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Solid Rocket Motor Development for Land-Based Intercontinental Ballistic Missiles

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Solid rocket motor development in the U.S. Air Force land-based intercontinental ballistic missile programs is briefly described. The new, radical approach to program management adopted by Bernard Schriever and the U.S. Air Force Western Development Division in 1954 is presented as one of the major reasons for the outstanding success of Minuteman I, II, and III; Peacekeeper; and Small Intercontinental Ballistic Missile Program. A broad technical discussion is included of solid rocket motor technical challenges and growth in performance and capability for Minuteman through Peacekeeper and the small intercontinental ballistic missile. Particularly significant are the service life characteristics of the three-stage solid rocket boosters. Data and future predictions are also provided. Finally, current and future challenges in the development of solid rocket motors to sustain the U.S. Air Force deployed intercontinental ballistic missile weapon systems are briefly discussed.

Introduction/Historical Background[1–8]

RESPONDING to the Soviet Union's successful hydrogen bomb test in August 1953 and reported Soviet development in long-range ballistic missiles, the U.S. Air Force adopted a new, radical approach and management structure for the design, development, test, deployment, and logistics support of ballistic missile systems. Bernard Schriever was selected to head the new organization in August 1954 as an outgrowth of the Tea Pot Committee Report. His field office, the Western Development Division (WDD), was established near Los Angeles, California. Schriever was designated as an assistant to the commander, U.S. Air Force Research and Development Command. The Ramo–Wooldridge Corporation was hired to provide systems engineering and technical direction of the programs. WDD was redesignated as the Ballistic Missile Division effective 1 June 1957.

Even as the U.S. Air Force was emphasizing deployment of its liquid-fueled intercontinental ballistic missiles (ICBMs) (Atlas and Titan) an extensive effort was in progress to develop a more effective, more flexible, rapid response and cheaper alternative. Project Q (eventually named the Minuteman Program) was initiated in late 1957 to study the feasibility of a three-stage, solid-fueled ICBM to be deployed in early 1960. A limited research and development (R&D) program was approved in June 1958. The R&D program culminated on 1 February 1961, in the first Minuteman flight test from Cape Canaveral, a full-up configuration. It proved to be a complete success.

Figures 1 and 2 present an overview of the U.S. Air Force ICBM weapon systems that were developed using the new, innovative management approach.

Management Approach

The management approach implemented by Schriever was based on the following key elements:

1) WDD would exercise overall systems responsibility in initiating purchase requests, preparing work statements and specifications, evaluating contractor proposals, selecting procurement sources and assessing performance, implementing tradeoff studies and analyses, and preparing, substantiating, and controlling budget requirements.

2) Air Material Command, collocated at WDD, would prepare and issue purchase requests, assist in procurement source selections, prepare and administer procurement instructions, and issue stop work orders and contract terminations.

3) WDD would employ Ramo–Wooldridge Corporation and its skilled resources of scientists, engineers, and technicians in an in-line function rather than a staff position to perform all system engineering and technical direction (SE/TD). To avoid charges of conflict of interest, Ramo–Wooldridge Corporation would be ineligible for development or production of the missiles or any missile components. The SE/TD role became systems engineering and technical assistance (SETA) in the 1970s.

U.S. Air Force/SETA Management Tasks and Process

The results of in-house analysis and cost, schedule, and performance tradeoffs were used to translate mission requirements into weapon system hardware solutions. U.S. policy considerations, political realities, arms control sensitivities, funding constraints, operational cost tradeoffs, congressional issues, and obviously the technical and military requirements and constraints are all evaluated when a weapon system is being conceived. Concept exploration is conducted to ensure that the U.S. Air Force has technical alternatives to pursue and includes input from potential associate contractors. Identifying the new technological advances required, and assessing the risk associated with these new technologies, is also a major task. Development risk is managed by selecting the appropriate technologies to be used in the detailed design. Mission requirements and the chosen technologies are melded into missile sizing studies and weapon system basing and operating concepts. Out of these studies come the weapon system design, including the missile, basing, and command and control elements. Weapon system element requirements are then translated into subsystem design requirements. Subsystem specifications are prepared from a top-level weapon system specification. The subsystem specifications in conjunction with a statement of work are then released to industry for competitive procurement and the selection of associate contractors. The associate contractor hardware development is closely monitored to assure a coherent, effective, integrated system. Functional and physical interfaces between the subsystems are defined and constantly reviewed. During development, configuration inspections, test results analyses, and performance evaluation are conducted to ensure hardware complies with requirements (see Figs. 3–5).

Concurrency

Traditional practices of sequential development of weapon system elements could not meet the desired operational system dates. Consequently, the U.S. Air Force introduced the concept of concurrency in development to meet ICBM schedule needs. Under a concurrent program, the interdependent weapon system elements are developed in parallel, each with well-defined interface requirements

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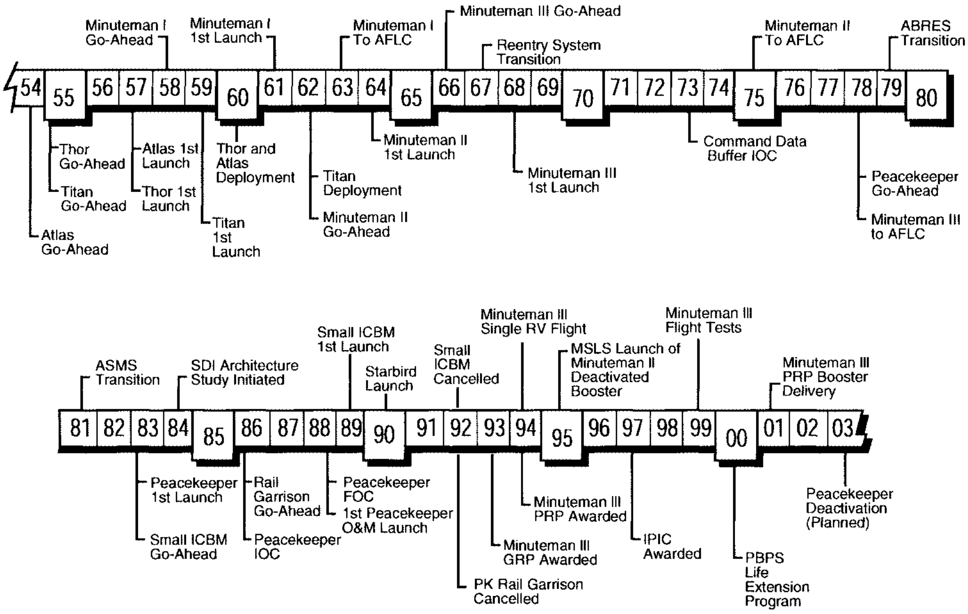
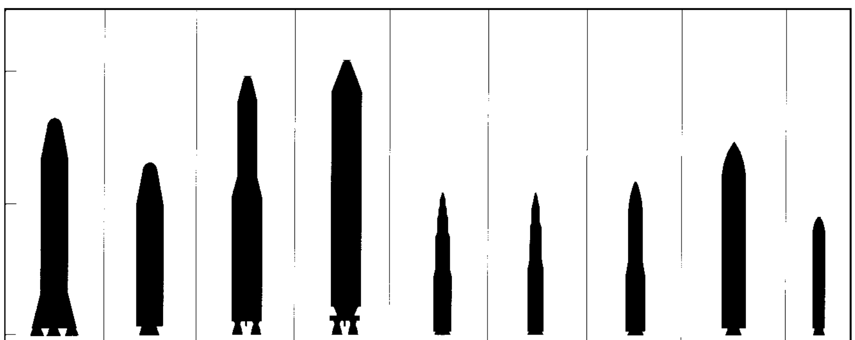


Fig. 1 U.S. Air Force ICBM timeline.



	ATLAS	THOR	TITAN I	TITAN II	MINUTEMAN I	MINUTEMAN II	MINUTEMAN III	MX PEACE-KEEPER	SMALL ICBM
LENGTH (FT)	82	65	98	105	55	57	60	71	44
DIA (FT)	10	8	10	10	5.5	5.5	5.5	7.7	4
WEIGHT (LBS)	269,000	110,000	220,000	330,000	65,000	70,000	76,000	195,000	37,000
LAUNCH 1ST DATE	6-11-57 FAILURE 12-17-57 SUCCESS	1-25-57 FAILURE 1-20-57 SUCCESS	2-6-59	3-16-62	2-1-61	9-24-64	8-16-68	6-17-83	
FULL SCALE DEV'MT INITIATION	6-55	11-55	4-57	10-59	2-58	4-62	3-66	12-72	
IOC	8-60	6-59	3-62	6-63	10-62	10-65	6-70	8-86	

Fig. 2 U.S. Air Force ICBMs: past and present.

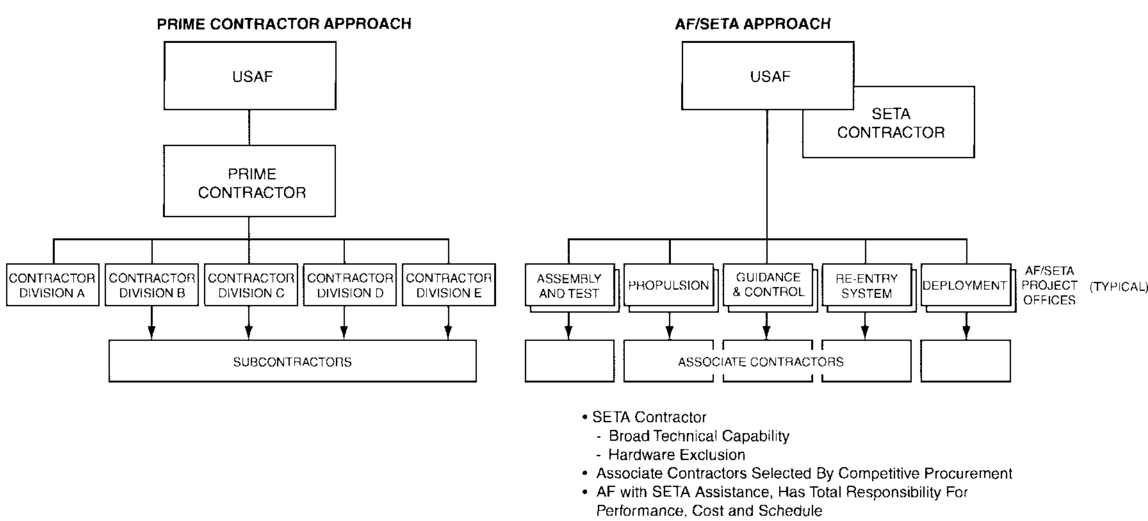


Fig. 3 Comparison of prime contractor and SETA approaches.

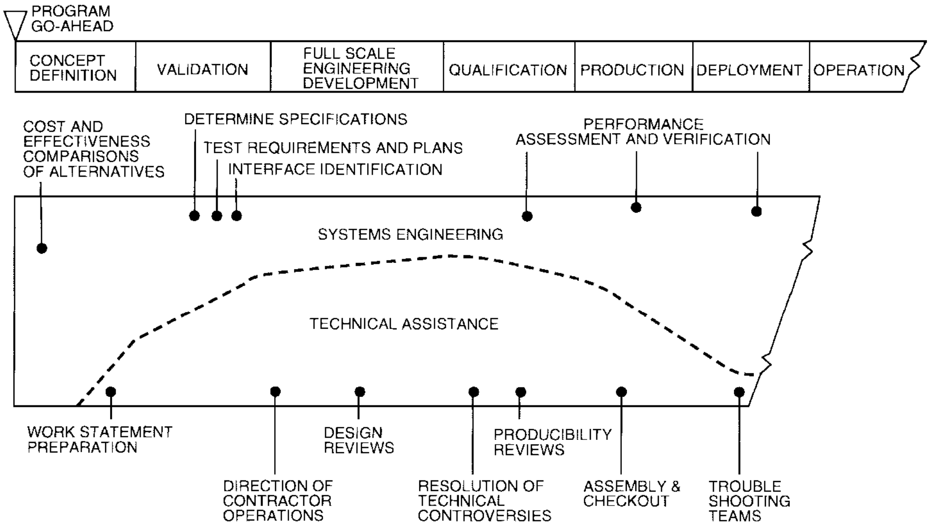


Fig. 4 U.S. Air Force/SETA management tasks (overview).

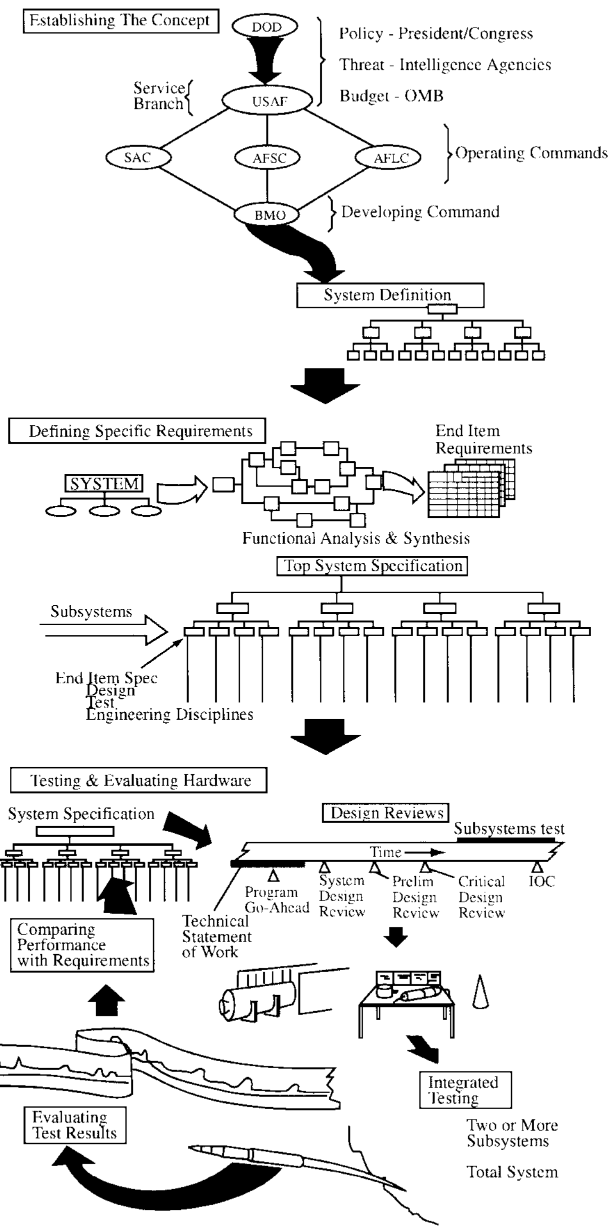


Fig. 5 U.S. Air Force/SETA management process.

to knit the weapon system into a functional whole. Ensuring that all interfaces were properly defined and rigidly controlled was pivotal to success.

Although concurrent development programs hold the promise of greatly accelerated deployment, they are susceptible to large schedule slips due to unanticipated development problems in any subsystem. These schedule risks were minimized by having an SE/TD contractor and associate contractors, each chosen for its special expertise and managed directly by a U.S. Air Force project officer with an assigned contracting officer. This gave the U.S. Air Force a great degree of contractual flexibility and rapid response. The U.S. Air Force could bring its technical and financial resources directly to bear on any technical problem in any program element. If a contractor experienced technical, financial, or schedule difficulties that required direct SE/TD technical assistance, contractual change, or increased financial commitment, the U.S. Air Force could respond quickly to the affected contractor's needs. Where development of specific subsystems was critical or questionable, parallel contracts were given to competing contractors to minimize the development risk.

Because of increased programmatic and technical risks associated with a concurrent program, the U.S. Air Force/SETD team defined a disciplined test philosophy of component and subsystem performance demonstration at the lowest possible level, insisting that flight testing be performed only after extensive ground testing.

Development History of U.S. Air Force Solid-Propellant ICBMs

About 1950, the U.S. Air Force found itself in a need of a small, inexpensive rocket for B-47 jet-assisted takeoff (JATO). Both liquid and solid rockets were investigated. Edward N. Hall, of the Wright–Patterson U.S. Air Force Base Propulsion Laboratory, began the search for a solid motor that could do the job. Immediately following World War II, the Army Air Corps had sponsored work at Allegheny Ballistic Laboratories and at Picatinny Arsenal on small (1000–4000 lb of thrust) double-base, solid-propellant rockets. Hall found the Army rockets too expensive and the double-base propellant too shock sensitive to be useful for JATO applications. To meet the unique B-47 JATO requirements, the U.S. Air Force, working with Phillips Petroleum, Thiokol Corporation, Standard Oil of Indiana, and Aerojet General, entered the solid rocket business to develop its own JATO rockets. By 1952, Hall and the Propulsion Laboratory at Wright-Patterson U.S. Air Force Base began to take a closer, more concentrated look at the feasibility of large rockets. A preliminary R&D program was begun for large, solid-fueled rockets.

Out of necessity, the first ICBM concepts used liquid rocket propulsion because large solid rocket motors had not yet advanced to a workable degree. Subscale tests and computer studies of solid rocket ICBM systems were encouraging, but it was clear that several advances in the state of the art would be required before solid-propellant ICBMs would be feasible. For example, the largest solid-propellant missile then existing was the General Electric Company/Thiokol Corporation RV-A-10, a 31-in.-diam, surface-to-surface missile with a 5000-lb polysulfide propellant grain. The Sergeant missile, also 31 in. in diameter but with a slightly longer, case-bonded, internal-burning grain, was just beginning development at the Jet Propulsion Laboratory. Liquid propulsion, which had undergone significant development under the U.S. Air Force Navaho Program, remained the technology of choice.

Solid propulsion development continued at a technology R&D level. A small cadre of U.S. Air Force and Ramo–Wooldridge Corporation engineers monitored and accumulated data on the developments, problems, and goals of those companies and programs involved in advancing solid-propellant technology. Contractors such as Aerojet General, Thiokol Corporation, Phillips Petroleum, and Grand Central Rocket Company worked on developing the formulations and processes for solid-propellant rocket motors and on the Large Engine Feasibility Program under contracts from the Wright Air Development Center in 1956.

By 1957, the technologies that had once denied solid motor ICBM feasibility had been developed to a favorable point. The U.S. Air Force programs had demonstrated solid motor feasibility. Reentry vehicle weight could be greatly reduced. Early reentry vehicle designs used massive copper heat sinks as the heat shield material. Ablative heat shield materials were developed that eventually demonstrated equal performance at one-third the weight. Higher yield warheads provided greater effectiveness. U.S. progress in reduced weight, higher yield warheads was outpacing the Soviets, with further improvements promised. Missile guidance technology was rapidly progressing, first by improvements in the ground-based radio guidance systems and later in the development of onboard computing and inertial guidance. It became clear that the combined trend of reduced weight, increased warhead yield, increased accuracy, and solid motor development technologies had brought the concept of solid-propellant ICBMs within reach. Ramo–Wooldridge Corporation computer studies showed that, with the projected improvements in technologies, a 5500-mile-range, solid-propellant ICBM was feasible, with a maximum gross weight of approximately 65,000 lb.

U.S. Air Force/SETD preliminary studies outlined the desirability and feasibility of solids, along with suggestions for new approaches to meeting the technical challenges unique to solid motor ICBMs. Schriever agreed that the approach deserved consideration. In August 1957, Hall accepted an open-ended assignment from Schriever to develop the solid ICBM idea.

The U.S. Air Force was well aware of the advantages of solid motor missiles. Quick reaction time, with an inherent high reliability due to the greatly reduced weapon system complexity, was key. Most appealing, however, was the potential to field large forces of solid-propellant missiles for relatively low costs. Costs of solid-propellant missile systems were anticipated to be roughly one-fifth those of an equivalent liquid-propellant system. In addition to their low acquisition costs, solids required far fewer resources to operate and maintain. Whereas it typically required a crew of six to launch a single liquid-propellant missile, early studies showed that by incorporating monitoring functions on the missile, a crew of only two could be totally responsible for the operation of up to 10 solid-propellant missiles, remotely located and widely dispersed. Annual maintenance costs were expected to be one-tenth those of the liquid systems. In addition, because of the smaller size and more rugged construction, solid motor missiles could be based in hardened underground silos to thwart an enemy attack. These characteristics were attractive to the weapon system user, Power, commander of the U.S. Air Force Strategic Air Command, who soon became a strong supporter of the Minuteman concept.

Concern over Soviet weapon advances was increasing. In June 1956, the Soviets demonstrated their growing weapon system capability by launching a fusion bomb on a test missile and detonating it at an altitude of 22 miles. On Saturday, 4 October 1957, the American public was rocked by the news of Sputnik. If the Soviets had once been regarded as a backward nation with subordinate technologies, now the American public was forced to recognize the advanced threat that the Soviets had become. Sputnik was symbolic of the perceived Soviet lead in missiles and space technology. The race for space had begun, and a missile gap with the Soviets was feared. In February 1958, funding was approved for the solid motor missile dubbed Minuteman, and contracts were awarded by the end of the year. Approval of the concurrent weapon system development and operation deployment funding soon followed (Table 1 and Fig. 6).

Table 1 Minuteman I missile contracting arrangements

Contractor	Responsibility
Ramo–Wooldridge Corporation	SE/TD
The Boeing Company	Missile assembly and test
North American Autonetics	Guidance and control
Avco Research Laboratory	Reentry vehicle
Thiokol Corporation	Propulsion, all stages (later selected for stage I)
Aerojet General	Propulsion, all stages (later selected for stage II)
Hercules Powder Company	Propulsion, stage III

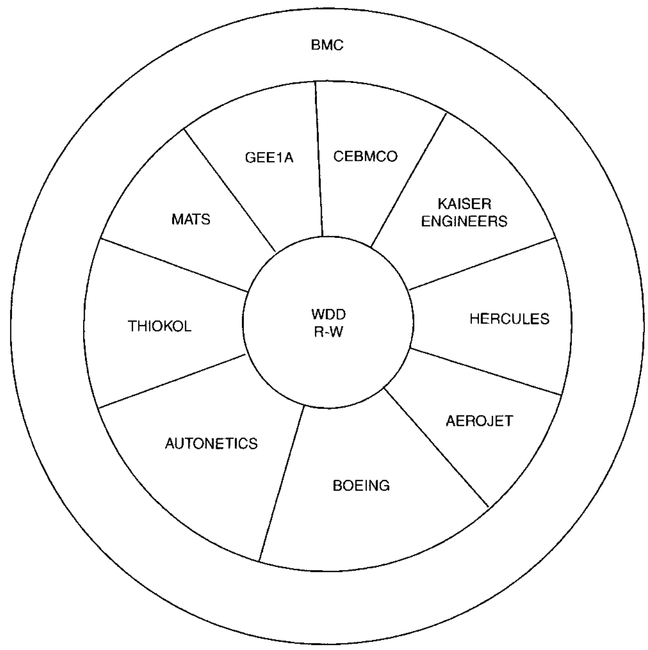


Fig. 6 MM team, 1958.

By 1959, there were indications that a Soviet missile force might be operational as soon as 1960, which could pose a serious threat to U.S. security. There was also fear that the new Atlas ICBM force could not be fielded in sufficient numbers to defend adequately the United States from a Soviet ICBM attack. The military looked to Minuteman for the solution. By creating a large Minuteman force, the United States could survive the first blow of a conflict and strike back decisively. In mid-1959, 18 months before the first flight, the U.S. Air Force accelerated the Minuteman initial operational capability date by one year, from July 1963 to no later than July 1962.

Widely dispersing missiles in nuclear-hardened, remotely controlled launchers was a novel idea. From its inception, the Minuteman program was oriented toward mass production of a simple, efficient, reliable, and highly survivable weapon system, based on a solid-propellant, three-stage missile, capable of withstanding storage in an alert ready condition for long periods of time. With a range of well over 5000 miles and a continuously operating inertial guidance system, each missile was capable of being launched, even after being subjected to nuclear environments and the blast overpressure, within 60 s after receipt of the appropriate coded launch signal.

The Minuteman program is commonly divided into three designations: Minuteman I, II, and III. As a parallel designation providing further refinement, the various configurations may be identified as wings in reference to the geographical grouping of missiles as they are deployed within the United States. The basic characteristics of the weapon system have not changed since the first Minuteman missiles were deployed. Advances in technology and changes in national policy have induced improvements in the original design; for example, the 800 Minuteman I missiles that stood guard for nearly 13 years were replaced by the more capable Minuteman II and III missiles. The ground systems, which house and support the missiles, have also been upgraded and made more survivable, efficient, and secure over the years.

Current Force Structure

Final Minuteman II operational flight testing was completed in 1988. Deactivation of the 500 missile Minuteman II fleet was initiated in 1992, with full fleet deactivation in 1995. Because of the high value of the deactivated Minuteman II booster assets, all deactivated boosters were transitioned to the U.S. Air Force Space and Missile Center Test and Evaluation Directorate for future uses, such as launch vehicles. To date, approximately 50 Minuteman II vehicles have been reconfigured and flown as target vehicles and launchers for suborbital scientific payloads.

The Minuteman III fleet has been continuously operational for nearly 30 years. Remanufacturing of the Minuteman III booster stages is underway, with the first article to be delivered in 2001 and an anticipated operational life through 2030 (required 2020, goal 2030). Additional modifications are being incorporated to improve targeting accuracy and reduce the three reentry vehicle (RV) payload to a single RV.

The Peacekeeper Weapon system was designed and developed to provide a high-accuracy targeting capability to the U.S. Air Force land-based ICBM fleet, with up to 10 multiple, independently targetable reentry vehicles (MIRV'd). Initially flight tested in 1983 and fielded in 1986, Peacekeeper has established an excellent flight record with 18 flight test launches and 27 operational test and evaluation launches. Deactivation of the Peacekeeper ICBM fleet is planned for 2003, with spacelaunch applications proposed for the approximately 70 deactivated boosters.

The recent changes in force structure are a direct result of the Strategic Arms Reduction Treaty (START) process with the former Soviet Union. We are now at the START 1 level, with START 2 to be implemented when Soviet Duma ratified START 2. The Peacekeeper will go away as a result of START 2. The date of 2003 (for Peacekeeper decommission) is only a planned date at the present time.

The following sections provide an overview of the evolution of the U.S. Air Force ICBM systems from Minuteman to Peacekeeper and small ICBM.

Minuteman I

Minuteman I Evolution

Minuteman wing I, or weapon system 133A as it is commonly called, provided the design on which subsequent Minuteman configurations were based. Construction of an operational force of 150 missiles, made up of three squadrons with 50 missiles each to form wing I, began at Malmstrom U.S. Air Force Base, Montana, in March 1961 and was completed in mid-1963.

Wings II–V remained the same, with the exception of additional configuration changes implemented to increase range and improve design margins. The aft dome of stage I included more propellant, and the exit cone was contoured to optimize nozzle efficiency. The stage II motor case was fabricated from titanium instead of the steel used in the wing I motors. The nozzles were recontoured to increase performance for the wing IV and V motors. Stage III remained basically unchanged. By August 1961 this improved version, weapon system 133B, was incorporated into the wing II operational force at Ellsworth U.S. Air Force Base, South Dakota. By June 1965, 800 Minuteman I missiles were on operational alert.

Minuteman I Technical Challenges and Solutions

Development of Minuteman on the original schedule was not easy or assured. Acceleration of the development schedule approached the impossible. Development and implementation of all of the emerging technologies presented serious technical challenges to the Minuteman development team, as discussed next.

Design and Development of Lightweight, Large-Diameter Steel Cases

Thin-walled pressure vessels of the size and weight needed for Minuteman required the heat treatment of large-diameter steel cases. Particularly important was uniformity of treatment and the retention of roundness criteria in mating with the upper stages. Facilities capable of handling the large-diameter cases did not exist. Development of a high-performance top stage with a glass case, double-base nitroglycerin propellant, four movable nozzles, and thrust termination ports offered great potential, but conventional wisdom said it could not be done in 1958.

Nozzle Throat and Exit Cone Materials

The combustion products of solid propellants were recognized to be particularly erosive due to the gas composition and presence of aluminum oxide particles in the gas stream. It was not clear that a vectorable nozzle could be designed to last the required 60-s firing. Eventually tungsten throat and ablative phenolic exit cone material were selected to withstand the erosive environment.

Methods for Mixing and Casting Large Volumes of Propellant

The first stage was to weigh about 45,000 lb. Up to that time, the largest solid rocket motor ever built (the RV-A-10 and the Sergeant missile) weighed just over 5000 lb. Early Polaris development was being conducted in parallel with Minuteman.

Movable Nozzles

Flight control studies showed the need for 8-deg vectoring of stage I thrust. Movable nozzles could provide such capability, but flexible joints that would withstand the high temperature and pressure of the combustion products and maintain a seal were not available.

Thrust Termination of Stage III

To achieve the desired missile accuracy, precise termination of stage III thrust was required. Reverse-thrust blow-out ports needed to be developed.

Environments Induced by a Hot Silo Launch

Key to the simplicity of Minuteman deployment was the ability of the missile to fly itself out of the silo. Silo length and launch, thermal, vibration, pressure, and acoustic loads on the missile and silo structure had to be determined and considered in the design.

Stage Ballistic Performance

Computer sizing studies showed that the new systems would need to deliver a minimum specific impulse of about 245 lbf/lbm-s. The state of the art at the time was 230 s. The addition of metals to the propellant would help, but would increase the erosive characteristics of the combustion products.

Motor Case Design and Fracture Mechanics Studies

Laboratory investigation of heat treatment and fracture toughness of high-strength metals achieved significant results. The objective of the investigation was to determine a particular material's sensitivity to small imperfections (such as the flaws induced by welding domes to cylindrical sections of the motor case) as a function of heat treatment and ultimate case strength. Material samples were heat treated to various levels and strengths. A fatigue-induced flaw was imparted to the sample, and the sample was tested for its ultimate strength capability. The tests showed that heat treatment of Minuteman motor cases should be lower than anticipated by traditional pressure vessel design practices. By lowering the heat treatment temperature, the material's susceptibility to flaws was decreased. The more ductile material provided adequate strength and a more reliable part. The testing also provided the empirical data necessary to determine the specific tradeoff between the increase in strength and the decrease in capability due to flaw sensitivity.

Computer studies helped define design criteria that took advantage of the increase in the strength of a material due to its biaxial stress state. Distortion energy theory predicted that materials with a biaxial stress ratio of 2:1 provide up to 15.5% greater strength than uniaxial stress samples. High-strength materials were tested to define how such a phenomenon could be used in rocket motor case design. The test, which included bursting hundreds of 2-in.-diam bottles, established that an 11% increase in material allowables due to axial stress augmentation could reliably be used in the design of Minuteman motor cases.

U.S. Air Force/SETA pioneered the establishment of design criteria to account for the buckling of thin-shelled cylindrical and conical structures. In the 1930s and 1940s, buckling of columns and flat plates was well understood. Buckling of shells of revolution, however, was not. In practice, the buckling capability of thin shells was sometimes 70% lower than predicted. TRW, Inc., defined and completed an experimental program to empirically derive knockdown factors to be used in the design of Minuteman interstages. The tests utilized Mylar® cylinders of various configurations and various loading conditions. The innovative use of Mylar, with its high strain-to-failure capability, allowed many specimens to be used repeatedly. The tests resulted in the definition of knockdown factors to be applied to theoretical buckling predictions as a function of the radius/thickness ratio r/t, length/diameter ratio L/D, axial load, and external pressure. These factors are still in use today in the design of thin shells of revolution.

Movable Nozzle Development

One of the most technically challenging aspects of the Minuteman program was the development of the motor movable nozzle systems. When the first graphite throats broke up and the complete nozzles were ejected upon ignition, U.S. Air Force/SETA initiated a very comprehensive structural, thermal, and gas dynamic test and analysis program in support of the motor contractors and their nozzle subcontractors. The basic failure mechanisms of the early nozzle designs were identified, and the needs for tungsten throat inserts and nozzle entrance flow straightening were established. The success of the Minuteman movable nozzle developments was dependent on the correct solution of many subtle design details, which the associate contractors correctly diagnosed and solved. The correct tungsten throat insert thickness was established, a structurally and thermally adequate throat and split line assembly was developed, and a minimum length and weight flow straightener was designed. Comparison of the Minuteman movable nozzles with contemporary designs shows that the Minuteman designs were truly outstanding for their weights, thrust levels, and firing durations. The U.S. Air Force/SETA-developed two-phase flow nozzle flowfield/performance analysis computer programs were shared throughout the industry and formed the backbone of the Solid Propellant Rocket Motor Performance Computer Program and its many versions used throughout the country.

Minuteman I Development Summary

The U.S. Air Force/SETD and a capable, dedicated team of propulsion associate contractors were able to meet these challenges and development goals. As insurance against development difficulties, at least two competing contractors were assigned to develop each stage (Table 1). All contractors proposed steel cases except Hercules Powder Company, which proposed to develop a glass case stage III motor. Stage I was a particular challenge, being considerably larger than any solid-propellant motor ever built. The first Thiokol Corporation firing in 1959 ejected all four nozzles at 30 ms, well before full-stage ignition. Several redesigns later, nozzles lasted 2.5 s before ejection. In October 1959 five motors and their test stands blew up in a row, once a week, each with its own unique failure mode. The first threw a ton of flaming propellant a half mile behind the stand, over a hill, into the only test stand instrumentation shed within 100 miles.

By December 1959, Thiokol Corporation had made sufficient progress on the stage I motor that Aerojet General was phased out of stage I development to concentrate on stage II, and Thiokol Corporation stopped all work on stages II and III.

A multiple contractor approach was also followed for the movable nozzles development. In addition to the nozzle subcontractors chosen by the stage associate contractors, other manufacturers were awarded contracts to carry on independent efforts. By the fall of 1960, Hercules Powder Company was selected for stage III development, having demonstrated the significant advantages of a high-performance glass case and double-base propellant system. Hercules Powder Company's Minuteman stage III was the grandfather of all composite cases.

The first launch, flight test 401, was conducted in February 1961, 30 days from the originally scheduled launch date, with spectacular success. The approach to the first flight test was unique for the time: Rather than being a gradual demonstration of missile capabilities over a series of flight tests over various ranges, typical of all liquid-propulsion missile programs to date, the Minuteman first launch successfully demonstrated all functions of the missile over full operational range, with acceptable accuracy. The first Minuteman I missile became operational in February 1962, with the first flight (10 missiles) turned over the Strategic Air Command in October 1962.

Minuteman II

Minuteman II Evolution

Before Minuteman I was deployed, contracts were awarded to begin work on the second-generation missile. This new system was designated Minuteman II and was to be deployed as wing VI. The initial objectives of the new design were twofold: improve stage I reliability and increase system performance with a more powerful stage II.

The stage I changes were needed to eliminate potential failure modes existing in the wing II–V nozzle and aft closure designs. Excessive cracking and ejection of pieces of graphite blast tube frequently occurred. Also, the throat support graphite in the thrust vector control nozzles cracked recurrently, and small pieces of graphite were often ejected from the nose section. To eliminate these failure modes, the U.S. Air Force embarked on a reliability improvement program (RIP) that resulted in what is known as the RIP configuration. (Actually, the changes were done in two steps. The first one was called nozzle verification motor, and the second step is called RIP.)

Stage II was to be a new rocket motor based on the experience gained on Minuteman I. New technologies were implemented to further enhance system performance. These design enhancements included a larger diameter, a single fixed nozzle with a liquid injection thrust vector control (LITVC) system, and a more energetic carboxyl-terminated polybutadiene (CTPB) propellant.

Early wing VI stage III motors were built to the wings I–V design. Static motor testing late in the wing IV and V production program, however, highlighted a problem with insulation burn throughs in the aft dome region. Based on these tests, the U.S. Air Force instituted the Stage III Operational Reliability Improvement (OPRI) Program. Wing VI, therefore, included the OPRI configuration, which introduced design changes to inhibit the flow in and around the aft dome propellant flap.

Wing VI became operational in January 1967. The U.S. Air Force subsequently modernized more of the operational force, and by May 1969 the force stood at 500 Minuteman I and 500 Minuteman II missiles.

Minuteman II Technical Challenges and Solutions

Propellant Formulation Study

The chemical basis for the mechanical strength of the stage II propellant was the formulation of polyurethane bonds (crosslinking) within the binder. During development of stage II, Aerojet General proposed a CTPB binder and methyl aziridine phosphine oxide (MAPO) crosslinking agent to replace the polyurethene propellant. Using propellant samples from Aerojet General U.S. Air Force/SETA initiated a laboratory program to identify potential degradation mechanisms associated with the cured propellant. Using a water extraction method in which water vapor was condensed on a sample of propellant, the investigation indicated a strong propellant crosslink hydrolysis reaction, i.e., breaking the polymer bonds. Chemical analysis of the extractant showed the presence of phosphate ions consistent with degradation of the MAPO crosslinker.

U.S. Air Force/SETA and Aerojet General's R&D staff developed a formulation that eliminated MAPO and implemented in the stage II qualification design. MAPO was also present in the propellant liner system; however, attempts to remove the ingredient from the liner yielded unacceptable bondline strength. To date, degradation of the stage II liner system is the basis for the service life estimate of 17 years. Recently Minuteman stage II has undergone a regraining effort in which the propellant was washed out and recast using the different propellant and a new liner system, which used a hydroxy terminated polybutadine (HTPB).

LITVC Development

Although LITVC was in use on the Polaris program, a particular challenge was the determination of how much vector capability would be required for Minuteman. This requirement defines, in part, the amount of injectant needed to accomplish the mission. Too little injectant could result in failure, whereas too much unnecessarily reduces system range performance. The problem required an understanding of the available technology, its capability, and the overall system performance requirements to evaluate the relative merits of various engineering solutions. Fundamental to sizing the LITVC system was the assumed efficiency of expelling the injectant from a tank under dynamic conditions. U.S. Air Force/SETA developed analytical models to predict injectant expulsion efficiency. These models were combined with LITVC capabilities (side impulse per unit injectant) and system performance requirements to define the development specifications for the LITVC system.

Halon 2402 was selected as the injectant and was confined in a Viton rubber bladder within the toroidal metal pressure vessel. During development of the system, there was concern that Halon 2402 would permeate across the bladder and, therefore, be unavailable for use as injectant. U.S. Air Force/SETA established a laboratory program to quantify the effect. Aerojet General performed a mini aging program and determined that of the 262 lb of Halon 2402 originally loaded within the bladder, 25 lb would permeate across the bladder wall before reaching vapor pressure equilibrium over the service life of the system. It was concluded that this amount would not affect the mission capability.

The LITVC system also included several burst disks designed to open hydraulic lines when the system was pressurized. To maintain reliable and repeatable transient response, the burst disks were required to function at repeatable burst pressures. Testing of the burst disks, however, revealed high variability. TRW, Inc., used an analytical model of the thrust vector control system to define acceptable burst pressure ranges.

These examples highlight an overall function of the U.S. Air Force/SETA approach in which strong technical capability, close coordination with the stage contractor, and a detailed understanding of system requirements are combined to reduce technical risk and ensure that the end product meets the program goals.

Motor Ignition Study

The U.S. Air Force/SETA performed a laboratory study to define propellant transient ballistic performance at motor ignition. Samples of propellant were obtained from Aerojet General, and subscale tests were performed to measure the velocity at which flame spreads across the surface of unburned propellant. Using these results, an analytical model was developed to predict the flame spread and ignition transient of full-scale motors. The model was used to evaluate grain configurations and the effects of a mold release agent used on stage II motors. The mold release, which facilitated extraction of the grain mandrel, left a residue on the surface of the grain that acted as an inhibitor to propellant ignition. This ignition predictive model was used to quantify the effect of the inhibitor and demonstrate the need to remove the chemical from the surface of the propellant. This design change resulted in decreased ignition variability.

Long-Range Service Life

During the concept definition phase of Minuteman, the U.S. Air Force's goal was to produce a weapon system with a service life of 5 years (originally it was 3 years). Considerable effort was expended toward developing predictive techniques for estimating the service life of solid propulsion subsystems. The techniques primarily involved test programs to monitor aging-induced changes of materials and components believed to be age sensitive. The trends were then extrapolated to analytically derived limits to estimate service life.

Table 2 Minuteman II stage overtest summary

Stage	Test	Result
I	Cooldown to 20°F	Propellant/liner debond at 38°F, propellant cracks at 20°F
II	Cooldown to 0°F	Inner bore and fin cracking at 0°F
II	Pressurization with nitrogen	No structural damage
III	Rapid pressurization with mineral oil, 8600 psi/s	Wing slot cracking at 500 psi

Of particular interest was the structural capability of the propellant and propellant-to-insulation bondline when subjected to the loads induced by long-term storage at cold temperatures and by motor ignition at high temperature. Early in the 1970s, the U.S. Air Force/SETA designed an approach to validate grain structural models, establish zero-time margins of safety, define aging trends, and predict age-related failure modes. The technique was divided into four phases.

The first phase involved motor overtests. Operational motors were instrumented with strain and temperature instrumentation on the bore and case surface. Some motors were subjected to a low-temperature environment. The case and propellant strain responses were recorded as a function of time and temperature. Event gauges monitored indications of cracks and unbonds. Other motors were subjected to rapid pressurization tests using mineral oil or nitrogen as the pressurant.

The second phase involved dissecting the loaded motor and testing material properties. The testing included those parameters used in the grain thermal/structural analysis, such as the coefficient of thermal expansion, tensile strength, modulus, and propellant/insulation bond strength.

The third phase was the validation of structural models. Using the loaded-case material properties from the dissected motor, analytical predictions of the motor response were made and compared to the measured response from the motor overtest, and the results were used to identify modeling sensitivities and deficiencies. The models were then corrected and calibrated to achieve good correlation with the measured response. Baseline margins of safety were then calculated using the calibrated models.

In the final phase, samples from the motor dissection were stored in controlled conditions and tested for aging trends in the material properties. The results were used in combination with the calibrated models to identify the margins of safety as a function of motor age.

This technique was implemented in the Minuteman II program under the title "Long Range Service Life Analysis" using approximately 10-year-old motors. The program resulted in the verification of minimum margins of safety and in some cases the identification of previously unknown failure modes, such as propellant/liner debonds at 38°F for the stage I motor. Table 2 provides a summary of some of the stage overtest results. Additional technical data on long-range service life is discussed later under Minuteman Success and Peacekeeper Service Life Estimate.

Minuteman III

Minuteman III Evolution

In July 1965, 1 month after the first 800 Minuteman I missiles were operational, the U.S. Air Force issued R&D contracts for Minuteman III. The Minuteman III was significantly different in that it was designed to carry three Mark 12 MIRVs and penetration aids, with a liquid fourth stage for payload deployment. The added weight associated with this design required a new, higher performance from the boosters. Stages I and II remained unchanged relative to the latest Minuteman II design. Stage III, however, was redesigned to include a larger case diameter and to have a single nozzle with LITVC. Aerojet General won the motor design/development competition using a single forward boot design. Later in the program, Thiokol Corporation and Chemical Systems Division (CSD) won production contracts using Thiokol Corporation qualified double boot design.

Stage III was increased to 52 in. in diameter, weighed over 8000 lb, used a glass epoxy case, and incorporated a CTPB propellant similar to stage II.

The force modernization was completed in January 1975, when wing V (Warren U.S. Air Force Base, Wyoming) was upgraded to Minuteman III. The Minuteman force then stood at 450 Minuteman II and 550 Minuteman III missiles.

Minuteman III Challenges and Solutions: Stage III Thrust Termination Ports

Precise termination of the stage III thrust was required to ensure system accuracy. On Minuteman I, thick carbon-phenolic tubes were integrally wound in the pressure vessel sidewall and sealed with snap ring closures. Explosive ordnance was used to release a frangible section of the snap ring, vent the chamber pressure, and extinguish the propellant. For Minuteman III, thrust termination was accomplished by initiating six circular, explosive charges directly on the forward dome. Early tests of the Minuteman III configuration, however, resulted in catastrophic rupture of the case in the forward dome. High-speed films and strain gauge data showed that the holes were cut within 20 μs and that the pressure vessel ruptured within 2 ms after the holes were cut. A postmortem examination of the pressure vessel showed cracks radiating from the hole edge.

To quantify the effect and evaluate potential corrective action, the U.S. Air Force/SETA initiated a finite element, transient response analysis of the event. The computer code NASTRAN was used to define the stress concentration and propagation near the hole. This was the first use of the now popular NASTRAN code at TRW, Inc. Based on the model validated by the known solution to the stress field around holes in flat plates, TRW, Inc., showed that, before the cut is made, the stress field in the area of the hole is essentially a one-dimensional membrane field aligned in the meridianal direction. After the hole is punched, the stresses realign and become significantly higher due to stress concentration. Away from the hole, the stresses do not significantly change. TRW, Inc., also used the model to define the local dome thickness required to reduce the magnitude of the stress concentration and eliminate the failure mode. As a design solution, Aerojet General integrally wound reinforcement doilies in the dome under the circular charges; testing of the modified configuration confirmed the elimination of the failure mode.

Minuteman Success

Although based on technologies developed in the late 1950s, Minuteman missiles continue to provide strategic nuclear deterrence from their silos in the midwestern United States. The strategic force structure currently includes 500 Minuteman III and 50 Peacekeeper missiles. Although they have never been used in times of hostility, Minuteman missiles are frequently flight tested to assess their operational readiness and to provide low-cost launch platforms for other defense-related projects. More than 700 flight tests of various Minuteman configurations have been conducted to date. Table 3 is a summary of Minuteman booster configurations.[9]

The long-range service life analysis and test program discussed under Minuteman II has identified the design life characteristics achieved by the propulsion associate contractors. The original (1958) design criteria for service life on each propulsion stage was 3 years required and a goal of 5 years. Table 4 shows the remarkable results achieved by each contractor. A long-range service life analysis (LRSLA) type overtest (cool down to −20°F) and margin of safety verification were also performed on the MM III stage III loaded case. Stage I current life estimate is greater than 30 years due to upgraded structural modeling effort and improved aging trend data. The cost savings to the U.S. Air Force have been enormous.

Peacekeeper

Peacekeeper Design Evolution and Features

During the late 1960s, the Soviet surge toward strategic superiority seemed relentless. By 1970, they had surpassed the United States by deploying a greater number of ICBMs. By the middle of the decade, they had fielded larger reentry vehicles, and in greater numbers, than the United States. To counter the threat, a newer, larger, more powerful U.S. Air Force ICBM, capable of MIRV'd payloads, was proposed. In late 1972, as the threat became more apparent, concept exploration and technology risk assessment began in earnest by the U.S. Air Force/SETA. In 1977, the final size and general configuration of the missile was solidified (see Figs. 2 and 7). The missile X (MX) missile, later renamed Peacekeeper, was to be a third taller and three times heavier (200,000 vs 78,000 lb) than Minuteman and was to carry not 3, but 10 advanced reentry vehicles. The magnitude of the Peacekeeper management challenge and interface complexity is shown in Fig. 8.

Several points are noteworthy when looking at the Peacekeeper program. It was one of the largest solid propulsion missiles developed for U.S. Air Force programs. To limit the overall length while utilizing high-expansion-ratio exit cones, the U.S. Air Force proceeded with the development of extendible nozzle exit cones (ENECs), which translated from a stowed position to the operational position during flight. The use of extendible exit cones was

Table 3 Summary of Minuteman booster configurations[9]

	Minuteman I		Minuteman II	Minuteman III
Specification	LGM[a]-30A wing I	LGM-30B wings II–V	LGM-30F wing VI	LGM-30G N/A
Contractors				
Stage I	Thiokol	Thiokol	Thiokol	Thiokol
Stage II	Aerojet	Aerojet	Aerojet	Aerojet
Stage III	Hercules	Hercules	Hercules	Aerojet (single boot)/ Thiokol/CSD (double boot)
Diameter/length, in.				
Stage I	66/190	66/190	66/190	66/190
Stage II	44/150	44/150	52/162	52/162
Stage III	38/85	38/85	38/85	52/92
Weight, lb				
Stage I	50,576	50,576	50,552	51,514
Stage II	11,552	11,400	15,507	15,509
Stage III	4,231	4,231	4,237	8,058
Nozzles				
Stage I	4 Movable	4 Movable	4 Movable	4 Movable
Stage II	4 Movable	4 Movable	1 Fixed	1 Fixed
Stage III	4 Movable	4 Movable	4 Movable	1 Fixed
Case				
Stage I	Steel	Steel	Steel	Steel
Stage II	Steel	Titanium	Titanium	Titanium
Stage III	Glass/epoxy	Glass/epoxy	Glass/epoxy	Fiberglass
Propellant (class)				
Stage I	PBAN[b] (1.3)	PBAN (1.3)	PBAN (1.3)	PBAN (1.3)
Stage II	Polyurethane (1.3)	Polyurethane (1.3)	CTPB (1.3)	CTPB (1.3)
Stage III	CMDB[c] (1.1)	CMDB (1.1)	CMDB (1.3)	CTPB (1.3)

[a]Launch guided missile. [b]Polybutadiene acrylonitrile. [c]Composite modified double base.

Table 4 Status of Minuteman SLE (as of December 1997)

Stage		Minimum margins of safety: Pre-LRSLA	Minimum margins of safety: Post-LRSLA[a] (failure mode)	SLE, yr: Pre-LRSLA	SLE, yr: Current	Current life controlling failure mode
MM II/III	1	0.37	1.1 (propellant/liner debond during storage)	10	30+	Inner bore cracking during firing
MM II/III	2	0.98	0.38 (inner bore cracking during storage)	10	17	Boot debond during firing
MM II	3	0.30	1.11 (inner bore cracking during ignition)	10	30+	Inner bore (wing slot) cracking during ignition
MM III	3	0.4	2.1 (inner bore cracking during storage)	5	17	Boot debond during firing

[a]Generally all margins of safety increased following LRSLA due to 1) less conservative failure limits established using overtests (externally mounted instrumentation only), 10-year-old motor, piggy-backed secondary failure modes, verified no unexpected failure modes (stage 1 model updated in 1994 using three-dimensional linear elastic analysis); 2) better material properties from motor dissection; 3) better aging trends from dissected motors; and 4) liner (SD-851) degradation in MM II stage II and MM III stage III motors, discovered LRSLA dissection, is the controlling aging mechanism leading to boot debond.

Table 5 Peacekeeper booster configuration summary

Characteristic	Stage I	Stage II	Stage III
Weight, lb	107,200	61,000	17,600
Case material	Kevlar–epoxy	Kevlar–epoxy	Kevlar–epoxy case, graphite–epoxy skirts and interstage
Integral throat	Carbon–carbon ITE	Carbon–carbon ITE	Carbon–carbon ITE
Exit cone	Carbon-phenolic	With one extendible section, both fixed and translating sections carbon-phenolic	With two extendible sections, both fixed and translating sections two-dimensional involute carbon–carbon
TVC type	Movable nozzle with omnivector flexseal and turbohydraulic TVA[a]	Movable nozzle with omnivector flexseal and turbohydraulic TVA	Movable nozzle with omnivector flexseal and turbohydraulic TVA
Propellant	HTPB class 1.3	HTPB class 1.3	NEPE[b] (WAY) class 1.1

[a]Thrust vector actuator. [b]Nitrate ester plasticized polyethane.

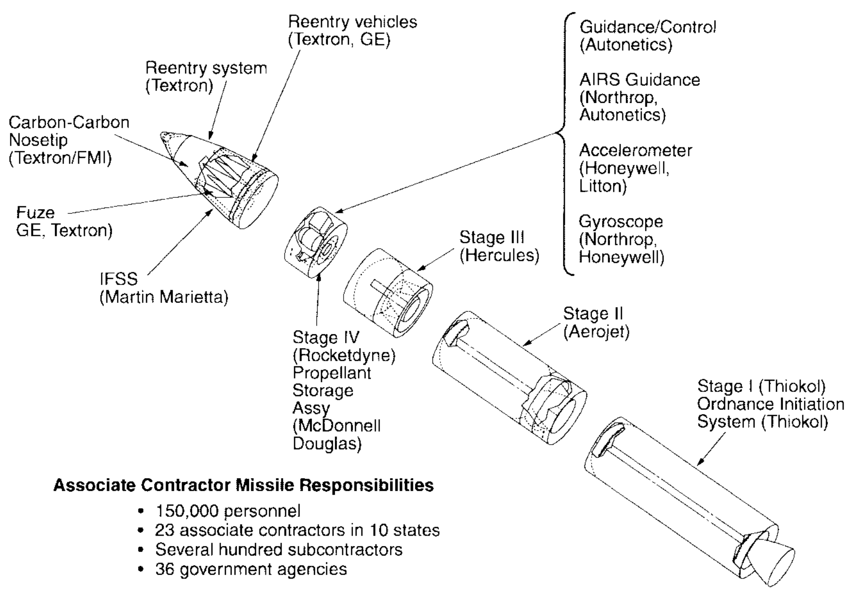


Fig. 7 Peacekeeper associate contractor team.

a first for ballistic missiles. Techniques and capabilities developed on the Minuteman program played a significant role in the conception and sizing of the Peacekeeper system. U.S. Air Force/SETA conducted system trade studies to evaluate ENECs, nozzle throats, Kevlar®–epoxy motor cases, carbon–carbon composite nozzle throat inserts [integral throat entrance (ITE)], missile diameter and length, and interstage separation geometry. In each case the system performance benefits were evaluated against the current technology and the development risk of engineering and qualifying the specific hardware. Mobile basing modes for Peacekeeper were explored and developed. Ultimately 50 missiles were fielded in converted Minuteman silos at Warren U.S. Air Force Base, Wyoming. The Peacekeeper program became the most successful ICBM development program in U.S. Air Force history, so declared Defense Secretary Caspar Weinberger, with 18 successful development flight tests, fielded on schedule and below cost. Because of the significant advances made in guidance systems, Peacekeeper possesses hard target kill capability, unique among the ICBM and submarine-launched ballistic missile operational force. Table 5 is a summary of Peacekeeper booster configurations.

Missile Sizing Studies

A key U.S. Air Force/SETA function is the definition of missile system and booster stage sizing. To generate preliminary missile and stage designs, a missile sizing computer program was written. Inputs to this program were various specification requirements and constraints, such as missile weight and stage diameters. One method of evaluating a proposed design is to simulate the flight using a three-degree-of-freedom trajectory computer program. While developing specifications for Peacekeeper, the need arose for a simple method of ranking the range performance of a proposed design for a fixed payload. U.S. Air Force/SETA developed an approach using a set of stage velocity equations that ranked proposed stage designs in the same order with respect to range as does a proven trajectory program, with appropriate constraints applied.

The equations calculate a figure of merit called range equivalent velocity. With a baseline missile design as a starting point, the equations were defined using the three-degree-of-freedom trajectory model. Independent variables in these equations were quantities that characterized the flight performance of the vehicle such as burn time, specific impulse, and stage weight. Variations of the baseline design were used in the trajectory program to compute the constants in the range equivalent velocity equations. The ability of the equations to rank designs was then validated using additional designs and the trajectory program. The equations were used in the sizing program as objective functions to develop optimal designs.

System Implications of ENECs

ENECs provide a means to package large-area-ratio nozzles in a limited envelope. The result is lower interstage inert weights and increased stage range performance. When Peacekeeper was in the concept definition phase, ENECs had not been flight tested. Design calculations showed significant performance enhancement, especially for the upper stage. Staging gasdynamics and stage motions during the staging separation event were quantified, and margins were established.

The trade study evaluated the range benefit of increased nozzle expansion, the best method staging, interstage geometry, axial and lateral staging gasdynamic loads, external aerodynamic loads, the weight of the structure necessary to adequately react to the loads, uncommanded nozzle motion, missile controllability, and the relative motion of the separating stages. The study took into account missile optimization as described earlier and the status of available material technology as it related to nozzle materials, propellant performance, motor case and interstage design, and thrust vector control (TVC). The study also made use of the results of an early U.S. Air Force R&D program that successfully demonstrated a metallic ENEC in a ground test.

Based on the trade study, it was concluded that the most promising design was a carbon–carbon translating cone utilized in a hot flyout staging scenario in which the interstage separation plane was forward of the stowed nozzle exit plane. The results of the trade study were used to define the stage II and III development specifications. The U.S. Air Force implemented the ENEC concept, and Peacekeeper was the first ballistic missile system to flight test an ENEC system.

Current Status of Peacekeeper Service Life Estimate (SLE)

Life estimates for all three solid booster stages are currently greater than 17 years. No life limiting failure modes have been identified to date. With guidance provided by the U.S. Air Force/SETA, validation of structural margins of safety through motor overtests for the propellant and propellant/liner bonds was accomplished. Although the overtests were similar to the Minuteman (MM) LRSLA program, the motors were also instrumented with internal gauges prior to casting, and the margins of safety were obtained for relatively young motors. A summary of this performance including explanation is shown in Table 6.

Table 6 Status of Peacekeeper SLE (as of December 1997)

Stage	SLE requirement (design life), yr	Current SLE extension[a] (required life), yr	Life limiting failure modes
I	10	> 17	None to date
II	10	> 17	None to date
III	10	> 17	None to date

[a]SLE extension possible due to 1) design margin testing (based on LRSLA), newly manufactured motors with imbedded instrumentation (prior to cast); 2) better failure limits due to validated models; 3) better material properties (by motor dissection and by newly developed plugging technique); and 4) better aging trend data (from plugs and motor dissection).

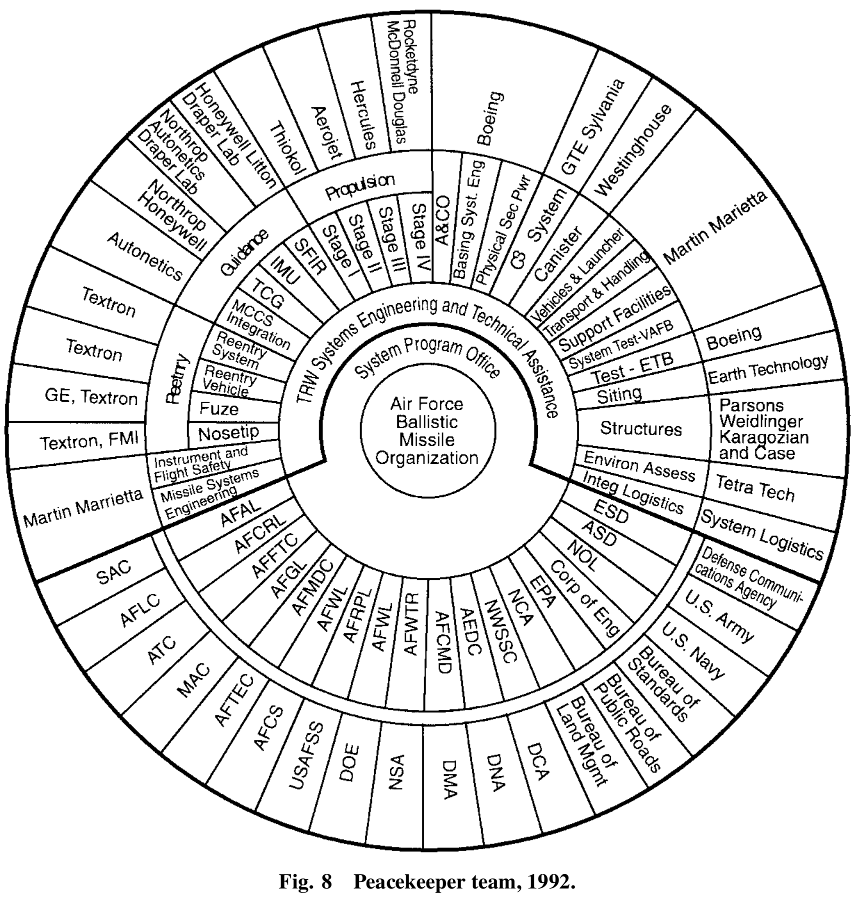


Fig. 8 Peacekeeper team, 1992.

Small ICBM

The small ICBM, commonly known as Midgetman, took the technological advances demonstrated on Peacekeeper one step further. Table 7 provides an overview of the booster stage configurations. Although solid propellant technology was clearly mature, economic and performance considerations fueled the need for innovative solutions to produce cost effective, lightweight components and stages. The following paragraphs highlight some of the technological advances and the current state of the art.

Lightweight, Graphite–Epoxy Cases

Whereas Peacekeeper demonstrated the viability of lightweight Kevlar–epoxy motor cases, the small ICBM demonstrated the viability of graphite–epoxy for the entire booster portion of the missile. The benefits of the graphite–epoxy material over the previously used Kevlar–epoxy are twofold: First, the inherent strength and stiffness of the material allows for thinner, lighter stages, and the lower missile inert weight is transformed into better system range performance. Second, the material and resulting motor cases are much less susceptible to interply delaminations. The improved case material also resulted in higher pressure motor designs with smaller nozzles so the need for expensive ENECs was avoided.

Staging Analytical Techniques

The Small ICBM system performance requirements resulted in the need for high-expansion-ratio exit cones. In combination with relatively small-diameter interstages, the resulting gas dynamic loads during I/II and II/III staging proved to be a significant challenge for the U.S. Air Force team. Quantifications of the loads were derived from a combination of subscale testing to simulate the condition and state-of-the-art analytical techniques to derive the bounding limits.

The U.S. Air Force funded several series of tests that involved the use of one-quarter-scale models. These tests produced data that characterized the wave shape (force vs time) characteristics of the 100-ms event. TRW, Inc., and Aerojet General developed an innovative technique involving Fourier and covariance analysis to statistically derive conditions beyond the scope of the subscale tests. Parallel, computational fluid dynamic analyses were completed to quantify the physical boundary conditions of the dynamic and unstable event. The two methods were merged to describe structural design loads for the nozzle and TVC system. Although the technique was not validated with statistically significant flight test data, it represented a promising approach for future systems.

Carbon–Carbon Nozzle Materials

Although Peacekeeper used a two-dimensional carbon–carbon exit cone for stage III, exit cones were typically tape-wrapped, ablative, carbon-phenolic liners with structural overwraps. Whereas the configuration was time-honored, effective, and mature, small ICBM demonstrated the benefits and feasibility of radiative carbon–carbon nozzle components. A U.S. Air Force/SETA/Aerojet General investigation of carbon–carbon processing highlighted those parameters of the stage II Novoltex exit cone material processing that significantly affect the material's thermal, mechanical, and physical behavior in a finished part. The stage III exit cone incorporated a three-dimensional weave of graphite fibers in a graphite matrix, which resulted in a lightweight exit cone that is thermally and structurally sound. Despite the need for increased thermal insulation due to the increased radiative environment, the technology remains an attractive alternative for high-performance systems.

Improving State of the Art

The Advanced Strategic Missile Systems (ASMS) program is the Department of Defense program for concept formulation and initial development of advances in missile and basing system technology. The Advanced Ballistic Re-entry Systems (ABRES) Program was a triservice evaluation of reentry vehicles and penetration aid technologies. Because ABRES was a triservice program, major contributions were made to the U.S. Navy's submarine launched ballistic missiles, the U.S. Army's Pershing, and many missile defense programs leading to the Strategic Defense Initiative (SDI). The Advanced ICBM Technology program, created to develop guidance and propulsion technologies for the MX missile was merged with ABRES to form ASMS. Peacekeeper, small ICBM, and Peacekeeper/Rail Garrison can all trace their roots to these ASMS programs. Figures 9 and 10 show this relationship.

Current and Future Challenges

Current Challenges

In 1994, the U.S. Air Force initiated the Propulsion Replacement Program (PRP) as a means to develop design solutions for the life

Table 7 Small ICBM booster configuration

Characteristic	Stage I	Stage II	Stage III
Weight, lb	25,600	7,200	3,400
Case material	Graphite–epoxy	Graphite–epoxy	Graphite–epoxy
Integral throat	Three-dimensional carbon–carbon	Three-dimensional carbon–carbon	Three-dimensional carbon–carbon
Exit cone	Dual density carbon-phenolic	Dual density carbon-phenolic	Woven three-dimensional carbon–carbon
TVC type	Movable nozzle with omnivector flexseal and turbohydraulic TVA	Movable nozzle with omnivector flexseal and warm gas blow-down TVA	Movable nozzle with omnivector flexseal and cold gas blow-down TVA
Propellant	HTPB/PCP[a]/NG[d]/BTTN class 1.1	PEG[b]/NG/BTTN[c] class 1.1	PEG/NG/BTTN class 1.1

[a]Program change proposal. [b]Polyethylene glycol. [c]1,2.4-Butanetrial trinitrate. [d]Nitroglycerin.

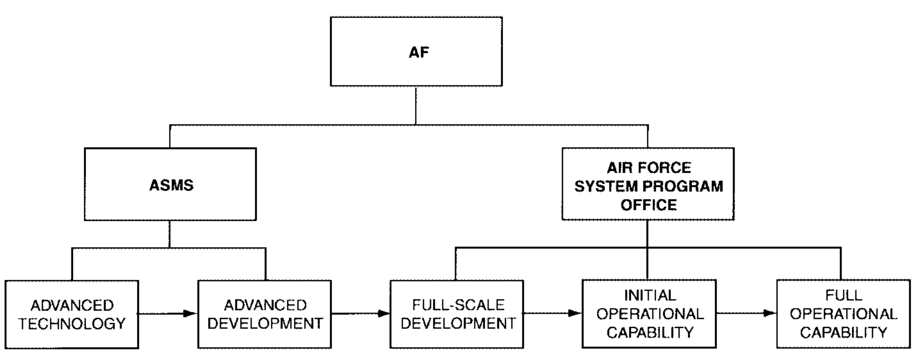


Fig. 9 ICBM technology infusion.

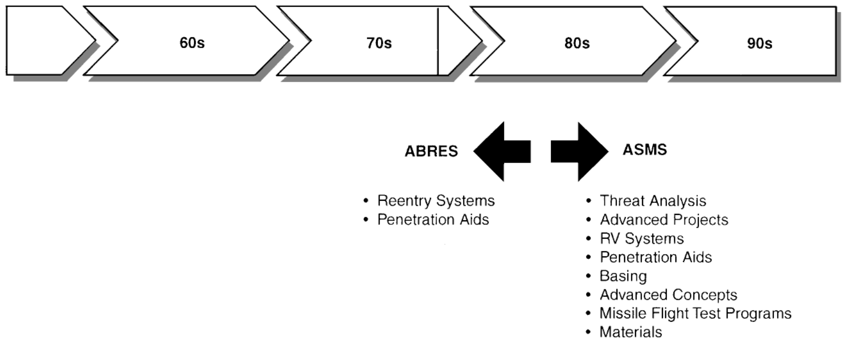


Fig. 10 ASMS, past and future programs.

extension of Minuteman III solid propulsion booster assets. The primary goals of the current technology insertion phase are to 1) establish and maintain a MM III production capability, 2) eliminate the life-limiting failure modes, 3) eliminate environmentally unacceptable materials, and 4) insert current manufacturing technologies to mitigate risk. As of this paper, each of three solid propulsion contractors has completed their critical design review and is preparing for design qualification. The primary challenge during this phase of the program has been the verification of component reuse requirements/criteria and establishing/maintaining a viable supplier base for qualified components and materials. To date, the program has proceeded smoothly.

Future Challenges

In 1996, the U.S. Air Force initiated the consolidation of the program management and execution functions for the MM and Peacekeeper weapon systems under an ICBM prime integration contractor (IPIC). TRW, Inc., and its teammates were competitively awarded the IPIC contract in December 1997. As part of this competitive procurement, TRW, Inc., proposed and is now executing a consolidated approach to remanufacture the MM solid stages. Under the consolidated approach, the production phase of the PRP for three solid stages will be executed by a propulsion joint venture consisting of Thiokol Corporation and United Technologies CSD. Validation of the consolidated approach is being performed in parallel with the PRP TI via the Consolidated Qualification Program (CQP). The fundamental challenge for PRP lies in the successful transition from a three-contractor approach to a two-contractor approach in time to satisfy the schedule requirements for first article delivery in 2001. Technical and schedule risk associated with the CQP is mitigated because CSD is currently qualified for stage III, which uses the same propellant formulation as stage II. Most other components will be procured from currently qualified vendors and suppliers. The consolidated approach will be further validated through flight test in 1999.

Conclusion

The developments of the U.S. Air Force solid rocket ICBM programs are reviewed, with particular emphasis on the technical challenges encountered and overcome. In 1957, a prompt response to the Soviet ICBM challenge was a national priority. The U.S. Air Force responded to the challenge with the development of the Minuteman ICBM, in record time. Using an innovative management approach, the U.S. Air Force formed a joint government/industry team utilizing a SE/TA contractor along with associate contractors. The U.S. Air Force mobilized industry talents and allowed the U.S. Air Force to achieve the goal of fielding the Minuteman system on near-impossible schedule. The then novel "systems engineering" approach was applied, addressing concept development, design tradeoffs, risk mitigation, and alternate and parallel technical development paths that successfully met the technical and schedule challenges of Minuteman. The technical challenges related to solid rocket motor development and their solutions are discussed for the Minuteman program, as well as the Peacekeeper and Small ICBM programs. Finally, the current and future challenges of the U.S. Air Force ICBM programs are delineated.

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