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]

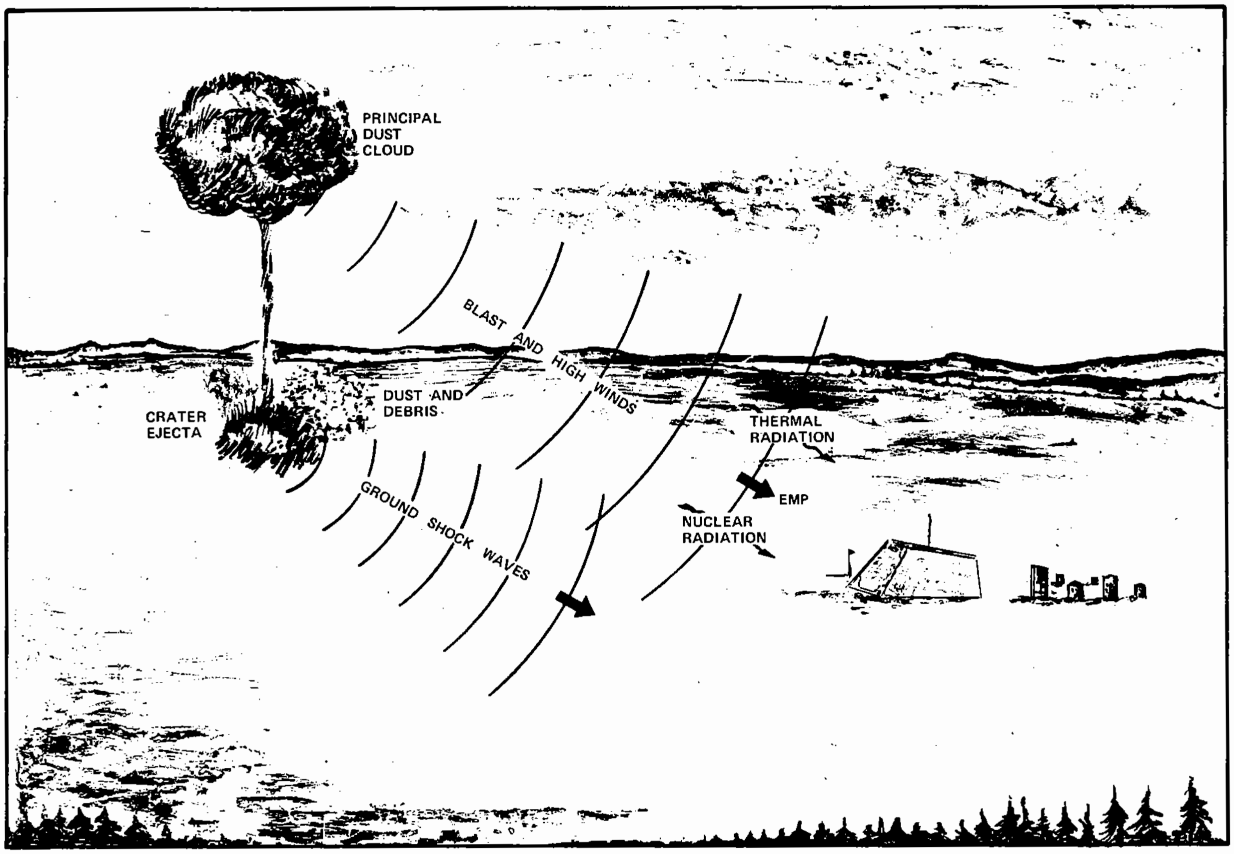


Figure 6-1. Nuclear Weapon Effects on System Facilities

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.

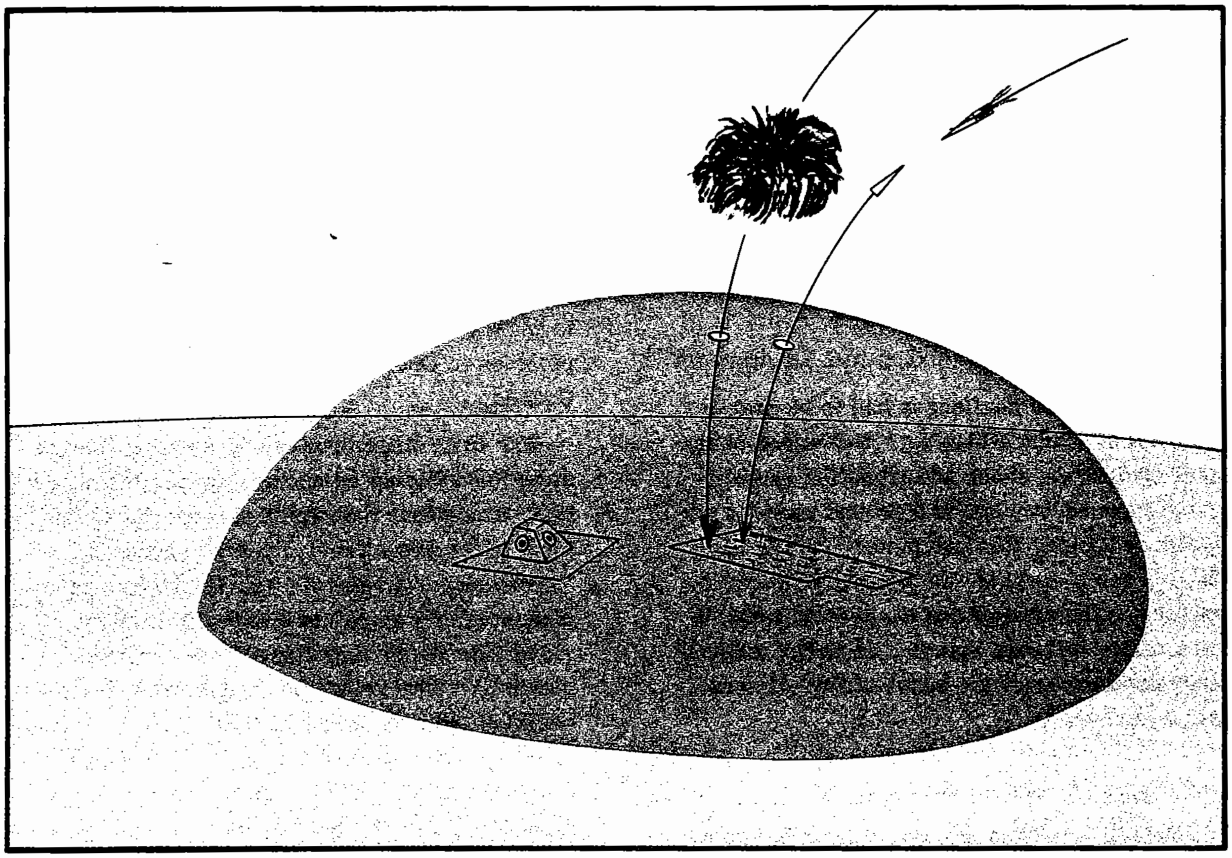


Figure 6-2. ABM Site Protection Volume

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.

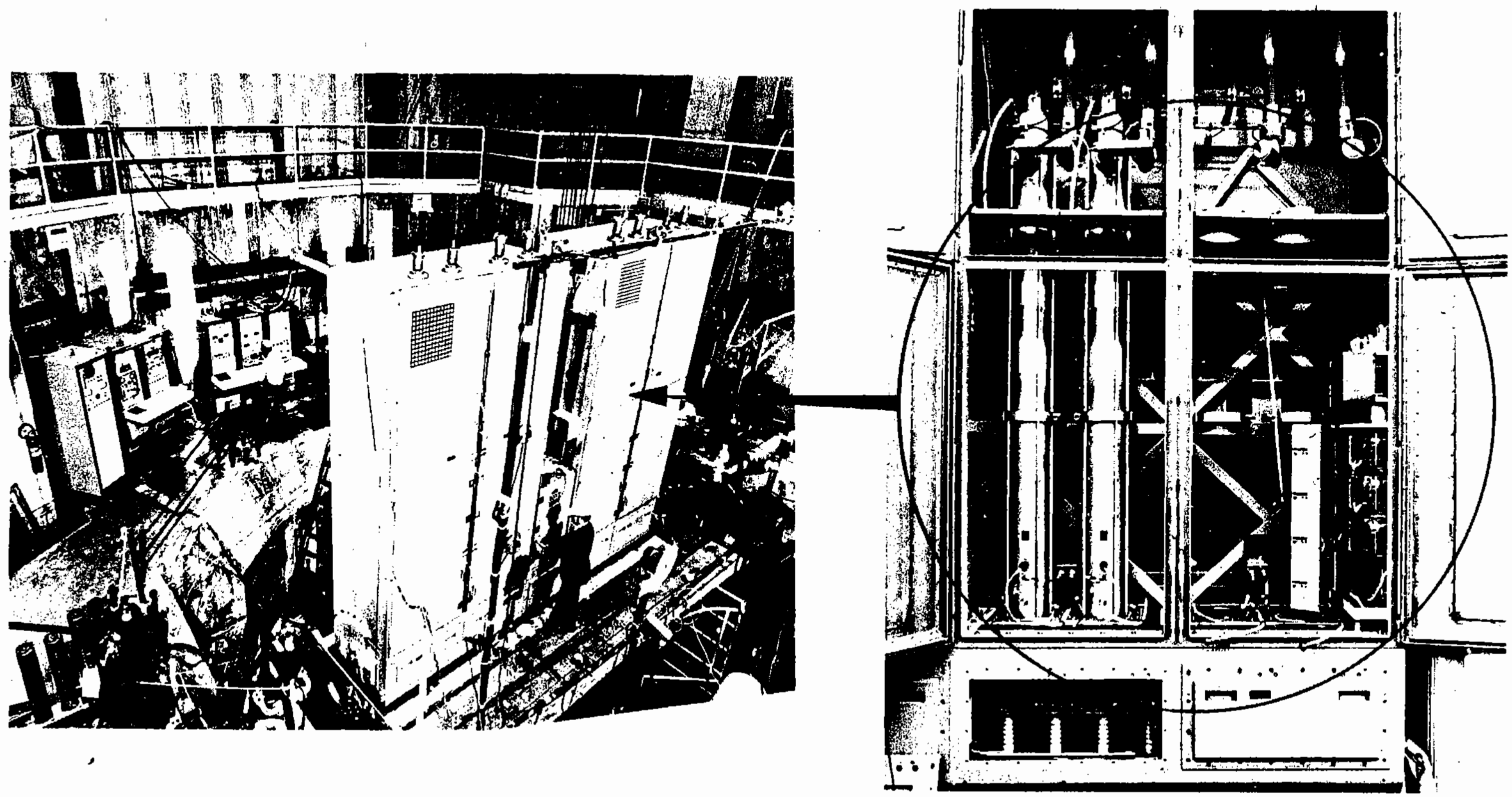
The PAR antenna element protrudes some 9 inches above the ground plane or radar face, and is exposed to a complex blast wave pattern. By the time the blast wave arrives, the antenna element has already been exposed to the thermal pulse from the nuclear weapon. The complexity of this environment posed 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.

*Listed in reference number 9.

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:

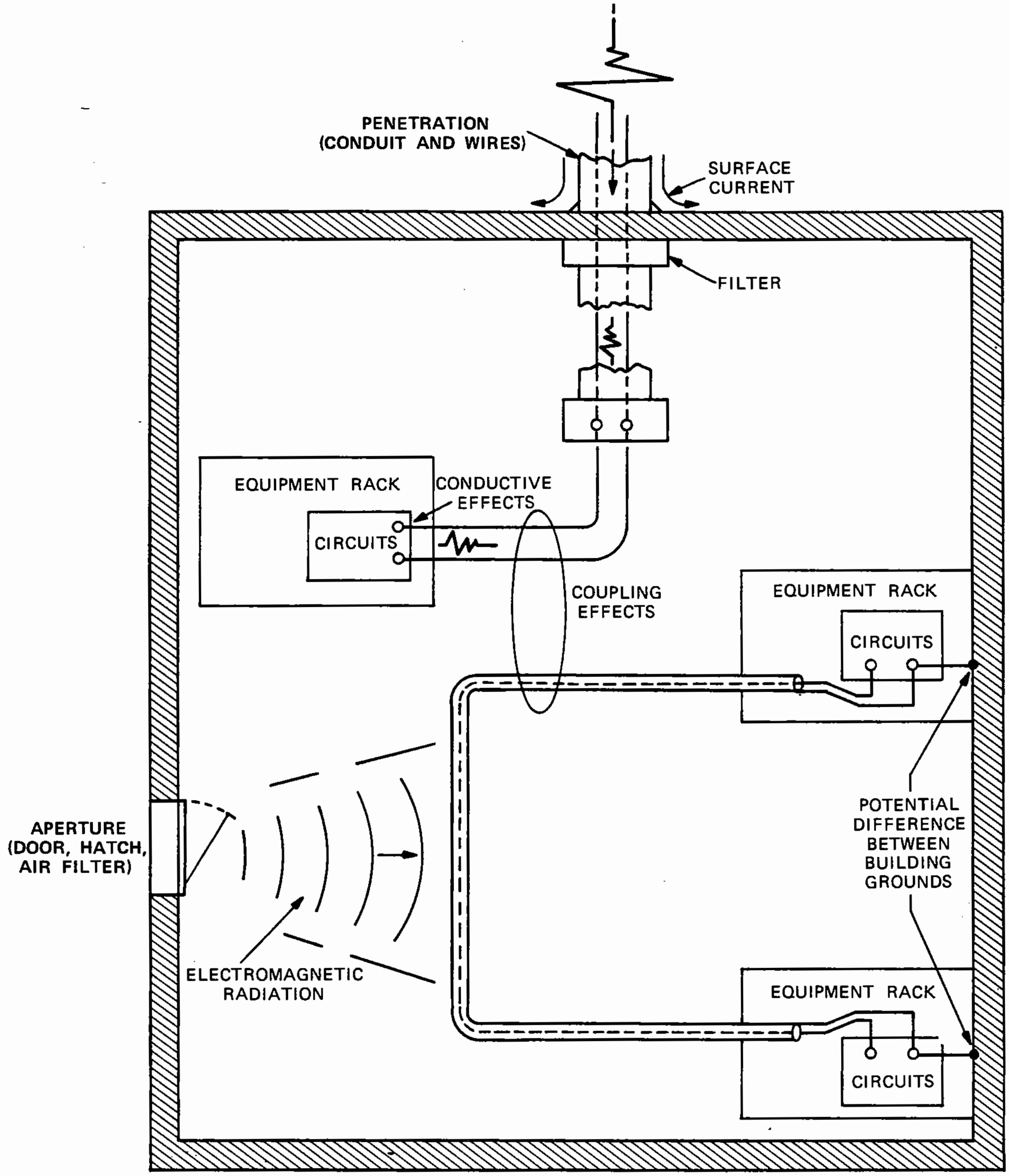


Figure 6-4. Modes of EMP Interaction with Shielded Building

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 inflight 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.

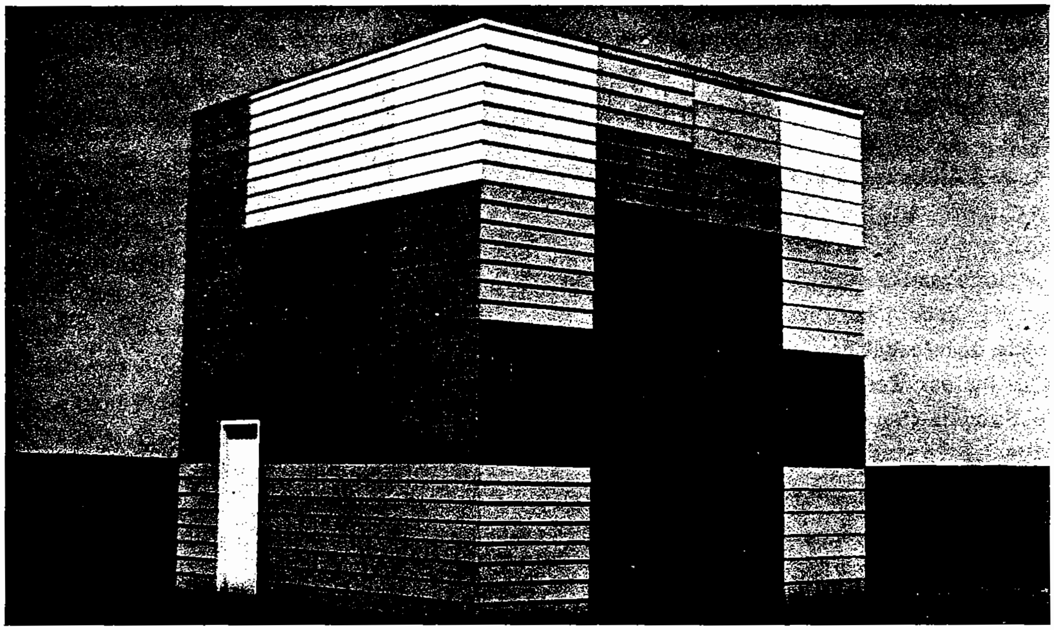
The results of this work were used in the SAFEGUARD Siting Criteria to specify safe distances for potential debris sources from SAFEGUARD missile sites and radars. For debris sources that could not comply with these criteria, system effectiveness studies were conducted to evaluate the extent to which 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

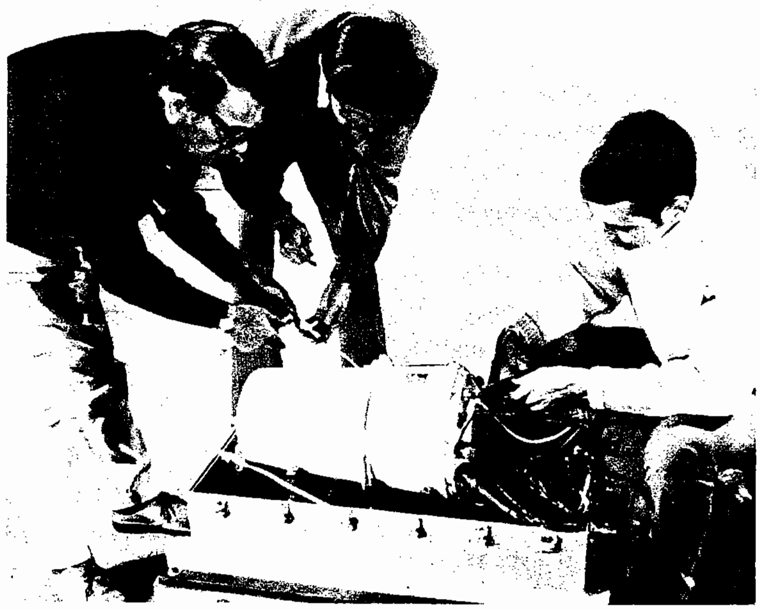


Figure 6-6. SPRINT Missile Guidance Set Being Readied for Gamma Radiation Tests at Aurora Facility

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.

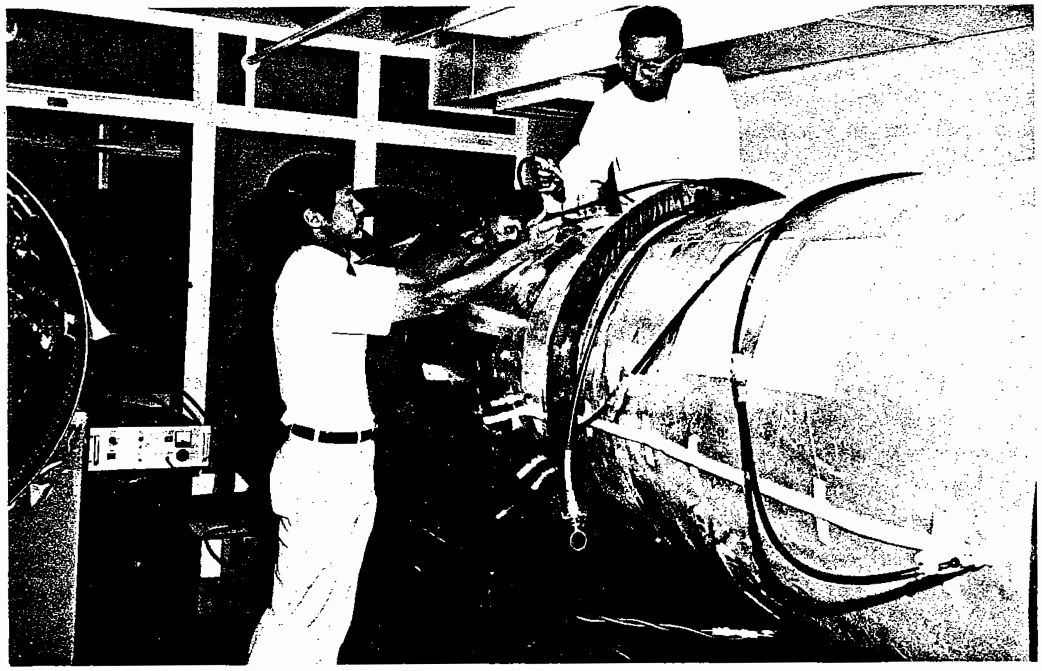


Figure 6-7. Internal EMP Testing of SPARTAN Missile at McDonnell-Douglas Astronautics Company

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

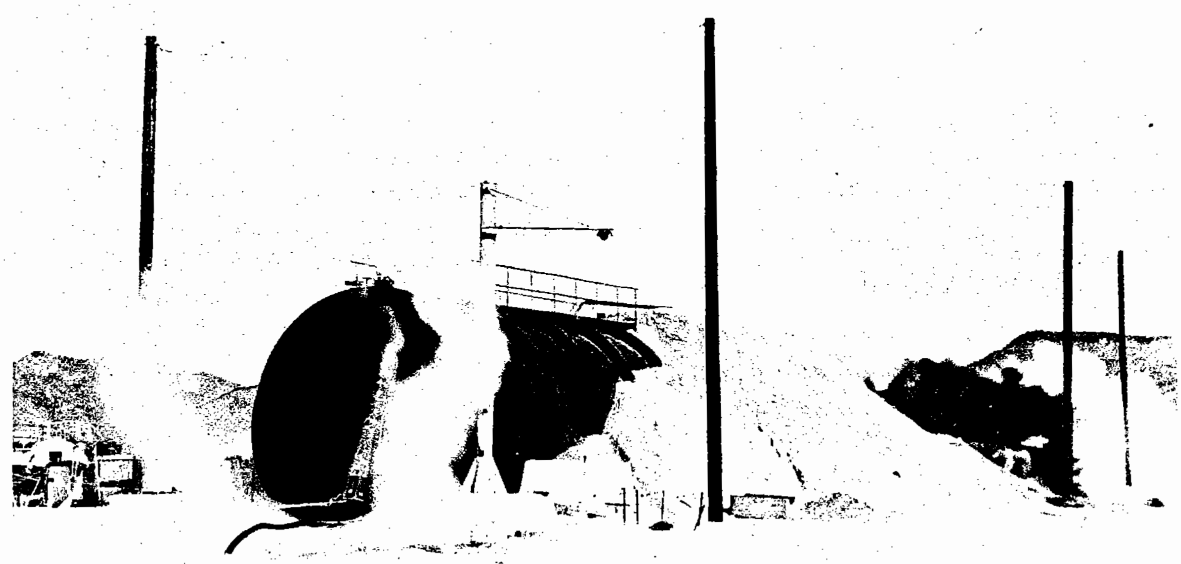


Figure 6-8. SPRINT Missile Undergoing Shock Tests at Sandia Laboratories

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]