Chapter 9.

SPRINT MISSILE SUBSYSTEM

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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.

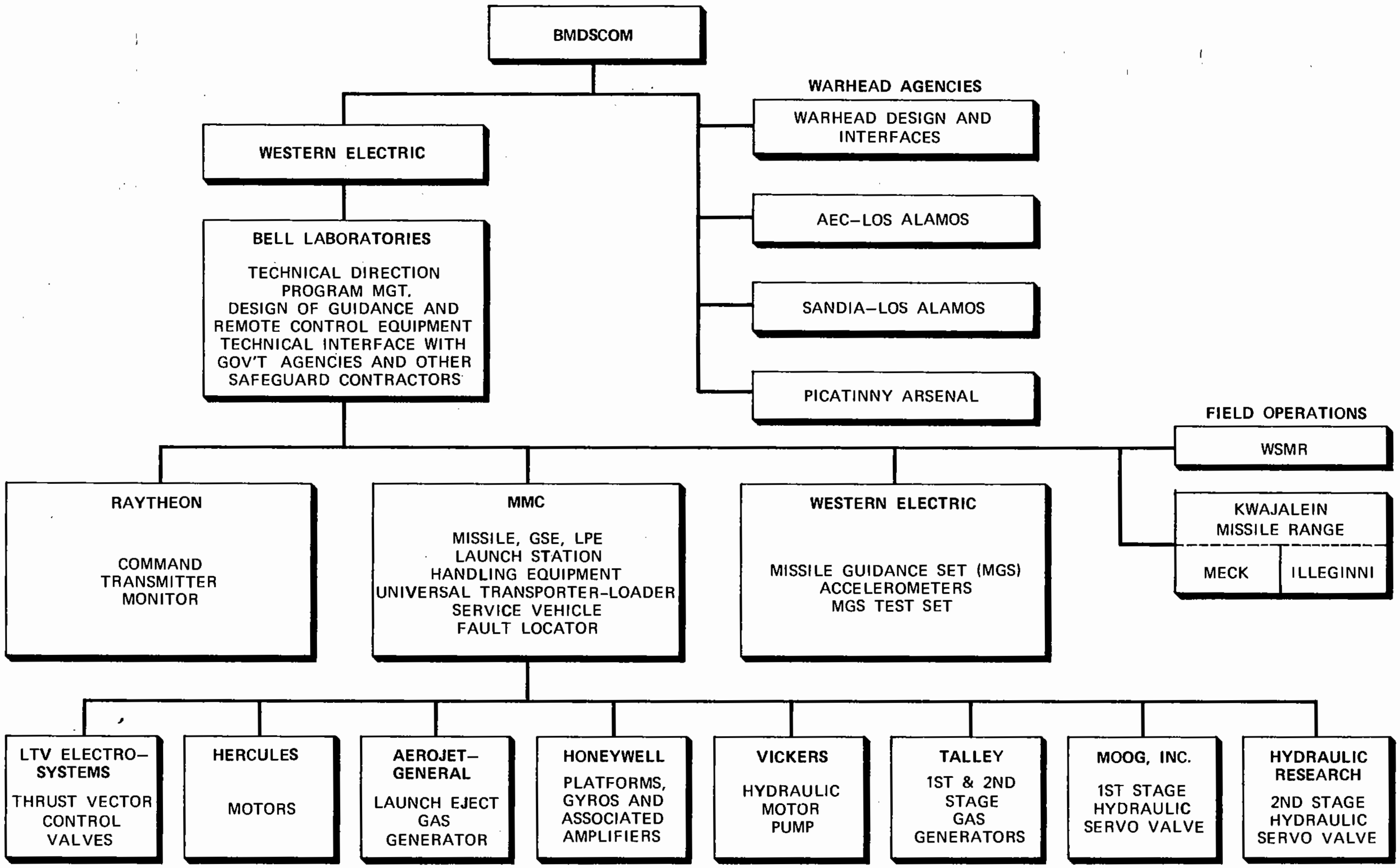

Figure 9-1. SPRINT R&D Organization Structure

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.

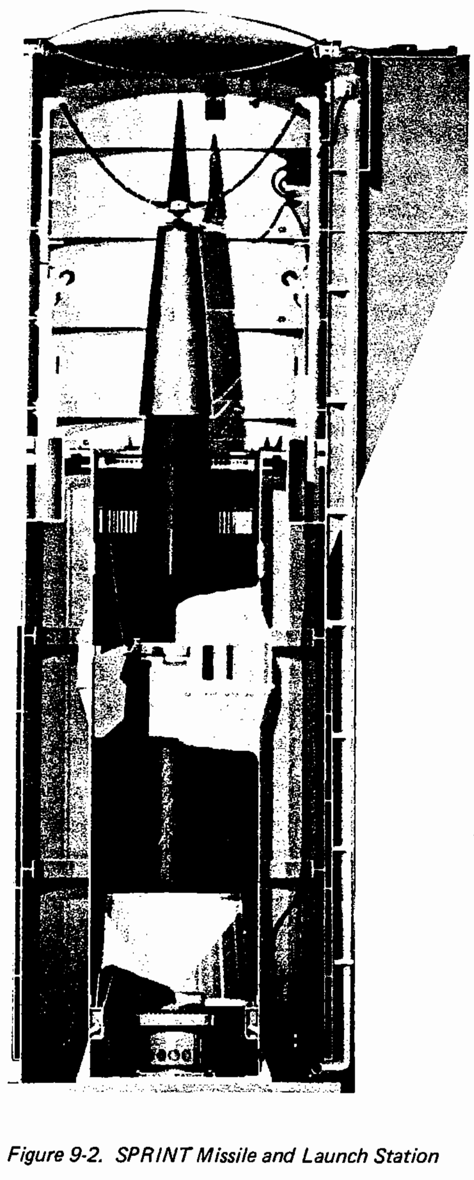

Figure 9-2. SPRINT Missile and Launch Station

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.

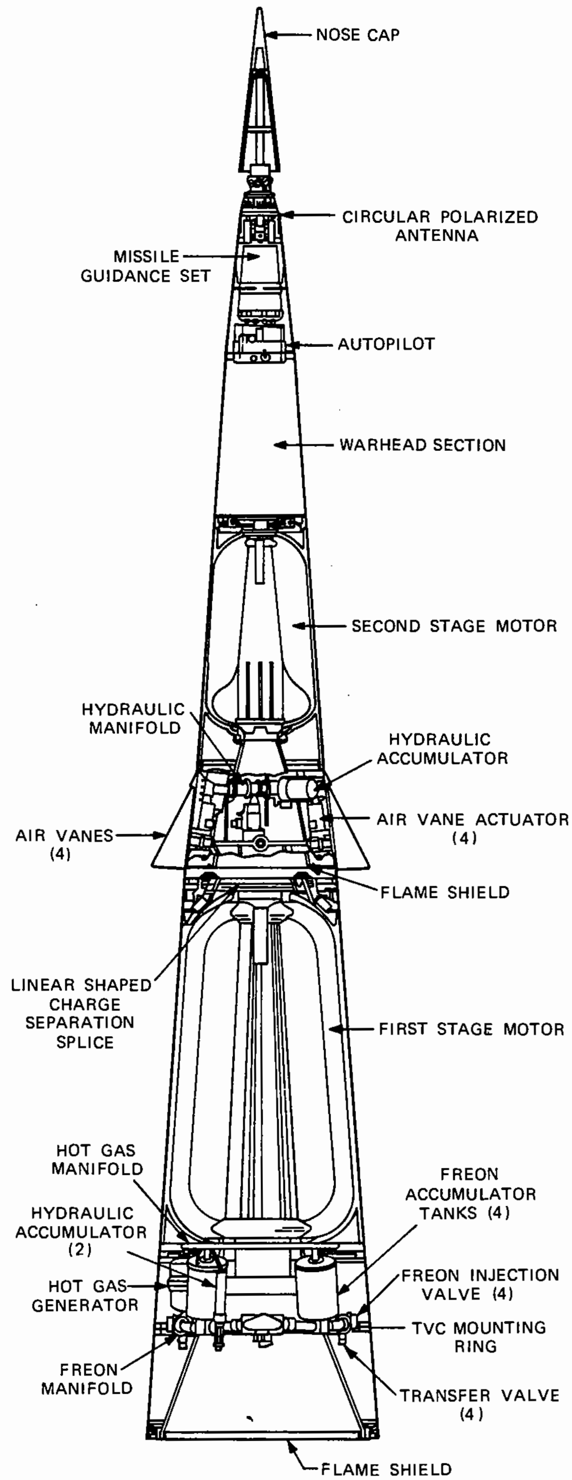

Figure 9-3. SPRINT Missile, Cutaway View

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 generator 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.

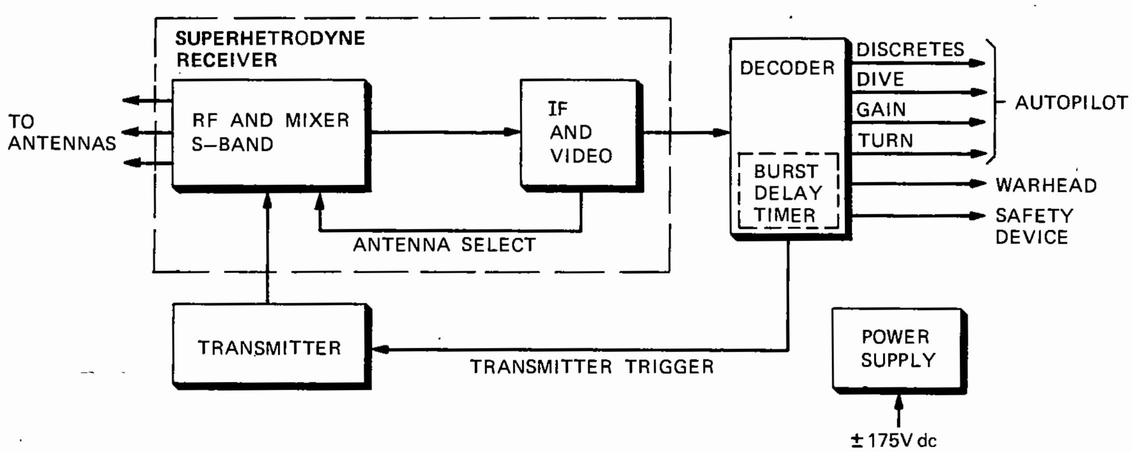

Figure 9-4. SPRINT Missile Guidance Set, Block Diagram

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[16,21] 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

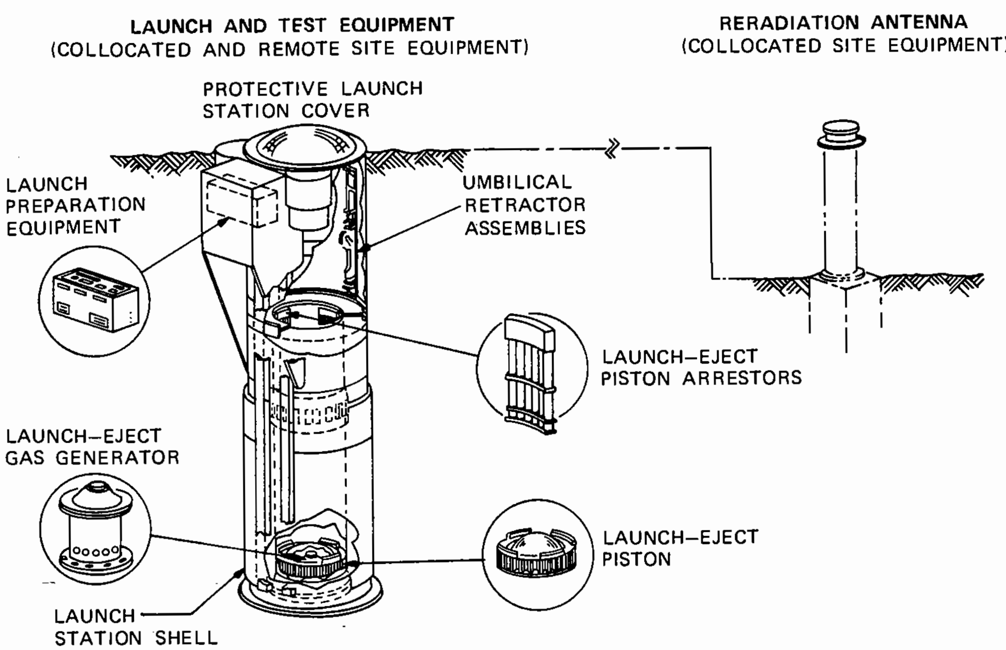

Figure 9-5. SPRINT Launch Station

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,

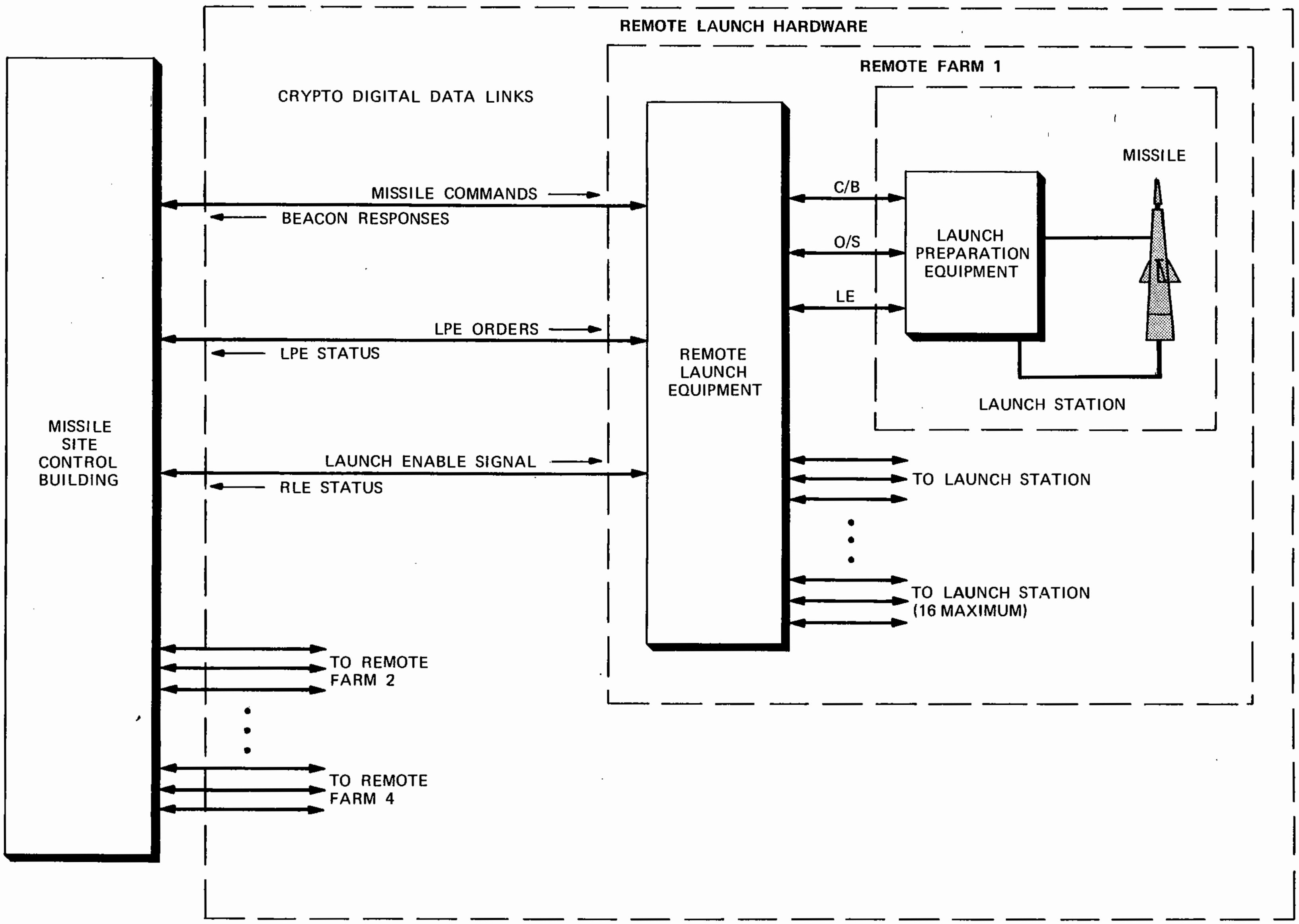

Figure 9-6. Remote Launch Equipment

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.

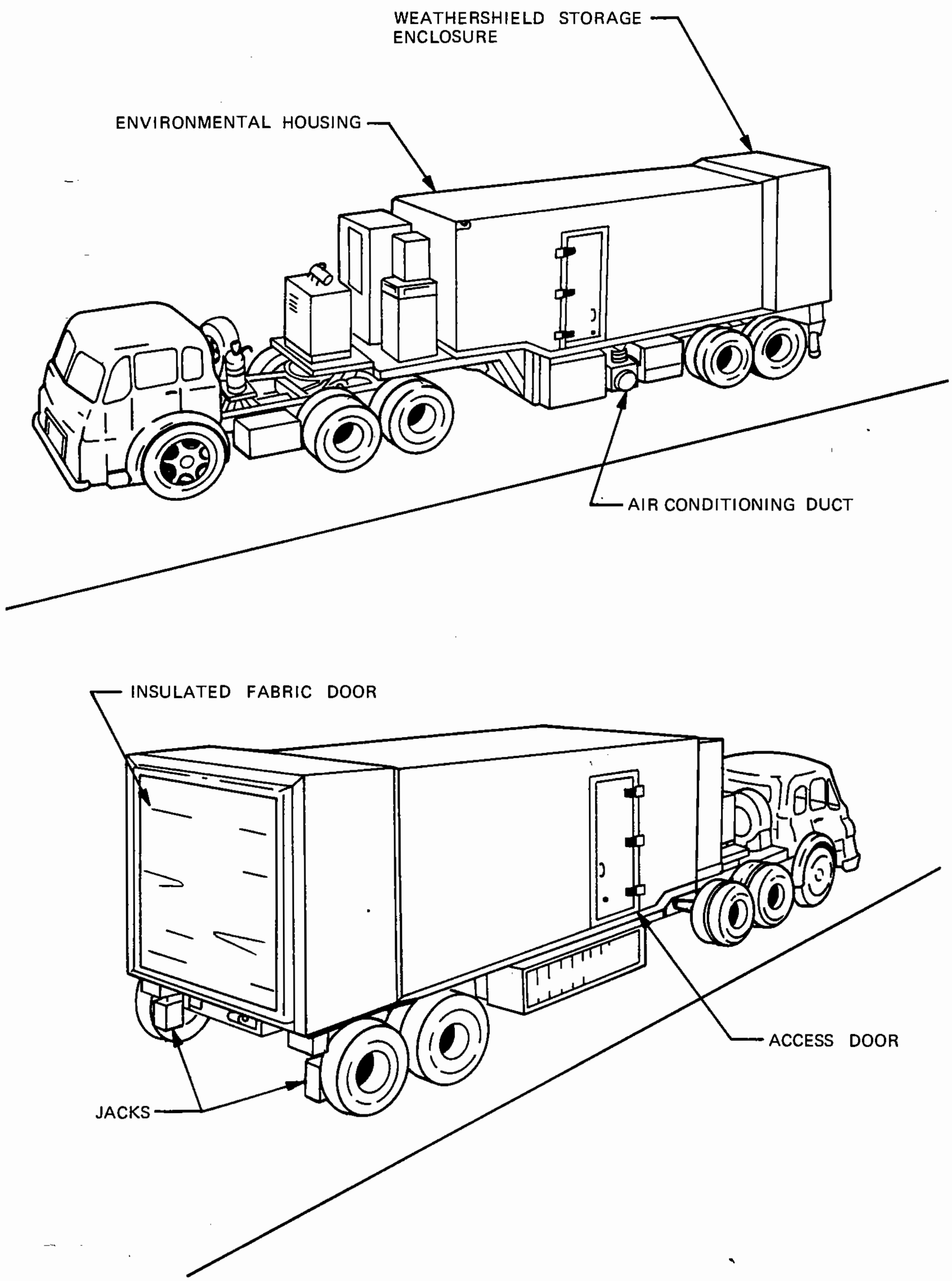

Figure 9-7. Universal Transporter Loader

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

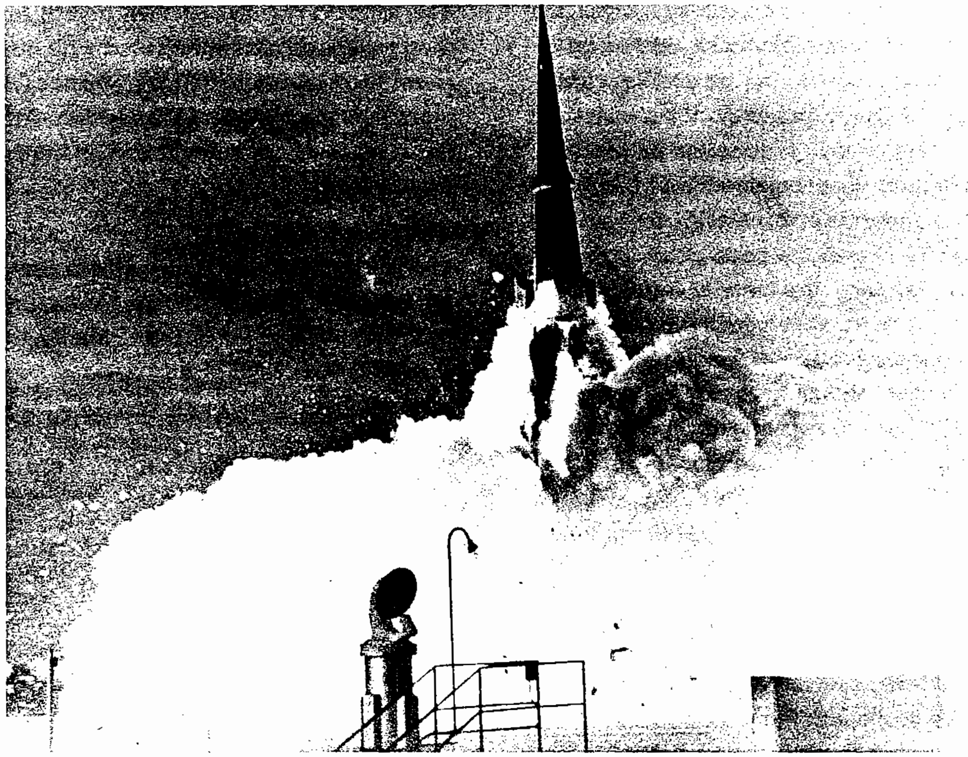

Figure 9-8. SPRINT Missile in Flight

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.