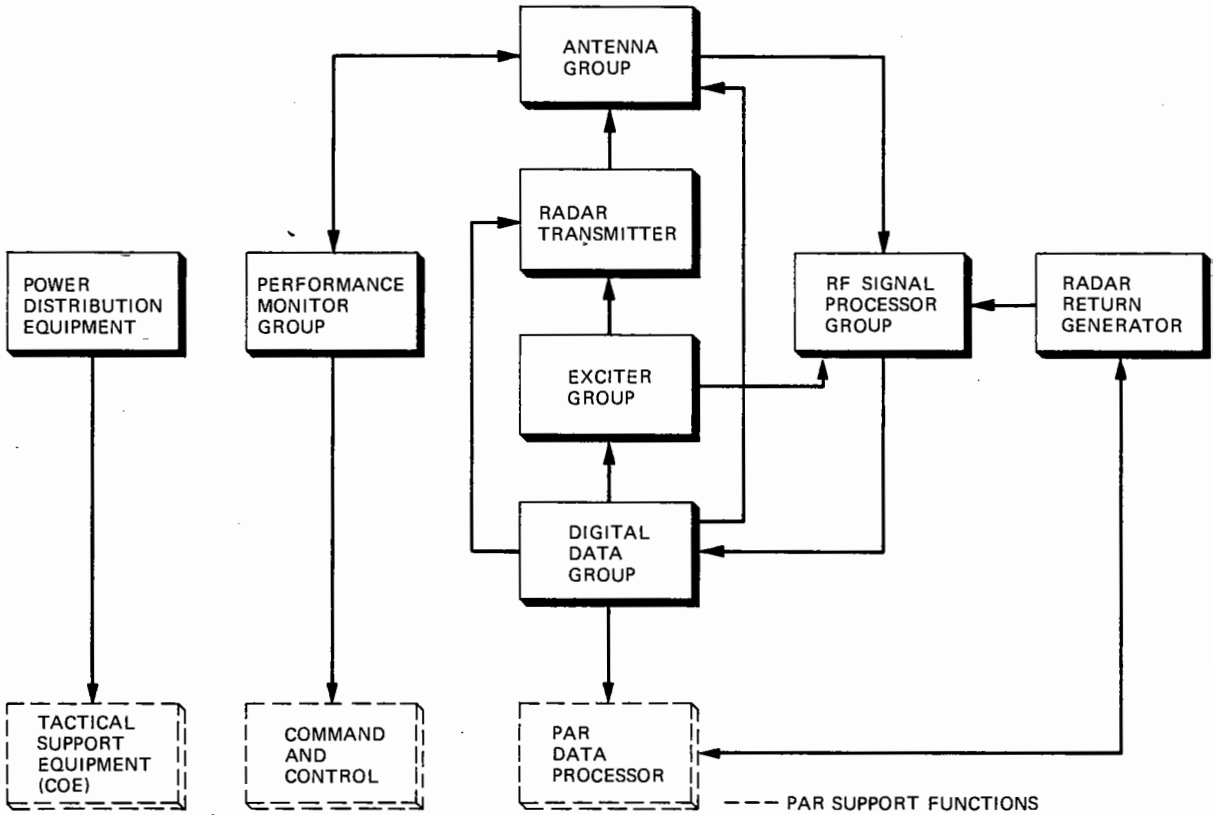


Figure 8-8. PAR, Block Diagram

subarray of 24 antenna elements. The receive signals are combined into appropriately formed search and track beams and then are processed by an RF signal processor.

The Digital Data Group (DDG) interfaces with the PAR Data Processor and provides timing signals and instructions for controlling the radar. Phase steering commands are generated in the DDG by the Beam Steering Computer (BSC). The digital equipment consists of two identical channels that operate simultaneously. Comparisons are made between the channels at numerous points to ensure errorless operation. This feature permits real-time fault detection and facilitates the isolation of a malfunctioning channel.

Radar performance is monitored by cyclic tests performed automatically every 50 milliseconds. Test signals are injected into a bi-directional element test network, which is used to distribute test signals to or from each antenna element for monitoring the receiver or for collecting samples of transmitter energy. Class A tests employ the element test network to monitor critical battle performance functions such as receiver sensitivity, transmitter power, and angle error. These tests are automatically interleaved with the tactical programs. Class B tests, performed on command by light-pen action at the Radar Maintenance Console, are used to monitor and display characteristics such as the transmit/receive antenna beam shape. Changes in the antenna beamforming alignment can be performed using Class B measurement data gathered through the element test network.

Equipment status is continuously displayed at the Radar Maintenance Console, where all performance and maintenance monitoring functions can be initiated by the console operator. Simulated test targets originated by the Data Processor are formed in the Radar Return Generator and injected into the signal processor's IF input.

COMPARISON OF PERFORMANCE OBJECTIVES AND RESULTS

The PAR subsystem performance requirements[18] were met or exceeded in almost every instance. An extensive test program was carried out to assure design compliance with special environmental requirements.[15] This program analytically assessed all the system components and performed experimental tests on a selected set of components representing each major design item. With the exception of the TWTs and certain retaining and fastening apparatus for which the vulnerability was assessed at 75 percent of the design level, all mission-critical equipment withstood the nuclear shock and vibration spectrum requirements.[19]

The PAR electrical performance parameters met or exceeded their required values in every instance. (See the Classified Supplement.) Due to higher transmitter power, better than expected receiver sensitivity, and slightly higher antenna gain, the overall system performance was about 4 dB greater than specified.[17,20]

Power density measurements, made on the ground in front of the PAR while the radar was operating in the tactical search mode, showed that the average power density was well below the 10-milliwatts/square centimeter hazardous levels at all ranges. Other tests verified the PAR's electromagnetic compatibility with USAF aircraft and Canadian communication equipment.

Using an airplane-borne signal source, a somewhat limited antenna pattern measurement program (main beam and sidelobes) demonstrated that the internal method of injecting a signal at the element test coupler yielded results comparable to external measurements of an array-normal beam.[21] The results showed agreement between the theoretical, internal, and external measurements within the stability* of the element path phase and amplitude values. A view of the PAR with the antenna measuring radar on top of the building is shown in Figure 8-9.

MAJOR CHALLENGES AND INNOVATIONS

VHF versus UHF

In 1967 when the PAR was changed from an early warning alert system to one that could provide tracking for the SPARTAN intercept role for area defense, studies were undertaken to redefine its capabilities in light of the new requirements.[22-35] As mentioned previously, the Institute for Defense Analysis study of nuclear blackout effects as a function of frequency resulted in changing the transmitted frequency from VHF to UHF. In addition to the reduced severity of nuclear effects at UHF, this frequency band was expected to ameliorate disturbances caused by the intense aurora of the northern latitudes† and would be less likely to cause radio frequency interference problems.[36] However, since there would be less target enhancement due to length resonance effects and some loss in equivalent target cross section at the higher frequency, an increase in the power aperture product was required. The UHF implementation required an increase in transmitter power by a factor of four. This increased cost was offset by the use of novel, block-combining techniques in the receiver and adaptation to a single, common transmit/receive array in place of the previous dual aperture design. The common aperture required less space, fewer elements, and only a single set of beam steering hardware and element phase shifters. Although a space feed was planned for the MSR, the extremely large anechoic chamber required by the PAR at UHF was

*This stability includes minor drifts on a short-term (days) basis.

†Bell Laboratories conducted a study at Prince Albert Radar Laboratory in Canada to investigate auroral effects at UHF.[36]

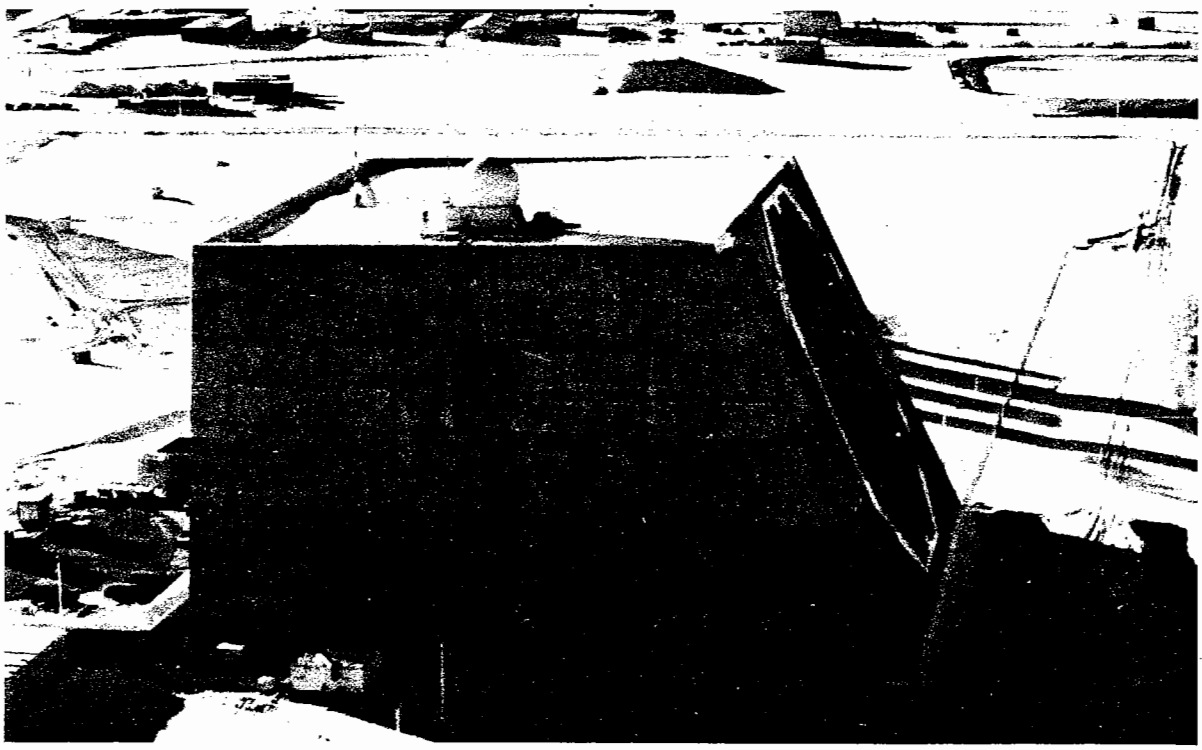


Figure 8-9. PAR, Showing Antenna Measuring Radar on Top of Structure

considered impractical and wasteful of space in a hardened structure. Hence, a corporate feed, similar to that of the previous MAR, was used for the PAR.

Transmitter

After considerable study[22-35] and review, TWTs (Figure 8-10) were finally chosen for the transmitter power amplifier. Several factors were involved in this selection.

- The tube was expected to have high reliability and long life (30,000 hours) since it was a scaled model of the proven L-band design developed jointly by Bell Laboratories and Raytheon for use in the NIKE-X MAR.
- The power output per tube made it a convenient unit to provide the required total summed power of 128 tubes.
- The choice enhanced reliability because of the inherent redundancy of multiple transmitter power sources.

Previously, tetrodes had been a leading contender in the General Electric design, but their reliability could not approach that of the TWT and power output would have had to be sacrificed for bandwidth. Solid state power amplifiers were also investigated, but their cost was not competitive with the TWT and there was little background to assure the development of such a transmitter within the time schedule.

The choice of a transmitted pulse waveform was related to the transmitter decision and involved some interesting tradeoffs. In working with solid state transmitters, consideration must be given to using a long, 6-millisecond, CW pulse to minimize peak power. When the decision was made to use the TWT, the required pulse energy could be obtained with higher peak power and shorter pulses. The desired range resolution was obtained using a chirped pulse with a compression ratio of 100 to 1.

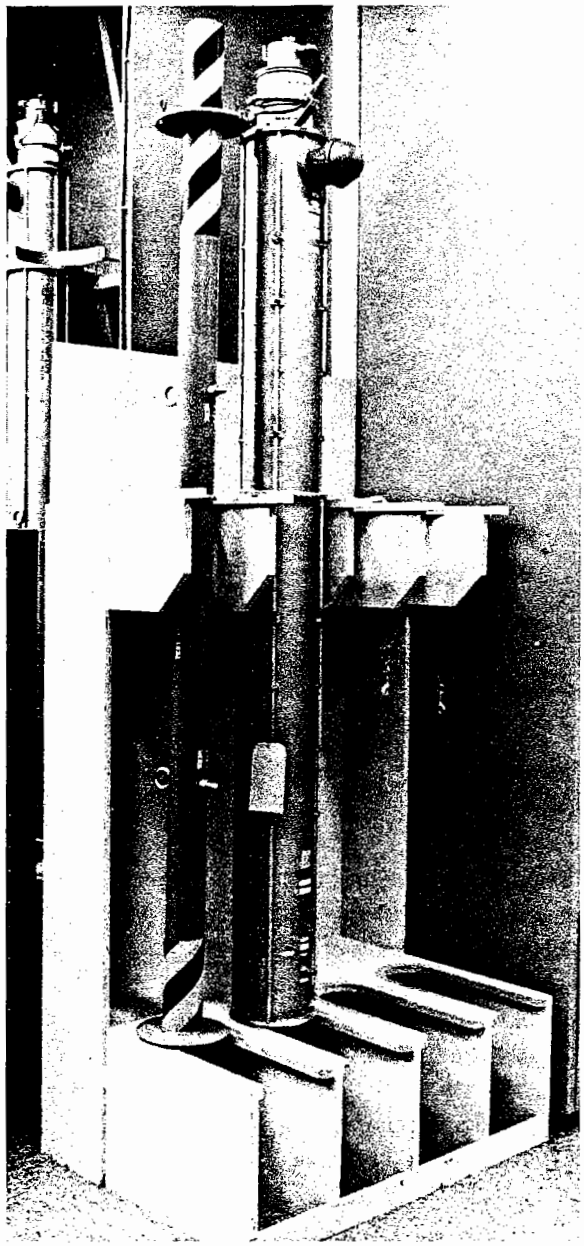


Figure 8-10. PAR Traveling Wave Tubes

The decision to use a chirped pulse provided a second-order benefit as demonstrated by the Prince Albert Radar studies.[36] It was found that in an auroral environment, the clutter returned was approximately proportional to the size of the range resolution cell. Therefore, a chirped pulse would return less clutter than an equal energy CW pulse, roughly in proportion to the chirp compression ratio. In addition, with a chirped system, the signal processor was much reduced in complexity since a single dechirp filter replaced the banks of filters, each matching a different doppler frequency, which would be required for a pulsed CW, search signal processor. Dispersive delay lines needed for the chirped pulse were available from the ZEUS Acquisition Radar and were modified for use in the PAR.

Antenna Element

The high powered, hardened elements (Figure 8-11) were one of the most vulnerable entities in the PAR design. General Electric was required to design them to withstand the combined direct effects of the blast and elevated temperatures of a nuclear explosion. The final design consisted of crossed-dipoles fabricated from beryllium copper, and inclined 45 degrees toward the array face. Phase correcting stubs were placed midway between each element to decrease the polarization ellipticity at wide scan angles. A Hardness Verification Test Program[37] (see Chapter 6) proved the capability of these elements to withstand nuclear attack with minimal degradation of electrical and mechanical properties. Environmental tests verified their ability to perform despite severe rain, ice, or snow accumulation.

Phase Shifter

Another notable development was the phase shifters (Figure 8-12), which are located directly behind the array and provide both transmit and receive beam steering.

Several designs were considered, including ferrite phase shifters, a lumped-constant microstrip phase shifter similar to the MSR unit, and a distributed constant diode-switched transmission line configuration. While the lumped-constant microstrip device was smaller and tended

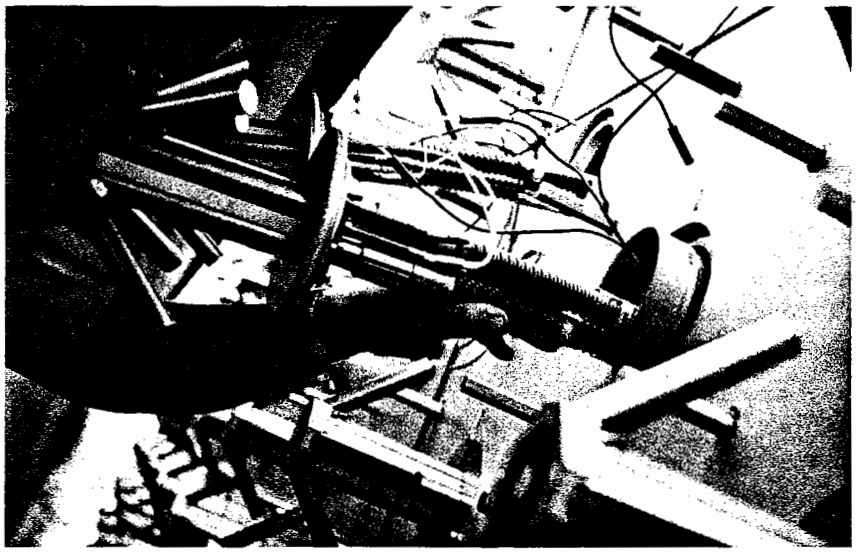


Figure 8-11. PAR Antenna Element

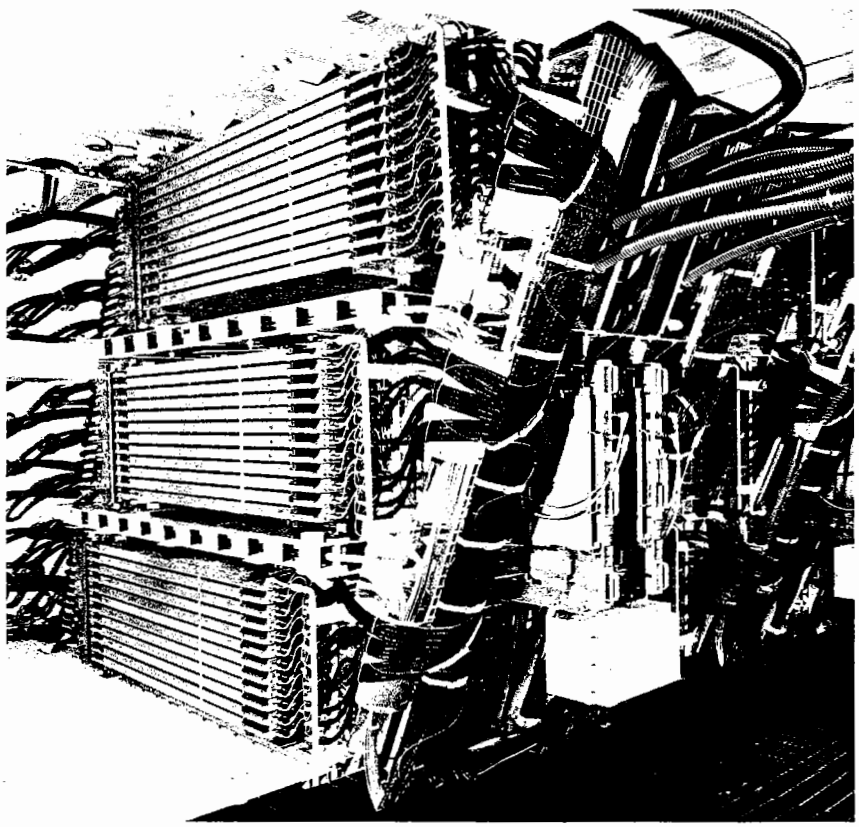


Figure 8-12. PAR Phase Shifter

to simplify space and maintenance requirements, its advantages were not considered significant when the PAR deployment was reduced to one site. The final design used high power PIN diodes for switching in an air-dielectric strip transmission line.

Extensive low-power and high-power tests were performed on these diodes to evaluate their characteristics and confirm their reliability.

Receiver RF Amplifier

Parametric amplifiers were initially considered for the PAR RF receive amplifiers because of their low-noise figure and the experience gained from their use in previous MAR designs. The improvement in low-noise transistors over the years, particularly some developed by Texas Instruments* for this frequency band, indicated that a transistor RF amplifier had definite advantages. The transistor amplifier was smaller, less expensive, easier to adjust and maintain, and had an improved noise figure and significantly lower power requirements than the parametric amplifier.

Maintenance and Redundancy

The maintenance philosophy was based on a balance of component availability/reliability[38] versus the cost of providing redundant units. The result of this balance was to provide redundant exciters, waveform generators, angle error detectors, analog-to-digital converters, radar control and conditioner units, beam steering calculators, and input-output controllers. The redundant Digital Data Group was designed to operate synchronously with the on-line unit. Error detection was designed to compare signals and, under software control, to automatically switch to the "good" unit. Redundancy was also built into the Data Processing System by providing one spare unit in each of the Processor, Program Store, and Variable Store Units of the Central Logic and Control.

*Before transistors of reasonable yield, high performance, and reliability were finally delivered by Texas Instruments, a great deal of consultation, assistance, and technical direction was required from several Bell Laboratories technical areas.

Chapter 9.

SPRINT MISSILE SUBSYSTEM

Chapter 9.

SPRINT MISSILE SUBSYSTEM

The objective of the SPRINT Development Program was to develop a missile subsystem capable of terminal defense intercepts at any azimuth, at relatively close ranges, and at altitudes at the extremes of the sensible atmosphere. The smallest practical vehicle capable of fast delivery of a specified nuclear payload was required.[1,2]

The missile was to be launched from an underground emplacement. A short reaction time was required to allow interception of an incoming Reentry Vehicle (RV) after it had penetrated the atmosphere and could be separated from debris or decoys by the effects of aerodynamic drag. The short reaction time demanded quick launch preparation and high missile-acceleration rates. High rates of control response and missile maneuverability also were required to allow time for ground radar to pinpoint the prime target and to effectively guide the missile to the intercept point.

The development effort was subcontracted to the Martin Marietta Corporation, Orlando Division, in May 1963. The task was to design a missile subsystem which could be manufactured and deployed by 1970.[3] The organization for the R&D effort that subsequently evolved is shown in Figure 9-1.

The early deployment date for a missile with advanced performance characteristics dictated an all-out development program to prove feasibility, reliability, and producibility quickly. Six months were allotted to a program definition phase prior to the formal development start. During the definition phase, it was decided that a single complete missile design would be readied for initial flight testing. This "all-up" approach required very careful design and extensive component testing, but had the advantage of offering complete subsystem test data on every missile flight. The first flight test was scheduled 25 months after development go-ahead, and this milepost was successfully met on November 17, 1965. However, while the program was underway, pressure for rapid development lessened, system requirements were changed, and the program duration was lengthened to support limited deployment in 1974-75.[4,5]

Flight testing was conducted at White Sands Missile Range (WSMR) between 1965 and 1970, and was then shifted to the Kwajalein Missile Range (KMR) for integration with other parts of SAFEGUARD in system tests and live target intercepts.[6,7] Deployment of SPRINT missiles at North Dakota began in June 1974.

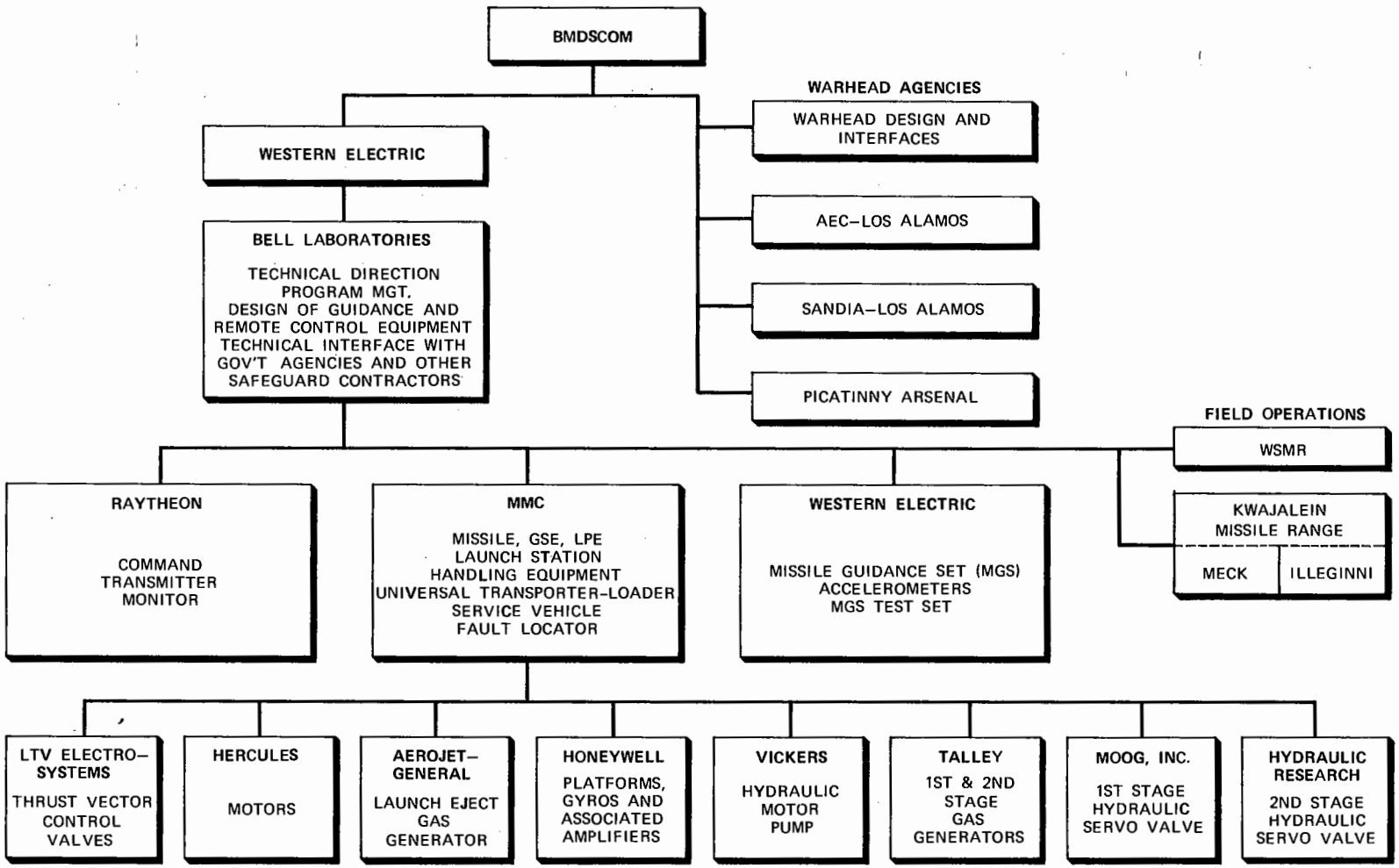


Figure 9-1. SPRINT R&D Organization Structure

MAJOR CHALLENGES AND INNOVATIONS

The implementation plan to develop and deploy an interceptor missile to meet the terminal defense concept required fabrication of a vehicle that would surpass the performance of previous missiles in many respects. Problems requiring solution included:

- A high-burning rate propellant which could maintain high g-loads had to be developed. The required burning rate represented an order of magnitude increase in solid propellant burning rates over that in use on such missiles as Pershing, Polaris, and Minuteman.
- The ablative heat shield had to survive a low-trajectory, high-velocity environment that generated extremely high boundary-layer temperatures without allowing the underlying missile structure to be exposed to destructive temperature. Also, ablative materials had to be free of contaminants which would attenuate radar communications.[8]
- Electromechanical and electronic components had to be designed to function at extremely high levels of shock, acceleration, and vibration. These levels exceeded the capability of the then-available technology.[9,10]
- Communications had to be maintained through the missile plume and ion sheath. At the beginning of the program, it was impossible to define the chemistry of the boundary layer in which this ion sheath was generated.
- The control system had to maintain stability for all flight conditions, including flight close to nuclear blasts.
- Thrust vector control requirements dictated the need to design a valve with a flow rate an order of magnitude higher than that in Minuteman.
- The missile structure and all its subsystems, including electrical components, had to withstand severe nuclear effects. The extensive program that achieved and assessed nuclear hardness has been thoroughly documented.[11] For more information on this program, see Chapter 6.

DESCRIPTION

Missile[12]

The SPRINT missile[12] is deployed in an environmentally controlled underground vertical launch station in a dormant state.[13,14,15] A cutaway of the launch station with its missile is depicted in Figure 9-2. Periodic tests of the missile subsystem are conducted to assure availability of the missile for instant launching. The missile is prepared for launch in a very short interval.*

*Specific missile performance parameters (e.g., preparation interval, motor burn rates and times, missile weights, velocities, and control capabilities) can be found in the Phase III Development Plan SPRINT Subsystem.

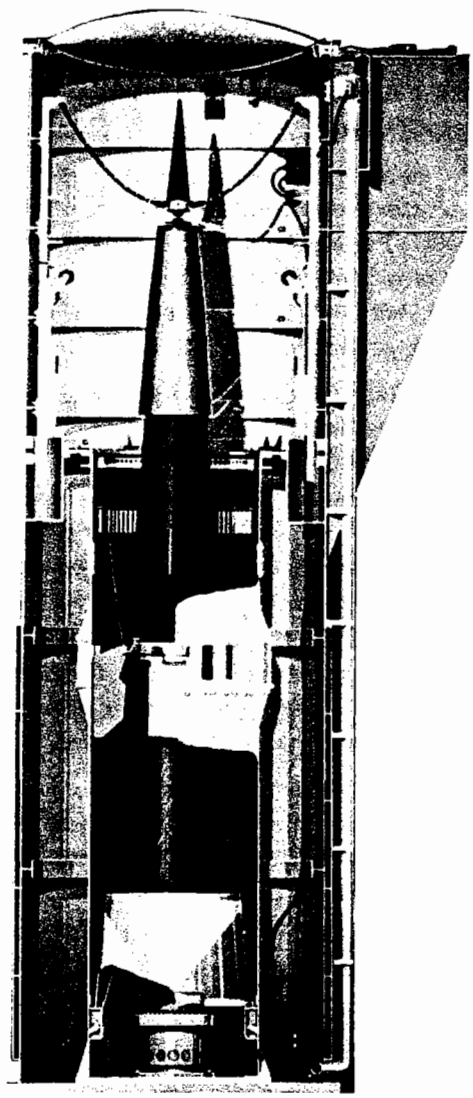


Figure 9-2. SPRINT Missile and Launch Station

When launch orders are given, the missile battery is activated, wiring circuits are checked, missile gas generators are ignited, control system hydraulic pressure in each stage is checked, first-stage thrust vector control valves are moved, and the second-stage aerodynamic control vanes are wiggled. Orders for the proper initial turn toward the intercept point are preset into the missile guidance set. The launch station cover is then explosively opened, the ground power umbilical cables are disconnected, the launch-eject gas generator is fired, and the missile is expelled from its launch station by a piston. The first stage ignites as the missile clears the launch station.[16]

The short first-stage burning provides a very high acceleration resulting in high velocity at burn out. Division of energy between the two stages is not optimized for maximum missile velocity, but is biased in favor of making the second stage smaller for better maneuver control.

First-stage separation is initiated by skin-cutting ordnance activated by ground command. After drag forces push the burned-out first stage away, the second stage is ignited by a preset signal or by ground command.[10] Second-stage ignition may be delayed either to extend interceptor range or to assure a higher dynamic pressure and higher maneuverability for end-game guidance to intercept. Intercepts can be executed beginning midway in the second-stage burning provided a minimum altitude requirement has been satisfied.

The flight time and maximum range capabilities of the initial missile design were later extended by adding a lubrication system to the second stage hydraulic motor pump and by enlarging the second-stage gas generator.

The SPRINT missile is conical with a length of 27 feet and a base diameter of 4.4 feet. At launch, it weighs about 7600 pounds. The main sections are illustrated in Figure 9-3. The monocoque airframe uses fiberglass filament-wound motor cases as a primary structure. The remaining load-carrying structure is aluminum.

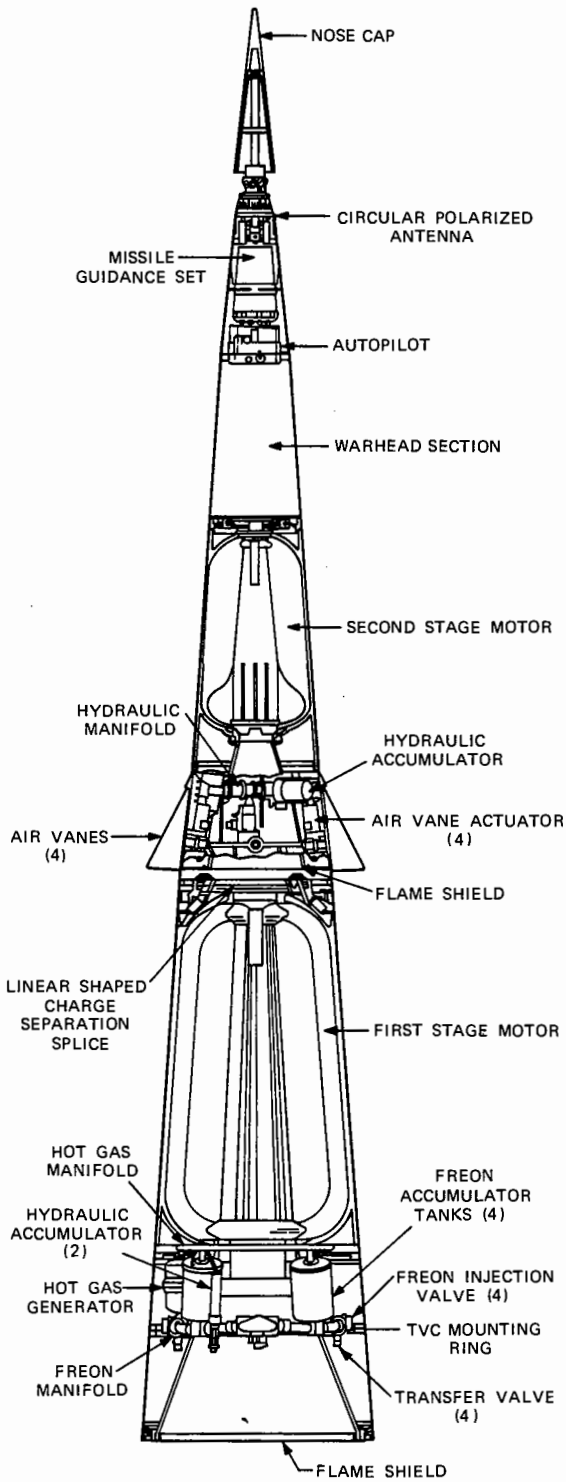


Figure 9-3. SPRINT Missile, Cutaway View

The thermal protective system of the second stage is designed to maintain the structural integrity of the aluminum alloy shell and the fiberglass motor case. The ablative nose cone consists of a hemispherically tipped, one-half-inch diameter nose cap flaring into a 6-degree half-angle conical section. The nose cap is formed with a center rod of quartz phenolic over which is wrapped phenolic-impregnated silica tape. The ablative shield covering the rest of the second stage is fabricated from silica cloth impregnated with phenolic resin mixed with rubber to allow additional elasticity. An exception is the material covering the leading edges of the air vanes. Because of the high heating rates imposed on these components, the leading edges are protected by molded edge-oriented quartz phenolic tape.

Since the first stage has a very short flight time and does not attain velocities nearly as high as in second-stage flight, sufficient protection of its structure is achieved by a coating of Epon 946.

Both before launch and during flight, missile commands are transmitted from the Missile Site Radar (MSR) to the Missile Guidance Set (MGS), where the commands are decoded and applied to the autopilot.[17-20] After launch orders, the autopilot sends signals to actuate the thrust vector control valve pintles which determine missile azimuth angle and pitchover angle after the missile leaves the silo.[21] Throughout flight, signals are sent to the second-stage air vanes to provide missile stability and maneuverability to the intercept point. The autopilot contains inertial sensors which maintain a stable roll reference and generate roll rate, pitch rate, yaw rate, pitch lateral acceleration, and yaw lateral acceleration signals for control system feedback. It also contains the dc and ac electrical power supplies for the missile.

The first-stage thrust vector control uses Freon* as a vectoring fluid to provide pitch and yaw forces. Freon flow is metered through each of the four three-barrelled injection valves which are positioned by transfer valves using hydraulic oil as the working fluid. A solid-fuel gas generrator pressurizes the Freon and hydraulic oil accumulators.

Second-stage air vanes are controlled by servo-actuators supplied with hydraulic oil from a closed-loop system containing a hot gas-driven motor pump. An accumulator provides the extra hydraulic power capacity to meet system transient flow requirements. The hot gas motor pump consists of a positive displacement gas motor integrally connected to a constant volume hydraulic pump. The motor pump produces 26 horsepower and weighs only 10.2 pounds. Overspeed of the pump is prevented by incorporation of a flow limiter, and lubrication is provided by a secondary gas-operated accumulator.

Both first- and second-stage motors are conically shaped, with cases made from filament-wound fiberglass with an epoxy binder.[15] Propellant for both motors is composite modified double base. The ignition train consists of a High-Energy Firing Unit (HEFU) capacitive discharge to an exploding bridgewire initiator firing into a basket of boron/potassium nitrate pellets which ignite the main propellant.

The missile electrical system consists of the battery system, inverter, interconnecting box, initiation system, umbilical and interstage connectors, and wiring harnesses. The Launch Preparation Equipment (LPE) provides power to verify missile operations during the periodic subsystem tests. This ground power enters the missile through umbilical connectors located just under the nose section. During the launch sequence, the umbilicals are automatically disconnected, the missile battery is activated, and, as the missile is launched, the nose cap slides down over the connectors to provide a continuous unbroken heat shield over the missile.

The SPRINT missile (and SPARTAN) is guided by a radio command guidance system which

*Registered trademark of E. I. DuPont de Nemours.

consists of ground-based radars, a ground-based computer, and the Missile-Borne Guidance Equipment (MBGE).[22,23] The functions of the MBGE are:

- To receive and decode missile command steering orders
- To receive and decode discrete commands for payload activation, destruct signals, or other purposes
- To receive and decode an autopilot gain control signal which is a function of computed dynamic pressure
- To transpond a beacon signal for ground station radar tracking purposes.

The MBGE consists of a Missile Guidance Set (MGS), an RF cable assembly, and three antennas.[24] The MGS, shown in Figure 9-4, consists of the:

- Superheterodyne receiver
- Beacon transmitter
- Amplifier-decoder group
- Power supply
- Burst delay timer.

Major MGBE design requirements included nuclear hardness, reliable operation in a severe acceleration and vibration environment, and minimal weight and volume.

The MGS contains a pulsed, three-channel, superheterodyne receiver that uses space diversity reception.[19] Each of the three channels is connected to one of the three antennas located 120 degrees apart on the airframe. The three channels of S-band, pulse-coded RF signals are heterodyned in microwave stripline mixers with the output of a single crystal-controlled solid-state local oscillator to obtain a pulsed IF signal. Each of the three channels is converted to a separate and distinct IF signal; these are combined in a single, main IF amplifier and limiter unit. This procedure enables the MGS to perform a power comparison between antennas. The antenna receiving the strongest signal is selected for radiation of the MGS beacon reply.

The rapid and deep signal-level fades expected from rocket plume and plasma sheath dictated use of an IF limiter arrangement. Another approach using an AGC system would have required a prohibitively long time interval to recover from sudden signal-level changes.

The MGS contains an S-band transmitter keyed by receipt of a valid message from the MSR. The transmitter consists of a solid-state modulator, a pulse-forming network, and a planar triode. A solid-state modulator was chosen over hard- and soft-tube modulators after consideration of the weight volume, reliability, life, and vibration environment.

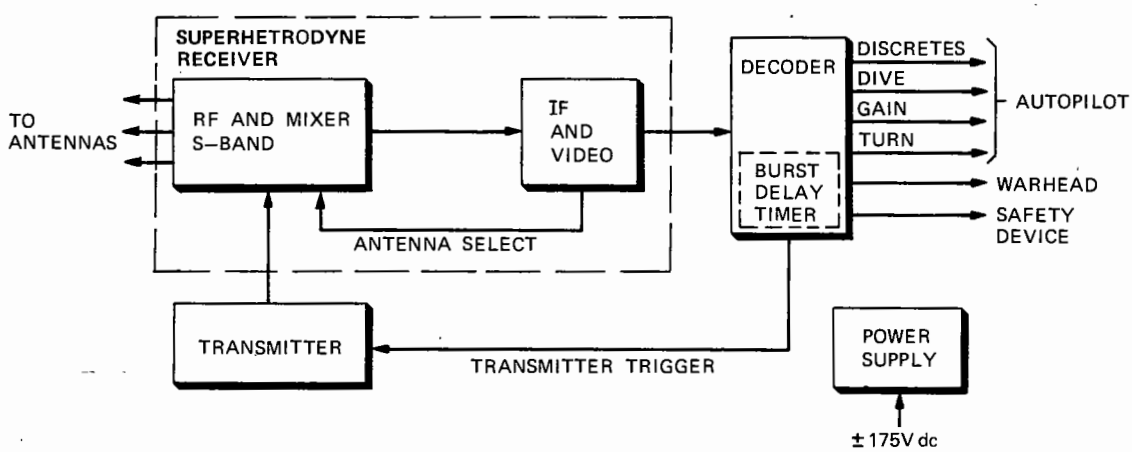


Figure 9-4. SPRINT Missile Guidance Set, Block Diagram

The decoder translates the coded command information transmitted by the guidance radar into signals compatible with the autopilot and warhead adaption kit. The input consists of the video output from the missile-borne receiver. The decoder outputs are in the form of amplitude or pulse-width modulated ac signals to the autopilot and ac signals to the warhead. The decoder employs transistorized digital techniques for message decoding, storage, and signal conditioning. A single code-type, high-reliability logic transistor is used throughout the decoder.

The Data Processing System (DPS) on the ground continuously updates the time to intercept for each missile during an engagement. This changing time interval is sent to each missile via the MSR link. The message is decoded in the MGS. A burst delay timer within the decoder starts to time out on the command time interval. Should the missile be enveloped in nuclear-induced blackout, resulting in a loss of communications with the MSR and DPS, the burst delay timer will send a burst command to the warhead at intercept.

The development program for the missile-borne guidance equipment (including the MGS) used on SPRINT is covered in Chapter 10, SPARTAN Missile Subsystem.[25,26]

Launch Station

The launch station, shown in Figure 9-5, consists of a cylindrical reinforced steel shell, 8 feet in diameter and 31 feet long. It houses a steel launch tube, the launch-eject mechanism, and the missile. The shell is closed at the bottom by a welded steel baseplate which rests on a concrete base. A compartment welded to the side of the launch shell houses the launch preparation equipment[16,27] and the environmental control system.

The missile is mounted on a launch-eject piston which is supported by 10 helical springs for nuclear and earthquake shock isolation. The springs are bolted to an intermediate baseplate and are electrically insulated from the piston. The launch-eject gas generator is located below the piston and is surrounded by a flame shield. During launch, upward motion of the launch-eject

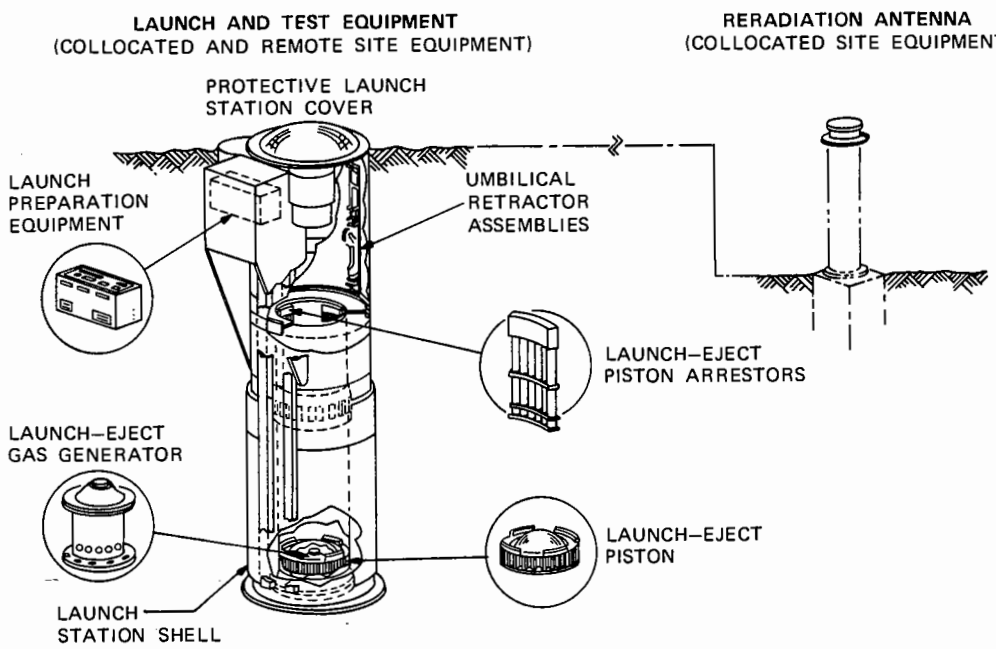


Figure 9-5. SPRINT Launch Station

piston is stopped within the launch cell by four crushable aluminum honeycomb arrestors. The missile is thus separated and protected from its launch-eject piston.

The umbilical retractor assemblies are mounted on the launch station wall, and are activated at launch to retract ground power and communication lines. The top of the launch station is closed by a fiberglass structure which is explosively cut into sections, allowing missile flythrough during the launch sequence. The closure provides environmental protection for the missile and equipment within the launch cell.

The missile and launch system are protected from hostile environments by the launch cell structure, shielding, and shock isolation system.[28,29] In addition, the Environmental Control System (ECS) controls the temperature and humidity in the launch cell and Launch Preparation Equipment Compartment (LPEC). The launch cell is maintained at 80 degrees Fahrenheit ±10 degrees and the LPEC temperature requirement is 40 degrees Fahrenheit through 125 degrees Fahrenheit. The temperature of the launch cell is controlled by the cell closure flange heaters (calrod type) and heater-blower combinations within the launch cell. The LPEC temperature is maintained through a strip heater-blower combination. The humidity is held below 50 percent by the use of desiccants. There are two desiccant chambers per launch station. The controls for the ECS are located in the LPEC within the LPE rack.

The LPE prepares, tests, and launches the missile upon command from the DPS. The Launch Sequencer (LSEQ), power supplies, ordnance safety box, Launch Enable Unit (LEU), and RF distributor comprise the LPE.

The LSEQ monitors and controls warhead functions, missile operation, gyro temperatures, and launch cell environment. These functions are broken into three distinct modes of operation; normal, preparation and test, and launch. During the normal mode, the LSEQ maintains and monitors the proper temperature and environmental conditions for the missile gyros. It will ensure that all door interlocks are properly closed, that umbilicals are mated, and that the missile is in a state of readiness to accept the preparation command. It also will indicate to the DPS missile monitor that all conditions are correct. If they are not, the LSEQ will generate a minor alarm.

When a missile subsystem is in the normal mode, it will accept the preparation order from the DPS at any time. Once the preparation order has been received, the LSEQ will begin to warm up the missile. Warmup is accomplished by applying missile ground power, spinning up the gyro, and aligning the roll platform. At the completion of warmup, the LSEQ will generate the RF Test Request (RFTR) indicating to the DPS that the missile is ready for testing and/or launch.

Upon receipt of the RFTR, the DPS will generate either the RF Test Order (RFTO) or Launch Orders (LOs). If the DPS orders the missile to be tested via RFTO, the MSR will transmit RF commands to the LPE RF section via the radar beam in the case of the collocated farm or via cable for the remote farms. During the testing phase, the LSEQ will test approximately 97 percent of the autopilot electronics and 98 percent of the MGS electronics. When the RF test phase of the preparation period is successfully completed, the LSEQ will generate the ready status signal indicating to the DPS that the missile has completed the test and is ready to be launched. If the test phase is not successful, the LSEQ will generate a major alarm. The DPS then has the option to either retest the missile or restore the subsystem to normal.

Nuclear weapons can only be used upon presidential authority and SAFEGUARD is released through the North American Air Defense Command (NORAD) at the Cheyenne Mountain Complex. The release information is transmitted in coded form over a data link to the Missile Defense Center (MDC) where the message is decoded and the contents displayed on a system status display.

A second message is then originated within the Launch Enable (LE) equipment as the first part of a chain of events to effect a missile launch or a system test. The elements of the second message pass through the Launch Enable Message Transmitter (LEMT) to the Launch Enable Message Receiver (LEMR) and then to the Launch Enable Transmission Set (LETS). Finally, the message is fanned out to Launch Enable Coded Switches (LECs) located in each of the missile launch cells. Receipt of a properly coded message by the LECSs produces a condition which permits missile launch orders generated by the DPS to pass to the missile. The LE equipment monitors and reports operating faults and status within each LECS.

After RFTR or ready has been generated by the LSEQ and the LE signal has been received by the launch enable coded switch, the LSEQ will accept launch orders to initiate the sequence which applies fire signals to the Launch Eject Gas Generator (LEGG). Between the receipt of LOs and ignition of the LEGG, the flight batteries are activated and checked, the control systems are activated and checked, the one-shot ordnance is fired, the umbilicals are retracted, etc. Failure to accomplish any of these operations will cause the LSEQ to abort the flight. Once the missile has been fired, the LSEQ will generate the missile-launched signal and after a short period of time, it will shut down removing all power from the launch station.

Remote Launch[30,31]

The SPRINT remote launch equipment, shown in Figure 9-6, allows communication with the SPRINT missiles emplaced in remote missile farms up to 25 miles from the Missile Site Control Building (MSCB). The function of the remote launch equipment is to enable remotely located SPRINT missiles and launch preparation equipment to communicate with the DPS for preflight testing and launching of missiles. This communication is accomplished via three two-way redundant crypto data links to each remote SPRINT missile farm for (1) missile command and beacon responses (C/B link), (2) LPE orders and status (O/S link), and (3) Launch Enable signal and RLE status (LE link).

The Remote Launch Equipment (RLE) receives missile commands from the DPS in digital form, transfers the data to the remote farms, and then transmits the missile commands as modulated RF signals to the missile LPE. The missile beacon pulse is received by the RLE, processed, and then transmitted to the DPS in digital form. The second data link receives LPE orders from the DPS in digital form and transmits data to the remote farms where they are converted into dc voltages for LPE operation. The dc LPE status information is received by the RLE, converted to digital form, and transmitted to the DPS via the return path of the order and status data link. The third data link transmits the remote launch enable signal in digital form to each of the remote farms where the signals are converted into a format used by the launch enable coded switch at each SPRINT launch station. The return portion of the launch enable data link transmits remote launch equipment status to the MSCB.

Ground Support Equipment

The Ground Support Equipment (GSE) consists of all the equipment necessary to maintain and support the launch station, launch preparation equipment, and missile.

The Fault Locator (FL) maintains the LPE and its associated cables by fault isolation to readily replaceable assemblies such as power supply, LSEQ, RF distributor, interconnecting cables, and missile sections. The FL receives a test enable signal from the DPS permitting the operation of the FL at the launch station and verifying all operational functions of the LPE. The missile is disconnected and replaced by the FL and all ordnance circuits are bypassed by FL cable interface during all FL operations. The FL exercises the LPE through normal, preparation,

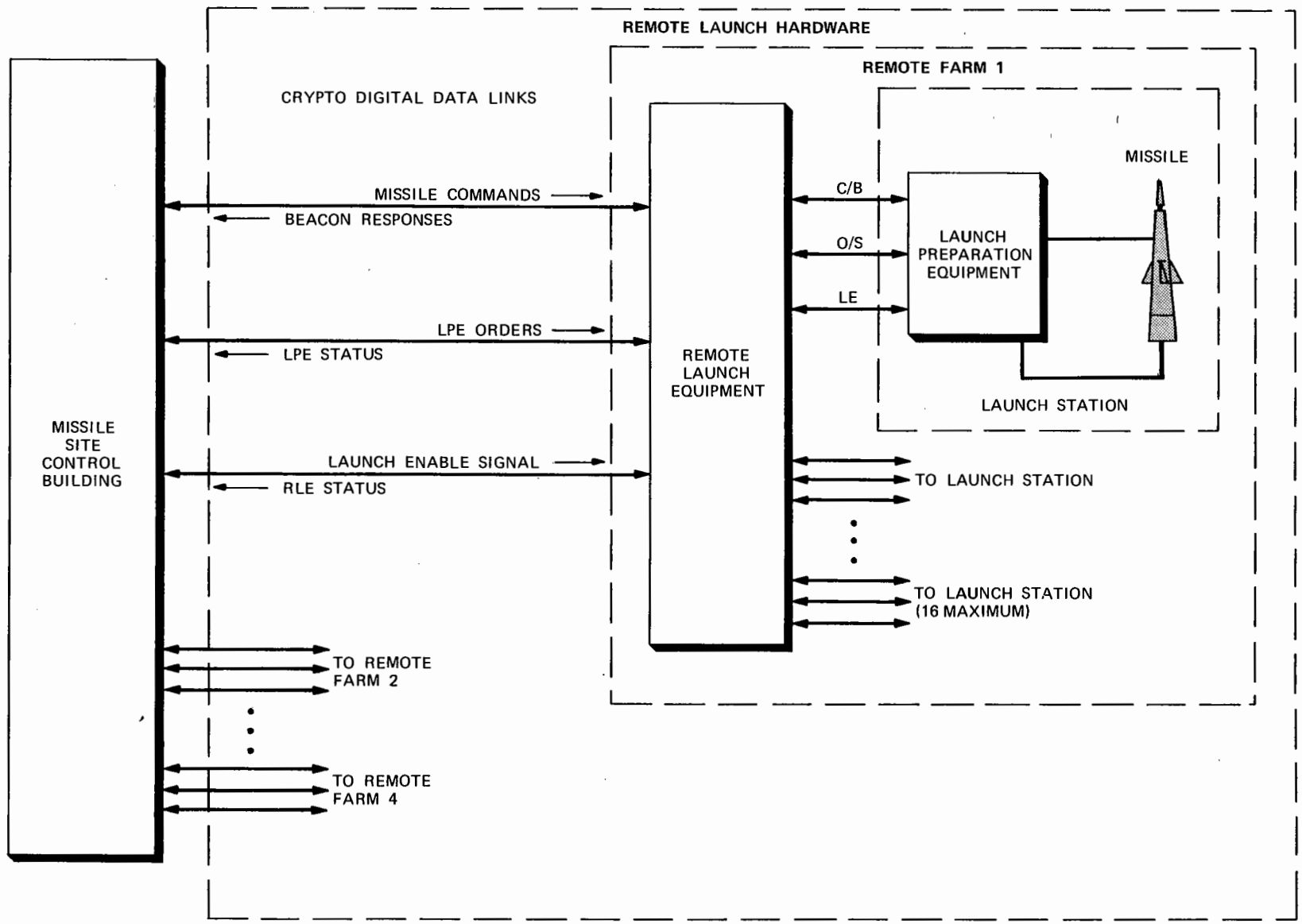


Figure 9-6. Remote Launch Equipment

ready, and launch modes to verify timing and performance functions. The FL is transported and housed for operation in the SPRINT Service Vehicle (SSV). The RF Test Set, which is used to verify the operation of the LPE RF distributor, is also transported by the SSV. The Electrical Circuit Test Set (ECTS) tests various missile networks and performs no-voltage ordnance safety tests as part of the installation and/or maintenance of missile sections. The SSV is a self-contained, environmentally controlled vehicle used to handle, transport, and install the SPRINT warhead section, guidance, and nose cone assembly of the missile. In addition, the SSV transports and stores the spare LPE, FL, RFTS, and ECTS which are used for maintenance of the missile, launch station, and LPE. The SSV carries its own weather shield and heating, cooling, and humidity control system to maintain a conditioned environment in the launch station during missile and/or LPE maintenance and handling operations. The SSV also carries missile sections and LPE handling fixtures used during either missile section or LPE replacement at the launch station.

The Universal Transporter Loader (UTL), shown in Figure 9-7, is a tractor-trailer vehicle used to load and unload the SPRINT first- and second-stage Propulsion and Control Assemblies (PACAs) at the launch station, and to transport the PACAs to and from the Universal Missile Assembly Building (UMB).[32] The UTL is also used for all SPARTAN missile section installations or removals. An environmentally controlled housing for the missile section is mounted on the trailer of the UTL and is erected over the launch station for missile loading/unloading.[33]

Included with the GSE are all missile loading and handling fixtures located at the UMB.[34] These fixtures facilitate the loading, unloading, and assembly of missile sections at the UMB.

SUBSYSTEM DEVELOPMENT PROGRAM

Propulsion

Early parametric performance studies determined that the overall missile conformation should be conical. Materials studies indicated fiberglass filament was the preferred motor case structural element to attain low inert mass fraction, while the maneuver requirements (and control response) of the missile and their resultant bending stresses dictated the thickness of motor case walls. Once the minimum wall thickness was established, maximum operating pressure of the motor became calculable. It was desirable to operate the motor as near maximum pressure as practicable, because higher pressure produces higher specific impulse.

Quick missile reaction meant rapid launching and ignition with resultant high shock levels. High acceleration resulted in tremendous axial loads during first-stage burning while abrupt maneuvers developed high side loads. Thus, the propellant to be developed had to have excellent physical properties. It was necessary to have a high propellent mass rate of discharge to attain the high acceleration and velocity levels required of the missile. Also, a decision was made to use the same propellent on both stages for ease of manufacture.

Propellent composition development was concentrated on casting powder types containing fine Ammonium Perchlorate (AP) and a small amount of aluminum in the form of "staple" or chopped foil. There was experimentation with several burning rate catalysts, but none produced sufficient effect to warrant their use. High concentration Nitroglycerin (NG) solvents were also tried, but the sensitivity increases with the increase of NG. This was demonstrated by an unfortunate incident in the Polaris program, which caused a limitation in the amount of NG in the solvent to be enforced early in the program.

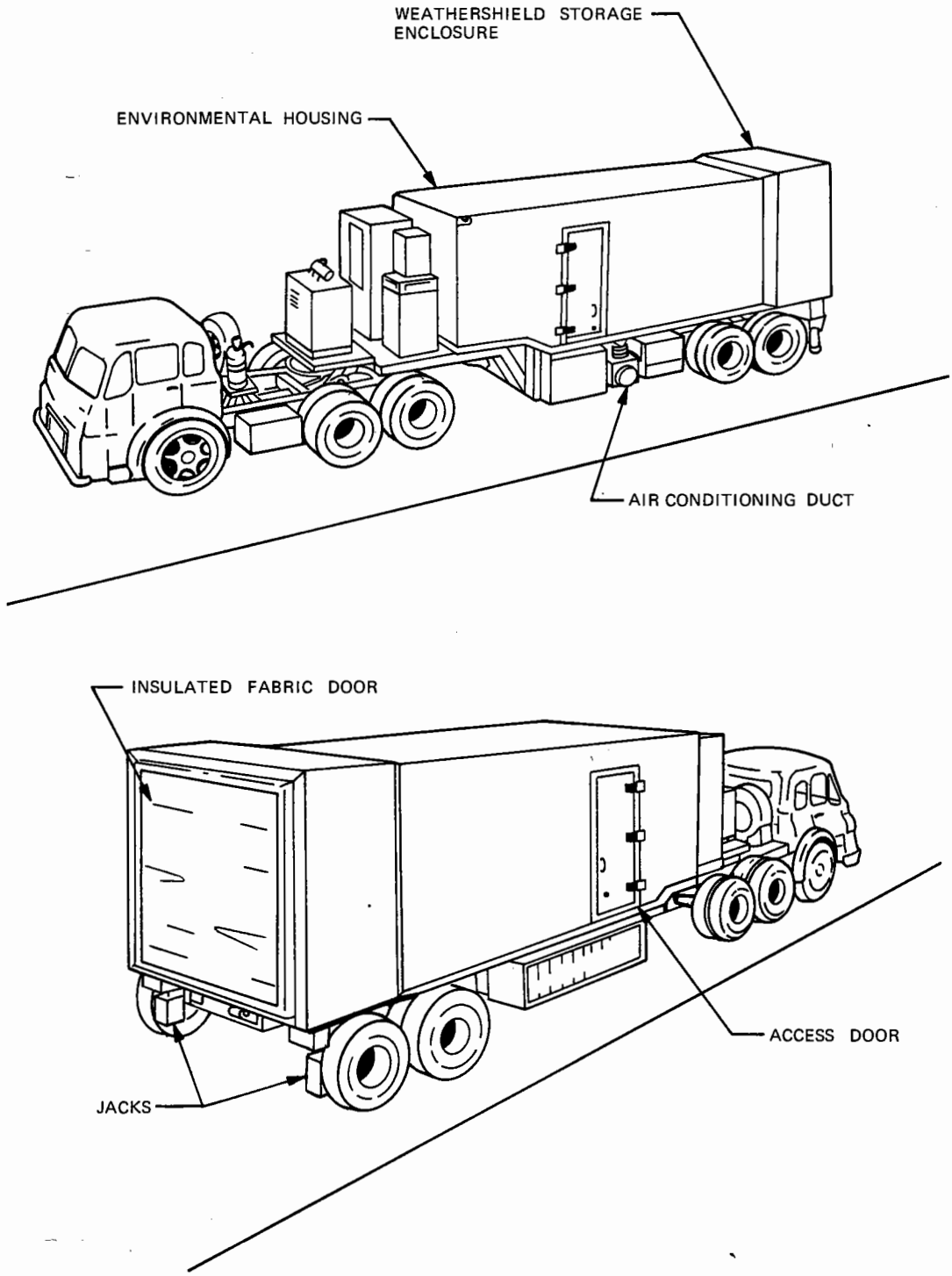


Figure 9-7. Universal Transporter Loader

A large increase in burning rates had initially been demonstrated as possible by the introduction of aluminum staple into the formulation, and a substantial effort was launched to optimize the staple dimensions. Aluminum content was limited to a low percentage in the final formulation to decrease the possibility of afterburning in the plume, and thus minimize ionization in the communication path to the missile. It was found that, although use of staple-aided heat and flame propagation made high burning rates possible, the size of the AP particles was also a significant factor. The ability to fine-grind the AP in a controllable and measurable fashion was the final key in allowing a suitable composition to be formulated in a repeatable way.

Large conical pressure vessels had never been filament-wound, and the high operating pressure introduced another unknown design problem for fiberglass pressure vessels. The helical winding pattern chosen to carry the axial loads was alternated with hoop windings to carry girth loads. Since girth loads were higher at the larger end of the 4-degree half-angle conical frustrum, more hoop windings were used at the larger end, and as successive hoop windings were added, they were terminated closer to the large end of the case; thus, a slightly tapered wall thickness was formed. High allowable hoop and helical stresses were attained in the glass filament windings.

To allow attachment of the motor cases to the aluminum structure of the other missile sections, fiberglass attachment stubs were fabricated from a combination of glass cloth and glass filament windings and bonded in place on the pressure vessels. Although the bonded stubs were thought to be structurally sufficient, tests showed that the variables of materials and, especially, manufacture made it impractical in the time available to design and develop a purely bonded joint to carry the large axial loads and the bending loads, resulting from both internal pressure and pitch-over maneuvers. Accordingly, two rows of steel bolts were added to both forward and aft stubs of the first-stage motor and to the rear stub of the second-stage motor to clamp the bonded stubs in place mechanically. No bolts were added to the forward end of the second stage, because the number of glass filaments to be cut in drilling holes for bolts would have weakened the structure.

The first-stage motor was designed with inert slivers under each of the six star points in the grain to allow design of a web with near-uniform thickness. A uniform web allows simultaneous burnout throughout the combustion chambers and thus an abrupt termination of thrust. Burning time was closely controlled and made predictable, which, in the case of first-stage flight, facilitated staging and first-stage case separation. In early designs of the first stage, wires from the forward end of the missile to the controls at the aft end of the first stage were passed through the interior of the motor under the inert slivers. Unfortunately, during hydrotest of the case, water was forced into the wiring insulation and caused subsequent electrical test shorts. Wires were then run on the exterior of the motor case.

Initially, the inert slivers extended not only through the main body of the vessel, but also curved into the domes at each extremity. Unfortunately, the elastic properties of the glass-microballoon filled slivers were not good enough to permit sufficient bending in the dome regions, and sliver cracks occurred during combustion pressurization. Crack propagation into the propellant permitted flame to reach the fiberglass and to burn through the wall. Slivers were redesigned to eliminate the curved ends.

The most serious propulsion development difficulty was a casting problem which affected the grains of both the first and second stage, because they are cast in the same manner. SPRINT motor propellant is made by using large quantities of base grain or powder which contains all of the solid ingredients, and by packing a motor case with base grain and adding solvent to polymerize the ingredients and bond the whole to the case wall. The process used sometimes allowed insufficient powder, but an excess of solvent, to

collect under the forward dome. The result was soft propellant or voids under the dome. The problem was first suspected after failure of a Propulsion Test Vehicle (PTV),[35] the second vehicle flown at WSMR to test propulsion, staging, and the heat shield. The problem was temporarily solved by cutting about 50 pounds of propellant in the forward end of the second stage and inhibiting the burning of the machined-propellant surface by bonding three layers of Buna-N rubber over it. The first guided and controlled SPRINT missile flew successfully with a second-stage motor of this configuration. Later in the program, when the problem manifested itself in the first stage, a similar temporary change was instituted. In the meantime, the inner surface of the forward insulation was changed, casting methods were modified, and both stages were thereafter successfully cast without encountering either the soft propellant or the need for the inhibitor.

Another problem in the propulsion program concerned the ability of the motors to withstand shock during transport. At first, the problem centered around two motors which blew up during static firing, and much later, a missile which exploded over its launch station during the early phase of a flight at KMR. The early failures occurred as a result of motors which had been test-dropped and then fired in an attempt to show their capability to sustain the shocks experienced — shocks which were selected to represent "worst-case" handling drops. The KMR failure generated concern that solution of the early problem had not been complete. Subsequent exhaustive investigation alleviated that concern, and showed that the motors were indeed very rugged and could withstand considerable punishment without detrimental effects.

To start at the beginning — part of the motor qualification program required that four sets of motors in their shipping containers be subjected to drop tests simulating worst-case handling shocks. This qualification requirement was regarded as routine, because analysis had shown that the motor had ample design margin over any stresses or strains which would be encountered. Furthermore, by the time the drop tests for qualification motors were made, many sets of motors had been shipped in wooden R&D shipping crates to Orlando and then to WSMR. In fact, several had made more than one round trip. No flight problem that could be traced to transportation and handling shocks had occurred. Thus, confidence and the desire to save time and money led to performing drop tests of both a first-stage motor and a second-stage motor in their separate containers before either was static-fired. Both motors blew up during firings on their test stands.

Although analysis showed no cause for either failure, the conclusion was reached that improperly fitting wooden supports in the shipping container had induced greater strain than had been predicted. The shipping containers were then redesigned to assure much better support for the motors. One first-stage and one second-stage motor in their respective new containers were then subjected to individual test drop sequences, and both were successfully static-fired.

In the meantime, a new directive required that motors shipped for deployment be assembled into a single unit containing the first- and second-stage motors and their control sections. Containers were then specifically designed to hold the propulsion and control assembly in a single package. A set of motors in this new assembly configuration and in the new container was then subjected to the qualification test drop sequence. Again, both motors were static-fired successfully.

To complete the planned qualification test program, two more sets of motors were drop-tested and both sets were shipped to KMR for flight tests. Immediately after the first of these missiles was launched, the first stage of the missile ruptured near the launch station. Failure investigation concluded that the probable cause was a weakness induced by the drop tests.

The second set of dropped motors was returned from KMR, the motors and their support systems were heavily instrumented, and a completely new set of drop tests was carried out with the same hardware. A new finite element analysis of the motor was conducted, and the values registered by the many strain gauges and accelerometers used during the instrumented drop tests were used as inputs for the new stress analysis.

Again, theory showed that the design allowances throughout the motor structure, case bond, and grain gave ample margin to withstand the shocks sustained. No damage to the motor could be found by any method used in the various examinations. The motors were then static-fired. Both were successful.

The conclusion was reached that if the motors were manufactured to the design specifications, they could stand the specified shocks that the qualification program imposed. Failure of the first-stage motor at KMR apparently was caused by manufacturing or material weakness, perhaps aggravated by the shocks suffered during the drop tests.

In contrast to the results of the qualification drop test series, two other static motor test series dramatically demonstrated the strength of the pressure vessels. Prior to being loaded with propellant, each pressure vessel was hydrotested to a pressure level 6 percent above its nominal peak operating pressure. The attachment stubs were subjected to both axial and shear loads which simulated normal propulsive forces and maximum maneuver loads. Some pressure vessels were also burst-tested to demonstrate their ultimate strength.

To further demonstrate safety margins, two first- and two second-stage motors were fired with throats machined to diameters slightly smaller than normal. Peak operating pressures were 15 percent above normal and no failures resulted.

Another design objective for the SPRINT motors was a long tactical life. Two motors were set aside for aging studies.[15] After approximately five years, one set of motors was used successfully at KMR. The other motor was successfully static-fired at Allegheny Ballistics Laboratory after aging for 7-1/2 years.

First-Stage Control System

Thrust Vector Control (TVC) was chosen to provide pitch and yaw forces during first-stage flight to attain fast response to initial turn orders and command maneuvers. Freon was chosen as the injection fluid because of experience gained with its use in both Polaris and Minuteman, even though SPRINT required a much higher flow rate. Initial development was started on two parallel paths: one using a fixed valve body and three movable pintles, and the other using three fixed pintles and a movable body. The movable pintle version was finally chosen when it appeared to involve fewer problems.

The TVC system, as initially designed, used Freon as both the injected fluid and as the working fluid for the servo-actuator assembly which controls pintle motion. The hydraulic fluid used as the working fluid in the servo actuator during ground testing was displaced with Freon during flight. Unfortunately, the two heterogeneous fluids caused variations in fluid density in the servo-valve nozzle and flapper area, and servo-valve performance was erratic. The problem was resolved by adding hydraulic fluid accumulators to the system to provide a separate and uniform hydraulic oil servo-actuator fluid throughout first-stage operation.[36]

Another modification to the hydraulic fluid system was added after early flights at WSMR. Data indicated that acceleration forces on the hydraulic fluid could partially deplete the actuator cavity during launch eject, and the temporary lack of fluid could cause delay in transmission of a TVC command. Effective with missile FLA-7, a stand-pipe was added to the overboard dump

line of the valve to counterbalance the fluid mass in the valve and actuator.

The pistons in the four Freon accumulators and in the two hydraulic fluid accumulators are pressurized with gas generated by an ammonium nitrate propellant. Because of the rapid ignition and pressure buildup requirements, the propellant is cast in four concentric annuli to provide the large burning area needed. The thin cylindrical annuli gain their strength from an epoxy binder. Although the propellant mixture was adapted from that used in gas generators to open covers over Minuteman silos, the manufacture of propellant in a repeatable process proved to be a difficult goal. Specified performance was met through very careful engineering and strict quality control standards.

The manifold conducting the hot gas from the gas generator to the Freon tanks was initially made of René 41 (a Columbian nickel alloy) with an inside coating of Avcoat as insulation. René 41 was selected because of its strength at the chosen design temperature. However, the alloy was difficult to weld, and the large amount of welding required for the manifold configuration made material rejection rates high and fabrication very expensive. The Avcoat insulation was applied internally in a liquid form and tended to be thinner in the vicinity of manifold junctions where insulation thickness was especially critical. A flame-sprayed coating of copper was applied over one critical area as a temporary expedient to conduct heat away from the load-carrying material. The final solution was to change the manifold material to 4130 steel with an inner sleeve of silica phenolic insulation slipped inside in sections and fitted and bonded at the various manifold branches and junctions.

Second-Stage Control System

The heart of the second-stage control system was a hot gas-driven motor pump which had been well along in development for the Skybolt missile. The selection of this particular pump made possible the design of a lightweight closed hydraulic system with fast response. The design of the motor pump allowed the missile flight time, and hence the operating time of the pump, to be increased by a factor of two. However, thermal considerations resulting from the extended exposure to hot gas indicated several changes. A forced lubrication system was added to the motor, and breakable inlet and exhaust seals were added to retain lubricating oil in the motor housing during storage. The motor housing was changed from cast aluminum to steel to lessen warpage, and the piston-to-bore clearance was increased to prevent scuffing or seizure.

Use of this particular pump size, important because existing Skybolt technology could be transferred directly, was made possible by incorporating a stepped piston in the air vane actuators. The piston arrangement, which has an area ratio of about 2.4 to 1.0, permits the larger area to be used to provide the required torque during periods of high vane loading, and allows the smaller area to be used when the vane torque requirement is low but the duty cycle is high. A hydraulically operated selector valve attached to each vane actuator directs flow to the proper actuator area on command from the autopilot.

The hot gas generator for the second stage was a source of more difficulties than the first-stage gas generator and required constant attention, not only throughout development, but also throughout the production phase. These problems included the propellant mix, casting, ignition, burning-rate catalyst, materials storage, moisture, contamination, and quality control. Most of the difficulties related to the ammonium nitrate, which undergoes crystalline-structure phase change at 90 degrees Fahrenheit with a consequent change in its specific volume. This temperature line is crossed and recrossed during mixing and casting, as well as in the normal storage and shipping of gas generators. Ammonium nitrate crystal shrinkage can cause microscopic voids throughout a grain, and burning rate increases because of increased exposed

surface. Grain dimensions were seen to change with age, and the initial gap width between the free-standing grain and the case wall changed. (The case-loaded grain must be bonded on one end only to allow expansion without crushing during burning.)

One missile, FLA-30, lost second-stage control when hot-gases from its end-burning grains penetrated around the circumference of one grain so as to burn through the wall of the metal case. Thereafter, great care was taken to measure the gap between grain and case wall on radiographs of assembled units. A study was also started to learn more about changes in this gap dimension with age of the gas generator. Repeated radiographs were made to determine that grain size had stabilized.

As with the first-stage gas generator, second-stage gas generator development and production were successful only because of careful, constant engineering surveillance and frequent, full interchange of information between the subcontractors and the system contractor.

Heat Shield

Thermal protection for the body of the missile was envisioned as one of the major development problems. Boundary layer temperatures were to reach peak values of thousands of degrees Fahrenheit, and the aerodynamics which determined temperatures and regions of most severe exposure were not well understood. No missile had ever flown at this speed in the dense atmosphere. Wind tunnel tests at the Air Force Arnold Engineering Development Center and at NASA Langley, together with analyses, provided the early thermodynamic models on which material selections were based. There were no ground test facilities that could simultaneously produce the flow velocity, dynamic pressure, and heating rates expected for the SPRINT vehicle.

The General Electric Malta Test Center produced realistic heating rates for relatively long periods of time using the exhaust from a liquid rocket motor. Tests in this facility were valuable for selection of materials for the missile forebody and air vanes even though the temperature and dynamic pressure were limited. Nose tip tests were conducted in the Cornell Aeronautical Laboratory Wave Superheater, where intense heat pulses could be produced with relatively high stagnation pressure and heating rate for a very brief time period. Specialized tests were also run in the Martin FLAME facility, which produced a severe thermal environment using the exhaust from a solid rocket motor, and at other test centers, but there was no facility that could provide a real composite thermal test environment.[37] Accordingly, a program to fly Material Test Vehicles (MTVs) was conducted by quickly fabricating and flying a simple two-stage vehicle using excess solid propellant Recruit and Cherokee motors. The environment in this test approached the velocity, dynamic pressures, and heating rates expected on the final SPRINT design. The recovered MTVs showed satisfactory response for the silica phenolic nose cap, the tape-wrapped silica phenolic heat shield over the body, and two molded silica phenolic air vane leading edges.

The first opportunity for a realistic test of the thermal barrier came in March 1965, with the successful flight of the first SPRINT air frame Propulsion Test Vehicle (PTV-1). This ballistic flight produced an aerothermodynamic environment which virtually duplicated that expected of a controlled SPRINT flight to its primary design point. This experiment showed that a lightweight heat shield fabricated almost entirely of silica phenolic could keep the aluminum substructure below the required temperature limit. The proof of the heat shield design was an R&D SPRINT missile test flight at WSMR in June 1968, which was programmed to experience thermal environments in excess of the design maximum. Erosion rates on both the nose cap and the air vane leading edge were less than predicted, and performance of the body heat shield was completely satisfactory.

However, there were development problems with the heat shield, particularly that portion over the second-stage motor pressure vessel. The fiberglass vessel expands slightly when it is pressurized, and the heat shield must do the same. Although rubber was added to the phenolic matrix to allow sufficient elasticity, the bond between the heat shield and the motor case did not always hold, partly because of an aluminum foil shield for protection against Electromagnetic Pulse (EMP) between the heat shield and motor case. The EMP shield installation was modified, but real help also came through a slight thickening of the heat shield occasioned by the increase in time of flight mentioned earlier.

EMP protection of the missile caused another problem which was not recognized until the loss of FLA-52 at KMR. Investigation concluded that failure occurred because of an improper bond between the heat shield and the structure at the leading edge of the second-stage motor. High-velocity air entered the gap at the interstage splice, found a small unbonded region under the silica phenolic material, and apparently tore off the heat shield exposing the fiberglass of the motor pressure vessel. It was then recognized that the FLA-8 failure at WSMR had probably not been properly diagnosed; its failure had the same signature as that of FLA-52. The problem originated with the requirement that the missile body provide a shield by being conductive throughout its length. As a result, the aluminum EMP shield over the fiberglass motors was bonded to the aluminum splice ring with a special copper-loaded conductive bond material. Applying the copper-loaded material evenly was difficult, and the heat shield leading edge sometimes puckered. A slight modification in which the leading edge of the heat shield was chamfered and covered with mylar solved the problem.

One of the necessary heat shield design considerations was the requirement of flying through impacting rain. Sled tests on portions of the missile were conducted at Holloman Air Force Base at speeds up to 6600 feet/second through a shower system which simulated a rainfall rate of 4.6 inches per hour. Other smaller scale tests were conducted at the Naval Ordnance Laboratory (NOL) 100-foot Hyberballistic Range. Data from Holloman and from NOL were used to construct a mathematical model which predicted erosion as a function of rain density and missile speed, and erosion for flight through thunderstorms for typical SPRINT trajectories. Results showed that SPRINT was well-designed for rain resistance.

Autopilot[38-40]

The initial autopilot design did not fulfill the philosophy of "tactical design" on the first flight, because the necessary information on body-bending frequency and missile flight response to commanded maneuvers was not known. However, the first autopilot design was complete and had full-flight capability. Significant changes reflecting flight data and new requirements were incorporated at three points in the program as "Mod" changes.

The Mod I autopilot design, effective with FLA-5, had modified compensation to improve stability at low dynamic pressure. This design generally met all the tactical requirements, but analytical studies with flight data indicated that the stability could be greatly improved if both the gain and compensation were made to vary with dynamic pressure.[24]

Thus, the Mod II design, effective with FLA-16, had compensation networks that varied with dynamic pressure, resulting in reduced extraneous vane motion and minimum hydraulic power consumption. The design was also more tolerant of variations in static margin (relative longitudinal displacement of the center of pressure and center of gravity). Interim radiation-hard circuits were introduced and improvements were made in the adaptive loop and in the filtering of control system disturbance induced by structural flexibility.

The most significant group of changes was introduced with FLA-32 and designated Mod III.[18]

These changes provided for a remote launch capability, improved radiation hardness, improved reliability, and easier autopilot installation. These changes also deleted the acceleration loop in the first-stage control circuits.

Subsequent to the introduction of the Mod III autopilot, other changes were made. Shock and vibration exposure during Mod III design qualification tests produced broken solder joints.[41] This problem was corrected by stiffening the printed circuit multilayer boards, effective with FLA-33. Pitchover accuracy and TVC efficiency were improved by increasing the command duration and eliminating a gain change during flight, effective with FLA-35. The wiring harnesses were modified, effective with FLA-40, to bring telemetry signals out to a special connector on the distributor and a telemetry buffer package was designed for mounting in the warhead section. With FLA-43, the ambient temperature of the electronics was reduced by changing the operating point of the rate gyros from 175 degrees to 145 degrees Fahrenheit, thus requiring the application of less heat. After a lengthy investigation, a number of changes were made to reduce possible interference with the free movement of the turntable due to contamination of the flotation fluids. Effective with FLA-67, the resolvers were encapsulated, lead wires were rerouted, and a higher torque spin motor for the rate gyros was provided. On FLA-80, a number of electronic component changes were made to improve the nuclear radiation hardness. Beginning with the first production missile, components with greater radiation hardness were used and the bonding of the seismic mass of the accelerometer was improved.

Other significant design changes were made in the course of the program. After a failure in FLA-2, a capability for testing the interval timer was introduced for FLA-3. The servo amplifiers were modified to reduce the quiescent current and thus the internal heat. Flight failure of FLA-5 was attributed to a broken gimbal balance pin in a rate gyro. Corrective action, effective with FLA-7, ended this problem. Flight failure of FLA-18 led to mechanical design changes to reduce the sensitivity to shock, and a shock test requirement was added to the acceptance test procedures. On FLA-25, voltage limiters were added to eliminate previously observed control signal oscillation during amplifier saturation. Investigation of a transistor failure on FLA-26 led to the discovery that detonation of the squib switches in the electronic control subassembly created excessive shock. Mechanical design changes were made to improve the isolation of these switches effective with FLA-27.

Launch Eject

When the missile is mounted in its launch station, the aft end of the first-stage skirt rests on a launch-eject piston. The missile itself is stabilized in its launch tube by one set of foam wedges near the missile midsection. A material change was made early in the flight program based on a lesson learned with FLA-3. When FLA-3 was given the launch order, it went through the standard automatic missile check series which precedes missile ejection, failed one test, and, consequently, did not proceed with ignition of the launch eject gas generator. However, the missile-flight gas generators had already ignited in their normal sequence and continued to burn while the missile sat in the launch station. The exhaust of the second-stage gas generator ignited one of the urethane foam upper wedges, which burned and heated one or more of the bolts in the forward end of the first-stage motor. Enough heat was transmitted through the bolts to ignite the first-stage propellant. The resulting explosion destroyed both the missile and the launch station. The foam material was then changed to self-extinguishing Hetrofoam.

Two environmental problems in the guidance section were caused by the launch-eject sequence.[42] One was a shock caused by the ordnance which was detonated to cut the fiberglass launch station closure just prior to missile ejection. Corrective action involved covering the guidance section

with a 2-inch thick "shock sock" of flexible urethane foam to attenuate the explosive effect of the closure ordnance. The foam was backed by a leaded vinyl sheet and fiberglass cloth and four nylon lanyards were provided to cut the sock and remove it during launch. To dissipate the heat from the gyro heaters, the shock sock was slotted and attached to an air duct from a blower in the launch station.

The second environmental problem in the guidance section was a higher-than-anticipated shock that occurred when the missile was launched and the nose cap slid over the opening where the ground power umbilicals had been connected. The situation was corrected by designing a hydraulic damping system in the nose cap slide tube.

Another problem involved a large shock which reverberated through the missile frame from the rear of the missile during the ejection phase. The metal piston itself was retained in the launch station, but the high-pressure gas under the piston escaped through holes in the side of the launch tube and was directed upward by the exterior wall of the launch station to impinge on the missile. The piston itself sometimes broke and ejected pieces became a menace. The solution was a design modification to the interior of the launch station to cushion the upward motion of the piston against an arrestor assembly. The assembly absorbed the energy in tubes filled with crushable aluminum honeycomb and formed a pressure seal to entrap the ejected gases until they could be bled away safely.

Another launch problem emerged near the end of the WSMR flight program, causing failures of FLA-34 and FLA-36. The first failure was initially diagnosed incorrectly. After the second failure, investigation and careful camera coverage during further launch-eject tests on dummy missiles revealed another foam wedge problem. A refined analysis of wedge loads showed that the loads on the upper wedges during eject were critical because these wedges were designed to guide the missile along the launch tube. Tight-fitting upper wedges located around the top of a first-stage caused eject-piston seal failures which caused the lower wedges, located around the circumference of the first-stage skirt, to buckle the first-stage skirt during launch. The lower wedges were relocated to serve as guide blocks on the piston, and the upper wedges were thereafter custom-fitted and shipped with their particular missile.

Staging

The successive flight failures of FLA-9 and FLA-10 in April and May of 1967 showed the presence of a staging problem. SPRINT was required to undergo staging at dynamic pressures not experienced in other missile programs, and there were some surprises in the severity of the staging environment and its subsequent effects. Missile separation was required at different altitudes and at different missile angles of attack. Also, the second-stage ignition in early flights was taking place while the first-stage case was still close enough to generate aerodynamic effects on the second stage.

Motion pictures, as well as available on-board instrumentation records, were studied closely to observe differences in separation phenomena between successful and unsuccessful flights. Two static second-stage motor firings were conducted with instrumented spent first-stage cases at selected separation distances. Wind tunnel tests were conducted at the Air Force Arnold Development Center with two models, and other special experimental tests were run in other tunnels from August to December of 1967. The results were incorporated into a staging analysis.

First, changes in timing of missile staging were made to allow drag to separate the first stage sufficiently before second-stage ignition. Second, a series of hardware changes was made. The second-stage nozzle closure was strengthened to prevent its implosion and the subsequent premature autoignition of the second-stage motor

by an unplanned entry of hot boundary layer air. The second-stage nozzle exit cone was strengthened to prevent its being fractured, either by vibration, large bending forces, or debris. The second-stage flame shield around the nozzle was modified to attain proper restriction of nozzle bending and also to ensure protection of wiring and control components. Interstage connectors were modified to lessen the possibility of damage; and hardware, wiring, and instrumentation on the first-stage dome area were concentrated near the center of the motor closure. A maraging steel "derby hat" protector was securely bolted over all of these first-stage appurtenances to prevent debris from being created and possibly thrown into the rear of the second-stage either by boundary layer forces or second-stage motor plume forces.

Three missiles were specially instrumented and flown at WSMR to assure proper identification of staging problems and their proper solutions. Measurements of the environment on these flights led to further changes. It had been initially speculated that vibration and shock environments during flight would be extremely high, and design specifications for components demanded extreme ruggedness. Special accelerometers had to be developed because none were available to meet expected vibration, shock, and acceleration. After the specially instrumented "staging" flights produced a better definition of the flight environment, it was realized that still further measures were necessary. Dacron-lacing of all wiring replaced the harness ties, and brackets were strengthened. The autopilot frame and the foaming of its components were modified to increase the unit's ability to withstand the forces generated during launch, separation, and maneuver.

FLIGHT TEST PROGRAM[43]

Development flights were originally conducted at WSMR to recover and examine flight hardware. Forty-two SPRINT missions were flown there to provide tests of all SPRINT missile subsystems in as many of the flight environments as possible. The flight program was then moved to KMR, where SPRINT was integrated with other components of the SAFEGUARD System for systems tests involving another 34 flights. All missiles flown were of the tactical design as shown in Figure 9-8.

The broad objective of the flight test program was to verify that all subsystems could perform as designed to the extent demonstrable at WSMR and KMR. To meet this broad objective, it was necessary to verify that:

- The propellant would survive the axial and lateral g-loads specified and would provide the required thrust to accelerate the missile to effect intercepts within the specified time.
- The heat shield would maintain its integrity under worst-case flight trajectories and would maintain the internal temperatures below specified limits.
- The inertial sensors would survive the acceleration and shock loads during worst-case flight trajectories.
- The first- and second-stage control systems would perform both within the required accuracy/time limitations and for maximum flight time.
- The communication link would be maintained during all flight phases.
- The launch station and ground support equipment would prepare and launch the missile within the specified interval, and would perform the required missile subsystem checks within the specified time periods.

The WSMR flight test program demonstrated that SPRINT missile performance parameters were as specified in applicable documents.[44] All performance requirements were achieved, verifying SPRINT missile readiness for the KMR system test program.[5]

The KMR test program was designed to gather data to support the evaluation of the tactical SAFEGUARD System. The KMR missions, from the SPRINT subsystem point of view, demonstrated the capability to launch and guide the missile with the MSR and the MSDP to intercept a live or simulated reentry vehicle. Intercepts were accomplished well within required miss

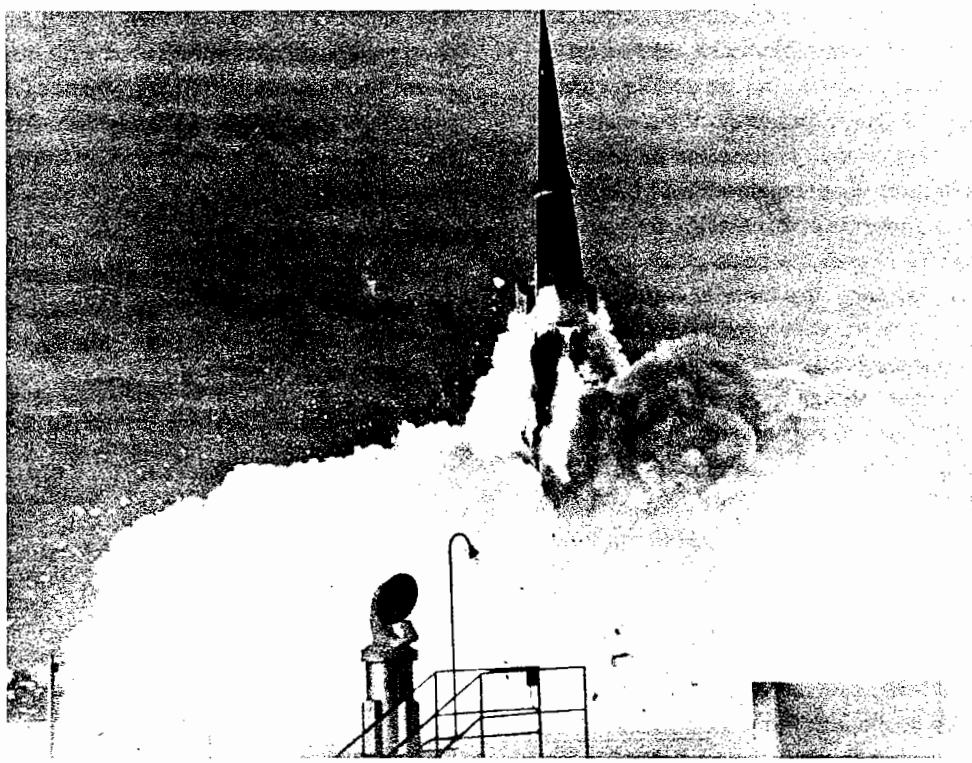


Figure 9-8. SPRINT Missile in Flight

distances. In fact, one intercept resulted in physical contact. SPRINT compatibility with the SAFEGUARD System was verified and data were gathered to evaluate SPRINT subsystem performance.

The system tests included the objectives of exercising the guidance/interceptor subsystem in engagements which tested the most stressed aspects of system performance and of obtaining data to substantiate the SPRINT guidance model used in system evaluation simulations. For example, the extended range mission provided valuable data to more precisely define drag characteristics for simulation purposes. Critical intercept conditions of interest were:

- Regions of low lateral acceleration capability
- Large crossing angles
- Near vertical trajectories
- Low elevation angles
- Long-range intercepts
- Intercepts shortly after motor burnout.

Significant accomplishments in the flight program included two successful flights through rain, a successful flight using aged first- and second-stage motors, successful performance of a cell closure after plume sweep from a missile launched from an adjacent cell, salvo launch capability, and successful intercepts of reentry vehicles. The flight program also demonstrated successful interchangeability of missile sections.

A summary of KMR (and WSMR) flight tests may be found in the Phase III Development Plan SPRINT Subsystem,[5] Vol. IV, Table 1-I. For intercept points and field of fire, see Figure 1-15 of the same reference, and for a summary of subsystem performance, see Chapter 1.

In summary, flight test results both at WSMR and at KMR demonstrated that important missile performance characteristics were significantly better than those specified before the start of the development program. Missile subsystem in-flight reliability for the last 30 flights of the R&D program was very high, and design changes resulting from failure analyses have been incorporated, so that deployed tactical missiles should meet the extremely high missile in-flight reliability objective. At KMR, the missile availability exceeded requirements.

Chapter 10.

SPARTAN MISSILE SUBSYSTEM

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SPARTAN MISSILE SUBSYSTEM

The role of SPARTAN in SAFEGUARD is to intercept ballistic missile targets at long range, with a large payload, in the exoatmosphere. The missile finally deployed at Grand Forks, North Dakota resulted from an extensive R&D effort which began in 1955 during the NIKE-ZEUS program. As requirements changed, SPARTAN evolved from a single-stage, hypersonic, winged antiaircraft missile, which was never built, through three configurations of antimissile missiles (DM-15A, B, and C) to the present design. Originally designated DM-15X2 (ZEUS-NIKE X), this missile was named SPARTAN in January 1967.[1] SPARTAN is similar to the NIKE-ZEUS DM-15C configuration, modified to increase motor performance, improve missile guidance, and increase warhead yield.

In January 1965, a nine-month study of the role of ZEUS in the NIKE-X System concluded that a ZEUS-type interceptor with a high-yield nuclear warhead would furnish a large-volume exoatmospheric kill capability against threats of interest. In March 1965, Bell Laboratories was authorized to proceed with Phases I and II of the R&D: defining the ZEUS missile subsystem based on NIKE-X system requirements and design trade-off studies, planning the development program, and completing the preliminary design.

Phase III of the R&D program began in October 1965 as formal design started and specific system and design trade-off studies continued.[2] The principal parts of the program were (1) a 29-month detailed engineering design, hardware fabrication, and ground test phase and (2) flight tests at Kwajalein and Meck Islands. An extensive functional and environmental test program, which included several months of system integration testing in the laboratory, was carried out before the first flight test in March, 1968 at Kwajalein. The R&D missile configuration reflected the basic approach of "do it once; do it right" —the projected tactical design was built into the first flight missile and interim test missile designs were avoided. Thus, the flight test data on each major component were directly useful in the final design. As a result, the missile development test program at Kwajalein consisted of only 15 missile flights. The first SAFEGUARD System flight test with a SPARTAN missile launched from Meck Island took place in April 1970. Twenty SPARTAN missiles were launched during the SAFEGUARD System test program, which was completed in June 1973. After that, five production missiles were flight tested during the Product Assurance Verification Test (PAVT) program.

As shown in Figure 10-1, many agencies, organizations, subcontractors, and suppliers took part in the development of SPARTAN.

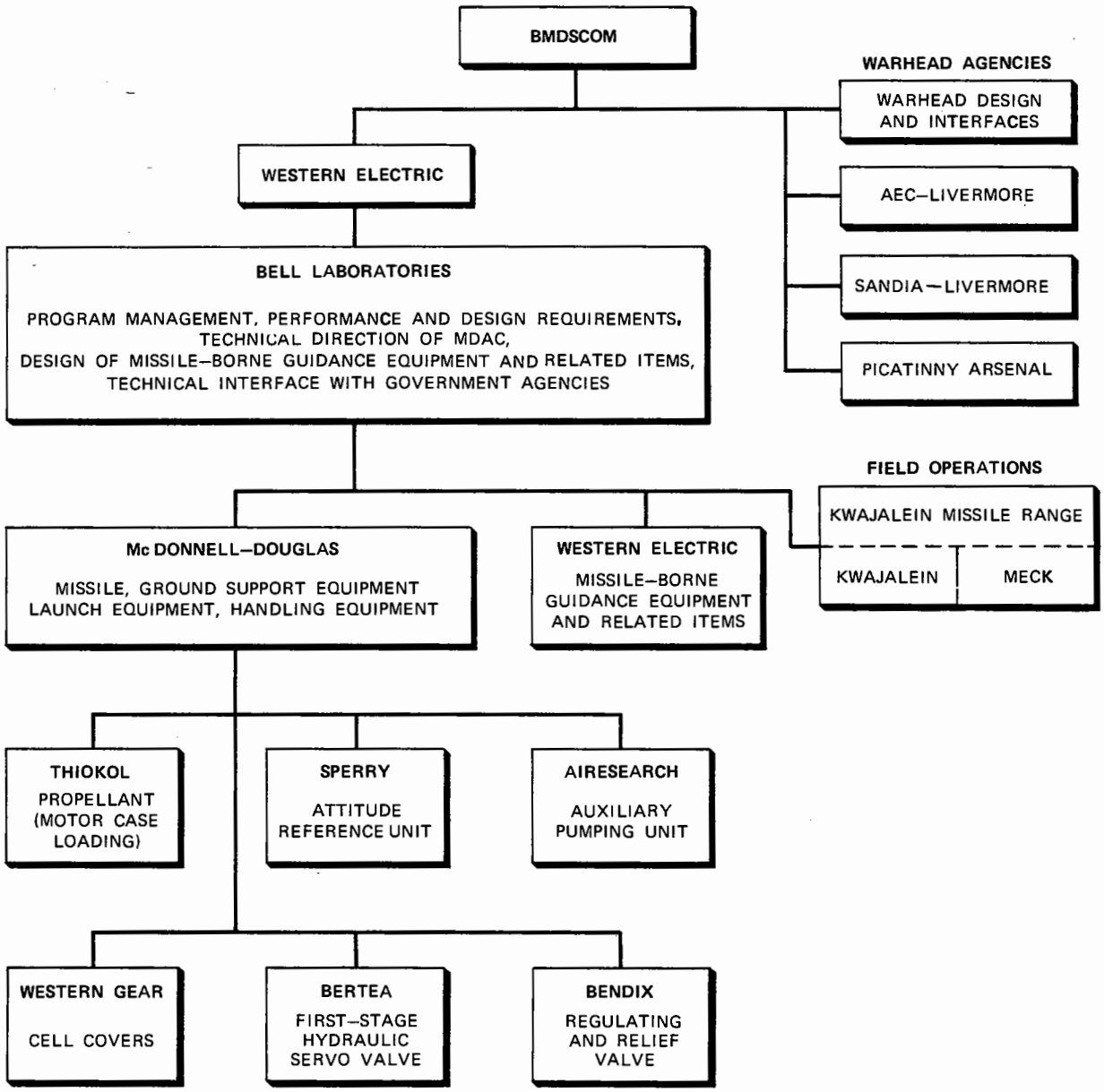


Figure 10-1. SPARTAN R&D Organizational Structure

MAJOR CHALLENGES AND INNOVATIONS

Because it evolved from earlier designs, developing SPARTAN did not require new technological breakthroughs. However, it did take determined and innovative engineering to produce a manufacturable design that functioned in the imposed environments with the specified availability and reliability. Several facets of this effort were:

1. Establishing a high reliability component program. Early in the development it seemed essential to establish a component procurement program under the strictest reliability procedures. The program included a Bell Laboratories-approved list of high reliability parts from qualified vendors. It also included procurement specifications designed to ensure reliability that far exceeded the MIL specifications commonly used by the military. Each SPARTAN missile contains roughly 10,000 high reliability electronic parts. This emphasis on ultra-high reliability contributed to superior SPARTAN performance during the Meck flight test program.[3]
2. The missile structure and all its subsystems, including electrical components, had to withstand severe nuclear effects. The extensive program that achieved and assessed nuclear hardness has been thoroughly documented.[4] For more information on this program, see Chapter 6.
3. Another SPARTAN innovation was an ablator, which is lightweight and applied with spray heads while a missile section is rolled on its axis. During R&D flight tests at Kwajalein, the ablator proved it could protect the missile from the extreme heat induced by atmospheric flight. Special instruments were imbedded in the ablator to determine the depth and rate of ablation.
4. The Missile Guidance Set (MGS) developed for SPARTAN is essentially the same as the SPRINT MGS. It uses extensive foaming of subassemblies and a preload arrangement to ensure proper operation during severe shock, vibration, and noise. The MGS has a three-channel receiver, which monitors the signal received by three equally spaced pairs of missile antennas and automatically switches the beacon transmitter pulses to the antennas with the strongest received signal. This transmitter switching feature, coupled with a hard limiting, instant response, intermediate frequency amplifier, lets the MGS detect and decode signals during the rapid fading caused by attenuation from missile plume and plasma sheath.
5. At first, a design based on discrete components was developed for the Launch Preparation Equipment (LPE). Later in the SPARTAN development cycle, Integrated Circuit (IC) technology which had become well proven, was shown to be more suitable for the LPE, especially from the standpoint of production costs. An Integrated Circuit LPE (ICLPE) design was introduced and proved to be highly reliable during flight tests at Kwajalein.
6. The Sperry fluid-sphere gyro in the SPARTAN attitude reference unit was the first application of this unique device in a major system. The concept of sensing pressure differentials between a rotating fluid and its container produced a device more reliable than the conventional gyro, which senses gimbal axle displacements with relatively delicate sensors.
7. Other innovations in SPARTAN included a sealed hydraulic control system and a quartz nose cap. The hydraulic system was found to be very reliable during storage and in-flight operation, while the nose cap withstood worst-case natural environments.[5]

DESCRIPTION

SPARTAN Subsystem Operation

The SPARTAN subsystem consists of high-performance interceptor missiles, controlled by ground radar and armed with nuclear warheads, plus associated ground support and launch equipment.[1] The missiles are deployed in a launch area near the Missile Site Radar (MSR) and emplaced in underground cells equipped with environmental control, testing, and monitoring equipment. Control and status-monitoring equipment are linked to the Missile Site Control Building (MSCB).

The three-stage, solid-propellant missile can intercept ballistic missiles at extremely high altitude and long range. The third-stage motor is normally used late in flight to achieve more accurate intercepts and to orient the warhead. As an option the motor can be used early in flight to extend SPARTAN's maximum range. The Missile Site Data Processor (MSDP) command guides the missile via the

MSR link, and an onboard transponder generates short beacon pulses to help the MSR track the missile.

At launch, a command from the MSDP ignites the SPARTAN first-stage motor and the motor lifts the missile from its underground cell. Ballistic flight is used during first-stage motor burning. The fixed first- and second-stage fins and the locked third-stage control surfaces keep the missile aerodynamically stable. At the end of first-stage burning, the second stage is ignited and its thrust forces separate it from the burned-out first stage. During second-stage flight, four movable control surfaces on the third stage aerodynamically steer the missile and control its roll rate.[6]

The second stage burns out within the atmosphere after approximately 25 seconds of missile flight, and the missile glides out of the sensible atmosphere. An MSDP command via the MSR can ignite the third-stage motor at any time after the missile leaves the atmosphere. Prior to intercept, the burned-out second stage is separated from the third stage, which contains the warhead. Skin-cutting ordnance separates the two stages shortly after the third-stage motor ignites,[7] and ground commands control both the ignition and separation. Nozzles in the rear edge of the third-stage control surfaces vector the exhaust of the third-stage motor to control exoatmospheric reaction.

To maximize warhead efficiency, commands from the ground properly orient the missile centerline with respect to the predicted intercept point before the third stage burns out.[8] The missile is then spin-stabilized to maintain this orientation until intercept.[9,10]

Missile

SPARTAN's first- and second-stage motor cases are built of high-strength steel (see Figure 10-2). Monocoque aluminum construction is used in the first- and second-stage cylindrical guidance section and in the two-piece conical

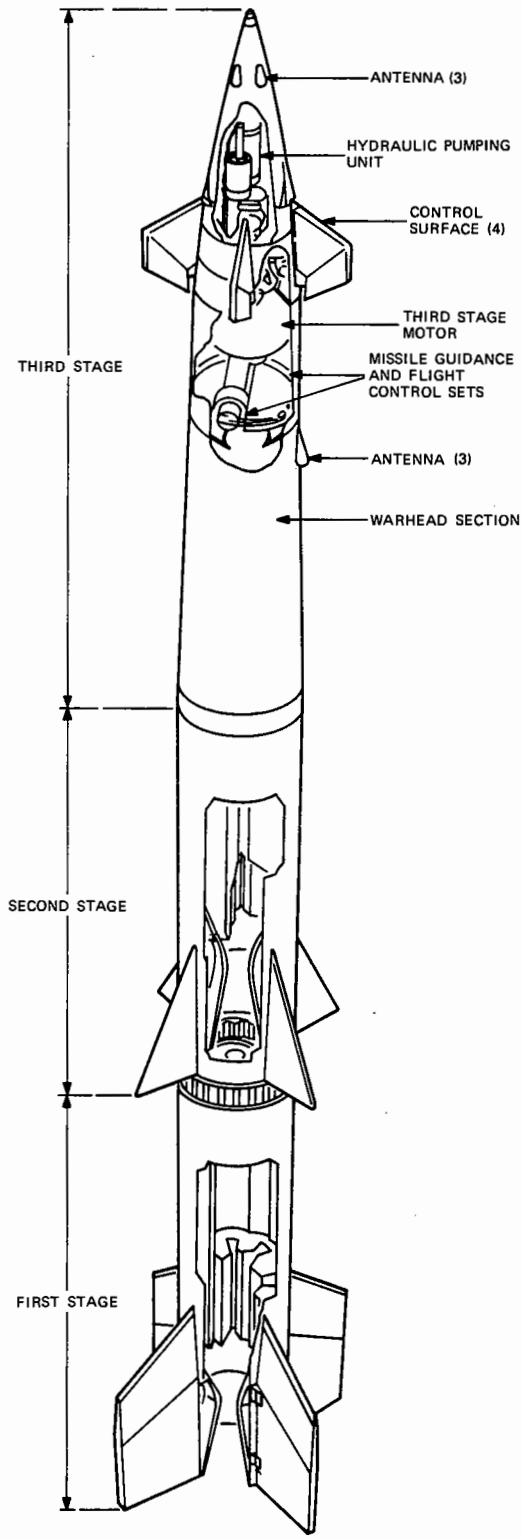


Figure 10-2. The SPARTAN Missile

control section. There are three antenna strakes at the forward portion of the warhead section and three additional antennas mounted on the nose fairing.

Ablative materials on appropriate sections of the missile skin dissipate boundary layer heat and limit internal missile temperatures. The three materials used are Teflon,* phenolic refrasil, and sparesyl. Teflon sublimes at high temperatures and is, therefore, used on the nose fairing and on the third-stage nozzle impingement pads.[8] Phenolic refrasil is used in the third-stage fin area and on the leading edges of the second-stage fins. The remaining surfaces of the second and third stages are insulated with a lightweight albator called sparesyl. The first stage does not require insulation.

The first and second stages are essentially propulsion units with stabilizing fins. The third stage contains the warhead section, missile guidance set,† flight control set,[11] hydraulic pumping unit, third-stage motor, and four control surfaces (thrust vector control). The missile guidance set receives steering orders from the ground and applies them to a flight control set to move the control surfaces through hydraulic servos.[12] Since the ground-based system elements do not sense missile attitude, orders from the ground are sent in earth coordinates. These orders are then converted to missile coordinates by the stable reference system in the flight control set.[13] The missile guidance set receives discrete commands, decodes them, and sends them to appropriate subsystems. These commands separate the third stage, start the third-stage motor, and control various warhead functions.

*Trademark of E. I. DuPont de Nemours.

†This guidance equipment also is used in the SPRINT missile. See Chapter 9 for a description of this unit.

The SPARTAN Hydraulic Pumping Unit (HPU) is shown in Figure 10-3. The gas generator, consisting of an initial and terminal grain, sends a flow of gas to the turbine. The flow rate depends on propellant formulation, chamber pressure, grain temperature, and grain geometry. The hot gas shutoff valve, which transfers from initial to terminal grain operation when required, functions in one of two modes of operation: the dwell mode, in which the initial grain has burned out before the valve is actuated, and the overlap mode, in which the valve is actuated when the initial grain is still burning. The operating gas pressure is controlled by the burn-rate control valve.

Under steady-state conditions, oil flows from the pump to the accumulator, through the accumulator relief valve, then to the reservoir, and back to the pump. The accumulator is prepressurized at initial-grain ignition with nitrogen released by the accumulator explosive valve.

Under transient conditions (when the control surfaces are active), the accumulator furnishes oil to the control surface actuators via the regulator valve. The reservoir receives the return flow from the actuators. Under these conditions, turbine speed will vary as necessary to restore and maintain steady-state operating pressure in the accumulator.

Launch Station

The SPARTAN launch station (Figure 10-4) consists of a steel-lined launch chamber, exhaust duct, Launch Preparation Equipment Vault (LPEV), the Mechanical and Electrical Equipment Vault (MEEV), and the launch area antenna.[14] The launch station provides long-term storage for the missile, tests and launches it, and protects it and its launch and test equipment from natural and battle-induced environments.[15,16]

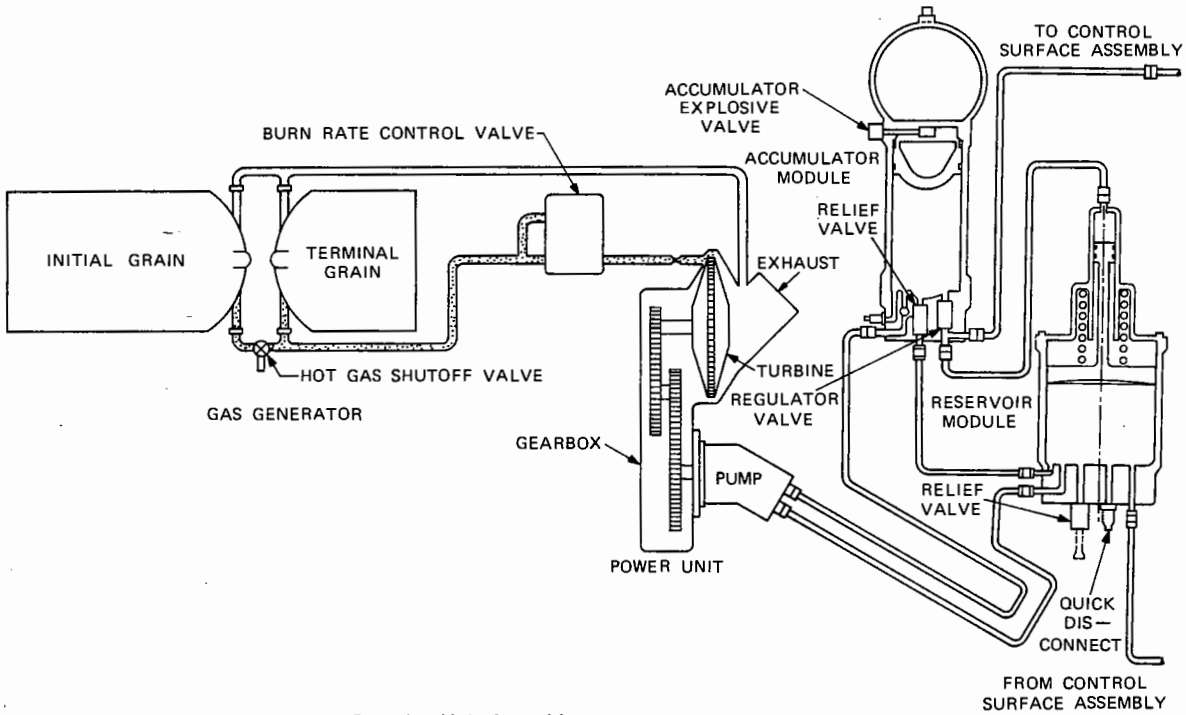


Figure 10-3. SPARTAN Hydraulic Pumping Unit Assembly

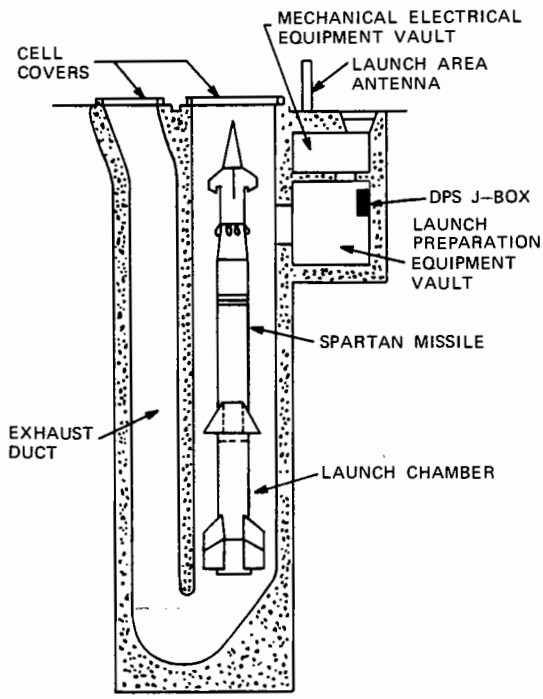


Figure 10-4. SPARTAN Launch Station

The launch chamber contains a launch rail to support the missile in a ready-to-launch attitude. Associated with the launch rail is the mechanism for extracting the missile umbilical, the forward cradle capture equipment, the first-stage igniter mounting, and the High-Energy Firing Unit (HEFU).[17] A shock-isolation system in the launch rail attenuates nuclear or earthquake ground shocks to less than 1 g.[18,19]

The launch chamber and exhaust duct are protected by two 2-piece cell covers (Figure 10-5). The covers, each half weighing 4800 lbs, are held closed by bolted plates. During launch, a linear-shaped charge severs the plates and the cell covers are moved rapidly to an open position by a piston and cylinder attached to each cover half. Each cylinder is pressurized by a hot-gas generator ignited by dual squibs.

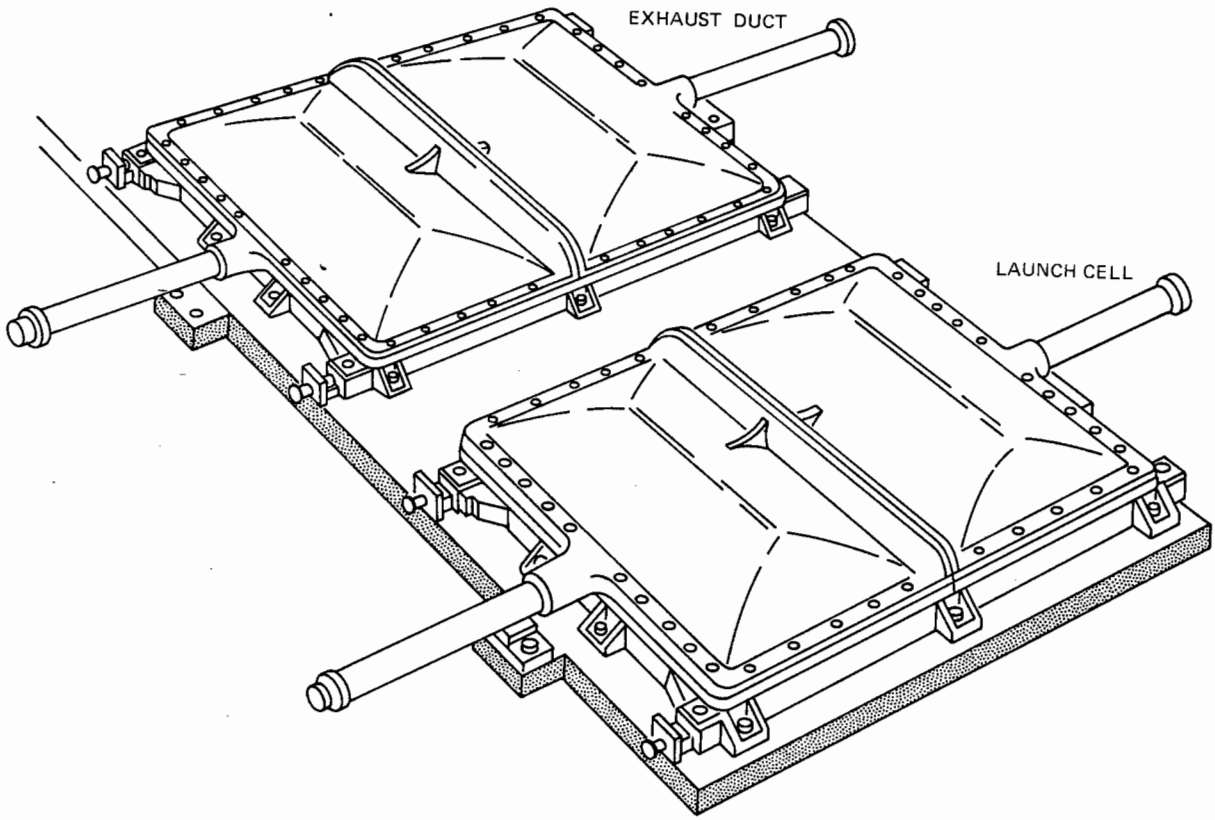


Figure 10-5. Launch Cell Protective Covers

The MEEV and LPEV are located on the side of the launch station.[20] The MEEV, which is above the LPEV, houses the launch station heating and air-circulation equipment and is reached through a submarine-type hatch cover. Air in the launch station is purged through the MEEV. The LPEV is entered through a hatch from the MEEV, and the launch chamber is entered from the LPEV through a blast door. The underground location and configuration of the LPEV shield it from nuclear and RF radiation.[21]

The Environmental Sensor Kit (ESK) is housed within the LPEV. In conjunction with remotely placed sensors, it monitors launch chamber and LPEV temperature, humidity, and water levels. An out-of-limits indication in an ESK sensor will generate a minor alarm which is transmitted to the MSCB via the Data Processing System Junction Box (DPS J-Box).

Launch Preparation Equipment Set

The Launch Preparation Equipment Set (LPES), Figure 10-6, is composed of the Launch Preparation Equipment (LPE), DPS J-Box, and High-Energy Firing Unit (HEFU). All elements of the LPES except the HEFU are inside the Launch Preparation Equipment vault; the HEFU is at the bottom of the launch cell. The LPES is the functional link between the Data Processing System (DPS), the MSR, and the cell-emplaced missile. It prepares the missile for launch by testing the missile systems and monitoring critical missile and launch cell support equipment during the preparation period, ready period, and launch sequence. It also supplies the missile with ground operating power for all tests until the missile is switched to internal power during the launch sequence. In addition to its

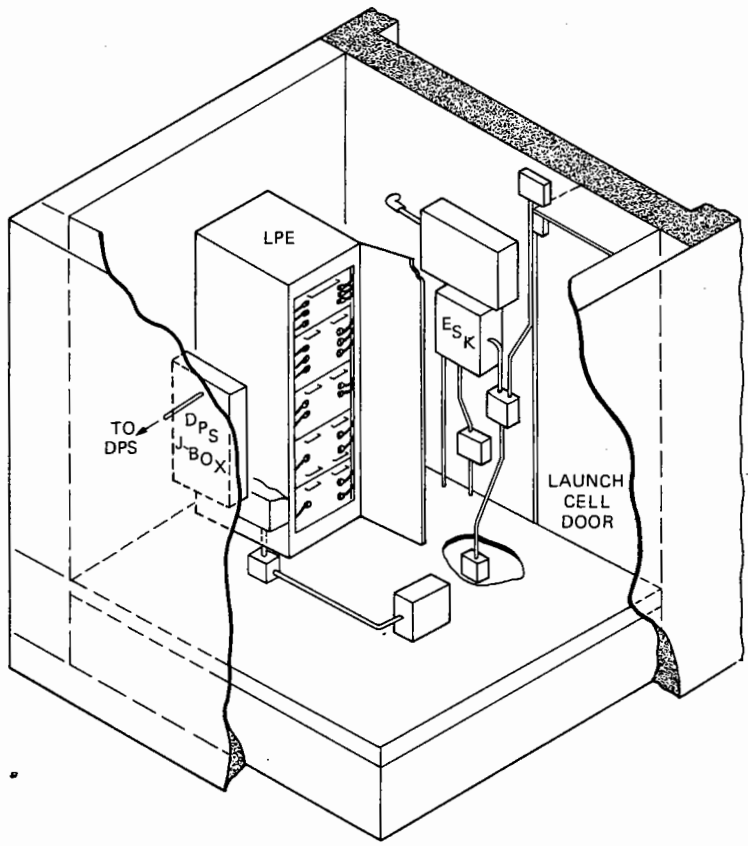


Figure 10-6. Launch Preparation Equipment Set (Tactical)

power and missile checkout function, the LPES, in conjunction with the DPS, can execute, interrupt, and recycle a preparation/RF test request at any time before the launch sequence starts.

Nuclear weapons can be used only upon presidential authority, and SAFEGUARD is released through the North American Air Defense Command (NORAD) at the Cheyenne Mountain Complex. The release information is transmitted in coded form over a data link to the Missile Defense Center (MDC), where the message is decoded and the contents are placed on a system status display.

A second message is then originated within the Launch Enable (LE) equipment as the first part of a chain of events that launches a missile or tests the system. The elements of the second message pass through the launch enable message transmitter to the launch enable message receiver and then to the launch enable transmission set. Finally, the message is fanned out to Launch Enable Coded Switches (LECSs) mounted in each of the missile launch cells. Receipt of a properly coded launch enable message by the LECS permits missile launch orders generated by the DPS to initiate the launch sequence. During the launch sequence, the LPES generates signals that activate the missile launch order squibs, set the remote arm switch, activate the cell covers, and charge and trigger the HEFU for the first-stage ignition.

Ground Support Equipment

The SPARTAN Ground Support Equipment (GSE) consists of field checkout and maintenance equipment, missile-handling equipment, and shipping containers. Some of the major items are:

1. The Fault Isolation Test Set (FITS) is used to isolate failures and to verify LPE operation when a major alarm is received from a launch station. The FITS first tests the LPES to isolate the fault to either the missile or the LPES. Faults in the LPES are isolated to the drawer level of the LPE and to the unit level of the DPS junction box. Maintenance crews replace the faulty units and the FITS/LPE test is repeated to verify that the fault has been corrected.

   If the LPES works properly, it is assumed that the missile is at fault. First, maintenance personnel enter the launch cell and disarm the missile.[22,23] Next, they remove the guidance/control section to gain access to the warhead section. The FITS and the LPE are used to test the warhead section functions. If a fault is detected in the warhead section, crews remove it and send it to the on-site warhead building for further testing.[24,25] If no fault is detected in the warhead section, the guidance/control section is presumed to be at fault and a spare section from the Universal Missile Building (UMB) is installed. Fault correction is then verified by the LPE.

2. The Third-Stage Test Set (TSTS), Figure 10-7, is used in the UMB and warhead

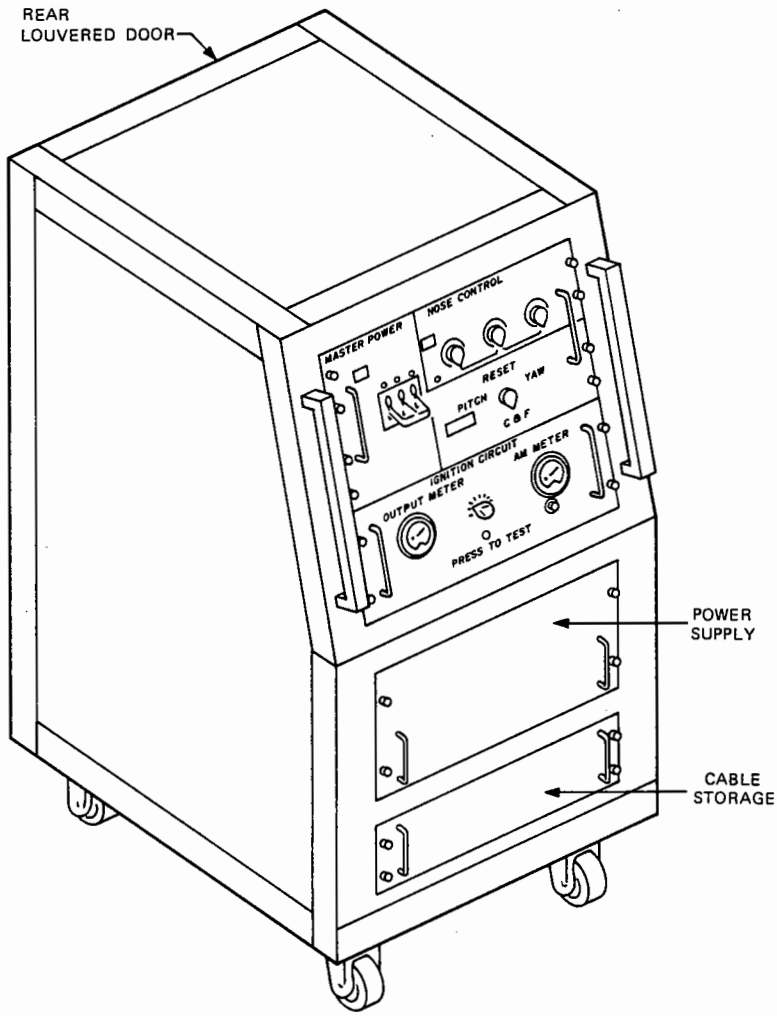


Figure 10-7. Third-Stage Test Set

buildings to functionally test the guidance section, control section, and warhead section interfaces. It can test third-stage ignition circuits, isolate control section faults, and isolate warhead section faults.

3. The maintenance van, Figure 10-8, can transport the spare LPE drawers, the FITS, and maintenance tools. The maintenance van has a shelter which is deployed over the entrance to the MEEV to allow access while protecting the missile from natural environments (rain, wind, and snow).[26]

   An overhead electrical hoist in the van removes and replaces LPES components and transfers test equipment between the van and the LPEV.

4. The missile-handling equipment includes all of the necessary fixtures, loading beams, and slings for assembling missiles at the UMB and at the launch station. It also includes the Universal Transporter Loader (UTL) shown in Figure 9-7 of Chapter 9.

   The UTL is a self-propelled vehicle that transports missile sections and loads them into cells. A weather shield protects the cells from natural environments during missile-handling operations.

SUBSYSTEM DEVELOPMENT PROGRAM

Propulsion

Development of the SPARTAN propulsion system started in April 1966. The effort was not extensive because the objective was to use NIKE-ZEUS technology as much as possible.

SPARTAN's first-stage motor is almost identical to the NIKE-ZEUS DM-15C motor. The first-stage pressure-vessel design is identical except for a change from special sandwich-rolled 4340 steel to cold-rolled 4340. This change resulted from improvements in steel-rolling techniques, which allowed use of the more economical cold-rolled sheet while retaining high quality and close dimensional tolerances. Other hardware changes were minor, and DM-15C's grain geometry was carried over to SPARTAN. SPARTAN also had an improved case insulation and a new propellent formulation that was common to the first and second stages.

The SPARTAN second-stage motor is a reconfigured DM-15C first-stage motor. The steel motor case is the same, except for the interstage connections and a larger port in the head end to accommodate the igniter. Both the propellent formulation and the grain configuration are new. A Carboxyl-Terminated Polybutadiene (CTPB) propellant with 87 percent solids was developed for the first and second stages. Since the Thiokol Chemical Corporation, which had the subcontract for the propellant, had extensive experience with the binder system and had done considerable research and development in high-total solids, a basic propellant formulation could be selected. The proper burning rate was reached and ballistic reproducibility was achieved by tailoring the oxidizer and fuel particle sizes, optimizing their distribution, and determining the proper amount of burning-rate catalyst. Seven full-scale second-stage motors and one first-stage motor were all successfully static-fired before the first flight test.

The third-stage motor design is the same as that used in the NIKE-ZEUS DM-15C missile.

After the first successful missile flight, the propellant-liner interface was found to be separated in the forward opening of the second-stage motor. This problem occurred in several motors and reappeared after the material containing the original separations was trimmed out. The difficulty was first diagnosed as a tooling problem, but visible head-end separations and/or subsurface defects kept occurring after tooling changes. The problem was solved for the remainder of the development program by removing propellant from the area where separations were found and replacing it with a cast-in-place burning-inhibitor boot.

Near the end of the production program, massive propellant separations appeared in some second-stage motors in the same forward dome area behind the boot. The defect appeared only in some but not all of the motors cast from

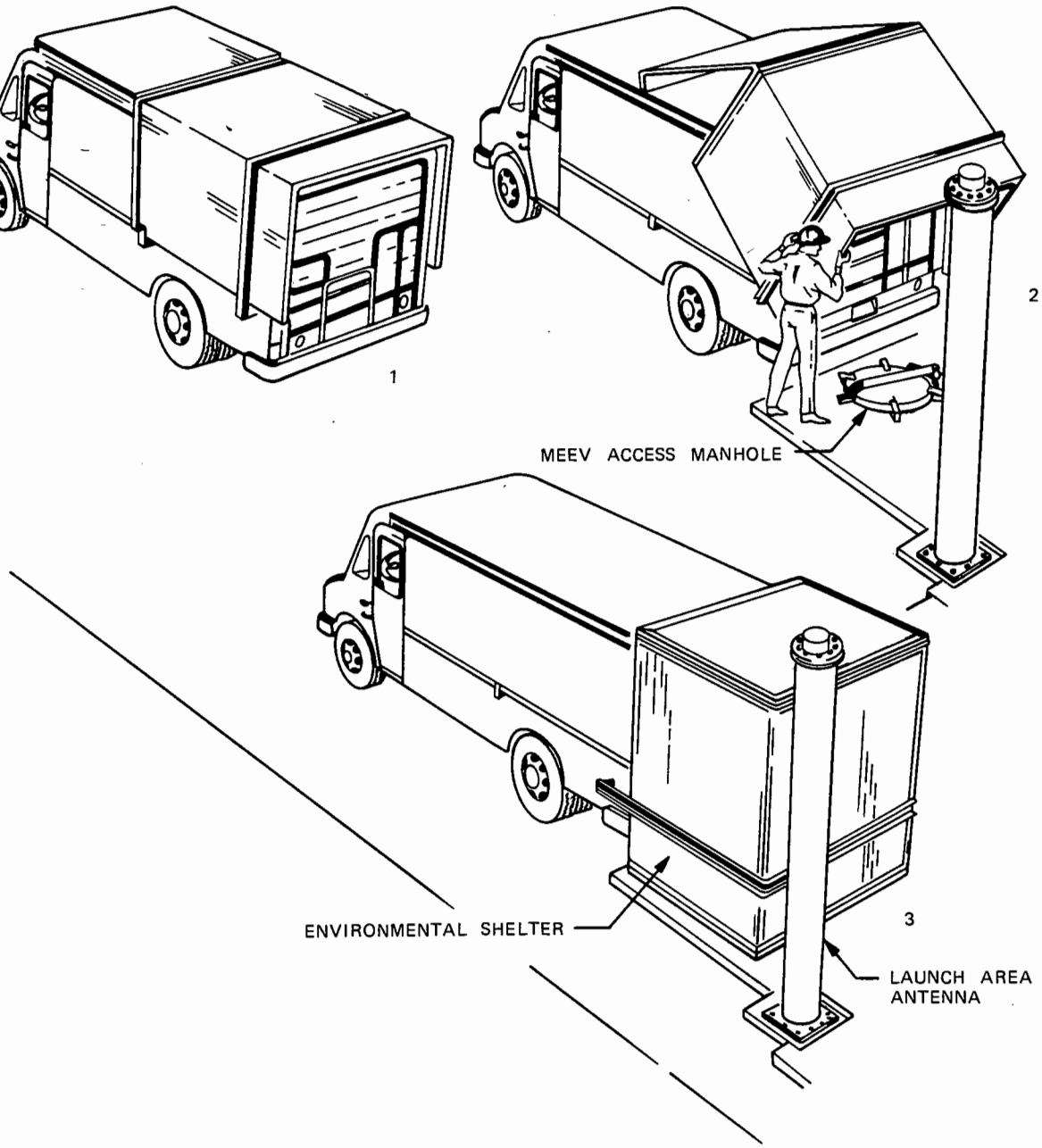


Figure 10-8. Maintenance Van Deployment Sequence

a particular lot of raw materials. Since the defect was confined to one materials lot, and since none of the motors from that lot were needed to meet the reduced deployment requirements, it was decided by the Ballistic Missile Defense System Command (BMDSCOM) that no funds should be provided to further isolate the problem. During this investigation, the effects of migration of the burning-rate catalyst were evaluated. It was found that the catalyst did not concentrate enough to impair the physical properties of the propellant-liner interface when the liner thickness was correct and proper cure time was used.

One SPARTAN development flight, KT-05, failed in November 1968 because of propulsion problems. Although the exact cause could not be pinpointed, it was deduced that the second-stage nozzle exit cone bent with respect to the nozzle entrance structure, perhaps because of vibration, shock, or acoustic noise, and allowed gas to leak through the insulation. The exit cone support structure was stiffened, and there were no further problems.[27]

In addition to SPARTAN motors used in other development tests, three sets of motors were given road tests, drop tests, and temperature cycling tests, in that order.[28] One set of motors was ground-fired and the remaining two sets were flight-tested. All motors performed normally.

Missile-Borne Guidance Equipment

Development of dual-frequency Missile-Borne Guidance Equipment (MBGE) began early in the NIKE-X program. The MBGE mounted in both SPARTAN and SPRINT missiles was designed to operate with signals from either the Multifunction Array Radar (MAR) on L-band or the Missile Site Radar (MSR) on S-band. The SPARTAN MBGE consists of a missile guidance set, six antennas, and interface cabling. At the outset, it was decided to design deployable hardware and not to go through an R&D phase followed by a redesign for production. This approach saved many hours of dead-end engineering.

After the MGS subassemblies (receiver, transmitter, decoder, and power supply[29]) were breadboarded, two prototypes were built. One, which consisted of foamed subassemblies, was used for shock, vibration, and centrifuge testing, while the other was used for electronic testing. Both units were built with electronic components purchased with the special high-reliability procurement specifications. The high-reliability program started at the beginning of MGS development to ensure that a quality product would be deployed. To achieve an extremely low failure rate during MGS life (storage and flight), the number of component types on the approved usage list was minimized. Stringent component specifications weeded out weak products. In many instances, specifications included component burn-in tests. Before a component was authorized for the approved usage list, the vendor's production lines were extensively qualified, and a single source was established for each component type during the R&D program. The approved usage list of electronic components became a requirement for SPARTAN and SPRINT missile-borne hardware and launch preparation equipment.

While the MGS was being developed, L-band and S-band missile antennas were designed and fabricated. S-band antennas, which are used on both SPARTAN and SPRINT, must withstand the shock and vibration of flight and the extreme heat generated on the missile skin. To optimize antenna coverage, various missile-mounting geometries were tested on scale models and antenna pattern measurements were made later on full-scale sections.[30] A combination of three antennas forward and three midway down the missile proved optimum for SPARTAN, while three antennas forward worked well on SPRINT.

A transmitter output oscillator development program was also in progress while work on the MGS and antennas proceeded. During the

earliest part of the NIKE-X development, work on an X-band magnetron design started. This design was abandoned in favor of L-band and S-band oscillators when the X-band mechanical radars of NIKE-ZEUS were replaced by L-band (MAR) and S-band (MSR) array radars. Several conceptual designs were started, including an integral tube and cavity and a pencil triode plus cavity, but the configuration finally chosen was the General Electric Company (GE) triode cavity oscillator. Besides meeting the stringent shock and vibration requirements placed on all MGS components, the triode cavity oscillator had a fast cathode warmup time that allowed quick missile reaction. This rugged unit was dropped from a second-story window to the parking lot pavement at GE and then brought back to the laboratory for test. It worked perfectly.

Two missile guidance sets were built for missile interface tests and later used as a simple way to exercise missile controls via an S-band link during flight simulation tests in the laboratory. With the successful conclusion of interface testing, missile-borne guidance equipment (MGS, antennas, cabling) was installed and checked-out in SPRINT flight missiles. The missiles were flown at the White Sands Missiles Range (WSMR) starting in November 1965.

During the SPRINT flight program, a special circuit was installed in several missiles to divert the MGS transmitter pulse to the antenna facing the missile tail. With this special circuit, data were gathered on S-band attenuation from motor plume and hot skin plasma sheath. Both up and down links had sufficient signal-to-noise (S/N) margins after the worst-case (40 dB) attenuation induced by the plume and plasma was taken into account. About that time, MAR was replaced by the Perimeter Acquisition Radar (PAR) and a decision was made to communicate with the SPARTAN and SPRINT missiles only via the MSR. Therefore, effort on L-band equipment was terminated.

The MBGE worked very successfully throughout the WSMR (SPRINT) and Kwajalein Island (SPARTAN) flight tests. These development flights were followed by a highly successful SAFEGUARD System flight test program at Meck Island (SPARTAN and SPRINT). The MBGE, which contains approximately 5000 components, has a record of one failure in 114 flights. The MGS that failed was recovered at WSMR and the trouble was isolated to a shorted capacitor. Special tests were added to the capacitor procurement specification to prevent future trouble. One MGS was recovered from the sand dunes at WSMR after a successful full-duration SPRINT flight test. When the missile was command-destructed at 40-kilofeet altitude, the MGS was blown free from the missile debris and tumbled through the atmosphere to crash into the ground. It was shipped back to Bell Laboratories, where it was powered up and given test commands. It decoded all discrete output commands and transmitted a normal S-band pulse with each test interrogation.

Launch Preparation Equipment and Fault Isolation Test Set

The SPARTAN development flight tests at Kwajalein (1968-69) and the early system tests from Cell 21 on Meck Island (1970) used modified NIKE-ZEUS checkout and maintenance equipment. As a result of the SAFEGUARD deployment decision, more sophisticated, automated Launch Preparation Equipment (LPE) was developed for the tactical system starting early in 1968.

A two-bay, twelve-drawer LPE with discrete high-reliability components was installed at Meck Island during the spring of 1970. Missiles were checked out and launched with this equipment starting that summer. During design and fabrication, the advantages of converting the LPE from discrete electronic components to integrated circuits was studied. It was concluded that conversion would increase LPE reliability, reduce production costs, and

improve maintainability. Design of the integrated circuit LPE started in the third quarter of 1970, with a first demonstration scheduled at Meck Island, Cell 22, during the last quarter of 1971. The LPE was reduced from a 12-drawer, 2-bay discrete version to a 5-drawer, single-bay IC version.[31] During design of the ICLPE, the RF unit that interfaces the MSR and missile was redesigned and repackaged for installation within the LPE. Prior to LPE redesign, the RF unit had been installed in a junction box on the LPEV wall.

Upon Nuclear Weapons System Safety Committee (NWSSC) recommendations, the DPS junction box was redesigned beginning in early 1972. This redesign incorporated:

- Input-output cable isolation
- Lightning surge arrestors on all cables to and from the launch station
- Locating the Launch Enable Coded Switch (LECS) within a locked enclosure.

A companion Fault Isolation Test Set (FITS) is used to troubleshoot the LPE. The FITS was redesigned to make it compatible with the IC version of the LPE.

Studies and improvements in the FITS improved reliability in three areas:

1. Certain logic cards within the FITS required a wire-to-post welding technique that demanded tight production controls for a reliable connection. Refined welding and testing techniques were developed to ensure consistently reliable wire-to-post connections.
2. Field and laboratory experience showed that tolerances for tests performed by the FITS were too tight. FITS/LPES test tolerances were relaxed to keep the FITS from rejecting a good missile.
3. The FITS production design was modified to include high-usage integrated circuits and high-reliability diodes and relays. These components were already being used in the LPES.

By incorporating these improvements, the overall reliability of the FITS was improved by 50 percent.

Hydraulic System

The basic elements of the NIKE-ZEUS hydraulic system were used in the R&D SPARTAN missiles, but a new tactical requirement—reliable operation after five years of storage with no testing or repair —was placed on the design. This requirement dictated a fairly radical departure from previous systems, which were designed for periodic filling, check out, exercise, pressurization, and refurbishing. Successful development was anticipated because:[32]

- Functional requirements had not changed significantly from the earlier NIKE-ZEUS configuration, and many components proven on the DM-15B and DM-15C missiles could be used.
- Effort could be concentrated on repackaging a known system to achieve reliable performance.
- Standard materials and conventional techniques would be employed as much as possible.

However, as development proceeded, it became evident that a very extensive engineering effort would be necessary to achieve the high level of availability required after extended storage and the required high in-flight reliability.[33] The most significant problems were:

1. A first-stage servo valve failed during a flight simulation test prior to the first missile flight. When the valve was disassembled, a buckled plunger rod was found. Isolating the plunger rod from the hydraulic environment with an end cap on the first-stage servo valve did not completely solve the problem. Further testing revealed that a pumping O-ring in the housing created pressure disturbances via positive feedback, so additional Teflon backup rings were added to eliminate axial clearances on the pumping O-rings. These changes eliminated problems in the first-stage servo valve.
2. Seized pistons in the hydraulic pump made the turbine overspeed when the first SPARTAN launch was attempted. The launch was aborted because of an unrelated problem, but the hydraulic system had already been activated and initially operated normally. Analysis showed that power input to the turbine was too high, and the burn-rate control valve was adjusted. However, on the

next missile flight, telemetry data indicated another turbine overspeed, and analysis showed that the system was operating at an even higher power output than in the first flight. Meanwhile, continuing ground tests of the HPU had uncovered other design deficiencies. To allow the flights to proceed in parallel with analyses, corrective actions, and tests, the ZEUS DM-15C pump was substituted on an interim basis. Corrective actions included:

a. Addition of an orifice to the turbine exhaust duct to correct for the effects of low turbine exhaust pressures at high altitude

b. A change to the pump design to incorporate features, clearances, and surface finishes used successfully in the DM-15C, initial SPARTAN, and DC-7 pump configurations.

3. Improper operations of the gas generator led to these modifications:

a. The grain design was changed to control progressivity (increase of burning area and pressure with time) and to eliminate a short pressure dip that occurred during two other missile flights. After a sequence of analyses and tests of unsuccessful modifications had been completed, it was found that wrapping the grain with added thicknesses of polyisoprene insulation solved the progressivity problem.

b. A molybdenum screen was substituted for the stainless steel screen in the gas generator exit port. The stainless steel screen burned through during a ground test and a piece lodged in the burn-rate control valve causing a transient pressure increase.

c. Design changes and procedural modifications precluded inadvertent shuttling of the hot gas shut-off valve during factory inspection. Several potential solutions were tested before a successful one was found.

4. The following bearing and gearbox probblems were encountered:

a. During one flight, turbine speed suddenly dropped. The drop was subsequently attributed to failure of a turbine bearing because the overlap mode of the gas generator was applying excessive loads to the turbine wheel. The turbine exhaust and the abort line were modified.

b. A power drive train apparently failed during one flight, and overspeeding of the turbine wheel caused it to disintegrate. Extensive redesign provided new bearings, higher preload bearing pressure, positive turbine shaft lock-up, heat treatment changes for the gears, and an increased volume of lubricating oil. In addition, acoustical signature tests were implemented.

5. A large oscillation of the accumulator regulating valve on one flight was attributed to a stiction-friction problem within the valve. The valve gain was reduced and small design modifications corrected the condition. A pressure drop with increasing hydraulic fluid temperature was attributed to the accumulator relief valve. Tighter manufacturing controls and a thermal shock test for flight qualification corrected this problem.

In summary, the hydraulic system evolved from the hybrid configuration used in the early R&D flights through a series of component changes to an integrated design that functioned extremely well during the last half of the flight test program.

Launch Cell Protective Cover

Two cell covers, each weighing 9600 pounds, protect the SPARTAN launch cell and exhaust duct. Each cover is divided into halves which are designed to explosively separate in less than 0.5 second during the launch sequence. Reaction time was tested at the McDonnell-Douglas, Santa Monica facility and later during live missile firings at Meck. During the Santa Monica tests, which simulated an environment of snow and ice, excessive condensation on the underside of the covers affected the explosive separation of the cover halves. To prevent condensation, insulation was applied to the underside of the cover.[34,35]

Also, after a cell cover was opened by explosive separation[36] during a SPARTAN launch at Meck Island, an investigation showed that the lips of the base frame were either broken or cracked and that lip strength was only half that required. Loads on the lip during the decelerating phase of the cover-opening cycle were reduced by adding two new bolts on each

cell cover half and modifying the decelerators (shock absorbers).

These changes were verified by a ground test and an environmental test (snow and ice) at the SAFEGUARD site in North Dakota. The reaction times between the cell cover initiation signal and the signal for cover fully open and locked averaged 0.35 second during the environmental test.

FLIGHT TEST PROGRAM

A comprehensive flight test program demonstrated that the SPARTAN subsystem would meet its performance requirements and function as an element of SAFEGUARD.[37] The program included the launch of extensively instrumented development missiles at Kwajalein. These were followed by system tests using SPARTANs launched from Meck Island as shown in Figure 10-9.

Kwajalein Development Tests

The primary requirements placed on the development flight tests were to develop, verify, and document the performance of individual missile subsystems and their ability to function as an integrated missile in the overall weapon system.[38] Fifteen missiles were used during this test phase. Because many test objectives were independent of missile trajectory, data on each round were obtained by appropriate instrumentation. Flight test planning of individual rounds was based on trajectory-dependent test objectives, which tested aerodynamics, thermodynamics (two-stage operation), flight control system operation (two-stage operation), third-stage operation, guidance communication, and warhead adaption kit operation.

To provide the data needed for these objectives, several trajectories and flight environments were used in the Kwajalein tests:

- Short, medium, and long (tangent) range
- Low, medium, and high altitude
- Low, medium, and high dynamic pressure
- Early, medium, and late third-stage ignition.

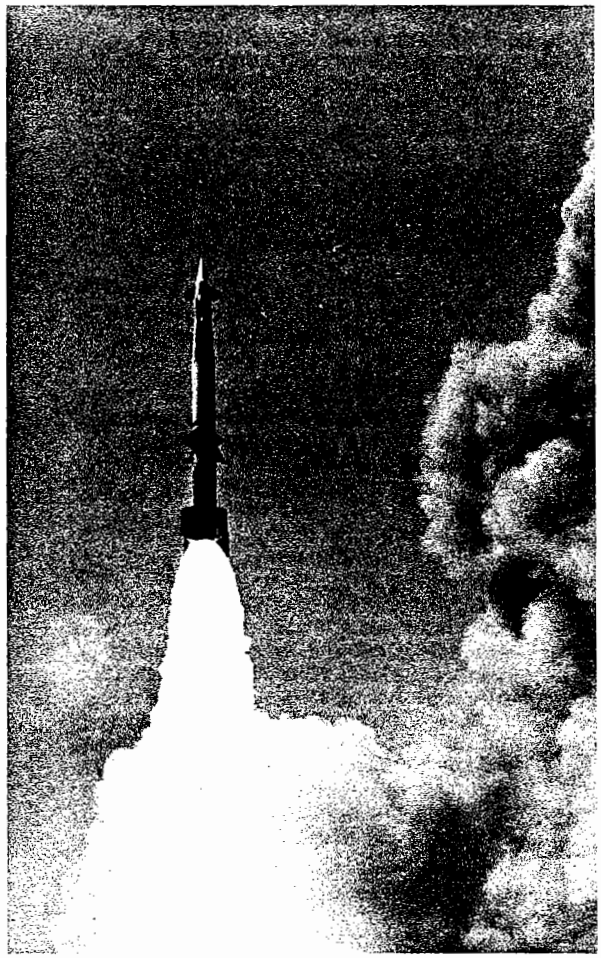


Figure 10-9. SPARTAN Missile in Flight

The test program was highly successful. The problems uncovered generated design improvements that were flight-tested in later development rounds[39] and contributed greatly to the success of the system tests. The test objectives, mission test plans, and flight test results for the Kwajalein development rounds have been documented in detail.[2]

Meck System Tests

Twenty R&D SPARTAN missiles were launched from Meck Island during the SAFEGUARD System test program,[40] followed by firing of five production missiles under the Product Assurance Verification Test (PAVT) program. The Meck test program demonstrated SAFEGUARD's ability to launch and guide SPARTAN missiles to intercept a live or simulated reentry vehicle. The intercepts were well within required miss distances. SPARTAN's compatibility with the rest of the SAFEGUARD System was verified, and additional data were gathered to evaluate the missile subsystem's performance, including performance in the more stressful regions of the field of fire. Reports on flight-test objectives, field-of-fire data, and flight-test results, including reliability and availability, for the Meck program have been prepared.[40,41]

Summary

Significant accomplishments in the Meck flight test program were successful performance of a launch cell protective cover, salvo-launch capability, and successful intercepts of live reentry vehicles. Complete interchangeability of missile sections was demonstrated during the test program. Both the Kwajalein Island and Meck Island flight tests showed that all important missile performance characteristics were significantly better than those specified before the development program started. The in-flight reliability of the last 30 missiles and the missile availability both exceeded the extremely high objectives set at the beginning of the R&D program.[42,43]

Chapter 11.

DATA PROCESSING SYSTEM

Chapter 11.

DATA PROCESSING SYSTEM

SAFEGUARD radars and missiles are directed and controlled by programs executed on the Data Processing System (DPS).[1] The primary function of the DPS is to perform all calculations necessary to identify and track the threat, to allocate and determine the point at which the threat can be intercepted, and to generate orders necessary to launch and guide defensive missiles to the intercept point. The Command and Control Display Subsystem (CCDS) of the DPS provides the interface between man and the system for nuclear weapons release, monitoring of automatic operation, and manual control, if required. Other major DPS interfaces include the Perimeter Acquisition Radar (PAR) or Missile Site Radar (MSR), the missile launch area (MSR only), and the data communications links to other SAFEGUARD sites. A Maintenance and Diagnostic Subsystem (M&DSS) locates and corrects trouble; a Recording Subsystem (RSS) monitors the system; and a System Readiness Verification (SRV) Subsystem exercises and evaluates the system.

The DPS was developed in two steps, DPS-1 and DPS-2. In 1963, Bell Laboratories, with UNIVAC as a major subcontractor, began developing DPS-1 for NIKE-X. A prototype system was operating at Whippany in 1967. A second system was later installed on Meck Island. At that time, development of DPS-2 was started to meet the requirements of the SENTINEL deployment, with the initial prototype checkout at Whippany targeted to begin in 1970. Bell Laboratories was the primary design agency, with Lockheed Electronics as a major subcontractor for memories and UNIVAC for design of the processor. DPS-2 was not a new design but rather a major modification[2] of DPS-1 to improve the ease and economy of manufacture and test, and to achieve higher operational reliability, increased throughput, and ease of maintenance. To achieve these ends, design improvements were concentrated in the following areas:

- Addition of the M&DSS, providing a programmable maintenance, diagnostic, and operation interface with the digital hardware via an automatic data bus
- Provision of a flexible DPS partitioned-system capability with complete hardware independence
- Simplification of input-output and peripheral device programming via hardware modifications
- Standardization of DPS-2 interfaces
- Use of 500-nanosecond core memory for both program and variable store (DPS-1 used 200-nanosecond coupled-film memory in addition to 500-nanosecond memory)
- Improvements in basic digital hardware, such as connectors, cold plates, etc.
- Use of beam-leaded Integrated Circuit Packages (ICPs)

- Use of a multiple disc-drive (disc pack) file bulk-memory system
- Development of tactical Cathode-Ray-Tube (CRT) consoles.

The first configuration of DPS-2 was installed and successfully checked out at Whippany beginning in 1970. Installation and checkout of a second system began at the Tactical Software Control Site (TSCS) in Madison the following year.

SUBSYSTEM DESCRIPTION

Figure 11-1 shows the relationship of the DPS to other elements of a SAFEGUARD site. The heart of the system is the Central Logic and Control (CLC), a multiprocessor, high-speed digital computer complex that interfaces directly with the radar and the CCDS. In addition to the CCDS, peripheral devices include the Exercise Control Unit (ECU), which is a part of the System Readiness Verification (SRV) Subsystem; the Data Transmission Controller (DTC); the M&DSS; the RSS; the Remote Launch Equipment (RLE); and the Logic-to-Relay Converter (LRC). The RLE and LRC are used only with the MSR. A brief description of each major component follows.

Central Logic and Control (CLC)

The CLC executes the programs that direct the operation of a SAFEGUARD site. It is a modular, multiprocessor system that performs all data processing and logical operations in the DPS in real time.[3] Multiprocessing permits as many as ten Digital Data Processors to simultaneously execute separate tasks or distinct parts of the same task. Multiprocessing also allows a number of unrelated programs to be processed at one time, thereby reducing any work backlog.

Its modular design enables the CLC to meet the requirements of a particular site, and permits it to be partitioned* into two separate and independent computer systems[4] when required either for system exercises or for maintenance

*Partitioning of the CLC into two distinct systems is discussed under System Readiness Verification.

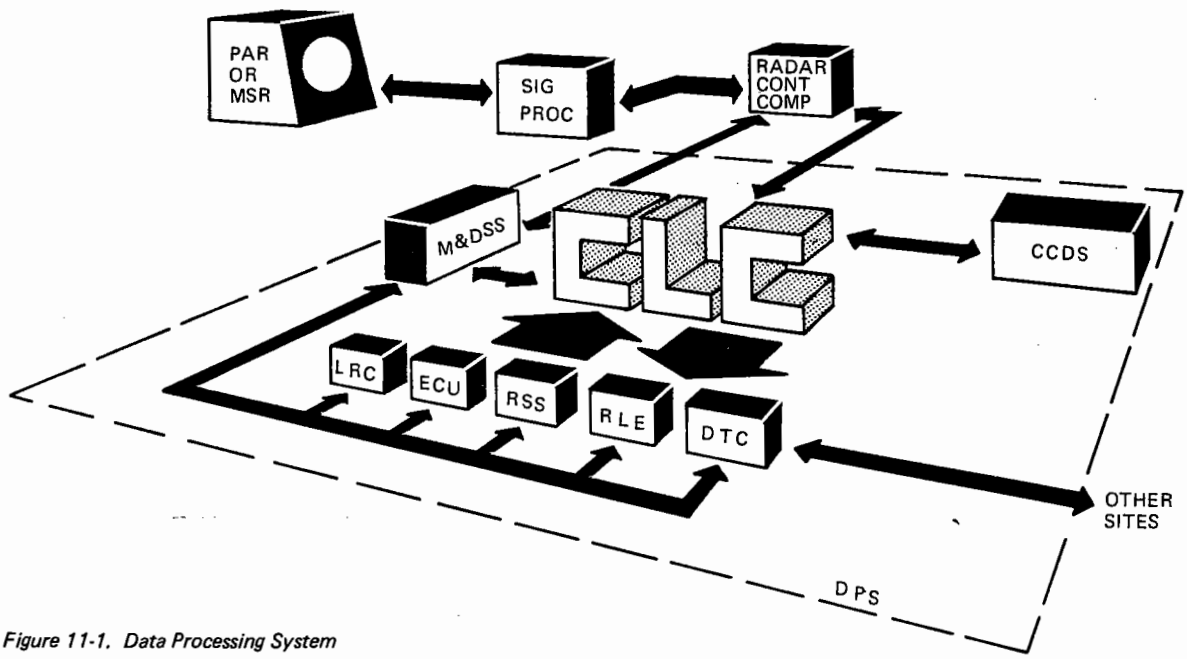


Figure 11-1. Data Processing System

operations. These two systems are designated "green" and "amber."

Figure 11-2 shows a block diagram of the CLC, which consists of:

- Digital Computer Group
  a. Digital Data Processor Units (PUs)
  b. Program Stores (PSs)
  c. Variable Stores (VSs)
  d. Input-Output Controllers (IOCs)
  e. Timing and Status (T&S)
- Precision Frequency and Time Generator (PF&TG)
- CLC Monitor (CM) (only used in TSCS).

Three basic equipment configurations meet the specific data processing needs of the three SAFEGUARD sites. Supporting the MSR is a 10-12-15-2-2 system consisting of 10 PUs, 12 PSs, 15 VSs, 2 IOCs, and 2 T&S racks. The PAR requires a 5-7-14-2-2 configuration, and a 1-3-3-1-1 configuration is used in the Ballistic Missile Defense Center (BMDC). There also is one PF&TG with each configuration. The CLC Monitor is used only in TSCS and is not a part of a tactical site. Interconnection between racks is through interface switching units built into each rack. To achieve nearly continuous operation as economically as possible, the CLC employs "n+1" redundancy.[5] Each of the five types of elements has a single replacement that is not required for running the application software and is therefore redundant. For example, if the application software requires 12 racks of program store for execution, then at least 13 are provided. The "n+1" element can be switched in to replace a failed element.

The SAFEGUARD hardware concept permits fabrication of the DPS from a standard stock of racks, chassis, and integrated circuit packages. The design is based on integrated circuit technology using a modified direct-coupled transistor logic circuit having circuit delays in the 5- to 6-nanosecond range.[6] The hardware provides a flexible system for interconnecting groups of integrated circuit packages on chassis, and chassis into racks as shown in Figure 11-3. Wire-wrapping the integrated circuit package connections on the chassis enhances their reliability. Each chassis accommodates 275 integrated circuit packages, which represent more than 600 logic circuits. As shown in Figure 11-4, the chassis are housed in the water-cooled rack with two chassis mounted side by side on a chassis carrier plate that locates, supports, and cools the chassis. The chassis carrier plates

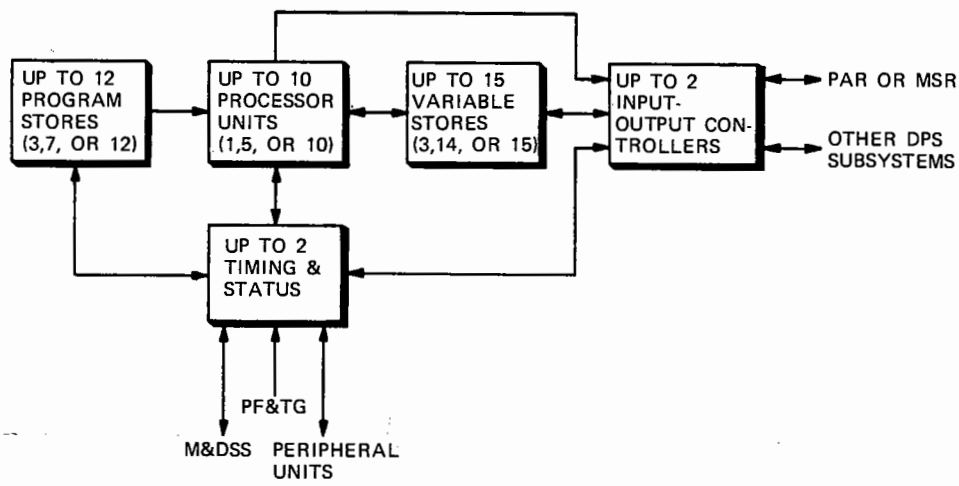


Figure 11-2. Central Logic and Control

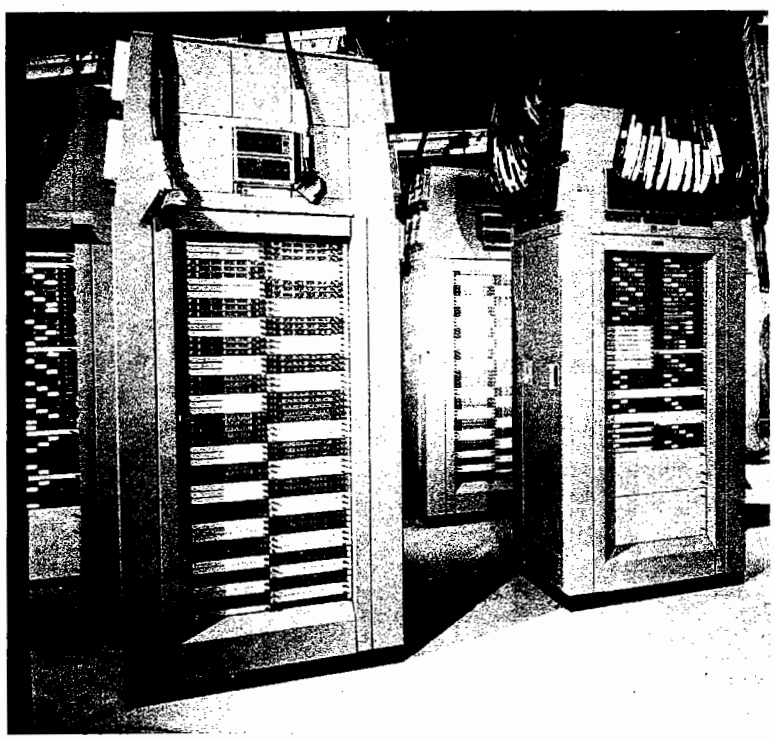


Figure 11-3. SAFEGUARD Digital Racks

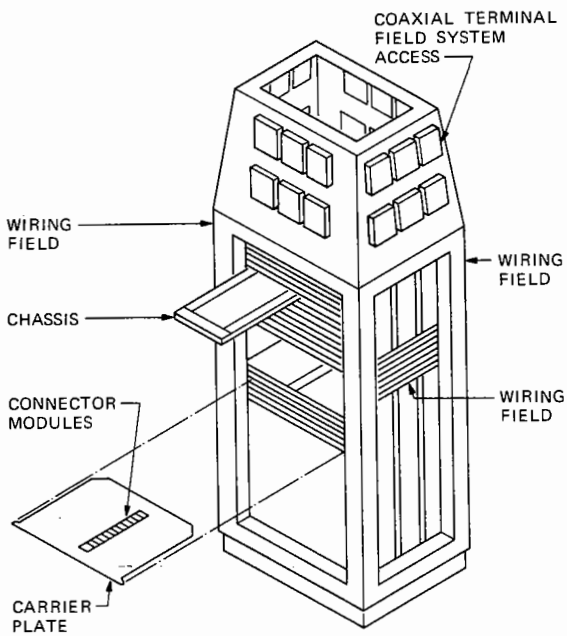


Figure 11-4. Construction Details of SAFEGUARD Digital Rack

are mounted at a 1-inch vertical pitch within the rack. There is a maximum of 59 levels in the rack housing 118 chassis.

The CLC required more access connections to the chassis than could be provided with rear access only. Therefore, both sides of the chassis are used for additional access terminals. The rear contacts to the chassis are made in a conventional plug-in manner. On the side, a linear-actuated cam arrangement engages the contacts after the chassis is properly positioned in the rack. Thus, wiring fields exist on three sides of the rack. In addition, internal connections are provided at the interface between chassis. The chassis are side by side on the carrier plate to provide near-neighbor connections between groups of chassis. In total, the rack has more than 40,000 possible signal connections. Since each rack has wiring on three sides, the racks must be arranged in a diamond pattern to allow physical access to all four sides of a rack.

Rack-to-rack interconnections are provided by plug-in coaxial terminal fields at the top of the rack, which allows as many as 11,520 connections.

To preserve the integrity of high-speed pulse transmission between the various units of the multiprocessor, a characteristic impedance of 100 ohms is maintained for the transmission of all signals. Coaxial cables are used for all connections between racks and for all rack-wiring runs longer than 5 feet. Twisted pair wiring predominates in the rack. The chassis connector maintains a fixed impedance across the connection by providing both a signal and a ground path using a highly reliable double-contact arrangement to enter a chassis.

The memory racks include a 16K by 68-bit-per-word core memory unit and the associated interface logic switching circuits, which provide interconnection to the multiple units. The core memory units are air-cooled. They operate at a cycle time of 500 nanoseconds and have an access time of 300 nanoseconds.

Digital Computer Group

Digital Data Processor Unit (PU).[7-9] The PU performs all arithmetic and logical operations for the CLC. As a part of a multiprocessor system, each processor operates asynchronously with respect to the memories, Input-Output Controller (IOC), and other processors. The processor is divided into five sections: Program Control Unit (PCU),[10] Arithmetic Control Unit (ACU), Operand Control Unit (OCU),[11] Program Interface Switching Unit (Program-ISU), and Operand Interface Switching Unit (Operand-ISU). The five sections operate in parallel, with minimum control between sections. The main function of the PCU is to fetch instructions from Program Store and distribute them to the ACU and OCU. The ACU performs the arithmetic and logic operations. The main function of the OCU is to fetch and store operands for the ACU. The ISUs provide the communication links for the processor, the memories, and IOC.

Program Store (PS).[12,13] The PS accommodates the executive program and the assigned programs used in the CLC. These programs are instruction words temporarily held in PS for subsequent transfer (fetching) to a requesting unit. The Store Transfer Unit (STU) in the T&S rack can store or fetch programs on request; however, the PU can only fetch programs. Therefore, loading and revising the contents of the PS must be performed via the STU. Each PS is divided into two independent, identical halves (A and B) each comprising an 8K memory and an ISU.[14,15] A processor can have interleaved access to the two halves within a PS. This reduces the effect of queuing. Interleaving involves arranging the address structure of a program so that adjacent words reside in the independent halves of the memory. The 8K memory is a ferrite-core, magnetic memory system having a storage capacity of 8192 68-bit words.

Variable Store (VS).[13,16] The VS stores operand data that is modified from time to time by the PU and provides temporary storage for programs. The IOC and the PU OCU can store or fetch data and can also store programs; however, only the PU PCU can fetch these programs. Transfer requests can be for the left half of the word (byte 1), for the right half (byte 2), or for the entire 68 bits (both bytes). Each VS is composed of a 16K ferrite-core, magnetic memory and an ISU.[15,17] Memory word length is 68 bits.

Input-Output Data Controller (IOC).[18-22] The IOC is a special-purpose computer that relieves the PUs of the time-consuming input-output operations. The PUs operate much faster than their peripheral devices and therefore would be slowed down or tied up if required to execute I/O instructions. Since the CLC is a multiprocessor system, the PUs would be competing with each other for access to peripheral devices, creating queuing problems if IOCs were not used; therefore, the IOC controls the flow of information between variable storage and the peripheral devices. Each peripheral device is connected to the IOC via one of 16 available channels.

Timing and Status (T&S) Rack.[23,24] The T&S rack has three essentially autonomous units that

perform four main functions in the CLC. The Timing Generator (TG)[25] provides real-time synchronization. The STU provides the means for writing data into PS. The Status Unit (SU) provides a means to assemble and evaluate system status information and to partition the DPS. The control of these units is provided through the Interface Transfer Unit (ITU), Interface Switching Units (ISUs),[15,26] and the Channel Control Unit (CCU).

Precision Frequency and Time Generator (PF&TG)[27]

The PF&TG provides precision frequencies and a time-of-day output for the DPS. It contains an oscillator that generates a 5-megahertz base frequency. This base frequency is multiplied and divided to produce the wide range of precision frequencies required by various units in the DPS. Time-of-day outputs are generated and distributed to synchronize events with real time. An external frequency standard is used to calibrate the 5-megahertz oscillator. The equipment is housed in an air-cooled rack. In case of power failure, a battery rack supplies emergency power to the 5-megahertz oscillator.

Central Logic and Control Monitor (CM)[28]

This unit is not a part of the tactical system but was designed and built for TSCS to aid the initial hardware-software checkout. It checks and records certain operations of the CLC for use in such areas as debugging, performance tuning, and performance projection studies. For example, it can provide a trace of the last 1000 tasks executed before DPS recovery was initialized, a history of Nuclear Employment Authority (NEA) and Hostile Identification Enable (HIE) Status Unit bit use, and a history of PU, PS, VS, and IOC utilization. It gathers information by direct hardwired signals and by a request-acknowledge routine with the requesting unit. The CM handles requests with accompanying data and address bits in their order of priority.

Recording Subsystem (RSS)[29]

The RSS (Figure 11-5) provides the facilities for recording, storage, playback, and readout of DPS data and programs. The major functions of the RSS are to support installation of DPS equipment, support test exercises, and record data to provide a history of operation and maintenance events. In addition, the disc storage holds the program semi-permanently for system recovery.

As Figure 11-5 shows, the RSS operates with two identical sets of peripheral equipment. This permits it to be divided into two independent systems and thereby provides full recording capability for both DPS subgroups when the DPS operates in a partitioned condition at the PAR or MSR.

The major components of the RSS include a digital rack called the Recording Set Controller (RSC) and the following commercially-manufactured peripheral equipment: magnetic tape transports, multiple hardened disc drive units, punched card readers, and computer output printers. Bidirectional data transfers between the peripheral devices of the RSS and the CLC are via the RSC on a request-acknowledge basis.

Interface Subsystems

The SAFEGUARD System requires three interface subsystems to implement local and remote missile launch functions and intersite communications. Two of these, the Logic-to-Relay Converter and the Remote Launch Equipment, are used only with the MSR configuration to provide an interface between the CLC and the local and remote missile launch facilities, respectively. The other subsystem, the Data Transmission Controller, is used with the BMDC, MSR, and PAR configurations to provide a communications interface.

Logic-to-Relay Converter (LRC)[30,31]

The LRC provides the necessary pre-launch communication and conversion link between the logic circuitry of the Input-Output Controller (IOC) in the DPS and the relay circuitry of the Launch Preparation Equipment (LPE) in the collocated missile field at the MSR. This link provides for the software-controlled launching of

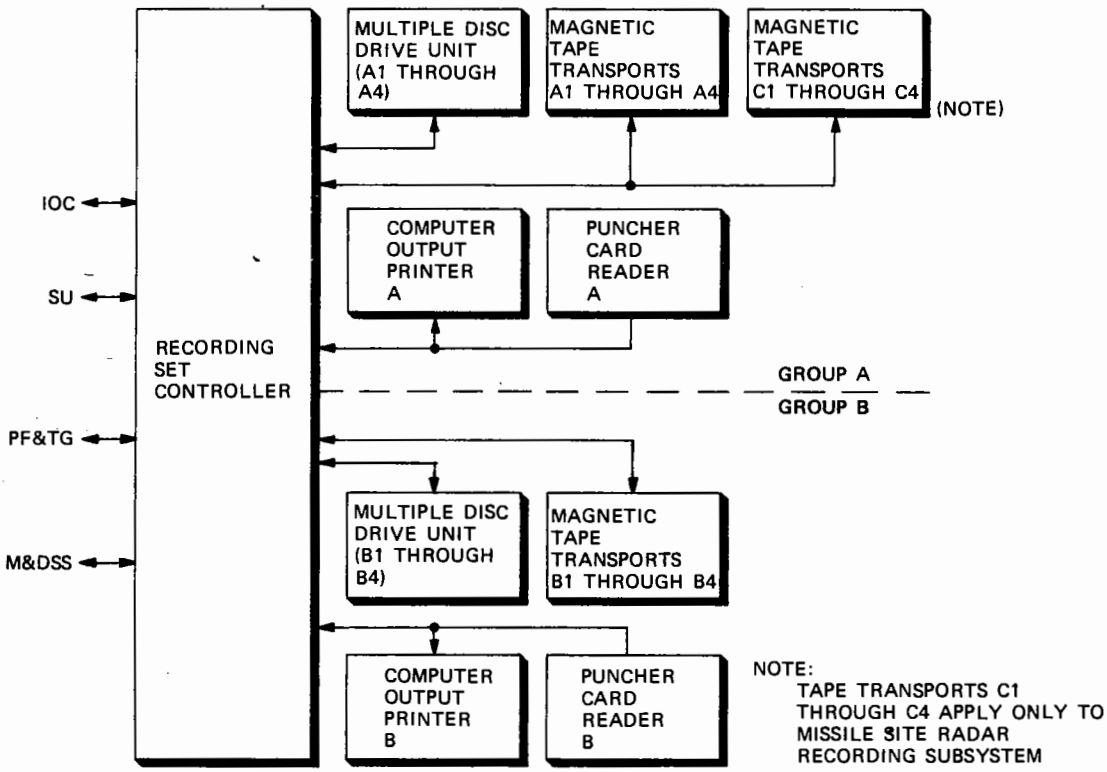


Figure 11-5. Recording Subsystem

SPRINT and SPARTAN missiles. The communication link between the DPS and the LRC is redundant throughout. The two LRCs used are functionally identical and interface with separate IOCs, but only one can be maintained on-line at a given time. The LRC is made up of the following units:

- The Missile Launch Equipment Controller (MLEC) which receives orders from the IOC in the form of 34-bit data words and interprets and forwards the data words, as logic levels, to the Missile Launch Equipment Adapter.
- The Missile Launch Equipment Adapter (MLEA) which converts the logic-level signals to relay control voltages, which constitute the missile orders that are transmitted to the LPE. Missile status signals, in the form of relay control voltages, are returned to the MLEA from the LPE. The MLEA converts the missile status signals to logic levels that are transferred back to the MLEC, where they are encoded into data words for transmission to the IOC.
- The Power Supply Set which supplies the dc voltages to operate the logic circuitry in the MLEC.

Remote Launch Equipment (RLE)

This interface is covered in Chapter 9, which describes the SPRINT Missile Subsystem.

Data Transmission Controller Group (DTCG)[32,33]

The DTCG permits wideband and voiceband digital communication links between MSR and PAR configurations and between sites in the SAFEGUARD System. The DTCG has redundant equipment for partitioning purposes. It consists of: (1) Data Transmission Controllers, (2) Data Transmission Controller Adapters, (3) cryptographic equipment, and (4) data sets with associated data set adapters. The government furnishes the cryptographic equipment and data sets.

Maintenance and Diagnostic Subsystem (M&DSS)[34-37]

The M&DSS (Figure 11-6) provides a central facility for SAFEGUARD digital equipment maintenance. Only units allocated to the amber system are so maintained. The M&DSS contains the hardware and software necessary to perform or aid in:

- DPS initialization
- DPS recovery and loading
- Hardware fault detection and location
- Visual display of individual digital equipment status, including allocation (green or amber partition and test enabled/isolated) and summary error information
- Remote control and monitoring of dc power.

The M&DSS has two distinct facilities for running diagnostics. The primary one uses the M&D Processor (MDP) Group to execute diagnostic tests in a fully automatic, high-speed manner, with automatic interpretation of results; the other uses the M&D Console Group as a back-up for manually aided execution and interpretation of certain diagnostic tests. Each test facility is linked via logic in the M&D Data Controller and special hardwired data paths to all the digital racks in the DPS and to certain digital racks in the radar areas. Using these data paths, M&DSS software can access each rack as required for DPS initialization, recovery, and diagnostic operations.

The diagnostic tests are executed on equipment placed off-line in the amber system. Monitoring of equipment in the green system is restricted to checking for correct output patterns.

System Readiness Verification (SRV) Subsystem[38]

The primary objective of the SRV subsystem is to verify the tactical readiness of the SAFEGUARD System, including its hardware, software, and personnel. To accomplish this, the CLC is partitioned into two independent systems (green and amber), and a combination of system tests and system exercises is performed. These assess site readiness by determining the availability and reliability of system hardware, the performance characteristics and functional capabilities of system hardware and software, and the proficiency of operating personnel,

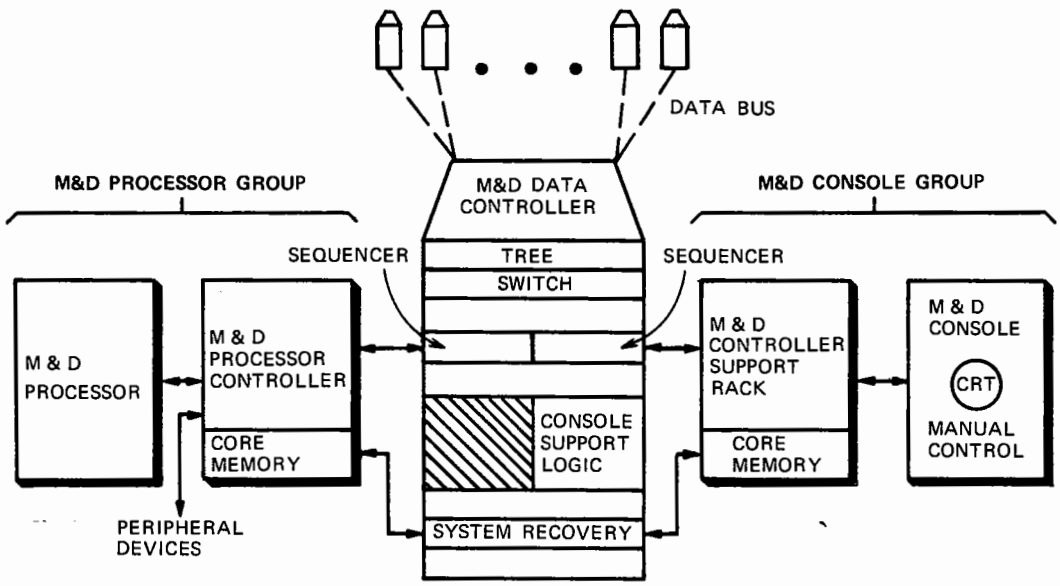


Figure 11-6. M&D Subsystem

particularly in the Command and Control Display Subsystem (CCDS). Before these tests and exercises can be performed, the personnel must identify the elements to be verified, describe the processes (hardware, software, and procedures) involved, and state the expected results.

The SRV subsystem contains the following elements:

- Exercise Data Processor (utilizing the amber partition of the CLC)
- Exercise Control Unit (a part of the DPS)
- Radar Return Generator (a part of the radar)
- System Exercise Console (a part of the CCDS).

Together, these elements form the exercise system in the amber partition of the DPS. In a system exercise, they drive the tactical system in the green partition of the DPS, causing the tactical system to respond as it would in a real engagement and thereby allowing evaluation of the dynamic system response and readiness.

The only part of the SRV subsystem in the DPS that has not been described is the Exercise Control Unit (ECU). This is a digital rack that provides the interface between the exercise system and the tactical system. It supplies the data and control paths necessary to: (1) monitor radar orders from the tactical system for the Exercise Data Processor (EDP) and inject simulated target information from the EDP into the tactical system via the Radar Return Generator, (2) monitor missile orders from the tactical system for the EDP and return simulated missile responses from the EDP to the tactical system, and (3) furnish communications between the exercise and tactical systems and/or between sites. It also interrupts all command paths to the missile launch stations to provide an extra measure of safety during system exercises.

Command and Control Display Subsystem (CCDS)[39-42]

The CCDS facilitates monitoring and directing the tactical operation and maintenance of the SAFEGUARD System.

The CCDS is composed of command and control equipments manned by personnel trained to perform tactical and maintenance operations. Tactical operations cover the weapon system response to the potential or actual threat to the protected area. Surveillance, target detection, target identification, and engagement activities are part of the tactical phase of operations in the CCDS area. Maintenance operations are concerned with maintaining each element in the SAFEGUARD System at its maximum availability by monitoring and coordinating maintenance for each subsystem.

Major operating equipment (Figure 11-7) used in the CCDS are:

- Logic Control Buffer — provides the interface with the CLC and the M&DSS
- Buffer Store — provides buffering to compensate for the difference between the data rates of the CLC and those required by the displays
- CRT Consoles — provide a dynamic interface between the human operators and the equipment (Figure 11-8 shows a typical CRT console)
- Console Logic Support Units (CLSUs) — include the circuitry required to generate the CRT console displays
- Non-CRT Consoles — provide operators with status information and controls to vary functions. With the exception of an end plate, they are electrically and mechanically identical to the Control Indicator Units associated with the CRT Consoles
- System Status Display Boards — provide status information on major elements of the SAFEGUARD System
- System Status Display Support Unit (SSDSU) — includes the circuitry required to generate the signals which drive the System Status Display Boards
- Teletypewriters (TTYs) — furnish communications between operating personnel and the CLC.

Other major operating equipments in the CCDS are:

- Nuclear Employment Authority (NEA) Equipment — consists of two Guided Missile Launch Enable Controllers (GMLECs) and a Guided Missile Launch Enable Group (or NEA rack) in the Combat Operations Center at Cheyenne Mountain and one NEA rack at the Missile Direction Center (MDC) in Grand Forks (see Figure 12-3 in Chapter 12)

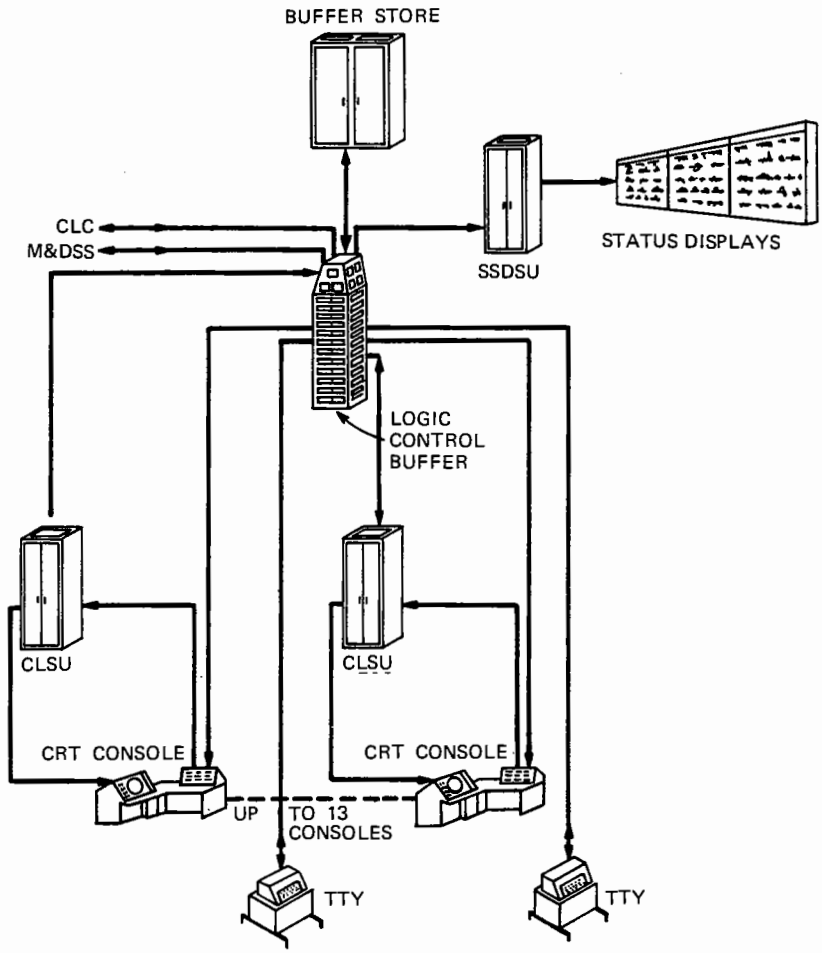


Figure 11-7. Command and Control Display Subsystem — Console, Wall Display, and Teletypewriter Interface

- Launch Enable Equipment (Figure 11-9) — consists of two Launch Enable Message Controllers (LEMCs) and one Launch Enable Message Transmitter (LEMT) in the Ballistic Missile Defense Center, and a Launch Enable Message Receiver (LEMR) with a Launch Enable Transmission Set (LETS) at the collocated missile farm and each of the remote missile farms.

The GMLECs control a coded message generator to release or withdraw authority to expend SPRINT and SPARTAN missiles. The generator can also produce a test message to check the major parts of the NEA system. The NEA rack at the MDC decodes the message and presents status independently to hardware (wall displays and Missile Monitor Test Console) and through the status unit to the tactical software, which drives the CRT displays. Redundancy is used when required in the NEA system design to assure reliability. Considerable fault indication and fault isolation circuitry also is included.[43,44]

The LEMCs control a coded message generator in the LEMT, which provides either an enable message or a disenable message to the Launch Enable system. A test message also can be generated for system checkout. The LEMT provides status signals to the DPS and LRC to indicate which message is being transmitted. The coded message is received by the LEMR, checked for errors, and slowed down for transmission

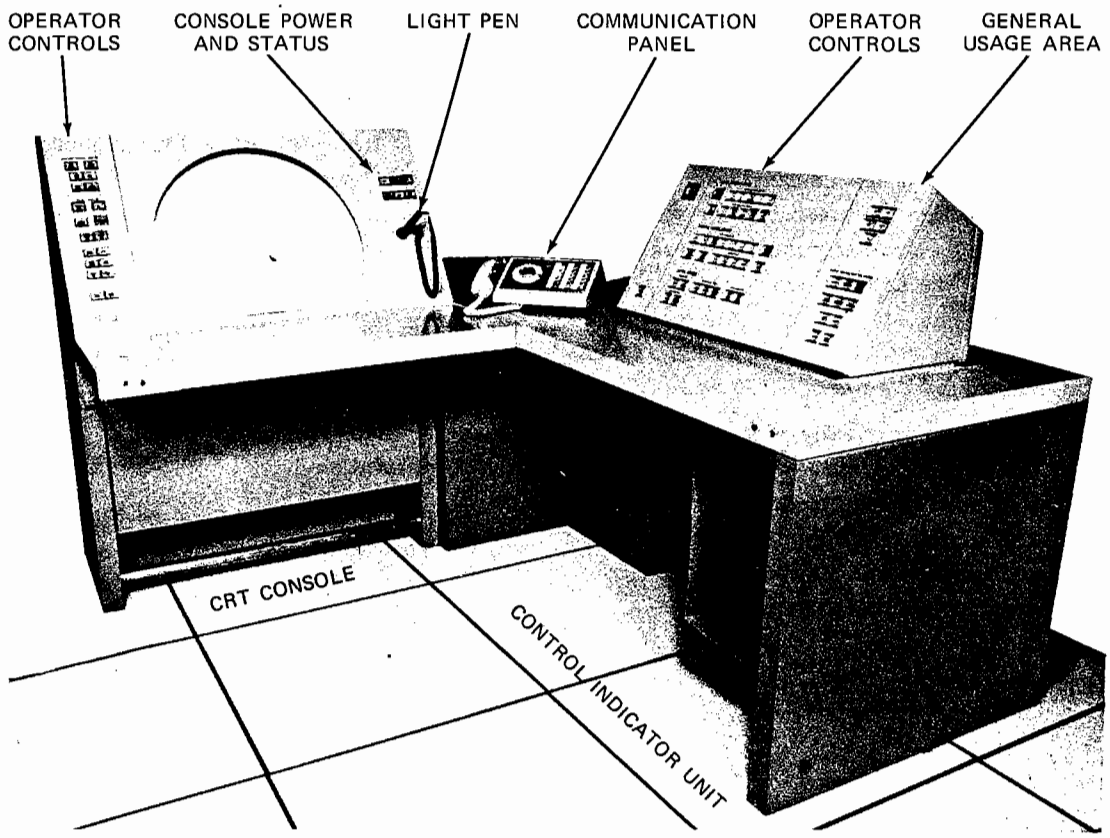


Figure 11-8. Typical CRT Console with Control Indicator Unit

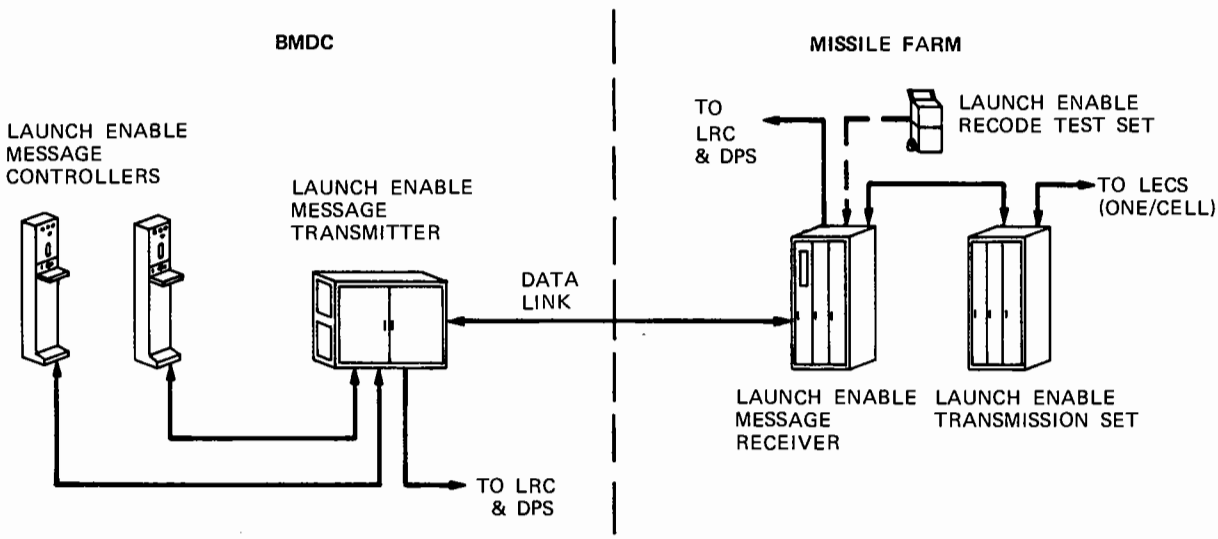


Figure 11-9. Command and Control Display Subsystem — Launch Enable Interface

through the LETS to the electromechanical Launch Enable Coded Switch (LECS) in each missile cell. The LECS has functional contacts, which interrupt the High Energy Firing Unit charge and trigger circuits and one of the Launch Order signals when the system is in the disenabled or safe condition. When in the enabled position, these paths are completed. The LECS also has a status monitor contact that indicates to the LEMR which state resides in the switch. These status signals are summed and fed back to the DPS and LRC.

The LECSs are electrically recodable from the LEMR by the Launch Enable Recode Test Set. Redundancy is used where required in the Launch Enable design to assure a high degree of reliability. Considerable fault indication and fault isolation circuitry also is included.[45,46]

COMPARISON OF PERFORMANCE OBJECTIVES AND RESULTS

One of the primary reasons for developing a parallel, modular computing system for SAFEGUARD is the potential for high performance. Besides having high availability, a multiprocessor organization possesses a great deal of reserve power, which, when applied to a problem with the appropriate degree of parallelism, can yield high performance. This type of problem is associated with a radar tracking system and must be solved in real time.

In a multiprocessor system, the processors gain access to main storage according to a priority rule. The rate at which each processor executes instruction depends, therefore, on the severity of this queuing at main storage. Throughput is defined as the number of instructions of a particular instruction mix executed per second by n processors.

Adequate performance or throughput of a parallel processing system depends on several hardware factors, which include the speed of the processor; the speed of program store, including its priority circuit; the total number of processors relative to the total number of independently addressable program stores; and the number of instructions executed per memory word fetched. From a software viewpoint, the distribution of programs and data sets within the modular memory and the instruction mix of the particular programs in execution also are important factors, which directly affect throughput.

Since variable store queuing, in general, is less than that at program store, its effect has been eliminated in the throughput data presented here. This has been done by dedicating a separate variable store rack to each processor for experimental studies.

Throughput data has been gathered using multiprocessor hardware with as many as ten processors. Benchmark programs, which provide varying instruction mixes, have been used. Four instruction mixes were selected for testing. The NOP mix, consisting of no-operation instructions, defines an upper bound on throughput. The LOGICAL mix is a representative mix similar to CLC operating system code that might be executed during real-time operations. The MATH mix is also a representative mix, since it is a portion of the cosine subroutine from the CLC operating system. The JUMP mix consists exclusively of jumps and represents a kind of lower bound on throughput.

Figure 11-10 shows the effect of requiring all processors to execute from one program store. The number of instructions executed per second increases with the number of processors until the program store is returning instructions as fast as it can. Throughput levels off when this point is reached, and a further increase in the number of processors does not increase throughput.

Figure 11-11 shows the effect of providing an equal number of processors and program stores. For this case, the number of processors and program stores is incrementally increased from one to ten. The program stores are not dedicated to a processor on a one-for-one basis, but their access by the processors is randomized such that several processors may be attempting to

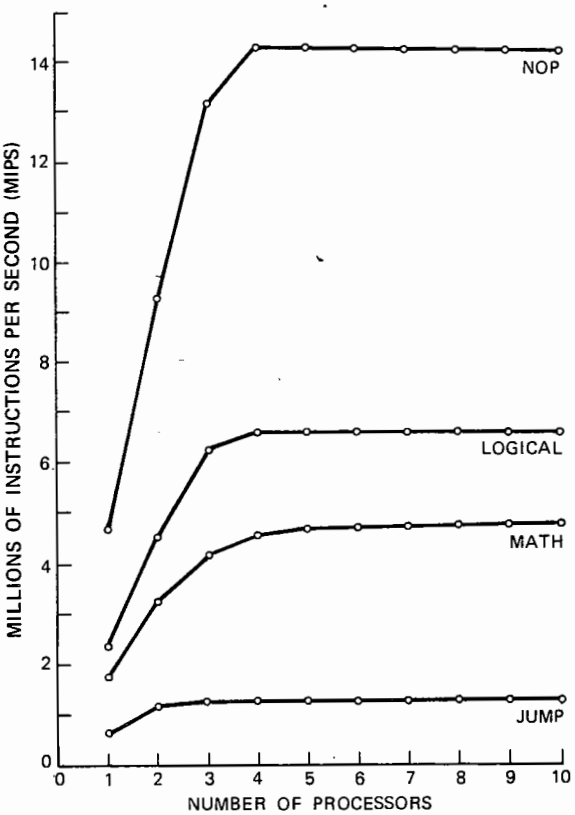


Figure 11-10. N Processors Executing from One Program Store

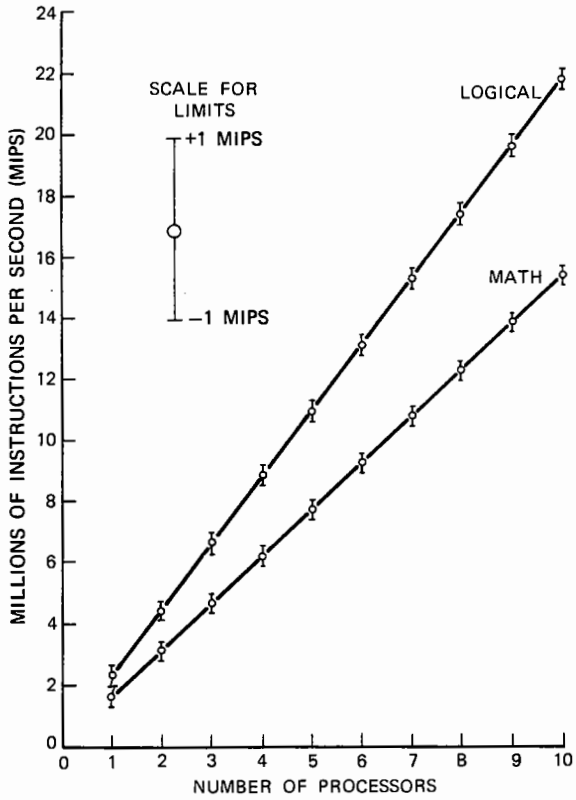


Figure 11-11. N Processors Executing from N Program Stores

read from the same program store at once. Hence, some reduction in throughput due to queuing is expected. The effect of queuing is small for one to ten processors; Figure 11-11 shows that throughput increases linearly with the number of processors. Data is shown for the LOGICAL and MATH mixes only.

Figure 11-11 shows an even distribution of memory access over all program stores. To determine what happens to throughput for an unequal workload distribution, a series of runs were made for both the LOGICAL and MATH mixes where the number of processors was kept equal to the number of program stores with one important difference; one of the program stores was selected as a "favored" program store and its fraction of total instructions executed was varied from 0 to 100 percent while the remaining program stores shared the remaining workload equally. Figures 11-12 and 11-13 show the results for the six to ten processor cases. The curves represent throughput as a function of the "favored" program store. Zero percent means ten processors are executing out of nine program stores. Note that throughput is highest when the "favored" program store shares equally in the workload.

The curves of Figures 11-12 and 11-13 show the sensitivity of throughput to an equal distribution of the workload in memory. For instance, if one considers a 10-percent reduction in throughput to be serious, the above curves show for the seven-processor case that a single program store can have almost 40 percent of the workload without a serious reduction in throughput. For the ten-processor case, the corresponding number is approximately 25 percent. Therefore, as long as the workload is not too unequally

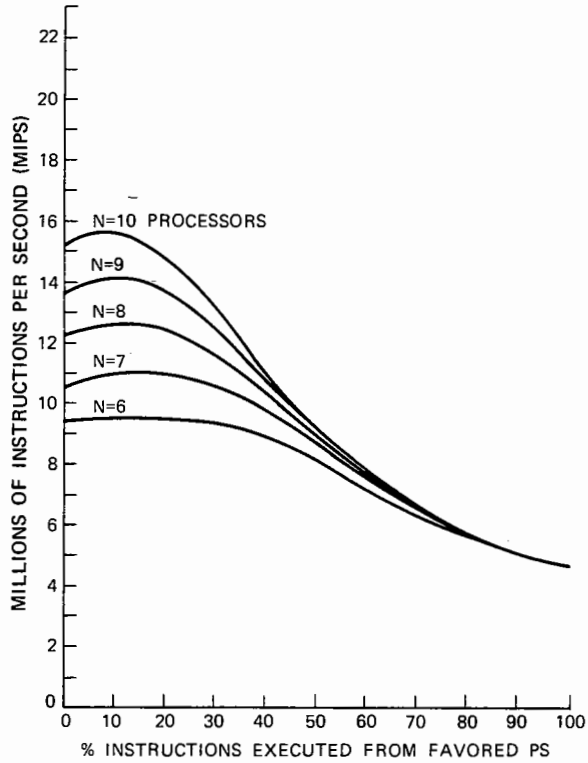


Figure 11-12. Unequal PS Loading, LOGICAL Mix

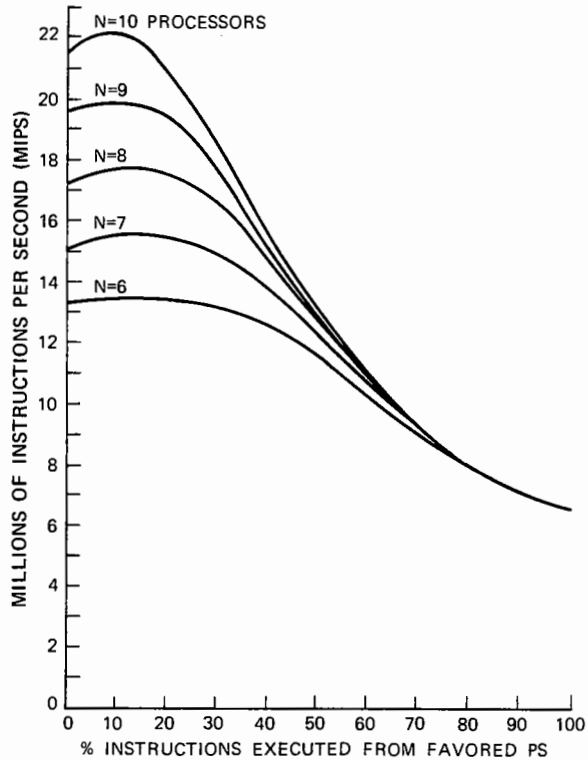


Figure 11-13. Unequal PS Loading, MATH Mix

distributed, the dependence of throughput on workload distribution should not be critical. Throughput dependence on more than one program store's having more than an equal share of the workload has not been investigated.

MAJOR CHALLENGES AND INNOVATIONS

The following major technical innovations were made during the development of the DPS.

A Multiprocessor, Partitionable System with (n+1) Redundancy

The CLC represents the first practical application of the multiprocessing concept to a large-scale computing system. In this modular design, as many as 10 processors and 2 Input/Output Controllers share as many as 32 memory racks. The units are interconnected by a flexible switching network that facilitates partitioning the system into two independent computers. Partitioning can be controlled by software, and complete reconfiguration can be accomplished in less than 1 second.

Although it may have been possible to design a single processor with adequate performance, the CLC is a multiprocessor machine for three reasons. First, a single processor sufficiently powerful would have been a complex machine, difficult to design, and difficult to get working. Second, a single-processor system would not have been expandable; if a more powerful machine were later needed and none were available, major software changes would have been required. Also, multiple processors satisfy a wide range of processing requirements,

including smaller applications. Finally, the multiprocessor design increases availability because processing can continue even if some processors have failed.

The processor is the most important element in establishing the real-time computing capacity of the CLC, so the design of a high-speed processor was a primary goal. Each processor contains three control units that operate asynchronously with respect to each other. Timing within each control unit is overlapped to some degree so that more than one instruction can be in execution. The use of high-speed arithmetic algorithms and associated logical implementation has been exploited advantageously to increase the flow of operands through the arithmetic sections. The resulting processor design can execute successive fixed-point add operations on full-word 32-bit operands at an average rate of 4.15 million per second. Results with more than one processor are given in Comparison of Performance Objectives and Results.

A multiprocessor design hinges on its storage design. A number of possible strategies are available to handle the necessary references of the multiple processors to main storage. The first strategy used in the design is the splitting of main storage into two independent portions, called program (or instruction) store and variable (or operand) store.

To further increase the data flow rate between processors and main storage, program and variable store are further subdivided into modular groupings. Variable store is organized as 16 independent racks, with an independent data path from each rack to each of the processors. Since queuing is heavier at program store than at variable store, program store is organized as 32 independent modules with an independent data path from each module to each of the processors. Processor addressing is interleaved between two modules; that is, the address structure is arranged so that adjacent program store words reside in two separate modules.

The memory module cycle time of 500 nanoseconds and the double-word size of 64 bits provide a memory bandwidth greater than that required for maximum performance of a single processor. Each program store and variable store rack holds 16,384 64-bit words. There are four parity bits associated with each memory word.

The CLC can be partitioned into two independently operating computers, each capable of executing its own job stream. By convention, these two partitions are called green and amber, with green usually designating the larger of the two fractions. However, since the computer is composed of a number of modular elements, the boundary between green and amber is almost completely flexible. In fact, all elements can be brought into the green partition to operate as a very large multiprocessor computer with as many as ten processors sharing the job load. As a further degree of flexibility, some elements (such as memory elements) may be placed into a shared green/amber state, in which they are available to both partitions simultaneously. Finally, an element may be defined as neither green nor amber but isolated. This state is necessary to remove malfunctioning elements without shutting down the entire system.

It is even more significant that partitioning is under program control. Further, the control logic for effecting partitioning is redundant. A fundamental asymmetry allows the green partition to have priority over the amber partition. The partitioning logic may be placed into a state whereby a master/slave relationship exists between the green and amber partitions. Control software residing on the green partition may alter the partitioning of the system at any time. The amber or slave partition can in no way alter the partition boundaries.

Early fault-tolerant systems employed 100-percent redundancy through use of a complete standby system; that is, the system required to support the full workload was duplicated, with

data processing proceeding in parallel on each system. This organization is conceptually simple and, upon detection of a failure in either system, the other system can carry on the data processing workload.

The multiunit system approach to high performance can provide high system availability without the need for costly, complete duplication. The "n+1" redundancy approach has reduced the amount of equipment added for redundance and for system exercise to a fraction of that required for a complete standby system.

A Versatile and Workable M&D Approach

The SAFEGUARD System's specific tactical mission is extremely brief compared to the life of the system. Once a tactical mission has begun, the M&DSS ceases fault isolation and repair; if serious failure occurs, system recovery must automatically execute, using its built-in redundancy. Therefore, the fault detection and isolation features of the M&DSS are directed toward maximizing system availability, which is the probability that, at any point in time, a complete set of fault-free DPS resources exists for a mission.

The M&DSS contributes to maximizing system availability in two ways. First, M&D tests are periodically run on critical DPS equipment to supplement real-time fault detection methods in minimizing the mean-time-to-awareness of hardware faults. These tests are automatically scheduled by real-time software in the green partition and the test requests are sent to the M&DSS over a special interface through the SU. In this way, every processor in the DPS is switched into the amber partition and tested once every hour; the complete amber partition is tested once each hour; and the green IOC with its slaved peripheral controllers is switched amber and tested once every four hours. The M&DSS passes test results back to green system software again via the SU interface.

Second, and more important, the M&DSS minimizes the mean-time-to-repair of faulty racks by rapidly identifying a minimum set of replaceable or easily repairable modules in which the fault is located. These fault isolation functions may be initiated in response to fault symptoms detected either in real time or during the non-real-time scheduled tests described above. In either case, fault isolation takes place with the failed rack isolated from the rest of the DPS.

The M&DSS accomplishes this goal through the unique integration of two significant maintenance concepts. First, it uses a special two-way maintenance data path into each DPS digital unit which bypasses normal data paths. Second, it uses a small general-purpose computer, dedicated to system testing, to apply tests over the maintenance paths and interpret test results.

The communication interface between the green partition SU and the M&DSS provide a rapid and flexible means for bringing maintenance resources to bear on any DPS fault indication. Nonetheless, until a specific faulty rack has been identified, the particular response to be made to any given fault indication often involves judgements based on the total status of DPS resources. Thus, normal SAFEGUARD maintenance operations involve a significant degree of manual interaction. In general, two primary maintenance management functions are performed manually:

1. Monitoring and response to overall system status as reported by green system real-time software and hardware displays
2. Direct control of maintenance testing; the M&DSS will not honor any scheduled test request unless manual "permission" is granted, any test in progress may be manually aborted, and alternate tests may be requested via green system software and the SU interface.

Experience has demonstrated the fundamental power and flexibility inherent in the primary M&DSS feature, the extensive maintenance data interface with the entire DPS, in concert with

the general-purpose computing capability of the M&D Processor. Just as encouraging, however, has been the performance of a set of extended M&DSS capabilities developed during the early phases of installation and operation, before the widespread availability of M&D tests.

Central to the extended capabilities of the M&DSS are the Digital Unit Exerciser (DUXs). One such program exists for each DPS rack type. Each DUX program facilitates controlling functional operations of a rack on a macroscopic level and "dumping" the contents of individual registers or groups of related registers within the rack. In actual hardware operation, DUXs have been used primarily to provide manual interaction, via the M&DSS, with a set of real-time programs originally developed to verify the complete functional capabilities of the DPS. Data currently being gathered at SAFEGUARD sites show that this mode of fault detection and isolation is still important. The various DUX capabilities also have provided an extremely powerful means of aiding system software debugging by allowing dumps and snapshots of otherwise inaccessible DPS registers without perturbing the very condition being probed. This capability has been used extensively throughout the SAFEGUARD software development.

A Processor Unit with a Basic Operate Time of 200 nsec

When the NIKE-X development began, operate speeds in this range were in advance of the state of the art. A demonstration of a prototype unit operating at this speed was conducted successfully at UNIVAC in 1965, and the first full-scale model was successfully operated in 1967.

A Coupled Film Memory with a 68-bit Word Length and 200-nsec Cycle Time

Memory speeds in this range were specified initially to match the processor design speed. During the early days of NIKE-X, laboratory models and small memories had achieved this speed, but the challenge of mass-producing large, fast memories remained. This challenge was met, and 200-nanosecond coupled film memories were manufactured successfully for the Whippany and the Meck Installations.

A System Readiness Verification Subsystem for Realistic Simulation without Relying on Processor Self-Checking

Experience with the Analog Tactical Environment Simulator in the Meck system and a 1968 study resulted in the exercise concept for SAFEGUARD. This concept uses the amber system CLC working through the ECU interface to drive the green system CLC or the Missile Subsystem in a simulation mode, and working through the Radar Return Generator to inject targets into the receiver to check system operation in its entirety. This concept permits the green system software to remain virtually unmodified in the exercise mode. The approach has been proven successful in system operation to date.

A Quick-Reaction, Remote-Controlled Nuclear Safety System

Previous Army nuclear safety systems relied on close proximity of the weapon to the officers responsible for weapon release. In addition, the time required to release SAFEGUARD had to be shorter than any previous system reviewed by the Nuclear Weapon System Safety Committee. The Launch Enable system, as designed, provides safety and remote release capability.

Chapter 12.

BALLISTIC MISSILE DEFENSE CENTER

Chapter 12.

BALLISTIC MISSILE DEFENSE CENTER

The Ballistic Missile Defense Center (BMDC) is the highest echelon of command and control in the SAFEGUARD System. The Commander-in-Chief of the Continental Air Defense Command (CINCONAD) exercises operational command through the BMDC. The BMDC, in turn, directs the activities of the Perimeter Acquisition Radar and the Missile Direction Center, and controls the launch and burst of nuclear missiles. BMDC facilities are collocated with the CINCONAD Combat Operations Center (COC) in the Cheyenne Mountain Complex of the North American Air Defense Command (NORAD).

ROLE

The BMDC provides a single-point interface for the Commanding General of the U.S. Army SAFEGUARD Command, whose forces staff the SAFEGUARD System, and CINCONAD, who is charged with the defense of the continental United States against air attack. After receipt of presidential authority to release nuclear weapons, the CINCONAD COC authorizes using the SAFEGUARD System's stockpile of nuclear missiles by entry of the Nuclear Employment Authority (NEA) at the COC. The BMDC, by consolidation and retransmission, provides the COC with the information necessary to support the authorization. (See Figure 12-1 for an overview of the SAFEGUARD command hierarchy.)

The BMDC also supports the SAFEGUARD System's mission by processing and consolidating early warning data on detections made by non-SAFEGUARD sensors, e.g., data the SAFEGUARD System needs to respond to submarine-launched ballistic missiles.

The COC/BMDC interface provides the SAFEGUARD System with alert and readiness-level coordination with other defense systems as well as coordination with the Strategic Offensive Missile Forces of the Strategic Air Command. The BMDC sends SAFEGUARD-generated early-warning, attack-assessment, and satellite-observation data to the COC.

DEVELOPMENT SCHEDULE

SAFEGUARD System Command authorized development of the BMDC Subsystem in April 1970.

Analyzing the hardware support required for the subsystem's development revealed that the Tactical Software Control Site at Madison, New Jersey, might not be suitable. Arrangements therefore were made for early delivery of the

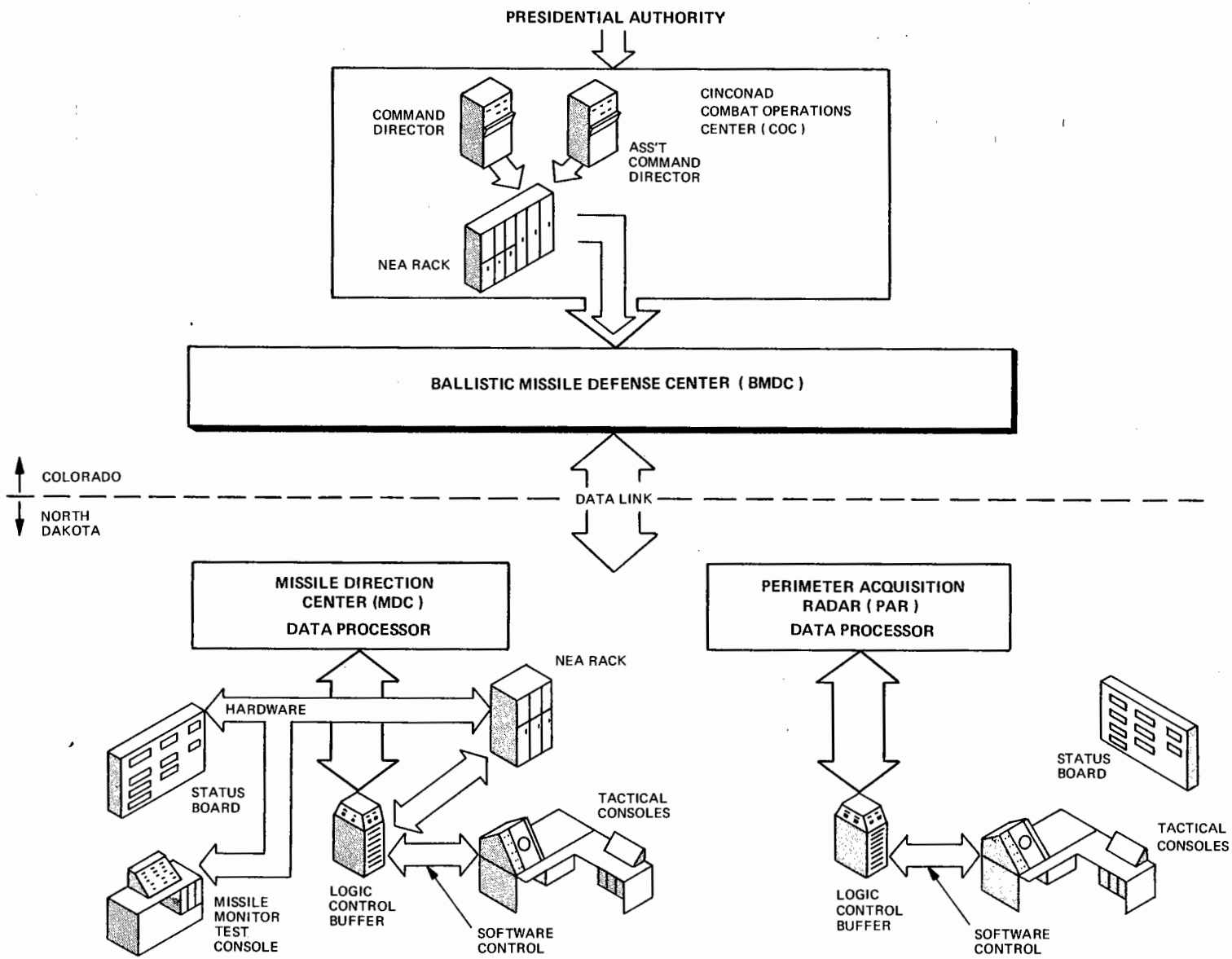


Figure 12-1. Overview of Command Hierarchy

tactical hardware to Guilford Center, North Carolina. This hardware, eventually destined for Cheyenne Mountain, was in Guilford Center ready for use by the software developers in September 1972. It was named the Early Ballistic Missile Defense Center (EBMDC).

The system development consisted essentially of three versions of the Weapons Process: BW1.0, BW1.1, and BW1.2.

The initial version, BW1.0, was released in December 1972, and contained the necessary interfaces and responses to satisfy the four-site deployment.

The second version, BW1.1, was released in June 1973. It was developed from information for a single-site deployment and contained corrections which were revealed by the test program for BW1.0. The EBMDC was removed from Guilford Center in August 1973, and in January 1974 was ready for use in Cheyenne Mountain.

In February 1974, BW1.2 was installed. This version included all features known to satisfy the requirements of single-site deployment. However, as a result of the functional and system test program, new Tactical Load Modules were periodically created until, on August 15, 1974, a final version of BW1.2 was released. This version was tested and turned over to the Army on October 1, 1974, thereby completing development of the BMDC.

DESCRIPTION

The BMDC contains a minimal, nonredundant processor using standard SAFEGUARD hardware. This processor primarily performs command, control, and display functions.

Hardware

The hardware consists of a Central Logic and Control, a Recording Subsystem, a Command and Control Display Subsystem, a Data Transmission Controller Subsystem, and a Maintenance and Diagnostic Subsystem.

Central Logic and Control (CLC)

The CLC used is the minimum configuration capable of supporting the BMDC mission. A nonredundant CLC is justified at the BMDC since it does not control radars or in-flight defensive missiles. The site mission can allow a significantly reduced Availability/Reliability Product without materially affecting the overall SAFEGUARD defense capability. In view of this reduced requirement, the standard SAFEGUARD hardware was considered sufficiently reliable.

The CLC for the BMDC consists of one Digital Data Processor Unit, three Program Store Units, three Variable Store Units, one Input/Output Controller, and one Timing and Status Unit. This is a "1-3-3-1-1" configuration.

Recording Subsystem (RSS)

The RSS used in the BMDC includes only those components required to support BMDC operations. These components are four disk memory units, four magnetic tape transports, two computer output printers, and one punched-card reader.

Command and Control Display Subsystem (CCDS)

The CCDS associated with the BMDC includes man/machine interface facilities to allow rational, manual control of the BMDC and the system as a whole. The major elements of the CCDS are briefly described in the following paragraphs.

BMDC Commander's CRT Console. The BMDC Commander's CRT Console enables the Commander to exercise manual control actions — such as Hostile Identification Enable, SPARTAN Hold Fire, and Nuclear Enable Inhibit — over the SAFEGUARD System.

In addition, the BMDC Commander may invoke Hold Fire, Cease Engage, and Force Intercept on individual targets. The associated CRT display provides the information needed to perform these manual actions.

Command and Control Consoles. The CCDS also includes three general-purpose Command

and Control Consoles. These consoles provide operating positions for the BMDC Tactical Director, Assistant Tactical Director, and System Capability Officer. At each console, any of the roles can be assumed without degrading manual capability. The console position normally manned by the Tactical Director does not include a teletypewriter, while those positions normally manned by the Assistant Tactical Director and the System Capability Officer do have teletypewriters. Figure 12-2 shows the three Command and Control Consoles as installed in the BMDC Operations Room.

Through his console position, the Tactical Director may exercise control over the entire SAFEGUARD System as well as control over the launch and burst of individual missiles. This degree of control is provided by manual actions, such as System Defense Mode Control, Missile Allocation Control, Hostile Identification, Hold Fire, and Cease Engage. The associated CRT display provides the information needed to perform these manual actions.

The Assistant Tactical Director's console allows this officer to support the Tactical Director. The teletypewriter at the Assistant Tactical Director's position allows manual entry of certain tactical messages normally received from the CINCONAD COC via the data link, thereby providing an alternate route for these messages.

The System Capability Officer's console informs that officer about BMDC hardware and software. In addition, the position permits the officer to restructure the BMDC Weapons Process to make optimum use of available resources as the tactical environment changes.

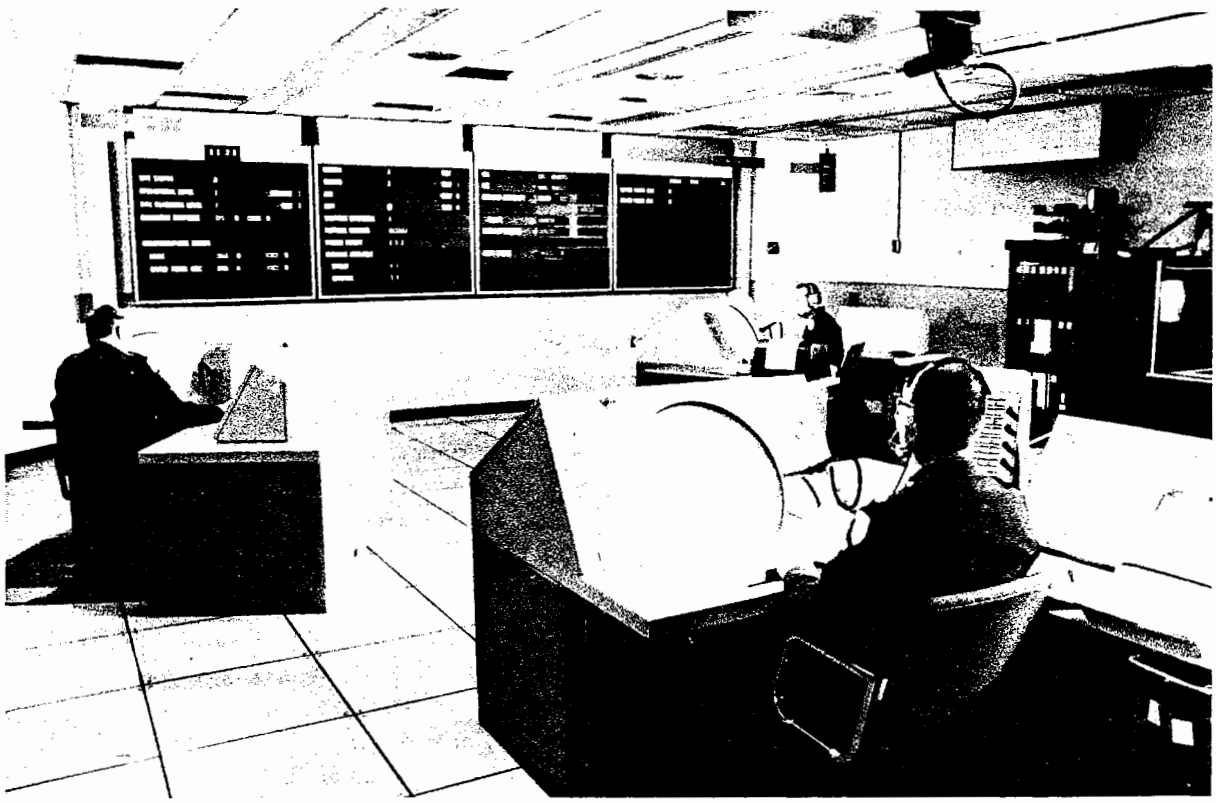


Figure 12-2. BMDC Operations Room with the System Capability Officer (left), Tactical Director (foreground), Assistant Tactical Director (right rear), and System Status Display Unit (rear)

The System Capability Officer receives enough data about the SAFEGUARD System as a whole to allow him to advise the BMDC Commander and Tactical Director about the system's capability. From this data, he also may coordinate maintenance for the entire system. The teletypewriter at this console position enables the System Capability Officer to inform the COC about the BMDC.

System Exercise Console. The System Exercise Console is used by the BMDC Exercise Director to manually control and monitor a single-site or multisite exercise.

In addition to the CRT console, the BMDC Exercise Director's position includes a teletypewriter so that he can manually modify the simulated system posture as well as the posture included in the system exercise.

Data Management Console. The Data Management Console allows manual monitoring of the data links connecting the BMDC with appropriate components of the overall system.

This non-CRT console permits intersite time synchronization of the BMDC Weapons Process with the interfacing SAFEGUARD System sites. In addition, the Data Management Console permits testing of the Data Transmission Controller, the Data Transmission Controller Adapter, and the connecting data links. This console position also includes a teletypewriter, which can be used to enter parameters and receive status reports from the Data Processing System (DPS) concerning the intersite data links.

Data Processing Console. The Data Processing Console permits the Data Processing Officer to manually control the subsystem's hardware and software.

In addition to the facilities provided by the CRT console, the Data Processing Officer's normal position includes two teletypewriters. These machines allow the officer to enter parameters and receive status reports about the subsystem's hardware and software. One of the teletypewriters is in an active mode and the other is in a standby mode.

Guided Missile Launch Enable Group. (See Figure 12-3.) The Guided Missile Launch Enable Group (also known as the NEA rack) is peripheral to the BMDC through the Command and Control Display Subsystem. The Guided Missile Launch Enable Group is in the CINCONAD COC. Two Guided Missile Launch Enable Controllers (GMLECs), also located in the COC, are used to release the NEA message. By virtue of the interface parameters, the Guided Missile Launch Enable Group appears to the Command and Control Display Subsystem as a special-purpose teletypewriter.

The signals generated when the Guided Missile Launch Enable Group is manually activated are related to the authorization by the National Command Authority to employ nuclear weapons. These signals require special handling by the BMDC Weapons Process. The NEA data is identified by the unique entry point in the hardware.

System Status Display Units. The System Status Display Units (Wall Status Panels) and Site Readiness Level Signs, with the associated System Status Display Support Unit, display data about the site and system status, National Defense Posture, and readiness and alert levels. The System Status Display Unit in the BMDC Operations Room (Figure 12-2) is a secondary display because most of its information is available on other display media, such as the CRT consoles.

The Site Readiness Level Signs and System Status Display Units in the Maintenance Control Center are more important. They are the primary source of information concerning alert and readiness status for personnel manning the center. The System Status Display Unit in the Operations Room is monitored by the COC through closed-circuit television as a major source of data about the SAFEGUARD System. This is an interim arrangement pending completion of the data link between the COC and the BMDC.

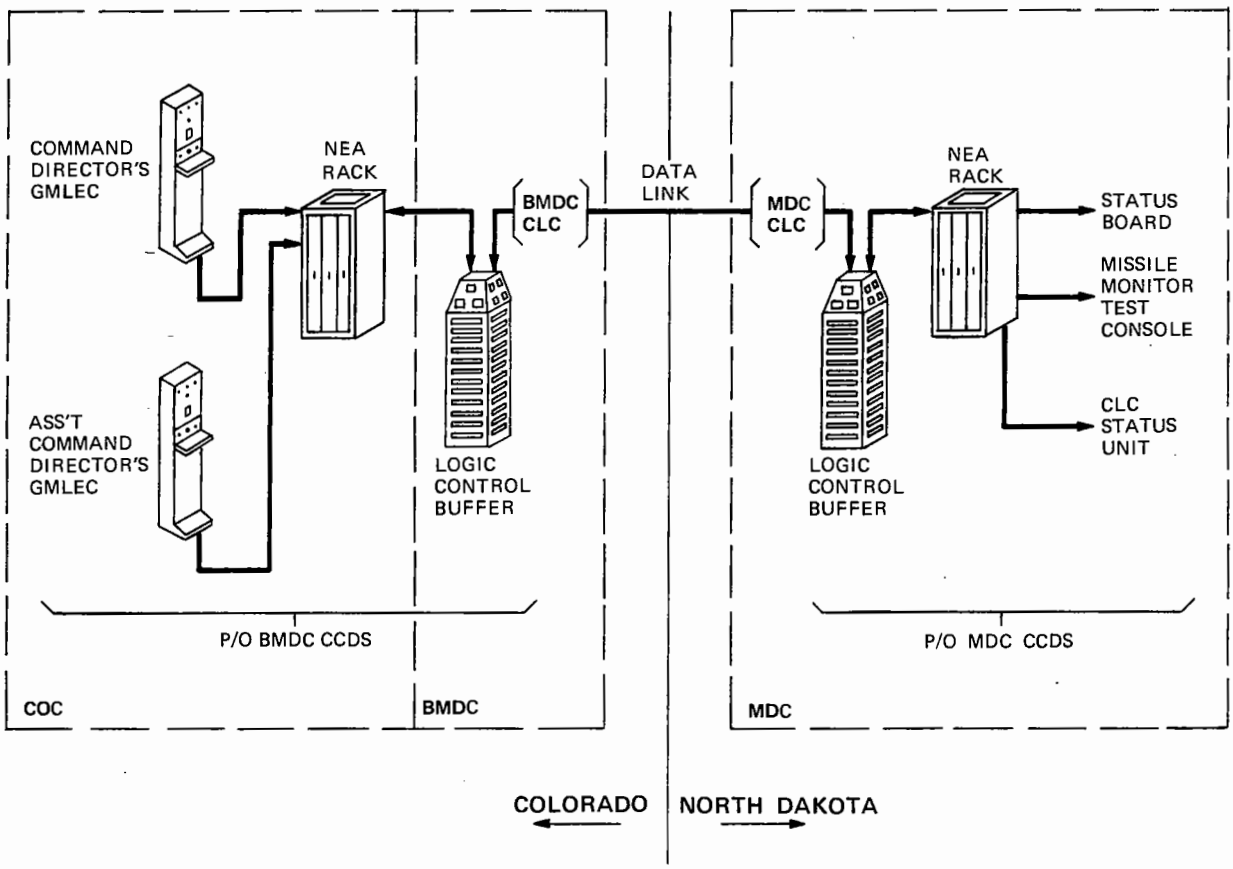


Figure 12-3. Nuclear Employment Authority Interface

Data Transmission Controller Subsystem

The Data Transmission Controller associated with the BMDC includes the appropriate logic modules to support an interface with three data channels. The data rate in the BMDC Data Transmission Controller is set at 4800 bits per second.

The SAFEGUARD System requires a data-link connection to the NORAD Communications Processor, which in turn provides a data interface with the CINCONAD COC and the Space Computational Center, both collocated with the BMDC in the Cheyenne Mountain Complex.

A data link from Cheyenne Mountain (Colorado) to Grand Forks Air Force Base (North Dakota) connects the BMDC to the remainder of the SAFEGUARD System (see Figure 12-1).

Maintenance and Diagnostic Subsystem (M&DSS)

The M&DSS at the BMDC includes maintenance-related equipment for computation, auxiliary input/output operations, and auxiliary information retrieval. It also provides the man/machine hardware interface to implement or support certain CLC loading and initialization operations, certain DPS recovery operations, and certain hardware fault isolation procedures.

Software

The BMDC software consists of a basic tactical software package (the BW1 Process), the

Tactical Operating System, a Basic Operating System, the CLC Control Facility, and appropriate M&D software.

The following paragraphs describe these software components, setting forth their unique characteristics and their interrelationships.

BMDC Weapons Process

The BMDC Weapons Process (BW1) meets the standards imposed by the DPS performance requirements.*

The BW1 is designed to create a software process that can adequately control error conditions and to provide a structure that can be efficiently maintained. Since the BW1 employs a single processor, the design must permit the system exercise function to co-exist with the weapons process in the DPS, yet it must be invisible to the tactical portion of the process.

To attain these goals, the BW1 was partitioned into five functional areas. These are the Process Coordination Major Functional Area, the BW-Operations Major Functional Area, the Displays and Controls Major Functional Area, the Intersite Communications Major Functional Area, and the System Exercise Major Functional Area. The following paragraphs present an overview of each Major Functional Area.

Process Coordination. This area is responsible for management and surveillance of the BW1 during tactical or system exercise, real-time operation, initialization, and termination.

BW1 programming tests for errors in the data base and in execution. The normalized cumulative error levels can be displayed to the BMDC System Capability Officer as an indication of subsystem sanity. Also, the Process Coordination Task and the Working Interface Table Request Processor Tasks provide the request and responses necessary to establish and terminate a system exercise.

BW-Operations. This area is divided into eight tasks: the Operational Mode Determination Task, the Visible Threat Consolidation Task, the Defense Status Consolidation Task, the Alert and Readiness Level Dissemination Task, the Nuclear Weapons Control Task, the Special Acquisition and Track Assignment Task, the Defense Mode Determination Task, and the NEA Transmission Task. The first seven of these tasks are cyclically enabled. When they execute, they determine if there are messages or manual actions to be processed.

The NEA Transmission Task is unique in its method of enablement. This task is enabled whenever the coded NEA messages are presented to the specially designated teletypewriter port of the Logic Control Buffer in the CCDS hardware (see Figure 12-3).

Displays and Controls. This area provides the software to drive consoles, displays, and teletypewriters of the Command and Control Display Subsystem. Because of the magnetic-core-size limitations for the BMDC Weapons Process, the Displays and Controls Major Functional Area uses disk-to-Variable-Store overlay extensively.

Intersite Communications. This area detects and validates messages from netted sites; it also formats messages to netted sites. In addition, this functional area monitors and evaluates communication links and maintains intersite time information. Manual access to the Intersite Communications Major Functional Area is provided by the Data Management Console. Upon successful completion of a DPS recovery, this area initiates the intersite messages necessary to update the BW1 data base.

System Exercise. This area supports both local and multisite system exercises for the BMDC, while remaining invisible to the tactical portion of the BMDC Weapons Process. In addition to certain control operations, such

*See reference number 40 in References for Chapter 4.

as initiation, termination, error recovery, and displays, the System Exercise Major Functional Area can simulate the tactical data interfaces with the Missile Direction Center and/or the NORAD Communications Processor (Combat Operations Center/Space Computational Center). Simulation of the Missile Direction Center implies simulation of the Perimeter Acquisition Radar. In any exercise mode, this functional area simulates all sites which interface with the BMDC but which are not participating in the exercise.

Tactical Operating System (TOS)

The TOS controls the real-time execution of SAFEGUARD DPS programs. This control involves sequencing programs, transferring data between storage and the peripheral devices, detecting errors and recovering from them, assigning available hardware as required, periodically testing DPS equipment, managing the CCDS and RSS, and providing communications and logic for controlling the operating system.

Basic Operating System (BOS)

The BOS provides a debugging environment for tactical software integration on the CLC. It allows single-processor, non-real-time execution on the CLC and facilitates manual interaction for patching, dumping, testing, and disc maintenance. Although the tactical software will function without BOS, the system provides essential tools.

CLC Control Facility

The CLC Control Facility provides the basic configuration, control, and loading functions required to do the following: to initially load the CLC and to reconfigure and recover the DPS, to partially or completely load the CLC, and to reinitialize the data base. Additionally, the CLC Control Facility provides such utility functions as a mathematics package, number conversion routines, time-of-day formatting, device allocation, device status management, a software interface with the CLC Status Unit, and string manipulation.

Maintenance and Diagnostic Software

The M&D software consists of a combined executive/utility system, which is resident in the M&D Processor; development programs that are used to build and debug all M&D Processor software; and user-oriented programs for hardware maintenance.

COMPARISON OF PERFORMANCE OBJECTIVES AND RESULTS

The BMDC subsystem delivered to the government on October 1, 1974, fully meets all performance objectives as delineated in the various design control documents.

Performance Measurement

Four tests measured the capability of the subsystem to meet the performance objectives: the Unit Test Sequence, the Progression Test Sequence, the System (End-Point) Test Sequence, and the Netted System Test Sequence.

Unit Test Sequence

The Unit Test Sequence verified that the performance of each distinct software module of the Weapons Process could meet the requirements imposed by the Functional Design Specification.

Progression Test Sequence

The Progression Test Sequence verified that each newly released Tactical Load Module could meet the performance requirements imposed by the design control documentation. The Progression Test Sequence measured the performance of the subsystem for given tasks, e.g., Visible Threat Consolidation, Defense Status Consolidation, etc.

System Test Sequence

The System Test Sequence verified the functional capability of the complete subsystem Tactical Load Module operating under a stress

or load condition. Subsystem response was derived from intersite messages and visual indications available through the display media in the subsystem.

Netted System Test Sequence

The Netted System Test Sequence is part of the System Integration and Evaluation Test Plan, which supports the overall SAFEGUARD System performance evaluation. The Netted System Test Sequence is a series of tests which evaluate the performance of the system in normal peacetime as well as in simulated attack conditions.

Performance Measurement Analysis

The data yielded by the four test sequences helped to validate the subsystem performance. The raw collected data was processed off-line using the SAFEGUARD Data Reduction System. The performance of the subsystem as evidenced by the reduced data was then compared to the performance objectives. Correlation between the reduced data and the predicted performance was considered to be evidence of attaining the performance objective in question.

By using this criterion, the subsystem was judged to meet all performance objectives imposed by the design control documentation.

Part III.

MANAGEMENT AND OVERALL APPROACH

Part III.

MANAGEMENT AND OVERALL APPROACH

To summarize the lessons learned from ABM R&D is challenging, because the period of time was long, the breadth of research wide, and the follow-on development program immense. This part of the report discusses the most important lessons learned about the management and overall approaches used in a project such as this. The discussion is discursive and makes no attempt to present detailed supporting data or arguments. Every member of Bell Laboratories Divisions 65 and 66 management contributed to this report by suggesting items, writing portions, and/or criticizing early drafts. There is a reasonable consensus on the views expressed here, but probably not on their relative importance.

Because this was a very big project, particularly the SAFEGUARD portion, the lessons are most directly applicable to other very large projects and many will probably also apply to smaller programs. There has been no effort to analyze the effect of project size or to modify the conclusions for different conditions.

Under the prime contract with Western Electric, Bell Laboratories had overall responsibility for essentially all R&D work. Since Bell Laboratories has its own special organizational characteristics, many of the statements made here have probably been affected by those characteristics. There has been no attempt to determine just how these characteristics have affected the conclusions or how the conclusions might be modified by different organizations. However, the close relationship between Bell Laboratories and Western Electric was exploited continuously during development and production.

OVERVIEW

Feasibility

Perhaps the most important lesson of this experience, and particularly of the SAFEGUARD part, is that development of a large weapons system can be completed on schedule to prescribed performance specifications, with effectively controlled costs. It is true that changes during development drastically cut down the overall deployment. Also, the overall system design was modified because of changes in objectives and because of test results obtained during development. However, the development, including integration of the first installed site, proceeded on schedule and the system met the prescribed performance specifications. Cost performance is harder to determine because of inflation during the period, deployment changes, and lack of a design-to-cost objective. But it seems clear that costs were controlled effectively.

Given the experience with some other important weapons system developments (most of them smaller or less complex than this one) in failing to meet schedules, performance specifications, or cost objectives, the ABM R&D effort is valuable as an example that such developments can be successful. This is particularly important because one major argument against developing SAFEGUARD was that it could not be done successfully.

Overall Approach

One principle followed during the entire research and development period was to continuously evolve the system concept; that is, to repeatedly synthesize and analyze systems that met prescribed objectives against prescribed threats. Although most of the effort was spent on research and development of specific subsystems (radars, missiles, data processors, etc.), there were continuous studies of how subsystems could be used within a system. The sensitivity of system performance to subsystem specifications and to changes in objectives and threat was repeatedly studied. Designers concentrated on aspects of subsystem performance most important to overall system performance.

The overall approach might be summarized as plan, simulate, test — plan, simulate, test — plan, simulate, test. Every part of the development benefited from detailed planning. While there was little or no attempt to specify a planning format or technique, every subproject manager was strongly encouraged to plan in detail the design, implementation, and testing of his piece of the system. Although these plans had to be revised many times, it was very beneficial to have them. To keep track of progress, several methods of reporting were tried, as discussed later.

Simulations were used on all levels of detail and for all parts of the design. In every case, simulations more than paid for themselves in either improved performance or reduced cost. When trouble was found, it was also discovered that more or better simulation would have prevented, or at least reduced, the difficulties. Because the simulation results were important, there were extensive efforts to validate them with data from real tests.

Perhaps the most important part of the overall approach was testing. Effective testing depends strongly on detailed test specifications. Most of the development time and cost went into testing, and it always happened that even more tests were possible and, in fact, desirable. Consequently, test planning almost always consisted of selecting only the most essential tests from among those desirable. After each test, data analysis continued until any failures or anomalies were understood. These comprehensive analyses, particularly of the Meck Island tests at Kwajalein Atoll, frequently resulted in significant system improvements.

Constructing the prototype Missile Site Radar (MSR) at the Kwajalein test site made way for the Kwajalein field experiments, which were undoubtedly the single most important step in achieving success. The project would have been even more successful if a more complete system prototype had been built. Building a prototype Perimeter Acquisition Radar (PAR) at a northern site early in the R&D program would have definitely produced a better system design. There were major problems with developing the PAR software, mostly because no complete, consistent set of requirements could be checked out on a prototype PAR system. Without a prototype, the problems with requirements were not identified clearly by the developers until the final development phase. No large project should be undertaken without allowing time and resources for constructing and extensively testing a complete prototype.

The Kwajalein tests are perhaps better termed "field experiments," and they were almost unbelievably successful. Successful tests meant not just meeting normal test objectives; they

produced data invaluable for completing system design. For instance, the data obtained on tank breakup were vital to the success of the project. Experiments were carried out in a carefully controlled environment (which helped both the conduct and analyses of tests) rather than in the design threat environment only. It would have been impossible to obtain data for the final design if the tests had only been trials against the design threat.

In many other projects, separate organizations within a company carry out their own field operations. A principal reason for the successful ABM field test program was the rotational assignment of systems, hardware, and software designers to the field sites. The reward was not only the transfer of design intent to the field tests but also the experience fed back to the design work when the designers returned to their laboratories.

Probably second in importance only to the Kwajalein tests were the tests at the Tactical Software Control Site (TSCS) in Madison, N. J. Not only were these tests vital to software development, they were also an important source of data on the hardware and helped validate the system simulations. Later sections of this discussion expand on the importance of testing and the TSCS.

The one constant factor throughout the project was the inevitability of change. At no time were the objectives, threat, design, or deployment completely stable, and it was unrealistic to assume that any of them would remain fixed. Therefore, it was vital to be prepared for changes and to have effective procedures for controlling them. Making changes in hardware was a familiar problem from Bell Laboratories' experience on Bell System and other military projects, and procedures for handling them were reasonably well established. But the complexity and high performance of the PAR and MSR systems necessarily produced a greater number of changes during testing and checkout than ever experienced before with smaller systems of lesser performance.

By careful planning, many changes were introduced into major subsystems — the MSR at Meck, the TSCS at Madison, the tactical MSR in North Dakota, and the PAR in North Dakota — during tests without materially affecting schedules. By scheduling test time among the many equipment users, changes could be introduced if the necessary drafting, shop, and quality assurance teams were available when required. A mutual understanding between designers of hardware and designers of software testing routines, plus careful scheduling, normally allowed enough time to physically disrupt hardware to introduce a change. Changes necessarily must be designed in small packages, but large packages of changes could be introduced because they were scheduled for periods when the system was down for a day or more and because work-crew schedules were kept flexible. After the changes, enough time was allowed for regression testing of areas affected by the changes.

By keeping the main technology fixed during the program, it was possible to produce, on schedule, equipment with proven reliable designs. On many other projects, hardware designs are continually changed to keep abreast of changing technology, schedules continually slip, and hardware is unreliable.

While controlling hardware design changes was a big problem, controlling system and software changes was even more difficult because procedures were not as well established. It took a great deal of effort to develop techniques for controlling such changes. These techniques, plus strict discipline, resulted in a control procedure without which the software development would have failed. (See Chapter 4 of Part II for a discussion of lessons learned in controlling software changes.)

Overall system requirements were specified early in the development, and formal procedures for controlling changes in these requirements

were immediately instituted. Software design was tied closely to these controlled system requirements. Even though there were many, many changes, this procedure was crucial to successful software development.

Organization

One of the most important characteristics of this project was the interface between Bell Laboratories and the Army agency responsible for ABM development. Relationships were open, frank, and informal. Although formal contractual requirements were carefully negotiated and carried out, most of the information exchanges between the Army and the contractor were informal. Consequently, problems could be discussed as they came up and proper action taken immediately. Also, the significance of problems could be determined and the right priorities established. Little effort was wasted on insignificant problems.

It was very important that the Army side of the interface be a single, responsible Program Manager. As with any very large project, there were many interfaces at various levels with the Army's SAFEGUARD organization both in Washington and in Huntsville, Alabama. In addition, liaison was necessary with many Army organizations; e.g., nuclear effects, facilities requirements, communications. Despite the many interfaces, the SAFEGUARD System Office and the SAFEGUARD System Command became an effective single agency responsible for resolving differences and adjudicating problems whenever they occurred.

Overall system changes were negotiated between the System Requirements Department at Bell Laboratories and the corresponding organization in the SAFEGUARD Project Office at Huntsville. Questions about system performance were discussed in proper context, and appropriate formal action taken to change the system requirements. Subsystem development was thereby protected from many "what if" studies which could have delayed progress.

This project, like others its size, took several companies to carry out. However, it was made clear that Bell Laboratories had overall responsibility, and top managers in Bell Laboratories used their authority to make major decisions quickly. If responsibility had been split among several companies, or if other red tape had impeded Bell Laboratories managers, it is improbable that schedules could have been met and very probable that costs would have increased. Because Bell Laboratories could make decisions quickly, technical authority over subcontractors could be delegated to lower levels when cost was not involved. This speeded up decision-making; it also increased motivation and inbred a sense of responsibility in the people working on the project.

Interfaces between Bell Laboratories and the subcontractors received special attention. In very large and technically complex development projects, the importance of this cannot be overemphasized. Technical developments and problems in each area affect other areas. Whether the related developmental areas are within a single company or split among contractor and subcontractor, almost continuous interchange of information is essential. Monthly or quarterly technical reviews are inadequate unless informal exchanges on the engineering level go on, by telephone and personal visits, at least once every week or two. With major subcontractors, it is often necessary to keep an engineering group at the subcontractor's plant. Without such frequent and informal engineering level exchanges, the technical development would not have been as quick or successful as it was.

In hardware subcontracting, enough time should be spent, before development starts, to work out a detailed design specification that both contractor and subcontractor fully understand. Requirements will change, so an early base for defining them is very important. This is particularly true for a cost/schedule/performance incentive contract.

Attention to contractor/subcontractor relationships was particularly important with software development. Because it is impossible to state software requirements precisely until after system design is completed, it is very difficult to employ subcontractors to develop complex software. If subcontractors are used, the interface must be carefully specified and monitored. The large subcontractor effort used to develop SAFEGUARD software was divided into smaller, well-defined tasks that interfaced directly with the Bell Laboratories first-line supervision. Tasks were rated monthly by the technical supervisor, and the rating results determined the final fee on the Cost-Plus-Award-Fee (CPAF) contract. This interface ensured responsive subcontractor performance at a manageable level on a very large project. These methods worked well, and when problems developed it was usually where the customary interface procedures had not been used.

Perhaps the most important principle followed in organizing the project was to install a top-quality manager over each subproject and give him full responsiblity for schedule, cost, and performance. The managers had broad and deep technical competence as well as managerial competence. Furthermore, they were expected to be aggressive in not just passively accepting a job definition and carrying it out. Instead, they actively explored interfaces between their subprojects and all others to anticipate problems. Although they used a variety of techniques to carry out their responsibilities, time after time their ability to recognize technical problems was fundamental in finding solutions to them. While it was certainly important to appoint the best general manager, it was absolutely vital that he have a high technical competence as well.

SPECIFIC SUGGESTIONS

This section contains comments less basic, but more specific, than those in the preceding sections. While the suggestions are grouped into general areas, each is largely independent of the others.

Requirements

System

To design and develop a large, complex system in a few years, a large number of people is obviously required (several thousand at the peak for SAFEGUARD). To properly coordinate their efforts, a good set of requirements and/or specifications is essential. For SAFEGUARD, the major specifications were:

- Brief overall SAFEGUARD System specifications
- Missile Site Equipment Subsystem specification
- Perimeter Acquisition Site Equipment Subsystem specification
- SPARTAN Subsystem specification
- SPRINT Subsystem specification
- Communication Equipment Subsystem specification
- Ballistic Missile Defense Center specification
- Data Processing System Performance Requirements (DPSPR).

The DPSPRs controlled software implementation and actually specified the detailed system requirements. The following comments are based on experience with all of the specifications, but mostly with the DPSPRs.

A decision about the level of detail and the completeness of requirements must be carefully weighed. The decision depends on the relationship between the organization preparing the requirements and the organization that implements them, the resources available, the time available, and various psychological factors. Obviously, the closer the organizational relationship, the less need for completeness. On the other hand, if the organizations belong to different companies, requirements must be complete and detailed. It is probably better to err on the side of too much detail rather than too little. On SAFEGUARD, too few resources (about 7 percent) were allocated to preparing the requirements.

Designers naturally object to overly detailed requirements because it limits them, and this important, legitimate criticism should be carefully guarded against. However, problems resulting from lack of detail can be even more serious, and therefore must be guarded against even more carefully.

It is vital that requirements be available as early in the program as possible. Those preparing requirements must make decisions quickly, on the basis of incomplete analyses, and publish them in the shortest possible time. Management should soften criticism of defects in the early issues of the requirements, because the defects inevitably result from pressure for early availability.

Because objectives change, because problems become better understood, and because requirements must be written quickly, changes are inevitable. It is absolutely necessary to institute a way to control changes relatively early in the process. This change control must keep proposed changes from getting lost and ensure that every designer is working with a consistent and updated set of requirements.

Requirements serve two purposes. They tell the customer what he is buying and the designer what he is designing. If these purposes conflict, the priority is to give the designer clear and unambiguous requirements. If necessary, give the customer explanatory material.

To summarize:

- Publish the first issue of requirements as early and as completely as possible. The first issue then forms a baseline for changes.
- Controlling changes in requirements is essential. The control system should become formal before the project is half completed.
- Carefully plan the degree of detail and completeness in the requirements. Do not allow unanalyzed resource restrictions to determine these answers.

Availability/Reliability

In a system like SAFEGUARD, a complete and easily understood availability and reliability budget is essential for each subsystem. This budget reflects the system effectiveness requirements. In the real world of fixed resources and flexible system objectives, these requirements should be considered as objectives. As such, they should be reviewed carefully at intervals to ensure that the system stays in balance and that the cost of achieving the original objectives is clearly understood. In SAFEGUARD, for example, if system effectiveness is measured by the number of Minuteman ICBMs that survive an attack, a wide range in availability and reliability will produce acceptable results. The original objectives were set for the SENTINEL Area Defense System, which required more stringent requirements than the Minuteman defense. More thorough consideration of possible reductions in objectives might have lowered some requirements for components and subsystems.

Man-Machine Subsystem

The requirements originally specified for the CRT console, the lightpen, the teletypewriter, and other units in the Command and Control Display System (CCDS) were far more extensive than necessary to support the man-machine relationship. Furthermore, it was found later that to supply many of these special capabilities required a software effort greater than the project could support. The man-machine interface was therefore greatly modified, resulting in two out of three available lightpen modes not being used. In addition, many CRT console capabilities, such as the A-scope mode and lower case letters, are unused throughout the CCDS. At the beginning, a hard-nosed and realistic examination of what man really had to do to control an ABM system, plus the assurance that requirements were compatible with the capability of supporting software, would have drastically reduced requirements on the Command and Control System. The equipment would have been more economical to design, produce, and maintain.

Similarly, the user directed that many engagement control actions be included in the requirements because they were useful in anti-aircraft systems, even though they were ineffective for ABM systems. These actions included Hold Fire, Force Intercept, and Command Destruct. If the requirements for ABM control actions had been agreed on sooner, the costs of designing, developing, and integrating display and control software would have been lower. While these problems did not significantly reduce capability of the man-machine subsystem, they definitely reduced the quality and "elegance" of the design.

Nuclear Surety and Safety

There should have been earlier, more effective communication among design organizations and the government agencies responsible for nuclear surety and safety: the National Security Agency (NSA) and the Nuclear Weapons System Safety Committee (NWSSC). Prompt liaison could have avoided misunderstandings, mistakes, and costly last-minute changes to the Nuclear Enable Authority and Launch Enable systems.

The agencies began intensive final reviews after designs, which incorporated changes suggested during their preliminary reviews, had been released for manufacture. Under these circumstances, designers were understandably reluctant to accept the agencies' comments and suggestions. After an additional year of review, NWSSC suggestions became a mandatory requirement for a new Launch Enable design concept. The designers regarded the new design and other practices imposed by the agencies as "ex post facto" requirements. Much cost, delay, and contention could have been avoided if:

- All the organizations involved had better understood the roles of NSA and NWSSC and the strength of their requirements and recommendations
- Before design work started, the agencies had documented their requirements, preferred concepts, and standards developed and imposed on other projects (e.g., use of nonsymmetrical connectors, omission of continuity loops, etc.)
- The above had been used as the basis for agency review with minimum application of criteria developed during review from "state of mind" guidelines
- The reviews had been more in parallel with design, to supply incremental concurrences from design through field test.

Intelligence Data

Gathering intelligence through U. S. observations of Soviet ICBM tests should have been much more responsive to the ABM development. The sensors on the U. S. instrumentation ships should have been modified so they could collect the required data. Instead, large sums were used for devising questionable frequency and radar cross-section scaling relationships, for extensive target modeling, and for costly simulations which could not always be validated.

Vast quantities of intelligence data were collected. There was enough information on the composition and levels of Soviet forces, and an adequate design threat was eventually defined. However, data essential for design, development, and evaluation of critical target selection and tracking algorithms were lacking. They could have been obtained by observing Soviet operational tests. During the years 1967 through 1972, data requirements were sent repeatedly to the Research, Development, Test and Evaluation (RDT&E) Directorate at Huntsville, who in turn, forwarded the requests to the intelligence agencies. With the advent of SENTINEL in 1967, UHF and S-band data were badly needed, yet UHF data remained scarce and incomplete and S-band data never were collected.

Radar cross-section and trajectory data for supporting the ABM development were needed at the operating frequencies, polarizations, and resolutions of the MSR and PAR. There should have been a deliberate effort to collect data on RV wake characteristics at S-band, on tank breakup at S-band, and on all exoatmospheric objects at UHF. Wake and tank breakup data were collected later by the Meck MSR during

live U. S. tests at Kwajalein, but these data were not totally adequate in the exoatmospheric regime.

Hardware Design Implementation

Hardware Design Release

When SAFEGUARD was committed to production, schedules were quickly established for releasing hardware designs for manufacture. These designs were developed during the R&D program, and had to be baselined and transferred from the R&D contract to the production contract. Hardware could then be manufactured according to production schedules, but subsequent design changes had to be made under formal production control procedures. These procedures proved to be cumbersome in making changes to R&D designs not yet stabilized for the production system. It would have been more cost effective to start manufacture with a less rigid configuration control program, and to control changes under somewhat less stringent procedures. Then, after a transition period to allow for design stabilization, formal production procedures could have been introduced.

A related problem was the Critical Design Review (CDR) required before the design could be released to production. The CDR was intended to allow the Army and Bell Laboratories to assure themselves that the design met system requirements and was ready for release to production. Since the equipment components had different lead times and were ready for release at different times, CDRs were held at various levels, on hardware ranging from magnetic apparatus to power supplies to power racks to subsystems. The CDRs should have been held only for large, very important items such as the MSR receiver, while lesser items should have been released prior to a CDR if required by production schedules. Army engineers could have been kept informed of the design status through the same type of regular contact with the design engineers that existed in the development program.

Design Drawing Reviews

In normal practice, the drafting organization and the responsible engineer spot-check completed drawings for accuracy and then release them for manufacture. If errors are detected later, the responsible engineer is notified and a change order for the correction is prepared.

In SAFEGUARD, an outside contractor reviewed selected drawings submitted for release to manufacture. The intent was to avoid subsequent change orders by assuring that the drawings contained no errors. In the early submittals, which came from reputable subcontractors, many errors were detected. More often than not, the errors did not affect manufacturing the product. Instead, they involved incomplete compliance with various drawing practices and format requirements.

The result was numerous drawing rejections and led to much effort being expended on additional checks of drawings before they were released. Subcontractors completely checked all their drawings before releasing them. Then a prime contractor representative visited the subcontractor plant and conducted a further review. In spite of these repetitive reviews, drawing changes were still required when shops used the drawings for procurement and manufacture, because the shops found real problems associated with product manufacture. The expensive, time-consuming drawing quality audit, more often than not, uncovered only superficial problems.

Drawing Designation

An excessive number of drawings were generated because of the initial requirement that each separate detail be on a different 11-million-numbered drawing. This volume of drawings is not required in commercial manufacture, nor is it used in the Bell System. It is expensive both in dollars and in the time required for drafting.

After much discussion of the cost of the program, the contracting agency gave some relief

by allowing contractors to include families of similar parts on a single drawing, with designation of a particular item by dash number. Certain drawing details were also permitted on top assembly drawings only when the detail did not have a separate requirement, e.g., as a spare part. If this relief had been extended to all subassemblies and been present from the start, considerable expense could have been avoided.

Organization of Work

System Responsibility

Major responsibility for SAFEGUARD was concentrated in two Bell Laboratories groups — the SAFEGUARD System Design Department and the SAFEGUARD System Evaluation Department. The System Design Department generated requirements for the various subsystems based on the overall design. Implementing these requirements was delegated to various project managers. The System Evaluation Department concentrated, at least initially, on evaluating the design, i.e., the requirements, rather than the implemented system. Neither of these departments was responsible for coordinating all implementation activities and no other organization was assigned that responsibility. Therefore, coordination had to be supplied by the individual project managers and higher levels of management.

The results were incompatibilities in system interfaces; significant delays in correcting system requirements; delayed awareness of difficulties; and lack of adequate system evaluation of process design, program execution times, missile and radar interfaces, and the manual display and control subsystem. All of these areas were corrected by individual project managers but only at the cost of added effort and delay.

In future projects, a system coordination group should be established within the systems area. The group should be responsible for (1) coordinating all implementation, (2) interface compatibility, (3) coordinating system evaluation, (4) establishing and achieving project schedules, and (5) technical reviews of system design, system evaluation, implementation, and test programs. In addition, the group should ensure that lessons and techniques learned from the prototype system are transferred to the tactical design. The group should act as a technical contributor to all of the above activities, not just as an administrative staff responsible only for standards, schedules, and reporting.

System Maintenance Organization

Most SAFEGUARD designers recognized the importance of maintenance, and considerable effort was devoted to maintenance by individual design groups. However, there was no centralized guidance for maintenance design, and results were less than optimum. For example, coordination of status reports and error responses from the various subsystems could have been improved, and documentation and testing of the overall maintenance system could have been better.

To get a better maintenance design, an organization with the following charter should have been established:

- Develop and maintain system and subsystem maintenance requirements consistent with the system availability goals
- Guide selection of maintenance techniques and tradeoffs in each hardware and software design area
- Guide development of operations and maintenance procedures and the associated documentation
- Develop plans for system-level tests of maintenance tools (especially for real-time operations).

Like any other element in a system, maintenance requirements will continually evolve as system design evolves. These requirements and their implementation are highly dependent on system Availability/Reliability goals (which themselves may change with time). Thus, it is important to keep system maintenance requirements up to date and appropriate to the system's primary mission.

Unified Responsibility for Design and Development

The success of a complex system, including its ability to operate on demand, depends on the availability and reliability of every essential element in it. Thus, "system" cannot mean portions of an overall complex, partitioned to fall within predetermined administrative jurisdictions; no element is separable if its failure would prevent the system from fulfilling its operational task. In SAFEGUARD, the critical complex includes support facilities, such as power, environmental cooling, and communications, as well as the technical equipment. A diesel engine, a cooling system fan, or a data transmission circuit may be just as crucial to battle readiness as a data processor unit or a missile guidance set.

An important reason for the success of the SAFEGUARD project was that responsibility for the design and development of essentially the entire system was concentrated in one organization. The only exceptions, the Tactical Support Equipment (TSE) and the communication system, caused significant problems. Also, there were difficulties because responsibility for training, supply, and maintenance was separated from the development responsibility.

Because the communication system's technical direction and funding were under the SAFEGUARD Communications Agency (SAFCA), not the SAFEGUARD System Command (SAFSCOM), issues which could not be settled mutually had to be resolved by the SAFEGUARD System Manager. As a result, some problems were ignored and others took more time and effort to resolve than necessary. There was also a tendency to insulate communications suppliers from Bell Laboratories designers, probably to minimize the number of design changes. But this impeded liaison on the working level, leading to poor understanding of how the communications interfaces worked and ultimately to interface problems. To try to coordinate communications system design, frequent meetings were held (typically monthly). These meetings used up time and manpower and required attendance by many agencies and companies, but they were no substitute for direct working-level contact among designers.

With the TSE, the prototype test site's outstanding success in meeting objectives would have been impossible without unified authority for operating and maintaining both technical and support facilities. Many problems surmounted only with difficulty (e.g., the problems with the Meck power plant) could have been lessened or eliminated if such authority had started earlier during design, procurement, and installation. At the tactical site, placing more of the administrative responsibility for TSE with the Weapon System contractor would have allowed more efficient operation with fewer problems and delays. During a demanding test and installation program, it is impossible to attain either adequate speed of response or a common view of priorities with divided authority. Hence, unified responsibility for the total system, including both technical and support facilities, is extremely important.

Management

Subcontractor Arrangements

The size of the development required that design work be assigned to subcontractors and responsibilities be shared with government agencies. The production phases required decisions as to which potential suppliers should receive contracts. The success of the project attests that almost all of the arrangements with subcontractors and agencies were quite successful; however, here too, there were also some difficulties.

Arrangements involved a wide range of subcontractors and items. For example, Martin Marietta for development and manufacture of the SPRINT missile, IBM for software development, a manufacturer other than the design agency for production of missile motor cases, the Atomic Energy Commission (AEC) and

its subcontractors for design and manufacture of the warheads.

Subcontracting work successfully requires attention to things which are, for the most part, obvious. However, these matters are so vital that elaboration is in order.

Consider first the design responsibility that the prime contractor gives to a subcontractor. Requirements must be consistent, controlled by the prime contractor, and understood well by each party. Note that requirements need not be perfect and that during the development they will change.

Ways to evaluate progress should be carefully determined before the subcontract goes into effect and then followed tenaciously so that real status is known by the technical project management on each side of the interface. Because requirements do change, progress will necessarily be assessed against a moving base.

Contracts and other formal arrangements must not impede the flow of information or inhibit changes. They should encourage progress, not stifle it.

The method for subcontracting the software development was somewhat unique. Work was broken into a collection of well-defined relatively small tasks that could be handled between prime and subcontractor at a first-line supervisory level. Progress was rated monthly by the prime contractor's supervisors, and the rating determined the award to the subcontractor on the cost-plus-award-fee contract.

Extreme care should be taken when it seems desirable to award manufacturing contracts directly from the government to other than the subcontractor who did the original design. If this is done with items that are intricate or use new technology, the expertise of the original designer is lost. Also, the expertise of the prime contractor in making system tradeoffs with respect to the item is lost. This kind of "breakout" should be used only where items are quite stable.

When an item involves multiple government and contractor agencies, such as development of a missile warhead, it is obvious that the responsibility and requirements assigned to each agency must be considered with care for all phases of the program. With warhead development, the designs and interfaces could have been simplified if complete responsibility, including the adaption kit, had been delegated to a single agency. Again, communication, flexibility, and constant monitoring are required if development is to be effective.

In summary, on a big project, assigning work to subcontractors is absolutely necessary, can be handled successfully, and requires constant management attention.

Cost-Plus-Award-Fee Contracting for Software Development

On the SAFEGUARD project, a large part of the software development had to be subcontracted. This posed a difficult problem, because the software had to be of high quality and be delivered on time, in spite of many requirement changes and complex interfaces. With all these constraints, development problems had to be sensed rapidly and accurately, and acted on promptly and effectively, or else development would get out of control. The key need was for close and continued attention to the subcontracts.

To attract and hold the attention of subcontractors, the profit from the job was determined by job performance. In principle, the Cost-Plus-Incentive Fee (CPIF) contract does this by adding a fee determined by applying a previously agreed-upon formula to objective measurements of cost and/or performance and schedule events, on completion of the work. Incentive fee contracts were used effectively on many parts of the SAFEGUARD development. However, CPIF contracts are difficult to use for developing complex software, because it is impracticable to set up predetermined performance goals to measure against the final product.

The Cost-Plus-Award Fee (CPAF) contract overcomes this handicap by providing that the fee be determined in real time and based on the subcontractor's performance as judged subjectively by the customer. The CPAF contract is a cost-reimbursable, level-of-effort arrangement in which the fee to be paid for each (predetermined) period is based on the customer's unilateral judgment of the supplier's performance, measured against previously agreed-upon subjective performance criteria. The fee is not subject to change. This type of contract had been used to some limited extent by NASA and the Navy, but was not in general use.

The SAFEGUARD CPAF subcontract for software development was in operation for more than four years, involved up to about 800 people, and as of October 1974, covered over $130 million. It has been a good vehicle for dealing with a large, complex, dynamic problem, where the customer needs as good a job as he can get, and on time. This type of contract requires good faith between customer and supplier, and substantial monitoring and evaluation. The format encourages good customer-supplier communications and the management involvement that is necessary for successful performance. The improved visibility of problems makes it possible to solve them quickly.

Incentive Contracts

Traditionally, during large, long-term development projects, principal events are used to demonstrate the achievement of significant milestones. Most military contracts now include incentives — contractually established monetary awards (positive or negative) — for achieving certain events. Many such incentive events were scheduled and successfully achieved during the SAFEGUARD development. The event system was valuable in demonstrating that performance requirements were being met and in encouraging project-wide planning. Furthermore, the events were interim goals, each clearly supporting and contributing to ultimate success, so that morale was boosted by a sense of achievement when goals were reached. The monetary awards associated with incentives can provide these same important advantages. However, requiring the completion of certain events in the contract ensures that they are scheduled, while the monetary awards ensure proper management attention.

Incentive contracting has potential disadvantages as well as advantages. Based on the SAFEGUARD experience, the following cautions and recommendations are given.

- Incentive contracting of performance, schedules, and costs is beneficial only if firm performance requirements, schedules, and costs can be negotiated. The effectiveness of incentives in state-of-the-art development projects is severely limited, because milestones cannot be easily identified and costs are difficult to negotiate. Incentive contracting loses many of its advantages if the contract has to be reopened because of major changes in requirements and schedules. If this happens, a contractor fully aware of his problems will make every effort to "get well" as part of the change negotiations.
- Incentive events must be significant, well-defined, and carefully chosen in-line milestones that must be reached to complete the project. They should be major performance or schedule achievements that require the success of many lesser milestones. Consequently, they should not be ends in themselves, and achieving them should not divert a substantial portion of the project's resources. Furthermore, if conditions change and an incentive event no longer serves its original purpose, the military and contractor should immediately negotiate to remove or modify it. To help avoid excessive diversion of resources, limit the time allowed for demonstrating an event.
- Establish incentive monetary awards only for results that are useful to the project. For example, an award should not be given for delivering a unit before it can be used. Similarly, an award should not be established for greater power output than other elements can handle or the system can use. Sound technical and business management skills are needed to work out the most challenging incentive events for a contractor and to assure overall success.
- Schedule incentive events infrequently to keep them significant and to allow preparations to be integrated with normal work.

For projects several years long, schedule incentive events no more often than every three to six months for each major subsystem. Events should be scheduled approximately eight to twelve months ahead of their demonstration date.

- Well in advance of performance incentive events, agree upon a reasonable time period or "window" for making the performance measurement. Failure to reach the event within that time period should result in a maximum penalty.
- Well in advance of a specific incentive performance, prepare a "catalog" to cover how the test is to be carried out, what instrumentation is required, what constitutes a success or failure, and how to score a failure from causes outside the contractor's responsibility. Murphy's Law states that if there is a chance for misunderstanding, it will occur. Therefore, careful attention should be given to preparing the catalog to make sure all factors are considered.

Reporting Systems

In large programs such as SAFEGUARD, reporting of technical performance, schedules, and costs is required for internal control and for informing the customer of program status. While these program aspects are interdependent, they are handled by separate reports and will be discussed separately. Each reporting system evolved over the years to meet changing program needs.

The goal of the reporting system is to convey the right level of timely information while conserving the effort required to prepare the report. Early in the program, technical progress reports were submitted every six months. They were difficult to prepare and, because of the interval covered, contained much outdated information which, while of historical interest, was not of immediate concern to program managers. Since then, and throughout most of the SAFEGUARD program, Bell Laboratories prepared monthly technical progress reports for the Army, submitting them by the 20th of the following month.

These reports had enough detail to present the current technical status for program management and to serve as a permanent record of job progress. Additional details were transmitted less formally by individuals, at meetings, and via memoranda. The monthly technical report also gave Bell Laboratories managers reasonably detailed information, not only about their own activities, but also about other phases of the program — a necessary part of the program coordination.

Several weekly TWX reports were sent between different project locations. These were useful because they were timely and concise.

For reporting schedules, Bell Laboratories evolved the SAFEGUARD Program Schedule Charts, which showed program milestone events. They were submitted to the Army at monthly intervals and were also distributed within Bell Laboratories. These significant benchmarks, plotted against a calendar grid, supplied the information needed to assess program status and to coordinate various program activities with other Army units, such as the Corps of Engineers.

These schedule charts tracked a limited number of easily recognizable milestones. Each represented substantial program effort and was essential to program completion. The charts were backed up by detailed schedules kept by each manager of a major subsystem. If the dissemination of the schedule charts raised questions, the manager could supply the answers from his more detailed schedules. The schedule charts retained all milestone dates once they were established. Where changes were required and new targets agreed on, the old dates were retained so that the slippages were easily visible. The dates when events were accomplished, either early or late, were also shown.

The level of detail in these SAFEGUARD Program Schedule Charts proved to be entirely adequate for the overall program management. They were much preferred to schedule systems that showed thousands of events, each involving a small amount of effort covering a short time interval. Had such a system been used, administrative costs alone would have been excessive.

Cost reporting used a system that summarized detailed cost information to facilitate management review and decisions. The reporting structure showed costs for each subsystem with a further breakdown to some half dozen separate accounts. In each account, costs were shown in four categories: Engineering, Drafting, Subcontracts, and Other Direct Charges. At the beginning of each year, a spending plan was submitted with this same structure. The Financial Management Report compared actual monthly costs against the yearly plan. When necessary, the responsible technical manager submitted a revised estimate of the costs for each remaining month of the year, with a concise explanation of the reasons for the revision.

Although every effort was made to see that the Financial Management Report clearly set forth program status, an analysis of this report, together with any recommendations for redistributing funds, was furnished to the Army each quarter. The analysis and recommendations were essential to keeping top-level management informed. This reporting system and its level of detail were adequate for the successful financial control of the program.

Managing the massive, highly complex software subsystem for SAFEGUARD presented new challenges, and new systems evolved to control it. In general, standardized reporting systems met internal project needs fairly successfully. They enforced a basic level of planning and stimulated periodic surveillance of status. However, different levels of management required different levels of detail, and their requirements often could not be satisfied by one report. The useful life of status information to managers who had to take direct action was much shorter than the shortest time it took to gather data for a project-wide report, prepare the report, and distribute it. Also, it was frequently difficult for managers to evaluate the accuracy of information in written standard reports. Most managers relied on direct one-to-one discussions with their subordinates to obtain information that required immediate action.

One of the reporting systems employed was the computerized Management Reporting System (MRS). Its data base, which had some 3000 items, contained scheduled start and completion dates of various significant activities. Dependencies between the various items were indicated. Information was updated each month and published as a standard report. The time needed to gather, process, and publish information was approximately three weeks.

In addition to the general positive and negative attributes of these standard reports, two aspects of MRS stand out:

1. Schedule problems between different project areas were highlighted.
2. Special weekly reports could be hand-tailored for one person. In some cases, they were more useful than the standard monthly report.

In software development, numerical measures of progress, such as the number of routines coded and the number of trouble reports corrected, were usually found to be of limited value. The quantities counted or measured were not uniform with respect to the amount of work involved or its importance. Consequently, it was very difficult to interpret their significance.

Principal Events Reports

The most successful report prepared for agencies outside Bell Laboratories was the Principal Events Report used for software development and system integration. It identified a number of important concrete milestones and defined them in detail. Many of these milestones marked the completion of tests on various functional capabilities. Reports on such events were normally made by TWX within 48 hours after their scheduled completion. The TWXs gave the dates for completion of late items, while follow-up TWXs were then sent on the rescheduled dates. The Principal Events Report, which was issued quarterly, described each item, gave its status, and accounted for previously completed events. This system of

reporting was extremely valuable to higher management, with the TWX reports particularly useful.

Miscellaneous

Alternative Problem Solutions

There are often many alternative approaches to solving management or technical problems. In many cases it was more effective to choose a good alternative and then carefully implement it rather than spend a lot of time trying to optimize the choice among alternatives. Often, the initial analysis of a problem leads to a complex solution which may not really be essential to implement, and further review may lead to solutions which are "elegant" in their simplicity. Project managers should repeatedly challenge their engineers to seek simple solutions to design problems.

In several instances, limited budgets led to modified requirements and less complex and costly designs. Constraints on dollar resources can establish hard priorities and stimulate simpler solutions. This was well expressed by Robert Townsend:*

> "A tight budget brings out the best creative instincts in man. Give him unlimited funds and he won't come up with the best way to a result. Man is a complicating animal. He only simplifies under pressure. Put him under some financial pressure. He'll scream in anguish. Then he'll come up with a plan which, to his own private amazement, is not only less expensive, but also faster and better than his original proposal, which you sent back."

Independent Testing Operations

Inevitably, the time allocated to hardware installation and testing in any big system will be compressed as much as possible. This obviously makes it desirable to parallel operations. However, in complex systems the required testing is also unusually complex. When the system is controlled by a centralized data processor, as in SAFEGUARD, the tests must usually include the data processor, so the amount of parallel testing possible is limited. Using relatively inexpensive minicomputers for much of the early testing can alleviate this problem. The savings from reduced installation and test time may be much greater than the costs of using minicomputers. One example of this approach concerned the Remote Launch Equipment (RLE).

A one-farm, two-missile prototype of the RLE had been tested at Kwajalein, and the tactical hardware had been given limited string testing in North Carolina. The first attempt to operate in a full four-farm configuration, over actual data links with a full complement of active launch cells, took place during installation and testing at Grand Forks, North Dakota. Therefore, rather complete tests were necessary.

During planning, it was predicted that when unit tests of RLE were complete, the ensuing system tests would require full-shift operation on most working days for several months. Schedule conflicts precluded timely completion of RLE system testing under control of the SAFEGUARD data processor. So a minicomputer, with a hardware interface unit and appropriate software, was temporarily installed at the tactical site to simulate the data processor. A similar installation had been used successfully at Meck Island during the prototype remote launch tests and at North Carolina locations for string tests. With the minicomputer, the tests were completed on schedule. The minicomputer also served as a diagnostic tool for difficult and complex design troubles, and surpassed the power of the Maintenance and Diagnostic (M&D) System and the built-in self-checks.

Communications for System Tests

Testing a system in a building as large and complex as the Missile Site Control Building (MSCB) requires a lot of internal communication, and running tests in several buildings at sites

*Up the Organization (New York, Knopf, 1970).

many miles apart is even more difficult. Careful planning is required for the communication system used during this testing. Instead of planning separate communication systems for testing and tactical operations, one should use the tactical communication system for testing wherever possible. However, nontactical circuits are required to support testing, particularly in the installation and early test phases. These circuits should be constructed around the basic framework of tactical communications. Such an approach allows an early evaluation of the tactical communication system, avoids the disruptions of switching from the testing to the tactical communications, and minimizes the cost of circuits required only for testing. This approach is best carried out by a single organization responsible for planning both the tactical communications and the testing communications.

Importance of Test Planning

It is universally accepted that good test planning is important to development of any system. For large real-time systems it may well be the most important part. Even when its importance is recognized, it is very difficult to make the best use of testing at each development stage. Although test planning in SAFEGUARD was probably more extensive than in any other single development, additional effort would have been worthwhile.

Many aspects of system development are strongly affected by the way tests are planned. The following are some of the most important effects recognized during the SAFEGUARD development.

- One of the first issues settled was the time allocated to system testing. Immediately after the deployment decision, the design, production, site construction, and installation had to be scheduled and coordinated. Inevitably, the planners wanted to achieve the earliest possible completion date. Because it had a direct impact on the completion date, one of the most important decisions was how much time to set aside for final system integration and test. It was impossible to list the problems which would be faced, and so it was very difficult to specify the tests and, therefore, a definite time interval. For a system as complex as SAFEGUARD, the test interval will be between one and two years. Hence, the question is an important one.

  With any system, the amount of testing (and therefore the testing time) is related directly, although in a very complicated fashion, to system quality. Reducing the amount of testing reduces quality, but increasing the amount of testing does not increase quality at a fixed rate. It is not at all unreasonable to limit the time and resources used for testing if it is recognized that doing so will have definite implications on quality.

  For a system like SAFEGUARD, a limited-quality product can be accepted at the outset of system life. Quality can then be constantly improved as testing continues at site installations and at the prototype development site. This additional testing does not have the same incremental cost in resources as testing during the development cycle, because most of the resources must be available for routine operation. For a multisite deployment, the first installation need not have the ultimately desired quality, because tests can continue while other sites are installed. Consequently, the system test program can extend well beyond the first installation and perhaps even well beyond the final installation in a multisite deployment. The planners must understand the implications for system quality before the entire test plan is finished.

  Another issue which has a major impact on schedule is the number of software tests. For a complex system, it is always possible to conceive of an infinite number of tests, so test planners must first establish a finite set. Next, project managers are rarely willing to allocate the time required for all the tests, so the problem is to select some subset of tests which is in some sense optimal. In SAFEGUARD, as a first step, the major functional capabilities to be used in implementing the system were listed. Then this set of possible tests was analyzed to see how it exercised these functional capabilities. A choice was then made as to whether each capability was to be exercised at all, nominally, or stressed to some extent. Then, a set of tests which implemented these decisions was chosen, and software test planning was pointed at that specific set. This approach seems to have produced an adequate testing program.

- Detailed test planning for system integration, based on experience with the prototype MSR, began in 1970, four years before Equipment Readiness Date (ERD). Planning considered test facilities (system

exerciser, threat tape generation) and the scope of testing (threat scenarios, traffic levels, system configurations and operating modes, threat excursions, confidence levels). Planning went on continually from 1970 until ERD, but even then, late deliveries of threat tapes caused problems in system test and integration at the TSCS. Although it is probably impossible to avoid this, careful monitoring is essential to minimize such problems because their impact on schedules can be major. In test planning, it is important to consider the reliability of test facilities. It is tempting to reduce the reliability requirements on test equipment not required for tactical operation (e.g., tape drives), but lower reliability will inevitably lengthen test time.

- As test planning proceeds, there will probably be important interactions with system design. The earlier these interactions are recognized, the lower their impact on cost, schedule, and system performance. Consequently, specification of system requirements should include requirements on the subsystems needed for testing.

  To illustrate such interaction, when design of the system exerciser was well along, a serious short-time peak developed in the data processing requirements to test the system at the desired traffic level. Providing this capacity by increasing the data processing hardware in the system exerciser would have been costly. By modifying the tactical system design, the requirements on the system exerciser were reduced and the necessity for the additional hardware was thus avoided. This design modification did restrict actual system performance, although only very slightly. If the situation had been recognized later, it could have been resolved only by much greater financial costs, disrupting the schedule, or limiting performance.

- Another major question is how much testing to do at each installation of the system. For SAFEGUARD, it was decided that each installation would be tested as thoroughly in all respects, including traffic level, as the system was during development. Hence, each installation was given a complete system exerciser facility, even though this involved substantial cost. Such a decision hinges on issues specific to a particular system. In the case of SAFEGUARD, the major issues were:

  1. Because the system might never be battle-tested prior to an actual engagement, it would be very difficult to determine whether its capability was deteriorating unless regular exercises could stress it to nearly its full extent.
  2. Because crews must be ready to respond in minutes, if not seconds, it was important to exercise their responses.
  3. It was important to thoroughly test each site, because each was assembled from tens of thousands of subassemblies, drawers, and racks; there were millions of interconnections and contacts and countless critical signal and timing interrelations. If a system could not be tested, it could not be made to work, or be kept working.

- Defining the requirements for data reduction of test results is important but difficult. In a system as complex as SAFEGUARD, every test produces a tremendous amount of data. For testing to proceed at a reasonable pace, the tester must be able to look at just the portion of the data he's interested in and to obtain it in the most easily understood way. However, early in the design he is unable to specify in detail what data he needs or how he wants to see it. Thus, it is difficult to build a data reduction facility by the time it is needed. In SAFEGUARD, this problem was approached by developing a series of data reduction systems. While this may be the only solution, it did require a very substantial effort. By applying more pressure earlier in the design cycle, designers would be forced to agree on a set of requirements to reduce this total effort.

Site for Prototype Testing

The TSCS, a partial prototype of the PAR and MSR, was built for developing software for the deployed system. Earlier in the program a prototype data processing system had been provided for developing the R&D software. Software could be verified with the TSCS only to a certain limit; because actual sensor and missile ground/interface equipment was lacking, the software development had to be completed at the field site. These R&D software deficiencies were remedied in the TSCS by including sensor parts that had direct or critical timing interfaces with the data processing system and selected parts of the missile ground and communications subsystem. Simulating responses for the sensor and other equipment is not a complete substitute for the equipment itself. Responses have to be limited, and the simulation can introduce artificial timing problems. It is difficult to

anticipate and design a simulation that has all the non-nominal and unexpected responses which can have serious impact on software operation. Simulation can only model the hardware, and the actual hardware may not conform to design intent.

The choice of equipment for the TSCS proved to be effective, and software developed and tested at the TSCS was brought up rapidly at the installation site. The software used to install the hardware at the site and later to maintain it was complete and of good quality. Not only did the high quality of this software allow the site installation to proceed quite rapidly, it also established a stable base for the more orderly development of the applications software at the TSCS.

Software designed to control hardware not included in the TSCS could only be partially debugged and tested at the TSCS; testing was completed at the tactical site. There was not a great deal of this software, but it was clearly not as well checked out when it arrived at the site.

As software was developed at the TSCS, many hardware design and manufacturing problems were uncovered. Many of the problems were corrected before hardware was installed at the site and, in almost all cases, solutions developed at the TSCS were available for site installation before the hardware was needed for the system test program.

The TSCS made site installation very efficient, so that the major efforts could be directed to solving problems unique to the site. Besides the efficiency gained in installation and checkout, the essential completeness of the prototype system-level problems could be identified and resolved. These problems, which included operational situations, were found long before they would have been detected at the tactical site. Hence, system integration progressed rapidly.

Dissemination of Information

It was hard for people to keep up with overall progress and problems of a job as complex as SAFEGUARD. To acquaint people with basic decisions and problems was essential, but it had to be balanced with the cost in time. For higher management, the need was amply met by monthly half-day sessions covering technical status and project-wide problems. Such meetings keep subsystem project heads technically sharp about problems in their areas of responsibility — particularly when the top managers have the technical acumen to probe sensitive areas. Clerical and support personnel were kept informed by quarterly filmed progress reports, and the inevitable time lag was acceptable for this audience. For lower management, there were occasional briefings on problems closely related to their work, typically on an organizational basis. Little in the way of information dissemination was done for nonsupervisory technical people.

More time should have been devoted to communicating with lower management and technical nonsupervisory personnel. The reports described earlier were good, but they were not always very current, could not be questioned, and frequently went unread. A better system might have been a half-day of several individual talks every month or six weeks. Information such as the following might have been communicated more effectively:

- Problems already solved and reflected in decisions. This area is important because the decisions can affect people's work directly, and the problem-solving techniques may be applicable elsewhere.
- Selected tough problems not yet solved. The payoff here is to encourage ideas from people who may be able to supply them. Also, a tough problem can sometimes be alleviated by energetic action in another area. A difficulty is that groups are reluctant to discuss a problem not yet completely solved, lest it suggest incompetence. Management should encourage the airing of such problems when necessary.

- Problems which have been formulated, but where solutions are not at all apparent, or are likely to be put off by the pressure of events. By raising these problems, they can be considered explicitly where they would otherwise have to be bypassed because of time pressure if left to upper management.

Transfer of Personnel

On a large development project, information must be exchanged between groups working on prototype systems and those working on production systems, and between groups preparing system requirements and those implementing them. The only feasible way to transmit most of this information, of course, is in writing or verbally. Some of this information exchange should occur via transfers of people between organizations so that ideas and points of view can be incorporated into the work as fully as practicable.

In the short term, transfers reduce the ability of the organization losing the personnel. However, this short-term cost is more than made up for by the long-term benefits of understanding gained by the receiving organization. On SAFEGUARD, substantial numbers of people were transferred from prototype to production development organizations and between other groups during production development. Even more transfer of personnel would probably have been desirable.

Timeliness of Problem Recognition

It is important that problems be recognized quickly, that solutions be carefully planned, and that proper resources be applied. Some problems which should be addressed early simply do not get timely attention. Others are addressed too early and inappropriately "solved," only to reappear later.

For example, initial attempts to design SAFEGUARD data reduction packages foundered because of inadequate attention. They were aimed at testing and integration activities then several years away, while operating system design, language processors, algorithm development, and guidance simulation were commanding prime attention. This tendency to discount* problems perceived as remote in space or time also hindered communication subsystem design.

The impact of discounting should be minimized; it probably cannot be eliminated. Management should guard against it by periodic reviews of plans, forecasts, and current design activities. A comprehensive development plan is a decided help. Management should also restructure groups or departments as necessary to start early attacks on late-maturing design problems. Both of these schemes were tried and found useful.

Staff Assistants for Managers

Staff assistants, called Management Report Analysts (MRAs), were assigned to many second-level managers with project management responsibilities. The MRAs were, in general, college graduates with backgrounds in planning, scheduling, and budgeting. They were trained in the objectives, procedures, formats, and use of the SAFEGUARD Managing Reporting System (MRS) and could input up-to-date information into the MRS through their close association with their project manager.

They also assisted the project managers by preparing and controlling budgets, administering contracts, planning, scheduling, allocating space, arranging personnel moves, recording and following up on action items generated at project meetings, and performing numerous other administrative details.

Almost all of the managers who were assigned MRAs were enthusiastic about their usefulness. By relieving managers of many purely administrative functions, the MRAs made it possible for managers to concentrate on the more critical technical aspects of the job.

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*See H. A. Linstone, IEEE Spectrum, April 1974, for a discussion of discounting and forecasting.

Part IV.

REFERENCE DOCUMENTS

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REFERENCE DOCUMENTS

Reference documents for the topics discussed in Part II, Chapters 1 through 11, are listed and annotated here. The references for each topic are arranged and numbered in their order of appearance in the appropriate chapter. Items listed include a broad representation of reports, memoranda, technical manuals, specifications, and design documents chosen to provide a thorough historical background for each subject area.

References for Chapter 1

NIKE-ZEUS System

1. NIKE-ZEUS Guided Missile System — System Study Report (U), Vol 1, Bell Laboratories, March 1, 1957. (SECRET-RD)

   Discusses the future air defense problem and the system requirements composed by such a threat. A description of the NIKE-ZEUS system appears in Part I. Part II treats, in more detail, the nature of the threat, the data-gathering facilities, the missile design and guidance, weapon capability, system integration and effectiveness, a proposed test and development program, and a resume of exploratory development.

2. NIKE-ZEUS Tactical Controls for Defense Against Ballistic Missile — Case 27495 (U), D. Gillette, Bell Laboratories TM, MM-58-4112-20, May 20, 1958. (SECRET)

   Discusses NIKE-ZEUS tactical controls for the anti-ICBM operation. The subsystems controlled are the Forward Acquisition Radar, the Local Acquisition Radar, the Local Defense Command, and a battery. The approach is to set up a model at a defense system and to cast the subsystems in their appropriate roles. The principles of organization and tactical control are then investigated.

3. NIKE-ZEUS Guided Missile System Ballistic Missile Defense (U), Bell Laboratories, April 1960. (CONFIDENTIAL)

   Describes the present (1960) NIKE-ZEUS System. Reflects system improvements that have been incorporated since issuance of the original system report in March 1957 (see Reference 1).

4. NIKE-ZEUS Guided Missile System Radars (U), Bell Laboratories, June 1960. (CONFIDENTIAL)

   Describes the NIKE-ZEUS radars and summarizes their physical and electrical characteristics.

5. A Tactical Philosophy for NIKE-ZEUS (U) — Case 27495-42, A. R. Eckler, Bell Laboratories TM, MM-62-4263-1, February 9, 1962. (CONFIDENTIAL)

   Describes tactical philosophy of the NIKE-ZEUS system, including engagement planning and engagement execution.

6. Dielectric Lenses — Case 27495-11, W. McMahon, W. A. Yager, and D. Edelson, Bell Laboratories TM, MM-58-112-16 and MM-58-111-11, February 21, 1958.

   A preliminary report on a study of materials and structures for dielectric lenses. Deals principally with spherical lenses of the Luneberg type. Loading low-density foams with small amounts of metal particles of the proper shape can provide media with all of the refractive indices required.

7. Target Detector for the NIKE-ZEUS Acquisition Radar — Case 27495-44 (U), G. L. Gamble, L. W. Jones, and W. F. Miller, Bell Laboratories TM, MM-58-4435-1, June 26, 1958. (CONFIDENTIAL)

   Describes the target detector for the NIKE-ZEUS acquisition radar. This detector provides averaged positional target information in digital form from analog signals received from the receivers of the acquisition radar.

8. The Proposed Design of the Track Initiator at the Local Acquisition Radar of the NIKE-ZEUS System — Case 27495-41 and 27495-44 (U), A. Ralston, Bell Laboratories TM, MM-58-4111-13, February 4, 1958. (CONFIDENTIAL)

   Discusses the design of the track initiator for resolved ICBM targets. Presents the logical design in its overall aspects, along with detailed discussion of the logical design of the various components. The reasons for using one mode of operation in preference to others are indicated.

9. NIKE-ZEUS DR — Operational Control of the High Level Transmitter — Case 27495-64, F. J. Schaefer, Bell Laboratories MFF, May 2, 1960.

   Describes the switching functions by which the power output of the Discrimination Radar High Level Transmitter may be controlled and directed. Also describes the proposed transmitter control layout for the DR Control Console.

10. Description of the Low Power Section of the NIKE-ZEUS DR Transmitter — Case 27495-64, R. E. Mahoney, Bell Laboratories MFF, February 27, 1961.

    Contains a condensed physical description of the low-power section of the Discrimination Radar Transmitter, along with a block diagram and description of the circuit operation.

11. NIKE-ZEUS DR — Off-Axis Accuracy — Case 27495-42 (U), W. L. Gaines and D. M. Vanden Akker, Bell Laboratories TM, MM-62-6434-4, October 4, 1962. (CONFIDENTIAL)

    Discusses the factors governing the accuracy of off-axis measurement of a radar system using phase monopulse.

12. NIKE-ZEUS TTR — Modes of Operation — Case 27495-42, W. L. Gaines, Bell Laboratories MFF, June 5, 1959.

    Lists and briefly describes the three principal modes of operation for the NIKE-ZEUS Target Track Radar (TTR). These differ from those of NIKE-AJAX and HERCULES Systems because of the extremely short warning before the NIKE-ZEUS TTR must be fully operational.

13. NIKE-ZEUS Target Track Radar Transmitter (U) — Case 27495-42, K. H. Haber, Bell Laboratories TM, MM-59-6436-13, October 1, 1959. (CONFIDENTIAL)

    Describes the TTR transmitter, including the chirp principle, the generation of receiver local oscillator signals, and the functioning of each transmitter portion.

14. Dynamic Analysis of a Three Gimbal Tracking Antenna — Case 27495, D. A. Conrad, Bell Laboratories TM, MM-57-114-39, September 23, 1957.

    Analyzes a three-gimbal tracking antenna. Reasons that, because of a third axis, the gimbal design is not wholly determined by directing the antenna at the target. A coupling of two or more motions of the axes fixes the system. The system's motion is described by an equation once the form's coupling is prescribed.

15. NIKE-ZEUS — Maximum Range of TTR — Case 27495-42 (U), W. L. Gaines, Bell Laboratories MFF, January 22, 1962. (CONFIDENTIAL)

    Calculates the maximum range of the TTR from the radar range equation.

16. NIKE-ZEUS MTR — Description and Test Results of the GS-59208 Transmitter — Case 27495-516 (U), D. B. Seamans, Bell Laboratories MFF, June 12, 1961. (CONFIDENTIAL)

    Outlines the design objectives and gives circuit description and typical performance data on this transmitter.

17. NIKE-ZEUS R&D Program Final Report (U), Vol 1 through 6, McDonnell-Douglas Astronautics Company, Report SM-49046, March 1966. (Vol 1 and 2 SECRET; Vol 3 through 6 CONFIDENTIAL)

Reviews the history of the development of the NIKE-ZEUS missile, and includes description and specifications for that missile.

18. NIKE-ZEUS Missile Guidance Section Seminar (U), Bell Laboratories, March 20-22, 1962. (CONFIDENTIAL)

Describes in detail the philosophy and operation of the Mod III guidance section for the NIKE-ZEUS missile.

19. NIKE-ZEUS Defense Center Data Processing System Study Report — Case 27495-44 (U), Bell Laboratories, April 13, 1962. (CONFIDENTIAL)

Summarizes a recent study of the tactical ZEUS Defense Center Data Processing System.

20. NIKE-ZEUS — The Target Data Consolidator Computer — Case 27495-44, L. L. Cochran and E. R. Weir, Bell Laboratories MFF, August 20, 1962.

Describes the Target Data Consolidator Computer and its functions, including data processing.

21. NIKE-ZEUS — Likelihood Ratios — Case 27495-42 (U), S. C. Reed, Bell Laboratories MFF, March 2, 1961. (CONFIDENTIAL)

Introduces the concept of likelihood ratios and explains their application to the decoy problem.

22. Card Changeable Nondestructive Readout Twistor Memory — Case 27495-42, J. Janik, Jr., Bell Laboratories TM, MM-58-4114-4 and MM-4431-2, March 10, 1958.

Describes the storage of information in the presence or absence of permanent magnets and the twistor. There is a continual search for a readily changeable yet nondestructive readout memory, one in which the information can be punched on a card and inserted into the array.

References for Chapter 2

NIKE-X System

1. Hardsite Defense (U), Bell Laboratories, July 14, 1964. (SECRET-RD)

   Discusses an early study which examined the system and component requirements for the active defense of hardened sites, concluding that effective levels of defense can be provided.

2. Active Defense of Strategic Missiles, Joint ARPA/Air Force Study, Vol 1-4, Bell Laboratories, August 25, 1966.

   Presents the results of a joint Army and Air Force study conducted by Bell Laboratories to determine the preliminary characteristics, effectiveness, costs, and schedules for the active defense of Minuteman, Titan II, and rebased advanced Minuteman forces.

3. NIKE-X Ballistic Missile Defense System — System Study Report (U), Vol 1 and 2, Bell Laboratories, October 1, 1963. (SECRET)

   Volume 1 discusses the threat and the requirements it imposes on a defense system, presents the general configuration of NIKE-X and its expected effectiveness against the threat, and gives fairly detailed descriptions of the subsystems which comprise NIKE-X. Volume 2 presents detailed technical material in support of critical design choices made in the course of the study.

4. Threat Analysis Study for the Secretary of Defense (U), Vol 1 and 2, NIKE-X Project Office, Bell Laboratories, and Stanford Research Institute, October 26, 1964. (SECRET-RD)

   Following a concise description of NIKE-X, the physical threat is described. A system operating plan is postulated, giving system responses against various aspects of the threat. Finally, deployment principles are discussed and quantative estimates are given for system effectiveness.

5. NIKE-X Weapon System — Tactical System Description (U), Bell Laboratories, January 15, 1966. (SECRET)

   Describes the NIKE-X System and its subsystems at the stage of development reached by 1966. The system by then included a VHF radar and the TACMAR option. The reference threats to which the system was being designed are given in some detail.

6. NIKE-X Defense Against Light Attacks, Report to the Secretary of Defense (U), NIKE-X Project Office, Bell Laboratories, and Stanford Research Institute, June 10, 1965. (SECRET-RD)

   Describes a NIKE-X System option that (1) provides a CONUS-wide defense against light attacks via a high altitude barrage defense with modified ZEUS missiles, (2) provides comparatively light (referenced to previous concepts) SPRINT terminal defense of high value population centers, and (3) provides for orderly growth to meet increasingly sophisticated attacks.

7. NIKE-X Deployment Study (DEPEX), Report to the Secretary of Defense (U), Office, Deputy Chief of Staff for Military Operations, Dept. of the Army, October 1, 1965. (SECRET-RD)

Describes a four-phase deployment concept for NIKE-X, initially optimized for area defense against a light attack from an Nth Country with particular emphasis on evolution of a ballistic missile threat from the CPR. Also provides for growth to meet massive and sophisticated attacks. Emphasis is on ZEUS barrage mode for area defense, but basically relies on relatively moderate (referenced to later concepts) deployment of system components.

8. System Study NIKE-X I-67 Defense Deployment (U), Vol 1 — System Description, Bell Laboratories, July 5, 1967. (SECRET-RD)

   Describes deployment and operational concept for countervalue (area) defense against CPR ICBM attack and for counterforce (Strategic Offensive Force) defense against USSR attack. Area defense was designed explicitly to deny damage by unsophisticated threats. Utilized PAR and SPARTAN as new system elements.

9. NIKE-X Studies for 1966 (X-66) (U), Vol 1-8, Office of Deputy Chief of Staff for Military Operations, Dept. of the Army, September 1, 1966. (SECRET-RD)

   Builds on previous studies with emphasis on more extensive range of attack situations. Reexamines previous studies. A very light area defense concept is postulated and tested ("Phase 0" of DEPEX), with emphasis on CPR.

10. Improved SPARTAN System Study Report (U), Bell Laboratories, April 1, 1968. (SECRET-RD)

    Summarizes system studies performed from July 1967 to March 1968 concerned with improving the SPARTAN missile in its area defense role.

11. NIKE-X Advanced Development, Hardsite Defense (U), Vol 1-5, Bell Laboratories, September 1968. (SECRET-RD)

    Reports on two system configurations: a fixed-radar and a movable-radar system to defend the existing Minuteman, rebased Minuteman force in harder silos, and a new ICBM force in hard-rock silos. The five volumes present the summary, threat and effectiveness, radar characteristics and design, radar operation and data processing, and interceptor supporting studies.

12. Hardsite Interceptor Study (U), Vol 1 - DAC-62407, Vol 2 - DAC-62408, McDonnell-Douglas Astronautics Corporation, November 1968. (SECRET-RD)

    Generated realistic interceptor designs for engaging ballistic and maneuvering threats in defense of hardsites including use of information from the ABMDA UPSTAGE experiment program.

13. NIKE-X — Discrimination Techniques for Hardsite Defense (U), N. Levine, (Bell Laboratories) and V. Lotsof (Cornell Aeronautical Laboratory), June 1, 1966. (SECRET-RD)

    Investigates the discriminants which might be effective against sharp, slender RVs and decoys from 100-kilofoot altitude down to 20-40 kilofeet.

14. Ballistic Missile Defense, Advanced Development Program, Advanced Data Processing, Vol 1, Bell Laboratories, September 30, 1969.

    The first of three annual reports; introduces the Parallel Element Processing Ensemble (PEPE) concept and details its architecture and software and initial simulations.

15. IEEE COMP CON '72 Digest:

    PEPE Computer Architecture, B. A. Crane, M. J. Gilmartin, J. H. Huttenhoff, P. T. Rux and R. R. Shively

    The PEPE Support Software System, D. E. Wilson

    Application of PEPE to Radar Data Processing, G. D. Bergland and C. F. Hunnicutt

    Parallel Processing of Ballistic Missile Defense Radar Data with PEPE, J. A. Cornell.

These papers present a brief overview of the characteristics, PHSD test implementation, and performance of PEPE in a general distribution publication. It was presented as an example of "Innovative Architecture," the theme of the Conference.

16. Ballistic Missile Defense, Advanced Development Program, Advanced Data Processing (U), Vol 2, Bell Laboratories, September 30, 1971. (SECRET)

    Presents an overview of the PEPE IC Model, details and results of PEPE application studies to Ballistic Missile Defense, ZOS, PHSD and Off-loading, and results of hardware implementation studies.

17. Ballistic Missile Defense, Advance Development Program, Advanced Data Processing (U), Vol 2, Bell Laboratories, September 30, 1969. (SECRET)

    Presents the results of studies of the Application of PEPE to SAFEGUARD, VIRADE, and to Coherent Waveform Processing.

18. Ballistic Missile Defense, Advanced Development Program, Advanced Data Processing, Vol 1, Parts 1 and 2, Bell Laboratories, September 30, 1970.

    This second annual report presents a detailed description of the Integrated Circuit (IC) PEPE model brassboard hardware and its support software and the PASS II evaluation studies.

19. Ballistic Missile Defense, Advanced Development Program, Advanced Data Processing (U), Vol 2, Bell Laboratories, September 30, 1970. (SECRET)

    Presents results of GPSS simulation studies of Ballistic Missile Data Processing and design alternatives and a study of the application of PEPE to SPRINT missile guidance.

20. Ballistic Missile Defense, Advanced Development Program, Vol 1, Advanced Data Processing, Bell Laboratories, September 30, 1971.

    The third annual and final report of PEPE studies at Bell Laboratories. Presents an overview of the PEPE system, hardware and software, and the principal final year studies and demonstrations, ZOS, PHSD, and offloading. Includes an introduction to proposed LSI implementation.

21. NIKE-X – Critical Review of BTL Optical Discrimination Program (U), Bell Laboratories, April 1, 1965. (SECRET)

    Reviews the accomplishments and future objectives of the optical/infrared measurement program and data analysis efforts. The sensor facilities and operational aspects of these data sources are defined.

22. NIKE-ZEUS Guided Missile System Test Planning Handbook (U), Bell Laboratories, July 1, 1963. (SECRET)

    Describes the early activities and target types available to the Reentry Measurement Program, prior to RMP-A. Sensor characteristics and data collection procedures are defined.

23. NIKE-X Re-entry Measurements Program Targets – Case 27703-1600 (U), R. Flex, Bell Laboratories MFF, May 19, 1966. (SECRET)

    Provides descriptions of both the RMP-A and RMP-B target vehicles. Preliminary instrumentation details and objectives are presented for the RMV-340 vehicle.

24. NIKE-X – Summary of Re-entry Measurements Tests to be Conducted at WSMR with NIKE-X Radars – Case 27703-1700 (U), J. N. Wright, Bell Laboratories MFF, December 15, 1964. (SECRET)

    Specifies the reentry test series planned for the WSMR and data objectives for the DR and TTR.

25. The NIKE-X Field Test Program Handbook (U), Bell Laboratories, November 1, 1964. (SECRET)

Presents the objectives of the Reentry Measurements Program and describes the targets associated with this program. Appendices provide tabulation of equipment (sensors) locations and a glossary.

26. NIKE-X — Description of Reentry Measurements Program (U), S. J. Buchsbaum, L. C. Hebel, Jr., C. W. Hoover, Jr., and R. E. Markle, Bell Laboratories, October 1, 1965. (SECRET)

    Reviews the NIKE-X discrimination program from its infancy in 1960 to 1965. Emphasis is placed upon the sleek-cone target class and those experimental measurements necessary for understanding the physics of reentry. The experimental program is explained in detail including those to be performed under RMP-B.

27. Radar Observations of Near Wake Velocities, RMAR 68-9 (U), J. R. Pignataro, Cornell Aeronautical Laboratory, Inc., Report UB-1376-S-149, August 1968. (SECRET)

    Describes a discrimination technique derived from radar observation of wakes of reentering objects.

28. NIKE-X Re-entry Measurements Program Non-RMV Targets — Case 27703-1600 (U), R. Flex, Bell Laboratories MFF, June 9, 1966. (SECRET)

    Presents parameters and characteristics for operational Reentry Vehicles, penetration aids systems, and research and development vehicles flown in the WTR and WSMR tests. Booster systems are defined.

29. NIKE-X Advanced Development, Analysis of Radar Data Obtained During the RMV-A Program (U), Bell Laboratories, May 1967. (SECRET)

    Reports overall results of RMV-A program and applicability to real-time discrimination.

30. NIKE-X Advanced Development — Objectives and Description of the Re-entry Measurements Program Phase B (RMP-B) (U), L. C. Hebel, Jr., Bell Laboratories, June 30, 1967. (SECRET)

    Describes objectives and plans for RMP-B.

31. The Kwajalein Field Measurements Program Handbook (U), Bell Laboratories, May 1, 1968. (SECRET)

    Describes the KTS/NIKE sensor and associated activities in support of offense and defense system development with emphasis on gathering, reducing, and reporting radar data in support of the RMP.

32. The Kwajalein Field Measurements Program Handbook Supplement (U), Bell Laboratories, June 1, 1968. (SECRET)

    Provides material of special interest to test planning and scheduling personnel. This supplement also was used to convey corrections and additions to the above handbook.

33. NIKE-X Advanced Development, On-Board Experiments in RMP-B (U), Bell Laboratories, September 1968. (SECRET)

    Presents a detailed discussion of each experiment in the RMP-B on-board RMV-340 measurement series. The on-board measurements contributed knowledge of basic vehicle conditions during reentry and knowledge of near wake and boundary layer properties to aid in the interpretation of field measurements.

34. Ballistic Missile Defense Advanced Development Program, Bell Sphere Experiment (U), Bell Laboratories, July 1, 1971. (SECRET)

    Contains the information obtained from the Bell Sphere Experiments. The Reentry Vehicle chosen for experimental measurements of physical and chemical processes

was the sphere. These experiments provided measurements of precursor radiation; plasma sheathing; wake scattering, resulting from pure-air species, and wake enhancement and elimination, resulting from additions of electron donor atoms and attachment molecule; and on-board measurements of boundary layer and base electron densities.

35. MAR-I Multifunction Array Radar at White Sands, Test Planning Handbook (U), Vol 1 and 2, Bell Laboratories, October 1, 1964. (Vol 1 UNCLASSIFIED; Vol 2 SECRET)

Defines the testing program outlined for the MAR-I at White Sands. In addition, gives a brief description of the MAR-I functional capabilities. Vol 2 offers a detailed description of the MAR-I system and its subsystems. The descriptions contain tables and figures of the MAR-I radar parameters.

36. MAR-I, An Atlas of the Multifunction Array Radar at White Sands (U), Bell Laboratories, October 1964. (SECRET)

Deals exclusively with MAR-I at White Sands. The level of detail in the document is greater than any of the others listed herein. Gives detailed coverage of both system design and operation. This volume contains a profuse collection of functional schematics and line diagrams of consoles.

37. NIKE-X Weapon System — Kwajalein System Description (U), Bell Laboratories, November 30, 1965. (SECRET)

Presents complete description of the Kwajalein System, including MAR-II. Detailed radar design parameters are given as well as functional drawings, etc. Siting considerations for MAR-II are also shown.

38. MAR Design Manual (U), Bell Laboratories, June 1965. (SECRET)

Lists functional requirements and gives detailed functional schematics, equipment location drawings, etc. Document also gives a detailed description of each MAR subsystem.

39. TACMAR Reconfiguration to CAMAR (U) — Case 27703-1300, H. D. Hurlbut, Bell Laboratories MFF, June 17, 1968. (SECRET)

Briefly outlines the major design iterations of the MAR to TACMAR to TACMARK to CAMAR.

40. NIKE-X Advanced Development — CAMAR Program Plan (U), Bell Laboratories, September 15, 1968. (SECRET)

Presents the CAMAR program plan based upon preliminary study. Includes the objectives, brief description of program elements and schedules.

41. CAMAR Program Definition (U), Bell Laboratories, December 1, 1968. (SECRET)

Presents a more detailed description of the CAMAR Program and supersedes the earlier report (Reference 40).

42. CAMAR — First Quarterly Report (U), Bell Laboratories, April 1, 1969. (SECRET)

Summarizes progress for the period 31 December 1968 through 31 March 1969.

43. GUARDIAN — Second Quarterly Report, N. Levine, Bell Laboratories MFF, August 25, 1969.

This is the next quarterly report of progress on the GUARDIAN Program (formerly named the CAMAR Program) (see Reference 42).

References for Chapter 3

SENTINEL System

1. I-67 System Study — Case 27703-1600 (U), J. R. Logie, Jr., Bell Laboratories MFF, August 1, 1967. (SECRET)

   Gives the results of a study to define an ABM defense system to counter a minimal CPR countervalue threat or a USSR counterforce threat.

2. System Study, NIKE-X I-67 Defense Deployment (U), Vol 1 and 2, Bell Laboratories, Vol 1, July 5, 1967; Vol 2, October 6, 1967. (SECRET)

   Records the results of a study of the I-67 deployment of an Antiballistic Missile Defense system. Volume 1 contains a statement of the objectives of the defense, the characteristics of the subsystems, the deployment and organization, and the effectiveness against representative threats. Volume 2 contains the analyses and rationale leading to the selection of the systems described in Volume 1.

3. NIKE-X — CPR and USSR Threat for the January 1967 (I-67) Deployment (U) — Case 27703-1600, W. F. Bauer and R. B. Swerdlow, Bell Laboratories MFF, September 6, 1967. (SECRET)

   Describes in detail the "Design Threat" for the I-67 deployment plan, based on USSR and CPR offensive capability.

4. SENTINEL Siting Analysis — Boston (U) — Case 27703-1600, R. S. Rush, Bell Laboratories MFF, May 2, 1968. (SECRET)

   Evaluates the SENTINEL site options selected for locating a PAR and MSR in the Boston area.

5. Air Defense Capabilities of a SENTINEL Site (U), Case 27703-1600, Bell Laboratories, May 3, 1968. (SECRET)

   Describes the inherent air defense capabilities of a SENTINEL site.

6. Role of the Northernmost PAR in the I-67 Deployment (U) — Case 27703-1600, J. C. Hemmer, Bell Laboratories MFF, August 9, 1967. (SECRET)

   Presents results of a preliminary examination of the role of the northernmost Perimeter Acquisition Radar in the I-67 deployment.

7. SENTINEL — Perimeter Acquisition Radar Face Requirements — Case 27703-1600 (U), R. M. Hangley, Bell Laboratories MFF, January 9, 1968. (SECRET)

   Reports on a study that was conducted to determine the required number of faces per PAR in the SENTINEL deployment.

8. The Hardsite Defense Program — Case 27709-14 (U), R. S. McCarter, Bell Laboratories MFF, December 15, 1967. (SECRET)

   Describes the general problem of a Ballistic Missile Defense system and how the defense objectives, combined with a system design philosophy, shape the defense system within the bounds of the technologically possible.

9. Hardsite Defense — Case 27703-1600, R. Emerson Thomas, Bell Laboratories MFF, January 6, 1968.

   Discusses and considers the general question of different attacks and defenses for hardsite studies.

10. SENTINEL — MDC Man/Machine Interface Functional Requirements for Defense Oriented Functions (U) — Case 27703-1600, H. D. Todd, Bell Laboratories MFF, July 20, 1968. (CONFIDENTIAL)

    Presents the philosophy of man and the computer in the Missile Direction Center of the SENTINEL System.

11. Command and Control — Proposed Implementation of Nuclear Surety (U) — Case 27703-2110, L. R. Bowyer, Bell Laboratories MFF, October 16, 1963. (CONFIDENTIAL)

    Proposes a method of controlling nuclear surety in the SENTINEL System to ensure that defensive missiles are launched and detonated only when appropriately authorized.

12. SENTINEL System — Command and Control Program Design Report — Case 27703-1500 (U), T. L. Saxton, Bell Laboratories MFF, August 14, 1968. (CONFIDENTIAL)

    Describes the Defense Management Programs required for implementing a major portion of command and control functions in the SENTINEL System, and the software interfaces with other major blocks.

13. SENTINEL System — PAR Subsystem Command and Control Requirements — Case 27703-1940, R. F. Ricca, Bell Laboratories MFF, January 6, 1969.

    Defines the interface between the Support Operation Center and the Perimeter Acquisition Radar Subsystem. Describes tactical and support functions of the PAR Manager in the Command and Control concept for the SENTINEL System, radar test and maintenance philosophy, and manual operations of the Manager.

14. SENTINEL System — MSR Subsystem Command and Control Requirements — Case 27703-1400, G. T. Kresan, Bell Laboratories MFF, November 6, 1968.

    Defines the tactical and support functions of the Missile Site Radar Manager in the overall command and control of the SENTINEL System. Outlines the radar test and maintenance concept, defines the radar status levels, describes the manual tactical and support operations of the Radar Manager, and describes the hardware and software required to perform the test and maintenance functions.

15. The Optimum Availability of the NIKE-X Missile Site Radar and Data Processor for the I-67 Deployment (U) — Case 27703-1600, W. H. Mac Williams, Bell Laboratories TM, MM-67-4242-1, October 16, 1967. (SECRET)

    Presents an analytical framework for determining a "best value" of MSR and Data Processor availability, with respect to the dual-purpose I-67 deployment, and discusses the question of whether or not the cost of redundant circuits required to achieve a stated level of reliability is justified.

16. Approximate System Availability Models — Cases 27703-1600 and 36294-22, K. Grace, Jr., Bell Laboratories TM, MM-68-6223-8, October 25, 1968.

    Discusses the evaluation of the steady-state availability of complex systems with limited numbers of spares.

17. Approximate Spares Optimization in Complex Systems — Cases 27703-1600 and 36294-22, S. J. Amster, Bell Laboratories TM, MM-67-6223-8, September 25, 1967.

    Analyzes a spares optimization criterion and shows that it yields spares allocations very close (if not identical) to the optimal criterion where both are applicable and can be readily extended to more complex system configurations.

18. NIKE-X SPARTAN Warhead Effects Analysis (U) — Case 27703-1600, T. R. Lehnert, Bell Laboratories MFF, June 2, 1967. (SECRET)

    Considers effect of missile reliability, different defensive tactics, and target configurations.

19. Effects of Reduced Missile Reliability on SENTINEL Effectiveness (U) — Case 27703-1600, J. E. Keilin, Bell Laboratories MFF, January 23, 1969. (SECRET)

Presents an analysis of two types of missile failures: those which occur during the first portion of the flight and can be replaced by launching a substitute interceptor and those which occur so late in the flight that a substitute cannot be launched. Associates the total in-flight missile reliability with penetrator damage at two defended sites.

20. System Readiness Verification — Site and Multisite Exercises — Case 27703-1600, E. J. Bowers, Bell Laboratories MFF, January 29, 1969.

Describes the site configurations and the required simulation for each type of System Readiness Verification exercises. Proposes an operational doctrine to accommodate real and simulated intersite communications.

21. NIKE-X — Software Generation Breakdown — Its Principles and Practices — D.3. — Case 27703-1500, D. C. Thayer, Bell Laboratories MFF, March 28, 1968.

Describes the organization, content, use, and maintenance procedures for maintaining the SENTINEL Software Generation Breakdown.

22. Evaluation through System Simulation — A Preliminary View — Case 27703-1600, D. W. Abmayr and C. P. Neuman, Bell Laboratories MFF, April 22, 1968.

Proposes that the most profitable approach to system evaluation is through an overall system simulation, examines several simulation approaches, and identifies one as most promising.

23. NIKE-X SPRINT Urban Defense Firing Doctrine — Case 27703-1600 (U), J. W. Shaw, Bell Laboratories TM, MM-67-6422-7, August 25, 1967. (CONFIDENTIAL)

Describes the SPRINT Intercept Allocation Program which is being assembled to perform intercept simulations, study firing doctrine, determine how various tactical problems will be countered, and serve as a framework for any future tactical program.

24. Damage Analysis Tactics Evaluator (DATE) — Case 27703-1600, J. R. Evans and D. L. Murray, Bell Laboratories MFF, May 19, 1967.

Discusses an ABM defense system tactics study model which facilitates the study of defense tactics or firing doctrines and system performance.

25. Optimal Defensive Strategies Using Damage Assessment — Case 27703-1600, C. W. Spofford, Bell Laboratories TM, MM-67-4263-11, August 25, 1967.

Examines the advantages gained by the defense in assessing damage between waves of an offensive missile attack, and the effect of this assessment on the optimal offensive and defensive strategies.

26. SPRINT Firing Doctrine (U) — Case 27703-1600, J. W. Shaw, Bell Laboratories MFF, October 9, 1968. (SECRET-RD)

Presents the figures and notes used in a briefing given to the October 3, 1968 meeting of the SPRINT Vulnerability and Effects Working Group. Covers (1) fratricide and lethality, (2) how SPRINT is to be used, (3) SPRINT-SPRINT spacings, (4) use of SPARTAN and SPRINT in the same battle space, and (5) current estimates of miss distance.

27. Penetrations of the Defense Due to Battle Space Limitations and Leakage — Case 27703-1600 (U), J. E. Keilin, Bell Laboratories MFF, February 19, 1969. (CONFIDENTIAL)

Plots the probability of no penetrations and the expected number of penetrators for various values of arrival probability, defensive single-shot kill probability, number of successful arrivers required to guarantee penetration, and the number of attempted enemy launches.

28. SENTINEL - Missile Site Radar Performance Requirements (U) — Case 27703-1600, R. A. Dayem and R. A. Marth, Bell Laboratories MFF, January 15, 1968. (SECRET)

    Presents the performance requirements placed on the Missile Site Radar (MSR) hardware to ensure fulfillment of its role in the SENTINEL Defense System. Discusses the functions, threat, and environment appropriate to the MSR hardware.

29. SENTINEL — Perimenter Acquisition Radar Performance Requirements — Case 27703-1600 (U), R. S. Larkin and T. E. Lenigan, Bell Laboratories MFF, January 15, 1968. (SECRET)

    Presents the performance requirements placed on the Perimeter Acquisition Radar (PAR) hardware to ensure the fulfillment of its role in the SENTINEL Defense System. Discusses the functions, threat, and environment appropriate to the PAR.

30. Constraints on Attack Density Due to SPARTAN-Induced PAR Blackout (U) — Case 27703-1600, M. J. Spahn, Bell Laboratories MFF, October 19, 1967. (SECRET)

    Describes studies made to determine traffic limitations imposed upon the SENTINEL System by self-blackout under certain conditions.

31. NIKE-X SPRINT Kill Probability — Case 27703-1900 (U), J. M. Protzman, Bell Laboratories MFF, February 21, 1968. (SECRET)

    Describes the kill model adopted, the application of the kill model, and the values of kill probability which result.

32. Graphs of Kill Probability as a Function of Miss Distance for SPARTAN Exoatmospheric Intercepts (U) — Case 27703-1600, J. E. Keilin (UNIVAC), Bell Laboratories MFF, November 27, 1967. (SECRET)

    Develops probability equations to predict kill probability as a function of miss distance, in the light of more recent information, and charts the results.

33. SENTINEL System - Basis for the Development of the SENTINEL Data Processing System Hardware — DPS-2 — Case 27703-1500, T. H. Crowley, Bell Laboratories MFF, July 18, 1968.

    Describes the basis on which the development of SENTINEL Data Processing System hardware is proceeding.

34. NIKE-X — Functional Generation Breakdown for the I-67 Deployment — Cases 27703-1500 and -1600 (U), J. F. McDonald, G. W. McPheters, T. L. Saxton, and P. R. Sternfels, Bell Laboratories MFF, November 28, 1967. (SECRET)

    Outlines the structure (Functional Generation Breakdown) that will be used to specify the I-67 system software requirements. Identifies ten data processing functional configurations, and presents a functional generation breakdown for each.

35. SENTINEL Support Software Philosophy and Structure — Case 27703-1500, W. Hagerbaumer, R. Held, J. J. Kaplan, and J. G. Standley, Bell Laboratories MFF, January 15, 1969.

    Presents design concepts for the SENTINEL Support Software (as distinct from the R&D Support Software), and describes the interrelationships among various support facilities.

36. Programming System for NIKE-X, Language Processor Requirements Temporary Manual, Bell Laboratories, May 1, 1967.

    Considers the goals, capabilities, and restrictions of: real-time and non-real-time programs; the operating system (NEXOS); and the program development facility (NETSS).

37. NIKE-X - Meck Test Program — Case 27703-1600 (U), S. F. Knakkergaard, Bell Laboratories MFF, March 5, 1968. (SECRET)

    Outlines current plans for developing and testing the SENTINEL System capabilities at Meck. These plans reflect the impact of the deployment decision and recent changes in emphasis and schedules.

References for Chapter 4

SAFEGUARD System

1. SAFEGUARD System — Grand Forks IOC System Capability Definition (U) — Case 27950-1600, H. D. Hurlbut, Bell Laboratories MFF, July 8, 1974. (SECRET)

   Summarizes the principal SAFEGUARD System capabilities that will have been demonstrated at Grand Forks for Initial Operational Capability (IOC). In addition, discusses capabilities included in the system but not tested by IOC. Also gives a listing of capabilities once considered for SAFEGUARD but no longer part of the system.

2. SAFEGUARD System — GF ERD System Capability Description — Revision 1(U) — Case 27950-1600, J. M. Wuerz, Bell Laboratories MFF, June 18, 1973. (SECRET)

   Defines the SAFEGUARD System Capabilities which will be available at Grand Forks by the October 1974 Equipment Readiness Date (ERD). Capabilities are given in terms of (1) the threat scenario, (2) traffic levels, (3) available functions, and (4) confidence.

3. Terminating Pindown Defense Operations — Case 27950-1600 (U), K. A. Raschke, Bell Laboratories MFF, May 28, 1971. (SECRET)

   Emphasizes the basic purpose of the pindown defense mode, and explains its basic vulnerabilities. Notes the current procedure for ending counter-pindown engagement planning, and gives three alternatives to the present rules.

4. SAFEGUARD Firing Doctrine (U) — Case 27950-1600, K. A. Raschke, Bell Laboratories MFF, October 16, 1970. (SECRET)

   Provides an up-to-date comprehensive summary of firing doctrine for the Phase 2a SAFEGUARD deployment. The information is based primarily on the June 15, 1970 issue of the SAFEGUARD Data Processing System Performance Requirements.

5. The SAFEGUARD Response to an Attack of Less-Than-Massive Magnitude (U) — Case 27703-1600, K. A. Raschke, Bell Laboratories MFF, July 31, 1970. (SECRET)

   Describes the SAFEGUARD response to an attack that is of less than massive magnitude (accidental launch defense mode). Considers system operation, Interceptor Response procedures, and features investigated but not incorporated.

6. The Response of the SAFEGUARD System to an SLBM Pindown Attack (U) — Case 27703-1600, K. A. Raschke, Bell Laboratories MFF, July 24, 1970. (SECRET)

   Examines the present pindown concept and SLBM threat, and the characteristics and capabilities of the SAFEGUARD response. Considers possible modifications and improvements in system response.

7. An Operational Description of the Functions of the Elements of the SAFEGUARD System During Each of the Defense Modes — Case 27703-1600 (U), J. R. Logie, Jr., Bell Laboratories MFF, February 24, 1970. (SECRET)

   Documents the functions required at the PAR and MSR for the defense modes of system operation.

8. SAFEGUARD System — Operational Concept — Case 27703-1600 (U), J. R. Logie, Jr., Bell Laboratories MFF, May 19, 1969. (SECRET)

   A design concept paper intended to establish a basis for writing a consistent set of Data Processing System Performance Requirements (DPSPRs). The concept covers the defense objectives, command and control configuration, and SPARTAN, SPRINT, PAR, and MSR operation.

9. SAFEGUARD Attack Assessment — A Preliminary Analysis of PAR Capability (U) — Case 27950-1600, R. S. Rush, Bell Laboratories MFF, June 5, 1973. (SECRET)

   Documents an analysis undertaken to evaluate Perimeter Acquisition Radar capability for attack assessment and early warning.

10. Terminal Defense Degradation from Low Altitude Offensive Blackout — Case 27950-1600 (U), L. Behrendt, Bell Laboratories MFF, July 12, 1972. (SECRET)

    Delineates nuclear "blackout" effects in a terminal defense area for various sizes of penetrator weapons.

11. SAFEGUARD Attack Assessment — A Preliminary Analysis of MSR Capability (U) — Case 27950-1600, R. S. Rush, Bell Laboratories MFF, May 14, 1973. (SECRET)

    Documents an analysis to support an evaluation of the Grand Forks Missile Site Radar capability to characterize certain attack patterns.

12. Interceptor Capability in Command Guidance Systems — Case 27950-1600, C. Imagna, Bell Laboratories MFF, October 20, 1970.

    Presents an improved solution to the command guidance system problem of choosing the best point on the capability surface of the guidance loop and computing the steering command which will move the interceptor to this point at intercept time.

13. SAFEGUARD System — The Rational Supporting the MSR Track Performance Requirements (U) — Case 27950-1600, A. W. Besse, Bell Laboratories MFF, December 4, 1970. (SECRET)

    Explains why the particular system configurations and design values were chosen for the Target Tracking portion of the MSR Weapons Process section of the Data Processing System Performance Requirements, and provides supporting documentation. Begins with a brief description of overall system operation.

14. SAFEGUARD — Tactical Wake Track Design — Case 27950-1600, J. E. Marowitz, Bell Laboratories MFF, February 28, 1974.

    Describes the DG-5 Wake Track design. Gives a general description of the overall design philosophy and the implementation of the design by the track function.

15. SAFEGUARD System — Performance of Tactical Kill Assessment (U) — Case 27950-1600, G. C. Smith, Bell Laboratories MFF, April 14, 1973. (SECRET)

    Discusses SPRINT kill probability under various engagement assessments.

16. SAFEGUARD System — Data Processing Performance Requirements Missile Site Data Processor (U), Part 1, G-437953, Case 27950-2110, Bell Laboratories, Revision December 1, 1969. (SECRET)

    This document was superseded by Reference 39, Part 1.

17. SAFEGUARD System — Data Processing Performance Requirements Missile Site Data Processor (U), Part 2, G-437953, Case 27950-2110, Bell Laboratories, Revision October 15, 1969. (SECRET)

    This document was superseded by Reference 39, Part 2.

18. SAFEGUARD System — Data Processing System Performance Requirements PAR Data Processor (U), G-437954, Case 27950-2110, Bell Laboratories, September 15, 1969. (SECRET)

    This document was superseded by Reference 38.

19. SAFEGUARD System — CLC Throughput Study — Status Report — Case 27950-1500, D. B. Knudsen, Bell Laboratories MFF, January 9, 1974.

Reports on the characterization of the CLC-2 hardware. The CLC-2 is a large, high speed, multiprocessor, general purpose computer which performs data processing for the SAFEGUARD System. Presents data on Program Store queueing and throughput of a 10-processor, 10-Program Store system.

20. SAFEGUARD System — CLC Throughput Study — Case 27950-1500, D. C. Ruberg, Bell Laboratories MFF, October 4, 1972.

Gives a preliminary report on the Central Logic and Control 2 throughput work being conducted at Madison, N.J.

21. SAFEGUARD — Meck Test System — IOC Characterization, Maximum Data Throughput Tests — Case 27950-1500, D. L. Fritzsche, Bell Laboratories MFF, February 24, 1971.

Deals with purpose and goals of IOC (Input/Output Controller). Describes measurement of Indirect Command execution times, and maximum data rate to and from each peripheral device; measurement of maximum IOC data throughput; simulation of worst-case M-2 Input/Output activity for evaluation of IOC capability margins.

22. SAFEGUARD System — Basic Deployment — MSR Data Processor Sizing — Case 27950-1600 (U), R. T. Herbst, Bell Laboratories MFF, October 8, 1971. (SECRET)

Provides the basis for the recommendation that the MSR DPS sizing for the basic SAFEGUARD deployment be 10 Processor Units, 12 Program Stores, and 14 Variable Stores, and that the basic deployment, 2 PARS and 4 MSRs, preserve the option to install more than 10 Processors at each MSR site.

23. SAFEGUARD System — Study of EMP Effects on Intrasite Data Communications (U) — Case 27950-2110, P. W. Grabow, Bell Laboratories MFF, June 22, 1972. (SECRET-RD)

Presents applicable Electromagnetic Pulse (EMP) waveforms and spectra for surface, air, and high-altitude bursts. Estimates the effects of these bursts on intrasite data transmission using Lenkurt 46C repeaters with Anaconda cable. Indicates that SPRINT-type air bursts will not produce data errors, whereas surface bursts within a Minuteman field and high-altitude bursts at any distance should be assumed to cause errors in intrasite communication.

24. Functional Description of the SAFEGUARD Data Transmission Subsystem — Case 27950-1100, D. K. Dixon and T. F. Turnmire, Bell Laboratories MFF, July 23, 1971.

Presents complete functional descriptions of the DTC and DTCA.

25. SAFEGUARD System — Tactical Communications Criteria (U), 11,425,721 Revision H, Bell Laboratories, May 31, 1974. (SECRET)

Presents tactical communication requirements including those for survivability, traffic loads, data rates, transmission disturbances, and circuit delay.

26. Procedures and Tolerances in SAFEGUARD Time-Keeping — Case 27950-1500, G. L. Gamble, Bell Laboratories MFF, February 15, 1972.

Presents a detailed description of the major time procedures to be performed at the master time site and at the slave time sites at start-up and on a continuing basis.

27. SAFEGUARD System — System Design Requirements for Displays and Controls (U), Vol 1, 11268704, Bell Laboratories, SDRSDCV1@SD##XXXX, June 30, 1974. (SECRET)

Contains a complete functional description of the tactical manual actions available at IOC at the BMDC, MDC, and PAR, and information relating to each console position.

28. SAFEGUARD System — MSR Radar Monitor Console Displays and Interfaces (Revision 1) — Case 27950-1400, G. T. Kresan and R. H. Thieme, Bell Laboratories MFF, December 5, 1973.

    Describes all Radar Monitor Console indicators, controls, and interfaces. Incorporates recent functional changes and reflects all Engineering Change Proposals that are outstanding for this console.

29. SAFEGUARD System — Command and Control Subsystem — Description of the Missile Monitor and Test Console and TTY — Case 27950-2110, J. J. Cappiello, Bell Laboratories MFF, December 15, 1970.

    Presents a description of the Missile Monitor and Test Console and its functions. Includes status and control signal information related to both remote and local missiles and associated equipment.

30. SAFEGUARD System — Data Management Console and Teletypewriter — Man/Machine Description — Case 27950-2110, I. A. Kronish, Bell Laboratories MFF, October 11, 1974.

    Presents a description of the tasks performed at the Data Management work position.

31. SAFEGUARD System — Command and Control Display Subsystem — Functional Description of the Data Processing Officer Console Position — Case 27950-1500, S. R. Peck, Bell Laboratories MFF, September 26, 1972.

    Presents a consolidation of the relevant material concerning the Data Processing Officer (DPO) console position. This material has been combined into a single, coordinated design specification. Also documents the current design philosophy for this operating position, including rationale, currently designed capabilities, and future expected capabilities.

32. User Oriented Description of the Maintenance and Diagnostic Processor Operating System, Version 1 (MDP/OS-1) — Case 27950-1100, R. A. Buccigrossi, K. J. Henderson, and J. R. Shutt, Bell Laboratories MFF, April 29, 1971.

    Presents a description of the Maintenance and Diagnostic Processor Operating System, Version 1 (MDP/OS-1), with its associated file on development programs.

33. SPRINT Remote Launch — Equipment Status, Control, Readiness Verification, Diagnosis and Maintenance — Case 27703-1000, D. P. Worrall, Bell Laboratories MFF, October 21, 1969.

    Proposes a maintenance concept for the electronic equipment being developed by Bell Laboratories to support remote launchings of SPRINT missiles. General testing, fault detection, status reporting, fault isolation, repair, and verification are considered. The hardware under consideration includes the Remote Launch Data Controller (RLDCT) and the Monitor and Control Multiplexer Local (MCML) located in the Missile Site Control Building (MSCB).

34. SAFEGUARD System — Description of a Logic Simulation Program to Aid in the Development of M&D Programs — Case 27950-1500, H. L. Benoy III and M. P. Smith, Bell Laboratories MFF, January 10, 1974.

    Describes the use and operation of the Maintenance and Diagnostic Logic Simulator (MDLSIM), a set of programs used to aid in developing maintenance and diagnostic test programs by simulating logic circuits found in the SAFEGUARD data processing system.

35. SAFEGUARD — Data Processing System — Maintenance and Diagnostic Processor Controller Functional Description, Case 27950-1500, J. A. Meyer and F. B. Torres, Bell Laboratories MFF, October 25, 1971.

    Presents detailed information on the Maintenance and Diagnostic Processor Controller, an interface and control unit designed by Bell Laboratories for use with the modified CDC-1700 computer. Provides a general physical description of the hardware and details for each part of the hardware.

36. SAFEGUARD System Software Development Plan (U), Vol 1 and 2, G486643, Bell Laboratories, July 1, 1971. Vol 1 (UNCLASSIFIED), Vol 2 (SECRET)

Describes the various activities and events proposed as a means of building the Data Processing System software required for the deployment of the Phase I SAFEGUARD System, and indicates the relationships between the various events. The plan reflects the principal assumptions, activities, and issues that are fundamental to the development and deployment of the SAFEGUARD Data Processing System software.

37. SAFEGUARD — IBM Support Computer System Utilization and Performance Guidelines — Case 27950-1500, E. S. Swanson, Bell Laboratories MFF, January 20, 1972.

Specifies guidelines for the practical solution of problems pertaining to the detection of bottlenecks in the support computer configurations, helps evaluate hardware/software changes before and after the changes are made, and helps provide the best computing service possible given the type of load presented to the computer.

38. SAFEGUARD System — Data Processing System Performance Requirements, PAR Weapons Process (PW1) PAR System Exerciser Process (EPX) (U), 11277025, L. C. Johnson, Bell Laboratories, SRDPARWP@PR##XXXX, June 15, 1970, Revised March 28, 1975. (SECRET)

Contains the Data Processing System Performance Requirements (DPSPRs) for the Perimeter Acquisition Radar (PAR) to be used as a basis for developing the PAR Weapons Process (PW1) and the PAR System Exerciser Process (EPX).

39. SAFEGUARD System — Data Processing System Performance Requirements, MSR Weapons Process (MW1) MSR System Exerciser Process (EMX) (U), 11277024 - Parts 1 and 2, L. C. Johnson, Bell Laboratories, SRDMSRWP@PR##XXXX, June 15, 1970, Revised April 7, 1975. (SECRET)

Contains the Data Processing System Performance Requirements (DPSPRs) for the Missile Direction Center (MDC) to be used as a basis for developing the MSR Weapons Process (MW1) and the MSR System Exerciser Process (EMX).

40. SAFEGUARD System — Data Processing System Performance Requirements, Ballistic Missile Defense Center (BW-1) (U), 11277026, L. C. Johnson, Bell Laboratories, SRDBMDCW@PR##XXXX, November 30, 1970, Revised March 15, 1975. (SECRET)

Contains the Data Processing System Performance Requirements (DPSPRs) for the Ballistic Missile Defense Center (BMDC) to be used as a basis for developing the BMDC Weapons Process (BW1).

41. SAFEGUARD System — CLC Resource Configuration and Initialization by the CLC Control Facility — Case 27950-1500, P. T. Guarneri, Bell Laboratories MFF, November 6, 1972.

Identifies the functions performed by the CLC Control Facility (CTL) which result in configuration and/or initialization of CLC resources, and defines the state of these resources when CTL transfers execution control to either the Basic or the Tactical Operating System.

42. SAFEGUARD System — Tactical Operating System (TOS) Functional Specification — COXTOSFN@FN01XXXX, S. A. Svach, Bell Laboratories, March 12, 1970, Revised January 4, 1971.

Discusses the functions performed by the TOS modules, their relationship to each other, and the relationship of TOS to other SAFEGUARD Data Processing System facilities.

43. Error Handling by the Tactical Operating System (TOS) — Case 27950-1500, J. G. Standley, Bell Laboratories MFF, March 31, 1972.

Explains the general philosophy and the detailed methods that TOS will use to handle and report error conditions. The general error handling philosophy, the TOS structure and division of responsibility for error processing, and the TOS mechanisms for error reporting are detailed.

44. CENTRAN: A Case History in Extensible Language Design, Case 27950-1500, B. N. Dickman, Bell Laboratories TM, TM-74-6623-3, April 1, 1974.

    Presents the design history of CENTRAN to describe how and why the computer language was designed and how it was implemented.

45. SAFEGUARD System — SAFEGUARD Tactical Computer Simulator (STACS) User Manual (U), IBM Corporation, FTXUSERM@UM##XXXX, Revised December 11, 1972.

    Describes the use of the SAFEGUARD Tactical Computer Simulator (STACS) program, with primary emphasis on the new STACS Control language. Encompasses STACS capabilities through Version C. STACS provides facilities for unit/task level testing of CLC-2 programs in a non-real-time environment.

46. SAFEGUARD — Configuration Management Operating System Manual for Operations and Maintenance, SAF-2009, Issue 1, Western Electric, September 1974.

    Gives the detailed structure and procedures for controlling SAFEGUARD hardware and software.

47. SAFEGUARD System — Software Configuration Management Plan, Bell Laboratories, DCCMGMNT@SM02XXXX, Revision 2, August 2, 1974.

    Outlines the general policies and procedures to be followed for controlling SAFEGUARD software to meet the contractual configuration management requirements.

48. SAFEGUARD — Tactical System — Patch Utility Program User Manual for PUP R4/A4 — Case 27950-1500, T. J. Buckley, Bell Laboratories MFF, March 27, 1974.

    Provides information on the use of the SAFEGUARD Patch Utility Program (PUP). This program provides a self-documented storage and maintenance capability for changes or modifications to the bound object code generated during software development at the tactical SAFEGUARD sites (including TSCS).

49. A Method to Add Configuration Identification Information to CLC Software — Case 27950-1500, R. A. Grubic, Bell Laboratories MFF, February 15, 1974.

    Describes a method that will allow Central Logic and Control (CLC) support software to maintain configuration identification information on disc. The method will aid in maintaining the credibility of SAFEGUARD Software by minimizing confusion in the disc patching of tactical software.

50. Execution Preparation Facility (XPF) — User Manual, IBM Corporation, FEXXPFUS@UM13XXXX, February 3, 1975.

    Describes the capabilities, operation, and procedures for using the Execution Preparation Facility. This software facility prepares a collection of programs and data sets for real-time or non-real-time execution on the Central Logic and Control (CLC2) computer or under the SAFEGUARD Tactical Computer Simulator (STACS).

51. SAFEGUARD Tactical System — Proposal for Implementation of a System Logging Function in the Tactical Operating System (TOS) Environment — Case 27950-1500, P. V. Guidi, Bell Laboratories MFF, August 19, 1970.

    Proposes a unified method for logging and recording critical system information based on current Tactical Operating System (TOS) Tape Manager, Error Control, and DEBUG Histogramming design.

52. The Breakpoint Timer — A Proposed Hardware Facility to Aid in Software Development at the TSCS — Case 27703-1500, T. L. Warner, Bell Laboratories MFF, February 17, 1970.

    Describes capabilities required of a proposed new Breakpoint Timer to permit on-line analysis of process tests.

53. SAFEGUARD System — Concepts and Facilities of the CLC Monitor — Case 27950-1500, T. L. Warner, Bell Laboratories MFF, May 25, 1973.

Presents the functions available through the Central Logic and Control Monitor, and provides initial information concerning the user's interface with this subsystem. The CLC Monitor is an independent subsystem which interfaces with the CLC to gather data for debugging, tuning, and evaluation of both software and hardware.

54. SAFEGUARD System — PAR-EPX QUICK LOOK Data Analysis Tool — Case 27950-1500, D. W. Sullivan, Bell Laboratories MFF, April 2, 1974.

Describes a subroutine, QUICK LOOK, which can provide an assessment of the overall functional performance of the PAR Weapons Process during the termination sequence of an exercise.

55. Proposal for SAFEGUARD Data Reduction System, Case 27703-1500, P. A. Highland, Bell Laboratories MFF, May 12, 1969.

Outlines the functional requirements for a fully developed data reduction system, gives examples from typical design areas, and proposes a software structure within which to develop the capability. Discusses the proposed reduction system in terms of its flexibility to handle user-developed routines, stage-by-stage development of capability, machine adaptability, and data reduction run structuring.

56. SAFEGUARD System — System Integration and Evaluation Test Plan (U), G-741752, Bell Laboratories, July 1974. (SECRET)

Contains the Weapons System Contractor's plan for integrating the major components of the SAFEGUARD System. The test plan encompasses basic integration tests, system-level integration testing, and Operational System Readiness Verification (OSRV).

57. SAFEGUARD System — System Test Specification Grand Forks Minuteman Defense Mode System Test (SYS/M3) (U) (80/015), M. J. Suralik, Bell Laboratories, SIBGMM03@SP##XXXX, March 15, 1974, Revised May 12, 1975. (SECRET)

Contains the system test specification for testing the Perimeter Acquisition Radar (PAR), the Missile Defense Center (MDC), and the Ballistic Missile Defense Center (BMDC) operating in a netted mode and in the Minuteman defense mode.

58. SAFEGUARD System — System Test Specification Grand Forks Accidental Launch Defense Mode MSR and PAR Test (U) (80/0610), M. J. Suralik, Bell Laboratories, SIBGAL01@SP##XXXX, March 15, 1974, Revised July 31, 1974. (SECRET)

Contains the system test specification for testing the Perimeter Acquisition Radar and the Missile Defense Center operating in a netted mode and in the Accidental Launch defense mode.

59. SAFEGUARD System — System Test Specification Grand Forks Pindown Defense Mode/Minuteman Defense Mode System Test (U) (80/035), J. F. Dorsch, Bell Laboratories, SIBGPM02@SP##XXXX, May 1, 1973, Revised May 13, 1975. (SECRET)

Contains the system test specification for testing the Perimeter Acquisition Radar, the Missile Defense Center, and the Ballistic Missile Defense Center operating in a netted mode and in the Pindown defense mode followed by a switch to the Minuteman defense mode.

60. SAFEGUARD System — System Test Specification Grand Forks Accidental Launch Defense Mode/Minuteman Defense Mode System Test (GF SYS/AM3) (U) (80/025), M. J. Suralik and R. R. Desiardins, Bell Laboratories, SIBGAM02@SP##XXXX, 11277144, March 15, 1974, Revised May 9, 1975. (SECRET)

Contains the system test specification for testing the Perimeter Acquisition Radar, the Missile Defense Center, and the Ballistic Missile Defense Center operating in a netted mode and in the Accidental Launch defense mode followed by a switch to the Minuteman defense mode.

61. SAFEGUARD System — System Test Specification Grand Forks Autonomous Missile Site Radar (MSR) Minuteman Defense Mode Test (U) (53/0560), J. F. Dorsch, Bell Laboratories, SIBGMA01SP##XXXX, 11277141, November 1, 1974, Revised December 16, 1974. (SECRET)

Contains the system test specification for testing the Grand Forks configured Missile Site Radar (MSR) site operating autonomously in the Minuteman defense mode.

62. SAFEGUARD System — Grand Forks Effectiveness Sensitivity to MSR and PAR Site Availability/Reliability Product (U) — Case 27950-1600, D. C. Swanay, Bell Laboratories MFF, February 1, 1973. (SECRET)

Presents updated calculations of SAFEGUARD System effectiveness sensitivity to MSR and PAR site Availability/Reliability (A/R) product. These calculations include the impace of SALT deployment limitations and reflect current system firing doctrine. The calculations were made in support of a recommendation on a deferred maintenance manning concept proposed for Grand Forks.

63. Evaluation of System A/R — Case 36294-11, K. Grace, Jr., Bell Laboratories MFF, November 8, 1971.

Presents an evaluation of System Availability/Reliability through a series of formulas and a block diagram. The aim of System A/R is to make possible the successful completion of a mission of duration T, based on the probability that the system is operational through the duration of the mission.

64. Simulation Model for System Availability — Case 27703-1600, T. A. Solomita, Jr. and K. Grace, Jr., Bell Laboratories TM, MM-69-8223-5, October 23, 1969.

Describes a SIMSCRIPT simulation model for determining the availability of a complex system by simulating the failure of on-line and spare units, and location, removal, repair, and replacement of failed units. Includes flowcharts and descriptions of the event routines and subroutines, and an example to illustrate the detailed output gathered from a sample run.

65. SAFEGUARD System — Post-IOC Operation and Maintenance Study Programs (Mini-CTM) — Case 27950-1500, D. R. Vogel, Bell Laboratories MFF, October 1, 1974. (UNCLASSIFIED)

Presents a plan for the evaluation of post-IOC operation and maintenance.

66. SAFEGUARD — BMDC System Status Displays — Functional Design Requirements — Case 27950-1500, D. R. West, Bell Laboratories MFF, October 27, 1971.

Defines the tactical display functional requirements for the Ballistic Missile Defense Center System Status Displays. Discusses display-panel locations, indicators, and functions.

67. SAFEGUARD System for Control of Nuclear Employment Authority (U) — Case 27950-2110, N. Ehrlich, Bell Laboratories MFF, May 31, 1973. (SECRET)

Describes the system for transmitting and receiving Nuclear Employment Authority (NEA) messages for SAFEGUARD. Includes the controls, displays, and system operation required for both the tactical and test modes.

68. SAFEGUARD System — MSR and PAR Equipment Readiness Center and PAR Equipment Readiness Officer — Man/Machine Description — Case 27950-2110, I. A. Kronish, Bell Laboratories MFF, November 30, 1972.

Presents descriptions of the most recent design configurations of the MSR and PAR Equipment Readiness Centers and the PAR Equipment Readiness Officer work position. This material replaces three sections of the Man/Machine Interface Description.

69. SAFEGUARD System — MSR Equipment Readiness Officer — Man/Machine Description Section 3.4.1 — Case 27950-2110, T. B. Henry, Bell Laboratories MFF, January 11, 1973.

Describes the Equipment Readiness Officer (ERO) position in the Missile Direction Center. Presents a detailed console description for the System Maintenance console (ERO's console), the functions of the cathode-ray tube and teletypewriter facilities, and specific tasks performed by the ERO. (The primary function of the ERO, on-line maintenance, is referred to elsewhere as the Site Maintenance Coordination Function.)

70. SAFEGUARD System — DPS Real Time Exercisers — Case 27950-1500, G. D. Kepley, Bell Laboratories MFF, January 27, 1970.

Defines the type of real-time exercisers required for the Data Processing Subsystem, and indicates their detection capabilities, as proposed implementation, and an error response philosophy.

71. SAFEGUARD System — Installation Test Program (ITP) Descriptions — Case 27950-1500, L. Lesser, Bell Laboratories MFF, August 11, 1972.

Contains a description of all Installation Test Programs for the Madison Tactical Software Control Site (TSCS) to aid operating and maintenance engineers in problem solving.

72. SAFEGUARD — A System Analysis of Tactical Mode Debugging Tools — Case 27950-1500, L. J. Gawron, Bell Laboratories MFF, April 1, 1974.

Presents an analysis of a number of tactical mode debugging tools and proposes a package of several such tools for implementation within the Tactical Operating System. The analysis involved a survey of test personnel at all three SAFEGUARD sites (MSR, PAR, and BMDC), as well as at the TSCS, to determine which debugging tools would be most useful.

References for Chapter 5

SAFEGUARD System Evaluation

1. SAFEGUARD System — Data Processing System Performance Requirements, MSR Weapons Process (MW1) MSR System Exerciser Process (EMX) (U), 11277024-Parts 1 and 2, Bell Laboratories, SRDMSRWP@PR##XXXX, June 15, 1970, Revised May 20, 1975 (Part 1), April 7, 1975 (Part 2). (SECRET-RD)

   Contains the Data Processing System Performance Requirements (DPSPRs) for the Missile Direction Center (MDC) SPARTAN/SPRINT site in the single-site deployment of the SAFEGUARD System, consisting of the Grand Forks Perimeter Acquisition Radar (PAR), Grand Forks Missile Site Radar (MSR), and Ballistic Missile Defense Center (BMDC) in Cheyenne Mountain.

2. SAFEGUARD System — Data Processing System Performance Requirements, PAR Weapons Process (PW1) PAR System Exerciser Process (EPX) (U), 11277025, Bell Laboratories SRDPARWP@PR##XXXX, June 15, 1970, Revised May 20, 1975. (SECRET)

   Contains the DPSPRs for the PAR Data Processor in the single-site deployment of the SAFEGUARD System, consisting of the PAR, the MSR, and the BMDC.

3. TACSAF Users Guide (U), J. Golub, General Research Corporation, Internal Memorandum DIM #332, November 15, 1974. (SECRET)

   Describes the SAFEGUARD Simulation, its capabilities and limitations, and the options available to the user.

4. MSRSIM Users Guide, Internal Memorandum DIM #333, John T. Fyfe, General Research Corporation, November 13, 1974.

   Describes the MSR Simulation, its capabilities and limitations, and the options available to the user.

5. Intercept Subsystem Evaluation Phase I (U), Vol I-II, McDonnell-Douglas Astronautics Company, Report No. MDC G1246, November 1969. (SECRET-RD)

   Contains an evaluation of SPRINT intercept capability; an analytical determination of miss distance and applicable regions of the field of fire; and an evaluation of the effects of warhead and RF shadowing on kill probability, and the utility of intercept-point bias and drag-bias guidance techniques.

6. Intercept Subsystem Evaluation Phase II (U), Vol I-II, McDonnell-Douglas Astronautics Company, Report No. MDC G1379, August 1970. (SECRET-RD)

   Describes the development of the non-real-time version of the SPRINT Engagement Simulation (SES) and Monte Carlo simulation of 80 intercept points over the field of fire to verify analytic results.

7. Intercept Subsystem Evaluation — Phase III (U), Vol I-II, McDonnell-Douglas Astronautics Company, Report No. MDC G1952, July 1971. (SECRET-RD)

   Describes the determination of guidance-critical intercepts for specifying Meck Test Program requirements, the evaluation of the effect of reduced missile and target-track rates on intercept effectiveness, the evaluation of the real-time target-prediction algorithm, and the development of linear-intercept effects models for system simulation.

8. Intercept Subsystem Evaluation, Phase IV (U), McDonnell-Douglas Astronautics Company, Report No. MDC G3719, August 1972. (SECRET)

Contains the effects of target wake on SPRINT intercept effectiveness, the investigation of exoatmospheric RV tumble on beta history during early reentry, and the initial evaluation of real-time guidance algorithms.

9. Intercept Subsystem Evaluation, Phase V (U), Vol I and II, McDonnell-Douglas Astronautics Company, Report No. MDC G4774, July 1973. (SECRET)

Contains the evaluation of the real-time guidance algorithms and their effectiveness in the waking-target environment, and the effect of target misidentification on intercept capability.

10. Intercept Subsystem Evaluation, Phase VI (U), McDonnell-Douglas Astronautics Company, Report No. MDC G5347, March 1974. (SECRET)

Contains the characterization of miss distance and intercept-point (IP) motion over the SPRINT field of fire, the determination of the linear region applicable to the tactical design, and the updating of the miss distance and IP motion models for the system simulation.

11. SPRINT Intercept Subsystem Validation — Final Summary Report (U), Vol I-II, McDonnell-Douglas Astronautics Company, Report No. MDC G5355, March 1974. (SECRET)

Describes the program of SPRINT intercept tests conducted at Meck to validate the SPRINT Intercept Simulation (SIS). Also indicates the overall approach to simulation validation, the reasons for selecting the particular tests, and the test results.

12. SPARTAN Intercept Subsystem Validation and Characterization — Final Summary Report (U), McDonnell-Douglas Astronautics Company, Report No. MDC G5336, March 1974. (SECRET)

Describes the program of SPARTAN intercept tests conducted at Meck to validate the SPARTAN Intercept Simulation (SPASIM). Also indicates the overall approach to simulation validation, the reasons for selecting the particular tests, and the test results.

13. SENTINEL System — System Development Plan, Vol IV — System Evaluation Program (U), Bell Laboratories, Report 69R019, March 1969. (SECRET)

Presents the results of early evaluation studies on PAR performance, specifically the probability of detection and performance of the nonuniform track scheme. Describes the initial simulations developed for system evaluation, including a SPARTAN footprint generator. Also contains the initial set of test requirements developed for the Meck Test Program.

14. SAFEGUARD System — System Development Plan, Vol 3 Parts I-III — System Evaluation Program (U), Bell Laboratories, March 1970. (SECRET-RD)

Presents the system evaluation results for 1969. Includes the MSR and PAR performance studies, the SPRINT and SPARTAN capability studies, and the performance of the battle-planning functions in the nuclear environment. Part III is devoted to simulation development and modeling for SAFSIM, MSRSIM, and the SPRINT and SPARTAN Intercept Simulations.

15. SAFEGUARD System — System Development Plan, Vol 3, Books 1-3 — System Evaluation Program (U), Bell Laboratories, March 1971. (SECRET-RD)

Presents the system evaluation results for 1970. Major activities included threat-evaluation system effectiveness versus offensive strategies and MSR/MSDP traffic-capacity studies. Also contains additional modeling information for SAFSIM and MSRSIM, updated test requirements and data analysis plans for the Meck Test Program, and results of the initial tests at Meck.

16. SAFEGUARD System — System Development Plan, Vol 3, Books I-III — System Evaluation Program (U), Bell Laboratories, March 1972. (SECRET-RD)

Presents the system evaluation results for 1971. Major activities included MSR/MSDP and PAR/PARDP traffic-capacity and overload-response studies, the environmental effects on SPRINT intercept capability, and initial studies of MSR track in the cluttered environment. Also includes Meck Test Program results and evaluation test plans for TSCS and the tactical site.

17. SAFEGUARD System — System Development Plan, Vol 3 — System Evaluation Program (U), Summary Report and Appendices (4 books), Bell Laboratories, March 1973. (SECRET-RD)

Presents the system evaluation results for 1972. Includes evaluation of MSR track in the cluttered environment (wake and tank breakup), PAR track of unresolved targets, SPRINT effective field of fire, SPARTAN effectiveness, traffic-capacity and overload studies, and system false alarm rates. Also includes Meck Test Program results and simulation development.

18. SAFEGUARD System — System Development Plan, Vol 3 — System Evaluation Program, Part 1, MSR Functional Performance (U), Bell Laboratories, January 1975. (SECRET)

Summarizes MSR/MSDP performance in the functional areas of surveillance, track, target selection, and SPRINT and SPARTAN intercept performance. Includes coast cluster track, wake track, tank breakup, and nuclear effects.

19. SAFEGUARD System — Analysis of Controlled Test Requirements (U), Bell Laboratories, May 1, 1970. (SECRET)

Contains a detailed discussion of the importance of maintaining control over the extraneous debris that normally accompanies target complexes so that data-gathering objectives can be more easily satisfied.

20. SAFEGUARD System — Revised Natural Breakup Model for Titan II Tank (U), Bell Laboratories, Report 73R126, September 1973. (SECRET)

Describes a natural breakup model for a Titan II tank for use by SAFEGUARD designers to evaluate the impact of this environment on system performance.

21. SAFEGUARD System — Tank Breakup — The Phenomenology of Contiguous Clutter (Titan II) (U), Bell Laboratories, Report 73R130, September 1973. (SECRET)

Reviews aspects of the Titan II tank breakup phenomenon relevant to understanding the contiguous-clutter effect.

22. SAFEGUARD System — Wake Track Functional Evaluation Report — Missions in the R19 Test Period (U), Calspan Corporation, Report No. UB-2946-S-35, January 1974. (SECRET)

Analyzes the performance of the wake-track algorithms during five Meck tracking missions. Includes results using targets on both radial and offset trajectories, performance of wake-track entrance and exit tests, and measurement accuracies (biases and measurement variance).

23. SAFEGUARD System — Track Through Tank Breakup Functional Evaluation Report (U), Calspan Corporation, Report No. UB-2946-S-52, October 1974. (SECRET)

Analyzes the performance of the track-through-tank-breakup algorithms during six Meck tracking missions. Two problems noted during analysis of early missions were investigated; solutions were found, implemented, and checked out on later missions.

24. SAFEGUARD System — Modeling of Radar Signal Returns From Wake Based on MSR M2/R17-R19 Data (U), Calspan Corporation, Report No. UB-2946-S-43, March 1974. (SECRET)

Documents wake models derived from individual pulse profiles (digital video recorder data) of wakes recorded by the Meck MSR. Presents a detailed description of the rigorous statistical techniques used to derive the models. The models described were incorporated in MSRSIM.

25. SAFEGUARD System — Wake Track Functional Evaluation Report — Missions in the R19E and R20 Test Periods (U), Calspan Corporation, Report No. UB-2946-S-48, September 1974. (SECRET)

Analyzes the performance of the wake-track algorithms during six Meck tracking missions in the R19E-R20 time frame. Extends the analysis to include targets on fly-by trajectories. Includes an evaluation of changes made in the wake-track algorithms.

26. SAFEGUARD System — Meck Test Requirements for SAFEGUARD System Evaluation (U), Bell Laboratories, June 1, 1968, Revised May 1, 1972. (SECRET)

Details requirements for all tests conducted at Meck to evaluate the system, including radar function test requirements and SPRINT and SPARTAN interceptor test requirements. Also details the data to be obtained on each of these tests.

27. SAFEGUARD System — Meck Test System Compared with the System to be Deployed Case 27950-1500, L. Bernstein, Bell Laboratories MFF, October 19, 1971.

Contains a broad description of hardware and software differences between the Meck and Grand Forks SAFEGUARD installations.

28. SAFEGUARD System — SPARTAN Intercept Function — M2/Tactical Differences Case 27950-1600, E. D. Ballard, Jr., Bell Laboratories MFF, March 9, 1973.

Contains a description of the differences in implementing the SPARTAN intercept function at the Meck and Grand Forks SAFEGUARD installations.

29. SAFEGUARD — Comparison of Tactical and M2 System Data Gathering Algorithms - Case 27950-1600 (U), M. E. Jacobs and R. A. Steigerwalt, Bell Laboratories MFF, January 3, 1973. (SECRET)

Contains a description of the differences between the Meck and Grand Forks implementation of the data-gathering algorithm.

30. SAFEGUARD System — Differences Between the Tactical and Meck Versions of the SPRINT Intercept Function — Case 27950-1600, W. P. Chapman, Bell Laboratories MFF, April 19, 1973.

Contains a description of differences between Meck and Grand Forks implementation of the SPRINT intercept function.

31. SAFEGUARD System — System Development Plan, Vol 1 — Meck Island System Description (U), Bell Laboratories, Revised April 1973. (SECRET)

Contains information concerning the SAFEGUARD System research and development equipment installed in the Kwajalein Atoll, including a comprehensive description of the subsystem and range instrumentation.

32. SAFEGUARD System — Summary of MSR Data Analysis — M1 Test Period (U), Cornell Aeronautical Laboratory, Report No. UB-2946-S-11, March 1972. (SECRET)

Summarizes the analysis of MSR performance based on data gathered during the M-1 test period at Meck. Includes data handling, bias analysis, single-pulse range and angle accuracy, analysis of track-filter performance, amplitude measurement accuracy, and RCS measurement analysis.

33. SAFEGUARD System — M-2 System Functional Requirements and Description (U), Bell Laboratories, August 1, 1972. Revised August 1, 1973. (SECRET)

Compiles the M-2 revision level R20 of the Meck software and includes a broad description of functional capabilities required for R20 and prior revision levels.

34. SAFEGUARD System — Meck System Test Program (U), Bell Laboratories, June 1, 1970, Revised February 28, 1974. (SECRET)

Contains information concerning the Meck Island research and development test program in support of the overall SAFEGUARD System evaluation program, including mission descriptions for all planned system tests.

35. SAFEGUARD System — Target Support Plan (U), Bell Laboratories, June 15, 1970, Revised January 15, 1974. (SECRET)

Contains information on the ICBM and IRBM targets used at Meck, such as procurement cycle, design requirements, description of Reentry Vehicles (RVs), auxiliary objects, target delivery systems, and broad target-related mission results.

36. SAFEGUARD System — Summary of Documentation Available for Meck System Evaluation Tests, S. F. Knakkergaard, Bell Laboratories MFF, May 16, 1975.

Contains a mission-by-mission tabulation of major premission and post-mission reports for the M-1 and M-2 periods. The following reports are included in the tabulation:

Mission Test Specification defines the mission objectives and requirements, and includes range instrumentation priority assignments.

Mission Test Plan restates mission objectives and requirements, and specifies operational details for conducting a mission.

Final Mission Test Report provides final critique on data qualification and presents data in a large number of plots. Data analysis is not included.

Target Data Summary summarizes the results of MSR data relating to the target delivery system performance.

Mission Data Summary Memorandum presents MSR data in a series of plots to be used as a tool for mission analysis and function evaluation.

Preliminary Mission Test Specification was used prior to 1972 to present an early representation of mission objectives and requirements.

Mission Data Analysis Summary Report summarizes results of primary analysis of MSR performance.

This memorandum also lists documents related to miss distance measurement data.

37. SAFEGUARD System — Summary of Meck MSR Measurement Performance Analysis (U), D. R. Johnson and R. A. VanSlooten, Calspan Corporation, Report No. UB-2946-S-42, February 1, 1974. (SECRET)

Summarizes MSR measurement performance. Includes analysis of results on frequency-dependent range biases (TRM-87), T3/T1 range biases (TRM-113), amplitude-dependent angle biases (TRM-113), target-track/missile-track biases (TRM-112), off-axis angle accuracy (TRM-98), and face-to-face biases (TRM-95).

38. SAFEGUARD System — Independent Miss Distance Measurement in the Meck Test Program (U), Bell Laboratories, Report 71R074-10, June 1971. (SECRET)

Discusses the various method considered for measuring miss distance on SPRINT and SPARTAN live-target intercept missions. Provides the rationale and justification for the recommended measurement technique.

39. SAFEGUARD System — System Integration and Evaluation Test Plan (U), Bell Laboratories, July 1973. (SECRET)

Contains a detailed description of the system test and evaluation program originally planned for SAFEGUARD. Describes the philosophy and approach taken in developing the program and the rationale for each of the test scenarios.

40. SAFEGUARD System — System Integration and Evaluation Test Plan Revision (U), Bell Laboratories, G-741752, Revised July 1974. (SECRET)

    Provides the same information as for the original program plan but for a test program that was reduced in scope. This was the program conducted for the SAFEGUARD System.

41. TACSAF Analysis of the M1/M3 (DPM) Scenario (U), General Research Corporation, Internal Memorandum DIM #324, July 26, 1974. (SECRET)

    Documents the results obtained with the system simulation for one of the five System Technical Verification Test (STVT) scenarios. (Also see References 42 through 45.) This scenario tested the Grand Forks configured MSR site operating autonomously in the Minuteman Defense Mode. The results of testing under all five scenarios provided the basis for the performance criteria contained in the test specifications. The scenario is described and the nominal system response to the scenario is provided. Variations in functional performance (i.e., detection altitudes, RV call altitudes, etc.) observed in a series of Monte Carlo runs are indicated. Variations in total system response due to relatively low probability occurrences are described and the probability of observing that particular response is estimated.

42. TACSAF Analysis of the SYS/A3 Scenario (U), General Research Corporation, Internal Memorandum DIM #321, May 17, 1974. (SECRET)

    Documents the results obtained with the system simulation for the netted PAR, MSR, and BMDC operating in the Accidental Launch Defense Mode.

43. TACSAF Analysis of the SYS/M3 Scenario (U), General Research Corporation, Internal Memorandum DIM #325, August 8, 1974. (SECRET)

    Documents the results obtained with the system simulation for the netted PAR, MSR, and BMDC operating in the Minuteman Defense Mode.

44. TACSAF Analysis of the SYS/AM3 Scenario (U), General Research Corporation, Internal Memorandum DIM #327, September 30, 1974. (SECRET)

    Documents the results obtained with the system simulation for the netted PAR, MSR, and BMDC operating in the Accidental Launch Defense Mode followed by a switch to the Minuteman Defense Mode.

45. TACSAF Analysis of the SYS/PM3 Scenario (U), General Research Corporation, Internal Memorandum DIM #326, September 10, 1974. (SECRET)

    Documents the results obtained with the system simulation for the netted PAR, MSR, and BMDC operating in the Pindown Defense Mode followed by a switch to the Minuteman Defense Mode.

46. SAFEGUARD System — System Test Specification, Grand Forks Autonomous MSR Minuteman Defense Mode Test (DPM)(U), (5410100) 11277146, J. F. Dorsch, Bell Laboratories, SIBGMA02@SP##XXXX, March 15, 1974, Revised June 10, 1974. (SECRET)

    Contains the System Test Specification (STS) for testing the Grand Forks configured MSR site operating autonomously in the Minuteman Defense Mode. Provides a detailed description of the scenario, together with the particular performance criteria applicable to the test. Includes the performance bounds and the procedures to be used for verifying the system performance. (Also see References 47 through 50.)

47. SAFEGUARD System — System Test Specification, Grand Forks Accidental Launch Defense Mode System Test (U), (80/010) 11277142, M. J. Suralik, Bell Laboratories, SIBGAL02@SP##XXXX, February 11, 1974, Revised April 15, 1975. (SECRET)

    Contains the STS for the netted PAR, MSR, and BMDC operating in the Accidental Launch Defense Mode.

48. SAFEGUARD System — System Test Specification, Grand Forks Minuteman Defense Mode System Test (SYS/M3) (U) (80/015), M. J. Suralik, Bell Laboratories, SIBGMM03@SP##XXXX, March 15, 1974, Revised October 30, 1974. (SECRET)

    Contains the STS for the netted PAR, MSR, and BMDC operating in the Minuteman Defense Mode.

49. SAFEGUARD System — System Test Specification, Grand Forks Accidental Launch Defense Mode/Minuteman Defense Mode System Test (GF SYS/AM3) (U), (80/025) 11277144, M. J. Suralik, Bell Laboratories, SIBGAM02@SP##XXXX, March 15, 1974, Revised December 15, 1974. (SECRET)

    Contains the STS for the netted PAR, MSR, and BMDC operating in the Accidental Launch Defense Mode followed by a switch to the Minuteman Defense Mode.

50. SAFEGUARD System — System Test Specification, Grand Forks Pindown Defense Mode/Minuteman Defense Mode System Test (U), (80/035) 11277145, J. F. Dorsch, Bell Laboratories, SIBGPM02@SP##XXXX, May 1, 1973, Revised August 23, 1974. (SECRET)

    Contains the STS for the netted PAR, MSR, and BMDC operating in the Pindown Defense Mode followed by a switch to the Minuteman Defense Mode.

References for Chapter 6

Nuclear Vulnerability and Hardening

1. SAFEGUARD System Special Environmental Criteria, 11425709 (U), Revision B, Bell Laboratories, February 5, 1973. (SECRET-RD)

   Specifies the nuclear environments for SAFEGUARD ground equipment.

2. SAFEGUARD System — SPRINT In-Flight Nuclear Requirements, 11327052 (U), Revision A, Bell Laboratories, October 16, 1974. (SECRET-RD-CNWDI)

   Specifies the nuclear environments for the SPRINT missile in flight.

3. SAFEGUARD System — SPARTAN In-Flight Nuclear Environments, 11327051 (U), Revision A, Bell Laboratories, October 16, 1974. (SECRET-RD-CNWDI)

   Specifies the nuclear environments for the SPARTAN missile in flight.

4. Effects of EMP on Bell System Long Haul Transmission Facilities, I. G. Durand, D. V. Batorsky, L. Coffey, R. L. Johnson, G. F. Raupp, and P. M. Simonelli, Bell Laboratories, April 30, 1974.

   Summarizes results of the SAFCA EMP Program in which Bell Laboratories and AT&T Long Lines evaluated the effects of EMP on SAFEGUARD communications circuits.

5. SAFEGUARD System — Missile Site Radar (MSR) Subsystem Hardware Assessment Report (U), Final Issue, Bell Laboratories, May 1, 1975. (SECRET)

   Reports results of MSR nuclear hardness assessment.

6. SAFEGUARD System — Perimeter Acquisition Radar (PAR) Subsystem Hardness Assessment Report (U), Final Issue, Bell Laboratories, January 15, 1975. (CONFIDENTIAL)

   Reports results of PAR nuclear hardness assessment.

7. SAFEGUARD System — Data Processing System (DPS) Hardness Assessment Report (U), Final Issue, Bell Laboratories, May 1, 1975. (CONFIDENTIAL)

   Reports results of DPS nuclear hardness assessment.

8. SAFEGUARD System — Common Equipment Hardness Assessment Report (U), Final Issue, Bell Laboratories, May 1, 1975. (CONFIDENTIAL)

   Reports results of nuclear hardness assessment of equipment common to more than one SAFEGUARD subsystem.

9. SAFEGUARD System — Summary Hardness Assessment Report: Electromagnetic Pulse and Miscellaneous Nuclear Effects (U), Bell Laboratories, May 1, 1975. (SECRET)

   Reports results of EMP hardness assessment for SAFEGUARD ground-based facilities. Also reviews criteria development and summarizes subsystem hardness assessments for aerial dust, crater ejecta impacts, debris, and blast/ground motion-induced building rotations.

10. SAFEGUARD System — SPRINT Missile Subsystem Final Hardness Assessment Report (U), Bell Laboratories, January 15, 1975. (SECRET)

    Reports results of SPRINT Subsystem nuclear hardness assessment.

11. SAFEGUARD System — SPARTAN Missile Subsystem Final Hardness Assessment Report (U), Bell Laboratories, February 15, 1975. (SECRET)

    Reports results of SPARTAN Subsystem nuclear hardness assessment.

12. SAFEGUARD System — Lessons Learned in the SAFEGUARD Nuclear Vulnerability and Hardening Program, Bell Laboratories, June 1, 1975.

    Points out lessons learned — both managerial and technical — by Bell Laboratories and its subcontractors during the SAFEGUARD Nuclear Vulnerability and Hardening Program.

References for Chapter 7

Missile Site Radar

1. The Missile Site Radar (U), R. C. Newhouse; and Technical Characteristics of the Missile Site Radar (U), P. L. Hammann, — Case 27703-1400, Bell Laboratories, May 19, 1964. (SECRET)

   Transcript of presentations on the Missile Site Radar (MSR) as conceived at the time of presentation, May 19, 1964. Summarizes the initial MSR system concept and details of the technical characteristics of the initial MSR design.

2. Work Statement for Development of the Missile Site Radar, GA-8532 Revision E, Bell Laboratories Report, May 6, 1964, Revised October 1, 1968. (SECRET)

   Establishes requirements for the work to be done in connection with the development of the prototype MSR installed at Meck Island. This work statement was a part of Bell Laboratories Contract 600630 with the Raytheon Company.

3. NIKE-X Redundancy Analysis — Case 27703-1600 (U), M. T. Fine, Bell Laboratories MFF, December 21, 1966. (CONFIDENTIAL)

   Presents the results of a study which shows the effect of NIKE-X subsystem availability and reliability on subsystem cost, considering redundancy. For purposes of this study, the missile site module, which includes the Missile Site Radar (MSR) and the Missile Site Data Processor (MSDP), was selected.

4. SAFEGUARD System — Final Report of MSR Hardware Tests at Meck Island — Case 27703-1710 (U), G. A. Ripsom, Bell Laboratories MFF, August 30, 1969. (SECRET)

   Covers MSR testing at Meck from the initial start date of February 1, to August 1, 1968 to the requirements of the GA-8532 Work Statement, Revision E, dated October 1, 1968.

5. NIKE-X Weapon System, Missile Site Radar Description (U), Bell Laboratories, April 1, 1967. (SECRET)

   Provides a brief description of the functions and characteristics of the MSR and its major subsystems. Covers operating frequencies; waveforms transmitted and received; digital, transmitter, receiver, and antenna major assemblies. Primarily describes the Meck prototype MSR and has not been updated to the tactical design.

6. Work Statement Specification for the Development (Phase IV) of the Tactical Missile Site Radar (MSR) SAFEGUARD System (U), GA-8601 Revision C, Bell Laboratories, May 24, 1968, Revised November 1, 1972. (SECRET)

   Establishes the design objectives for the MSR and defines the work to be performed in adapting the prototype design, as defined in GA-8532, for use in the tactical SAFEGUARD System. This work statement was a part of Bell Laboratories Contract 601873 with the Raytheon Company.

7. IMSR Hardware Development and Installation Schedules — Case 27703-1400, P. L. Hammann, Bell Laboratories MFF, January 28, 1970.

   Summarizes the development and installation schedule and incremental hardware cost for the IMSR radar modification.

8. SAFEGUARD System — Tactical System Interface Missile Site Radar Operational Description (U), G-634441, Bell Laboratories, January 1, 1971. (SECRET)

   Contains information on the general characteristics of the radar and on how each subsystem performs.

9. SAFEGUARD System — MSR Hardness Status — Report of Hardness Review at Raytheon, October 7-8, 1969 — Cases 27703-2130 and 27703-1400, P. B. Grimado and L. A. Peralta, Bell Laboratories MFF, December 4, 1969.

   Comments on the October 1969 review of the program to harden the Missile Site Radar equipment against shock and vibration (principally nuclear).

10. SAFEGUARD System — Missile Site Radar (MSR) Subsystem Hardness Assessment Report (U), Bell Laboratories, Final Issue October 15, 1974. (SECRET)

    Final summary Hardness Assessment report for the Missile Site Radar, including exposed and housed equipment.

11. Crater Ejecta Threat to Faces of SAFEGUARD MSR Building — Case 27950-2130 (U), J. M. Jacisin, Bell Laboratories MFF, June 25, 1973. (SECRET)

    Assesses the severity of the crater ejecta environment on the element faces of the SAFEGUARD Missile Site Radar building for a specified peak overpressure.

12. SAFEGUARD System — Review of MSR Antenna Service Vehicle — Case 27950-2110, H. W. Lubow and J. G. Trautman, Bell Laboratories MFF, July 19, 1973.

    Documents the results of a review of the MSR Antenna Service Vehicle held at Bell Laboratories, Whippany, N.J., including such aspects as safety, human factors, and corrosion control.

13. NIKE-X MSR — Antenna Performance with Large Numbers of Failed Elements — Case 27703-1400, T. H. Feiertag, Bell Laboratories MFF, May 6, 1966.

    Discusses curves of root-mean-square (rms) sidelobe degradation, gain loss, and rms steering error for the MSR when 0 to 50 percent of the front radiating elements are made inoperative.

14. SAFEGUARD — The System Impact of MSR Q-Channel Blanking Performance (U) — Case 27950-1600, W. F. Boyer, Bell Laboratories MFF, April 15, 1974. (SECRET)

    Documents a study conducted to determine the system performance implications of the current estimate of Q-channel blanking performance. Concludes that this current Q-channel performance does not significantly degrade the overall system and recommends a revision of the MSR Performance Design Specification.

15. NIKE-X — MSR Q-Channel Performance — Case 27703-1400 (U), S. B. Windes, Bell Laboratories MFF, July 8, 1966. (SECRET)

    Defines the MSR Q (broadbeam receiving) channel and investigates its effectiveness in helping to prevent sidelobe tracking with and without a clutter fence.

16. SAFEGUARD System MSR — Q-Channel Evaluation — Case 27950-1400, P. D. Hansell, Bell Laboratories MFF, December 13, 1973.

    Outlines a procedure for determining MSR Q-channel receiver parameters using only the receiver. The purpose of this procedure is to measure the effect of these parameters on Q-channel blanking performance and to define a range of values for which performance meets or exceeds specified values.

17. SAFEGUARD System — MSR - Prototype and Tactical Phase Shifter Diode Reliability — Case 27950-1400, M. R. Dungan, Bell Laboratories MFF, March 18, 1971.

    Records a presentation covering prototype (Meck) diode failures and rates, accelerated aging test and effectiveness, evaluation of the tactical diode reliability, and predicted tactical system phase shifter failure rates.

18. A High Power, S-band, Reciprocal, PIN Diode Phase Shifter — Case 27703-1400, G. C. Di Piazza and R. J. Gutmann, Bell Laboratories TM, MM-65-6468-1, August 21, 1965.

    Describes design details of diode phase shifter built for initial MSR design. Present MSR phase shifter design was based on work reported here, extrapolated to the higher power requirements of the prototype and tactical systems.

19. Diode Specification for High Power Microwave Phase Shifters and Switches — Cases 27703-1950 and 27703-1800, A. Zacharias, Bell Laboratories TM, MM-67-2652-5, March 9, 1967.

    Explores the interaction between circuit parameters and diode parameters in high-power microwave phase shifters and switches, and presents a design procedure for producing a shifter or switch that is optimum for a given application.

20. NIKE-X MSR — Relation Between Phase Shifter Bit Size Error and Antenna Performance — Case 27703-1400, S. B. Windes, Bell Laboratories MFF, September 21, 1966.

    Documents a computer-aided study to determine how MSR antenna performance would be affected by uncertainties in determining the average size of the phase shifter control bits.

21. NIKE-X MSR Antenna Performance vs. Number of Phase Shifter Bits — Case 27703-1400, R. J. Tromley, Bell Laboratories MFF, April 22, 1966. (CONFIDENTIAL)

    Summarizes calculated MSR antenna performance as a function of the number of phase shifter bits. The data include effects of antenna random errors which result from manufacturing tolerances, reflections, and calibration inaccuracy.

22. NIKE-X MSR — Proposed Methods of Antenna Per-Element Phase Alignment — Case 27703-1400 (U), P. T. Sproul, Bell Laboratories MFF, March 20, 1964. (CONFIDENTIAL)

    Describes the phase shifter bit measurement system and estimates accuracy of measurement. Discusses implementation for fault location use.

23. SAFEGUARD — MSR — Use of RF Absorber on Small Array Adapter Ring — Case 27703-1400 (U), S. B. Windes, Bell Laboratories MFF, January 15, 1970. (CONFIDENTIAL)

    Presents reasons for recommending that absorber material be added to the adapter

ring around the Missile Site Radar array. Signal-to-clutter ratios that meet system requirements are among the objectives of this recommendation.

24. SAFEGUARD System — MSR Antenna Retrofit for Absorbing Spill-over Energy — Case 27703-1400, D. L. Chandler, Bell Laboratories MFF, June 9, 1970.

    Describes the methods of retrofit possible when adding an absorber to attenuate the feedhorn spillover energy on the RF chamber front-end adapter of the Missile Site Radar.

25. SAFEGUARD System — MSR Array Surveys — Case 27950-1400, D. L. Chandler, Bell Laboratories MFF, August 24, 1971.

    Presents detailed optical methods for determining the effective pointing direction and clocking angle of each tactical MSR array. Includes a method to relate these parameters to system coordinates. The optical techniques apply equally to Meck and tactical arrays.

26. SAFEGUARD System — Missile Site Radar Monopulse Comparator Alignment — Case 27950-1400, E. O. Martin, Bell Laboratories MFF, January 3, 1974.

    Details a simple and effective technique for monopulse comparator alignment on the Meck Missile Site Radar. This technique was used successfully at the Grand Forks MSR.

27. SAFEGUARD System — MSR — Tactical RF Receiver Compression Performance — Case 27950-1400, E. W. Potter, Jr., Bell Laboratories MFF, September 29, 1971.

    Briefly describes the main difference between the tactical MSR RF receiver and the prototype designs. Includes a block diagram description of the tactical RF receiver and plots of the compression curves and input/output measurement curves for the double conversion mixer, the UHF Mixer/IF amplifier, and the three-stage parametric amplifier stages of the tactical design.

28. SAFEGUARD — Dispersed Pulse Amplitude Measurement and Adaptive Thresholding for the Tactical MSR (Summary) (U) — Case 27950-1400, P. D. Hansell and K. M. Hueter, Bell Laboratories MFF, June 27, 1972. (CONFIDENTIAL)

    Discusses design concept of dispersed pulse measurement, which will provide improved tracking of waking targets and improved AGC operation.

29. NIKE-X Missile Site Radar — Low Level Transmitter Configuration, J. H. Pruden, Bell Laboratories MFF, March 8, 1965.

    Describes the planned MSR low-level transmitter configuration and its connections to other MSR equipment, and describes a suggested revision. Compares the two configurations and presents objections and a possible compromise to the revision.

30. Missile Site Radar (MSR) Command, Control, and Interface Computer (CCIC) — Functional Description (MSR 4.1-11), Raytheon Company, Revision 1, July 31, 1969.

    Describes how various digital radar-controlled transform computers generated orders as timing pulses for analog radar equipment and how replies based on these orders are generated for processing by the computer.

31. SAFEGUARD System — MSR Transmitter — Summary of VA-144 Performance — Case 27950-1400, P. T. Sproul, Bell Laboratories MFF, December 27, 1974.

    Summarizes performance of the VA-144 klystrons at Meck and at Grand Forks. Includes discussion of problems encountered and solutions achieved. Also considers life experience at Meck versus design goal.

32. VA-144 ESM RB-9 Program, Vol I-VIII, Varian Associates.

    Documents all work performed in final development of the VA-144 klystrons for tactical MSR transmitter. Includes copies of key technical memoranda.

33. Waveguide Breakdown Effects at High Average Power and Long Pulse Length, A.S. Acampora and P. T. Sproul, BSTJ, Vol 51, No. 9, November 1972.

Discusses waveguide breakdown due to particulate matter in the presence of long pulses and high average power and develops an analytical solution to predict breakdown performance. Confirming experimental results are presented.

34. SAFEGUARD System — MSR — Feedhorn and Waveguide Arc Logic — Case 27950-1400, J. H. Pruden, Bell Laboratories MFF, August 3, 1971.

Reviews logic associated with recent findings concerning the mechanisms of waveguide and feedhorn arcing in the MSR to ascertain that the corrective and protective actions taken in the high level transmitter are optimum to maintain MSR operation.

35. SAFEGUARD System — MSR Grand Forks Collector Pressure Increase Problem Summary — Case 27950-1400, P. T. Sproul, Bell Laboratories MFF, March 20, 1975.

Summarizes the effort to identify the source of a pressure drop increase in the klystron cooling channel. The problem was encountered only at the Grand Forks installation. Includes the results of the study and corrective action.

36. NIKE-X Missile Site Radar Interface with in Input/Output Controller of the Data Processing System — Case 27703-1400, J. O. Hardy, Bell Laboratories MFF, December 13, 1965.

Documents information on the interface between the Input/Output Controller of the NIKE-X Data Processing System and the Missiles Site Radar Command, Control, and Interface Computer.

37. SAFEGUARD System — Tactical System Interface — Missile Site Radar/Data Processor (U), Digital Data Format Specifications, G-438801, Bell Laboratories, KMFTSIMD@FS##XXXX, October 1, 1969, Revised February 3, 1975. (SECRET)

Contains information on the various instructions and interfaces, with the parameter contained in the interface words identified as to value and limits.

38. SAFEGUARD System — MSR/MSDP Interfaces, Vol II — Hardware/Software Interactions (U), Books 1 and 2, G-741636, Bell Laboratories, June 1, 1973. (SECRET)

Contains information on the data paths selected in the MSR based on the transmit and receive instructions and what information is generated as radar replies.

39. SAFEGUARD System — MSR/MSDP Interfaces, Vol I — Timing and Control (U), Part 1, G-741636, Bell Laboratories, August 31, 1973. (CONFIDENTIAL)

Contains information necessary to determine what timing operations occur within the Missile Site Radar as a result of a radar transmit or receive instructions in all modes of operation.

40. Missile Site Radar (MSR) Beam Steering Computer (BSC) Functional Description, (BAA 4.2-11), Raytheon Company, September 15, 1967.

Describes the process of converting $\sin\alpha$ and $\sin\beta$ steering angles to phase differences between adjacent radiating elements.

41. Digital Control Group Concept Document, Vol I-IV, L. Shear, Raytheon Company, BR-7579, November 1973.

Contains information on the design concepts and descriptions of the various digital controllers that interface with the analog sections of the MSR.

42. SAFEGUARD System — MSR Radar Monitor Console Displays and Interfaces — Case 27950-1400, G. T. Kresan and R. H. Thieme, Bell Laboratories MFF, December 21, 1971.

Describes all Radar Monitor Console (RMC) indicators, controls, and interfaces.

43. NIKE-X MSR — Outline of Required Internal Radar Tests — Case 27703-1400, R. A. Reed, Bell Laboratories MFF, January 20, 1966.

    Outlines those MSR tests requiring more than one subsystem and varying degrees of control by the MSDP. Establishes overall requirements for these tests.

44. SAFEGUARD System — Study of MSR Digital Control Group (DCG) Diagnostic Test for Fault Location — Case 27950-1400, L. R. Hamilton, Bell Laboratories MFF, December 9, 1971.

    Describes the results of a study of the controller located in the control rack to determine the feasibility of using the test outputs for fault isolation and maintenance purposes in the DCG.

45. System Development Plan, Vol 3 — System Evaluation Program, Part 1 — MSR Functional Performance (U), Bell Laboratories, January 1975. (SECRET)

    Contains all significant evaluation results for the tactical MSR and Missile Systems. Includes the Calspan analyses of sphere and satellite tracking data showing range and angle tracking accuracies.

46. SAFEGUARD Performance/Design Specification Missile Site Radar (U), 11327054 Revision B, Bell Laboratories, October 16, 1974. (SECRET)

    Specifies the performance and design characteristics of the MSR to establish a production base. This specification is the highest generation document covering the MSR.

47. MSR Stateside Antenna Subsystem Test Report (U), Raytheon Company, BR-4644, August 1, 1968, with Errata Sheet, December 23, 1968. (SECRET)

    Pertains to measurements of a full-scale MSR antenna array on a pattern measurement range.

    Part 1 — Data summary by performance areas, specifications, and design objectives.

    Part 2 — Appendix A: Antenna Patterns

    Part 3 — Appendix B: Contour Plots

48. SAFEGUARD System Reliability Program Review, April 5 and 6, 1972, Minutes, Bell Laboratories, April 1972. (SECRET)

    A review and update of the current A/R values for the SAFEGUARD System and its major equipment based on currently available data reflecting the Phase I deployment concept.

49. NIKE-X — MSR Antenna — Characteristics of EMP Considered as Threat to MSR — Case 27703-1400 (U), T. H. Feiertag, Bell Laboratories MFF, September 29, 1966. (SECRET)

    Calculates the spectrum and energy content of a typical Electromagnetic Pulse (EMP) caused by a nuclear detonation to determine its effect on the MSR antenna front element and phase shifter.

50. NIKE-X — MSR Antenna — EMP Threat to MSR Antenna — Case 27703-1400 (U), S. E. Windes, Bell Laboratories MFF, August 25, 1967. (SECRET)

    Updates a previous memorandum by T. H. Feiertag, dated 9/29/66, entitled, "Characteristics of EMP Considered as a Threat to MSR."

References for Chapter 8

Perimeter Acquisition Radar

1. PAR Phase IA Report (U), General Electric Company, EHM-11043, March 1, 1967. (SECRET)

   Summarizes the initial definition phase of the Perimeter Acquisition Radar (PAR) development. Includes detailed requirements and configuration for the PAR.

2. PAR Phase II Definite Plans (U), Revision A, Vol I-X, General Electric Company, EHM-1134/75, Revised May 1968. (Vol I-V, VII, and IX — SECRET; Vol VI, VIII, and X — UNCLASSIFIED).

Volume I	Executive Summary
Volume II	Technical Development Plan
Volume III	Specifications, Books 1-10
Volume IV	Program Operations Plan
Volume V	Manufacturing Plan
Volume VI	Site Activation Plan
Volume VII	Test Plan
Volume VIII	Configuration Management Plan
Volume IX	Reliability and Quality Assurance Plan
Volume X	Engineering Support Plans

   Summarizes the development of the PAR, including the design, development, and manufacture of the PAR equipment.

12. SAFEGUARD System — Technical Requirements for Facilities Construction, Vol 1 and 3, Issue 2, Rev 2C, J. G. Matthews, Bell Laboratories, November 16, 1972.

    Volume 1 General, Drawing Nos. 11277040, 11277041, and 11277042, Issue 2, Rev 2C.

    Volume 3 PAR Building, Drawing Nos. 11277048, 11277049, 11277040.

    Contains detailed drawings of the PAR facilities to be constructed in North Dakota (PAR-1) and Montana (PAR-2).

14. SAFEGUARD System — PAR-1 R&D Test Plan, Revision A, Bell Laboratories, August 2, 1972.

    Defines the test program to verify system performance for the PAR installation at Grand Forks, North Dakota.

15. SAFEGUARD System — Special Environmental Criteria, Bell Laboratories, 11425709 Revision B, August 18, 1971. (SECRET)

    Defines the environmental criteria the radar equipment had to meet to withstand nuclear effects.

16. Analysis of the Beam Steering Errors Arising from Antenna Element Displacements of a Phased Array Radar, D. J. Enright, Bell Laboratories TM, TM-75-6512-1, April 10, 1975.

    Analyzes beam steering errors caused by mechanical displacements of the antenna elements.

17. SAFEGUARD System — PAR — PAR Spectrum Signature Summary Report (U) — Case 27950-1940, V. D. Vanacore, Bell Laboratories MFF, March 26, 1975. (SECRET)

    Summarizes the characterization of the PAR spectrum signature, including electromagnetic compatibility.

18. SAFEGUARD Performance/Design Specification Perimeter Acquisition Radar (U), BMDMP 4.04.A, 11327060, Revision B, Bell Laboratories, November 21, 1969, Revised October 16, 1974. (SECRET)

    Contains the radar subsystem performance requirements for the PAR.

19. SAFEGUARD System — Perimeter Acquisition Radar (PAR) Subsystem Hardness Assessment Report (U), Case 27950-2130, Bell Laboratories, Final Issue, January 15, 1975. (CONFIDENTIAL)

    Summarizes the program to evaluate the ability of the hardware to withstand the nuclear shock and vibration requirements.

20. SAFEGUARD System — An Analysis of the Effect of Thermal Noise on the PAR Angle Tracking Precision (U) — Case 27950-1940, D. J. Enright, Bell Laboratories MFF, December 18, 1972. (SECRET)

    Analyzes the effect of thermal noise on the PAR angle tracking precision, including expected PAR performance.

21. SAFEGUARD System — PAR External Receive Pattern Measurements Program — Final Report (U), A. T. Vitenas, Bell Laboratories MFF, July 26, 1974. (SECRET)

    Describes a program to measure the antenna receive pattern. Includes an analysis of the measurement results.

22. NIKE-X PAR Trade-off and Study Report (U),
35. Volume I-XIV, General Electric Company, July 1, 1967. (SECRET)

Volume I	Cost Optimization Study
Volume II	Transmitter Study
Volume III	Antenna and RF Component Study
Volume IV	Signal Processing Synthesis
Volume V	Monitoring Study
Volume VI	Environment and Propagation Studies
Volume VII	Radiation Control Study
Volume VIII	Specifications — Tube
Volume IX	Specifications — Solid State
Volume X	Surveillance Performance Studies
Volume XI	Noise Measurement and Threshold Determination Studies
Volume XII	Parametric Studies
Volume XIII	Availability vs Cost Analysis
Volume XIV	Cost and Schedule Study

    Discusses the results of a study concerning system design problems, schedules, cost, and trade-offs for a PAR program evolving from the NIKE-X system. Includes the rationale for component selection and specifications for equipment to be used in the PAR.

36. Analysis of Auroral Data from Prince Albert Radar Laboratory, Final Report, W. E. Jaye, W. G. Chestnut, and B. Craig, Stanford Research Institute, SRI Project 7465, September 1969.

    Summarizes the results of a study conducted at Prince Albert Radar Laboratory in Canada to investigate auroral effects at UHF.

37. SAFEGUARD System — Description of the Hardness Verification Program for the PAR Ground Plane and Antenna Elements — Case 27950-2130, L. Y. Cooper, Bell Laboratories MFF, January 20, 1971.

    Describes a program to evaluate the PAR facility and equipment for hardening against nuclear shock and vibration, thermal stress, dust, and debris to ensure that PAR integrity could be maintained during an attack.

38. PAR Sensor Subsystem — Availability and Reliability Summary (U), General Electric Company, October 24, 1973. (CONFIDENTIAL)

    Discusses the availability and reliability of components in the PAR.

References for Chapter 9

SPRINT Missile Subsystem

1. SAFEGUARD System — SPRINT Warhead Section Tests — Case 27950-1000, D. B. Seamans, Bell Laboratories MFF, October 28, 1971.

   Summarizes the results of SPRINT Warhead Section tests to date, including results of both the preflight ground testing of the FTQs (Flight Test Qualification Units) as well as flight tests.

2. SAFEGUARD SPRINT Interceptor Response — Intercept Deadzone (U) — Case 27703-1500, S. C. Nordberg, Bell Laboratories MFF, March 26, 1970. (CONFIDENTIAL)

   Describes a method developed to determine the upper and lower limits of the missile capability deadzone along the trajectory of a particular object. Assumes that missile capability bias is available, and shows how a two-iteration process is used to compensate for approximations of missile and target flight. Accuracy of the method is well within the limits required by SPRINT Interceptor Response for intercept planning.

3. SAFEGUARD Performance/Design Specification SPRINT Subsystem (U), 11327045 Rev. A, Bell Laboratories, December 31, 1969, Revised December 18, 1974. (SECRET)

4. SPRINT Phase III Development Program Summary, Martin Marietta Corporation, OR-3650-1, February 1973. (SECRET)

   Accents the highlights of the development program.

5. Phase III Development Plan SPRINT Subsystem (U), Vol I-IV, Martin Marietta Corporation, OR-3650-2, July 1974.

   Volume I — System Description and Overall Development Plan. Gives an overall description of SPRINT, including major changes that have occurred. (SECRET)

   Volume II — Engineering Development and Test Programs. Gives a complete description of the development and testing of major assemblies. Included are some problems encountered and their resolutions. (SECRET-RD)

   Volume III — Support Activities. Gives a description of support activities such as programming, quality, reliability, procurement and documentation. (CONFIDENTIAL)

   Volume IV — Flight Test Program. Includes a listing of the flight test program with significant milestones highlighted. (SECRET)

6. SAFEGUARD System — Missile Subsystem Interface Description (U), Bell Laboratories, January 1, 1974. (SECRET)

   Combines remote launch design requirements with all hardware and software interfaces, except Guidance, which is covered below (Reference 7).

7. SPRINT I Missile Subsystem Interface Specification – Guidance Software with SPRINT I Missile Hardware (U), 11268700, Bell Laboratories, November 27, 1973. (SECRET)

8. SPRINT – S-Band Attenuation Measurements on SPRINT 1st and 2nd Stage Motors (U) – Case 27703-1000, E. P. Chowaniec and L. L. LeBlanc, Bell Laboratories MFF, February 3, 1965. (CONFIDENTIAL)

   Presents results, methods, and correlation for RF attenuation measurements performed on SPRINT first- and second-stage motors at the Allegheny Ballistics Laboratory. These measurements were part of the SPRINT communications program designed to achieve the first slant-look measurements at S-band through full-scale flame plumes.

9. SAFEGUARD SPRINT/SPARTAN Component Parts, First Source Status Program (G741194) – Cases 27703-1000 and 27703-1010, J. Brown, Bell Laboratories MFF, April 28, 1969.

   Discusses the program written to list the SPRINT/SPARTAN Component part "first source" information. Lists the functions of the program and indicates the key-punching formats.

10. SAFEGUARD System – First Stage Ballistic Trajectories for Remote Launch of the SPRINT Missile – Case 27703-1000, R. H. Whiting, Bell Laboratories MFF, May 12, 1969.

    Derives the algorithm and justifies the assumptions used to calculate trajectories for SPRINT after first-stage burnout with delayed second-stage ignition.

11. SAFEGUARD System – SPRINT Missile Subsystem – Final Hardness Assessment Report (U), Bell Laboratories, January 15, 1975. (SECRET-RD)

12. A Reliability Model for the SPRINT Missile – Case 27703-1600 (U), S. Dier, Bell Laboratories MFF, June 30, 1967. (SECRET)

    Generates and makes available probabilistic data and analysis pertinent to the development of a reliability model of the SPRINT missile.

13. SAFEGUARD Performance/Design Specification – SPRINT Control Equipment (Remote) (U), 11327050 Rev. A, Bell Laboratories, May 26, 1970, Revised October 16, 1974. (SECRET)

14. SPRINT Interceptor Response – Location of SPRINT Missile Blackout – Case 27950-1500 (U), R. L. Buchwalter, Bell Laboratories MFF, December 10, 1970. (CONFIDENTIAL)

    Describes an analytical method for locating blackout along the SPRINT trajectory. The method considers the characteristics of the SPRINT trajectory, the blackout volume, and the times of formation and dissipation of the fireball.

15. Final Report – Aging and Deterioration Test Program – First and Second Stage Rocket Motors, Martin Marietta Corporation, Document No. TRP 10301481-008, June 27, 1975. (UNCLASSIFIED)

    Presents the results of tests on SPRINT missile motors aged in a configuration and environment simulating the tactical in-cell conditions. Discusses motor design, propellant, test configuration, and test procedures.

16. SAFEGUARD Performance/Design Specification – SPRINT Launch Equipment (U), 11327047 Rev. A, Bell Laboratories, October 16, 1974. (SECRET)

17. SPRINT Test Control and Monitoring Unit (MGS Testing), S. Gross, Bell Laboratories TM, MM-67-6223-3, May 17, 1967.

    Describes the operation and circuit structure of the SPRINT Test Control and Monitoring Unit, which is being used for automatic, long-term reliability testing of the SPRINT Missile Guidance Set.

18. Shock Testing of SPRINT Missile Guidance Sets and Safety and Arming Devices in Simulated Flight Environments — Cases 27703-1000 and 25601, A. F. Stormont, Bell Laboratories MFF, March 20, 1969.

    Reviews test criteria; describes test apparatus, instrumentation and data analysis methods; and compares flight-produced and laboratory-simulated shock environments in the guidance, control, and warhead compartments of the SPRINT missile.

19. SAFEGUARD System — SPRINT Burst Delay Timer Effectiveness Study (U) — Case 27703-1600, M. J. DeFazio, Bell Laboratories MFF, June 23, 1969. (SECRET-RD)

    Describes a study made to determine the conditions, if any, under which a SPRINT Burst Delay Timer would be useful for enhancing the effectiveness of the SAFEGUARD System. Includes consideration of SPRINT self-blackout and effects of ionizing radiation.

20. Accleration and Acoustic Testing of SPRINT/SPARTAN Cables and Antennas — Cases 27703-1000, 27703-1010 and 37994-2, R. T. Wood, Jr., Bell Laboratories MFF, September 8, 1969.

    Records results of acoustic noise and acceleration tests made on SPRINT/SPARTAN cables 11276263, 11275280, and 11275152.

21. SAFEGUARD System — SPRINT — Effects of Launch Station Verticality and Azimuth Errors on the Pitchover Error Budget (U) — Case 27950-1000, E. F. Engelbert, Bell Laboratories MFF, February 14, 1972. (CONFIDENTIAL)

    Make a determination as to the extent of station verticality and azimuth errors on the overall pitchover error budget for the SPRINT missile system.

22. Recommendations for Harnessing Techniques for SPRINT — Cases 37992-1 and 27703-1810, G. J. DeVries, Bell Laboratories MFF, July 29, 1968.

    Discusses a lecture-demonstration on the preparation of wiring harnesses for the SPRINT missile. Shows the advantages of different processing techniques, including the use of flat wireboards, master template breakouts, precut wires, and preterminated shields.

23. SPRINT MBGE Test Set Encoder Section — Case 36294-22, L. Rosa, Bell Laboratories MFF, May 22, 1964.

    Reports results of Bell Laboratories reliability analysis of the memory system contained in the encoder section of the SPRINT Missile-Borne Guidance Equipment test set. Mean time between replacements figures for the memory system, the encoder less the memory, and the encoder with the memory are included.

24. Calibration of SPRINT Autopilot Accelerometer (U) — Case 27703-1810, H. J. Luer and R. G. McCoy, Bell Laboratories MFF, July 20, 1964. (CONFIDENTIAL)

    Describes statistical analysis undertaken in setting performance parameter limits for the SPRINT autopilot accelerometer. Discusses nature of SPRINT missile error budget and the application of the Central Limit Theorem in the statistical approach to the calibration of the autopilot accelerometer. Tabulates maximum errors allowable in accelerometer calibration.

25. SPRINT/SPARTAN — Reliability Study of MGS R&D Field Experience — Case 36294-22, W. J. Akstulewicz, Bell Laboratories MFF, September 29, 1969.

    Documents a reliability study of Missile Guidance Sets under research and development field conditions. The study considered (1) units in ground test programs, (2) those sets designated for flight tests, and (3) sets in storage.

26. SPRINT Missile Guidance Set, Reliability Evaluation Results — Case 36294-22, Richard G. Smith III, Bell Laboratories MFF, September 11, 1970.

    Describes implementation of the test program defined in SPRINT Guidance Set Reliability Evaluation Specification G485090 and documents the test results.

27. SPRINT — Launch Preparation Equipment — Case 36294-22, T. L. Tanner, Bell Laboratories MFF, March 26, 1971.

Reviews the reliability predictions for the integrated-circuit version of the SPRINT Launch Sequencer (IC LSEQ), which replaces the discrete LSEQ in the Launch Preparation Equipment for the tactical SPRINT system.

28. SENTINEL System — Explosive Quantity — Safety Distances for SPARTAN and SPRINT Missiles — Case 27703-2110, C. G. Reinschmidt, Bell Laboratories MFF, September 4, 1968.

Documents a reduction in the distances required between quantities of SPRINT and SPARTAN missiles and the nearest inhabited building. The revised safety classification should permit easier handling and controlling of missile sections during checkout.

29. SAFEGUARD System — SPRINT EED No-fire Characteristics — Case 27950-1000, J. A. Freund, Bell Laboratories MFF, June 25, 1971.

Describes tests of SPRINT missile Electro-Explosive Devices (EEDs) to determine input power levels induced in the devices by several types of electromagnetic fields.

30. SAFEGUARD System — Missile Subsystem Safety Interlocks — Case 27950-1000, D. P. Worrall, Bell Laboratories MFF, February 4, 1974.

Reviews the utilization of safety interlocks and Safety Interlock Override in the missile subsystems and the remote launch equipment.

31. NIKE-X — Acquisition of a SPRINT Missile in the Toss-and-Catch Mode — Case 27703-1600 (U), W. P. Chapman, Jr., Bell Laboratories MFF, February 28, 1967. (CONFIDENTIAL)

Reviews the problem of establishing track on a SPRINT missile after it is launched from a site several miles from the tracking radar.

32. SAFEGUARD System — SPRINT PACA Safety Margins (U) — Case 27950-1000, J. A. Freund, Bell Laboratories MFF, July 20, 1972. (SECRET)

Analyzes safety margins for various electromagnetic radiation environments during transportation of the SPRINT missile Propulsion and Control Assembly (PACA).

33. SENTINEL System — SPRINT — Proposed UTL Testing Program — Case 27703-1000, J. R. DeTizio, Bell Laboratories MFF, March 18, 1969.

Proposes a test program for the two SPRINT/SPARTAN Universal Transporter Loader (UTL) prototypes. The test program is composed of (1) Design Development Testing, (2) Acceptance Testing, (3) Design Verification Testing, and (4) Qualification Testing.

34. NIKE-X — Factor of Safety, Proof Testing and Recertification Testing — Case 27703-1600, C. G. Reinschmidt, Bell Laboratories MFF, June 29, 1967.

Clarifies the use of safety factors in the design of NIKE-X equipment and the requirements for proof testing and recertification of handling equipment before use.

35. SAFEGUARD Performance/Design Specification — SPRINT Air Vehicle (U), 11327046 Rev. A, Bell Laboratories, January 7, 1970, Revised December 18, 1974. (SECRET)

36. SENTINEL System — Flame Propagation Tests on Hydraulic Fluids — Case 27703-2110, J. A. Wojciak, Bell Laboratories MFF, January 23, 1969.

Describes procedures and results of flame propagation tests performed on five hydraulic fluids. Based on results of these tests, recommends the use of fire resistant fluids in new hydraulic system designs rather than the currently used petroleum based fluids or enclosure of hydraulic lines to eliminate the possibility of spraying oil from a ruptured line.

37. Environmental Requirements for the SPRINT Subsystem (U), Specification MO-141H, Martin Marietta Corporation, September 15, 1971. (SECRET)

38. SAFEGUARD System — SPRINT — Autopilot Timer Error Study — Case 27950-1000, R. C. McCrea, Bell Laboratories MFF, August 19, 1970.

    Presents the results of a study into the effects of early "time-out" of the timing circuit on SPRINT initial pitchover angle.

39. "Space Phase Lag" and SPRINT Steering Order Resolving Schemes (U) — Case 27703-1000, G. J. Ryva and J. C. Hsu, Bell Laboratories TM, MM-65-4264-6 and 65-4232-11, May 20, 1965. (CONFIDENTIAL)

    Seeks to clarify the deleterious effects of SPRINT "space phase lag" (the continual error between the spacial orientations of the commanded and achieved lateral accelerations when the missile rolls). Compares the three-resolver scheme currently used for SPRINT to the more common one-resolver scheme regarding effectiveness in reducing space phase lag.

40. Preliminary Study of Blackout Effects on SPRINT Miss Distance (U) — Case 27703-1600, F. J. Hinger, Bell Laboratories MFF, July 5, 1967. (SECRET)

    Presents the results of a preliminary study of the effects of blackout on SPRINT guidance. The results were obtained by Monte Carlo methods applied to a two-dimensional simulation of a SPRINT guidance package.

41. Simulation of SPRINT Launch Eject High-Frequency High-Level Shock Environments — Cases 25601 and 27703-1000, P. Johansen, Bell Laboratories MFF, June 28, 1967.

    Summarizes alternative methods available for simulating the SPRINT Missile-Borne Guidance Equipment and Autopilot shock environments, and presents results of a laboratory evaluation of a ballistic pendulum method.

42. SPRINT Launch and Test Planning Feasibility Study of SPRINT Launch Recovery System, D. Lomax, Bell Laboratories MFF, September 9, 1964.

    Presents a Martin Company mathematical simulation of the loading dynamics of the Shock Recovery System used for SPRINT launch eject tests, summarizing the analytical method used.

43. Deriving Body Attitude from SPRINT Flight Data — Case 27703-1000, B. D. Jensen, Bell Laboratories TM, MM-66-6481-3, December 15, 1966.

    Shows how the complete dynamic history of a missile flight can be determined if the acceleration vector is given in both the missile and battery coordinate systems and the angular rate about one of the missile axes is known.

44. An Investigation of Staging Transients on SPRINT WSMR Flights 7 and 8 — Case 27703-1000 (U), W. P. Wesley, Bell Laboratories MFF, July 5, 1967. (SECRET)

    Presents the result of an investigation to determine the nature and origin of previously unexpected forces acting on the SPRINT missile during separation from the first stage. The Simulated Analog Missile, a full 3-dimensional analog simulation of the SPRINT missile which contains a detailed program of the missile functions and nominal missile aerodynamics, was used in the investigation.

References for Chapter 10

SPARTAN Missile Subsystem

1. SAFEGUARD Performance/Design Specifications, Bell Laboratories.

   SPARTAN Subsystem, 11327041 Rev A, December 18, 1974. (SECRET)

   SPARTAN Air Vehicle, 11327042 Rev A, December 18, 1974. (SECRET)

   SPARTAN Launch Equipment, 11327043, August 12, 1970. (SECRET)

   SPARTAN Ground Support Equipment, 11327047, December 1974.

   Provide performance requirements and design specifications. Also establish a base for tactical production drawings and associated test and logistics support requirements.

2. SAFEGUARD System — SPARTAN Subsystem — Development Plan (U), Vol I—III, McDonnell-Douglas Astronautics Company, January 31, 1966, Revised August 1972. (SECRET)

   Summarizes the design and planning effort. Descriptions of the role of SPARTAN in the SAFEGUARD System, missile configuration, site facilities, and program schedules (including yearly milestone and flight test schedules) are presented. Also included are program plans and schedules for engineering, ground testing, flight testing, manufacturing, quality control, reliability, logistics, procurement, documentation, facilities, and field site operation.

3. SAFEGUARD/SPARTAN Fault Tree Analysis, McDonnell-Douglas Astronautics Company, MDC G5183, June 1974.

   Presents a quantitative assessment of inadvertent missile launch. Identifies components whose failure would result in a critical event, indicates probability of occurrence, and shows critical paths and associated failure probabilities.

4. SAFEGUARD System — SPARTAN Missile Subsystem Final Hardness Assessment Report (U), Bell Laboratories, February 15, 1975. (SECRET)

   Final issue in the series of SPARTAN missile subsystem hardness assessment reports. Contains results of each program and lists all pertinent documentation.

5. SPARTAN Missile Rain Erosion Test — Case 27950-1000, N. R. Lampert, Bell Laboratories MFF, October 8, 1970.

   Describes the results of recalibrating the pressure instruments used in high-speed rainfield tests of a SPARTAN missile nose cone.

6. SAFEGUARD System — SPARTAN Response to Guidance Orders (U) — Case 27950-1010, J. B. McCauley, Bell Laboratories MFF, January 26, 1972. (CONFIDENTIAL)

   Explains briefly the nature of the SPARTAN missile response to a guidance command during second-stage flight.

7. SENTINEL-SPARTAN Explosive Separation System Development and Test Results, McDonnell-Douglas Astronautics Company, DAC 58769A, September 1968.

   Describes the development, design, and testing of the interim design explosive separation system for the SPARTAN missile.

8. Implementation of Loss of RF Destruct for SPRINT and SPARTAN — Cases 27703-100 and 27703-1010, J. L. Henry, Bell Laboratories MFF, October 15, 1969.

   Proposes a means of interfacing the Missile Guidance Set/Warhead Adaption Kit missing messages which trigger missile safe destruct.

9. SAFEGUARD System — SPARTAN — SPARTAN Third-Stage Orientation Accuracy (U) — Case 27950-1010, J. B. McCauley, Bell Laboratories MFF, May 10, 1972. (SECRET)

   Explains the nature and extent of aerodynamic effects on the centerline orientation of the SPARTAN third-stage vehicle during the final flight phase before intercept.

10. Qualification Testing of the SPARTAN Safety and Arming Device (SAD) — Case 27950-1000, J. Lowe, Bell Laboratories MFF, April 2, 1971.

    Describes tests and results of qualification testing of the SPARTAN II safety and arming device. Shock response spectrum graphs for the 2500 g, 0.067-millisecond qualification test are shown.

11. NIKE-X/ZEUS: Analysis of Space Phase Lag with a Four-Gimbal Stable Platform (U) — Case 27703-1010, E. J. Schuler, Bell Laboratories MFF, March 25, 1966. (CONFIDENTIAL)

    Analyzes Space Phase Lag (spatial orientation between the commanded and achieved lateral acceleration vectors of a missile in flight), considering only the effect of missile roll. Investigates use of a stable four-gimbal platform for the ZEUS missile.

12. NIKE-X/ZEUS — Documentation of Missile Acceleration and Attitude Error Analysis Programs for Steering Control Systems — Case 27703-1010, J. W. Levengood, Bell Laboratories MFF, December 15, 1966.

    Documents two digital computer programs for analyzing SPARTAN missile acceleration and attitude errors caused by gain and null errors in the SPARTAN steering control systems.

13. Explanation of the Stable Platform Flip Maneuver and the Laboratory Simulation of this Maneuver — Case 27703-1810, F. M. Stepniak, Bell Laboratories MFF, August 1, 1966.

    Explains the execution of a "Flip" maneuver by the all-attitude, four-gimbal SPARTAN stable platform as required for maintaining proper reference under certain conditions of SPARTAN flight.

14. SAFEGUARD System — Thermal Stress Analysis of SPARTAN Launch Area Antenna Window — Case 27703-1810, J. R. Mc Kay, Bell Laboratories MFF, July 13, 1970.

    Analyzes thermal stress during nuclear blast to which the SPARTAN launch area antenna window may be subjected and concludes that the window is unlikely to fail.

15. SAFEGUARD System — SPRINT/SPARTAN Tactical Electromagnetic Radiation (EMR) Environment — Cases 27950-1000 and 1010 (U), J. A. Freund, Bell Laboratories MFF, July 18, 1972. (SECRET)

    Documents the basis for calculating the tactical EMR environments produced by the Missile Site and Perimeter Acquisition Radars (MSR and PAR). A worst-case environment is defined for the SPRINT and SPARTAN missiles during flight, their launch stations, the universal missile building, the warhead facility, and the remote SPRINT launch site.

16. SAFEGUARD System — EMR Induced Inadvertent Launch Analysis for the SPRINT and SPARTAN Missiles (U) — Cases 27950-1000 and 1010, J. A. Freund, Bell Laboratories MFF, July 20, 1972. (SECRET)

    Gives safety margins for electromagnetic radiation induced inadvertent launch of SPRINT and SPARTAN missiles for in-cell configurations of closed cell, open cell, and maintenance mode.

17. SAFEGUARD System — SPARTAN Launch Cell Thermal Analysis — Case 27858-1010, W. R. Sieling, Bell Laboratories MFF, October 19, 1973.

    Discusses the possibility of SPARTAN motor autoignition if the SPARTAN auxiliary power unit gas generator should fire inadvertently. Predicts the worst case of temperature environment within the SPARTAN launch cell.

18. SAFEGUARD System — SPARTAN — Results of the MDAC Analysis to Determine the Lock-out Requirements for the Axial Isolation System — Case 27950-1010, C. S. DeSilets, Bell Laboratories MFF, November 30, 1970.

    Discusses the McDonnell-Douglas analysis of the dynamics of launching the SPARTAN missile supported by an unlocked axial isolation system.

19. SAFEGUARD System — SPARTAN — Response of the Axial Isolation System to Earthquake Induced Ground Motions — Case 27950-1010, C. S. DeSilets, Bell Laboratories MFF, April 7, 1971.

    Presents an analysis of the responses of damped structures to earthquakes. This analysis was initiated because of the concern that the axial isolation system, being designed to keep the vertical acceleration of the SPARTAN missile supported on its launch rail below 1 g during nuclear ground shock conditions, may not be able to maintain the structural integrity of the missile during earthquake-induced loading conditions.

20. SAFEGUARD System — SPARTAN — Reevaluation of Environmental Criteria and Stress Requirements for Equipment in the SPARTAN Launch Station Deflector Region — Case 27950-1010, G. N. Zacsek and W. R. Sieling, Bell Laboratories MFF, June 16, 1971.

    Presents an analysis to determine the dynamic temperature history of a surface on which SPARTAN missile exhaust gases impinge, e.g., the deflector plate and junction boxes in the cell. The analysis was initiated in response to data which indicate that temperatures in the tactical design launch station will be considerably higher than those found in the old shallow-depth cell.

21. SAFEGUARD System — SPARTAN Launch Cell Preparation Equipment Vault (LPEV) — LPEV Nuclear Ground Shock Environment Requirements — Cases 27950-2130 and 27950-1010, J. F. Stevenson and C. S. DeSilets, Bell Laboratories MFF, September 29, 1970.

    Outlines procedures used in establishing requirements for nuclear ground shock environmental testing. Records data on shock spectra envelopes and acceleration-time histories that are consistent with the shock spectra, to be used for mathematical analysis purposes, as well as aiding in establishing future test criteria for LPEV equipment.

22. SAFEGUARD System — SPRINT/SPARTAN EMR Vulnerability in Abnormal MSR/PAR Environments (U) — Cases 27950-1000 and -1010, J. A. Freund, Bell Laboratories MFF, August 3, 1973. (SECRET)

    Provides data in answer to the Nuclear Weapon System Safety Committee proposal to inhibit MSR and PAR radiation when the cover of a launch cell containing a missile with a war reserve warhead is open for entry.

23. SAFEGUARD System — SPRINT/SPARTAN EMR Vulnerability in Abnormal MSR/PAR Environments (U) — Cases 27950-1000 and -1010, J. A. Freund, Bell Laboratories MFF, October 10, 1973. (SECRET)

    Presents data to show that the SPRINT and SPARTAN missile subsystems are safe under conditions of MSR or PAR RF Inhibit Mask control failure. Proposes, therefore, deletion of Rule 9 of the Nuclear Weapons Systems Safety committee, which would prohibit MSR and PAR radiation when the cover of a launch cell containing a missile with a war reserve warhead section is open.

24. SPARTAN — Reliability Study of the Burst Delay Timer — Case 36294-22, W. J. Akstulewicz, Bell Laboratories MFF, May 28, 1969.

    Presents results of a reliability study performed on the SPARTAN burst delay timer design.

25. Qualification Tests of the SPARTAN Burst Delay Timer — Case 27703-1010, J. L. Henry, Bell Laboratories MFF, June 13, 1969.

    Describes the procedures and results of qualification tests (operation under extremes of temperature, random and sinusoidal vibration, shock, acceleration, pressure, and acoustic energy) performed on the SPARTAN burst delay timer.

26. SAFEGUARD System — Evaluation of SPARTAN Auxiliary Heating/Cooling and Ventilating Unit — Case 27950-1010, G. N. Zacsek, C. S. DeSilets, and D. F. O'Sullivan, Bell Laboratories MFF, April 21, 1972.

    Reviews the capability of a trailer-mounted air conditioning unit that is being assembled by the Army to ventilate a SPARTAN cell while personnel are in the cell performing maintenance operations. Examines the compatibility of this unit with the launch station's environmental control system and its capability to maintain the station's temperature and humidity requirements in accordance with the facility criteria.

27. Potential Adhesives For Use On Model 115 ZEUS-NIKE-X Nozzle, McDonnell-Douglas Astronautics Company, Report No. SM 49189, April 27, 1966.

    Determines mechanical and physical properties of adhesives for bonding nozzle liners to steel shells; includes methods for evaluation and selection of an adhesive system.

28. Three-Motor Transportation and Handling Environmental (THE) Test Program Test Results, McDonnell-Douglas Astronautics Company, Interim Report Vol I and II, MDC G3876, December 1972, and Final Report, MDC G4662, July 1973.

    Details the test plan and results of the program which evaluated the capability of the SPARTAN motors to survive the ground handling environments.

29. MGS Power Discrete Circuit Operation — Case 27703-1010, L. G. Johansson, Bell Laboratories MFF, October 2, 1967.

    Presents worst-case output data and describes the operation of the Missile Guidance Set (MGS) power discrete circuit under end-of-life condition. Discusses and evaluates the effects of radiation on either a triggered or untriggered circuit.

30. Relocation of SPARTAN Strakes and Effect Upon Antenna Gain (U), Bell Laboratories Report, September 25, 1965. (SECRET-RD)

    Presents the results of an antenna pattern measurement program conducted as a result of a requirement to relocate the aft antenna strakes of the SPARTAN missile.

31. Design and Reliability Considerations for Integrated Circuit Operational Amplifiers Used in SPRINT/SPARTAN Launch Preparation Equipments — Cases 27703-1000 and 27703-1010. F. J. Zgebura, Bell Laboratories MFF, May 7, 1970.

    Describes the electrical and reliability differences that exist between the two basic forms of integrated circuit operational amplifiers proposed for use in the SPRINT /SPARTAN Launch Preparation Equipment.

32. SPARTAN Hydraulic Control System Review: June 6, 1968 — Case 27703-1010, E. J. Schuler, Bell Laboratories MFF, June 26, 1968.

    Presents a review of problems and design changes in the hydraulic control system of the SPARTAN missile.

33. SPARTAN HPU Vibration Signature Analysis — Theoretical Background — Data Handling Techniques — Application and Empirical Refinement, AiResearch Manufacturing Company, Report 72-8442, September 1972.

Describes the development of the exceedance curve method of vibration signature analysis used for acceptance testing of SPARTAN hydraulic power units.

34. SAFEGUARD System — SPARTAN — The Problems of Condensation on the Inner Surfaces of the SPARTAN Launch Cell Covers — Case 27950-1010, W. R. Sieling, Bell Laboratories MFF, August 13, 1970.

Investigates likelihood of condensation forming on the inner surface of the SPARTAN launch cell covers and estimates insulation requirements necessary to prevent condensation under worst-case conditions.

35. SAFEGUARD System — SPARTAN — SPARTAN Launch Cell Cover Insulation (U) — Case 27950-21, Filing Case 27950-1010, W. R. Sieling, Bell Laboratories MFF, November 24, 1970. (CONFIDENTIAL)

Considers the possibility of completely removing the silicone rubber insulation from the outer surface of the SPARTAN launch cell covers.

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Data Processing System

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Part V.

GLOSSARY

Part V.

GLOSSARY

A

ABM	Antiballistic Missile
ABMDA	Advanced Ballistic Missile Defense Agency
ABRES	Advanced Ballistic Reentry Systems
ACBIAS	Acceleration Bias
ACC	Area Control Center
ACU	Arithmetic Control Unit
A/D	Analog-to-Digital
ADES	Area Defense Engagement Simulation
AEC	Atomic Energy Commission
AET	Antenna Element Test
AF	Air Force
AFB	AF Base
AFCC	Alternate Fire Control Center
AFWL	AF Weapons Laboratory
AGC	Automatic Gain Control
AICBM	Anti-ICBM
AL	Accidental Launch
ALCOR	ARPA-Lincoln Laboratories C-Band Observable Radar
ALTAIR	ARPA Long Range Tracking and Instrumentation Radar
AMC	Army Materiel Command
AMPL	Receiver Encoder Level
AMRAC	Anti-Missile Research and Advisory Council
AP	Ammonium Perchlorate
A/R	Availability/Reliability
ARA	Allowable Reentry Angle
ARADCOM	Army Air Defense Command
ARCS	Average RCS
ARDC	Air R&D Command
ARGMA	Army Rocket and Guided Missile Agency
ARPA	Advanced Research Projects Agency
ARU	Automatic Reference Unit
AT&T	American Telephone and Telegraph Company
ATC	Advanced Technology Center
ATES	Analog TES
A to D	Analog-to-Digital Conversion
ATR	Acceptance Test Requirement Active Track Recognition
ATS	Antenna Test Set

B

BCB	Battery Control Building
BCC	Battery-Centered Cartesian Coordinate System
BF	Burst File
BFS	Beamforming and Steering
BMD	Ballistic Missile Defense
BMDATC	BMD Advanced Technology Center
BMDC	BMD Center
BMDOC	BMD Operations Center
BMDOR	BMD Operations Room
BMDSCOM	BMD Systems Command
BMDTP	BMD Test Program
BMEWS	Ballistic Missile Early Warning System
BOD	Beneficial Occupancy Date / Building Occupancy Date
BOS	Basic Operating System
BRCS	Body RCS
BRL	Ballistic Research Laboratory
BRV	Ballistic RV
BSA	Buffer Store Assembly
BSC	Beam Steering Computer
BSS	Board Steered System
BW	BMDC Weapons Process
β	Ballistic coefficient in lb/ft^2

C

CAL	Calspan Corporation (formerly Cornell Aeronautical Laboratory)
CALCOMP	Calspan Computer
CAMAR	Common Aperture MAR
CAT	Catastrophic Test
C&C	Command and Control
CCB	Configuration Control Board
CCDS	C&C Display Subsystem
CCU	Channel Control Unit
CDP	Central Data Processing
CDR	Critical Design Review
CDT	Conditional Drop Track
CENTRAN	CLC Translator
CEP	Circular Error Probability
CFAR	Constant False Alarm Rate
CG	Center of Gravity / Commanding General
CINCONAD	Commander-in-Chief of CONAD
CIU	Control Indicator Unit
CLC	Central Logic and Control
CLSU	Console Logic Support Unit
CM	Configuration Management / CLC Monitor
CMC	Cheyenne Mountain Complex
CMDS	Contractor Maintenance Data System
C/N	Clutter-to-Noise ratio
CN	Normal Force Coefficient
CNWDI	Critical Nuclear Weapons Design Information
COC	Combat Operations Center
COE	Corps of Engineers
CONAD	Continental Air Defense Command
CONOPS	Continuous Operations Test
CONUS	Continental US
CP	Center of Pressure
CPAF	Cost Plus Award Fee
CPCC	Central Program Change Control

CPIF	Cost Plus Incentive Fee
CPR	Chinese People's Republic (also see PRC)
CPU	Central Processing Unit
CR	Correction Report
CRT	Cathode Ray Tube
CSB	Control Switch and Buffer
CSPS	Coherent Signal Processor System
CTM	Contractor Technical Maintenance
CTPB	Carboxyl-Terminated Polybutadiene
CW	Continuous Wave

D

DARTS	Debugging Aid for Real-Time Systems
DCA	Digital Controlled Attenuator
DCDP	Defense Center Data Processor
DCDPS	Defense Center DPS
DCG	Digital Control Group
DCU	Digital Control Unit
DD	Discrimination Demonstration
DDG	Digital Data Group
DDR&E	Director of Defense R&E
DDS	Display Subsystem
DEPEX	NIKE-X Deployment Study
DET	Design Evaluation Threat
DG	Data Gathering
DICBM	Depressed ICBM
DKR	Direct Kill Region
DM	Defense Mode
DOD	Department of Defense
DP	Data Processor
DPCC	Data Processing and Control Computer
DPM	Dispersed Pulse Measurement
DPO	Data Processing Officer
DPS	Data Processing System/ Subsystem
DPSI	DPS Installation Facility
DPSPR	DPS Performance Requirements
DR	Detection Radar Discrimination Radar
DSS	Display Subsystem
DT	Design Threat
DTC	Data Transmission Controller
DTCA	DTC Adapter
DTCG	DTC Group
DTES	Digital TES
DTS	Dynamic Traffic Simulation
DUX	Digital Unit Exerciser
DVR	Digital Video Recorder

E

EBMDC	Early BMDC
ECM	Electromagnetic Countermeasures
ECP	Engineering Change Proposal
ECS	Environmental Control Station Environmental Control System
ECTS	Electrical Circuit Test Set
ECU	Exercise Control Unit
EDP	Exercise Data Processor
EED	Electro-Explosive Device
EGS	End Game Simulation
EMP	Electromagnetic Pulse
EMX	MSR System Exerciser
EOB	End-Of-Boost phase
EOD	End-Of-Dive phase
EPX	PAR System Exerciser
ERC	Equipment Readiness Center

ERD	Equipment Readiness Date
ERS	Extended Range Search
ESK	Environmental Sensor Kit
ESL	Environmental Status Level
E-Tape	Software Parameter Histories
ETR	Eastern Test Range
EXIT	Exit Surveillance Region

F

FAR	False Alarm Rate / Forward Acquisition Radar
FCC	Face Cartesian Coordinates / Fire Control Center
FCS	Flight Control Set
FITS	Fault Isolation Test Set
FL	Fault Locator
FLAM	Fault Locating and Monitoring
FLAR	Fault Locating and Recording
FMP	Field Measurement Program
FOBS	Fractional Orbit Bomb System
FORTRAN	Formula Translator
FSC	Flight Safety Console
FSS	Flight Safety System
FTS	Flight Termination System

G

GE	General Electric Company
GETSS	GE Time-Sharing System
GMLEC	Guided Missile Launch Enable Controller
GMLEG	Guided Missile Launch Enable Group
GMT	Greenwich Mean Time
GPDC	General Purpose Digital Computer
GRC	General Research Corporation
GSE	Ground Support Equipment
γ	$1/\beta$

H

HDR	High Data Rate
HEFU	High-Energy Firing Unit
HF	Heating Factor
HI	Hostile Identification
HIA	HI Authority
HIE	HI Enable
HIS	Honeywell Institute System
HLT	High Level Transmitter
HPU	Hydraulic Pumping Unit

I

IA	Intercept Accuracy
IBM	International Business Machines Corporation
IC	Integrated Circuit
ICBM	Intercontinental Ballistic Missile
ICLPE	IC Launch Preparation Equipment
ICP	IC Package
ID	Identification
IDA	Institute of Defense Analysis
IDR	Interface Data Reduction
IEMP	Internal EMP
IF	Intermediate Frequency
IMSR	Improved MSR
I/O	Input/Output
IOC	Initial Operational Capability / I/O Controller
IP	Intercept Point
IPS	IP Selection
IQD	Intercept Quality Data
IR	Interceptor Response

IRBM	Intermediate Range Ballistic Missile
ISU	Interface Switching Unit
ITP	Installation Test Program
ITU	Interface Transfer Unit

J

J-Box	Junction Box

K

KA	Kill Assessment
KMR	Kwajalein Missile Range
KOR	Known Object Recognition
KREMS	Kiernan Reentry Measurement Site
KT	KOR Track
KTR	KOR Track Recognition
KTS	Kwajalein Test Site

L

LA	Launch Accuracy
LAC	Launch Area Control
LAR	Local Acquisition Radar
LBO	Low Beta Object
LCB	Logic Control Buffer
LCC	Launch Control Center
LDP	Local Data Processor
LDR	Low Data Rate
LE	Launch Enable
LECS	LE Coded Switch
LEDM	Limited Engineering Development Model
LEGG	Launch Eject Gas Generator
LEMC	LE Message Controller
LEMR	LE Message Receiver
LEMT	LE Message Transmitter
LETS	LE Transmission Set
LEU	LE Unit
LLT	Low Level Transmitter
LO	Launch Order Local Oscillator
LP	Launch Point
LPE	Launch Preparation Equipment
LPEC	LPE Compartment
LPES	LPE Set
LPEV	LPE Vault
LQD	Launch Quality Data
LRC	Logic-to-Relay Converter
LSB	Least Significant Bit
LSEQ	Launch Sequencer
LSI	Large-Scale IC

M

M	Minuteman Defense Mode
MA	Missile Acquisition
MAC	Maintenance Activity Center
M&D	Maintenance and Diagnostic
M&DSS	M&D System/Subsystem
MAR	Multifunction Array Radar
MBGE	Missile-Borne Guidance Equipment
MCC	Missile Command Code
MCM	Missile Command Monitor
MDAC	McDonnell-Douglas Astronautics Company (formerly Douglas Aircraft)
MDC	Missile Defense Center Missile Direction Center
MDI	Miss-Distance Indicator
MDP	M&D Processor Missile Data Processor
MDVS	Minuteman Defense Value Structure

MDX	Miss-Distance Magnitude
MEEV	Mechanical and Electrical Equipment Vault
MFM	Missile Farm Monitor
MGS	Missile Guidance Set
MI	MSR Installation Process
MIL	Military
MINLCC	Minuteman Launch Control Center
MIPS	Millions of Instructions Per Second
MIRV	Multiple Independently Targeted RV
MIS	Missile Interaction Simulation
MISSIM	Missile Simulation
Mk-( )	Hostile ICBM
MLEA	Missile Launch Equipment Adapter
MLEC	Missile Launch Equipment Controller
MM	Minuteman
MMC	Martin Marietta Corporation
MMI	Minuteman I
MMTC	Missile Monitor Test Console
MN	Mach Number
MOI	Moment of Inertia
M-1	Programs for MSR testing with capability of interception-to-space point
M1-( )	Mission designation
MOSAR	Modulation Scan Array Radar
MPR	Master Problem Report
MR	Measurement and Recording
MRA	Management Report Analyst
MRS	Management Reporting System
MRV	Multiple RV
MSB	Most Significant Bit
MSCB	Missile Site Control Building
MSDP	Missile Site Data Processor
MSDPS	Missile Site Data Processing Subsystem
MSR	Missile Site Radar
MSRDP	MSR Data Processor
MSRSIM	MSR Simulation
MSTP	Meck System Test Program Missile Site Test Program
MT	Missile Track
MTR	MT Radar
MTRACK	MSR MT Simulation
MTS	Mission Test Specification
MTV	Material Test Vehicle
MW	MSR Weapons Process

N

NA	Not Applicable Not Available
NASA	National Aeronautics and Space Administration
NCA	National Command Authority
NCMC	NORAD Cheyenne Mountain Complex
NEA	Nuclear Employment Authority Nuclear Engagement Authority
NEARR	Nuclear Employment Authority Recorder-Reproducer
NG	Nitroglycerin
NICOL	NIKE-X Compiler Language
NOL	Naval Ordnance Laboratory
NOP	No Operation
NORAD	North American Air Defense Command
NPD	Normal Path Diagnostic
NPV	N-Pulse Validation
NSA	National Security Agency
NTH	Nonthreatening

NWSSC	Nuclear Weapons System Safety Committee

O

OCU	Operand Control Unit
ODDR&E	Office of Director of Defense R&E
OLDR	Off-Line Data Reduction
OS	Operating System
OSB	Ordnance Safety Box
OSCAR	On-Site Configuration Activity Reporting

P

P_k	Kill Probability
P_{RV}	Probability that target is an RV
PACA	Propulsion and Control Assembly
PAL	Parallel Assembly Language
PAR	Perimeter Acquisition Radar
PARDP	PAR Data Processor
PARSIM	PAR Simulation
PASS	Parallel ABM System Simulation
PAVT	Product Assurance Verification Test
PBAA	Polybutadiene Acrylic Acid
PCO	Program Change Order
PCS	Position Capability Surface
PCU	Program Control Unit
PDF	Prototype Development Facility
PDS	Performance Design Specification
PEPE	Parallel Element Processing Ensemble
PFA	Probability of False Alarm
PFOBS	Potential FOBS
P-FOR	Parallel version of FORTRAN
PF&TG	Precision Frequency and Time Generator
PHSD	Preliminary Hardsite Defense
PI	PAR Installation Process
PIN	Positive Intrinsic Negative
PL/1	Program Language 1
PM	Preventive Maintenance
PMR	Pacific Missile Range
POMDA	Post-Mission Data Analysis
POR	PAR Object Recognition
POT	Purged Object Track
PP1	Pulse Pattern 1
pps	pulses per second
PPS	Policies, Procedures, and Standards
PPTL	Parallel Plate Transmission Line
PRC	People's Republic of China (also see CPR)
PRF	Pulse Repetition Frequency
PS	Program Store
PSL	Physical Science Laboratory
PT	PAR Test Process Precision Track
PTV	Propulsion Test Vehicle
PU	Processor Unit
PW	PAR Weapons Process
PWRCS	Peak Wake RCS
P/Z	PAR/SPARTAN

R

RADOT	Recording Automatic Digital Optical Tracker
RANC	Refraction Attenuation Noise and Clutter
R&D	Research and Development
R&E	Research and Engineering
RCA	Radio Corporation of America
RCS	Radar Cross Section

RD	Restricted Data
RDT&E	Research, Development, Test & Evaluation
REFOBS	Reference Object Search
RF	Radio Frequency
RFCM	RF Calibration and Monitoring
RFTO	RF Test Order
RFTR	RF Test Request
RFTS	RF Test Set
RLE	Remote Launch Equipment
RM	Measured Missile Range
RMC	Radar Measurement Coordinate System
RMI	Range Mark Indicator
RMP	Reentry Measurements Program
rms	root-mean-square
RMV	Reentry Measurements Vehicle
RP	Predicted Missile Range Resmooth Program Retro-Package
RPCC	Orthogonal Coordinate System
RRG	Radar Return Generator
RSA	Rate Saturation Attack
RSC	Recording Set Controller
RSS	Recording Subsystem
RTE	Real-Time Exerciser
RTI	Range Time Intensity
RUR	Region of Unresolved Replies
RV	Reentry Vehicle
RVCC	Range-Velocity Cartesian Coordinates

S

SAC	Strategic Air Command
SAFCA	SAFEGUARD Communications Agency
SAFSCOM	SAFEGUARD System Command (now called BMDSCOM)
SAFSEA	SAFEGUARD System Evaluation Agency
SAFSIM	SAFEGUARD System Simulation
SAFSM	SAFEGUARD System Manager
SALT	Strategic Arms Limitation Treaty
SAMSO	Space And Missile System Organization
SAMTEC	Space And Missile Test Center
SAS	Status Accounting System
SBI	Seconds Before Impact
S/C	Signal-to-Clutter ratio
SCD	Small City Defense
SCO	Software Change Order Specification Change Order
SCVS	SPARTAN Capability Value Structure
SDF	Slowdown Filter
SDPL	SENTINEL Data Processing Laboratory
SDRDC	System Design Requirements for Displays and Controls
SDRS	SAFEGUARD Data Reduction System
SDVS	SAFEGUARD Defense Value Structure
SENSIM	SENTINEL System Simulation
SES	SPRINT Engagement Simulation
SEST	SAFEGUARD System EMP Site Test
SET	Small Endoatmospheric Target
SFSD	Southern FOBS Self Defense
SG	SPRINT Guidance
SHAR	System Hardness Assessment Report
SIDLOB	Sidelobe Tracking Indicator
SIETP	System Integration and Evaluation Test Plan

SIMVAL	Simulation Validation
SIR	SPRINT Interceptor Response
SIS	SPRINT Intercept Simulation
SIT	Site Information Tape
SLBM	Submarine-Launched Ballistic Missile
S/N SNR	Signal-to-Noise ratio
SNX	Symbolic NIKE-X (assembly language for CLC)
SOC	Support Operation Center
SPASIM	SPARTAN Intercept Simulation SPARTAN Intercept Subsystem Simulation
SPO	Special Projects Office
SPSIM	SPARTAN Intercept Effectiveness Simulation
SR	Satellite Recognition
SRV	Single RV System Readiness Verification
SSBO	Second-Stage Burnout
SSDSU	System Status Display Support Unit
SSDU	System Status Display Unit
SS-9	Hostile ICBM Booster (USSR)
SSP	Search Signal Processor
SSV	Sequential-State Vector SPRINT Service Vehicle
ST	Surveillance Track
STACS	SAFEGUARD Tactical Simulator
STAG	SAFEGUARD Threat Action Generator
STC	Sensitivity Time Control
STM	Special Test Mission
STS	System Test Specification
STTF	Site Threat Trajectory File
STU	Store Transfer Unit
STVT	System Technical Verification Test
STVTR	STVT Requirements
SU	Status Unit
SV-( )	SAFEGUARD Vehicle
SWOC	SPARTAN Warhead Output Contour
SYSEX	System Exerciser

T

TA	Track Acquisition
TACMAR	Tactical MAR
TACMSRSIM	Tactical MSR Simulation
TACSAFSIM	Tactical SAFEGUARD Simulation
TALO	Time After Liftoff
T&S	Timing and Status
TATCOG	Tri-Agency Technical Coordination and Operations Group
TBS	Tape Buffer System
TBU	Tank Breakup
TDP	Target Data Processor
TES	Tactical Environment Simulation
TF	Track File
TFBCT	Tracking Filter Ballistic Coefficient Test
TG	Timing Generator
TGO	Time to Go
TI	Time of Intercept
TIC	Target Intercept Computer
TID	Tracking for Identification Data
TIG	Track Initiation and Grouping
TJH	Time of Jethead Ignition
T/M	Telemetry
TM	T/M Flight Data
TMR	Target Measurements Report
TMRC	Technical Maintenance Repair Center

TOD	Time Of Day
TOF	Time Of Flight
TOO	Target Of Opportunity
TOP	Trajectory Obscuration Program
TOS	Tactical Operating System
TR	Transmit-Receive Trouble Report
TRADEX	Target Resolution and Discrimination Experiments Radar
TRADOC	Training and Doctrine Command
TRM	Test Requirements Memorandum
TRP	Telemetry Reduction Program
TS	Technical Specification
TSA	Target Selection Aid
TSB	Temporary Storage Block (buffers)
TSCS	Tactical Software Control Site
TSE	Tactical Support Equipment
TSF	Target Selection Function
TSI(A), (B), (C)	Track for SPARTAN Intercept Part A, B, C (tracking intervals)
TSL	Time Since Launch
TSP	Target Selection Process
TSTS	Third-Stage Test Set
TT	Target Track
TTR	Target Tracking Radar
TTY	Teletypewriter
TUB	Trajectory Uncertainty Bound
TV	Technical Verification
TVC	Thrust Vector Control
TWT	Traveling Wave Tube
TWX	TTY Exchange

U

UHF	Ultra High Frequency
UMAB	Universal Missile Assembly Building
UMB	Universal Missile Building
UOR	User-Oriented Requirement
UOV	User Operational Verification
UREC	Utility Recording
US	United States
USSR	Union of Soviet Socialist Republics
UTL	Universal Transporter Loader

V

VCO	Voltage-Controller Oscillator
VHF	Very High Frequency
VIRADE	Virtual Radar Defense
VOL	Verified Objects List
VPC	Video Pulse Converter
VS	Variable Store
VSL	Verification Scheduling List
VTM	Visible Threat Message

W

WAGC	Wake AGC
WECo	Western Electric Company
WG	Gate Width (range)
WICOR	Wave Band Correlated
WL	Wake Length
WSMR	White Sands Missile Range
WT	Wake Track
WTR	Western Test Range
WUSSR	Western USSR

X

XPF	Execution Preparation Facility

Z

ZAR	ZEUS Acquisition Radar

ZIR	SPARTAN Interceptor Response	ZOS	Zero Order Software
ZMAR	ZEUS Multifunction Array Radar	ZSIM	SPARTAN Missile Simulator Segment of SPASIM