Ballistic Missiles and Reentry Systems: The Critical Years

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For nearly 20 years, Aerospace played a vital role in advancing the nation's strategic ballistic missile and reentry system capabilities.

Aerospace has a rich history in the development of the U.S. intercontinental ballistic missile (ICBM) force, and this history is interesting in light of current events as well as the insight it provides into the evolution of a corporate expertise that was eventually applied to other launch, reentry, and reusable launch-vehicle systems.

Aerospace involvement in this area extends from 1960, when the corporation was founded, to 1979, when the last division engaged in ballistic missile activities was reassigned. Those two decades were the most dynamic in the Cold War era. The Cuban missile crisis of 1962, in which the Soviets deployed nuclear missile batteries in Cuba and threatened to launch them if the United States attacked the island, heightened tensions to an unprecedented level and increased the urgency of Aerospace work in ballistic missiles. President Kennedy's threat of a U.S. counterstrike against the Soviet Union and Cuba convinced Soviet Premier Khrushchev to withdraw the missiles, leading to a long era of détente based on the policy of mutual assured destruction (MAD).

The evolving Soviet threat involved not just the development of ballistic missiles capable of intercontinental flight, but also the development of reentry vehicles capable of carrying nuclear warheads through the atmosphere to the target (the Soviets had also demonstrated fusion bomb technology in atmospheric tests). Furthermore, in the late 1960s and 1970s, Soviet missile systems became accurate enough to raise concern about their ability to destroy hardened targets in the United States, as did the Soviet deployment of large missiles capable of carrying multiple independently targeted reentry vehicles. In parallel, the Soviets were developing antiballistic missile systems, and in the mid-1960s actually deployed long-range interceptor batteries around Moscow together with the radars necessary to track reentry vehicles at great ranges. It is this series of threats that the U.S. ballistic missile and reentry system programs had to address.

Effective deterrence hinged upon the mutual certainty that a first strike would trigger a devastating retaliatory strike. Thus, the Department of Defense needed to ensure that the U.S. fleet of ICBMs would not only survive a nuclear missile attack, but would still deliver warheads to their intended targets without fail, despite the presence of any Soviet defense system. Accordingly, Aerospace's developmental work in ICBM systems focused on four principal areas: advanced ballistic missiles, survivable basing systems, advanced reentry vehicles, and defense-penetrating reentry systems (see sidebar, Organized Support).

Advanced Ballistic Missiles

The Atlas liquid-propellant ICBM, declared operational in 1959, was the primary land-based launch vehicle when Aerospace began supporting the U.S. ICBM program. The Atlas was soon joined by the Titan II, deployed in hardened silos. By the late 1960s, these systems were supplanted by the Minuteman, a small, solid-propellant missile that would also be deployed in hardened silos. Three versions of the Minuteman were ultimately developed.

Aerospace contributed to all these missile systems, with particular emphasis on the Minuteman. Through participation in the Air Force's Minuteman Effectiveness Evaluation Group, Aerospace helped identify new or upgraded systems for this missile. The effort covered larger-payload missiles, improved guidance, and improved command and control.

Aerospace participated in studies that led to improvements in the Minuteman II, which had a significantly longer range than its predecessor. Minuteman II also employed solid-state electronics and was the first U.S. ICBM to use decoys in its warhead section. Following these achievements, Aerospace helped develop the powerful multiple independently targeted reentry vehicle (MIRV) concept for the Minuteman III. This approach gave the Minuteman a fourth stage (known as a bus) with adequate small motors to maneuver accurately when separated from the booster. As a result, each of several reentry vehicles could be directed to different targets. Aerospace's detailed analysis of the deployment of three reentry vehicles from the missile to different targets established the feasibility of this concept.

In implementation, this meant replacing the single large reentry vehicle on the Minuteman II with three smaller reentry vehicles on the Minuteman III—a tremendous force multiplier. This concept was copied by the Soviets some years later.

At the same time, Aerospace was examining other advanced weapon systems, identifying new system concepts, evaluating the feasibility of promising ones, performing preliminary designs, formulating cost and schedules, and supporting preparation of requests for proposals for the Air Force.

Aerospace also sought to identify advanced subsystems that would economically improve performance and reliability of new and existing ballistic missiles, deriving the specifications for promising technologies and overseeing contractor activities during the development phase. Important improvements were made in areas such as guidance and control, command of missile systems in the field, and propulsion.

Survivable Basing Systems

Given the accuracy of Soviet missiles, combined with their high-yield warheads, the U.S. strategic missile community worried that ICBMs housed in fixed sites could be vulnerable to a missile attack. To counter this threat, Aerospace studied more than 60 concepts for protecting land-based ICBMs, including the use of mobile launchers, superhard silos, and antiballistic missile systems for silo defense. The studies derived conceptual designs for each approach, assessed the technical risks, and estimated the cost of implementation.

Artist's conception of a reentry vehicle passing through the atmosphere. The sharp, conical shape is a legacy of the work done by the Advanced Ballistic Re-Entry Systems program in the 1960s. (U.S. Air Force)

The superhard silo approach provided the lowest confidence of survival because an increase in enemy missile accuracy would negate the harder silo. Hardness estimates for this basing option were derived using computer codes developed at Aerospace for analyzing the effects of nuclear blasts on missiles and silos. Defense of silo fields was considered a better option, though this would really require a mobile system because fixed radars and interceptors would surely be targeted by enemy missiles.

The mobile ICBM concept was deemed the most viable in terms of providing survivability with the highest confidence. Numerous mobile deployment schemes were considered.

For example, one promising candidate was a system for carrying a missile on a large aircraft, such as the C-5 cargo plane, which would scramble upon warning of incoming missiles (a Minuteman was launched successfully from a C-5 in 1974 to validate this concept); such a system, however, would be costly. Another intriguing idea was to house missiles on "surface effect vehicles," which are akin to hovercraft. These vehicles can move at high speeds and provide off-road capability over some terrain. Although studies showed the feasibility of this approach and the systems were defined, no development took place. A similar concept that received funding envisioned a fleet of small missiles on mobile carriers that would travel throughout the country, on or off road. The missile was developed successfully, and the transporter was nearing completion, but the program was canceled.

Other proposals included carrying missiles and launch equipment on barges on the Great Lakes or other bodies of water; burying missiles in deep holes drilled in hard rock mountains or in abandoned mines; and housing a large number of small missiles in silos dispersed throughout the United States (though this raised concern that the number of missiles needed would exceed the number allowed under arms limitation treaties).

The most effective approach arose through Aerospace studies in 1966 of a new missile system, WS 120A, conceived as the successor to the Minuteman and planned as a major deterrent for the late 1970s and beyond. The WS 120A would be a large missile packed with 10 to 20 reentry vehicles (this range encompassed the eventual Peacekeeper MX). The WS 120A basing study proposed deploying the missiles in superhard silos, at least 10 times harder than Minuteman silos. Options were designed for additional missiles in off-road mobile and defended modes. A second study in 1969 included deceptive basing of mobile missiles.

These studies led to no immediate development; however, the Air Force drew upon the concept of deception in evolving its final deployment strategy for the Peacekeeper MX. The Peacekeeper basing strategy entailed concealing a missile in one of many aboveground shelters. These shelters would not provide the same nuclear hardness as a silo, but they would be spaced far enough apart to prevent a single enemy warhead from disabling more than one. A mobile missile carrier with an enclosed cargo compartment would go from shelter to shelter, sometimes with a missile, and sometimes without. The carrier would be designed such that no sensor, on the ground or in satellites, could discern whether it held an active missile. The number of shelters would be determined by the number of expected reentry vehicles targeting America's land-based missiles. It would be the supreme shell game. Still, although a number of MX missiles were produced and deployed in silos, the multiple-shelter concept was not employed, partly as a result of warming relations with the Soviet Union.

Advanced Reentry Vehicles

Improvements to the missiles created opportunities for better reentry systems, which was the focus of the Air Force's Advanced Ballistic Re-Entry Systems (ABRES) group. Aerospace provided general systems engineering and technical direction to this program.

Initially, the objective of ABRES was to derive systems to penetrate Soviet antiballistic missile systems, which were undergoing significant testing and development at the time. U.S. intelligence indicated that the Soviets were developing a long-range exoatmospheric system based on an early-warning radar that would detect objects in its threat corridor and cue a second radar that tracked them with sufficient accuracy to launch a long-range interceptor.

One obvious way to counteract such a system would be to minimize the reentry vehicle's radar cross section (the amount of electromagnetic energy reflected back to the radar). That way, the reentry vehicle would avoid detection until it was much closer to the target. The smaller cross section would also make it easier to design credible lightweight decoys.

A relatively sharp nose cone would reduce the radar cross section substantially, compared with the large, blunt-nosed reentry vehicles of the prior era (which actually needed a blunt nose to slow their descent through the atmosphere to minimize heating). Moreover, a sharp cone-shaped missile would maintain a high velocity all the way to the ground, making it more difficult to intercept.

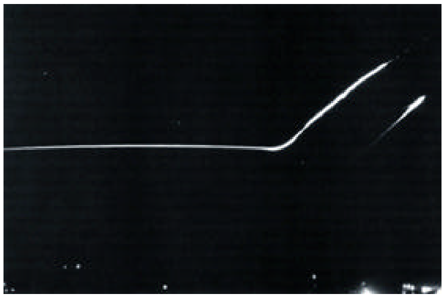
On the other hand, the smaller internal volume of the slender cone called for innovative warhead design and miniature multipurpose fuses. More important, the tremendous heat rate and pressure on the small nose radius demanded new materials, many of which hadn't been developed and flight-tested for this sort of application. In fact, on some vehicles, the nose tip ablated (burned away) and exposed interior components to excessive heating; on others, it ablated asymmetrically, which caused the vehicles to deviate from course.

The ABRES team attacked this problem vigorously, conducting extensive ground tests and flight tests of various nose-tip materials and designs. Eventually, researchers began to understand the phenomenology and could implement corrective measures. Since then, the nose tips have performed with great success.

Aerospace helped develop the powerful multiple independently targeted reentry vehicle (MIRV) concept for the Minuteman III. (U.S. Air Force)

Program efforts then turned to another problem of trajectory perturbations, which were having an adverse effect on impact accuracy. These perturbations were linked to the spin or roll that is intentionally induced to stabilize the vehicle as it travels through the exoatmosphere. As some reentry vehicles traversed the atmosphere, the roll rate slowed or completely stopped, while for others, it increased to levels above the pitch/roll stability threshold. In both cases, the vehicles strayed from their intended trajectories.

As with the nose-tip problem, extensive ground and flight tests helped identify the problem, and, as before, remedies were found and implemented. With the fixes in place, reentry vehicles were no longer a major contributor to the total accuracy errors of U.S. ICBM systems.



Flight test of the Advanced Maneuvering Reentry Vehicle in early 1980. The path of the reentry vehicle is the upper streak of light, with the booster tanks immediately below. Lights from the Kwajalein Atoll in the Pacific can be seen in the lower right corner. (U.S. Air Force)

The new sharp-coned reentry vehicle, designated Mark 12, became the warhead of choice for the Minuteman III and was developed by the Minuteman program office. Because three Mark 12s fit on one launch vehicle, they presented a significant challenge to a potential antiballistic missile system, which would have to deploy three times as many interceptors. In fact, the ABRES program later designed a smaller reentry vehicle that could be packed in groups of seven aboard the Minuteman III. Such a system was tested in flight and declared ready for deployment. Moreover, in anticipation of a larger, more accurate launch vehicle than the Minuteman III (i.e., the MX), the ABRES team also designed and developed a larger reentry vehicle capable of even greater accuracy. Known as the Advanced Ballistic Reentry Vehicle, it could be delivered singly on a Minuteman III or in groups of ten on the larger Peacekeeper MX. The Advanced Ballistic Reentry Vehicle was deployed on both the operational Peacekeeper and the Navy's Trident II ballistic missiles—a significant achievement of the ABRES program.

These efforts could not have succeeded without the help of cutting-edge scientific research at Aerospace. Although all the technical disciplines made significant advances, two areas in particular—fluid dynamics and materials science—made new discoveries and developments with widespread applicability.

For example, Aerospace researchers developed new numerical techniques to solve problems of hypersonic flow and heat transfer, including the effects of chemistry and ablation of the reentry-vehicle surface. Also, in studying the implications of changing the shape of the nose, Aerospace developed testing and analysis procedures that could be used to analyze the flow around aircraft control flaps and the 3-dimensional heat-transfer environment around vehicles traveling at angles of attack.

Other areas of inquiry included radio-frequency propagation through ionized boundary layers, chemical and ionization reaction rates and byproducts of wake-quench chemicals and air at high temperatures, and measurement of the aerodynamics and ablation rates of candidate materials for nose tips in hypersonic and arc-jet tunnels. Aerospace also devised a lightweight roll-control system for reentry vehicles that was later demonstrated by ABRES. In regard to advanced materials for nose tips, heat shields, and antenna windows, Aerospace provided a quick-reaction failure-analysis capability, including critical nondestructive testing techniques to ensure the quality of materials on reentry vehicles. Research into the high-temperature properties of carbon and graphite gained national recognition.

Penetrating Missile Defenses

Defense penetration programs progressed in tandem with research and development of ballistic reentry vehicles. The idea was to provide a number of options for neutralizing both current and anticipated Soviet antiballistic missile systems. The ABRES program developed and tested many methods for penetrating such a defense.

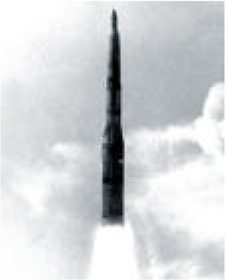
One such method, designed to counter long-range exoatmospheric defenses, used exoatmospheric chaff to confuse Soviet antiballistic missile systems. This chaff was composed of thin metallic dipoles of the proper length to absorb and reflect the energy of the Soviet radars, which would register only a series of opaque "clouds," hiding the reentry vehicle in one and the third stage in another. The first design to be flight-tested for Minuteman II showed serious problems, and ABRES was asked to develop a solution. Time was critical, because the U.S.S.R. was deploying its antiballistic missile system around Moscow. Within a few months, successful flight tests were conducted, and a nine-cloud system was deployed on the Minuteman II. These flight demonstrations prompted the Soviets to cancel their system around Moscow because they realized they would have to use nine interceptors to destroy one reentry vehicle.

Compared with the Minuteman II, the Minuteman III permitted a more straightforward method of chaff deployment. The fourth stage of the Minuteman III could maneuver to different places and drop off a bundle of chaff at each, such that all chaff clouds would look like they were going to the same target. The Minuteman II never had that capability, so cans of chaff had to be fired off of the third stage to the right positions—a much tougher job.

To penetrate a layered (exoatmospheric and terminal) defense, ABRES focused on a maneuvering reentry vehicle. This vehicle would be coupled with an early-reentry decoy, which would remain viable down to the altitude at which the reentry vehicle could maneuver. Researchers determined that the extremely high lateral g forces that the maneuvering reentry vehicle could pull would be more than sufficient to evade the terminal interceptors.

The first maneuvering vehicles tested were large flap-based units, three of which were successfully flight-tested over the Pacific in the late 1960s. Vehicles that used reaction jets to maneuver were also considered, but design studies and wind tunnel data indicated that the simpler flap arrangement could perform all the maneuvers required. Three full-scale flap-based vehicles were flown over the Pacific Ocean in 1973–1974, followed by three successful preprototype flight tests of the Advanced Maneuvering Reentry Vehicle in 1981. The vehicle was declared operational for the Minuteman III or the MX.

The success of the Advanced Maneuvering Reentry Vehicle was made possible in part by its innovative guidance system, a small nuclear-hardened inertial platform that could achieve the same accuracy as a ballistic reentry vehicle even after experiencing high-level accelerations. Eight years had gone into the development of this guidance platform, and its introduction was highly significant. Whereas guidance systems for ballistic missiles can weigh well over 100 kilograms and only have to withstand acceleration up to 10 g's, the guidance system for the Advanced Maneuvering Reentry Vehicle could weigh no more than 13–18 kilograms and had to retain accuracy after experiencing g forces more than an order of magnitude higher. The early design employed small gyros and accelerometers in a small, hardened, gimbaled platform, which was immersed in a liquid to relieve the g force loads; however, this arrangement generated thermodynamic and chemical interactions among the electronics, instruments, and liquid. These problems were eventually resolved, and the small hardened inertial platform achieved its performance goals, providing a model for future development.



The Minuteman II had a much longer range than its predecessor and was the first U.S. ICBM to use decoys in its warhead section.
(U.S. Air Force)

End of an Era

The Air Force, with Aerospace concurrence, transferred its ABRES program to TRW in 1979, ending an era of Aerospace participation in ballistic missile development. Still, the expertise developed through this program continued to produce benefits. Many Aerospace engineers and scientists applied their new tools and expertise to evolving missile-defense and launch-vehicle programs. Indeed, many of these ICBMs were themselves converted into space launch vehicles, with Aerospace assistance. Future investigations into ICBM modernization will no doubt build upon the success of the early ICBM development program, which owes part of its legacy to Aerospace.

Postscript and Acknowledgements

This article has covered only a fraction of all the ABRES system developments and preprototype demonstrations. The systems and technology described here are of high importance; nevertheless, 10 additional systems were developed through the preprototype stage along with considerable other critical technologies. The ABRES program was a team effort involving the Air Force, Aerospace, 57 contractors, other government agencies and laboratories, and other nonprofit organizations. The large U.S. lead in reentry systems was clearly observed by Soviet ships in the Pacific Ocean and surely contributed in some measure to the end of the Cold War.

This article draws upon details from a limited-distribution document by Roy E. Fowler and Sanford L. Collins. The author also thanks Robert F. Clauser for clarifying Aerospace's participation in the Minuteman III and Mark 12 decisions and Richard Allen of TRW for information on the Small Mobile Missile program.