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

Development of U.S. Air Force Intercontinental Ballistic Missile Weapon Systems

Tony C. Lin*
Northrop Grumman Mission Systems, San Bernardino, California 92402

The history of the development of U.S. Air Force intercontinental ballistic missiles is briefly discussed. Emphasis is placed on the technical challenges and the achievements made by the intercontinental ballistic missile team over the past 56 years. The discussion covers all important subsystems in the construction of an intercontinental ballistic missile, that is, rocket propulsion, missile basing, guidance/control, and reentry systems. One of the most remarkable accomplishments of the program is its actual service life, which has far exceeded the original design requirements and goals. The intercontinental ballistic missile program has been one of the most successful programs in the history of the Department of Defense. Besides achieving its nuclear deterrence mission and helping the United States win the Cold War, the intercontinental ballistic missile program also made pivotal contributions in the early stages of the space race with the former Soviet Union. Technologies developed by the intercontinental ballistic missile program have also contributed to nonmilitary and scientific application. Notable examples are miniaturized, high-speed computer chips, composite materials, and high-temperature thermal protection systems.

Introduction

AFTER World War II, it was realized in the United States that mating two war-developed technologies, the atomic bomb and the German V-2 guided ballistic missile, could completely revolutionize weaponry and strategic warfare. To achieve this capability, the U.S. government initiated the intercontinental ballistic missile (ICBM) effort in 1946 with studies and research by Consolidated–Vultee (later Convair Division of General Dynamics Corp.) in stabilization and guidance for a missile with a 1500–5000 mile range.[1–4] Initially, the U.S. Department of Defense (DOD) position was that the ICBM possibility merited only a small, leisurely research program. It was not a program to guarantee that an ICBM would be achieved at the earliest possible date. However, the Atomic Energy Commission's Bikini Island tests in 1952 and 1953 provided a major breakthrough in nuclear warhead technology. About the same time, Charles Draper at the Massachusetts Institute of Technology (MIT) Instrumentation Laboratories achieved significant improvements in missile guidance accuracy. The expectation of a lighter warhead and more accurate missile guidance vastly improved the prospect for an ICBM. Then, in the fall of 1953, U.S. military intelligence concluded that the former Soviet Union had a several-year head start over the United States and was well along in the development of an ICBM. A surprise strike by a large fleet of Soviet ICBMs carrying nuclear bombs could destroy the United States in half an hour. This news caused great alarm and triggered a major shift in the nation's security plans and priorities. The DOD initiated a crash effort to counter this serious threat. Major developments were put in place to upgrade our strategic offensive and defensive nuclear forces, elements of which were assigned to each of the three services. The U.S. Army was responsible for land-based intermediate range ballistic missiles (IRBMs), for example, Jupiter, and antiballistic Missiles (ABMs), for example, Nike and Zeus; the U.S. Navy was responsible for submarine launch ballistic missiles (SLBMs), for example, Polaris and Poseidon; and the U.S. Air Force was responsible for ICBMs, for example, Atlas, Titan, Thor, and Minuteman, in addition to the strategic bomber forces. This paper focuses on the U.S. Air Force ICBM program. However, many of the technology development needs were common across the services, and all programs benefited significantly from cross fertilization.

This major shift in U.S. defense strategy in 1953 essentially set the future course of military strategy and also laid the foundation for the nation's space program. The follow-on ICBM program became the largest technical development ever attempted by the U.S. military, even exceeding in assigned resources the wartime Manhattan Project to develop the atomic bomb.

For an ICBM to have military utility, several key technical problems had to be solved. In 1953, these problems seemed to be close to insoluble. To begin, the technology then available for guiding an ICBM was so inaccurate that a target 5000 miles away would be missed by 20–30 miles or more. The gyroscope, accelerometer, and radar involved in the guidance and control of a missile and the transmission of information about its operation during a flight had to be enhanced by a factor of 10 or more over the proven art in accuracy, range, strength, lightness, reliability, and speed of response. Although an H bomb would pack great explosive power and do considerable damage even if it detonated far off its target, the early H bombs were extremely heavy and bulky. Furthermore, in 1953, there was virtually no reliable scientific knowledge on hypersonic aerodynamics and the related thermal heating issues. For instance, the enormous heat generated by the payload during its streaking reentry into the atmosphere would damage the bomb unless it was protected from the heat by a thick blanket of thermal protection material. Such a covering would add even more weight. Hence, it appeared that rocket engines of gigantic size would be required to boost the heavy reentry vehicle into space.

Many interrelated technical disciplines were involved in the ICBM designs. In each engineering field, technical breakthroughs were needed if the ICBM was to become a reality in a short period of time. It was evident in the early 1950s that a business as usual approach would not produce a successful ICBM program. Fortunately, a new management approach was recognized at the outset of the program by the U.S. officials. The approach eventually created a new management scheme, which today we call system engineering. Another important strategy identified was parallel and competitive development for some high-risk subsystems as discussed in the following section.

New Management Approach

In 1953, at the prodding of Trevor Gardner, then the Special Assistant to the Secretary of the Air Force, a Strategic Missile Evaluation Committee was established. Chaired by Princeton University Professor John Von Neumann, the committee assessed the ICBM program in light of the new atomic technology.[1–3] Among the 11

Received 3 January 2003; revision received 12 March 2003; accepted for publication 4 April 2003.

*Member of Technical Staff, Missile Defense Division. Member AIAA.

prominent scientists and scholars on the committee were Simon Ramo and Dean Wooldridge. At the request of Gardner, Ramo–Wooldrige (RW) Corp. was given a contract to serve as technical staff to the committee. After the disclosure of the Soviet's advances in the ICBM, the Von Neumann committee concluded that Convair's technical and managerial approach on the Atlas program was inadequate. The committee specifically recommended that a new agency be formed to make a comprehensive study of the ICBM's possibilities and to recommend a particular ICBM program. In response to this recommendation, the Air Research and Development Command formed the Western Development Division (WDD) under Bernard A. Schriever.

By August 1954, there were four well-defined alternatives for the management of the ICBM program: 1) a single prime contractor, such as Convair, in the tradition of the aircraft manufacturing industry; 2) the creation of a new, large laboratory within a university (such as the Lawrence Livermore and Los Alamos National Laboratories in the Manhattan Project); 3) a prime contractor, with RW acting in a technical staff capacity to the WDD commander; and 4) a group of associate contractors with RW performing as a line organization for system engineering and technical direction (SE/TD) and also as a technical staff to the WDD command. Schriever chose the fourth alternative. Thus, the U.S. Air Force commissioned RW to set the basic system concepts and specifications and then to coordinate and direct, from a technical standpoint, subsystem development by several large companies, to be known as associate contractors. RW's major responsibilities were as follows: 1) define ICBM missile system specifications and constraints, 2) specify subsystem overall requirements, 3) perform tradeoff studies on various design concepts and approaches and downselect to the optimum design/approach, 4) perform system studies to assure weapon system effectiveness in meeting the requirements, 5) manage the interfaces among the different disciplines and associate contractors, and 6) provide technical direction to associate contractors.

To attain the objective of developing operational missile systems as soon as possible, WDD and RW replaced the conventional sequential development pattern with concurrent development. Within the framework of a single overall plan, development, production, testing, and initial operational capability (IOC) actions were undertaken simultaneously. Although it is not an entirely new concept, the U.S. Air Force applied concurrent development on a scale never before used in military development programs. This parallel approach worked, in part, because of the new system engineering management technique.

This type of program integration represented a revolutionary approach to management of large, complex programs. From the start, the U.S. Air Force attempted to mitigate industry concerns by excluding RW from hardware production. RW also created a separate entity named Space Technology Laboratories to handle the Air Force ICBM effort. RW merged with Thompson Products in 1958 to form TRW, Inc.[4] Eventually, on 4 June 1960, the Air Force established The Aerospace Corporation, a nonprofit organization, to handle most of its SE/TD works related to space and satellite programs. (In 1976 the term was changed to system engineering and technical assistance.)

The ICBM team involved many disciplines, contractors, and parts vendors. Besides the DOD and Department of Energy interfaces, the integration of various contractors was a significant challenge. At the same time, RW defined the design specifications, monitored the technical aspects of the program, provided technical direction, and mitigated schedule slippages and cost overruns. This innovative management approach worked well and has proven to be one of the reasons that the ICBM program has enjoyed such great success. Besides that, the ICBM program benefited from outstanding leadership. The overall program leader, Schriever, played a pivotal role. He possessed a remarkably strong aptitude for the post, including determination, great leadership and organizing talent, excellent grounding in science and engineering, intimate knowledge of the workings of the Pentagon, Congress, and the U.S. government as a whole, and an uncanny sense for evaluating and managing people. Furthermore, RW was able to bring together an highly competent group to supervise the scientific and engineering aspects of the program. Many of those energetic and capable engineers went on to become prominent managers in government and industry.

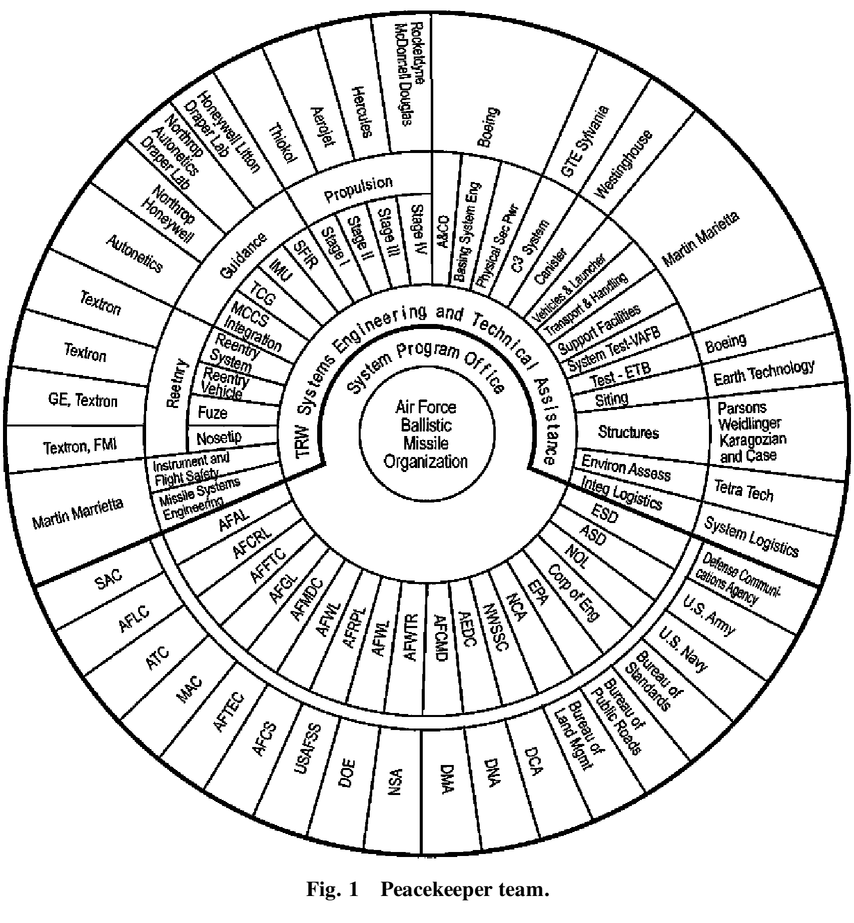


Fig. 1 Peacekeeper team.

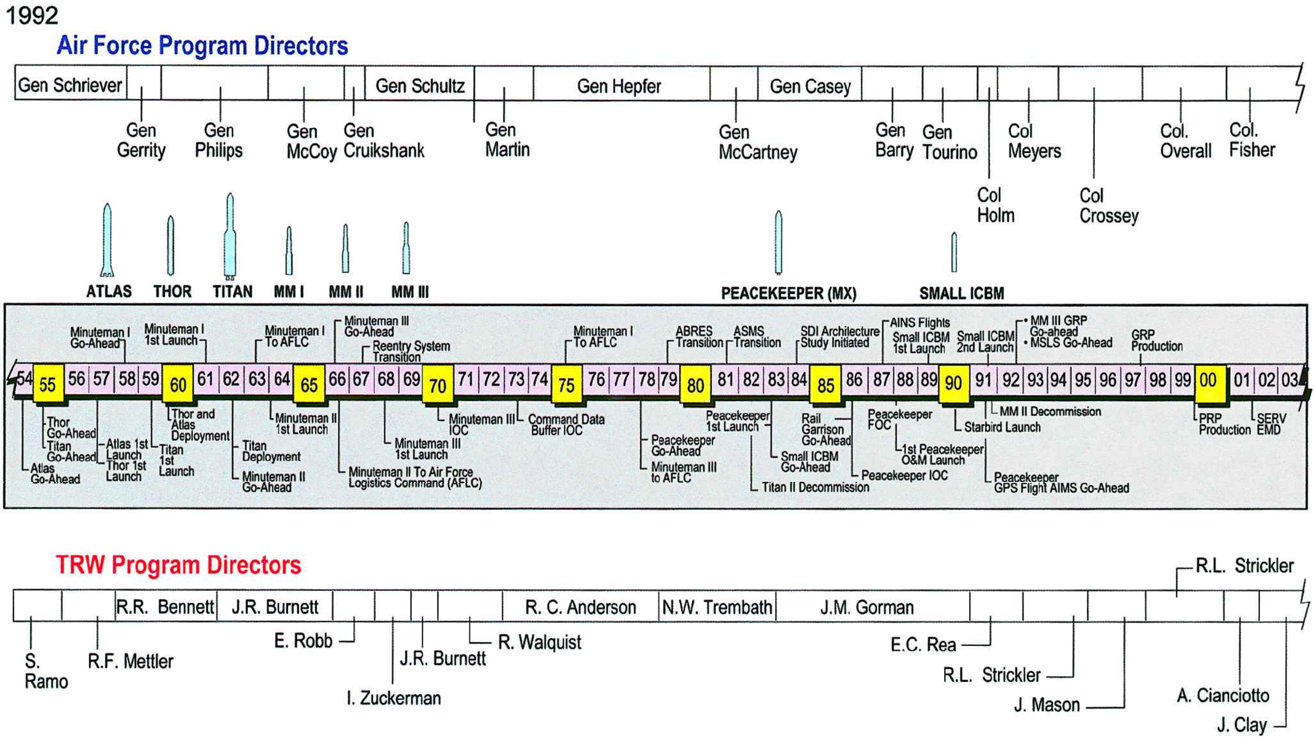


Fig. 2 U.S. Air Force ballistic missile programs.

As mentioned before, many disciplines are involved in the design of an ICBM weapon system. The U.S. ICBM program has been fortunate to have many competent associate contractors to build the system components. Figure 1 shows the participants for the Peacekeeper program, in which more than 40 government agencies and associate contractors were actively involved. It shows the magnitude of the management challenge and the complexity of the interface within which RW performed SE/TD functions. Over the years, the boosters were built by Thiokol Corp., Aeroject, Hercules Aerospace Co., Chemical System Division, Rocketdyne, and The Boeing Co. The U.S. Air Force Rocket Propulsion Laboratory played a significant role in the development of new propellants and liners. The missile guidance, navigation, and control (GNC) systems were designed and built by Autonetics, Northrop Corp., and Honeywell, Inc. Charles Draper Laboratories has made important contributions in this area. The reentry vehicles (RVs) and the fuzing subsystems were built, over the years, by General Electric (GE) Co., Avco Corp., and McDonnell Douglas Corp. Sandia National Laboratories and the U.S. Air Force Research Laboratories also made important contributions in RV designs. For reentry guidance, Litton and Honeywell, Inc., made important contributions. In the software arena, Logicon RDA, The Boeing Co. and TRW, Inc., were important players.

Figure 2 lists the ICBM program managers over the years for both the U.S. Air Force and TRW, Inc. In Fig. 2, the important milestones are also identified.

The following sections briefly discuss the development histories of several important technical disciplines in ICBM design: rocket propulsion, missile basing, guidance and control, and reentry systems.

Rocket Propulsion[5,6]

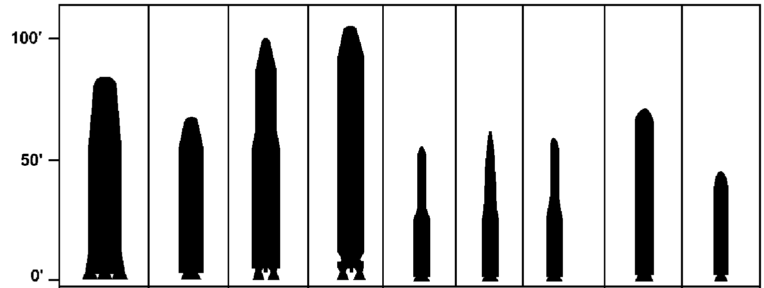
Figure 3 shows the U.S. Air Force ICBM program's past and present missiles and associated RVs. The missile length, diameter, and weight are also given in Fig. 3.

First Generation ICBM Propulsion

The first U.S. ICBM was the liquid propellant Atlas. It combined Germany's V2 ballistic missile technology and Robert Goddard's research work. Initially, Atlas used a liquid oxygen/hydrocarbon (LOX/RP-1) propulsion system developed by Aerojet. The propellant tank was made of stainless steel. Convair Division of General Dynamics produced three different operational models of the Atlas. The first successful Atlas series A missile flight was conducted on 17 December 1957. The short-range booster impacted 575 miles downrange from Cape Canaveral. During the flight, all systems performed satisfactorily. The first operational version of the Atlas, the series D deployed in August 1960, was a one-and-one-half stage (360,000 lb of thrust) ICBM equipped with radio-inertial guidance and a nuclear warhead. It was stored in a horizontal position, in an aboveground launcher and had a range of approximately 6500 n miles. The second Atlas ICBM configuration, the series E, was deployed in August 1961. It possessed all inertial guidance, improved liquid engines (389,000 lb of thrust), and a larger warhead; it was also stored in a horizontal position in a coffin-type launcher. The series F missile, deployed in July 1962, possessed further improved engines (390,000-lb of thrust) and a quicker reaction time due to its improved liquid propellant efficiency, for example, the improved cryogenic cooling technology. The Atlas F missile was able to be deployed in a silo-lift launcher, which stored the missile vertically in an underground, blast-protected silo and used elevators to raise the missile to ground level for launch. Atlas pioneered the use of the missile's outer skin as a liquid propellant container and was the first missile to employ gimbaling engines for directional control.

In contrast to Atlas, the Titan I ICBM, produced by Glenn L. Martin Co., was powered by two-stage, liquid propellant rockets (first stage with 300,000 lb of thrust and second stage with 80,000 lb of thrust) and incorporated both radio and all inertial guidance. The oxidizer used on Titan I was nitrogen tetroxide, and the fuel was 50–50% mixture of hydrazine and unsymmetrical di–methyl hydrazine (Aerozine-50). The propellant tank was made of aluminum. Deployed in August 1961 in a silo-lift launcher, the Titan I had an effective range of 5500 n miles. Technically and operationally, it is significant that the Titan missiles were powered by storable rather than cryogenic propellants. This change also improved the missile safety and reliability.

The Titan II was the largest ICBM ever built in the U.S. Air Force inventory. It was also a two-stage liquid-fueled rocket, which incorporated significant performance improvements over the earlier Titan I weapon system. Titan II had more powerful engines (first



	ATLAS	THOR	TITAN I	TITAN II	I (MINUTEMAN)	II (MINUTEMAN)	III (MINUTEMAN)	MX PEACE-KEEPER	SMALL ICBM
Length (ft)	82	65	98	105	54	60	60	71	53
Diameter (ft)	10	8	10	10	5.5	5.5	5.5	7.7	3.85
Weight (lb)	269,000	110,000	220,000	330,000	65,000	70,000	76,000	190,000	37,000
First Launch Date	12-17-57	1-25-57	2-6-59	3-16-62	2-1-61	9-24-64	8-16-68	6-17-83	-
Full-Scale Development Initiation	6-55	11-55	4-57	10-59	2-58	4-62	12-65	12-82	10-83
OPS Inventory (IOC)	8-60	6-59	8-62	6-63	2-62	10-65	6-70	8-86	-
Launch Mode					Hot	Hot	Hot	Cold	Cold
Reentry Vehicle	1MK2/3*/4	1MK2	1MK4	1MK6	1MK5	1MK11 A/B/C/D	3MK12/12A	10MK21	1MK21
Deployed	1960-62	1960-62	1961-62	1963	1962-65	1965-73	1970-75	1986-88	
Retired	1965	1963	1965	Aug 87	1975	Nov 95	Operational	Operational	Terminated

Fig. 3 U.S. Air Force ICBMs, past and present.

stage with 430,000 lb of thrust and second stage with 100,000 lb of thrust), a larger warhead, all inertial guidance, hypergolic fuel and onboard oxidizer, and the ability of being fired from a hardened underground silo launcher. Titan II, like Titan I, had an effective range of approximately 5500 n miles. Titan II missiles became operational in 1963. For the United States, the era of liquid propellant ICBMs came to a close on 18 August 1987 with the inactivation of the last Titan II wing. The reasons that the Titan II service life was much longer than Atlas or Titan I were its storable liquid propellant and larger warhead. There are several configuration derivatives of Titan II. For instance, Titan III is a modified Titan II with strap-on solid-propellant booster motors. It was used in U.S. Air Force and NASA satellite and space programs.

During the development of Atlas and Titan, there was a parallel effort to build an IRBM. Initially, the U.S. Air Force developed the Thor missile, and the U.S. Army and U.S. Navy jointly developed the Jupiter missile. On 26 November 1956, the Secretary of Defense, Charles E. Wilson, issued a memo that all missiles, ICBMs as well as IRBMs, with a range of more than 200 miles, would be the Air Force's responsibility. For the Thor designs, North American Aviation was to provide the propulsion system, Bell Telephone Laboratories provided a radio guidance system, and Douglas Aircraft was the airframe integrator. Thor was developed on a faster timescale than the ICBMs. For instance, on 19 April 1957, Thor had its first successful flight (range $\sim$1300 n miles) on the Atlantic Missile range just 16 months after the development contract with Douglas Aircraft was signed. Therefore, one of the important contributions of Thor missile program is that it served as a test bed for many important ICBM subsystem developments, such as rocket engines, guidance and control, and RVs. Thor missiles were operationally deployed in the United States in March 1960, and they were also deployed in England as early as June 1959. After the Thor missile was decommissioned, Douglas Aircraft modified the missile to deliver commercial payloads and renamed it the Delta rocket.

The development of the United States first ICBM also benefited nonmilitary programs.[3] On 4 October 1957, three years after the start of the focused ICBM program, the former Soviet Union launched the first man-made satellite, Sputnik, into Earth orbit. This event stunned the free world and started the space race. To the U.S. ICBM team, Sputnik was not overwhelming because they knew it was possible to put a lighter payload (as compared to a heavy RV) into orbit, using the rocket propulsion capability of an ICBM with a range of several thousand miles and with a crude guidance system. Early space capability was developed through the use of the Thor booster and a modified Vanguard second stage. This combination was to become known as the Thor/Able booster vehicle. This capability was demonstrated by the ICBM team on 11 October 1958. A Thor/Able booster was used to launch the NASA Pioneer I satellite, the first successful space probe, to a new altitude record of over 70,717 miles above the Earth; it transmitted data flawlessly all of the way before falling back into the Earth's atmosphere.

On 18 December 1958, Project Signal Communication Orbiting Relay Equipment (SCORE) used an Atlas Missile 10B to place a communication repeater satellite into orbit and broadcast President Eisenhower's Christmas message to the world. Project SCORE demonstrated the practical operation of a satellite radio relay system using ICBM booster, guidance, and electronic communications. Later, on 13 April 1959, a U.S. Air Force Thor/Agena booster lifted Discoverer II into orbit from Vandenberg Air Force Base. Discoverer II became the first satellite to be stabilized in orbit in all three axes, to be maneuvered on command from Earth, to separate an RV on command from the mother satellite, and to send its RV back to Earth. Although the capsule ejection system malfunctioned, the RV still safely reentered the atmosphere and impacted near Spitsbergen rather than near Hawaii as planned.

On 1 April 1960, a Thor/Able II booster placed NASA's Infrared Observation Weather Satellite into the most accurate orbit yet achieved by any U.S. satellite. It opened a new era in meteorology. An U.S. Air Force Thor/Able booster was used to launch NASA Pioneer V spacecraft on its journey to Venus on 11 March 1960. The satellite was designed by TRW, Inc., engineers, and it carried the first U.S. digital computer to outer space. The satellite measured radiation and magnetic fields between Earth and Venus, transmitting data for six months.

On 5 May 1961, under NASA's Project Mercury, an Atlas booster propelled the first U.S. astronaut, Alan Shepard Jr., into orbit. Atlas, Thor, and Titan boosters have been used extensively since their military retirement in the U.S. space launch program. The United States was fortunate that the then newly developed ICBM technologies (propulsion, electronic communications, hypersonic

Table 1 MM missile motor specifications

	MM I stages			MM II stages			MM III stages		
Category	1	2	3	1	2	3	1	2	3
Total weight, lb	51,251	12,072	4,484	51,230	16,057	4,443	51,230	16,039	8,197
Propellant weight, lb	45,670	10,380	3,668	45,670	13,680	3,668	45,670	13,680	7,292
Length, ft	24.1	9.1	5.1	24.1	12.6	5.1	24.1	12.6	8.5
Diameter, ft	5.5	3.7	302	5.5	4.3	3.2	5.5	4.3	4.3
Thrust, lb	220,000	45,600	17,100	220,000	70,000	17,100	220,000	70,000	38,000
Motor case material	D6AC steel	Titanium	S-901 fiberglass	D6AC steel	6AL-4V titanium	S-901 fiberglass	D6AC steel	6AL-4V titanium	S-901 fiberglass
Propellant material	TP-H1011 TP-H1043	ANP-2862 ANP-2864	CYH and DDP	TP-H1011 TP-H1043	ANB-3066	CYH and DDP	TP-H1011 TP-H1043	ANB-3066	ANB-3066 type 1
Manufacturers	Thickol	Aerojet	Hercules	Thiokol	Aerojet	Hercules	Thiokol	Aerojet	CSD

aerothermodynamics, and guidance and control) and hardware could be readily applied to the civil and military space programs.

Minuteman I Propulsion

Even as the U.S. Air Force was deploying its liquid-fueled ICBMs (Atlas and Titan), an extensive effort was underway to develop an alternative that would be safer and less expensive, as well as more effective, flexible, and responsive. The Air Force sponsored technology studies for large, solid-propellant rocket motors suitable for use in an ICBM. The major advantages of the solid-propellant rocket over the liquid-fueled rockets are costs, safety, and rapid launch capability. The initial cost of Minuteman (MM) I was one-fifth that of Titan I. The annual maintenance costs for MM I were only 1/10 those of Titan I. For combat operations, Titan required six crewmembers for each missile, whereas a crew of two could launch a flight of 10 Minuteman I missiles or a salvo of several flights.

Project Q (eventually named the Minuteman Program) was initiated in late 1957 to study the feasibility of a three-stage, solid-propellant rocket ICBM to be deployed in early 1960. A limited research and development (R&D) program was approved in 1958, but rapidly accelerated. The R&D program culminated on 1 February 1961, in the first MM flight test from Cape Canaveral, a fullup configuration.

Development of the MM missile on the original schedule was neither easy nor assured because the emerging technologies presented serious technical challenges to the Minuteman team. Some difficult areas are the following: 1) design and development of lightweight, large-diameter steel cases, 2) stage ballistic performance (increase of specific impulse), 3) nozzle throat and exit cone materials, 4) methods for mixing and casting large volumes of solid propellant, 5) movable nozzles, 6) thrust termination of stage 3, 7) environments induced by a hot silo launch, and 8) motor case design and fracture mechanics.

The U.S. Air Force, the SE/TD contractor, 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, for example, stage 1 was assigned to Thiokol Corp. and Aeroject. All contractors proposed steel cases except Hercules Powder Co., which proposed to develop a fiberglass filament-wound composite case for stage 3 (although the stage 2 case material later was changed to titanium). Stage 1 was a particular challenge, being considerably larger than any solid-propellant motor ever built. The first Thiokol Corp. firing in 1959 ejected all four nozzles at 30 ms, well before full-motor ignition. Several redesigns later, the nozzle lasted 2.5 s after ignition. In October 1959, five motors and their test stands blew up in a row, once a week, each with its own unique failure mode. However, by December 1959, Thiokol Corp. had solved its design issues and made sufficient progress on the stage 1 motor that Aerojet General could be phased out of stage 1 development to concentrate on stage 2. At the same time, Thiokol Corp. stopped all work on stages 2 and 3.

A multiple contractor approach was also applied to the development of movable nozzles. 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 Co. was selected for stage 3 development, having demonstrated the significant advantages of a high-performance fiberglass filament-wound composite case. MM I stage 3 thus became the grandfather of all composite cases. Table 1 lists the rocket motor components, the types of propellant used, the motor case materials, and the manufacturers.

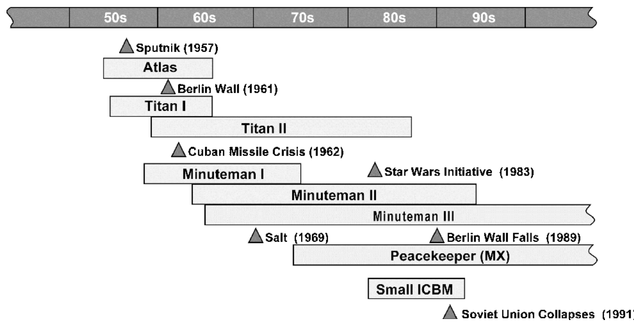


Fig. 4 Sputnik to glasnost.

The first launch, flight test 401, was conducted from Cape Canaveral on 1 February 1961, 31 days from the originally scheduled launch date. This flight proved to be a complete 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 distances, typical of all liquid-propulsion missile programs at that time, the Minuteman first launch successfully demonstrated all missile functions over a full operational range, with acceptable accuracy.

MM I, with one RV and one-target capability, was able to withstand storage in an alert “ready” condition for long periods. With a range over 5000 n miles and a continuously operating guidance set, it could be launched even after being subjected to overpressure from a nuclear blast. The time-to-launch after receipt of the appropriate signal was less than 60 s. The first MM I missile became operational in February 1962, with the first flight (10 missiles) turned over to the Strategic Air Command in October 1962. The MM I remained on strategic alert until mid-1975. Figure 4 shows the operational time frame of different U.S. Air Force ICBM missile systems, from Atlas to small ICBM with various important world events also identified. Figure 5 presents the MM missile deployment and modernization roadmap from the 1950s to 2002.

MM II Propulsion

Before MM I was even deployed, plans were in place to develop a second generation of solid rocket propellant boosters. The new system was designated MM II. The initial objectives of the new design were twofold: improve stage 1 reliability and increase system performance with a more powerful stage 2, to give the missile greater range and enable it to carry a heavier payload. Additionally, the use of integrated circuits allowed designs that were capabile of changing

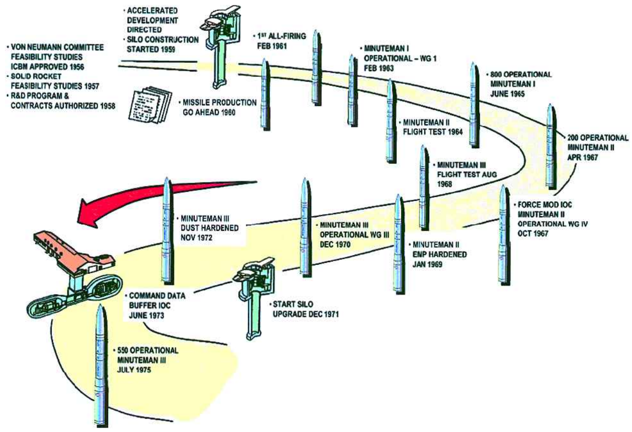


Fig. 5a ICBM deployment and modernization roadmap.

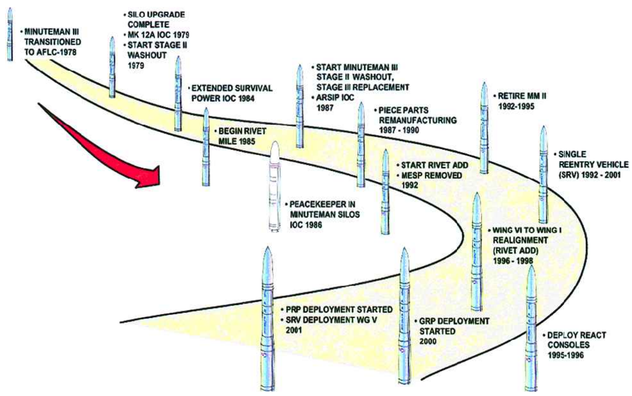


Fig. 5b ICBM deployment and modernization roadmap (continued).

the target assigned to any particular silo. This was driven by a desire to have a system with better counterforce target capability.

Changes to stage 1 were needed to eliminate potential failures in the nozzles and aft closure. The graphite throat support in the thrust vector control nozzles cracked recurrently, ejecting small pieces of graphite. To eliminate this failure mode, the U.S. Air Force and SE/TD team embarked on a reliability improvement program that eventually resolved the problem.

MM II stage 2 was a new solid rocket motor using new technologies to further enhance system performance. The design enhancements included a larger diameter, a single fixed nozzle with a more energetic carboxyl-terminated polybutadiene (CTPB) propellant, a liquid (freon) injection thrust vector control (LITVC) system for pitch/yaw control, and hot-gas generators for roll control. Other notable improvements over the MM I missile were improved warhead, flexible targeting options, enhanced nuclear surety/safety, improved stage 2 mass ratio, and improved guidance accuracy.

During the operational testing of MM I, a problem was identified concerning insulation burnthrough in the aft dome of the third stage. In response, the U.S. Air Force instituted the stage 3 operational reliability improvement program, which introduced design changes inhibiting the flow in and around the aft dome propellant flap.

During the concept definition phase of the Minuteman Program, the U.S. Air Force goal was to produce a weapon system with a service life of five years (originally it was three 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 that appeared to be age sensitive. The trends were then extrapolated to predict service life analytically. 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 1970, the U.S. Air Force and TRW, Inc., defined an approach to validate grain structural models, establish zero-time margins of safety, define aging trends, and predict age-related failure modes. This technique was implemented in the MM II program under the title Long Range Service Life Analysis using approximately 10-year-old motors. The program verified minimum margins of safety and, in some cases, identified previously unknown failure modes, such as propellant/liner debonds at 38°F for the stage 1 motor.

MM II was fielded in 1964 and continuously improved over the years. In 1995, MM II was decommissioned. However, MM II (and its derivative configurations) have continued to be flown to the present time by the Rocket Systems Launch Program for the Multiple Service Launch System test launches. For instance, several National Missile Defense programs use MM II booster combinations for launching their target vehicles.

MM III Propulsion

During the development and deployment of MM II, U.S. military planners became seriously concerned about the growing size of the former Soviet Union ICBM and ABM fleets. Our response was to increase the number of RVs without increasing the number of missiles and to provide a penetration aids (chaff and decoys) option. Multiple independently targeted RV (MIRV) technology was a new challenge and called for the development of postboost deployment, propulsion, and guidance systems. The task was further complicated because, with smaller RVs (and smaller warheads), accuracy again had to be improved. The final ingredient that led to the development of MM III was the refinement of warhead technology that offered a reasonable warhead yield in a small package, thus, making MIRV deployment possible on a MM-sized booster.

MM III go ahead was approved in 1966. It would be significantly different from its predecessors in that it would carry three MK12 MIRVs, penetration aids, and a storable liquid propulsion fourth stage called the postboost vehicle (PBV) for payload deployment. The added weight required a higher performance booster. Stages 1 and 2 remained unchanged from the latest MM II designs. Stage 3 was redesigned with a larger case diameter and a single nozzle with LITVC. Eventually, stage 3 grew from 37 to 52 in. in diameter, weighed over 8000 lb, used a glass epoxy filament-wound composite case, and incorporated a CTPB propellant similar to stage 2. These changes increased flight range and maneuverability because of the PBV and enhanced accuracy through improved electronics and more computer memory for the MIRV mission. Other notable improvements from MM II to MM III were 1) elimination of the optical guidance alignment for primary azimuth reference and instead relying on a gyrocompassing technique, 2) use of strontium perchlorate as the liquid injectant for stage 3 TVC, 3) use of the electromechanical pintel valves for injection of strontium perchlorate for stage 3 pitch and yaw control, and 4) refinements in nuclear hardness and survivability features.

During the development of MM III propulsion subsystems, sophisticated analytical algorithms and computer simulations were widely used to extrapolate the ground-test data to flight environments. One example was to use a computer code NASTRAN in the mid-1970s to help resolve the design issues involving the stage 3 thrust termination port (TTP). With the help of test data and NASTRAN computer results, the TTP failure mode was clearly identified, and design solutions were made accordingly.

Peacekeeper Propulsion

As the MM III missile was being deployed in the early 1970s, it became apparent from the accuracy of former Soviet Union missile flight tests that MM would eventually become vulnerable to attack. By the mid-1970s, the Soviets had fielded greater numbers of ICBM boosters with larger and more accurate RVs. To counter this threat, a newer, larger, and more powerful U.S. ICBM, capable of MIRV payloads and deployed in a survivable basing mode, was proposed. In 1977, the size and general configuration of the missile was finalized. It was known as missile experimental (MX) later renamed Peacekeeper by President Reagan. The Peacekeeper (PK) missile is 10.9 ft longer, 26 in. larger in diameter, and nearly three times heavier (200,000 vs 78,000 lb) than MM III and was designed to carry not 3 but 10 advanced RVs (Fig. 3). Actually, PK can carry 11 RVs, but is restricted to 10 by the Strategic Arms Reduction Treaty. To limit the overall length of the missile while utilizing high-expansion-ratio exit cones, the U.S. Air Force developed extendable nozzle exit cones (ENECs), which translate from a stowed position to the operational position during flight. The ENECs provide improved expansion of exhaust gases and greater specific impulse, without a corresponding increase of motor length.

Techniques and capabilities developed under the MM program played a significant role in the conception and sizing of the PK system. Extensive system trade studies were conducted to assess the new materials available, interstage separation geometry, and missile optimum diameter/length. In each case, the system performance benefits were evaluated against the current technologies and the development risk of qualifying new materials or hardware. All of these preliminary design approaches and tradeoff studies were conducted by TRW, Inc., and the associate contractors. In many cases, the most advanced technologies at the time were used in the designs. For instance, the stage 2 motor case material is Kevlar®–epoxy filament-wound composite, the nozzle throat insert is carbon–carbon composite, and the extendible exit cone is made of carbon phenolic. The stage 3 motor is Kevlar–epoxy filament-wound composite (graphite-epoxy skirt), and the extendible exit cone is made of carbon–carbon composite. These were all new technologies and advanced materials at the time.

The PK system has proven to be the most successful ICBM system ever developed and deployed. The flight-test program, comprising 18 developmental and 31 operational flights to date, has demonstrated a highly accurate system, surpassing its given requirements. Stages 1 and 2 employ solid propellants (hydroxy terminated polybutadine), and stage 3 incorporates class 1.1 propellant (nitrate ester plasticized polyether) for greater thrust from a smaller package. The PBV, an aluminum structure using storable hypergolic liquid propellants (monomethyl hydrazine as fuel and nitrogen tetroxide as oxidizer), also houses the guidance and control (G&C) system and supports the reentry system. A raceway, carrying cables for missile control and ordnance initiation signals, extends down the outside of the missile from stage 3 to the stage 1 aft skirt. The stages were totally configured on delivery, requiring only stacking and connection at the launch site. Technology improvements include propellant, propellant/insulation bond system, insulation materials (carbon phenolic), ENECs, guidance accuracy improvements (as will be discussed later), RV release mechanization, and RV changes.

The PK is the first U.S. ICBM program to use cold launch technology. The missile is loaded inside a canister placed in the launch facility. When launched, high-pressure steam ejects the missile from the canister in the launch silo to an altitude of 150–300 ft. Once the missile has cleared the silo, stage 1 ignites and sends the missile on its intended trajectory. This technique allowed the much larger PK missile to be deployed in MM silos. Figure 6 shows a representative ICBM flight sequence of events from launch to impact for a three-stage rocket and one post boost vehicle PBV maneuver.

Small ICBM Propulsion

Development of the small ICBM, which weighs about 37,000 lb, was recommended by the U.S. Air Force Scientific Advisory Board

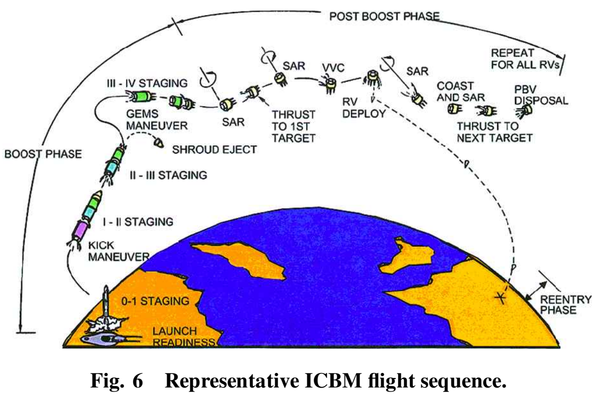


Fig. 6 Representative ICBM flight sequence.

(chaired by the retired Schriever, a founding father of the ICBM program) as one of the nation's highest priorities at the time. Small ICBM, popularly known as Midgetman, took the technology demonstrated on PK one step further. Because it was to be deployed in a mobile basing mode, economic and performance considerations drove the need for innovative solutions to produce cost-effective, lightweight components and stages. For instance, whereas PK demonstrated the viability of the lightweight Kevlar–epoxy motor case small ICBM demonstrated the viability of graphite–epoxy for the entire booster portion of the missile. The benefits of graphite–epoxy over Kevlar–epoxy are twofold. First, the inherent strength and stiffness of the material allows for thinner, lighter stages, which translate into greater range. Second, the material and resulting motor cases are much less susceptible to delaminations. The improved case material also permitted higher pressure motor designs with smaller nozzles, so that the need for expensive ENECs was avoided.

The small ICBM program was canceled by President Bush on 28 January 1992 during his State of the Union speech because of the end of the Cold War.

Ordnance[7]

Ordnance subsystems are crucial to ICBMs. Ordnance is required for stage ignition, stage separation, TVC system actuation, battery actuation, thrust termination, and RV release. In addition, an ordnance destruct subsystem is mandatory for each flight test. Over a hundred ordnance items were designed and developed for ICBM launch and flight operations. Effective guidelines were established early in the program and were then adhered to by the later ICBM systems. A commonality of design for all three booster stages was established. A safe and arm device (S&A) was designed by Thiokol Corp., an arm/disarm switch by Hercules Aerospace Co., and an interstage separation mechanism was developed by the Boeing company Unidynamics. Safety was established as an ordnance design priority. Motor ignition was considered the most important; therefore, a redundant, rotatable explosive train was designed for the S&A. The stage separation was the second most important, so a rotatable electrical switch design was employed. Existing, proven designs were adopted where possible. For instance, the hot bridgewire (HBW)-based detonators were taken from U.S. Navy aircraft applications. An array of electrolytic and thermal batteries was initiated with squibs originally developed for outer space and military programs.

In the 20 years of evolution from MM I to MM III, the original design ordnance components were maintained with new components added only as required. This approach had to be abandoned for the PK design in the late 1970s. The Strategic Arms Limitation Treaty 1 required that the ground-based ICBM silo size be limited to that before the treaty, that is, MM silo size. Carrying out the objective of delivering up to 10 MK 21 RVs with a range comparable to that of MM III required increasing the missile diameter from the MM III 53 in. to 92 in. Thus, the canisterized missile would just fit into the silo. This projected increase in missile diameter eliminated the possibility of sending a crew into the silo to safe ordnance manually before missile ordnance health. Another major reason to find a new ordnance design for PK is that it was initially envisioned as a mobile missile. Therefore, a more reliable and safer ordnance was desired. At that time, several advanced ordnance system designs were available. The final selected design was an exploding bridgewire initiator (EBWI) and confined detonating-cord-based ordnance initiation system. EBWI is loaded with an insensitive secondary explosive, pentaerythritol tetranitrate, which requires a shock stimulus to initiate detonation. The shock is achieved by discharging a capacitor charged to thousands of volts through the bridgewire. Because of the high voltage and energy required, it is intrinsically safer than an HBW-based squib or detonator. In 1975, EBWI systems had been successfully used in the U.S. Army Pershing I missile and the U.S. Navy Polaris and Poseidon (C-3) missiles. A good performance database was, therefore, available.

The small ICBM was to be a mobile missile. It was designed to launch a single RV and be carried by a low-profile, diesel-powered, nuclear environment hardened, mobile launcher (HML).

Both HBW- and EBWI-based ordnance systems were determined to be unfavorable for this system. Under prolonged, low-level vehicle vibration, gaps and voids can form in the squibs and detonators at the HBW/explosive interface, with resulting failure. Laser-initiated ordnance became an attractive choice because of the high resistance to fatigue breakage of the quartz optic fibers and because, with a builtin test (BIT) for end-to-end checkout of the optical path, continuity can be safely and reliably demonstrated. In HBW and EBWI systems, the actual bridgewire on an assembled missile cannot be tested with electricity. As a result, laser ordnance was selected for the small ICBM. The development was very successful considering that the dynamic environments for the small ICBM were much more severe than those for either MM or PK. In the two flight tests, the ordnance firing system (OFS), including the BIT, performed flawlessly. The success of the OFS generated broad interest in laser ordnance systems around the country. Following the termination of the small ICBM program in 1992, NASA worked with industry and successfully demonstrated an OFS in other missile and launch vehicle applications.

Missile Basing

For the U.S. Air Force ICBM systems to become operational, a basing system was needed. It was envisioned in 1954 that the missiles would be located in widely separated silos. The basing mode needed a tight security system for the silo, a substantial degree of hardness and invulnerability, a means for ensuring and monitoring readiness, and a foolproof command, control, and communication (C^3) system, not readily susceptible to jamming or destruction in a precursor nuclear attack. None of these attributes were available at the time. Initiatives to break new ground and develop new technology were required.

Early Missile Basing Mode

The launch facilities for the first Atlas squadron initially (April 1958) consisted of two soft series D Atlas complexes at Cooke Air Force Base, California. The Atlas D missile was stored in a horizontal position aboveground and erected in a vertical position during launch. Later additions included one semihard Series E coffin-type and two hard Atlas F silo-lift launchers. On 31 October 1959, a Series D Atlas equipped with a nuclear warhead went on strategic alert ready to launch on 15 min notice from Vandenberg Air Force Base, California. For Titan II and MM I, the capability was developed to launch from hardened and widely dispersed underground silos. Compared to their predecessors, Titan II and MM I were more economical to operate and more reliable because of their silo capability and use of earth storable propellants (Titan II) or solid propellants (MM I).

During the early development phase of MM, the U.S. Air Force favored deploying at least a portion of the programmed force (from 50 to 150 ICBMs) on railroad cars. A series of tests was conducted beginning on 20 June 1960. A modified test train, operating out of Hill Air Force Base, in Utah, traveled across the western and central United States. Its purposes were to evaluate the ability of the nation's railroads to support mobile missile trains, to identify problems associated with C^3, and to assess the effects of vibration and acceleration on sensitive missile and launching equipment. In August 1960, the Air Force announced that the test of the MM railroad mobility concept had been completed satisfactorily. However, the Air Force still assigned top priority to the fixed silo-based MM concept, because of its lower expense, better accuracy, and faster reaction time. As deployed, each MM I missile was housed in an unmanned, hardened, and widely dispersed underground silo launch facility (LF). A missile combat crew of two officers was stationed in a hardened, underground launch control center (LCC) to monitor each flight of 10 launch facilities.

Initially, the MM I basing option included air-mobile and ground-mobile concepts. The feasibility of launching a missile from an aircraft was demonstrated on 24 October 1974, when a live MM I was extracted from a C-5A cargo aircraft using drogue parachutes and then fired for 30 s.

Minuteman Basing Mode

MM missiles were eventually deployed in six locations throughout the United States. Each location is called a wing. Each wing consists of three or four 50-missile squadrons. Each squadron is divided into five flights, and each flight has one launch control facility and 10 launch facilities (each with one missile). All launch facilities are separated by at least 3–7 miles. The launch control facilities are separated by at least 11.5 miles to minimize loss should an attack occur. Wing 1 is situated at Malmstrom Air Force Base, Montana; wing 2 was at Ellsworth Air Force Base, South Dakota; wing 3 is at Minot Air Force Base, North Dakota; wing 4 was at Whitman Air Force Base, Missouri; wing 5 is at Warren Air Force Base, Wyoming; and wing 6 was at Grand Forks, North Dakota. Today, only wings 1, 3, and 5 are still operational.

The issue of hardened silos vs mobility surfaced almost immediately when the MX missile was proposed. The U.S. Air Force, with the technical assistance of TRW, Inc., examined nearly 40 basing modes. On 7 September 1979, President Carter made the decision to house the MX missile in a horizontal, multiple protective shelter, land-mobile basing mode to maximize force survivability in an attack. Full-scale engineering development of MX began on 15 September 1979. President Reagan, desiring more rapid deployment of the new missile, canceled the horizontal shelter plan on 2 October 1981.

From 1982 to 1986, an extensive silo hardening study program was conducted to understand the practical limits of hardening for closely spaced basing. Full-scale silos with typical ground support equipment were subjected to simulated nuclear repeated environments, and hardness limits of several kilobars were deemed achievable.

Studies that addressed PK basing issues in the early 1980s identified another basing mode that appeared to be less expensive than mobile protective shelters and did not sacrifice survivability. This mode, called closely spaced basing (CSB), consisted in constructing hard silos for PK missiles that were arranged in a rectangular array with very small separation between each silo and the ones adjacent to it. One or two accurately delivered nuclear weapons with relatively high yield would be required to destroy each of the silos because of the hardness of the silos construction. Although an attack on a single silo would be effective, the small separation distance between the silos meant that a weapon delivered against one silo was likely to be destroyed by the effects of a weapon delivered against an adjacent silo, and the second silo to be attacked would, thus, survive. This effect, in which one attacking weapon destroys another, is known as fratricide and would have severely limited the damage that an attack could do to PK missiles in CSB.

On 22 November 1982, President Reagan announced CSB as the final solution to the MX basing problem. However, Congress rejected the CSB and refused to approve PK funding. President Reagan then appointed a commission on Strategic Forces chaired by Brent Scowcroft. The Scowcroft Commission report, issued on 6 April 1983, encouraged the development of a small, mobile, single-warhead ICBM to meet the long-range threat, but recommended the immediate deployment of 100 PK missiles in existing MM silos. This system became known as the Peacekeeper in Minuteman Silos. President Reagan and Congress concurred with the Scowcroft Commission findings.

However, Congress limited PK deployment to 50 missiles until the administration could produce a more survivable basing plan. President Reagan's solution for basing the remaining 50 missiles, announced 19 December 1986, was PK rail garrison. Under the rail garrison concept, the remaining 50 PK missiles would be placed on trains stationed at various U.S. Air Force installations. To improve survivability, the 25 trains, each carrying two missiles, would deploy offbase and onto the national railroad network during periods of international tension. F. E. Warren Air Force Base would serve as the main operating base for the garrison force. In May 1988, the Secretary of Defense authorized the Air Force to proceed with Peacekeeper rail garrison full-scale development.

After the announced decision to proceed with the development of small ICBM, weighing 37,000 lb and carrying a single RV, President

Reagan also decided on 19 December 1986 to base the small ICBM on HMLs. Two options were considered at the time, that is, HML at Montana facilities and HML in random movement. After extensive studies, central Montana was selected for the deployment and operation of the small ICBM. At 100 existing MM sites, 200 HMLs would be stationed, each pair parked in an aboveground, earth-covered building within the fenced area of the site. Experiments on the HML engineering test units were made at Malmtrom Air Force Base under many situations. The test results revealed that the test units had better than predicted mobility even under the worst winter conditions.

In 1989, the Berlin wall fell, and the Cold War was drawing to an end. After the collapse of the Soviet Union, the United States reviewed its strategic needs. On 27 September 1991, President Bush announced a wide-ranging plan to reduce the United States nuclear arsenal and canceled the PK rail garrison program. On 8 October 1991, the HML portion of the small ICBM program was also canceled.

C^3

C^3 are important design issues for ICBMs. Early ICBM systems (Atlas and Titan) located the crew and the weapon system together, with the positive control link with the crew. MM was the first launch system that deployed missiles in unmanned silos. Therefore MM required an additional positive link and sophisticated physical security system due to the unmanned location of each missile. The MM command and control system was originally developed in 1960–1962. The information control concept was used to control the initiation of a missile launch, that is, nuclear release control via code word comparison. Cryptographic systems provide this secure control link between the missiles and their remote ground and airborne combat crews and ensure that only authorized personnel are allowed to control the launch of each missile. System design and code controls prevent the critical functions of authorizing, launching, prearming, or arming of MM/PK missiles except when directed by competent authority. An overview of the many communication links is shown in Fig. 7.

Once the National Command Authority makes the decision to initiate launch of the ICBM forces, directions for control of a nuclear release are transmitted, in the form of Emergency Action Message and a combination of Nuclear Release Orders via various available communication systems. The U.S. Air Force receives these messages at numbered Air Forces, ICBM wing command posts, and ICBM LCCs. After proper authentication, the message commands the combat crews to transition to high-alert status, retarget missiles, and provide the release authorization to launch missiles. In the event of destruction of the MM/PK's LCCs, one of the airborne LCCs (ALCC) can be ordered to issue nuclear release commands directly to the missile LFs.

Two different C^3 architectures are used in the MM weapon system. The MM A-M C^3 (also used by PK) architecture is based on a hub and spoke configuration as shown in Fig. 8, it is deployed at wings 1, 3, and 5. The Minuteman B system uses a bus architecture augmented with uhf radio communication. The hub of the system is the Missile Alert Facility, which consists of the aboveground support buildings and a hardened belowground LCC (Fig. 9). Each LCC is connected to 10 LFs via the hardened intersite cable system (HICS). The HICS is a direct buried cable system linking the LCCs with the LFs. The A-M system is extensively wired and interconnected, whereas the B system is much less interconnected because it relies on the medium frequency mf radio for survivable communication capability. The mf radio system (427–450 kHz) is used to transmit and receive command and status data. Only one node transmits at a time with all nodes receiving all messages. Each squadron is assigned a frequency so that there is no overlapping into another squadron. In the early 1990s, the mf system was replaced with modern solid-state equipment. Antennas are buried for survivability.

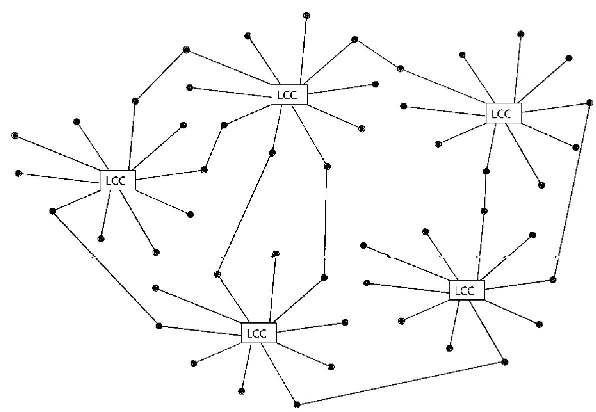


Fig. 8 Squadron interconnectivity.

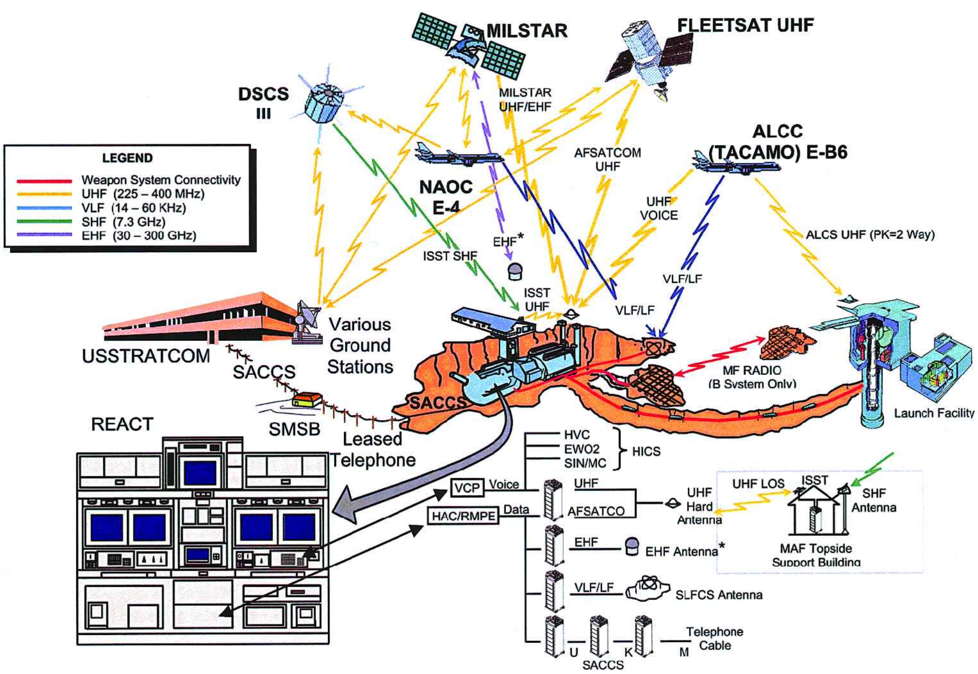


Fig. 7 Communications network.

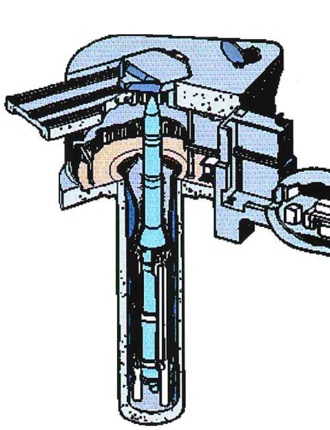


Fig. 9a Typical launch facility and launch silo.

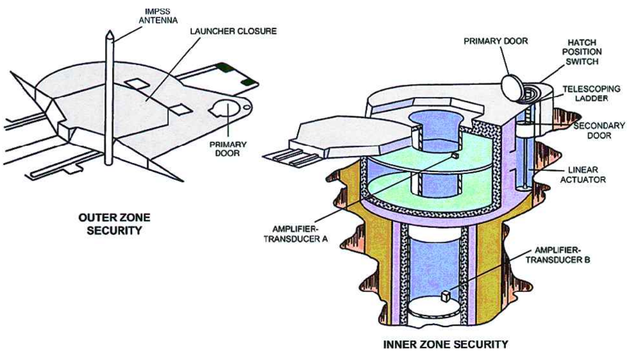


Fig. 9b Typical launch facility security system.

The ALCC became operational in May 1967. It provides the capability to launch surviving missiles from an airborne platform. A timer system in the LF allows communications from the ALCC to be acted on by the missile ground systems. Normally the combat crew periodically sends an airborne holdoff command to the LF, which prevents the timer from running out and, thus, allowing ALCC access. Each MM LF has a uhf radio, and each PK missile has an additional uhf transmitter, allowing uplink to the ALCC of status information.

The MM/PK communication security systems have evolved significantly over the past 40 years. The primary considerations for making modifications to the weapon system communication security have been nuclear surety and operational efficiency. Major upgrades include encryption of the data traffic between the LCC and the LF, positive enable system, remote secure data change, and the rapid execution and combat targeting (REACT), to name a few.

Physical security of the LFs is critical to the operation of the MM/PK weapon system. The encrypted data deliver the inner and outer zone status in the operational status reply. To mitigate potential threats, a sequence number is overlaid onto the data. This is one example of many security precautions that are taken to maintain nuclear surety of the weapon system.

The code processing system (CPS) is a highly complex system that is responsible for providing all secure codes to the various MM/PK subsystems. Originally, the CPS operated through manually operated, hardwired logic; it then evolved to a computer-controlled, punched Mylar® tape, and manual bookkeeping system; and lastly to a computer-controlled, magnetic tape, and automatic bookkeeping system. Because of the obvious implications that could occur if the code system is compromised, elaborate processes and procedures are in place to protect the security of the code material.

Missile GNC[8]

First-Generation GNC

During the early 1950s, the state of the art in GNC technology was the command radio guidance system. The Atlas missile was the first ICBM developed for the U.S. Air Force, and it had the capability of carrying a nuclear payload 6000–9000 miles with a 10-mile target accuracy [circular error probable (CEP)]. The Atlas radio guidance system was distributed between a ground system and an airborne system. The ground system consisted of a position measurement system, velocity measurement system, and data processing and command link computer. The ground system performed position and velocity measurements of the missile via radar and the computed control commands, which were sent to the airborne system via a radio link. In 1957, Burroughs Computer Corp. developed one of the first transistor-based computers for the Atlas ground guidance computer, the AN/GSQ-33. Atlas used the radio guidance system developed by G.E. A total of 18 Atlas ground guidance systems were built for guidance of the Atlas ICBMs. The Atlas radio guidance was used on the Atlas A and C prototype missiles and on the Atlas D operational missile as well.

Because the radio guidance system could be subject to interference, jamming, and the difficult operating conditions of a postattack environment, a new GNC technology was sought. Two groups of engineers were assigned to develop the new GNC systems. MIT Instrumentation Laboratories was awarded a contract to design an all inertial guidance system, including the development of inertial and electric components. AC Spark Plug Co. was to work with MIT and would fabricate and test the complete guidance system. At the same time, the Arma Corp. also received a contract to design, develop, and fabricate a complete airborne all inertial guidance system for a ballistic missile as a back up to the MIT/AC Spark Plug effort. On 26 August 1958, Arma Corp. was the first one that successfully developed an inertial guidance system for Titan I missile. Then the decision was made to transfer the newly developed inertial guidance system to the Atlas program and use it on the Atlas E and F operational missiles. In its place, an updated radio guidance system was developed by Sperry and Western Electric with a Remington Rand Univac digital computer. Later, a new pure inertial guidance system was also successfully developed by AC Sparkplug Co., based on a Charles Stark Draper Laboratory, Inc., design, for use on the Titan II ICBM.

MM I GNC

The U.S. Air Force initiated design studies on developing a new GNC system in parallel with Project Q or the MM I solid rocket program. This approach was necessary because the MM I revolutionary operational requirements, unattended launch sites (widely separated, blast hardened) and continuously operating/ready missiles, required a better GNC system than that on Atlas and Titan missiles. These requirements led to the following design concepts: buried silos, solid-propellant motors, and high reliability, solid-state, inertial GNC.

The technical knowledge gathered during the development of Atlas and Titan was applied to the MM I GNC design. The major elements of the MM I missile-borne GNC hardware consisted of 1) NS10 missile guidance set (MGS), 2) downstage flight control nozzle control units, 3) angular accelerometer assembly, and 4) reliable and long-life batteries. Inertial guidance was selected due to its independence from external systems and influences, such as radio guidance schemes (which were well developed at the time). The reliability objectives corresponded to the need to operate for months without failure or adjustment vs the then-typical capability of operating for days or weeks before adjustment or failure. Inertial guidance offered not only anti-jamming advantages, but also greater system reliability, faster reaction time, and reduced operating and maintenance costs.

The level of reliability demanded by MM I had not even been imagined (let alone achieved) before this time. The development program made high reliability its top priority with extensive design, process development, discipline development, and test activities specifically aimed at this objective. The electronics design concepts and disciplines included the following: integrated circuit solid-state technology (transistors, diodes) without vacuum tubes, relays, etc.; standardization of electronic part type (minimize developments through increase use of selected devices); no adjustable components (potentiometers, etc.); analysis of circuits to demonstrate margins beyond worst-case parts parameters (worst-case circuit analysis); use of parts derating and thermal management/cooling to minimize stresses on the electronic parts; and rotating magnetic memory with numerous special purpose loops to offload most high-speed tasks from the general purpose section of the digital computer.

The electronic parts (transistors, diodes, resistors, capacitors, inductors/transformers) development included physics of failure analyses and tests, accelerated life testing, destructive physical analyses and postmortem analysis, process development and yield improvement studies, and development of functional, burn-in, and environmental tests for the parts acceptance.

The intent of these designs and component initiatives was to achieve something like two orders of magnitude improvement (over typical current hardware) in the failure rate of electronics. To achieve compact packaging and a relatively low operating temperature during silo operation, the MGS used a water glycol solution for cooling the electronics and stabilized platform.

The TVC system for each stage consisted of four hydraulic actuators driving movable nozzles. The hydraulic power supplies (one at each stage) were driven by electric motors which were powered by ordnance-activated silver/zinc batteries (one in stage 1, one in stage 2, and one in the NS10 MGS). The actuator control loops were closed via downstage electronics located on each stage, whereas the flight control (outer) loops were closed through upstage MGS electronics. Pitch and yaw angular rate data were provided by the inertial platform. The downstage flight control hardware was normally not energized during silo operations, but was powered up and tested periodically as a part of a missile test. This semidormant operation was aimed at long life and high (semidormant) reliability in the silo.

The first MM I flight test occurred only two-and-one-half years after the start of the formal development program; that is, FTM-401 flew on 1 February 1961, following R&D startup in August of 1958. Multiple models and configurations of the NS10 were developed and flight tested before IOC in October 1962. This provided reasonable opportunities for corrective actions before commitment to production of the NS10 MGSs.

Because some nuclear effects were not well understood at the time, the MM I GNC lacked many design and operating features necessary to achieve near-normal performance if exposed to a nuclear weapon attack. This issue was addressed in MM II and MM III.

Overall, the MM I GNC program achieved a good reliability record both in flight tests and during silo operations, and it even exceeded its accuracy objectives. The alignment, calibration, and guidance schemes were rather unsophisticated (largely due to computer technology at that time), but quite adequate for the accuracy objectives of the weapon system. There was no hardening against nuclear radiation and electromagnetic pulse environments in the silo or in flight and no provisions to accommodate prelaunch seismic environments. Also, the preferred orientation inertial platform and its alignment scheme limited the MM I capability to change targets.

MM II GNC

As MM I production was approaching completion (with 800 silos/missiles to be deployed), a plan was developed to improve system performance. The improved G&C system was referred to as the NS17. Specifically, the enhanced performance objectives were in the following areas: 1) addition of a gyrocompass gyro/assembly, which afforded the flexibility to remotely command and change platform azimuth orientations, that is, change targets, while maintaining accurate reference to the optical reference; 2) much improved gyros and accelerometers, which significantly improved measurement accuracy; 3) replacement of the D17 computer with the D37 computer, which increased processing throughput and programmable memory; 4) liquid (freon) injection for pitch/yaw axis control (pintle actuators) and hot gas for roll control on the stage 2 motor; 5) analysis of electronic circuits and control loops to assure operability after exposure of gamma, neutron, and x-ray effects; and 6) addition of special shielding to protect electronics from the damaging effects of x rays.

Figure 10 shows where the components of the MM II GNC were located on the missile. There were 775 NS17 MGSs produced

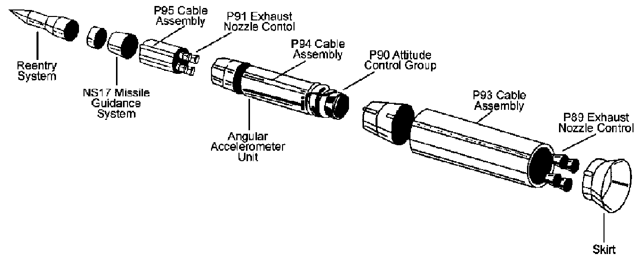


Fig. 10 MM II missile configuration and G&C components.

between 1964 and 1968, and up to 500 MM II missiles were deployed in operational silos. Before the decommissioning of the MM II missile force in the early 1990s, 130 operational tests were conducted from Vandenberg Air Force Base. GNC accuracy was better than its requirement/goal and improved with time (primarily via software changes) during the operational deployment phase of the program, that is, from 1965 to 1991. Nuclear hardness and survivability characteristics were good, considering the short development cycle and the existing knowledge of nuclear effects. Retargeting capabilities were much improved over those provided by MM I. However, accuracy considerations and the operational guidance program software prevented an immediate change to a target greater than 10 deg from the platform heading.

MM III GNC

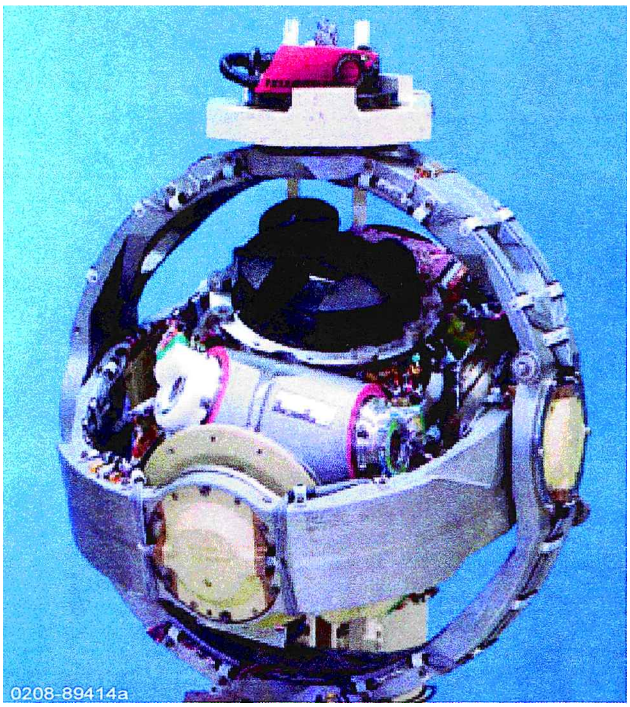
On MM III, the MGS was updated to the NS20 by increasing the computer memory size and throughput to handle the MIRV mission, refining the nuclear hardness and survivability design features, and improving precision azimuth alignment by employing gyrocompassing as a replacement for the optical alignment transfer scheme (Fig. 11a). The MM III GNC program was highly successful with considerable attention given to silo reliability initiatives, the post-boost mission functions (largely software), self-alignment technique mechanization, that is, self-determination of platform alignment, and hardness improvement. Although the early operational guidance system accuracy and related characteristics were acceptable, numerous changes and improvements were implemented to improve weapon system accuracy, flexibility, and supportability. The significant programs were the Command Data Buffer Program, Hybrid Explicit Flight Program, Guidance Improvement Program, Guidance Upgrade Program, Gyro S Coefficient, and Minuteman Extended Survivability Program.

Through these challenging upgrade programs, the GNC CEP was essentially cut in half. The NS20 also met the hardness requirement in the various radiation environments. In the early 1990s, the U.S. Air Force Strategic Force Planning changed to require that MM III deployment be extended through 2020. At that time, concerns regarding supportability and possible future degradation in flight reliability of the NS20 MGS led the Air Force to initiate the Guidance Replacement Program (GRP). Phase 1 of this program, to replace all electronics in the NS20 MGS was completed in 2001. Flight tests using the new GNC components began that same year. The system upgraded via the GRP program is designated the NS50 MGS.

PK GNC

The most significant improvement in the PK guidance system was the advanced inertial reference sphere (AIRS), which is a floated inertial measurement ball-based on technology first conceived by MIT's Instrumentation Laboratory in the 1950s. AIRS (Fig. 11b) was selected in the early 1970s as the inertial measurement unit (IMU) technology having the greatest potential of meeting the more stringent PK accuracy requirements under the demanding launch, flight, and nuclear threat environments. The heart of AIRS accuracy is the third-generation inertial instrument, the third-generation gyroscopes and the specific force integrating receiver (SFIR) accelerometers. Each AIRS IMU contains three orthogonally mounted third-generation gyros (TGGs) and three orthogonally mounted SFIRs. The three orthogonally mounted SFIR accelerometers measure

a) PK AIRs



b) MM III NS20 gyro-stabilized gimbal set

Fig. 11 G&C hardware used on MM III and Peacekeeper missiles.

velocity with respect to inertial space, and the three orthogonal gyros provide angular reference with respect to inertial space for the accelerometer. Thermal and magnetic isolation is essential to inertial instrument accuracy. Maximum structural stiffness is equally important to AIRS accuracy. The flotation replaces metal gimbals, which can bend under high gravitational acceleration loads, thus distorting the attitude frame of reference. The flotation fluid is a very efficient gimbal, in terms of weight and volume.

Other AIRS attributes important to PK are 1) platform alignment without the use of external aids or updates, 2) continuous calibration and alignment required to meet accuracy under high-alert availability and short reaction times, 3) no preferred launch orientation to avoid accuracy degradation for trajectory and target changes, and 4) whole word velocity readout, whole word attitude readout, and hardened time reference to recover from circumvention due to nuclear events.

The results, as demonstrated in flight tests, is a guidance system that improved accuracy by more than a factor of two over previous ICBMs.

Small ICBM GNC

Whereas its propulsion, basing modes, and missile construction offered technical challenges, the GNC proved to be the most difficult aspect of the small ICBM program because of the small CEP requirement against the former Soviet Union's hardened silos. State-of-the art technology was used in developing a guidance system for the missile. A competitive development program resulted in two candidate advanced IMUs, one a stellar updated inertial system and the other a strap-down ring laser gyro system. The candidates were tested via rocket sled tests and a piggyback flight on a MM III vehicle. Because of time constraints to field a mobile system, the PK AIRS IMU was selected as the baseline system with an advanced system to be phased in at a later point. Because mobility was a key objective of the small ICBM vehicle, an extensive land navigation test program was conducted to evaluate navigation performance for extended durations of time, that is, mobile relocation of the missile launcher. Additional studies were undertaken to assess semidormant performance, in which the guidance system is kept in a low powered (semidormant) mode and only powered up when needed, for improved reliability.

Autopilot and Stability Analysis

Autopilot and stability analyses were basic tasks performed by TRW, Inc., in its system engineering role in the early days of ICBM development because these analyses required data from all subsystems. To allow the analysis, the reference trajectory was first established and published, and then the missile bending modes were computed. The dynamic model used in stability analysis was established and continually updated. Various computer programs at different level of sophistication for stability analysis were developed. The effects of fuel sloshing on the stability of liquid-propellant missiles warranted special attention. Around 1956, there was controversy on how to model this effect. The first correct model for cylindrical tanks was developed by George Gleghorn of TRW, and later derived independently by Convair engineers. As a result of these analyses, stability problems were deemed sufficiently serious in the Atlas missile that baffles were developed for the propellant tanks.

Maximum thrust vector deflection is an important refinement for ballistic missiles. Because most missiles are aerodynamically unstable, if thrust deflection hits the stops during flight, a catastrophic failure will result. If excessive deflection is specified, the design is penalized. This was particularly true for MM where deflectable solid rocket motor nozzles were a significant development item risk. The model used for wind and wind shear during missile flight led to the determination of the maximum expected thrust deflection. System engineering analysis by TRW, Inc., resulted in a change from an excessively severe wind profile model to one based on measured wind statistics. This, in turn, led to a major reduction in thrust deflection requirements, permitting the removal of flared skirts at the end of MM stage 1. These had initially been placed there to reduce the missile's aerodynamic instability and, thus, reduce the required thrust vector deflection.

Attitude rates were initially measured by angular accelerometers during the first and second stage operation, but these were later eliminated as unnecessary. All compensation to stabilize the control system is accomplished digitally within the guidance system's general purpose computer, which outputs signals to the nozzles. All switching of control system gains and compensation is accomplished by changing algorithms in the computer software. This G&C integration seems straightforward today, but at the time (1960s) caused concerns because the required frequency of the control updates could overload the guidance computer and could cause loss of system stability. These concerns were addressed, and the integration effort was successfully accomplished. System checkout was also greatly simplified. The concentration of functions in the general purpose computer had the added benefit of simplifying the ground support equipment located in each silo.

Guidance Software

Autonetics was the associate contractor for the MM guidance system, which included the flight and prelaunch software. This software was programmed in assembly language into a D17 disk computer. TRW, Inc., provided the guidance equations that Autonetics programmed and was also responsible for the verification of the flight software. When MM I became operational, the flight computer was the only digital computer in the system. The targeting was done at Strategic Air Command (SAC) Headquarters by the Operational Targeting Program developed by TRW to execute on an IBM mainframe computer.

Sylvania Electronics Systems was selected to develop the first ground-based command and control system using a programmable computer. They developed the software, the message processing and control unit, for wing 6. To support the deployment of the wing 6 system, TRW, Inc., developed the execution plan program (EPP) for a mainframe computer at SAC and performed an independent checkout of the command and control software. The EPP assisted in assigning targets and launch times for the missiles.

The MM II missile was deployed with a D37C disk computer. Autonetics also programmed the code inserter verifier that was used at wing headquarters to generate the codes to go into the airborne computer. It became necessary now to verify not only that the software was correct, but that there was no code that would lead toward an unauthorized or accidental launch. TRW, Inc., continued its role of independent verification that first was called verification and validation and then became nuclear safety cross check analysis (NSCCA). Logicon RDA was selected to perform the NSCCA of the targeting and execution plan programs developed by TRW.

When MM III was developed, Autonetics generated the guidance equations that were programmed into the D37, which contained a hybrid explicit guidance system for the first time. A new class of program was required by the Joint Strategic Targeting Planning Staff to select targets for the multiple warhead system. The Missile Application Programs were developed for these functions.

The next major update to the operational software was called command data buffer. This was a major change because the targeting and execution plan programs were to be placed at the LCC in the field and in the ALCC. TRW, Inc., was selected to develop the targeting and execution plan programs written in FORTRAN, also the command and control programs in the weapon system computer. Logicon RDA was selected to perform NSCCA on the TRW-written programs.

MM III's latest software update was made under the Guidance Replacement Program. Autonetics (later acquired by The Boeing Co.) developed the necessary software for the new flight computer.

For PK, Autonetics was again the contractor for development of the Operational Flight Program. The flight computer (Missile Electronics Computer Assembly) was coded in assembly language. An additional 96 kB of memory was allocated but was resident in the launch control system controller (LCSC) located in the launch facility. The storage space also provided the ability to download IMU performance data to the LCSC, which was then ultimately transmitted back to the wing headquarter for further analysis.

The REACT program was initiated to update the LCCs with modern computers and human interfaces. Loral was chosen to develop the command and control software, and Logicon RDA was selected to perform NSCCA. Logicon RDA became the targeting and execution plan program contractor and TRW, Inc., performed NSCCA.

Reentry Systems

One of the formidable technical problems in the design of an ICBM in the early 1950s was the reentry of the payload into the atmosphere. Here the technology would have to start from scratch. Knowledge of how heat is generated by very high-velocity flow through air was essentially nonexistent in 1954. Even the basic aerothermal chemistry of such phenomena was not known at that time. There was no ground-test facility in 1950s that could simulate the reentry thermal environments, and computer capacity was still in its infancy.

RV nose cones are exposed to exceptionally severe levels of heating, pressure, and temperature because of high and sustained velocities during reentry. Air temperatures in the flowfields surrounding the vehicles exceed 12,000°F. The heat created during reentry would be expected to ablate, boil, or burn off the solid material of the nose cone, so that its surface would face a complex and unfamiliar mixture of air and emitted, chemically reacting flow at enormous speeds, pressures, and temperatures. To survive these conditions, the nose cone would have to be made of an unusual material. (Researchers in 1954 gave this material the name of unobtainium.) Complex nuclear hardness and weather encounter requirements further aggravated the clear air environment. From a system development perspective, these demanding environments translated into unique design challenges for tailored thermal protection materials, electronic components, and specialized test facilities.

Recognizing the difficult task of designing RVs to penetrate the former Soviet Union's ABM shield, the Secretary of Defense in 1963 established the Advanced Ballistic Reentry System (ABRES). It was a triservice program. Its objectives were to develop and demonstrate technology and devices that could penetrate Soviet ABM defenses, as well as to conduct research and development to support a U.S. ABM system development. The effort was focused on RV designs and penetration aids. During the next few years, the program expanded to cover all important aspects of reentry technologies, with activities that extended from the early study phase, through ground development, and on to test under full ICBM conditions.

In 1983, the name of the ABRES program was changed to Advanced Strategic Missile System (ASMS) and expanded in scope to include all ICBM technologies including basing, propulsion, and guidance. Its major responsibility was still the development of RV, penetration aids, and strategic missile technology, including development of basing concepts for missile/RV survivability and endurance. One of the important tasks of ASMS was to identify current and future threats and to develop plans to mitigate them. An ASMS long-term study sought to design a versatile small missile that could function in a variety of basing modes; it became the basis of the small ICBM program. Also, the ASMS/ABRES program designed and tested decoy and chaff concepts and several maneuvering RVs (MaRVs). Many prototypes of operationally important RVs, decoys, chaff, and penetration aids were designed and flight tested by ASMS/ABRES contractors. Figure 12 shows some of the reentry flight tests conducted by ABRES/ASMS and the ICBM team.

The following sections summarize the histories and technical accomplishments of ballistic RVs, penetration aids, MaRVs and reentry guidance.

First Generation of RVs

In 1954, little was known on how to estimate heat transfer in high-speed flow, test data were scarce, and few reliable thermal protection system (TPS) materials were available. Consequently, the first Atlas RV used a copper heatshield, that is, MK2 (Fig. 3), which was essentially a giant heat sink. To reduce the heat transfer rate to a manageable level, RVs were designed with large nose radii to provide high aerodynamic drag that would slow the RV down before high heating and dynamic pressures would occur. This is referred to as a low beta vehicle, that is, low ballistic coefficient, $\beta = W/(C_D A)$, where β is the ballistic coefficient, W is RV weight, C_D is RV aerodynamic drag coefficient, and A is RV base area.

Second Generation of RVs

The next-generation TPS employed special ablative heatshields, which have large sublimation or melting energy. Atlas F and most of the later RVs were protected by ablative materials (such as Teflon® or silica phenolic). This design reduced the RV weight by at least one-third. The first successful launch of an ablative RV over ICBM ranges (~4500 n miles) took place in early 1958 in the program phase known as Able-0. This RV was built by Avco Corp. Later in 1958, the second U.S. Air Force Thor/Able reentry (nose cone) test vehicle, testing a GE ablation-type nose cone, was launched from Cape Canaveral and completed a 6000-n mile flight down the Atlantic Missile Range. Although the nose cones were not recovered,

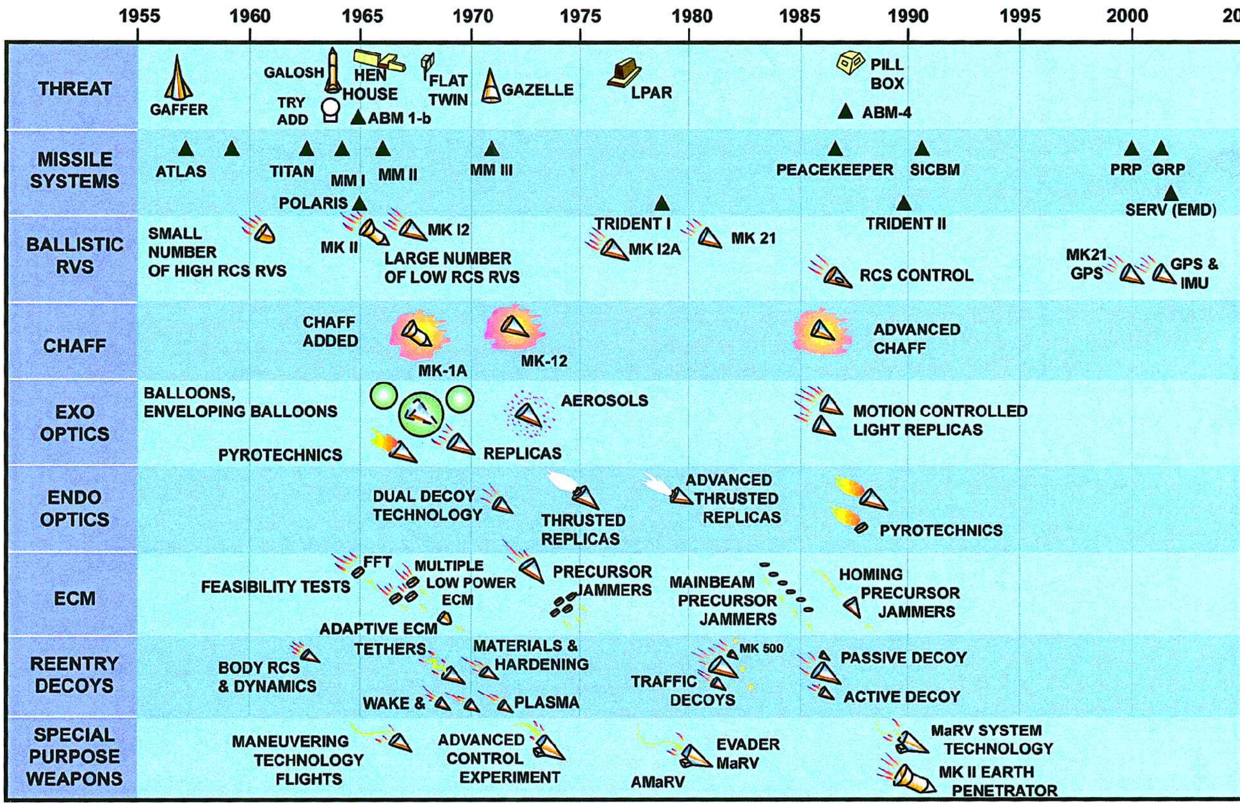


Fig. 12 U.S. Air Force ICBM flight-test history.

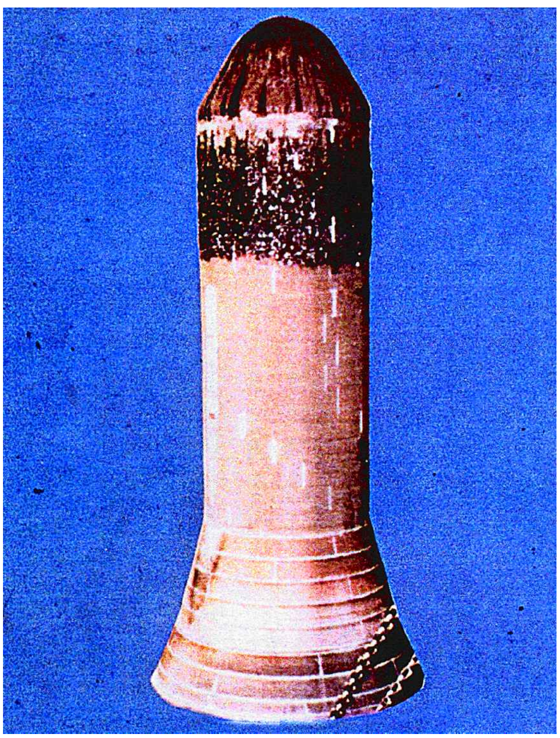


Fig. 13 First recovered U.S. Air Force RV with ablative heatshield flown at ICBM range.

these two flights proved that the ablated TPS can survive a full range ICBM flight, including reentry. On 9 April 1959, the first nose cone from a Thor/Able reentry test vehicle was recovered after its ICBM flight (Fig. 13). The photograph shows that the ablated nosetip and the frustum still maintained their structural integrity.

Teflon was initially used in many flight vehicles, and satisfactory results were obtained for some low beta flights. Later composite materials such as asbestos phenolic and quartz phenolic were developed for thermal protection. MM I carried the MK5 RV, and MM II carried the MK11 A/B/C/D RV. Both RVs used silica phenolic heatshields. This type of TPS material, classified as a melting and pyrolysis ablator, is adequate for low-to-medium beta vehicles.

Third Generation of RVs

When the design emphasis shifted from reentry survival to defense penetration, the first order of business was to reduce the radar observables of the RVs to minimize the reaction time of the defense. Most radar reflection comes from the blunt nose region and, during reentry, from the wake. This led to the design of a slender conical RV with a nose radius of inches rather than feet. This sharp configuration has very low aerodynamic drag and, due to its rapid flight through the atmosphere, can reach its target with high impact accuracy. Furthermore, it has lower radar observables and reduced impact dispersion. However, the slender cone imposes severe technology problems on the RV designer. The nosetip and heatshield are subject to very high heating rates and pressures, which demand the development of very sophisticated TPS materials. Inside the vehicle, volume constraints become critical to the design of warhead and its arming and fuzing system. Figure 14 shows the evolution of nosetip materials and nose structural configurations. Essentially, the design evolved to take advantage of advancements in the U.S. heatshield material technology.

The MK12 was initially deployed on the MM III booster. It was modified and upgraded to the MK12A in 1982. The development of MK12/MK12A represented a major breakthrough in TPS design. The MK12 composite nose was replaced with a three-dimensional carbon–carbon (C/C) retrofit plug nose, which improved the accuracy and weather capability of the MM III fleet.

The final design on MK12/MK12A used a three-dimensional C/C nosetip, for example, fine-weave pierced fiber (FWPF), 223/CC, and a tape-wrapped carbon phenolic (TWCP) frustum, which rendered superior reentry thermal performance. The development of nose cone structural construction, for example, from shell to plug design (Fig. 14) and the material evolution, for example, from graphite to three-dimensional weaved C/C, represents an important milestone in RV design. The material selection and the construction were

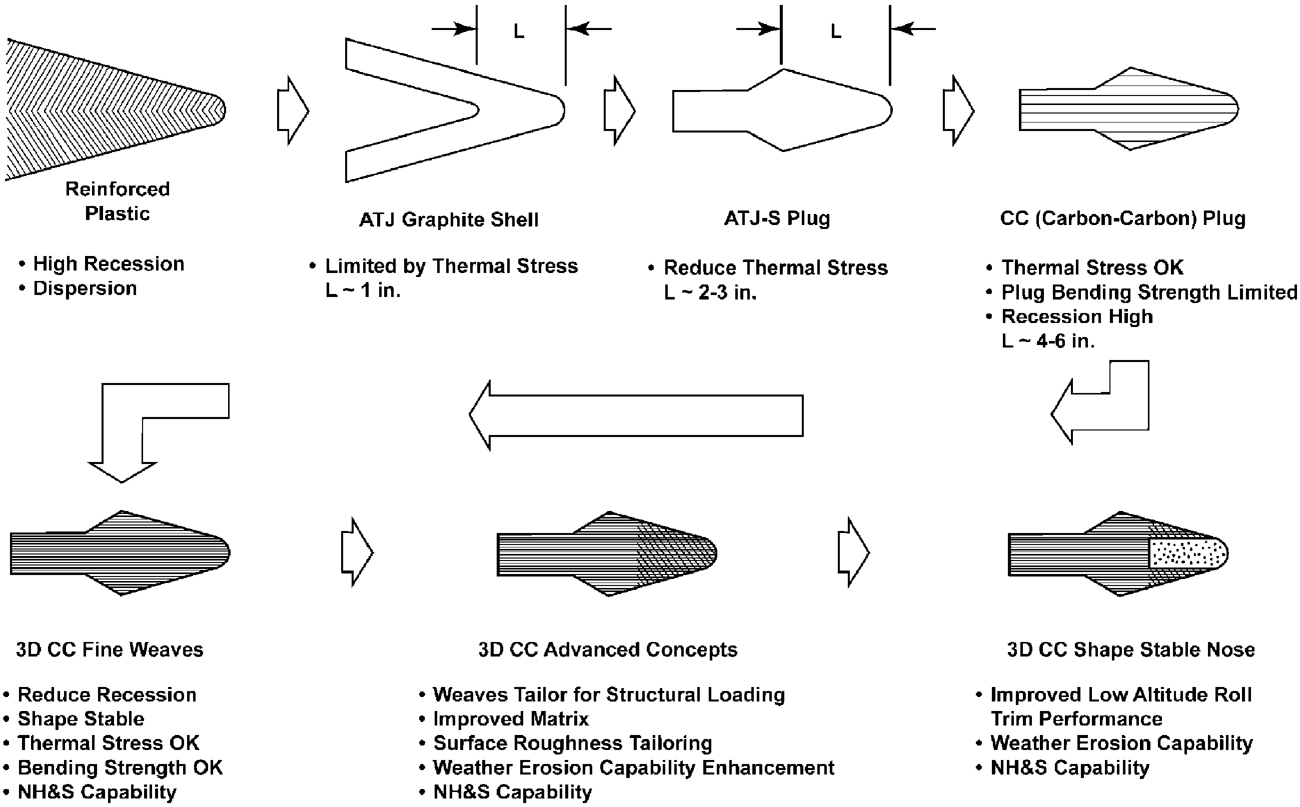


Fig. 14 Evolution of nosetip structural configurations and materials.

sophisticated to a degree that they not only fulfilled thermal protection requirements, but also enhanced RV overall performance. For instance, the manner in which a TWCP heatshield is manufactured can be used to control and tailor the RV's roll dynamics. Therefore, no active roll control mechanism is necessary when TWCP is used, thus reducing RV weight and increasing reliability.

Besides the passive nosetip approach such as three-dimensional C/C design, active cooling technology was also explored over the years. The two concepts investigated extensively were gas jet nosetip and transpiration cooling nosetip. Several flight tests were conducted to validate the design maturity.

Thermal protection materials are required not only in the nose cone and frustum portions of an RV, but also such parts as the fuze window, RV base, and bonding glues. The material covering the antenna window has to be transparent to electromagnetic wave propagation at all temperatures and have ablation characteristics compatible with the surrounding heatshield. Additionally, the window material must have adequate nuclear hardness performance. Many candidate window materials were considered, for example, quartz, fused silica, Notroxyceram, boron nitride, AS3DX, AD3DQ, etc., and carefully screened. Extensive ground tests in arc facilities, flight tests, and even underground nuclear tests were made to sort out the best candidates.

On PK, the most advanced RV, the MK21, was selected as the baseline RV. Although it is heavier than the MK12A and more costly to manufacture, it offers some unique advantages: safer payload (insensitive high explosive), better natural weather encounter survival capability during reentry, increased nuclear hardness capability, smaller reentry impact dispersion, and significant fuzing enhancement in the areas of accuracy and reliability.

The MK21 initially employed a TWCP frustum heatshield and a FWPF or 223/CC nosetip. The nosetip was further upgraded to a shape stable design in 1995 to enhance its roll trim performance (Fig. 14). MK21 on PK is the most accurate ICBM system ever built. Figure 15 shows a long exposure photograph of 10 MK21 vehicles impacting at Reagan Test Site. Each trajectory is almost a straight line. The RVs passed through the clouds and impacted accurately

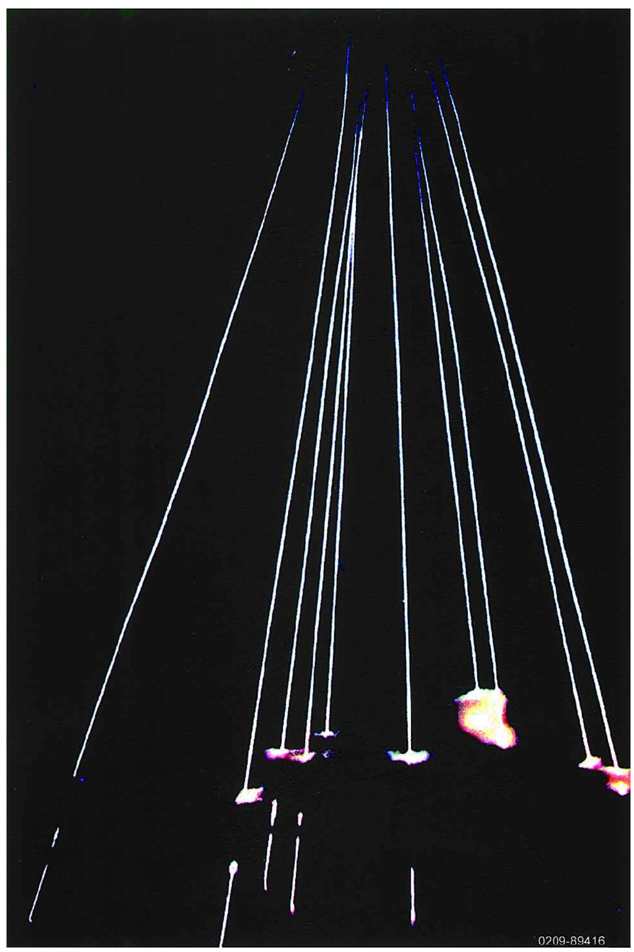


Fig. 15 Long-exposure photograph of PK reentry at Reagan Test Site.

near the Kwajalein Atoll. MK21's all weather capability and high ballistic coefficient trajectory are vividly shown in the photograph.

Fuzing

Fuzing is a crucial part of RV design. Various fuzing devices have been designed, manufactured, and flight tested. The fuze initiation can be triggered by g-switch, delta-velocity detector, path-length integrator, altimeter, or other sophisticated devices. In some instances, the shock layer plasma effects have to be taken into account to get satisfactory performance. Additionally, nuclear hardness requirements dictate that hardened electronics and microprocessors be used. The MK21 design is 1980 technology and has the following fuze options: path-length fuze, path-length interactive fuze , contact fuze, altitude fuze, and proximity fuze.

Penetration Aid Technology

Penetration aid (PenAid) development programs were initiated in parallel with the ICBM development program to provide credible radar and optical targets capable of seriously compromising an enemy's defense system. Examples include the Atlas MK4 PenAids, Titan II MK6 PenAids, MK11C MK1A PenAids, and MM III PenAids. The challenge that has existed throughout PenAid development is to arrive at a system that is viable but not too large, heavy, or costly. The system may include decoys, chaffs, jammers, aerosols, electronic countermeasures (ECMs), or a defense suppression vehicle (DSV). Over the years, particularly in the ABRES/ASMS and MM III programs, sophisticated PenAids, both radar and optical, were designed and flight tested and some were deployed successfully, for example, MK 1A and MK12 chaff). The basic concepts and design approaches to enhance RV penetration involved simulation, masking, antisimulation, and suppression. All of these concepts were investigated and assessed; hardware was designed, built, and flight tested to provide an on-the-shelf-demonstrated capability.

From the mid-1960s to the mid-1970s, the focus was on designing and flight testing enveloping balloons, that is an RV encircled by a balloon (Figs. 12 and 16) and aerosols as exoatmospheric flight optics and radar PenAids in response to a combined radar/optical threat. A series of Reentry Vehicle Technology and Observable and Safeguard System Target Test Program flights was conducted to test out the effectiveness of the designs. In the endoatmosphere flight regime, more sophisticated designs, such as a thrusted replica decoy (TREP), were designed and successfully flight demonstrated by ABRES. In Avco Corp.'s TREP design, the decoy was erected after separating from the PBV. After pressurization, its outer contour was almost identical to a RV. It also had an onboard lightweight thruster to duplicate the RVs endodynamics and beta history, that is, deceleration history. The feasibility of this concept was successfully demonstrated in a TREP flight in 1975.

Later during 1984–1988, the ASMS evader replica PenAid program further advanced the state of the art in simulation to include matching the RV's 1) angular motion and angle-of-attack convergence history through using attitude rate reducer on the decoy and 2) optical signature by using multilayer insulation in its outer layer heatshield construction.

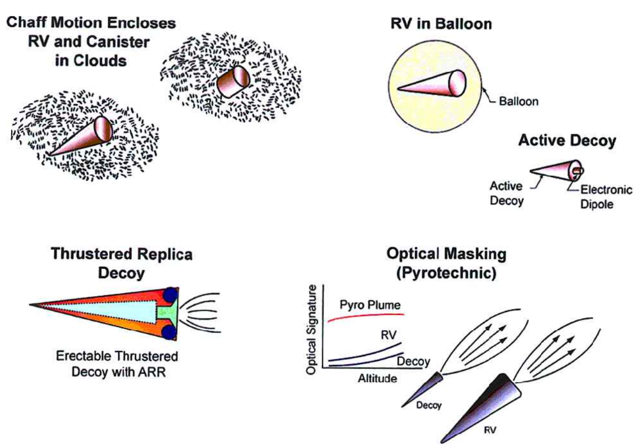


Fig. 16 Candidate PenAids investigated by ABRES/ASMS program.

In the MM III program, MK12 decoys and chaffs were designed and their performance was verified in many flights. The chaff package was eventually installed on the regular MM III PBV as part of the payload. More sophisticated decoy and chaff designs were undertaken in 1980–1987 under the ASMS program (Figs. 12 and 16). In early 1980, a MK500 decoy was developed to supplement the U.S. Navy's MK500 MRVs. Lightweight traffic decoys were studied to assess their effectiveness in the exo- and endoenvironment. The ASMS advanced chaff program developed sophisticated dispensing devices and deployment schemes. The performance and effectiveness of these chaff system designs were modeled for and validated by many flight tests. From 1984 to 1989, using sounding rockets and ICBMs, well over a dozen chaff payloads were successfully tested.

Significant works were done on improving decoy and countermeasure designs in the early 1980s. Passive and active decoy programs were part of these efforts. The simulation of RV bare body (including the plasma sheathing effects) and wake observables with small and lightweight decoys was included in the design consideration. An elaborate ablative heatshield was developed to enhance decoy wake radar cross section (RCS) return during reentry to match that of the RV. Many ballistic range tests were conducted to guide the design efforts. In the active decoy program, electronic circuits were placed on the small decoy known as the electronic replica decoy (ERD). The ERD actively simulated the RV RCS when illuminated by a high-frequency threat radar, making the RV and decoy indistinguishable. The efforts cumulated in three successful flight tests in the mid-1980s on the passive and active decoy designs.

The concept of masking to defeat optical discrimination was explored in the pyrotechnic program. The basic idea was to install a small rocket on a lightweight decoy. When the rocket was fired during reentry, it created a large plume, whose size and optical signature intensity were at least 10 times larger than the RV/wake size and 10 times brighter than the RV's optical signature (Fig. 16). Consequently, the threat infrared sensors could not differentiate between an RV and a decoy. This concept was demonstrated in a flight conducted in 1987.

In the ECM arena, the ABRES/ASMS programs made a sustained effort from late 1960 to late 1980 to design and flight test many jammers (Fig. 12), from a precursor jammer, to a main beam jammer, to a homing jammer. Concept feasibilities for all these were verified in flight test programs. In mid-1980, a DSV program investigated the feasibility of designing a lightweight MaRV to home on and destroy a defense radar. Extensive numerical simulations, hardware designs, and ground tests were made to assess its effectiveness and feasibility. However, no flight test was conducted on this concept.

MaRV Technology

The value of an RV that could maneuver to evade ABM interceptors was realized early in the ICBM program as were the technical difficulties of ensuring that this approach would be effective.

Because the interceptors also maneuver, a MaRV must win the interception duel by generating and sustaining the higher rates of turn. These are usually measured in terms of the normal or lateral acceleration during the turns. As a reference, a piloted interceptor aircraft might pull 6–8 g during combat with other aircraft. A MaRV, on the other hand, must pull approximately 10–20 times as much gravitational-acceleration to evade a typical ABM interceptor such as the U.S. SPRINT. The resulting loads are felt on all of the structure, controls, and internal components of the MaRV and demand new design approaches, particularly for guidance and electronic components.

Simultaneously, there is a difficult nuclear environment to consider because, even if the interceptor were out dueled and forced to miss the MaRV, it could detonate at the point of closest approach to create high gamma ray and neutron fluxes. These could deteriorate the heatshield or the warhead, and the effects on the G&C system could be disastrous. At the same time, blast effects from a detonation can perturb the aerodynamic flow to add still higher gravitational acceleration loadings and potential destabilizing effects.

Despite its complexity, MaRV development appeared to be the best way to strain the design of the former Soviet Union's ABM systems to a high degree of technical difficulty and, therefore, low dependability, and an active program was started in 1964. Besides performing evasive maneuvers, a MaRV has other advantages. For instance, it can also improve RV impact accuracy and enlarge its footprint (crossrange as well as downrange). Additionally, MaRV has the capability to attack deeply buried targets, for which tailored impact conditions are required.

One of the first issues to be resolved in MaRV design was whether to maneuver by aerodynamic control surfaces or by reaction jets. The maneuvering ballistic RV (MBRV) program studied how multiple control surfaces, for example, cruciform trailing flaps, at the base of the vehicle could control attitude during high gravitational acceleration evasions. Four MBRVs were developed and launched by Atlas boosters from Vandenberg Air Force Base in the late 1960s. These were large vehicles (even heavier than the Atlas operational vehicle) and permitted the guidance systems to be very sophisticated to control the vehicles to preset trajectories and impact points south of Hawaii. Despite some difficulties in the interfaces between the MBRV and the Atlas, the flight series demonstrated the feasibility of aerodynamic controls and pointed the way to simplifications that would be needed for operational designs.

Another significant accomplishment of the MBRV program was a demonstration of two-way electromagnetic transmission for a radar altimeter through the plasma in the shock and boundary layers. This gave hope that radar-type devices might be used by a MaRV to fix its position during flight.

The next important milestone in MaRV design was the boost–glide RV (BGRV) flights. The MaRVs with high lift-to-drag ratio configurations ($L/D \sim 3.5$) had long slender biconic bodies ($\sim$275 in. in length) and used variable flare trim control devices. The MaRV trajectory consisted of a level glide at high altitude to demonstrate the capability of obtaining large footprints. The long flight times demanded different types of TPS, such as a radiation-equilibrium-type TPS system on the frustum and the transpiration cooling technology in the nosetip. Four flight tests, using Atlas boosters launched from Vandenberg Air Force Base, were conducted in 1966–1968 to demonstrate the boost–glide concept and the new TPS technologies.

With funding from the Advanced Research Projects Agency, ABRES, with McDonnell Douglas as the vehicle contractor, conducted the Maneuvering Reentry Controls and Ablation Study (MARCAS) to determine how well jet reaction control (JRC) could function during reentry. Flight tests were conducted on the White Sands Missile Range. Valuable data were obtained that could be used in tradeoff studies with the MBRV program.

A third control system was also under consideration. This consisted of canting the nosetip of the vehicle to provide the normal force and then controlling the angle of attack either by internal mass movement, for example, radial center of mass movement, by swiveling the nose, or by combinations thereof. Experiments showed that, although the evasion capability of nose control systems may be more limited than the base flaps or JRC approach, the operational designs could be made more simple and could lead to an earlier IOC. This control concept was successfully flight tested six times at the Atlantic and Pacific ocean test ranges. By direction of the Director of Defense Research and Engineering, the U.S. Navy took up the nose control development for inclusion in the SLBM system (MK500 program).

Design studies using flight- and wind-tunnel test data suggested that a configuration with a much simpler flap arrangement was capable of providing all of the operational maneuver required with a roll-to-steer guidance and control system. This system was adopted for the flight-test series called the aerodynamic control experiment (ACE) program. Again, Atlas was the booster from Vandenberg Air Force Base; impacts were planned near Kwajalein Atoll to take advantage of the excellent tracking and telemetry equipment in that area. The aerodynamic data obtained confirmed the validity of the control concept and that very high gravitational acceleration levels could be sustained.

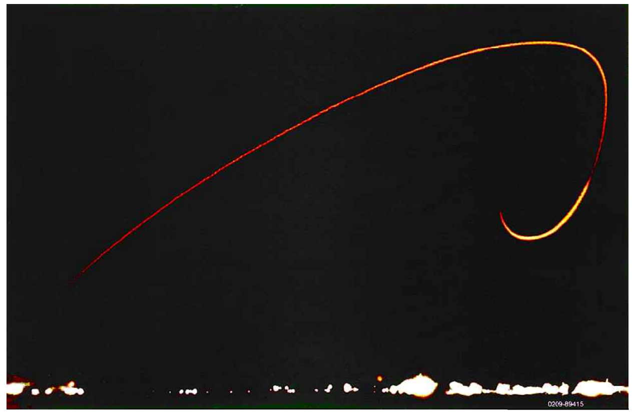


Fig. 17 Long-exposure photograph showing MaRV trajectory near impact at Reagan Test Site.

The design concept and the associated technologies were sufficiently established in 1976 to proceed to build and fly preprototype vehicles. The preprototype, called the advanced MaRV AMaRV, successfully completed a three-flight series in 1981. AMaRV configuration is a bicone with a surface cut and slice in the windward plane. The control mechanism was a bank to turn using a split-windward-flap concept. The flight results clearly demonstrated the feasibility of the design and established performance characteristics superior to those originally predicted. Figure 17 shows a MaRV trajectory streak line during its reentry at the Reagan Test Site, Kwajalein Atoll. This long exposure photograph demonstrates the MaRV's trajectory shaping capability in contrast to a ballistic flight as shown in Fig. 15.

After the end of Cold War, there was interest in using an ICBM to deliver an earth-penetration weapon (EPW). ASMS initiated several studies to design a versatile RV that could make the necessary trajectory shaping to deliver a heavy EPW with stringent requirements on impact accuracy and conditions. One of the challenging issues is packaging the heavy EPW weapons. The study identified several optimum RV configurations using different concepts of controlling the end conditions, for example, ballute, multiflap, etc., but the study was terminated at the critical design review (CDR).

Besides the EPW mission, there was interest in using ICBMs in a worldwide coverage mission. This mission would require development of a high L/D MaRV. Many exotic configurations (wave riders, etc.) were investigated in a program called High Performance (HP) MaRV. Wind-tunnel tests were conducted on configurations of interest. Trajectories such as skip trajectory, phugoid (glide at maximum L/D), and constant high-altitude glide were analyzed and traded off. Again, the HP-MaRV program was stopped at CDR and never went to flight testing.

Reentry Guidance Technology

For a MaRV to perform an evasive or lifting maneuver, it needs G&C and autopilot algorithms. ABRES developed and demonstrated guidance technology in two different areas, small IMUs and terminal fix systems. Although the immediate application was a MaRV, wider applications can be found in other strategic and tactical systems.

The IMUs used in missile guidance systems typically are too heavy and bulky for RV applications. At the same time, the nuclear environment of a MaRV can be at least an order of magnitude more severe than in the missile guidance system. In 1972, ABRES took the first step in MaRV IMU development by miniaturizing gyroscopes and accelerometers. The resulting instruments were then incorporated into a gimbaled platform for MaRV reentry guidance with the requirement to keep the MaRV's impact accuracy, after an evasive maneuver, equal to that of a ballistic RV under similar initial reentry conditions. Known as the small hardened inertial platform (SHIP), these units weigh about 30 lb with electronics and were successfully tested up to their design requirements. At about the same time, ring laser gyro-based inertial reference showed promise such that it was flown piggyback with the SHIP on ACE-3. The results were most encouraging, and this new system, called dormant inertial navigation systems (DINS), was selected to provide inertial guidance for MaRV. DINS was a strap-down system using three ring laser gyros and three conventional accelerometers. In 1980–1981, the DINS flew on three AMaRV flights.

In the late 1980s, ABRES initiated a program called advanced IMU with Honeywell, Inc., to further improve the guidance technology. Later the U.S. Navy picked up the technology and produced the hardware called reentry IMU (RIMU) for operational use. With the addition of a stellar fix to provide azimuthal alignment in flight, these lightweight IMUs (DINS, RIMU, etc.) might be used to supply the total guidance function for advanced small missiles, thus replacing much heavier and more costly systems.

Although the IMUs just described would be capable of maintaining basic missile accuracy throughout MaRV evasion trajectories, it may be necessary to achieve still greater accuracy for attacks on hard targets. This might be done by taking location fixes on terrain features near the target, that is, terrain fixing. In 1964, ABRES initiated a program called terrain contour matching (TERCOM), which was based on the principle that elevation contours over a region constitute an indelible signature (like a fingerprint) for that region. If the contours are known with good accuracy and a vehicle can measure its location relative to them, then its location relative to a local map, and thus to the target, can be determined. TERCOM consisted of a radar altimeter, a correlator to perform arithmetical operations for position fixing, and a memory for storing digital terrain data. In 1972, ABRES identified two derivatives of TERCOM that were predicted to offer higher accuracy and less vulnerability. These are pulse Doppler map matching and range-only correlation system.

Present and Future Challenges

Currently, the primary focus of the ICBM program is to sustain the MM and PK systems at a high level of readiness. The PK is planned to be decommissioned by 2006. The U.S. government plans to keep 500 MM IIIs operational through 2020. By that time, a decision on MM IV design will have been made. Still in the planning stage, MM IV is a next-generation ICBM strategic missile weapon system, which will be designed to deal with the threats of 2020 and beyond. Its architecture will depend on the war fighter requirements, future threat and scenario, targets of interest, and life cycle costs. Figure 18 shows the Integrated ICBM Long Range Program road map.

In 1994, the U. S. Air Force initiated the Propulsion Replacement Program as a means to extend the life of the MM III solid-propellant boosters through 2020. The primary goals are to maintain MM III existing interfaces and performance, establish and maintain a MM III production capability, and insert current manufacturing technologies to mitigate risk. MM III boosters, propellants, and liners and stage 3 chamber materials were replaced, and flight tests were conducted to validate performance. Similarly, the Guidance Replacement Program was established by the Air Force in 1993. Many aging materials, such as the electronic parts, were replaced with modern technology. The new system was designated as NS50. In September 1999 and April 2000, two demonstration flights substantiated the new design.

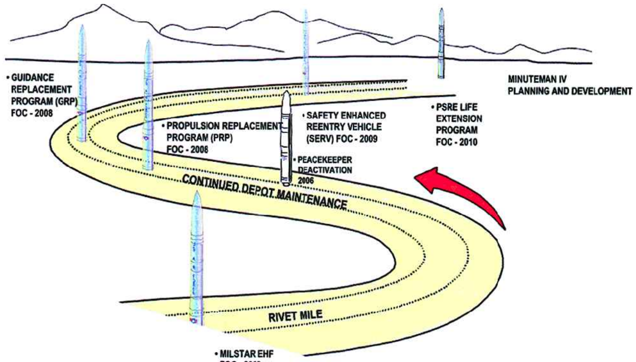


Fig. 18 ICBM roadmap: where we are going?

Table 2 Role of U.S. Air Force ICBM in the triad

Capability	Bombers: B-52s, B-2s	Land-based ICBM systems: MM, PK	Sea-based missile systems: Trident I, Trident II
Range	●	●	●
Payload	●	●	●
Accuracy	●	●	●
Penetration		●	●
Flexibility	●	●	●
Communications	●	●	
Reliability	●	●	
Security	●	●	
Recall	●		
Availability		●	
Survivability		●	●
Postattack life		●	●
Assessment	●		
Reaction time		●	●
Collateral damage		●	●
Arms control	●	●	●
Crisis management	●		

In 2002, system development and demonstration began on a safety enhanced RV. The program will install a single MK21 on the MM III booster and increase the system's safety, reliability, and fuzing capability. Major tasks involve the modification of the reentry systems and software. Production is planned to begin in 2004.

In 1995, under the recommendation of the U.S. Strategic Command USSTRACOM's Strategic Advisory Group (SAG), Congress established the Integrated Application Program (IAP). The purpose of IAP is to sustain industry's technology base (in terms of a baseline capability of skills, components, facilities, and manufacturing) to address hardware aging phenomena and replacements, and to prepare for the future design and development of a new missile system when conditions and the need arise. IAP consists of the Propulsion Application Program (PAP), Reentry Vehicle Application Program (RVAP), Command and Communication Application Program, and Guidance Application Program (GAP). The major participants include Lockheed Martin Corp. and Textron Systems under RVAP; Autonetics, Charles Stark Draper Laboratory, Inc., and Honeywell, Inc., under GAP; and Thiokol Corp., Aerojet, and Hercules Aerospace Corp. under PAP. The SAG has periodically reviewed the IAP programs since their inception and found that the activities have been appropriate and progress has been satisfactory.

Conclusions

For over 40 years, the U.S. Air Force ICBM has played a major role in the U.S. strategic triad of deterrence (Table 2). It required intricate and interrelated technologies to make the ICBM a reality in the early 1950s. This paper has reviewed the development of these technologies in the silo-based ICBM program, with particular emphasis on the technical challenges encountered and overcome. Attention focused on four technical areas: rocket propulsion, missile basing, G&C, and reentry systems.

In 1954, a prompt response to the former Soviet Union ICBM buildup became a national priority. The U.S. Air Force responded to the challenge with the development of Atlas, Titan, and MM ICBMs in record time. With use of an innovative management approach, the Air Force formed a joint government/industry team, utilizing an SE/TD contractor along with associate contractors. Mobilizing industry and academic talents, the Air Force achieved the goal of fielding the ICBM systems on a near impossible schedule. The technical knowledge gained and the hardware developed under the ICBM effort were also applied to the early U.S. space race with the Soviet Union. This accomplishment, often overlooked, saved the U.S. government substantial time and money.

Besides achieving the nuclear deterrence mission and winning the Cold War, the ICBM program also made significant contributions to the scientific communities. For instance, the knowledge of high-temperature gasdynamics, rarefied aerodynamics, and heat transfer in hypersonic flows obtained in ICBM missile/RV tests helped in the design of the space shuttle and other space vehicles. Ground-test facilities built during the ICBM program, for example, the high-temperature arc facilities and high-speed wind tunnels at Arnold Engineering Development Center, Tullahoma, Tennessee, were used for many civilian and space programs. Some of the most sophisticated computational fluid dynamics codes and thermal ablation and heat conduction codes were initiated by the Air Force because of the ICBM programs. Those codes are still widely used by researchers today. Other significant contributions that have spunoff to nonmilitary and scientific usage include miniaturized, high-speed computer chips, composite materials, and high-temperature TPS.

The ICBM program not only defeated the former Soviet Union in the race to field the first operational force, it also was remarkably free of major cost overruns, schedule slippage, waste, and fraud. The hardware service life has proved to be much longer than originally planned, that is, three to five years. Today, the MM III stage 1 is still in operation, and its service life has been demonstrated to be greater than 30 years. This is possible because of better understanding on the material aging, improved structural modeling, and improved aging trend data.

References

[1]Neufeld, J., *The Development of Ballistic Missiles in the United States Air Force 1945–1960*, U.S. Government Printing Office, April 1989.

[2]Johnson, S. B., *The United States Air Force and the Culture of Innovation, 1945–1965*, U. S. Government Printing Office, Aug. 2002.

[3]Snyder, T. S., *Space and Missile Systems Organization—A Chronology, 1954–1976*, Office of History, Headquarter, Air Force Space and Missile Systems Organization, 1978.

[4]Ramo, S., *The Business of Science, Winning and Losing in the High-Tech Age*, Hill and Wang, New York, 1988.

[5]Kennedy, W. S., Kovacic, S. M., Rea, E. C., and Lin, T. C., "Solid Rocket Motor Development for Land-Based Intercontinental Ballistic Missiles," *Journal of Spacecraft and Rockets*, Vol. 36, No. 6, 1999, pp. 890–901.

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

[7]Webster, B. D., Yang, L. C., and Pyles, C., "Evolution of Ordnance Subsystems and Components Design in Air Force Strategic Missile Systems," AIAA Missile Sciences Conf., Dec. 1996.

[8]Nease, R. F., and Hendrickson, D. C., *A Brief History of Minuteman Guidance and Control*, Rockwell Defense Electronics, Autonetics, Anaheim, CA, 1995, pp. 1-2–3-46.

E. V. Zoby
Editor-in-Chief

Color reproductions courtesy of Northrop Grumman Mission Systems.