JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 40, No. 4, July–August 2003

Evolution of Ordnance Subsystems and Components in Air Force Strategic Missile Systems

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Ordnance subsystems and components are critical elements in intercontinental ballistic missile systems. Ordnance is required for stage ignition, stage separation, thrust vector control system actuation, fluid isolation valve actuation, battery actuation, thrust termination, and release of reentry vehicles. In addition, an ordnance destruct subsystem is mandatory for each flight test. The similarity between missile systems enabled the development and evolution of ordnance designs; for example, the isolation valves, linear-shaped charges for destruct subsystems, linear explosives for stage separation rings, and confined detonating cords for explosive train interconnections were used on all five missile systems developed by the U.S. Air Force since the early 1960s. The approach did not prevent the adoption of new technologies to improve performance. High-temperature resistant hexanitrostilbene explosive was adopted and the through-bulkhead initiator and exploding bridgewire initiator replaced the hot bridgewire-based squibs and detonators. A laser/fiber-optics-based ordnance firing system was developed for a mobile missile system. Hermetic seal technologies were adopted for achieving a longer service life for explosive devices. Better methods were adopted for ordnance testing, for example, the thermal transient pulse test and the builtin reflectometry. These approaches dramatically improved reliability, safety, weight efficiency, service life, and cost effectiveness.

Introduction

THE evolution of U.S. Air Force intercontinental ballistic missile (ICBM) systems has been reported in Ref. 1. Here we briefly narrate the history as pertinent to their ordnance subsystems and components. Minuteman I (MM I) was the first significant U.S. Air Force solid stage ICBM deployed. It consisted of three solid propellant booster stages, a guidance and control (G&C) system, and one Mark 11 reentry vehicle (RV). Over 100 ordnance items were designed and developed for the missile launch and flight operations. When one looks back, it is apparent that very good guidelines were established early in the missile development and were then adhered to by the later ICBM systems. Several examples are given. First, commonality of design for all three booster stages was established. An in-situ safety and arm device (S&A) and an arm/disarm switch (A–D) were designed. A high reliability squib and an interstage separation mechanism were also developed. Second, safety was established as an ordnance design priority. Motor ignition was considered most important; therefore, a redundant rotatable explosive train was designed for the S&A. The stage separation was second most important; thus, a rotatable electrical switch design was adopted for the A–D. Third, to maximize squib and detonator reliability, a low bridgewire resistance, high-current initiation approach was adopted. The low resistance is also beneficial for rf environment survivability. The missile batteries supply up to 30 A of surge current. The Department of Energy was responsible for the ordnance internal to the RV. The ordnance for RV release, spin generation, shroud jettison, and retro-motor ignition were application unique and were developed separately. Fourth, existing proven designs were adopted where possible. Several examples exist. The hot bridgewire (HBW)-based detonators were adopted from U.S. Navy aircraft applications. An array of electrolytic and thermal batteries was initiated with squibs originally developed for batteries from other space and military programs. Fifth, four thrust termination (TT) ports were attached on the aft cylinder section of stage III. The ports were assembled and held in place by snap rings, which contained a frangible sector. The sector contained cyclotetramethylenetetranitramine (HMX) explosive initiatable by an HBW detonator. The snap rings would be deactivated by firing the detonators. The four detonators were controlled by the G&C via an A–D switch. Sixth, tradeoffs were conducted on ordnance requirements. At the time MM I was developed, the guideline for ordnance components and systems had already been well established. MIL-STD-1512 specified a number of safety and reliability requirements, for example, the 5-min 1-W–1-A no-fire test, the 500-pF–25-kV electrostatic discharge (ESD) test, and the hermetic seal requirement. Under the constraint of miniaturization, reliability, and schedule, these requirements were not implemented fully. (MM I was a schedule accelerated program.) However, rigorous environmental testing, acceptance, and qualification were followed for all MM I ordnance components. The guideline of redundant channels for high reliability was adopted on a system level.

In the later 1960s, stage II was redesigned to have a larger diameter. A single nozzle with a liquid injection thrust vector control (LITVC) and a gas jet roll control (R/C) replaced the quadruple electrically operated nozzles. The new MM II ICBM included one Mark 11C RV plus a number of RV decoys and penetration aid deployment systems (PADS). These additions increased the number of ordnance components required.

In the early 1970s, stage III was redesigned to have a larger diameter, a new class 1.3 propellant grain design, and a glass composite motor case. Again, a single nozzle, LITVC, and R/C replaced the quadruple electrically operated nozzles. The number of TT ports was increased from four to six, and the ports were relocated to the forward end of the motor. Because the ordnance battery was marginal to initiate simultaneously 12 HBW detonators (2 per port) and to ensure simultaneity, a detonation harness/manifold system based

Presented at the AIAA Missile Science Conference, Monterey, CA, 3–5 December 1996; received 3 January 2003; revision received 10 March 2003; accepted for publication 4 April 2003.

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on using confined detonating cords (CDC) was designed to initiate linear-shaped-charge-(LSC-) based port cutting mechanisms. A hybrid arm-disarm/safe-arm (A–D/S–A) containing a rotatable detonator and electrical switches was designed specifically to operate the stage III TT ordnance and to arm R/C and LITVC ordnance circuits. The number of RVs was increased to three (Mark 12), as well as the necessary decoys and penetration aid deployment systems (PADS). A liquid bipropellant (monomethylhydrazine and N_2O_4)-based propulsion system rocket engine (PSRE) module containing four roll, two yaw, four pitch, and one axial engine was added to MM III between stage III and the G&C. This implementation required the addition of a separation ring between stage III and PSRE, an explosive cable separation module, and five explosive-actuated isolation valves to control the propellants and the helium gas for propellant tank pressurization.

In the 20 years of evolution from MM I to MM III, the same design ordnance components were maintained with new components added as required. This approach had to be abandoned for the Peacekeeper ICBM design in the later 1970s. Carrying out the objective of delivering of up to 10 Mark 21 RVs with a range comparable to that of MM III and a missile length deployable in the MM silo, the optimized design for three Kevlar® composite case-based solid booster stages and a postboost vehicle (PBV) similar to PSRE required increasing the missile diameter from the MM III 1.35 m (53 in.) to 2.34 m (92 in.). This size would just fit into the existing MM III silo planned for use in the Peacekeeper ICBM program. However, an unexpected problem due to ordnance was encountered. Each MM A–D, S&A, and A–D/S–A was equipped with a manually operated safing pin. The pin can only be reached by removing a small access cover on the missile. The arming of the missile, only allowable under full missile alert, that is, before the launch, is achieved by inserting a rod key into the missile and manually turning all of the pins. The projected increase in missile diameter eliminated the possibility of sending a crew into the silo for this arming procedure. The Nuclear Weapon System Safety Group required this positive interruption mechanism. However, the group did indicate that if a more reliable and safer ordnance system was designed for Peacekeeper, the safing pin requirement could be relieved.

At that time, two advanced ordnance system designs were available. Laser ordnance, which uses a high-power laser pulse as the stimulus and fiber-optic cables as the energy transfer medium, was attractive because it was intrinsically immune to rf interference and ESD. The technology had been pioneered by NASA for over 10 years after both components were available. Initiation of a number of explosive compositions by laser pulses was successfully characterized. A preliminary assessment indicated that a laser/fiber-optics-based ordnance system could be designed for Peacekeeper with weight and cost savings. However, it was new and had no established reliability record. The decision was made in favor of the exploding bridgewire initiator (EBWI) and CDC-based ordnance initiation system.

EBWI is also based on a bridgewire; however, it is loaded with an insensitive secondary explosive, pentaerythritol tetranitrate (PETN), which requires a shock stimulus for successful detonation initiation. The shock is achieved by a discharging capacitor charged to thousands of volts through the bridgewire. The high-energy discharge explodes the wire, and the shock initiates the PETN loaded on it. Because of the high voltage and energy required, it is intrinsically safer than an HBW-based squib or detonator. Shock is also required for initiation and propagation in a CDC. Even in a bonfire environment, these components deflagrate rather than detonate, thereby eliminating the threat of inadvertent firing of the missile. In 1975, EBW systems had been successfully used in the U.S. Army Pershing I missile and the U.S. Navy Polaris (A-3) and Poseidon (C-3) missile systems. A good performance database was, therefore, available.

The adoption of the EBW ordnance design led to an outstanding feature of the Peacekeeper ordnance, the standardization of ordnance components. There are essentially only three system components: 1) the high-voltage capacitor-based firing unit (FU)/EBWI assembly; 2) the CDC-based ordnance transmission assembly (OTA), where the end tip of the OTA provides a detonating output, replacing all detonators; and 3) the through-bulkhead initiator (TBI), which provides a deflagration output on actuation of the OTA end tip, replacing all squibs.

This standardization enabled the U.S. Air Force to take the cost effective step of making a single prime contractor responsible for all ordnance. Thiokol Corporation was selected for the development and production of the Peacekeeper ordnance initiation subsystem (OIS). In addition to the traditional initiation function for motors, isovalves and gas generators for thrust vector system (TVS) and staging ordnance, the OIS also covers the airborne power supply battery initiation, initiation of the launch ejection system, the gas generators for the extendible nozzle exit cones (ENEC) used in stages II and III and the shroud ejection motor.

The small ICBM was a mobile missile developed under a U.S. Air Force ICBM modernization program. It was designed to launch a single Mark 21 RV and be carried by a low-profile, diesel-powered, nuclear environment hardened, mobile launcher. Both HBW and EBW-based ordnance systems were determined to be unfavorable for this system. Under prolonged low-level vehicular vibration, gaps and voids can form in the squibs and detonators at the HBW/explosive interface with resulting failure. A Peacekeeper study on the OTA found that the vibration could induce fatigue-originated breakages in the metal sheath around the explosive core in the CDC, again resulting in failure. In addition, the Peacekeeper OIS requires a very bulky battery-inverter assembly, which would not be weight efficient. Laser ordnance was attractive because of the high resistance to fatigue breakage of the quartz optic fibers and because a builtin test (BIT) for end-to-end checkout of the optical path continuity can be safely and reliably implemented. In HBW and EBW systems, no BIT for end-to-end checkout of the actual bridgewire using electricity is allowed on an assembled missile.

As a result, laser ordnance was selected for the small ICBM. Hercules Aerospace Company was selected as the prime contractor for this ordnance firing system (OFS). The development was highlighted by a compact, central, high-power, pulsed laser-based FU (LFU), a multiple-channel, fiber-optic-cable energy transfer system, and a laser-initiated detonator (LID). The development was very successful, when it is considered that the dynamic environments for the small ICBM were much more severe than those of either Minuteman or Peacekeeper. In the two flight tests, the OFS, including the BIT, performed flawlessly. The functions of the OFS were essentially identical to the Peacekeeper OIS with the omission of ENEC gas generator initiation (not in use in the small ICBM). The success of the OFS generated broad interest in laser ordnance systems around the country. Following the termination of the small ICBM program in 1991, NASA worked with industry and successfully demonstrated using of an OFS in other missile and launch vehicle applications. With the advancement of the state of the art, much easier to use laser diodes have been adopted to replace the crystal laser rod and xenon flash lamp based LFU. Additional cost saving and system simplicity can be achieved. An OFS can be easily adopted for all ICBMs and tactical missile applications as well; however, no retrofit of this system for MM III or Peacekeeper was planned.

This paper reports the trends and the needs of the evolution of the ordnance subsystems and components with the emphasis on technology availability, maturity, and the payoff. The trends for future design are highlighted, and long service life and cost effectiveness are addressed.

MM III Ordnance Design

Except for the all ordnance TT (AOTT), MM III inherited the early MM ordnance design with added components as required.

S&A

Figure 1 shows the exterior configuration of the S&A. Two squibs are located in a rotor housing sealed by a thin metal diaphragm. The flange and an O-ring seal the assembly to the motor igniter port as shown in Fig. 2. The igniter is cylindrically shaped (Fig. 3). In the safe position, the rotor is 120 deg misaligned with the entrance hole of the igniter so that, if the squibs are inadvertently initiated, the B/KNO_3 pellets in the igniter will not be initiated. Arming produces

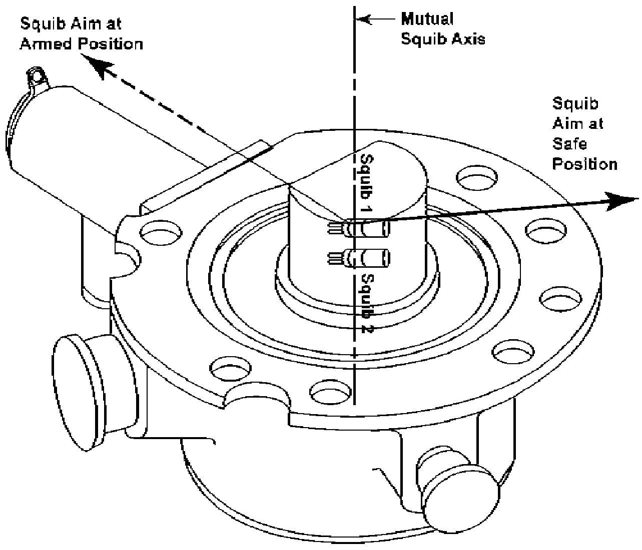

Fig. 1 Exterior configuration of S&A.

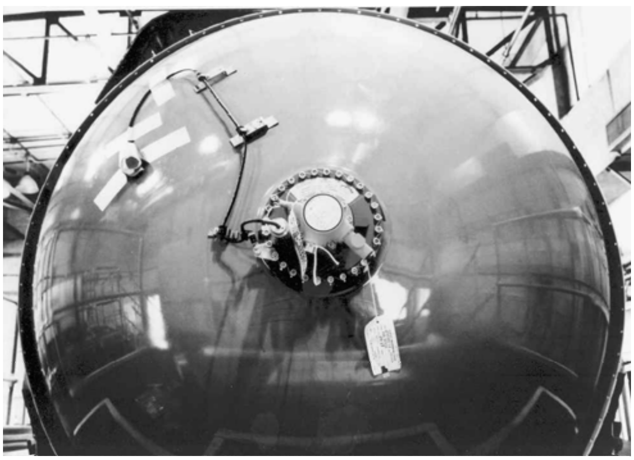

Fig. 2 S&A installation configuration.

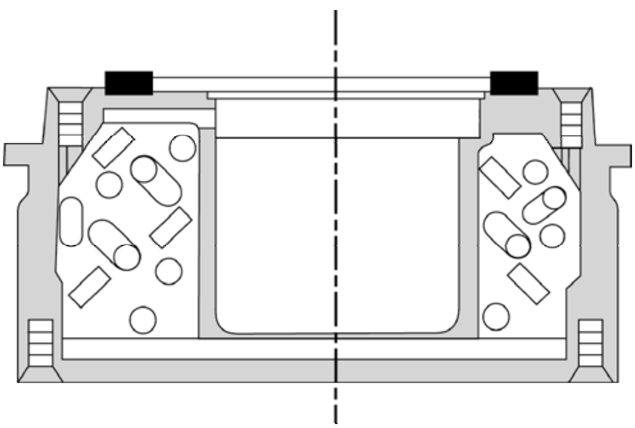

Fig. 3 Typical igniter design for interfacing with S&A.

a 120-deg rotation of the rotor so that the holes and the squib outputs are aligned for flame propagation. This design offers a triple redundant safety feature because the squib ignition leadwire connect and disconnect switch contacts are also controlled by the rotor, and when in safe state, the squib leadwires are shorted together. A safing pin further inhibits the rotor from inadvertent arming. The pin can only be deactivated by inserting and manually turning a key through an access cover on the missile. Figure 4 shows the S&A electrical schematic diagram and interior profile. It has two electrical connectors, one for the dc motor bidirectional rotation control

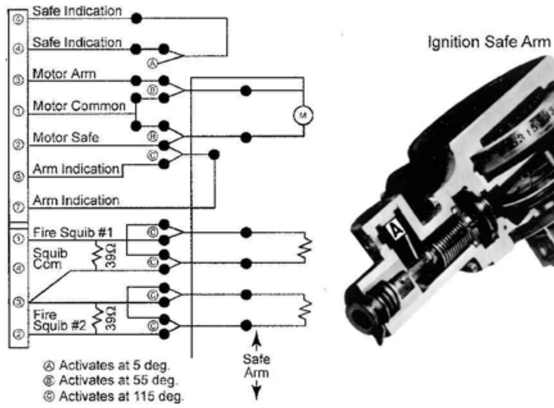

Fig. 4 S&A profile and electrical schematic.

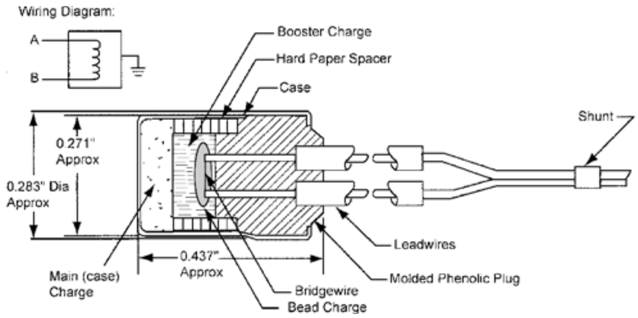

Fig. 5 ES-003 squib schematic diagram.

and monitor circuits and one for the squib firing lines. The separated circuits were implemented per MIL-STD-1512. The purpose of the 39-Ω "stub-stat resistor" was to provide a known load for firing line continuity checkout when the S&A is in the safe state. System-level checkout of the firing line in the arm state is prohibited. The S&A uses a minimum number of O-rings. The safing pin is sealed by a metal bellows, thereby eliminating the need for a rotary O-ring seal. Both features have proven to be superior to the later models of S&A used in space launch vehicles in terms of service life and reliability.

ES-003 Squib

Figure 5 shows the design of the ES-003 squib used in the S&A. It is derived from a popular commercial squib, U.S. Flare Model 207, with a slightly increased output pyrotechnic charge. The construction is based on the crimping of an aluminum can on a molded phenolic plug and is, therefore, not hermetically sealed. The design was necessary to achieve miniaturization because the size of squibs using a glass-to-metal seal design containing two leads is usually much larger. It was also taken into consideration that the S&A was environmentally sealed and protected by O-rings. The output main charge (90 mg) is made from zirconium–nickel/$KC1O_4$ composition. A relatively insensitive pyrotechnic composition, $KClO_4$/lead thiocyanate with an inert additive, was used as the initiation charge (~6 mg) and the booster charge (60 mg). The initiation charge was applied on the bridgewire by a slurry or beading technique, which forms a high-integrity bonding all around the bridgewire. The resistance of the nickel alloy bridgewire is approximately 0.2 Ω. The key performance parameters of the ES-003 are included in Table 1 along with other key squibs and detonators used on MM III.

A–D Switch

The A–D is a bidirectional, dc motor-driven, multiple contact, electrical switch that controls the firing lines of the squibs and detonators. It does not contain an explosive train. Its electrical function is quite similar to that of the S&A shown in Fig. 4; however, its electrical contacts are based on a multiple pin contact design, whereas the S&A uses a printed circuit contact. An A–D switch is capable to operate four firing circuits as compared to the two channels only in the S&A. Similarly, it has the same type monitors for arm and safe,

Table 1 Typical function characteristics of MM III squibs and detonators

EED identification	Usage	BW resistance, Ω	Firing current, A	Firing time, ms	Firing energy, mJ
ES-003	S&A	0.19 ± 0.03	7	1.5	14.7
D3A2	A–D/S–A, PSSS&A	0.07 ± 0.03	7	0.12	0.40
XUD-1094	Staging	0.45 ± 0.1	7	1.0	22.1
UMH-1051	Battery	0.13 ± 0.02	7	2.0	12.7
Atlas IGN-111	Command destruct batteries, C band telemetry	0.22 ± 0.12	9	2.5	44.5
Holex 3675	PSS battery	0.22 ± 0.12	9	4.4	78.4
AGX-2601	Command destruct S&A	0.18 ± 0.05	7	0.05	0.44

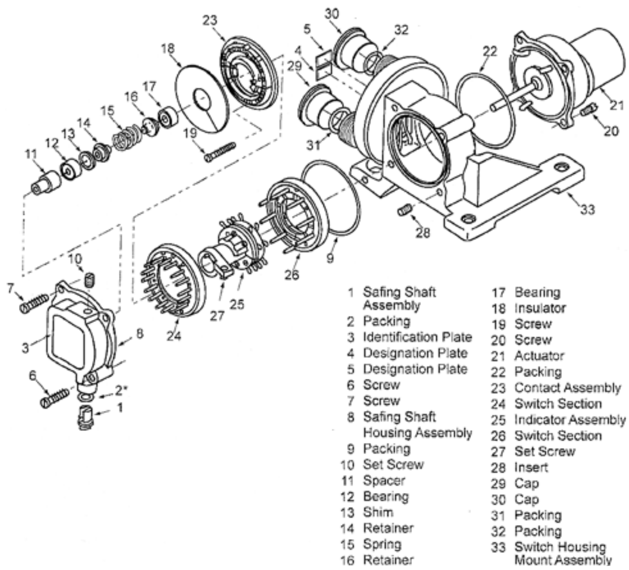

Fig. 6 Exploded view of A–D switch.

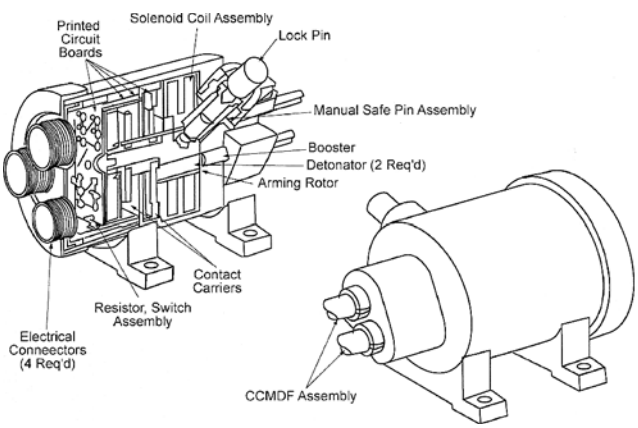

Fig. 7 A–D/S–A configuration.

39-Ω circuit verification resistors, a visual indicator, and a safing pin (called safing shaft). An exploded view of the A–D is shown in Fig. 6. Note that it is also sealed and protected by several O-rings. There are five A–D switches used on MM III, three for staging control, one for R/C and LITVC control for stage II, and one for isovalve actuation control on the PSRE.

A–D/S–A

This device adopted a hybrid design for a stage III unique implementation. It contains a rotary switch similar to the A–D and a rotary explosive train for initiation of the CDC harness of the AOTT. Both are driven by a single bidirectional dc motor. It is different from the S&A in that the output is redundant detonating stimuli with two CDCs. [In Fig. 7, it is shown as completely confined mild detonating fuse (CCMDF), an alternate acronym for CDC.] It contains

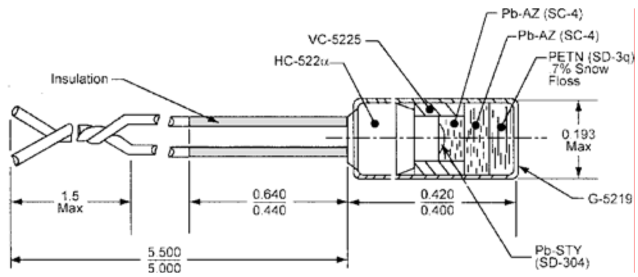

Fig. 8 D3A4 schedule diagram.

two redundant and electrically initiated HBW detonators, D3A2, at fixed positions. The outputs of the detonators face two end tips of CDC with a rotary barrier wheel separating them. The wheel also contains two cyclonite (RDX) filled lead explosive capsules. In the safe state, the barrier interrupts the detonation transfer even in an inadvertent D3A2 initiation. In the arm state, the lead explosive capsules align with the train, thereby allowing the detonation transfer. The circuit, safing pin, and visual indicator designs are essentially similar to the S&A and A–D.

D3A2 Detonator

The D3A2 was adopted from the U.S. Navy Mark 70 Mod 0 electrical detonator for aircraft applications. The only change is the bridgewire resistance, from 3.0–7.0 to 0.05–0.1 Ω. To achieve miniaturization, the D3A2, like the ES-003 squib, uses a molded plastic and crimped stainless steel can design, that is, it is not hermetically sealed. The explosive train consists of slurry beaded lead styphnate on the bridgewire, 40 mg of initiation lead azide, 50 mg of booster lead azide, and 80 mg of output PETN. Later, silicon sealant was used to seal the can/plug interface near the crimp line at the bottom of the detonator. The improved detonator, designated D3A4, has essentially the same performance characteristics as the D3A2 (Table 1). Figure 8 shows the design of D3A4.

Interstage Ordnance

The objectives of the interstage ordnance are twofold: to separate stages, or staging, and to remove the skirt for payload range efficiency. These two ordnance events arise from a single initiation event, but with a prescribed time delay between them for the protection of the nozzle exit cone. The time delay is 16 s for the I–II interstage and 1 s for the II–III interstage. The sequence of explosive events, as shown in Fig. 9, is as follows:

1) The firing command passes through the A–D switch, 8, and fires the redundant detonators, 1 (Fig. 10).

2) The detonators fire the circumferential linear explosive, 2 (Fig. 11), to effect the stage separation, actuate the mechanical safe and arm device, 4 (Fig. 12), by a lanyard pull, and initiate the delay detonators, 3 (Fig. 13).

3) The redundant delay detonators in turn initiate the high explosive leads (RDX) in the S&A.

4) The output of the S&A initiates the RDX-based H-booster, 5 (Fig. 14).

5) The H-booster initiates the linear explosives, 7, to separate the skirt from the departing stage. The purpose of the H-booster is to provide a crossover of explosive trains for additional reliability.

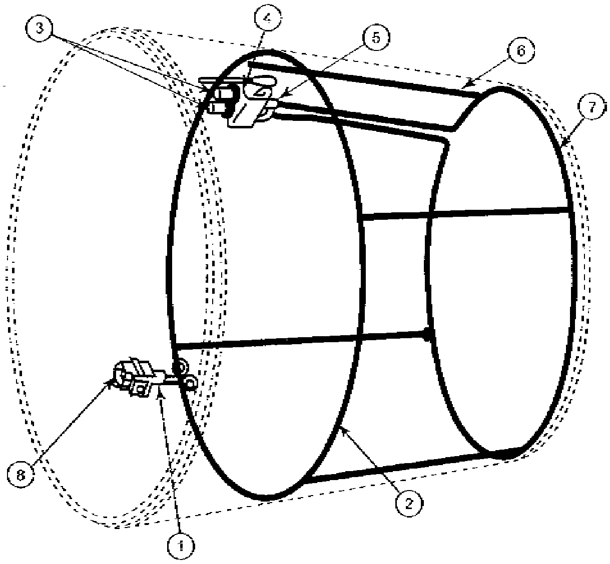

Fig. 9 Interstage ordnance configuration.

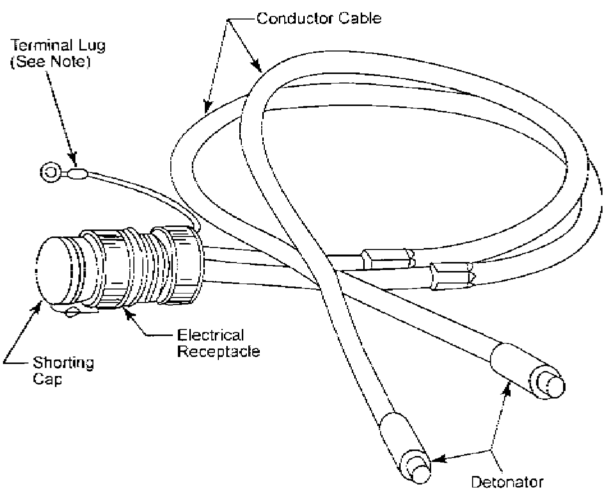

Fig. 10 Staging detonator external configuration.

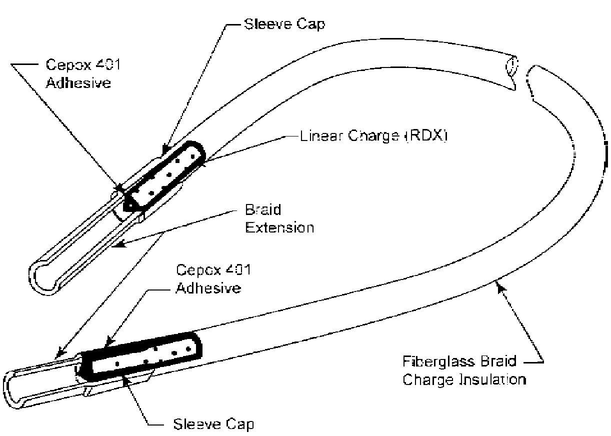

Fig. 11 Linear explosive design.

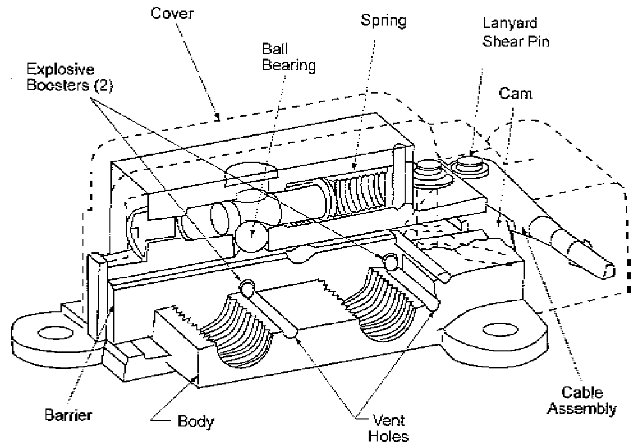

Fig. 12 Staging mechanical S&A design.

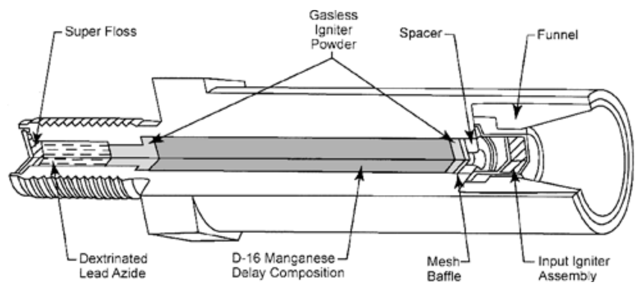

Fig. 13 Construction of the 1-s-delay booster detonator.

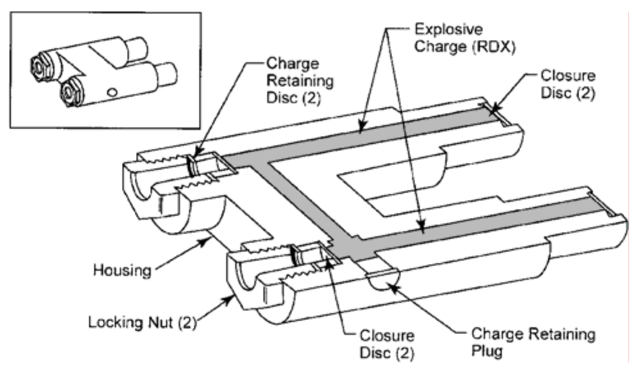

Fig. 14 H-booster interior configuration.

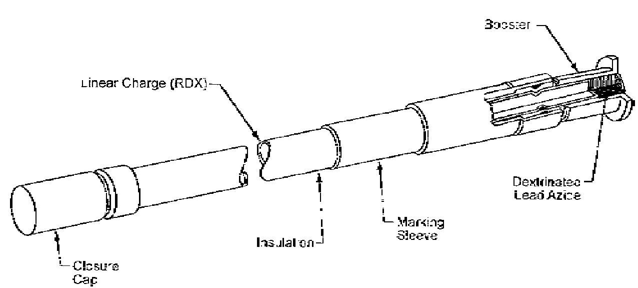

Fig. 15 Design of the longitudinal linear explosive.

6) The four longitudinal linear explosives, 6 (Fig. 15), sever simultaneously the cutoff interstage into four equal segments (Fig. 16).

The linear explosives are simply a lead sheath, 12.3 grains/ft of RDX-based mild detonation fuse with a thin layer of fiberglass braid. The input and output ends of the delay detonator are loaded with lead azide. The delay mix, D-16, is a manganese-type composition per MIL-M-21383. The A1A mix (formulated per MIL-P-22264) is critical for the D-16/lead azide propagation interface. The mesh baffle for holding the gasless A1A igniter powder at the output end of the delay detonator has proven to be a marginal design to prevent the migration of the A1A powder. A low percentage of detonator failure-to-propagate was noted in some flight tests. Although skirt removal is not a mission critical event, the delay detonator will be redesigned in the next round of ordnance refurbishment.

Figure 17 shows the configuration of the separation joint. The linear explosive is held by a half tube-shaped charge holder ring.

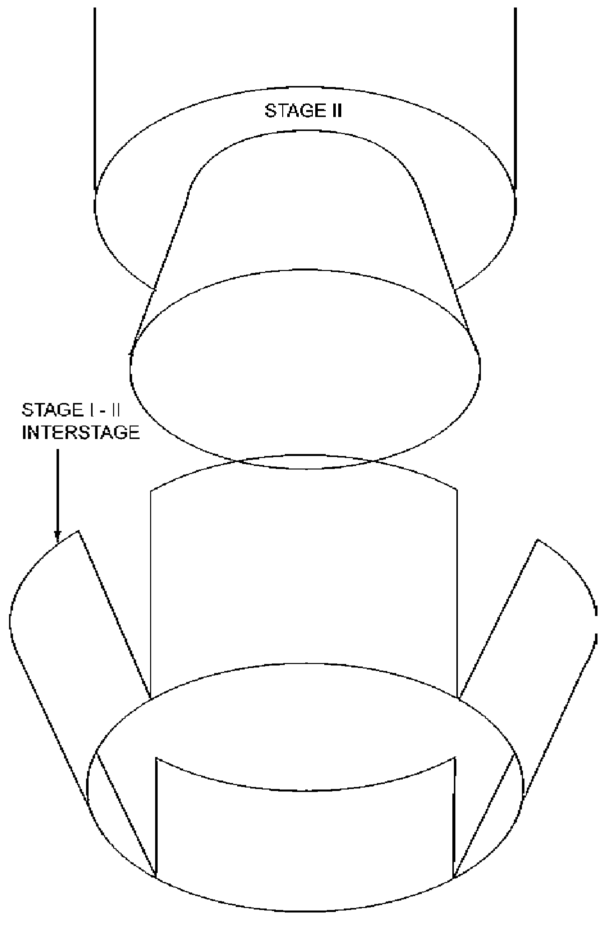

Fig. 16 Completion of skirt removal operation.

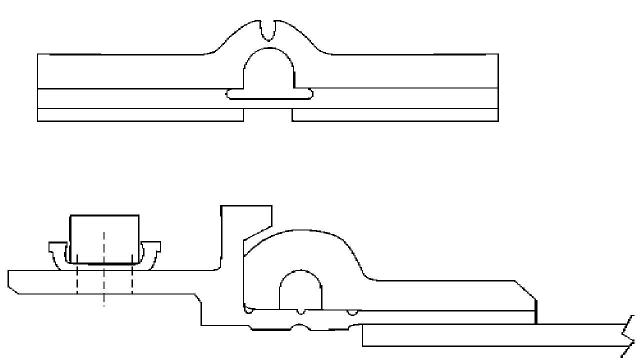

Fig. 17 Typical MM separation joint configuration.

The interstage surface facing the charge ring, containing the linear explosive, is either thinned down or provided a stress relief groove to facilitate severance. This type of design is also selected for use in Peacekeeper and development of small ICBM.

The detonator XUD-1094 is fabricated as a part of the staging cable assembly. The output charge contains 215 mg of polyvinyl lead azide and is designed to be hermetically sealed. The maximum helium leak rate requirement is relatively loose, only 10^{-4} cm^3 helium/s vs 10^{-6} cm^3 helium/s usually used for detonators per MIL-STD-1512. The entire detonator/cable assembly has a rigorous electrical shield design for safeguarding against radio frequency interference (RFI). Other explosive components in the interstage ordnance do not have a hermetic seal requirement.

Initiators for R/C, LITVC, Cable Separation Cartridge, and Isolation Valves

ES-003 squibs were packaged to provide a deflagration output to initiate the ammonium nitrite- (AN-) based gas generators for the R/C, LITVC, P107 cable separation module, and the booster charge in the isovalves. In these applications the size of the initiator was not an issue; therefore, a larger, hermetically sealed squib body was possible containing both redundant ES-003 squibs and the addition of booster charges, for example, SOS-109 ($TiH_2/KClO_4$), Hercules High-Temp powder, and B/KNO3 pellets (Figs. 18 and 19). The inherent high reliability of the ES-003 minimized the testing scope required. Cost effectiveness was achieved.

AOTT

The six TT ports equipped with LSCs for cutting of stage III forward dome case (~0.100 in. thick) are initiated by a CDC harness

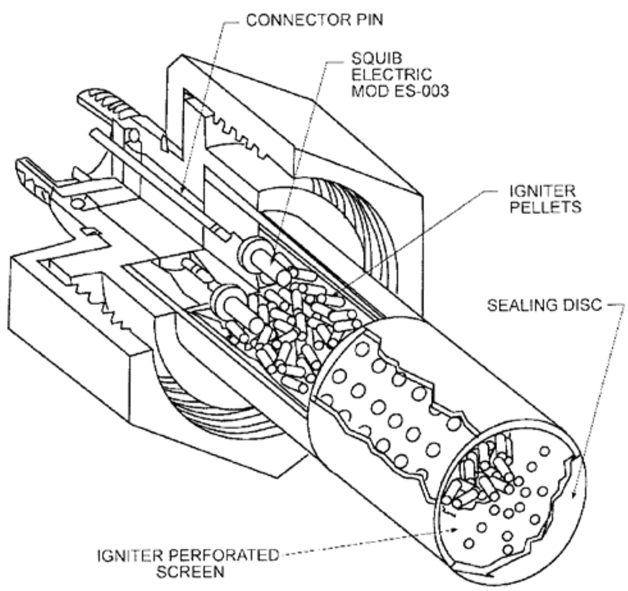

Fig. 18 R/C initiator schematic diagram.

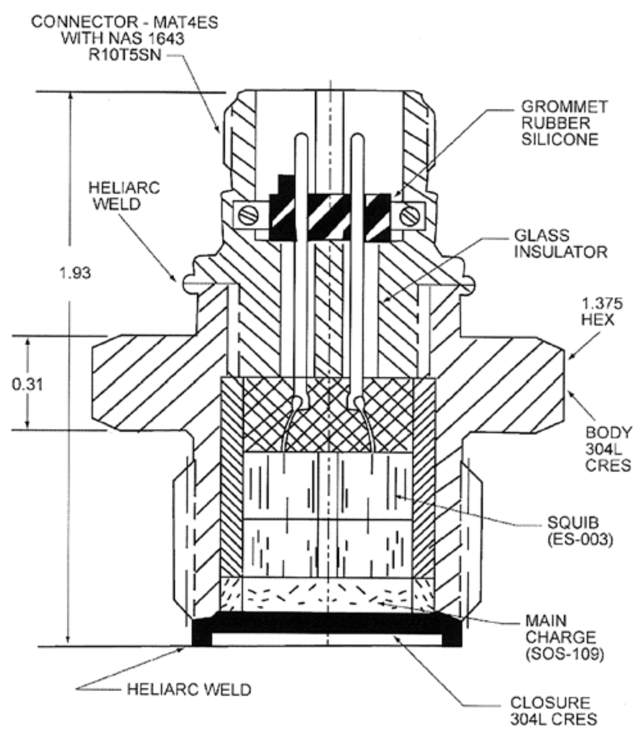

Fig. 19 Isolation valve initiator cartridge schematic diagram.

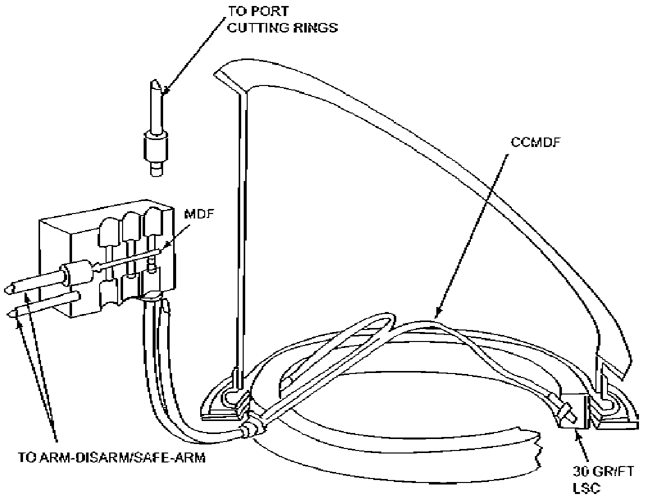

Fig. 20 AOTT explosive train configuration.

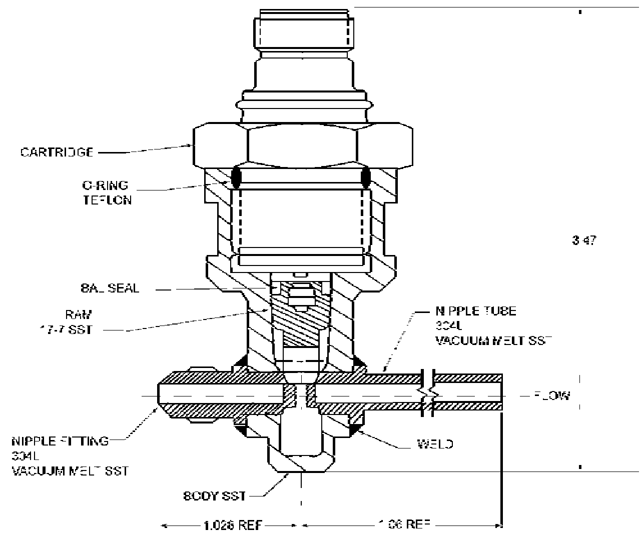

Fig. 22 Gas flow control isolation valve.

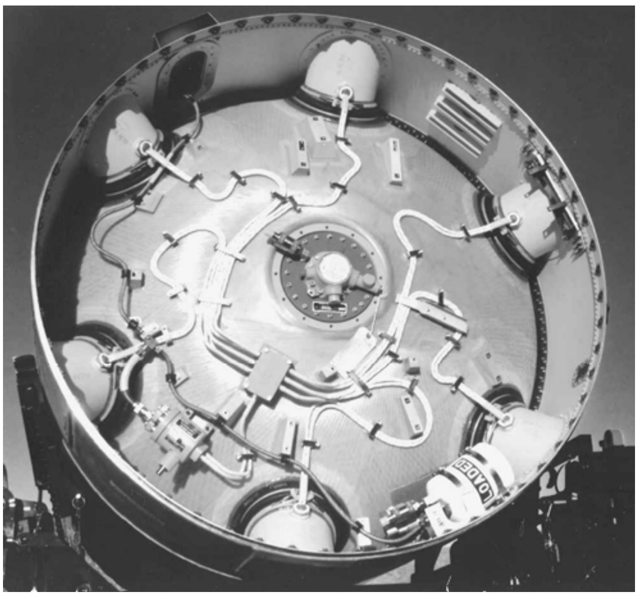

Fig. 21 Stage III AOTT layout.

system. The redundant outputs of A–D/S–A are routed into a CDC junction box and split into 12 CDC outputs, 2 per port (Fig. 20). The CDC routing is secured on the stage 3 forward dome as shown in Fig. 21. The CDC consists of seven layers of fiberglass-shielded, lead-sheathed, 2.5-grains/ft RDX-loaded mild detonating fuse (MDF). Each CDC end is integrated with a 100-mg PETN end tip to initiate the circumferential LSC in the port. The LSC is lead-sheath based and contains 30 grains/ft of RDX. This amount of charge not only can sever the case, but also the rubber internal insulation inside the case. This fundamental CDC design concept was also used in the Peacekeeper OIS design.

Isolation Valve

There are minor differences between the valves for control of the helium gas and the liquid propellants in the PSRE and that used on stage III LITVC helium gas control (for pressurization of the injection liquid). Basically, the design (Fig. 22) originated from the NASA Gemini spacecraft. The design utilizes a nipple fitting, or a nipple tube with integral shear cap nipples, to provide a hermetic seal for the normally closed valve. A booster charge (SOS 109 composition) initiated by the squibs drives a shear ram to sever the nipples and open the flow path. This design was adopted for the Peacekeeper and small ICBM liquid propellant-based PBVs.

All Ordnance Destruct System (AODS)

Aluminum-sheath, RDX-based, LSC assemblies were designed for the all ordnance destruct system (AODS). The loading of LSC is 200 grains/ft for stage I (steel cases) LSCA and 100 grains/ft for stages II and III LSCAs and the PSRE (metal tanks) LSCAs. The LSCAs are redundant and connected in series from stage to stage via detonating cords. The LSCs can be initiated from a command destruct S&A in the PSRE, which contains two AGX-2601 detonators and two explosive leads. Both sides can be fired by the command destruct receiver/control because the AODS is launched in the armed state. The design is very similar to later models used for space launch vehicles, both for normal ordnance and destruct systems. An example is the Thiokol Corporation Model 2134B S&A used for the Delta and Titan IV launch vehicles. On the forward end of stages I–III, a premature stage separation (PSS) S&A is added. The S&A is actuated by a lanyard connected between stages I and II, or stages II and III, and by a mechanical actuator on stage III. During PSS, the S&A is armed, and the two D3A2 detonators contained in it are connected to the PSS destruct batteries via a timer to effect initiation. In normal staging, the timer is not activated; thus, destruct does not occur (Fig. 23).

G&C Interface

The ordnance events are fired by the selected outputs of the G&C system. The firing pulse is rated at 30 A and is 1 s in duration. With a quadruple simultaneous firing event, each HBW device, thus, has an average firing current of 7.5 A. The function data in Table 1 and the approximately 2-A thresholds of these devices assure a large reliability margin. In a nuclear weapon system a unique signal device (USD), a coded safety device, is required. MM missiles have a partial USD, named the command signals decoder (CSD). It is a 27 code posts, time wheel system, to accept a preset code (Fig. 24). It is located on stage I and is commanded by ground control. The full arming of the device is necessary to fire stage I.

S&A, A–D, A–D/S–A CDS&A, PSSS&A Performance Checkout

At both 18-V and 30-V input levels, 22 performance parameters can be checked for each device. Because of the design commonality in these devices, a single test set can be used for all of them. In 1990, a microprocessor-based test set (AN/GWN P/N 1000500-1) was qualified for the automated checkout of all of the devices. The system is capable of comparing the test result with preset limits and prints out a pass/fail for each test. Only devices that pass the test are installed. An example for the S&A 18-V test sequence is shown in Table 2.

Table 2 Electrical checkout criteria for S&A device test set

Step	Test set, circuit	Limits
1	Arm motor coil resistance	20 Ω (minimum)
2	Safe motor coil leakage current	5 μA (maximum)
3	Arm monitor circuit leakage current	5 μA (maximum)
4	Safe monitor circuit resistance	0.60 Ω (maximum)
5	Squib simulator 1 resistance	38–40 Ω
6	Squib simulator 2 resistance	38–40 Ω
7	Squib simulator 3 resistance	38–40 Ω
8	Squib simulator 4 resistance	38–40 Ω
9	All circuits to case; insulation leakage current	5 μA (maximum)
10	Control circuits to fire circuits; insulation leakage current	5 μA (maximum)
11	Arming time	1000 ms (maximum)
12	Arm motor coil leakage current	5 μA (maximum)
13	Safe motor coil resistance	20 Ω (minimum)
14	Arm monitor circuit resistance	0.60 Ω (maximum)
15	Safe monitor circuit leakage current	5 μA (maximum)
16	Squib 1 resistance	0.60 Ω (maximum)
17	Squib 2 resistance	0.60 Ω (maximum)
18	Squib 3 resistance	0.60 Ω (maximum)
19	Squib 4 resistance	0.60 Ω (maximum)
20	All circuits to case; insulation leakage current	5 μA (maximum)
21	Control circuits to fire circuits; insulation leakage current	5 μA (maximum)
22	Safing time	1000 ms (maximum)

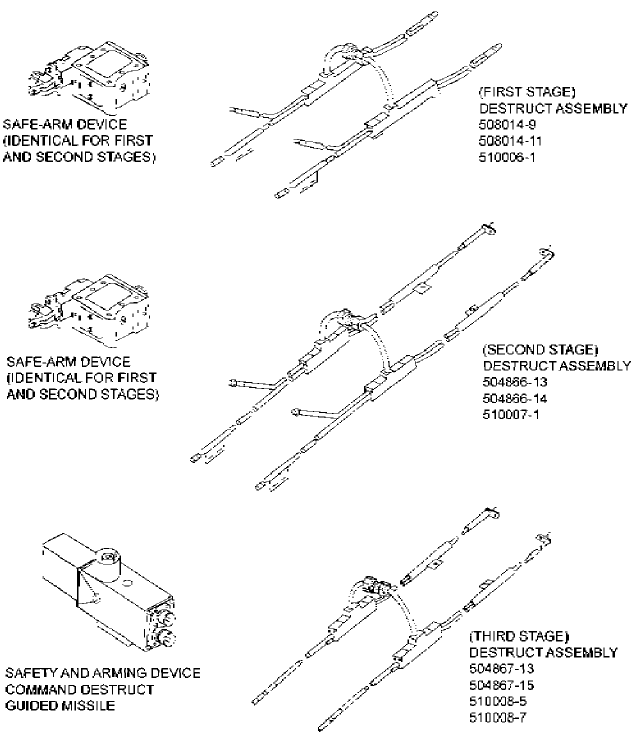

Fig. 23 AODS components.

ESD and 1-Watt–1-Amp Testing

Because of the high degree of miniaturization of the ES-003 squib, the XUD1094 detonator, and the D3A2 (D3A4) detonator, two size-dependent test requirements per ordnance specifications, MIL-STD-1512, MIL-STD-1576 and Department of Defense DoD-E-83578, cannot be met. The ESD requirement is 3000 V/5000 pF vs the required 25,000 V/500 pF. The no-fire test requirement is 1 A for 15 s vs the required 1 A–1 W for 5 min per MIL-STD-1512 and MIL-STD-1576. The composited initiators made by encasing ES-003s may meet the 1-A, 5-min requirement. Because the ES-003 and D3A4 are mainly for installation inside S&A and A–D/S–A devices, the risk of ESD due to the handling is mitigated.

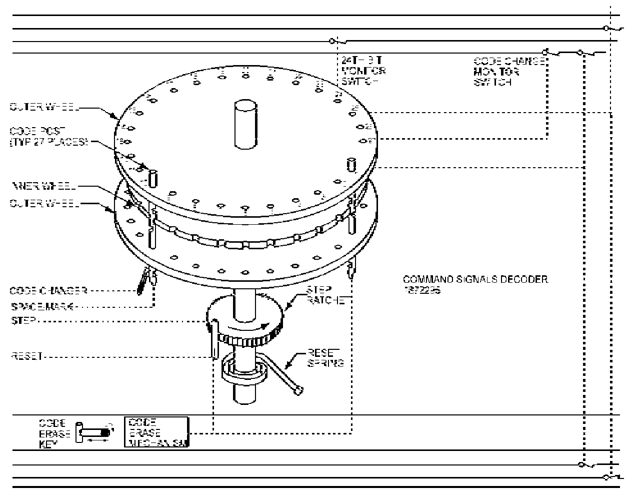

Fig. 24 Command signal decoder interior configuration.

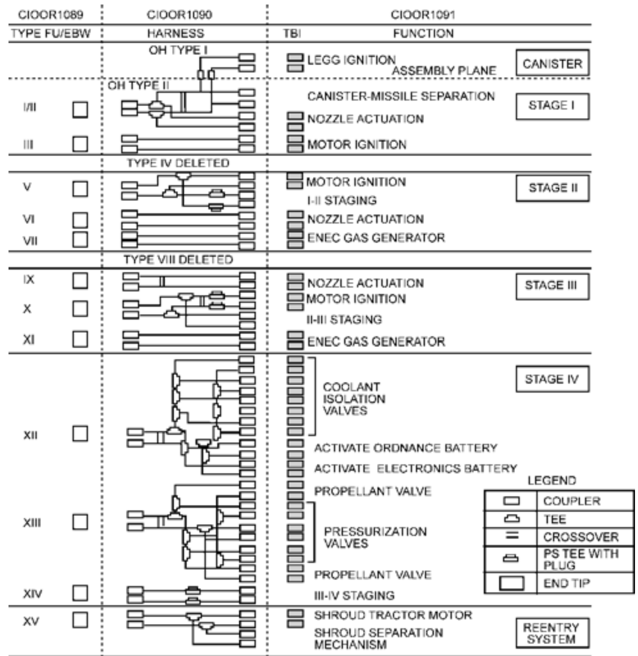

Fig. 25 Peacekeeper ordnance initiation system. (Note that this is not necessarily representative of exact physical orientations.)

Peacekeeper Ordnance Design

OIS

The standardization of ordnance components in FU/EBWI assemblies, OTAs, and TBIs greatly simplified the Peacekeeper OIS. The OIS missile function is shown in Fig. 25. A localized, distributed FU implementation was adopted, that is, FUs are located near the ordnance events, usually on the same stage. A significant weight efficiency was achieved with this approach. Simultaneous initiations are implemented by using OTAs in "Tee" connections. These interconnected OTA harnesses were assembled at the factory and delivered to the stage contractors in ordnance harness (OH) kits. There are 12 types of OH kits used on the missile. A "crossover block" design is used for OTA connections across the staging plane where required.

EBWI, TBI, and OTA are also used on the Peacekeeper destruct system, the flight termination ordnance system (FTOS). The design of the FTOS along with these components has been reported in Ref. 2. Both EBWI and TBI are hermetically sealed (10^{-6} cm^3 helium/s maximum leak rate). The CDC used in the OTA design is

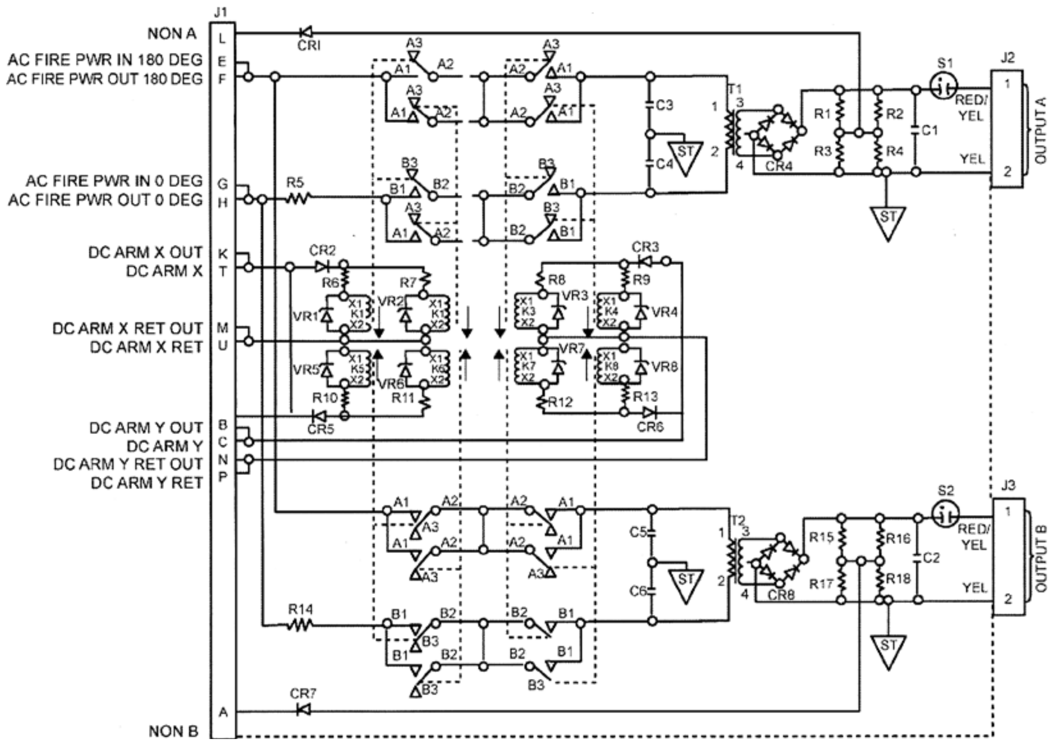

Fig. 26 Peacekeeper OIS FU schematic.

significantly improved over that used on MM III. It has two layers of stainless steel braids for better ruggedness, an aluminum sheath replacing the lead sheath in the MDF, polyethylene and polyurethane tubes for moisture protection, and high-temperature resistant hexanitrostilbene (HNS) replacing the RDX for the MDF core load.

Firing Unit

The OIS FU is different from the FU for the FTOS reported in Ref. 2. Both FUs are fundamentally high-voltage discharge-based designs for initiation of the same EBWIs. The FTOS FU high-voltage capacitor has a slow charging current and is continuously powered through prelaunch and flight phases by a builtin dc-to-dc converter. The OIS FU has a fast charging rate and is charged as part of the ordnance function. Thus, a high-current (30-A) 17-kHz central inverter, located in the G&C, was designed for a better system weight saving. The schematic diagram of OIS FU is shown in Fig. 26.

A single FU contains the control and firing circuits for both redundant EBW channels. To minimize the lead wire impedance load-down effect on EBW firing efficiency, both EBWIs are directly connected to high-voltage connectors on the FU. The FU contains two high-voltage circuits, one for each channel. Each section incorporates four relays (used as control and blocking elements), a step-up transformer, a full wave bridge rectifier, a high-voltage capacitor, a spark gap, and a bleeder/monitor resistor network. After activating the necessary relays to connect the respective channel, an ac fire-power signal is applied through the relays to the transformer. For reliability, the ac signal is turned on after the relay contacts close and off again before the contacts open. This signal (200 ± 25 V, zero to peak square wave at 17 kHz) is stepped up at a 1:21 ratio. The ac signal is full wave rectified and begins to charge the high-voltage capacitor. When the charge on the high-voltage capacitor reaches 1700 V, the overvoltage gap switch breaks down, and the capacitor discharges its energy into the EBWI. The capacitor and the gap were adopted from U.S. Navy and Department of Energy (DOE) designs, respectively. The EBW firing threshold is approximately 800 V; therefore, an adequate margin is achieved.

The relay contacts are configured for a series-parallel operation to achieve maximum reliability. A single contact/relay transfer will not activate the unit, and a single relay failure to transfer will not prevent package operation. Each FU contains four relays. The dc arm X signal controls a set of two relays, with each relay pulling in a contact on the ac high side and the ac return side and with the two contacts on each side wired in parallel to each other. The dc arm Y signal operates in an identical manner. The firing command for the EBW is 14 ms in duration with a 10-ms separation between the redundant channels. This implementation conserves electrical power and provides a better reliability under nuclear radiation exposure. The nominal function time for an EBW during the flight is 4–6 ms.

Other Ordnance Components

There are five separation rings on Peacekeeper [launch eject gas generator (LEGG)/stage I/stage II/stage III/ PBV/shroud]. Their designs evolved from MM designs either using MDF or LSC with HNS core loads (except for the I–II stage separation ring in which RDX is used). Peacekeeper did not incorporate skirt removal ordnance because, with the ENEC design, the length-to-diameter ratios of interstages are small and it is safe to install a single separation ring for both skirt removal and stage separation. The five isolation-valve-based liquid propellant handling system is a direct copy of the MM III PSRE with TBIs replacing squib cartridges. Of course, all S&As, A–Ds, and A–D/S–A are eliminated on Peacekeeper.

G&C Interface

The G&C provides dc arm signals and 17-kHz ac power to each FU via a G&C cable set. A USD with 64 stepping motor steps is inserted between the G&C and the FUs. This USD is a direct adoption of the USD used in the Mark 21 RV, therefore, achieving additional cost effectiveness and reliability.

Small ICBM Ordnance

OFS

The successful development of the small ICBM OFS is reported in Ref. 3. At first glance it appears that the OFS used totally new technologies; however, its implementation actually followed very closely the good design guidelines of previous U.S. Air Force ICBM ordnance systems. As a matter of fact, the OFS is more like the HBW ordnance initiation system used in MM III than the EBW OIS used in Peacekeeper. The OFS adopted a central LFU located in the PBV. Optical pulses replaced electrical current pulses; fiber-optic cables replaced electrical cables. The optical fiber channel had a standard terminal design so that electrical cable and connector designs were readily adopted for fiber-optic cable interconnections. A standard LID was designed to initiate all ordnance events in conjunction with the TBI adopted from the Peacekeeper OIS. This approach simplified interfaces, achieved cost effectiveness, and enabled a single contractor, Hercules Aerospace Company (now Alliant TechSystems), to be selected for the OFS development.

LFU

The LFU was designed with emphases on weight, cost, and safety efficiencies. The unit consists of two redundant xenon flash lamp-pumped high-power pulsed lasers (wavelength of 1.06 μm). Each channel has a stepping solenoid-based optical distribution mechanism to direct the laser beam to separate focusing lenses that interface with separate fiber-optic channels to initiate LIDs for different ordnance events. The mechanism is equipped with a safe position and position monitors, resembling a sophisticated S&A. A 16-step dual code-wheel USD used in the Pershing missile was adopted in the LFU to arm two optical shutters. This mechanically interrupted arm/safe capability resembles the safing pin and is superior to the EBW OIS. For electrical power efficiency, in addition to the central laser implementation, a slower charging rate of 1 s (before each initiation event) is used for the converter/high-voltage xenon lamp discharge circuit. The discharge is safeguard by a Sprytron trigger gap developed by the DOE specifically for the LFU.

LID and Fiber-Optic ETS

The LID contains 2-(5-cyanotetrazolato) pentaamminecobalt (III) perchlorate (CP) explosive, an advanced composition developed by DOE modified for light absorption efficiency. One unique design feature of the LID is its optical window, which is coated with a dichroic film. The film is transparent to the 1.06-μm wavelength firing laser pulse but is totally reflective to the 0.85-μm wavelength low-power diode laser pulse. This enables a diode laser-based BIT to be implemented in the LFU in parallel with the main laser optical transmission path with a high degree of safety. At the component level or for preinstallation checkout at the launch site, a commercial optical time-domain reflectometer (OTDR) was used to check out the LID and fiber-optic cable. The OTDR inspection determined the optical transmission characteristics of the channels and the location of any anomaly should one be encountered.

The low-energy loss in the optic fiber itself is superior to common copper wire. This loss is only of the order of 10 dB/km. The system loss mainly occurs in the fiber-to-fiber mating in a connector, resembling the electrical contact resistance. The terminal pairs for fiber mating in the ETS connectors were fabricated with much higher precision than their electrical counterparts and were acceptance tested per the fiber-optics military standards. The LID is hermetically sealed. It has a laser initiation threshold of approximately 5-mJ. Thus for a minimum LFU output of 300 mJ, ample system reliability is achieved.

Other Ordnance Components

The designs for the five separation rings and the isolation valves used on small ICBM are very similar to those used for Peacekeeper. The Peacekeeper FTOS was adopted for small ICBM with the necessary linear shaped charge assembly (LSCA) design changes to sever the graphite composite-based motor cases used on all three solid booster stages.

Unique System Testing

Highly nuclear radiation resistant optical components were used for the OFS design, for example the gallium–scandium–gadolinium–garnet (GSGG) crystal laser rod and the plastic-clad pure-quartz optic fiber.[3] The components were evaluated by simulated pulsed ionizing radiation tests and a ground nuclear test and performed satisfactorily. An extensive bonfire test series was performed on the OFS explosive components because a fire is a credible environment for a mobile missile. The results indicated that the LIDs are fire safe and superior to HBW and EBW ordnance components.

Future Aspects

The optical alignment procedure at the factory was critical for LFU performance. This elaborate alignment was successfully achieved. Since the termination of small ICBM, laser diode technology has continued to advance. Diodes with outputs on the order of 10 W at an efficiency of the order of 1-W/1-A input current pulse have become available. Because of the much smaller size and lower cost of a single diode system, including the electronics, as compared to the crystal laser rod, high-voltage pulse-discharge-operated xenon lamp laser system used in the LFU, a dedicated laser per each ordnance event could now be implemented. A central LFU consisting of multiple diode laser modules can be fabricated much simpler. In addition, the high-current pulse normally used to initiate the HBW-based squibs and detonators can now be directly used to pulse the laser diode. Figures 27 and 28 show a conceptual design

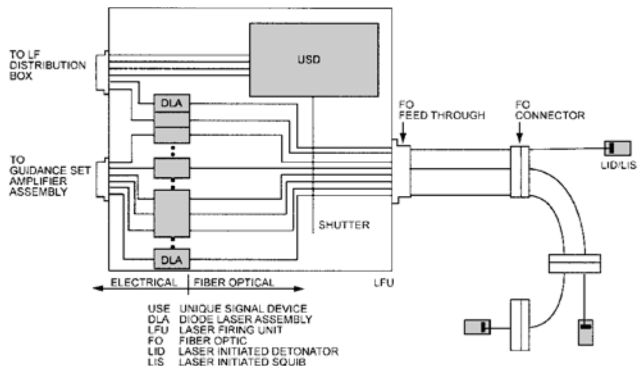

Fig. 27 Diode laser ordnance firing system concept.

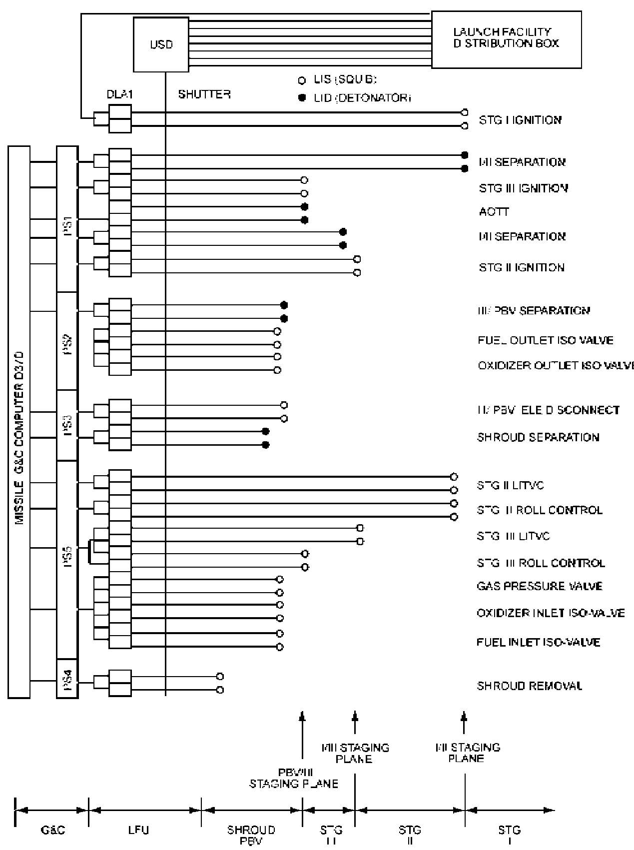

Fig. 28 Concept for applying diode laser ordnance firing system to MM III.

for applying the system to MM III ordnance initiation. The work was only an exercise during a small ICBM technology transfer study after the termination of the program because no plan has been made to execute the retrofit due to cost constraints and the fact that current designs work well. However, it does illustrate a direction for future applications on new missiles and space launch vehicles.

Ordnance Subsystem and Component Testing

The success of ICBM ordnance subsystems and components may be attributed not only to good design but also to thorough testing programs. Besides the extensive testing during the development, the ordnance productions were highlighted by formal qualification and acceptance testing, both of which were performed at the subsystem, assembly, and component levels. In addition, screening tests and in-process tests were established for critical parts and processes. Table 3 briefly summarizes the test requirements and approaches from which the following comments can be made.

Large Test Sample Size

The ordnance guideline, MIL-STD-1512, has very stringent sample-size requirements for demonstrating high reliability in ordnance components and systems. Because of the commonality in design, this extensive testing was required on fewer components, resulting in significant cost savings. This design feature is particularly notable in Peacekeeper ordnance, in which only two initiation components, the EBWI and the TBI, were used.

Unique Test Methods

The combined temperature cycling and humidity test per MIL-STD-331 method 105 was adopted for a thorough test of all subsystems and components. A combined high-altitude and thermal shock test provided good simulations for both the vacuum and aerodynamic heating environments. The transportation vibration environment was elaborate but successfully tested. These tests exceeded the scope of current ordnance specifications, for example, MILSTD-1576 and DoD-E-83578A.

Benign Temperature Requirements

Because all ICBMs are housed in temperature-controlled silos or launch-eject tubes and there are minimum aeroheating effects in the interior of the missile, the operating temperature range of the ordnance components is limited to 45–110°F, much more benign than in nature. Therefore, component tests could be conducted at ambient temperature, making tests at a stringent temperature extreme unnecessary. This contributed to more cost savings. High-temperature exposure is possible for a very limited number of ordnance, for examples the initiater for the shroud removal tractor motor and the raceway LSCAs. Effective thermal insulation was designed to solve any high temperature exposure problems.

Good Prediction of Missile Dynamic Environments

When MM I was designed, very little was known about the shock and vibration conditions the missile would experience. These requirements were specified on a localized basis, that is, a different level and spectrum for each location on the missile. The most severe vibration level was adopted for all ordnance components on Minuteman missiles. The staging ordnance shock is the strongest, as indicated in Peacekeeper and small ICBM requirements, which were universal for all missile components. A shock test was not thoroughly evaluated for Minuteman ordnance. However, most squibs and detonators were integrated in other assemblies (S&A, A–D/S–A, R/C, etc.), which were mounted on "secondary structures" rather than on the "primary structures" of the missile. Therefore, the shocks reaching these ordnance components are potentially of lower levels. In recent years, S&As and CDCs of similar designs were shock tested at high levels without failure, indicating that the ordnance component designs used on the Minuteman missile are shock resistant. This conclusion is also supported by good flight-test results. In the next round of MM III ordnance refurbishment, the shock specification used for the MM III PSRE and RV components, on the order of 2500–4500 g, will be the guideline for the ordnance components.

Safety Tests

In 1966, 23 Minuteman ordnance components, including the S&A, A–D, ES-003, D3A2, and XUD-1094, were thoroughly evaluated for 1-W–1-A rf susceptibility by the Franklin Institute Research Laboratories. All components passed the MIL-STD-1512 required tests. The only electroexplosive device (EED) in the Peacekeeper OIS and FTOS, the EBWI, was also successfully tested by the Franklin Institute in 1982. All ordnance electrical packages, for example, OIS and FTOS FUs, S&A, A–D, and ordnance cables, were successfully tested for RFI per MIL-STD-461, MILSTD-462, and Ballistic Systems Division (BSD) Exhibit 62-87 (an earlier RFI test requirement document similar to 461 and 462). The only safety requirement that some Minuteman missile ordnance components have difficulty meeting has been the ESD test as reported earlier in this paper. Because of their good safety record and to save costs, we intend to maintain the design with enhanced safety procedures in the handling and assembly of these components.

Flight and Aging and Surveillance (A/S) Tests

The performance of ordnance components and subsystems is constantly evaluated by four independent means: flight tests, simulated electronic launch MM, aging and surveillance (A/S) static firing tests of stage motors, and ordnance components A/S testing. Flight tests are the ultimate measures of ICBM system and subsystem performance, including all ordnance components. These flights are divided into the earlier development test and evaluation (DT&E) and, for fielded systems, the later operational test and evaluation (OT&E). Over the years, over 160 OT&E flight tests were conducted on MM I, II, and III systems. For Peacekeeper, 18 DT&E and 22 OT&E flight tests were conducted. Only two DT&E flight tests were conducted for small ICBM.

Because of the redundancy of ordnance components, a successful flight does not prove that all channels successfully functioned. This is especially true for MM systems in which the HBW channels were fired simultaneously. In Peacekeeper, because there is a time delay in commanding the firing of the redundant EBW, the surge current characteristics of the ordnance batteries are used to evaluate the successful function of the bridgewires of both channels. However, this still does not provide information on the explosive train itself. The rather slow nature and variability of missile events, for example, stage ignition, stage separation, and gas generator ignition, would overshadow the redundant ordnance event timing information.

Stage motors are static tested to evaluate their performance under controlled conditions. Examples of evaluated parameters are internal insulation erosion, nozzle maximum deflection response, nozzle throat erosion, case temperature, and vibration due to combustion resonance. Because a static test is a ground test, instrumentation can be deployed to record component performance including ordnance. Each stage is typically static tested every one to two years. Because the removal of a MM interstage skirt is a very difficult test, A/S staging tests are not performed frequently. Also, this ordnance has a demonstrated service life of 17 years. Because this ordnance is replaced every 17 years due to stage II and III motor refurbishment, it has not been necessary to pursue regular A/S testing of interstage ordnance. In Peacekeeper, the separation rings and interstages are part of the stage, and so interstage severance tests are performed as a part of stage A/S tests.

The traditional approach for ordnance component A/S testing was adopted for ICBMs. Samples of approximately 10% of each lot were set aside and 5–10 units were nondestructively inspected and static tested (at ambient temperature only). The successful testing results in a service life extension (SLE) of one to three years for the component lot tested if statistical analysis of the data warrants it. This method was applied to squibs, detonators, and staging ordnance (LSC and MDF) except that subscale units were used for the latter.

Unlike ammunition ordnance, in which the lot size and A/S sample numbers are large, missile ordnance A/S assets are limited and are rapidly depleted. MM I was originally designed for a 3-year

Table 3 Test requirements for MM III, Peacekeeper, and small ICBM ordnance components

Tests	ES-003	D3A4	Staging ordnance	S&A	A–D	A–D/ S–A	AOTT	AODS	OIS FTOS	OFS
Nondestructive										
Inspection	Y[a]	Y	Y	Y	Y	Y	Y	Y	Y	Y
Resistance	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Radiographs and T^{3}[b]	N[c]	X ray, T^3	X ray	N	N	N	N	N	X and n rays, T^3	X and n rays
Helium leak, cm^3/s	N	N	N	5×10^{-4}	1×10^{-5}	1×10^{-6}	N	N	1×10^{-6}	1×10^{-6}
Safety										
6 and 20 ft drop	Y	Y	Y	N/A	N/A	N/A	Y	Y	Y	Y
1 W/1 A, dc, s	15	30	15	15	N/A	N/A	N/A	N/A	N/A	N/A
1 W/1 A, rf	Y	Y	Y	N/A	N/A	N/A	N/A	N/A	Y	N/A
ESD	300 V, 5000 pF	N	7700 V, 500 pF	N/A	N/A	N/A	N/A	N/A	25 kV, 500 pF	N/A
RFI	N/A	N/A	N/A	Y	Y	Y	N/A	Y	Y	Y
Environments										
Nonoperational										
Temperature	−35	−65	−5	−35	−35	−35	−35	−35	−58	−37
and humidity, °F	+125	160	+125	+125	+125	+125	+125	+125	+126	+140
Transportation	3.5	N	1.5–3.5	1.5–3.5	1.5–3.5	1.5–3.5	1.5–3.5	1.5–3.5	3.9	2.16
Vibration, g rms	5–300 Hz		5–300 Hz	5–300 Hz	5–300 Hz	5–300 Hz	5–300 Hz	5–300 Hz		
Flight										
Acceleration										
(axial, lateral), g	N	N	15, 4	15, 3	21, 21	15, 3	15, 3	15, 3	11, 11	15, 2.5
Vibration										
Random	20–69 g rms	0.03 in.	0.6 g^2/Hz	0.2 g^2/Hz	0.3 g^2/Hz	0.1 g^2/Hz	0.1 g^2/Hz	0.1 g^2/Hz	22 g rms	18.7–60 g rms
Sinusoid	6–1.2 g	——	12 g rms	0.5 g rms	0.4–14 g rms	2.8 g rms	3.5 g rms	1.0–2.5 g rms	——	——
Shock, g	N	N	200	N	N	1800–2900	N	N	6,750–13,500	6,750–37,000
Acoustics, dB	N	N	N	N	N	N	N	N	143	154
Vacuum and										
Temperature	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
shock, °F		220	380	450	350	250	250	250	280	280
Sampling										
Qualification	700	700	−41 Assemblies	44	44	33	41 Assemblies	41 Assemblies	600[d] + 18 Assemblies	N/A[e]
Acceptance	10–25%	40 units	25%	10%	Electrical only	Electrical only	Electrical only	10% LSCA	10%[d] + 1 Assemblies	10%
Function test, °F	Ambient	35, 220	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	45, 110

[a]Y = required. [b]T^3 = thermal transient test. [c]N = no requirement. [d]For EBWI and TBI. [e]Did not accomplish due to program termination.

service life, but it has successfully completed 25 years of service. The assets are still in use today for the Rocket Launch System Program (RLSP).

An alternate A/S approach taken from the rocket motor A/S program was used in parallel to the lot SLE approach. In a well-designed ordnance component, the lot-to-lot variability is small. Therefore, the A/S inspection focuses on the design. The successful testing of a component of known age gives confidence to components of the same design but of a younger age, independent of the lot history. In addition, key performance parameters are evaluated statistically as a function of age to determine the trend from which the limit of service life is projected based on the quantitative performance requirements. This is trend analysis life estimate (TALE). It is very important in rocket motor A/S prediction.

Because of the commonality of ordnance design described earlier, we have a good record and database on MM ordnance with 30-year-old ES-003 squibs, linear explosives, and other application-unique squibs and detonators that have been successfully tested in spite of not being hermetically sealed. MM AOD components, because of their high depletion rate, are procured in three-to-four year increments with an established eight-year service life, and no A/S tests are performed based on TALE and continuing successful flight application. The Peacekeeper OIS and FTOS components are periodically tested for go/no-go attribute data and followed by TALE analysis. The program is efficient in reducing test frequency and sample size and is so far highly successful. The D3A2 encountered some problems attributed to moisture absorption in the ignition lead styphnate charge, aggravated by age. Therefore, the D3A4 with an improved seal was fielded as the corrective action as described earlier.

Because they can be thoroughly tested by test sets and have performed successfully in flight, A/S was not implemented for the S&A, A–D, A–D/S–A, PSSS&A, CDS&A, and FTOS FU. Very low failure rates are encountered. The S&As and A–Ds used in the RLSP flights are well over 30-years old. A/S tests are conducted on the Peacekeeper OIS FU because it is less accessible in the fielded missiles. Approximately 10 years of test data have been compiled and are being evaluated. Note that the majority of rejected units were failed based on their original requirements. A thorough evaluation of the requirements usually revealed that units, which did not meet the requirement at the component level, actually had minimum or no impact on the system-level function, that is, they can be used successfully on the missile. Two good examples are the arming and safing time of 1 s of S&A and A–D, which is noncritical, and the 10-MΩ insulation resistance between pin and case in the FTOS FUs, which can be much lower with no functional impact.

It is worthwhile to report the successful utilization of the thermal transient pulse (also call thermal transient test). A good description of the test principle and applications may be found in Ref. 4. When a bridgewire in an HBW or EBW unit is subjected to a low-current step pulse, its temperature increases as an inverted exponential function and can be measured via the temperature coefficient of resistance effect, that is, the voltage across the bridgewire rises accordingly if a constant current is maintained. The time constant is determined by the heat sinks surrounding the bridgewire. The test can determine whether there is a gap between the wire and the explosive loaded on it or whether smeared solder is present on the wire if it is soldered to pins. In addition, a loosely welded or soldered bridgewire can be detected because the response will show erratic signatures, drastically deviating from the exponential characteristic. With statistical analysis, it also may detect the presence of moisture in the explosive. Because of its diversified capability, MIL-STD-1512 adopted this test as a standard method for testing EEDs. The test has been used for inspection of the soldering of the bridgewire in the D3A4, Peacekeeper EBWI A/S inspection, and, recently, for ES-003 squib A/S diagnostic. It can enhance both production quality control and the A/S inspection effectiveness and can lead to significant cost savings.

To support the life extension of MM III to the year 2020, an ordnance refurbishment program has been initiated with the following focuses: 1) replacement of all explosive components; 2) study the refurbishment for S&A, A–D, and A–D/S–A; 3) improve the hermetic seal capability of all explosive components; and 4) replace environmentally unacceptable material used in the construction and processing of the components. Based on the success obtained so far and the good traditional practices, we anticipate that the MM III ordnance program will continue to achieve its goals with cost effectiveness.

Conclusions

1) The evolution of the U.S. Air Force ICBM ordnance components and subsystems has emphasized safety. In the history of these ICBM programs, not a single accident has been attributed to an ordnance malfunction.

2) The ordnance programs achieved this high degree of reliability through good design and thorough testing. In the history of the ICBM flight-test program, not a single mission failure has been attributed to an ordnance malfunction.

3) Cost effectiveness was achieved by following sound design and fabrication practices. Hardware exceeding 30 years of age is functioning well, still in service, and subject to a thorough A/S program.

4) A pedigree of good design continuity has been maintained. Requirements were traded off when necessary in relation to their reliability and safety impacts.

5) These programs adopted advanced state-of-the-art technologies under severe schedule constraint.

6) By pioneering new technologies, especially with laser ordnance, these programs set trends for better ordnance designs, which have been beneficial for other governmental and commercial programs.

Acknowledgments

Hundreds of people from the U.S. Air Force, Northrop Grumman Mission Systems, contractors, subcontractors, and suppliers supported the ordnance program reported in this paper. Their dedicated work is gratefully acknowledged. For this paper, we would like to thank our colleagues, D. R. Sessler, J. A. Riley, and J. D. Aadland for critical review and comments and S. B. Rawls for supplying data on A–D/S–A, D3A2, and D3A4.

References

[1]Kennedy, W. S., Kovacic, S. M., and Rea, E. C., "Solid Rocket History at TRW Ballistic Missiles Division," AIAA Paper 92-3614, July 1992.

[2]Ramsey, J. A., Sessler, D. R., and Yang, L. C., "Peacekeeper Flight Termination Ordnance System," AIAA Paper 95-2409, July 1995.

[3]Chenault, C. F., McCrae, J. E., Bryson, R. R., and Yang, L. C., "The Small ICBM Laser Ordnance Firing System," AIAA Paper 92-1328, March 1992.

[4]Carter, C. R., Blotter, P. T., and Webster, B. D., "Aging Analysis of Bridgewire Initiators Using the Thermal Transient Response Method," Chemical Propulsion Information Agency, Publ. 637, Dec. 1995, pp. 189–197.

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