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From the Editors

The launch vehicle community is in the midst of a historic transition. The diverse launch systems that served the country’s defensive and scientific needs for decades have reached the end of their active service life. One by one, these heritage systems are being phased out and supplanted by a new generation of Evolved Expendable Launch Vehicles. With the recent inaugural launches of these EELVs, the U.S. launch community has embarked upon a course of assured, responsive, and economical access to space.

EELV systems represent the immediate future of U.S. space launch activities, but they trace their roots to programs that began more than 40 years ago—to the ballistic missile and space-race efforts of the early Cold War. Then, as now, Aerospace was essential in helping system designers meet performance objectives and national defense priorities. Aerospace made significant contributions to the Gemini program, solving a vexing problem of rocket oscillation, as well as the strategic ICBM program, helping to derive the multiple independently targeted reentry vehicle concept. Later, Aerospace helped convert early missiles to launch military payloads into space. Construction of the Air Force launch ranges also benefited from Aerospace contributions.

The full range of Aerospace activities in launch vehicle development and certification would be too much to cover in a single Crosslink. Thus, we have elected to focus on historical programs for this issue. A comprehensive discussion of design and analysis tools, engineering expertise, advanced concepts, and technical approaches will follow in a future edition. In the meantime, we hope this Crosslink will provide useful background and shed light on the company’s considerable involvement with the major U.S. space-launch initiatives.

Dear Crosslink Reader,

As this issue goes to press, we mourn the tragic loss of the seven astronauts who perished aboard the space shuttle Columbia. Their loss reminds us of the high stakes and human impact of space exploration. We extend our condolences to the family members of those who died and to our colleagues at NASA.

William F. Ballhaus Jr., President and CEO
Black Box for Spacecraft

In an effort to pinpoint sites where space debris will land on Earth, the Aerospace Corporation’s Center for Orbital and Reentry Debris Studies (CORDS) is working with the Air Force Space and Missile Systems Center to develop a “black box” similar to the flight-data recorders found on commercial aircraft.

“A black box could provide clues as to how changes in materials and construction might prevent large pieces of space debris from hitting Earth’s surface,” said Bill Ailor, CORDS director.

Many spacecraft, or pieces of them, return to Earth. A black box that would survive reentry may one day give researchers information about changes in material temperatures and loads on spacecraft as they reenter the atmosphere. The box may also help determine the “footprint” or area of Earth’s surface where debris will fall.

Surviving pieces of varying sizes can be spread over hundreds of miles. Many factors, including atmospheric conditions and the aerodynamic characteristics of the objects, influence the footprint location.

EELV Launches

Two successful rocket launches in the fall of 2002 inaugurated the Air Force’s Evolved Expendable Launch Vehicle (EELV) program, the first new government-sponsored launch system in two decades. The Atlas V launched on August 21, and the Delta IV rocket lifted off in a spectacular night launch November 20.

In launches from Cape Canaveral Air Force Station, Florida, the Atlas V (below left) carried a commercial TV broadcasting satellite into orbit, and the Delta IV (below right) inserted a communications satellite in a nearly perfect geosynchronous transfer orbit.

“Successful first launch of each EELV system establishes the next generation space launch capability to meet the government’s needs for the next 20 years,” said Linda Drake, EELV general manager at Aerospace.

Although these were commercial missions for Eutelsat, the EELV program is managed by the Air Force Space and Missile Systems Center. The first government EELV payload, a Defense Satellite Communications System (DSCS) satellite, was scheduled to launch aboard a Delta IV from Cape Canaveral in March. Aerospace provided technical support to both initial launches and launch verification for the DSCS launch.

“Aerospace’s role has grown increasingly significant since the program’s inception in 1995,” Drake said. The corporation has provided technical insight to the Air Force throughout the EELV program development, assessing system design and qualification, monitoring launch processing, and providing launch verification for the DSCS launch.

The government-industry partnership is developing the next-generation expendable launch vehicle to give the country more reliable, affordable space transportation for the 21st century through improved operability, significant cost reduction over current systems, and a standard payload interface flexible enough to accommodate changing mission requirements.

Titan II Launches

A Titan II G-14 rocket successfully launched NOAA-M, the National Oceanic and Atmospheric Administration’s newest environmental satellite, from Vandenberg Air Force Base on June 18, 2002.

After the satellite was carried to a near-perfect position in space, its apogee kickmotor provided final circularization of its near-polar orbit 450 nautical miles above Earth at an inclination of 98.7 degrees from the equator. The satellite will collect meteorological data and transmit the information to users around the world to enhance weather forecasting.

Aerospace, as sole provider of Titan II launch verification and validation for the Air Force, verified that all critical hardware, software, and mission analyses met requirements for flightworthiness. “The Titan II G-14 processing, checkout, and verification process was exceptionally smooth,” said Ray Johnson, vice president of the corporation’s Space Launch Operations.

Aerospace also had a role in the Titan II G-4 launch from Vandenberg in January.

The mission, known as Coriolis, was sponsored by the Air Force Space Test Program and carried two experimental payloads for DOD. The first, WindSat, is reportedly the first passive sensor to measure ocean surface wind velocity. The second, the Solar Mass Ejection Imager, is an Air Force Research Laboratory experiment to forecast geomagnetic disturbances.

The Coriolis mission will last for three years. Aerospace provided technical oversight during the spacecraft’s development, payload integration, and testing.
Space Shuttle Launches Mini “Satellite Inspectors”

A pair of experimental miniature satellites were launched by the space shuttle Endeavour December 2, 2002, as part of a series of test flights researchers hope will result eventually in autonomous “ride-along” spacecraft that can be released on command to inspect parent satellites.

Connected by a 15-meter nonconducting tether to facilitate detection by ground-based radar and emulate formation flying, the picosatellites were ejected from a spring-loaded launcher built by The Aerospace Corporation and installed in Endeavour’s cargo bay. The miniature satellites, which measure approximately 10-by-10-by-12.5 centimeters and weigh only 1 kilogram each, were built by Aerospace in partnership with the Jet Propulsion Laboratory.

The launch demonstrated the capability of deploying picosat-scale satellites (1 kilogram and under) on virtually any shuttle flight. Aerospace principal investigator Ernie Robinson said that this launch capability is extremely valuable for low-cost ready access to space by anyone developing technology to picosat scale.

The diminutive satellites are serving as pathfinders for a new capability that might become the standard for conventional satellites: autonomous inspection. As envisioned by their designers, these inspection picosats will feature an onboard imaging capability and other sensors that will enable them to assess spacecraft damage and provide rapid feedback to spacecraft operators on the ground, thus helping to ensure continuous service to users and optimal spacecraft longevity.

The MEPSI project, or microelectromechanical systems (MEMS)—based picosat inspector, calls for incremental advances that will result in autonomous and fully functional inspector satellites comprising MEMS components, such as radio-frequency switches, gyros, accelerometers, and thrusters. The principal payload aboard the picosats launched December 2 consisted of inertial measurement units. During the three-day mission, the picosats transmitted signals to a ground station at Menlo Park, California, and performed inertial measurement exercises.

Aerospace Takes Part in NASA CRYSTAL-FACE Mission

The Aerospace Corporation played a key role in the recently completed airborne cloud sampling campaign of the Cirrus Regional Study of Tropical Anvils and Cirrus Layers—Florida Area Cirrus Experiment (CRYSTAL-FACE).

The campaign was part of a continuing interagency effort to better understand the ways in which aerospace propulsion-system combustion emissions affect atmospheric chemistry and radiation. Sponsored by NASA, the CRYSTAL-FACE effort extends previous joint Air Force and NASA work under the Rocket Impacts on Stratospheric Ozone (RISO) program.

“Preliminary analysis of the data has provided new insights into the size, shape, and chemical composition of cirrus and contrail ice crystals and how these clouds could affect global warming,” said Martin Ross, Aerospace RISO program manager.

Ross served as co-flight scientist (with Randall Friedl of NASA’s Jet Propulsion Laboratory) for high-altitude aircraft WB-57F payload integration and operations during CRYSTAL-FACE deployment to Key West Naval Air Station, Florida, in the summer of 2002. He directed a team of more than 100 scientists and engineers operating 27 instruments carried by the WB-57F to study how high-altitude cirrus clouds are formed, dissipate, and affect the heat balance of the lower atmosphere.

William Engblom of Aerospace applied state-of-the-art computer models to simulate the flow of air around the WB-57F during flight in an effort to understand how aircraft-induced changes in air pressure and temperature could influence the response of instruments carried by the aircraft. Highlights of the month-long CRYSTAL-FACE mission included sampling a variety of thunderstorm-related cirrus clouds, close high-altitude formation flying with the NASA ER-2, and sampling of the WB-57F’s own contrail.

More detailed results from CRYSTAL-FACE will be presented at the spring meeting of the American Geophysical Union in Nice, France. The continuing collaboration between the Air Force, NASA, and other agencies under the RISO program provides the Air Force with important credibility, as well as engagement with the atmospheric science community with regard to the impacts of aircraft and rocket-engine combustion emissions on the atmosphere.
The Path to Mission Success: The Aerospace Role in Launch Certification

Independent launch certification is a core competency of The Aerospace Corporation. Aerospace operates as a federally funded research and development center for the United States Air Force, and as such, is directly accountable to the Air Force Space and Missile Systems Center (SMC) for the verification of launch readiness.

Prior to any launch, Aerospace provides a letter to SMC documenting the results of the launch-verification process and confirming the flight readiness of the launch vehicle. This letter is not just a formality, but represents the culmination of a long and rigorous assessment that draws upon the collective expertise of scientists and engineers within the program office and the engineering staff.

A Long History
The Aerospace role in independent launch-readiness verification began with the Mercury-Atlas program in 1960, shortly after the corporation was founded. The program had already suffered two failures, and a complete turnaround in reliability was required before human spaceflight could be attempted. Thanks in part to the risk-reduction techniques developed at Aerospace, the mission was ultimately a success. Similar techniques were later applied to the Gemini-Titan launch system and the Atlas space-launch vehicle.

The corporation has applied this process to the design, development, and operation of several hundred launches, including the Atlas, Delta, Inertial Upper Stage, and Titan launch system variants. The process has also been tailored to support other government and commercial launches, including the Atlas V and Delta IV launch systems being procured through the Evolved Expendable Launch Vehicle program. It has allowed Aerospace to overcome major programmatic and technical challenges ranging from the conversion of the massive Titan II intercontinental ballistic missiles into reliable launch vehicles, to the return to expendable launch vehicle programs after the loss of the space shuttle Challenger. The contributions of the launch verification process to system reliability may be difficult to quantify; nonetheless, government launch programs that include independent design certification exhibit a tenfold reduction of risk as compared with commercial launch programs for the first three flights.

The Verification Letter
To accomplish the entire spectrum of launch-verification activities requires a cadre of engineers with expertise in a wide variety of disciplines, including system engineering, mission integration, structures and mechanics, structural dynamics, guidance and control, power and electrical systems, avionics, telemetry, safety, flight mechanics, environmental testing, computers, software, product assurance, propulsion, fluid mechanics, aerodynamics, thermal engineering, ground systems, and facilities and operations. These engineers provide valuable input through all phases of launch vehicle development and operations. This provides the basis for Aerospace’s certification of each mission.

The launch-readiness verification letter that Aerospace delivers to the Air Force provides assurance that all known technical issues have been assessed and resolved and that all residual launch risks have been assessed in a satisfactory manner. Thus, the mission can proceed with an acceptable level of confidence in launch mission success.

Ray Johnson
erospace 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.

**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-loadout 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.

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

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

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**Organized Support**

Aerospace’s early work in ballistic missiles was conducted through two divisions—the Missile Systems division and the Reentry Systems division. The Missile Systems division had three subdivisions: Advanced Minuteman, Advanced Systems, and Advanced Subsystems.

The Advanced Minuteman group investigated short- and long-term improvements to America’s land-based ICBM operational force. This group directly supported the Air Force’s Minuteman System Program Office through participation in the Minuteman Effectiveness Evaluation Group. Aerospace assisted studies by the Air Force and its primary contractor, TRW, that led to improvements in the Minuteman II and paved the way for the powerful multiple independently targeted reentry vehicle (MIRV) for the Minuteman III.

The Advanced Systems group provided a focal point for development of advanced weapon systems. The group identified and evaluated promising system concepts, performed preliminary designs, formulated cost and schedules, and helped prepare requests for proposals for the Air Force.

The Advanced Subsystems group sought to identify subsystems that would economically improve performance and reliability of ballistic missiles. Important improvements were made in areas such as guidance and control, command and control of missile systems in the field, propulsion, and basing. In addition, the group conducted extensive research on the effects of nuclear blasts on silos and missiles, including shock loads, debris clouds, and electromagnetic pulse. The electromagnetic pulse research helped to optimize the location and connection of the rebar in the silos’ concrete and also provided confidence in the hardness estimates for superhard-silo basing proposals.

Aerospace’s Reentry Systems Division was established in August 1964, when the technical operations at San Bernardino were reorganized to achieve functional alignment with Air Force activities. The task was to provide general systems engineering and technical support to the Air Force’s Advanced Ballistic Re-Entry Systems (ABRES) program as well as the Army’s Nike and Safeguard antiballistic missile programs. Initially, the primary objective of ABRES was to figure out how to penetrate Soviet antiballistic missile systems, which were undergoing significant testing and development at the time. In its most active period, ABRES would routinely flight-test 10 to 15 small-scale vehicles and four full-scale vehicles in a year.
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.

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.

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 radiofrequency propagation through ionized boundary layers, chemical and ionization reaction rates and byproducts of wakequench 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
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, 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 gyro's and accelerometers in a small, hardened, gimballed 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.

**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.

**Further Reading**


As NASA’s Project Mercury concluded its final flight in May 1963, America’s future success in the space race was by no means assured. Although all of the program’s major goals had been accomplished, an enormous amount of work still needed to be done before any attempt could be made to send an American to the moon—which was, at the time, the ultimate goal of the U.S. space program. Moreover, the United States was still lagging behind the Soviet Union, which had already completed a successful two-man flight in 1962 and sent the first woman into space, cosmonaut Valentina Tereshkova, the following year.

To bridge the gap between the Project Mercury flights and the planned Apollo moon landing, in December 1961 NASA announced plans for a series of flights carrying two astronauts using modified Mercury capsules. NASA planners had considered such an interim program, named Mercury Mark II, as early as 1959, but reached no clear consensus as to what its major goals should be. By the time Robert Gilruth, director of NASA’s Manned Spacecraft Center, announced the creation of the program at a Houston press conference, the range of possible objectives had been narrowed to three, although many of the management and operations details were still not clearly defined.

The Genesis of Gemini
The first objective was to achieve rendezvous and docking of two vehicles in orbit and to maneuver the two spacecraft using the target vehicle’s propulsion system. The second was to complete long-duration flights of up to two weeks. These objectives were chosen primarily because of their direct application to the upcoming Apollo missions. A third objective was to develop a means of landing the returning spacecraft on an airstrip in the United States, though this objective was later shelved after several tests of the proposed paraglider landing system ended in failure. On January 3, 1962, the Mercury Mark II program was formally designated “Project Gemini.” The program acquired its new name from the Gemini constellation, which was itself named for the twins Castor and Pollux of ancient Greek mythology.

NASA chose the Titan II ballistic missile to launch the Gemini capsule. The Agena target vehicle would be launched by an Atlas rocket. The Air Force Space Systems Division (SSD) would serve as NASA’s agent, responsible for the development, procurement, and launch of major articles of flight hardware except for the Gemini capsule. Thus, with NASA’s overall funding and direction, SSD provided the Agena target vehicle, the Atlas launch vehicle for the Agena, the Titan II launch vehicle for the Gemini capsule, and the launch services for all of these. Separate contractors were selected for the Titan II, its first- and second-stage engines, the Agena, and the Atlas rockets.
The first step would be to reconfigure the Mercury capsule to support the Gemini mission. For example, the cabin needed to be much bigger to accommodate two astronauts while providing them the maneuverability needed to perform the planned docking procedures. The spacecraft contractor implemented a number of changes to allow greater pilot control, including simplified circuitry, redesigned instrumentation, and the addition of rendezvous radar and retrorockets. The Gemini capsule weighed about 2.5 times as much as its Mercury counterpart, with about a 20-percent increase in overall size, but with an approximately 50-percent increase in interior cabin space. The new capsule no longer contained an escape tower; instead, ejection seats were built in to provide a means of emergency escape.

SSD asked The Aerospace Corporation to assume responsibility for general systems engineering and technical direction for both the Titan II and the Atlas/Agena. Aerospace’s primary responsibilities were to modify the Titan II to permit piloted spaceflight and to maintain the Pilot Safety Program, which had proved so successful during Project Mercury. Additional responsibilities included modifying Launch Complex 19 at the Atlantic Missile Range to accept the Gemini-Titan and erecting the rocket once it was on the launchpad. A Gemini Program Office was established at Aerospace in January 1962, just one month before John Glenn completed the first American orbital flight. The goal was to coordinate the work that Aerospace was performing at both the Atlantic and Western test ranges.

**Rocket Science**

At the time of its selection in December 1961, the Titan II was not fully operational. Some of the difficulties arose simply because the Titan II was far more advanced than the original Titan ICBM, and was in many ways an entirely new missile. For example, the Titan II was fueled by a hypergolic fuel-oxidizer combination. These fuels, consisting of unsymmetrical dimethyl hydrazine and nitrogen tetroxide, were in some ways easier to handle and did not require a complex ignition system. Although they were very dangerous in terms of their combustibility and toxicity, they could be stored at room temperature and preloaded into the rocket long before flight. The Atlas rocket, which used cryogenic liquid oxygen, did not offer that capability. In addition, the Titan II generated more than 31,100 newtons greater thrust at liftoff than the Mercury-Atlas, making it an attractive vehicle for the heavier Gemini spacecraft.

NASA intended to minimize modifications of the Titan II, but Aerospace soon recognized that important changes would be necessary. For example, Aerospace advocated the use of inertial (rather than radio) guidance and successfully argued for backup circuits for the electrical systems, backup flight controls, a redundant hydraulic system, and a malfunction detection system. While other proposals never made it beyond the analysis stage, the changes that were incorporated into the launch-vehicle hardware were of critical importance to the overall program.

One of the most important legacies of the Aerospace team was the solution to a major oscillation problem with the Titan II. These longitudinal oscillations were referred to as “pogo” because they resembled the motion of a pogo stick. Although the pogo vibrations might be acceptable for an armed missile, they would certainly prevent the astronauts from performing their in-flight duties, and could even be fatal. Following the initial discovery of this anomaly during the Titan II’s first test flight on March 16, 1962, Aerospace engineers and other members of the Gemini team realized that a solution was needed before the rocket could be used.

SSD asked Aerospace to guide the pogo investigations. After reviewing the static firing data from the previous year, Sheldon Rubin, a member of the Aerospace technical staff, believed he could solve the problem if he had access to the data of the transfer function of the Titan’s engines. Aerospace convinced the Air Force to provide about $1 million to the engine manufacturer to conduct the necessary measurements. After receiving the data, Rubin developed an analytical model that solved the problem. By the end of 1963, Rubin’s recommendations were fully adopted, and pogo suppression devices were added to the rocket. Subsequent flights over the next five months proved Rubin’s modifications to be a complete success.

Another important Gemini activity under Aerospace direction was the Gemini Stability Improvement Program, also known as Gemsip. This program was developed by the contractor as a byproduct of the design reviews that were conducted for the Titan’s first- and second-stage engines, and was to improve control during the reentry phase of the spacecraft. This program was designed to improve the stability of the Titan II by adding a number of control surfaces to the rocket and modifying the internal structure to reduce the effects of pogo vibrations. The improvements resulted in a more stable and controllable rocket, allowing the spacecraft to achieve a higher degree of precision during reentry.

A Titan II rocket boosts Gemini 3 into orbit on March 23, 1965. This flight, the first with an onboard crew, demonstrated that the Gemini spacecraft was qualified for human flight.
In 1963, Aerospace began phasing in the space developed a new injector for the Titan II to reduce combustion instability during the second-stage engine's start transient. This was another serious problem observed during flight tests and ground tests. The manufacturer realized the value of an ongoing review process after the injector selected by Aerospace prevailed in tests over the manufacturer’s proposed injector. By the end of 1964, Gemsip had become an established program at the manufacturing plant.

Aerospace also performed a vital “lessons learned” review with the Titan II contractor during the process of approving the Gemini launch vehicle for human flight. Aerospace had initiated successful rating procedures during the Mercury program for the Atlas rocket with its Pilot Safety Program, so it was only logical that SSD would ask the corporation to continue with the Titan II. However, the integrating contractor had by now changed. To complicate matters, Titan II parts were manufactured and designed in Denver, but the actual assembly took place in a Baltimore facility that had previously manufactured only airplanes. The change of contractors required Aerospace to assume an active role in virtually every step of the Titan II assembly procedure and to recommend numerous changes in manufacturing. These contributions added to the growing reputation of Aerospace as an impartial but vital observer and contributor. Ron Thompson, who began his Aerospace career in the Gemini Program Office in 1964, recalls, “Aerospace added a second set of eyes and ears to provide an independent review. This definitely caused contractors to be more diligent, and to some degree that legacy remains the same today.”

In fact, the contractor’s handbook for Gemini launch vehicle employees stated that, “As part of the Pilot Safety Program, SSD and Aerospace impose stringent requirements during the acceptance phase. Hardware is not accepted until SSD and Aerospace are convinced that the hardware and documentation comply with appropriate specifications and other contractual requirements... Acceptance is characterized by a methodical approach and an uncompromising attitude.”

**Fixing the Target**

With Project Mercury wrapping up in the spring of 1963, Aerospace began phasing out its Mercury Program Office. Following the closure of the office that fall, Ben Hohmann and Ernst Letsch took over direction of the Gemini Program Office, which was officially known as the Gemini Launch Systems Directorate. By this time, the hard work of Aerospace engineers and the rest of the Gemini team was beginning to yield results, as the performance of the Titan II continued to improve in test launches. The first Gemini launch vehicle, GLV-1, was ready for testing in May 1963, but the vehicle was found to have defects, including serious problems with the wiring in the second stage. In July, Aerospace and SSD rejected GLV-1 after a combined systems test revealed numerous problems, including a lack of documented flight status for major components. After a second test in October, GLV-1 was approved and sent to Cape Kennedy to prepare for its launch as Gemini-Titan 1, the first of two scheduled flights without an onboard crew. Additional problems delayed the launch until April 8, 1964, but the flight was a complete success for both booster and payload, with the capsule remaining in orbit for nearly four days before reentering the atmosphere. Ben Funk, SSD Commander, described Gemini-Titan 1 as “just completely a storybook sort of flight.”

As the process of approving the Titan II for passenger flight continued, Aerospace received a formal request from SSD to begin technical surveillance of the Gemini Agena Target Vehicle (GATV). The target vehicle was a standard Agana, modified to permit docking with the Gemini spacecraft.

Work on the Agena started relatively late in the program because it was not scheduled for use until the fifth Gemini mission. Still, early development progressed very slowly, and the Air Force hoped that Aerospace could help the contractor sort out the problems. Indeed, SSD sought to alter its oversight strategy, applying Aerospace’s technical expertise in all phases of the Gemini program that were operated under Air Force contracts. As such, Aerospace was responsible for monitoring the Agena vehicles from subsystem fabrication through testing through prelaunch and launch. Portions of the Pilot Safety Program were applied to the target vehicle, but the difficulties continued, and the first Gemini Agena Target Vehicle, GATV-5001, was not ready for tests until November 1964. From the very beginning of systems testing, the vehicle displayed serious problems.

Meanwhile, as Aerospace engineers grappled with the ongoing difficulties of the Agena, preparations continued for the launch of Gemini-Titan 2. Even though it experienced several near-disasters while sitting on the launchpad at Cape Kennedy—

Joe Wambolt, Tom Shiokari, and Jim McCurry of Aerospace meet with astronauts Gus Grissom and John Young at Cape Kennedy. The meeting took place in March 1965 shortly before the two astronauts were launched on the Gemini 3 craft, which Grissom dubbed the “Molly Brown.” Left to right: John Young, Jim McCurry, Joe Wambolt, Gus Grissom, and Tom Shiokari.
including being struck once by lightning and twice by hurricanes—the rocket was finally launched on January 19, 1965. This suborbital mission, the final launch without passengers, almost equaled the success of Gemini-Titan 1 and cleared the way for Gemini 3, the first piloted launch.

Bold Moves
NASA, in danger of falling behind schedule, decided to wait just two months before launching Gemini 3, which was now scheduled for March 23, 1965. Mercury veteran Gus Grissom and crewmate John Young made up the flight team. Following the Mercury tradition of giving official names to the spacecraft, Grissom dubbed his Gemini capsule the “Molly Brown,” a reference to the Broadway play The Unsinkable Molly Brown. He chose the name because his Mercury spacecraft, the “Liberty Bell 7,” sank shortly after landing in the Atlantic Ocean. Perhaps because NASA officials felt that “Molly Brown” was undignified, Gemini 3 was the last to receive an official name. Future Gemini spacecraft would only receive a numerical designation. With only a few minor problems during its three-orbit mission, Gemini 3 met all of its major objectives and proved that the Gemini/Titan II configuration was suitable for human flight.

The first months of 1965 witnessed two successful Gemini launches, and the U.S. space program had now advanced well beyond the capabilities demonstrated during Project Mercury. Two additional successful missions followed with the launches of Gemini 4 on June 3 and Gemini 5 on August 21. The four-day flight of Gemini 4 was especially noteworthy, as it marked the first time that an American astronaut performed an extravehicular activity. Ed White’s “space walk” was important for morale, because Soviet cosmonaut Alexei Leonov had achieved the world’s first space walk on March 18. The ability of the Gemini team to duplicate this feat such a short time later meant that the U.S. space program was rapidly catching up with the Soviet program. Gemini 5, an eight-day mission, demonstrated the spacecraft’s rendezvous, radar, and long-duration flight capabilities.

Gemini astronauts were now ready to try a rendezvous and docking with an Agena target vehicle. The first attempt was scheduled for 1966, but was moved to the fall of 1965 to coincide with the launch of Gemini 6. On the morning of October 25, 1965, the Agena target vehicle (GATV-5002) was launched from Cape Kennedy. About two miles away, astronauts Wally Schirra and Tom Stafford were seated in their Gemini capsule awaiting their own launch so that they could begin pursuit of the Agena. In spite of a seemingly perfect liftoff for the Atlas rocket carrying the Agena, the initial joy of the flight controllers soon turned to confusion as they lost contact with the rocket just after six minutes into the flight. Radar observers reported several blips on their screens, and flight engineers were forced to conclude that the Agena had exploded over the Atlantic. Just 54 minutes after the countdown began for Gemini 6, NASA was forced to scrub the entire mission as a result of the Agena failure.

To get the problem-plagued GATV program back on track, SSD and Aerospace introduced Project Surefire in November 1965. This initiative, given emergency priority by SSD, was intended to ensure the flightworthiness of the Agena target vehicle. Project Surefire began by convening a symposium of propulsion experts, which concluded, in corroboration of the Aerospace analysis, that the vehicle’s use of a fuel lead propellant (i.e., a quantity of fuel that precedes the oxidizer into the thrust chamber during ignition) had led to engine failure.

The Agena’s engine would have to be redesigned, and members of Project Surefire would provide oversight and technical direction for this initiative. In one instance, Aerospace engineers prevailed upon the manufacturer to eliminate a lock-in relay in the pilot-operated solenoid-valve control circuitry, which they felt was unnecessary and could lead to potential problems. Joe Wambolt, who moved over to the Gemini Program Office following his work with Project Mercury, still feels pride in Aerospace’s activities during this time. “Project Surefire culminated in the best configuration obtainable, from hardware, procedural, and performance standpoints. There were no further engine failures on Gemini Agena vehicles.” Another benefit of Project Surefire was the close working relationship that it fostered among NASA, Air Force, Aerospace, and contractor personnel following the acceptance of many of Aerospace’s technical recommendations.

A Second Try
Following the cancellation of Gemini 6, NASA boldly decided to make a second attempt before the end of the year; however, rather than launch another Agena, the first rendezvous would be achieved through a dual launch of Gemini 6-A (as the flight was now renamed) and Gemini 7. This joint mission, which garnered the unofficial nickname “Spirit of 76,” began with the launch of Gemini 7 on December 4.
Astronaut Ed White performs the first American extravehicular activity on June 3, 1965, during the flight of Gemini 4. White was attached to his spacecraft by an umbilical line and a 7-meter tether line, which were wrapped together to form a single cord.

Astronauts Frank Borman and Jim Lovell were scheduled for a 14-day flight, which would set a new world record and prove that humans could live in near-zero gravity for extended periods.

The launch of Gemini 6-A was set for the morning of December 12. But just one second after engine ignition, the launch vehicle automatically shut down, and the launch was canceled. Soon after Schirra and Stafford were removed from the capsule, the launch was rescheduled for December 15, and engineers began searching for the cause of the aborted launch.

Aerospace personnel, who were already working around the clock, helped review all the available data. They discovered a drop in oxidizer pressure and argued that the oxidizer system should be dismantled. Ron Thompson recalls that “There was reluctance on the part of the contractor, but the Air Force insisted on checking out the problem.” The cause of the pressure drop was a dust cap that had been accidentally left in place between the oxidizer check valve and the injector.

Wambolt remembers this data review as a key lesson that still resonates in the work of Aerospace personnel. “Post-flight analysis is probably one of the cornerstones of our launch-vehicle readiness process that we have today for Atlases and Titans.” Aerospace historian Everett Welmers neatly summarized this discovery: “Careful attention to oscillograph wiggles had prevented a potential disaster.” With the dust cover removed, Gemini 6-A was launched on December 15, and the craft achieved rendezvous with Gemini 7 six hours after its flight began. The two capsules came within one foot of each other during the rendezvous operation. The next day, Gemini 6-A landed in the Atlantic Ocean, and Gemini 7 made its reentry on December 18.

Docking and Rolling

On March 16, Gemini 8 was lifted into orbit carrying astronauts Neil Armstrong and David Scott. The first space docking in human history went smoothly at first, but the astronauts soon found themselves out of alignment with their original position. Armstrong and Scott were unable to locate the source of the problem and believed the fault lay with the Agena vehicle. Once they managed to separate their spacecraft, however, Armstrong and Scott found themselves spinning uncontrollably. Apparently, the fault lay with their own craft. With the astronauts in danger of blacking out and their fuel supply running low, NASA ordered an emergency termination of the mission. Armstrong realized that a malfunctioning thruster was the cause of their gyrations, and the orbital attitude maneuvering system was shut down. The craft was stabilized only after the reentry system was activated and bursts were periodically fired from the small thrusters. Gemini 8 made a safe splashdown in the Pacific Ocean, east of Okinawa, after beginning its seventh orbit. A near tragedy of major proportions had been averted, and the crew had made the U.S. space program’s first emergency landing. Despite the problems with the Gemini craft and the early termination of the mission, the Agena target vehicle had performed extremely well in its first in-flight test after the Project Surefire modifications. The final objective of the Gemini program had now been achieved.

As a result of the successful modifications made to the Agena target vehicle, on January 16, 1966, GATV-5003 was given the green light for launch in conjunction with the upcoming Gemini 8 mission. Gemini astronauts had so far demonstrated that humans could function in space long enough to accomplish a lunar mission and could maneuver one orbiting spacecraft to achieve rendezvous with another. NASA was now anxious to perform a docking with the assigned target vehicle, as this was the final Gemini objective. With the conclusion of Gemini scheduled before the end of the year, NASA’s Gilruth wrote Funk in February to express his thanks for the contributions of Aerospace personnel and encourage their continued participation. “Aerospace has played a large part in making the Gemini Launch Vehicle (GLV) Programs successful to date, and we have come to respect and depend upon the services they provide the Government.”

Wambolt remembers this data review as a key lesson that still resonates in the work of Aerospace personnel. “Post-flight analysis is probably one of the cornerstones of our launch-vehicle readiness process that we have today for Atlases and Titans.” Aerospace historian Everett Welmers neatly summarized this discovery: “Careful attention to oscillograph wiggles had prevented a potential disaster.” With the dust cover removed, Gemini 6-A was launched on December 15, and the craft achieved rendezvous with Gemini 7 six hours after its flight began. The two capsules came within one foot of each other during the rendezvous operation. The next day, Gemini 6-A landed in the Atlantic Ocean, and Gemini 7 made its reentry on December 18. Funk sent his congratulations to Aerospace president Ivan Getting; “Even though faced with the disappointment of an aborted launch, a perfect countdown and a successful launch followed and made possible this nation’s first rendezvous. Please convey my thanks to all the members of your organization for their participation in this achievement.” In turn, Getting sent a telegram to Ben Hohmann, saying, “The contributions by you and your staff reflect great credit on The Aerospace Corporation.”
A Successful Close

During the remaining four flights, Gemini 9–12, astronauts performed additional rendezvous and docking maneuvers with the target vehicle and conducted more extra-vehicular activities. The reentry and recovery of the Gemini 12 craft on November 15, 1966, brought the program to a highly successful close. The list of accomplishments was staggering, considering some of the early problems that the program had faced. Ten passenger flights took place within the space of a mere 20 months, and the entire program came in on time and within budget. Astronauts acquired important experience working in conditions of near-zero gravity for extended periods and performed the U.S. space program’s first space walks. Many of the problems of rendezvous and docking had been solved, and the modified Titan II had proved itself as a capable launch vehicle. Invaluable lessons were learned for the upcoming Apollo missions, and all of this was achieved with a 100-percent safety record. In addition, by Gemini’s conclusion, the Soviet Union was no longer the clear leader in the space race. During the nearly two years of Gemini flights, the Soviets failed to launch a single piloted mission. The early post-Sputnik years of humiliation for the American space effort were largely forgotten by the time the Gemini program ended.

The entire space community made note of the Aerospace contributions to Gemini. The solid work performed alongside the Air Force and NASA made an outstanding contribution to The Aerospace Corporation’s legacy of partnership and trust. Fifteen Aerospace representatives received Outstanding Achievement awards from the Air Force for their work with Gemini. In a ceremony held at the Manned Spacecraft Center, NASA presented awards to Wambolt, Hohmann, Letsch, J. W. McCurry, Newton Mas, and Leon Bush. Words of praise for the Aerospace team poured in from around the country, but Vice President Hubert Humphrey perhaps best summed up the nation’s thanks in a letter he wrote to Getting on December 8, 1966. “Above all, this Gemini program has revealed how a team representing the Federal Government and private industry can work together and, in so doing, show the world in an open fashion the vitality and efficiency of our democracy and free enterprise system. I congratulate you and your associates for your contribution to Gemini. The American people are proud of your role and participation.”

Acknowledgement

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Further Reading

The Aerospace Corporation Archives, Ivan Alexander Getting Papers, Collection AC-036.
G. Kranz, Failure Is Not an Option: Mission Control from Mercury to Apollo 13 and Beyond (Berkley Books, New York, 2000).
Since its founding in 1960, The Aerospace Corporation has maintained an important presence at both the eastern launch range at Cape Canaveral Air Force Station in Florida and the western launch range at Vandenberg Air Force Base in California. Aerospace has provided on-site general systems engineering and mission assurance for essentially all the boosters, upper stages, and spacecraft launched since the beginning of the national space program. Each launch range offers specific advantages that reflect unique histories, locations, and development priorities. Similarly, the Aerospace teams at the east and west ranges have acquired the expertise and specialization needed to support these very different launch sites.

**Eastern Range**

Aerospace support at the Eastern Test Range began with Project Mercury in September 1960. The corporation’s role soon expanded to include support of the Gemini program, which used a modified Titan II intercontinental ballistic missile (ICBM) to launch two astronauts aboard a modified Mercury capsule (see “A Stellar Rendezvous”). With the successful completion of the Gemini program in 1966, the Titan launch vehicles became the Air Force’s primary workhorses and the main focus of Aerospace support for the Eastern Range.

An early task for Aerospace was the development of the Titan Integrate-Transfer-Launch (ITL) system and its associated Titan family of launch vehicles, Titan IIIA, IIIC, and IIIE. The ITL system was designed to assemble, check, and integrate the major components of the Titan IIIC before the booster would be transferred to the pad for payload mating and launch operations. The ITL system was conceived by Aerospace, which at the time was responsible for general systems engineering and technical direction for the facility design, the ground systems handling apparatus, the checkout procedures, and the launch equipment.

Aerospace participated in all ITL design reviews and oversaw the construction of...
The Eastern Range

The Eastern Range launch facility is located at Cape Canaveral Air Force Station on the Atlantic coast of Florida. It’s situated on a barrier island between the Banana River and the ocean, which provides a natural safety buffer around the launch area. The installation provides overwater flight for low-inclination and equatorial orbits and includes instrumentation sites along the Florida coast that support suborbital launches and mobile air and sea launches. The facility encompasses 15,800 acres, bordered by more than 23 kilometers of ocean coastline and nearly 20 kilometers of river shoreline. The Eastern Range headquarters are located at Patrick Air Force Base, about 33 kilometers to the south. The base was established by the Navy in 1940 to house antisubmarine patrol planes during the second World War. In 1948, it was transferred to the Air Force for use as a joint long-range proving ground. The first missile launch, a German V-2 equipped with a second stage, occurred in July 1950. The first U.S. orbiting satellite, Explorer 1, was launched from Cape Canaveral in early 1958. The first Atlas V evolved expendable launch vehicle blasted off the Cape in August 2002.

The Western Range

Vandenberg Air Force Base is located on the central coast of California, almost midway between San Diego and San Francisco. It’s the third largest Air Force Base in the nation, encompassing 98,400 acres. The first military installation on the site, an Army camp, was constructed in late 1941. Years later, the base was handed over to the Air Force, which, in 1957, began construction of the infrastructure and launchpads, beginning with seven Thor ballistic missile launchpads. The first Western Range launch of a Thor missile occurred in December 1958. In February 1959, the world’s first polar orbiting satellite, Discoverer I, lifted into space aboard a Thor/Agena from Vandenberg. That same year, Vandenberg housed the first nuclear ICBM to be placed on alert in the United States. By June of 1960, the Western Range had flight-tested 45 ballistic, orbital, and probe launch-vehicle systems. The Air Force annexed more land at the southern tip of the base in 1966 to construct Space Launch Complex 6 for the proposed Manned Orbiting Laboratory, which was never completed. The complex is being refurbished to accommodate the Delta IV evolved expendable launch vehicle.

The complex (which actually includes two launch areas, Launch Complex 40 and 41). Construction on the complex began in November 1962 on “islands” created using 5 million cubic meters of landfill dredged from the adjacent Banana River. A major contribution was to convince the Air Force to relocate the site from its planned location (just east of Cape Canaveral’s south gate) to its present location because range safety concerns would force the closure of the south gate and road during hazardous operations and launches.

Aerospace also provided general systems integration and technical direction for the launch of the Titan IIIA vehicles from Launch Complex 20 and for development of the Titan IIIC launch vehicle. Titan IIIC was based on the Titan IIIA core vehicle; these IIIA flights were important for demonstrating that the liquid-propelled core stages were ready to be mated to the newly developed solid-rocket motors to form the Titan IIIC and for verifying the viability of the Transtage upper stage. Aerospace also supported the launch of several Defense Satellite Communication System satellites during this period, followed by a series of Defense Support Program launches.

A Shift to the Shuttle

As the decade came to a close, Aerospace continued to support development of the Inertial Upper Stage (IUS) and to help transition the Air Force to the space shuttle. When the first IUS launched in October 1982, Aerospace had a team in place that had participated in the design reviews and early IUS testing (see “Evolution of the Inertial Upper Stage”). Shuttle launches took place at NASA’s Kennedy Space Center; Aerospace established an office there, primarily to ensure a smooth transfer of technology from NASA to the Air Force, which was developing its own space-shuttle launch capability at Vandenberg. But although Aerospace assisted in the testing and evaluation of the shuttle based on Air Force requirements, the office at Kennedy was never directly involved in shuttle processing or launch operations.

Following the first shuttle flight in April 1981, NASA and the Air Force began phasing out expendable launch vehicles. The government encouraged private industry to build and operate expendable launch vehicles to deliver commercial payloads, such as communications satellites; the shuttle would serve as the primary launcher for government payloads. This policy quickly changed after the loss of the Challenger in early 1986, which was joined by the failures of two Titan IIIs, a Delta, and an Atlas/Centaur, all within a span of 18 months. These incidents required extensive failure investigations and costly corrective actions before flights could resume. They also showed that no one launch vehicle could provide the guaranteed access to space that the nation clearly needed.

Staging a Comeback

Shuttle operations for Air Force programs ceased after the Challenger failure. Within a year, Launch Complex 41 was refurbished and reactivated to accommodate the heavy-lift Titan IV with its solid-rocket motor upgrade.

When the Air Force returned to the management of the military expendable launch vehicle programs, Aerospace already had a cadre of experienced personnel at Cape Canaveral who had participated in the Atlas ballistic missile development and Mercury-Atlas, Gemini-Titan, and Agena
space launches as well as Atlas facility construction and other pad conversions. This staff was later augmented by experienced Atlas engineers from Vandenberg. The Atlas/Centaur facility conversion was completed in 1991, and the first military launch took place the same year. The Aerospace Atlas team provided general systems engineering and integration support for military launch operations and third-party oversight of commercial launch vehicle processing. Many of these contributions were indeed significant. For example, following Centaur propulsion failures on two commercial Atlas vehicles, Aerospace determined that the problem could have been caused by a leaking cool-down check valve that allowed the ingestion of wet air into the Centaur’s turbo pumps during the boost phase. This theory was verified by an Atlas investigation team, and no similar Centaur failures occurred after the proposed fix was implemented.

As for the Delta launch vehicle, the Aerospace staff at Cape Canaveral gained invaluable experience observing the fledgling commercial Delta program, which prepared them for the accelerated GPS launches in the early 1990s. The GPS satellites were originally intended to fly on the space shuttle, so Aerospace had a large task in ensuring that the transition to the Delta II could support the mission.

Continued Evolution
After a period of contraction, the aerospace industry appeared to pick up in the mid-1990s, and more defense contractors sought to expand their presence in the potentially lucrative but risky commercial launch market. These contractors pressed for more autonomy, and in response, the Department of Defense (DOD) began to shift its procurement strategy, granting greater control and greater responsibility to primary contractors. The Evolved Expendable Launch Vehicle (EELV) was one result of this priority shift. The idea was to acquire launch services (rather than hardware) on a vehicle owned and operated by the contractor.

Aerospace involvement was expected to be minimal. Congressional funding cuts in the 1990s had reduced the Aerospace workforce by 30 percent. Following the failure of a Titan IVA in 1998, the Air Force recognized that a modest level of support would be beneficial. Staffing levels at the Eastern Range were raised slightly in 2000 and have continued to grow each year since then.

Range-Safety Hazard Analysis
Government regulations impose stringent safety requirements on launch planners. Perhaps that’s why no member of the general public or launch-site workforce has ever been killed in a U.S. launch. The Aerospace Corporation helps the Air Force’s Range Safety Offices maintain this admirable record of public safety. Examples of range-safety efforts include:

**Jettisoned-Body Impact-Point Prediction.** For all Titan II and Titan IV launches, Aerospace performs standard analyses to validate contractors’ predicted impact points for all planned jettisoned objects, including solid-rocket motors, thrust-chamber covers, payload-fairing sectors, and spent stages.

**Population Overflight Risk Assessment.** Overflight of populated areas carries a risk to human safety. If an anomaly brings down a launch vehicle before it achieves orbital velocity, people in its path can be injured or killed. Aerospace maintains a toolkit that can calculate the human safety risk for any trajectory; it combines detailed trajectory simulations with a comprehensive database of population density.

**Sonic-Boom Footprint Prediction.** A launch vehicle generates a sonic boom, and certain trajectories can produce focused shock waves that create significant overpressures. Aerospace has tools to compute sonic-boom footprints for ascent trajectories and has provided analyses for Titan IV, Titan II, and Atlas II launches.

**Near-Pad-Explosion Damage Assessment.** Inadvertent or emergency destruction of a launch vehicle can cause significant damage to nearby structures, possibly even destroying the launchpad itself. Aerospace has performed numerous statistical analyses to quantify the risks resulting from near-pad explosions. The methodology was recently used to evaluate the risk that a hypothetical EELV failure posed to neighboring launch facilities. Aerospace investigated multiple near-pad failure modes, calculated the probability of damage resulting from debris impact or blast overpressure, and recommended risk-mitigation procedures.
As in the heritage programs, Aerospace quickly earned trust and confidence as a “value-added” EELV contributor. Aerospace has been clearly recognized in the successful program milestones to date, including the launch of the first EELV, Atlas V, from Cape Canaveral in August 2002. The second EELV, the Delta IV, was launched from the Eastern Range in November 2002.

Western Range

Aerospace engineers were first assigned to the Western Test Range in support of the classified orbital Discoverer missions now known as the Corona program, which launched the world’s first photo reconnaissance satellites for the U.S. government. Support for this program began even before Aerospace established a permanent physical presence at the range.

An Aerospace office at Vandenberg was officially opened in 1962 to provide on-site monitoring and support to several emerging programs, most notably the Nike-Zeus antiballistic missile system and the Satellite and Missile Observation System. Aerospace was primarily focused on an extensive series of Atlas flight tests in support of the Advanced Ballistic Re-entry Systems (ABRES) program, which achieved its first Atlas launch in November 1964 (see “Ballistic Missiles and Reentry Systems: The Critical Years”). These tests typically involved launching long-range missiles over the Pacific toward the Kwajalein Atoll to test not only the long-range capabilities of the U.S. nuclear arsenal but the antimissile systems stationed for testing at Kwajalein.

Aerospace participated in 81 ABRES launches and 52 space launches using refurbished Atlas ICBMs during a 30-year period. These space launches typically occurred at Space Launch Complex 3 (SLC-3), which was built for the Air Force in the early 1960s to launch Atlas D/Agena and subsequently modified to launch the Thor; Atlas E, F, and H; and Atlas II family of boosters.

The Birth of SLC-6

Aerospace personnel additionally began to provide operational planning and activation support to the Manned Orbiting Laboratory (MOL), a near-Earth space station that would let military astronauts conduct experiments and reconnaissance for up to 30 days. Construction of Space Launch Complex 6 (SLC-6) began at Vandenberg in March 1966 to prepare for the initial launch. Aerospace served as the general systems engineer and technical director for MOL, and as such, played a key role in conceiving, designing, and developing the project. Following construction of SLC-6, a plan was proposed to launch seven laboratories from Vandenberg on modified human-flight-rated Titan IIIM boosters. Five launches—including one with an onboard crew—were planned to begin in December 1969. As a result of technical problems, schedule delays, changing national priorities, and the cost of fighting the Vietnam War, the program was canceled in June 1969. With its cancellation, the nearly completed SLC-6 lay unused for almost 10 years.

Although the MOL program was gone, overall launch vehicle activity at the Western Range continued at a busy pace. About 30 to 40 launches were completed each year—including launches of development versions of the Minuteman ballistic missile pro-

Why Two Ranges?

Although the eastern and western ranges share many similarities, each has distinct limitations and advantages. Two azimuths, 35 degrees north and 120 degrees south, represent the space launch limits from the Eastern Range. Any trajectory further north or south would send a spacecraft over an inhabited landmass. This would adversely affect safety provisions for abort or vehicle separation conditions and raise the undesirable possibility that a solid-rocket booster or external tank could fall in foreign territory. Although it is possible to access polar orbits from Cape Canaveral, it would require an energy-expensive “dogleg” flight path, resulting in a significant loss of payload capacity. The opposite is true for Vandenberg: Polar orbits are readily achieved without significant safety concerns, but equatorial space launches are precluded by overflight of the United States (a retrograde equatorial launch—opposite to Earth’s rotation—would not be advantageous because of the greater energy costs). The Western Range, from its inception and throughout its history, has essentially been a DOD “war-fighting” asset, established to conduct research and development of ballistic and air-defense missiles and to support national defense space lift operations. While supporting the common requirement for military access to space, each range has evolved its individual, complementary specialization.
and Titan II ICBM as well as space launchers such as Thor/Agena, Titan/Agena, Titan IIID, Atlas/Agena, and Scout. Aerospace launch operations support concentrated on Atlas E and F and Titan IIB and IIID space missions.

In January 1979, the Air Force approved a six-year plan to transform SLC-6 into a space-shuttle launch facility and assigned Aerospace the role of general systems engineering and integration. Preparation for the shuttle would require substantially more than just refurbishing and modifying the SLC-6 site. Additional infrastructure would be needed, on both the south and north sides of the base. Aerospace provided technical direction for development and testing of the ice-suppression system, sound-suppression system, hydrogen-disposal system, power plant, and wastewater treatment plant (see “The Air Force Space Shuttle Program: A Brief History”).

The Air Force relocated its Shuttle Activation Task Force from Los Angeles to Vandenberg in 1981; Aerospace established a shuttle office there as well, and onsite Aerospace personnel became directly involved in every aspect of the project.

After major construction had been completed and systems installed, the space shuttle Enterprise was brought to Vandenberg and erected to perform form, fit, and function tests. This system-test unit—which was transported atop a jumbo jet and never actually flew in space—marked the culmination of years of hard work by Aerospace, Air Force, and contractor personnel. Its successful test runs paved the way for a fully operational Air Force space shuttle.

In October 1985, after an expenditure of about $4 billion, SLC-6 and the associated shuttle infrastructure achieved initial launch capability, and a first launch was scheduled for 1986; however, following the loss of the Challenger, SLC-6 was again abandoned. Enterprise would be the only shuttle that SLC-6 would ever see.

**Resurrecting the Titan**

The Air Force refocused its attention on the Titan 34D. The catastrophic failure of a Titan 34D shortly after liftoff from SLC-4E starkly illustrated the risks of adding solid rockets to launch vehicles. Following this incident, Aerospace recommended that the launch control center be moved to a safe distance more than 25 kilometers away.

On the East Coast, Launch Complex 41 was being readied to receive the Titan IV, and DOD saw the need for a similar capability at Vandenberg to handle large and heavy payloads. Aerospace was asked to assist in the construction, activation, and launch of the Titan IV vehicles.

The Air Force determined that modifications to the Titan III launchpad at SLC-4E would be the cheapest and fastest way to get the Titan IV up and running. To speed up the process, it was decided that Titan III systems and equipment would be reused whenever possible. This turned out to be a bad decision.

The first significant challenge involved the reuse of the mobile service tower and the supporting foundation. The old mobile service tower could not be enlarged to accommodate the Titan IV. This late revelation caused the Air Force to reevaluate its management approach; it increased Aerospace support and formed “Design Tiger Teams” staffed with Aerospace and contractor personnel. Aerospace was present at all critical design decision points and provided both technical and operational inputs to the Air Force. The contractor submitted the facility design criteria and payload requirement document in September 1986. Aerospace participated in all upgrades and delineated important lessons learned from similar facility modification projects.

According to a new modular construction plan, the mobile service tower would be built in sections at a facility in Oregon, shipped by barge to Vandenberg, transported to SLC-4E, and erected using jacking towers. At the same time, SLC-4E would be modified to receive the mobile service tower modules. The steel umbilical tower would be erected, foundation work completed, and the underground utilities and cabling installed. Aerospace participated in the daily and weekly planning of these activities and supported development of the ground support equipment design, which proceeded in parallel with the launch complex modification.

This effort involved the design of the command and control interfaces between the Titan IV vehicle and the ground support systems, including the propellant, pneumatics, electrical power, environmental controls, and control software. The Titan Flight Readiness Plan, developed by Aerospace, was the first readiness plan for space launch vehicles without an onboard crew. It was patterned after the successful Mercury and Gemini Pilot Safety Programs and specified both continuous and milestone requirements for Titan launch vehicle processing. It became the governing document for Titan processing and was subsequently adopted for other space programs as well.

The development of the Titan IV launch capability at Vandenberg included several other major infrastructure improvements.
beyond the SLC-4E modification. Major upgrades and specialized command and control equipment were added to the remote launch control center to monitor the prelaunch processing and launch activities. Aerospace provided support to the Air Force for all facilities during these critical developments. Initial launch capability for the Titan IV at SLC-4E was declared in October 1990.

Facility Upgrades

Also in 1990, SLC-6 got a new assignment, and Aerospace again assisted the conversion plans. This time, the pad would be used for a Titan IV booster with a Centaur upper stage. Development of the so-called Titan/Centaur Launch Complex at SLC-6 progressed through concept evaluation and preliminary design; however, the Air Force terminated construction in early 1991, citing insufficient launch requirements to justify the expense.

In 1992, the Air Force decided to upgrade SLC-3E from an Atlas I to an Atlas II site to provide medium-lift launch capability for surveillance, communications, and exploratory satellites. Affected by the end of the Cold War and increased commercial launch services competition, the Air Force implemented a partnering program for management and concurrent engineering. This included increased government participation early in the process of generating requirements; incorporation of lessons learned during the construction and modification of SLC-4 and Launch Complexes 40 and 36 at Cape Canaveral; and active government involvement in the design, construction testing, activation, acceptance, and contract closeout activities. Aerospace played a significant role in this effort by providing systems engineering support. The new acquisition methodology required close collaboration between the government and contractor, with Aerospace providing programmatic and technical assistance. Cross-functional product development teams (the precursor to modern integrated process teams) were established to develop the SLC-3E ground support systems during the design phase.

In the course of modifications, contractor crews dismantled and removed an existing 64-meter mobile service tower and umbilical mast, built a new tower and mast on top of a launch services building, and modified the services building itself. Other tasks included installation of a heating/ventilating/air-conditioning system and various physical security facilities, as well as expansion of the complex’s fuel storage and loading systems. The resulting SLC-3E provides unprecedented launch and satellite vehicle access and processing capabilities, with a protected working environment for its crew. Initial operating capability was achieved in September 1997, and the first Atlas IIAS left the pad in December 1999, carrying NASA’s 4850-kilogram, $1.3 billion Earth Observing System satellite. The second Atlas IIAS success followed in September 2001, with the launch of a classified NRO payload. Operations of Atlas II facilities at SLC-3 are scheduled for closeout in 2003. Another NRO mission is scheduled for mid-2003; the fate of the facility after that launch has not yet been determined.

In 1994, the Air Force leased out SLC-6 to a contractor interested in testing a new small launch vehicle. The first launch attempt in August 1995 failed to place its payload into orbit, but did accomplish the first successful launch from SLC-6 after nearly 30 years and several major program efforts. Following three successful launches, the program was moved to the Kodiak Launch Site in Alaska.

Soon thereafter, SLC-6 was again leased out, this time for the Delta IV EELV program. Transformation of the complex began in 2000. In addition to modifications to the launch site, a new horizontal integration facility was built as well as a new operations control center within the existing remote launch control center on the north side of the base. Aerospace participated in all design reviews and provided the Air Force acquisition office with detailed insight into activation activities. With this effort, the Aerospace field site engineers at Vandenberg—like their counterparts at Cape Canaveral—are transitioning to the era of EELV and plan to support the first West Coast EELV Delta IV launch in 2003.

Conclusion

During the course of 50 years, the two test ranges have conducted more than 4000 major launches—including 123 at Vandenberg in one year alone. As the early period of intensive research and development wound down, the ranges continued to serve the nation’s ballistic missile development program and expanded their roles in civilian and commercial space. Over the years, the two ranges have hosted every major launch vehicle program in the history of the U.S. space program. Aerospace provided technical support for more than 1100 launches during its 40 years at the ranges, including Thor, Atlas, Delta, and Titan launches; all U.S. passenger spaceflights; and launches of the Scout, Pegasus, and Taurus rockets. Był to zdanie odesłane do Crosslink. Winter 2002/2003 • 21
On January 1, 1986, the maiden flight of the Air Force space shuttle program was just six months away. This flight, mission 62-A, would mark the beginning of the Air Force’s shuttle launch service from Vandenberg Air Force Base in California. The crew—which included Edward “Pete” Aldridge Jr., then Secretary of the Air Force—was completing preflight training at Johnson Space Center in Houston, Texas. The space shuttle Discovery had accomplished its latest mission in August 1985 and was being serviced at Kennedy Space Center in Florida prior to its shipment across the country. The external tank, which carries the fuel and oxidizer for the orbiter’s main engines, was being certified in the checkout facility at Vandenberg, and the solid-rocket booster segments were in prestack processing at the solid-motor facility. The first payloads were nearly set to go, pending final integration. Vandenberg’s flight-hardware processing facilities were ready, and Space Launch Complex 6 (SLC-6), where the space shuttle would launch, was nearing the end of its operational readiness testing. Meanwhile, Aerospace personnel were wrapping up their training at Kennedy Space Center, Johnson Space Center, and Vandenberg to support launch operations. Among its many firsts, the launch of mission 62-A was to be the first human spaceflight into polar orbit.

A Long Road

These final preparations marked the culmination of a long and intense development process that included extensive Aerospace support. In fact, the Air Force space shuttle program dates back to 1971, when the first conceptual studies concerning payload capability, upper stages, and launch sites were initiated. The Air Force began these studies in concert with NASA, but each organization had somewhat different priorities. NASA, for example, was most concerned with planetary exploration and scientific missions using satellites inserted in equatorial orbits. The Air Force, on the other hand, needed to launch critical defense and reconnaissance satellites, primarily into polar orbits.

Aerospace participated in early studies that showed a West Coast launch site for Air Force missions would be needed to complement NASA’s East Coast launch site at Kennedy. Launch-site studies in 1974 led to the selection of SLC-6 at Vandenberg, which was well situated for launching classified satellites into polar orbits. The complex had been built in 1969 to launch the Air Force’s Manned Orbiting Laboratory, but was never used because the program was canceled before first flight. By modifying the existing structures on this site, the Air Force hoped to save $150 million in construction costs.

These cost savings never materialized. Instead, the launch complex went through an extensive series of redesigns to satisfy changing requirements. Some of these changes reflected new Air Force mission...
requirements, while others arose to meet changes in the space shuttle itself, which was still evolving in response to NASA testing, which was proceeding in parallel with SLC-6 construction.

Aerospace oversaw facility design studies that led to the unique features of SLC-6 needed for Air Force missions, such as a secure payload processing facility within 300 meters of the launchpad. Aerospace was responsible for developing system and facility specifications, supporting contractor selection, evaluating designs, developing activation plans, and overseeing the final construction and activation testing of SLC-6 and other facilities for flight hardware processing, control, and crew operations.

Special attention and analyses were necessary to adapt the existing site to the special requirements of the space shuttle. These included small-scale test programs and extensive analyses of liftoff loads and dynamics, ice formation, launch vibro-acoustics, orbiter handling and space shuttle assembly, flight crew emergency egress, sonic booms, and hazards to the closely spaced facilities and surrounding environment.

**Groundbreaking Work**

Modification of the abandoned SLC-6 for space shuttle operations began in January 1979. A small contingent of Aerospace engineers was stationed onsite from the start of construction; a larger complement would follow afterward, when the entire program office would be moved from Los Angeles to the launch site at Vandenberg.

Most of the refurbishment focused on the main launch complex, though SLC-6 itself was not the only challenge. The Air Force space shuttle program also required a landing strip nearly 5 kilometers long and various specialized facilities—for mating and demating the orbiter and its 747 carrier aircraft, orbiter maintenance and checkout, flight crew preparation, logistics and supply, processing the external tank, refurbishing the solid-rocket booster, and recovering the solid-rocket booster. Aerospace oversaw the design, construction, activation, and operational readiness testing of all these installations, including the commissioning and sea trials of the naval vessel for retrieving the solid-rocket boosters after launch.

While assisting the facility development, the Vandenberg team also participated in space shuttle testing at Johnson Space Center, Marshall Space Flight Center, and Kennedy Space Center leading up to the first NASA launch in April 1981. Aerospace helped formalize the lessons learned from these efforts, reported them to the Air Force, and ensured that they were implemented into the systems at Vandenberg.

Partly because of the location, and partly because of the different nature of Air Force missions, the new facilities at Vandenberg...
required capabilities that the NASA complex at Kennedy did not provide. For example, SLC-6 had a 4000-ton moveable wind screen standing 70 meters tall to shelter the orbiter during mating with the external tank. Sound suppression was enhanced through a 3-meter-diameter underground water system flowing nearly 3.8 million liters per minute. This water system absorbed the launch acoustics generated by the rocket thrust and prevented its reflection into the flight systems and payloads. A water-treatment facility reclaimed nearly 1.9 million liters of this sound-suppression water, which was contaminated with exhaust products from the solid motors after each launch. A unique hot-gas heating system powered by a pair of turbofan engines was used to prevent ice formation on the external tank. The payload processing facility (which was designed to handle three \(4.5 \times 18\)-meter satellites simultaneously) was equipped with state-of-the-art electromagnetic shielding. A 15-megawatt power plant provided dedicated power for all these facilities. The whole complex employed a seismic design capable of withstanding a severe earthquake.

With construction nearly complete, the Aerospace program office was transferred to Vandenberg in early 1982 to support formation of a site-activation task force. Operational verification testing began in 1984, and a joint NASA/Air Force operations team was formed, with Aerospace in the lead technical support role for the government. Facility verification tests using the orbiter Enterprise (an unpowered experimental model that was deployed from a jumbo jet, not launched from a launchpad) were completed in March 1985. All systems were go for an auspicious first launch in the summer of 1986.

All Systems Stop
That first launch never happened. On January 28, 1986, the Challenger accident resulted in the death of seven astronauts and the demise of the Air Force’s space shuttle plans. The White House rescinded its 1982 mandate requiring all government payloads to fly on the space shuttle and instructed the Air Force to restart the expendable launch vehicle production lines. The space shuttle facilities at Vandenberg were once again abandoned, partly because the investigation into the Challenger failure resulted in design changes that rendered the shuttle incapable of lifting the satellites planned for polar flights out of Vandenberg. The Aerospace space shuttle program office was disbanded, and its personnel were reassigned to the new expendable launch vehicle programs and advanced launch studies. The primary payload flew on a later space shuttle mission out of Cape Canaveral; however, the second payload, Teal Ruby, never flew in space. The remaining DOD shuttle payloads planned for Vandenberg were placed on the manifest for the older Titan 34D and the new Titan IV launch systems. No human spaceflight has yet taken place in polar orbit.

**Further Reading**
Space Launch Complex 6

The 125-acre Space Launch Complex 6 (SLC-6), with its three massive moveable structures, was the major development for shuttle operations at Vandenberg; nonetheless, large-scale facility construction occurred throughout the base as well as at the Navy facility at Port Hueneme, California. In fact, 53 major facilities were constructed at 14 sites. A chronology of the development of SLC-6 is pictured here.

SLC-6 as it looked in 1979, just before the start of modifications for the Air Force space shuttle. The large mobile service tower in the right foreground, the exhaust duct in the center, and the buildings in the distance were all modified for space shuttle use.

Line drawing of an early SLC-6 configuration for the Air Force space shuttle, circa 1976. Changing requirements spawned at least six major design configurations. In early plans, the Payload Changeout Room (the moveable structure in the left foreground) hoisted the payloads vertically from a staging area below ground.

Artist’s rendering of SLC-6 at the start of construction in 1979. At left is the payload staging area, which grew into an aboveground secure multiple-payload processing facility of huge proportions. The building was fully hardened to withstand the launch environment despite its close proximity to the launchpad. The mobile Payload Changeout Room, located in the center of the drawing, was modified to transfer the payloads horizontally instead of vertically from the staging area and also to lift the orbiter and attach it to the external tank. Slide wires—to carry the flight crew in baskets from the orbiter to an explosion-proof bunker during an emergency evacuation—can be seen in the middle background.

Artist’s rendering of SLC-6, circa 1982, in its final configuration. This layout shows all three of the massive moveable structures, each weighing more than 4000 tons. The last addition was the moveable windscreen (or Shuttle Assembly Building), used along with the mobile service tower to hoist the orbiter from its transporter, rotate it to the vertical position, and mate it to the external tank without damaging delicate interface fittings during gusty winds. The original design used hydraulic arms on the front of the Payload Changeout Room, but this concept was abandoned in light of new information obtained during NASA space shuttle operations. Partially visible at the far left (just above the Payload Preparation Room) is the Launch Control Center, just 350 meters from the space shuttle at liftoff. Plans for a remote control center were under way, but it would not be available for the inaugural launch.

Artist’s rendering of SLC-6, circa 1982, in its final configuration. This layout shows all three of the massive moveable structures, each weighing more than 4000 tons. The last addition was the moveable windscreen (or Shuttle Assembly Building), used along with the mobile service tower to hoist the orbiter from its transporter, rotate it to the vertical position, and mate it to the external tank without damaging delicate interface fittings during gusty winds. The original design used hydraulic arms on the front of the Payload Changeout Room, but this concept was abandoned in light of new information obtained during NASA space shuttle operations. Partially visible at the far left (just above the Payload Preparation Room) is the Launch Control Center, just 350 meters from the space shuttle at liftoff. Plans for a remote control center were under way, but it would not be available for the inaugural launch.

This photo of SLC-6 in March 1985 shows the space-shuttle stack—consisting of the orbiter Enterprise mated to an external tank and inert solid-rocket motors—sitting on the launch mount. The Enterprise, a nonflight orbiter used in approach and landing tests, was used to verify the launch complex design. It is now under the care of the Smithsonian's National Air and Space Museum.
The intercontinental ballistic missile (ICBM) and intermediate-range ballistic missile (IRBM) programs progressed rapidly in the 1950s and 1960s, spurred by the need to establish a nuclear deterrent. But DOD realized that superiority in space would ultimately prove as important as a long-range strike capability. As a result, many of the medium-lift boosters that came from these ICBM and IRBM programs were enhanced to meet the demanding performance requirements of space-related missions. In particular, many versions of the Thor/Delta and Atlas boosters were modified to fly with various upper stages, such as the Burner, Agena, and Centaur. The Aerospace Corporation played a vital role in these early space-related booster developments, and continues to support the advancement of medium-lift launch vehicle technology.

First Flights
The first Thor IRBM was launched in January 1957, followed by the first Atlas ICBM in June. Within a short time, the first polar-orbiting satellites—including the very successful but highly classified Discoverer series—were launched using the Thor booster and Agena upper stage combination. Atlas orbital missions began in December 1958—just in time to permit the first satellite transmission of a Christmas message from President Eisenhower.

By mid-1960, Thor had flown more than 90 flights, and various Atlas configurations had flown 55 times; however, success rates for both vehicles barely reached 65–70 percent. NASA, newly formed in October 1958, teamed with the Air Force Ballistic Missile Division to oversee modification of...
the Atlas D booster for the piloted Mercury spacecraft and later the Titan II booster for the piloted Gemini flights. The Air Force in turn asked the newly formed Aerospace Corporation to provide general systems engineering and integration. Many of the Aerospace engineers on the Mercury-Atlas program came from the Atlas ICBM development project. As a result, Aerospace was able to use its technical expertise to directly influence the success of the piloted Mercury and Gemini missions. Aerospace also became involved in the Atlas standard launch vehicle flights in support of classified Air Force programs.

Upgrading the Atlas

While the Atlas was achieving notable success in the spaceflight area, its usefulness for purely military applications was coming to an end. With the advent of the solid-fueled Minuteman ICBM, the liquid-fueled Atlas E/F vehicles were deactivated as weapons systems in 1965 and shipped to Norton Air Force Base in California for storage. In the next six years, more than 30 of them were flown to support the research efforts of the Advanced Ballistic Re-Entry Systems program (ABRES), which was investigating ways to penetrate Soviet missile defenses. As a result of these research flights, the Air Force Space Test Program discovered the economy of these vehicles, and sought to use them for selected scientific space missions.

From 1970 to 1971, Aerospace recommended several reliability improvements that would foster the use of weapon-grade Atlas E/F boosters for space-related programs. For example, Aerospace pressed for upgrades in electronic part quality, redundancy in hydraulic control systems, and additional environmental testing of critical guidance components. Other improvements included redundant ground guidance computers and a greater emphasis on failure analysis and corrective action.

In 1971, the Air Force transferred responsibility for the Atlas E/F assets from the Ballistic Missile Division to the Launch Vehicles System Program Office. But converting these defensive missiles into safe and reliable space launch vehicles was no easy task, and Aerospace focused attention on the need for increased technical oversight. For example, the decommissioned ICBM fleet had been deployed and filled periodically with propellants as part of military training exercises. Consequently, they would need refurbishment and modification to bring them back to baseline condition. The Air Force implemented a program to remove the aging Atlas vehicles from storage and refurbish them on an “as needed” basis. With Aerospace assistance, the Air Force would conduct a formal validation of each booster after the refurbishment was complete. Aerospace worked closely with the Air Force to construct a Launch-Readiness Certification program for every mission flown on Atlas E/F, employing all the Air Force systems engineering policies in effect at the time. Essentially the same approach is used today on Atlas and Delta missions, including the component evaluation and emphasis on failure analysis and corrective action.

The user community grew in the mid-1970s, and Aerospace’s general systems engineering and integration responsibilities expanded to include many missions that posed unique requirements for integration and launch vehicle design. The most challenging, for example, was Seasat, which integrated an Agena second stage with the
Atlas E/F for the first time and flew from a modified launchpad. The Seasat mission was the heaviest upper stage and satellite combination ever flown on the Atlas E/F, and it necessitated a new approach to structural and flight-control system design and analysis. Likewise, early GPS missions employed a newly developed two-stage spin-stabilized upper stage, which required extensive analysis and testing to ensure that the separation of the spinning stages would be stable.

During these years, Aerospace developed an array of tools for independently analyzing loads, controls, trajectories, and environments. Three-dimensional load analysis was introduced to Atlas for the first time. Original plans to launch an occasional Space Test Program mission grew to include 52 missions, which depleted the inventory of stored Atlas E/F vehicles (including several retrieved from museums). The first of these missions was launched successfully in October 1972. Although 28 successful missions were achieved, three failures involving propulsion prompted a major technical upgrade of the remaining 21 vehicles in 1981, including a complete teardown, rebuild, and hot fire of the Atlas MA-3 engine systems.

The Atlas, Delta, and Titan II boosters are generally considered medium-lift launch vehicles because of their payload capacity, though the distinction is somewhat arbitrary. Generally speaking, a medium launch vehicle can place a payload of 360 to 6800 kilograms into a 185-kilometer polar orbit. Small launch vehicles such as Pegasus and Taurus can lift about 270 to 900 kilograms, and a heavy-lift vehicle such as a Titan IV or space shuttle can deliver more than 14,500 kilograms to the same orbit. Medium launch vehicles generally cost about a third or less than a heavy-lift Titan III/IV.

DMSP, GPS, DSCS, and most research spacecraft are sized to meet the mass, height, and diameter specifications for a medium-class booster. The process of payload/booster integration is decided in early studies before final design. Given the international competition among launch vehicle providers, this becomes a large effort for spacecraft designers.
The upgrade changes were made to all critical systems of the Atlas E/F booster, including ground checkout equipment and procedures. Aerospace initiated a yearlong independent review to evaluate the changes being made to the remaining 21 Atlas E/F boosters to instill confidence that those missions would be successful. In addition to the engine overhaul program, flight-control and guidance systems, hardware, and test equipment were retrofitted with the solid-state electronics that were being used in the newly manufactured Atlas space launch vehicles. The Air Force funded this upgrade effort and also formed a permanent reliability improvement program to allow for the evaluation and implementation of new ideas as the flyout continued. As a result, all 21 of these upgraded Atlas E/F vehicles successfully placed satellites into their prescribed orbits, serving programs and organizations as diverse as the Defense Meteorological Satellite Program, Global Positioning System, National Oceanic and Atmospheric Administration, Space Test Program, and National Reconnaissance Office. The last such mission was successfully flown in March 1995.

Aerospace support for the Atlas E/F refurbishment and launch program lasted more than 24 years. The Atlas E/F provided an economical (less than $15 million) and reliable booster for many research and development programs and proof-of-concept test flights.

**Priority Shifts**

In 1972, with the end of the space race, President Nixon decreed that the United States would rely on the partially reusable space shuttle for routine, reliable, inexpensive access to space. This represented a major shift in the national priority: No longer would the United States employ expendable launch vehicles based on the original ICBMs.

With this strategy in mind, DOD and NASA began to launch the last of their expendable launch vehicles and stopped investing in any facilities, infrastructure, and

The Atlas II booster was 2.7 meters longer than the Atlas I and featured more powerful and efficient engines. The Atlas IIAS, shown here, added four solid-rocket boosters to the core Atlas stage. The Atlas II series has achieved 100 percent operational success.
The lift capacity for the Delta family of rockets has increased significantly throughout the years. The latest Delta II configuration features elongated graphite-epoxy strap-on solid-rocket motors (SRMs).

Payload to geosynchronous transfer orbit in kilograms

- **1960**: Delta
- **1963**: C
- **1964**: D
- **1965**: E
- **1968**: J
- **1970**: M
- **1973**: M6
- **1975**: 904
- **1977**: 2914
- **1980**: 3914
- **1982**: 3920
- **1989**: PAM-D
- **1990**: 3910
- **1995**: 2914
- **1996**: Delta II 7925
- **1998**: Delta II 7925
- **2002**: Delta II 6925
- **2005**: Delta II 6925
- **2009**: Delta II 6925

### Range systems

Range systems that were not required to support the space shuttle. NASA adapted facilities developed for the Apollo program to support the space shuttle at Kennedy Space Center in Florida, and the Air Force undertook a $4 billion development program to build and certify extensive shuttle processing and launch facilities at Vandenberg Air Force Base in California.

The loss of the Challenger in January 1986 prompted a total reversal of space policy. President Reagan directed federal programs to reinstate an expendable launch vehicle capability for all future routine satellites as well as for DOD satellite programs previously on the space shuttle manifest.

As a result, the Air Force selected the Delta II to launch GPS satellites and the Atlas II to launch Defense Satellite Communication System (DSCS) satellites. These high-priority defense payloads, which had been designed to fly on the space shuttle, were compatible in size and mass with the boost capability of the medium launch vehicles. Moreover, the
Delta II and Atlas II represented further evolutions and refinements of the original ICBM designs, enabling them to accommodate these satellites.

Switching Back: Delta II and Atlas II

Acquisition reform wasn’t an official policy in 1988, but the Air Force nonetheless sought to streamline procurement by buying launch services from both contractors. In this way, the Air Force would support the contractors’ plans to build launch vehicles to a single standard of quality for NASA, the government, and the resurgent commercial satellite market.

The strategy would provide the Air Force with an economical price based on larger production runs while encouraging the contractors to invest in quality processes and manufacturing facilities. Aerospace was contractually permitted to participate in the development decisions and was charged with determining the launch readiness of every DOD-assigned launch vehicle as it progressed through production and launch preparation.

Aerospace performed an independent analysis for each booster-payload configuration (such as GPS, DSCS, STP) and did not repeat the analysis unless a major change was made to the launch vehicle or satellite. These analyses emphasized hardware performance evaluation, anomaly resolution, flight data review, and an extensive “pedigree” evaluation of mission-critical components.

This pedigree evaluation has since become a cornerstone of Aerospace launch-readiness assessments. A tedious and labor-intensive process, it entails a background check of the hardware: process and test history for more than 200 critical components. Aerospace engineers familiar with the design and manufacturing details of the electronic components, pumps, regulators, engines, valves, and explosive ordnance review the critical hardware to ensure that assembly and testing of each part was completed in a satisfactory manner.

Thanks in part to this pedigree evaluation, the Delta II achieved a remarkable success record for the Air Force, prompting NASA to adopt it for space science missions. In 1992, Aerospace began to conduct component pedigree services for NASA Delta II missions as well, and still performs this service, providing confidence that experienced specialists have conducted painstakingly detailed review of the critical hardware flown on each mission.

By 1992, 13 GPS satellites were successfully deployed, and the 24-GPS constellation was completed in March 1994 using the Air Force’s redeveloped Delta II. The medium-lift launch vehicle program is still compiling an excellent track record, with 11 of 11 Atlas/DOD launches and 37 of 38 Delta II launches achieving ultimate mission success. The only failure of a Delta II involved one of the eight graphite-epoxy strap-on solid motors. This problem was particularly puzzling, because 333 of these solid motors had already flown without incident. Aerospace determined that the failure was caused by undetected damage to several layers of graphite-epoxy fibers in the protective case surrounding the solid propellant. As the protective outer layers of graphite-epoxy fibers failed, the ability of the motor case to contain the pressure of the internally burning propellant decreased, eventually resulting in rupture. As a result, all motors are now given an extensive ultrasonic inspection prior to flight to find hidden damage from handling and manufacturing.

Conclusion

The medium class of Atlas, Delta, and Titan launch vehicles has provided military, civilian, and commercial space programs with hundreds of successful missions. By helping to develop the “best practice” processes now in place, Aerospace made a major contribution to the ultimate success of these boosters. Applying these reliable processes to the new generation of Atlas and Delta evolved expendable launch vehicles will extend the remarkable performance records for these versatile medium-lift boosters.

Evolution of the Atlas

The research and development phase of the Atlas ICBM program produced three experimental models, Atlas A, B, and C. Three subsequent models reached operational status. The first, Atlas D, was a liquid-fueled one-and-a-half-stage missile equipped with radio-inertial guidance and a nuclear warhead. It was stored horizontally above ground in an unprotected launcher. Atlas E featured all-inertial guidance, stronger engines, and a larger payload capacity; it was also stored horizontally, but in a semihardened launcher. Atlas F also used all-inertial guidance, but these missiles were deployed in underground, blast-protected silos; stored vertically; and raised on elevators for launch. All Atlas models had a range of approximately 12,000 kilometers.
Epic Proportions: 
For decades, Titan boosters have provided unflagging medium and heavy launch capacity for critical military payloads.

Art Falconer

The Titan Launch Vehicle

The history of the Titan space launch vehicle covers more than 40 years and has its roots in the early age of space rocketry. From its earliest role as an ICBM, the Titan has evolved through dozens of configurations to serve diverse military and scientific missions. With more than 360 launches to its name, the Titan has deservedly earned a reputation as the workhorse of the U.S. fleet of expendable launch vehicles. Aerospace personnel count among the thousands of dedicated individuals who share credit for the Titan’s remarkable long-term success.

The Early Impetus

The Titan II ICBM was first converted into a space launch vehicle to support the Gemini program (see “A Stellar Rendezvous”). At about the same time, the Air Force asked the newly formed Aerospace Corporation to evaluate two proposals for launching a piloted orbital glider. The first involved a new vehicle using a solid-motor first stage with a liquid-powered second stage; the second was the liquid-powered two-stage Titan II, modified by adding strap-on solid motors for the initial stage. The Titan II approach won out, and the booster was renamed Titan III. The Air Force established a system program office in November 1961.

Although the Air Force had not identified any payloads for the Titan III other than the orbital glider (which was canceled before final testing), it became clear that future payloads would cover a spectrum of space needs: reconnaissance, communications, military orbital development systems, satellite inspection and interception, surveillance and early warning, and nuclear test detection. A modular approach to the Titan III would permit at least four configurations: the two-stage core vehicle, the core vehicle with a final upper stage, the core

U.S. Air Force
with solid-rocket boosters for an initial stage, and the core with solid boosters and an upper stage.

The Air Force hoped to achieve first flight of the standard two-stage core vehicle by mid-1963 and a flight of the core with solid-rocket motors by mid-1964. Ultimately, these goals proved unreasonable, but they served to expedite the project startup. Five major “associate contractors” were selected, including Aerospace, which was responsible for general systems engineering and technical direction. The “associate” concept was a departure from the usual “prime contractor” concept and placed considerably more burden on the Air Force. Aerospace was centrally involved in the development of the Titan III vehicle and a new launch-site processing concept called “Integrate, Transfer, and Launch.” This revolutionary concept was driven by the configuration variability of the vehicle and the predicted launch rates as high as 60 per year (see “A Complete Range of Launch Activities”).

**The ABCs of Titan III**
The first of the Titan III variants—Titan IIIA—consisted of the Titan II core vehicle strengthened to incorporate a third stage (known as the Transtage). The maiden flight in September 1964 failed when the Transtage pressurization system malfunctioned and the engine shut down prematurely. Three subsequent test flights were successful, the last in May 1965.

The next Titan III to reach orbit—Titan IIIC—was the first version to use solid-rocket motors to boost the performance of the liquid-fueled core vehicle. The solid-rocket motors were the first to use the stacked-segments concept. Aerospace assisted their development and qualification. The five-segment solid motors were ignited for liftoff and propelled the vehicle through “stage zero” of the flight before the stage-one liquid-fueled engines kicked in, at which point the solids were cast off. This configuration could deliver a payload to a geostationary orbit. Ultimately, 36 Titan IIICs were launched from Cape Canaveral, the first in June 1965 and the last in March 1982. The payloads were almost exclusively military. Five of these missions failed, but three of those failures occurred during the initial eight-vehicle development phase of Titan IIIC.

In 1965, the Air Force directed its space efforts toward the Manned Orbiting Laboratory (MOL), a massive structure that would require something larger than a Titan IIIC to reach orbit. The resulting design—Titan IIM—represented a substantial change from the Titan IIIC. Almost every system was modified or redesigned to meet the increased performance and safety requirements. This included lengthening the first stage, upgrading the liquid-rocket engines and their propellant-feed systems, developing a seven-segment solid-rocket motor, upgrading the avionics, and installing a new ground checkout system. Titan IIM development continued for several years, successfully getting through ground tests of the new engines and seven-segment solid-rocket motors; however, MOL was cancelled in 1969 before any Titan IIMs were produced. Nonetheless, even though Titan IIM never got to the launchpad, its development became the foundation for many improvements phased into future Titan configurations.

Following Titan IIIC into space was Titan IIB, which looked very similar to Titan IIIA but used an Agena instead of a Transtage upper stage. Of the 57 Titan IIBs launched from Vandenberg between 1966 and 1983, 56 were successful. Yet another variation—Titan 34B—used an elongated first stage and Agena upper stage in a 3-meter fairing. The 34B achieved 11 of 11 successful launches from Vandenberg between 1975 and 1987. Typically, the Titan IIB and 34B carried satellites into polar near-Earth orbits.

The Titan IID—created to deliver even heavier reconnaissance satellites—had the Titan IIIC core and five-segment solid-rocket motors, but without the Transtage. Of the 22 Titan IIDs launched between 1971 and the early 1980s, all were successful.

In a departure from the usual Air Force operations, NASA had system responsibility for the Titan IIIE. By adding a Centaur upper stage to the Titan IID and developing a larger, 4.3-meter-diameter payload fairing, NASA was able to use the rocket for planetary exploration. The first launch took place in 1974. Although it flew only seven times, the Titan IIIE made a significant contribution to planetary science, sending the Viking probes to Mars and the Voyager space vessels to the far reaches of the solar system.

In the late 1970s, the Air Force ordered yet another class of Titan III vehicles. This version, called Titan 34D, was to provide launch services for military payloads until the space shuttle became fully operational. The initial order was for seven, but as shuttle schedules slipped, eight more had to be built for payloads that couldn’t wait. Titan 34D employed the high-performance 34B
core but with new five-and-one-half-segment solid-rocket motors strapped to each side. Extremely versatile, the Titan 34D could accommodate three different upper stages—the Transtage, the Agena (although the Agena never flew on a Titan 34D), and the Inertial Upper Stage (IUS). Although Titan 34D provided a bridge to the shuttle era as intended, it had its share of setbacks. Three of the 15 missions ended in failure. Nevertheless, Titan 34D was considered the military powerhouse of the 1980s.

**Critical Responsibility**

Aerospace’s role as associate contractor during the early years of the Titan III program was quite different from its role today. In addition to general systems engineering responsibility, Aerospace had technical direction authority—meaning it could issue directives, approved by the Air Force, to the other associate contractors regarding design, construction, testing, and launch. This authority was generally not exercised because a collaborative team approach became the mode of operation.

In addition to contractor oversight, Aerospace had several inline functions, including independent verification and validation of guidance software and vehicle loads, writing the guidance steering equations, developing mission specifications, and “pedigree review” of all critical flight hardware. Aerospace also had technical responsibility for all government-furnished equipment—such as the command-control receivers required by range safety.

The Aerospace contribution to postflight reconstruction of flight data was particularly noteworthy. The contractor’s initial analytical approach was very simple and risked missing potentially important indicators of performance. Aerospace devised a much more sophisticated model using all significant flight parameters. This model identified several critical performance deficiencies, such as reduced specific impulse of the propulsion systems, incorrect payload weight, and a bias in the solid-rocket motors.

Similarly, Aerospace was intimately involved in all phases of testing, from development through qualification, hardware acceptance, and systems checkout. In addition to developing test requirements, Aerospace witnessed and supported much of the development and qualification testing. All test failures were assessed by Aerospace engineers, who would typically work concurrently with the contractors to analyze failures and formulate corrective actions and recovery plans.

During these years, Aerospace was developing the analytical methodologies, tools, models, and databases it would need

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**Titan Launch History Summary**

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Launch summary for the Titan family. More than 360 Titans have been launched within the last 40 years. Overall success rate exceeds 86 percent. Discounting the early Titan ICBMs, the success rate jumps to more than 93 percent. Key: VAFB—Vandenberg Air Force Base; CCAFS—Cape Canaveral Air Force Station; ICBM—intercontinental ballistic missile; SLV—space launch vehicle. (Source: Lockheed Martin Space Systems)
The Titan 34D provided the starting point for the CELV. The 3-meter-diameter propellant tanks were lengthened to hold more fuel, and this enhancement in turn drove more upgrades to the liquid engines to increase thrust and burn time. The 34D five-and-one-half-segment solid-rocket motors were replaced with seven-segment stacks, first proposed for the Titan IIIM years before. To be compatible with shuttle payload capacity, the Titan payload fairing was increased to 5.1 meters in diameter. The CELV would include a Centaur upper stage and launch exclusively from Cape Canaveral.

With the loss of the Challenger in 1986, DOD payloads were taken off the space shuttle manifest. CELV was renamed Titan IV, and the 10-vehicle contract was expanded to 23. For a while, Titan IV became the sole heavy-lift launch vehicle for the military. With this expanded role came the need for increased versatility to meet a spectrum of different payload and mission-specific requirements.

Seemingly overnight, the Titan program shed its “going out of business” mentality and began expanding once again. The resurgence, coupled with concerns over two Titan 34D failures in 1985 and 1986, made it clear to the Air Force that Aerospace’s expertise would be needed to recover from the failures and embark on development, acquisition, and operation of the new fleet. Accordingly, the Air Force contracted Aerospace for general systems engineering and integration support. Aerospace would provide fully independent launch verification for each Titan mission.

The basic configuration of the Titan IV comprised a common-core vehicle and solid-rocket motors; however, thanks to a modular approach, the basic model could be configured to accept either the IUS or Centaur upper stage for missions requiring delivery beyond low Earth orbit. The payload fairing would also be modular, and could be provided in lengths from roughly 17 to 26 meters. Launches could take place from Vandenberg as well as Cape Canaveral. Five basic Titan IV configurations were created: two with no upper stages for launching satellites into low Earth orbits from Vandenberg, and one with the Centaur, one with the IUS, and one with no upper stage for launches from Cape Canaveral. Lift capability grew to nearly 18,000 kilograms for a low-Earth orbit.

The first launch of Titan IV, later named Titan IVA, took place in June of 1989 from Cape Canaveral. Eventually, 22 Titan IVAs were launched, the last in August 1998. Only two of these missions failed.

At about the same time that Titan IV was initiated, the Air Force decided to convert a number of deactivated Titan II ICBMs for use as medium-lift space launch vehicles. From the fleet of 54 deactivated Titan IIs, 14 were modified to provide launch capability from Vandenberg into the polar orbit plane. Modification entailed removing the core vehicle’s warhead interface and replacing it with a space payload interface and a 3-meter payload fairing. The electronics, avionics, and guidance systems were also upgraded using Titan III technology. An attitude-control system was added for stabilization during the coast phase after second-stage shutdown and before payload separation.

To date, 12 of 13 planned missions have been successfully completed. Payloads have included military reconnaissance and weather satellites as well as civil meteorological and imaging satellites. The success of the modified Titan II is especially remarkable considering its use of nearly 40-year-old hardware, designed to 1960s technology but still meeting modern needs for access to space.

**The Final IV**

Even before the first Titan IVA was launched, the Air Force wanted to upgrade its performance and reliability. Thus was born the final member of the Titan family, Titan IVB. Procurement began in 1989 with a contract for 28 vehicles (though only 17 were ever built). A new three-segment solid-rocket motor upgrade replaced the seven-segment units. This upgrade not only provided a 25-percent increase in payload capability, but yielded a more reliable stage-zero booster, thanks to the reduction in number of components and improvements in manufacturing and inspection techniques. Extensive upgrades of Titan’s electrical and guidance systems were implemented to replace obsolete technology and vintage parts that were growing increasingly difficult to procure. Production processes were redeveloped to employ a “factory-to-launch” approach. The goal was to deliver problem-free hardware requiring a minimal amount of assembly at the launch site. The manufacturing would be kept at the factory, and the launch site would only be used for the final stacking, checkout, countdown, and launch. Accordingly, the checkout equipment was
modernized and automated to improve vehicle health checks during the final assembly and countdown.

The end result was the Titan IVB standing 61 meters tall, with a lift capability of 21,680 kilograms to low Earth orbit and 5760 kilograms to geosynchronous orbit. Its maiden launch in February 1997 used an IUS to deliver a payload for the Defense Support Program. Of the 12 Titan IVB launches so far, all but one (the 1997 Cassini mission to Saturn) carried critical military satellites. Of these 12 launches, 11 were successful. The sole failure, in April 1999, was followed by seven successes in a row. (Another anomalous mission in April 1999 was attributed to the IUS and is not counted as a Titan IVB failure.) Five Titan IVB missions remain, four from Cape Canaveral and one from Vandenberg, all with DOD or NRO payloads.

Aerospace functioned as a full partner with the Air Force and contractors in verifying that each Titan IV and modified Titan II was ready to launch with acceptable risk. Independent analyses and evaluations performed by Aerospace contributed to improved risk assessment and sometimes even failure avoidance. A good example was the evaluation of a proposed change to the Titan IV stage-two engine-nozzle skirt. The nozzle’s ablative liner was made of asbestos phenolic impregnated with resin, and an alternate resin was being proposed. Aerospace became concerned about the thermostructural capability of the new skirt because of uncertainty regarding resin properties at high temperatures. These concerns were key in driving the need to demonstrate that the skirt was structurally sound under engine hot-fire conditions. The skirt failed the test and was declared unsuitable for flight. A new skirt using quartz phenolic in place of asbestos phenolic was next proposed. Aerospace was instrumental in developing the testing requirements to qualify the new design. Subsequent hot-fire tests proved its suitability.

In spite of the dedicated efforts by the contractors, Air Force, and Aerospace to verify that each launch vehicle was flight-worthy, Titan missions sometimes ended in failure. In these instances, Aerospace was always part of the return-to-flight process. For example, the first failure of a Titan IVA occurred in August 1993: About 100 seconds into flight, the casing of one of the solid-rocket motors burned through, and the vehicle was destroyed. Through extensive image analysis, graphical modeling, and analytical work, Aerospace identified a suspect segment of the solid-rocket motor. A subsequent search of build records showed that a defect may have been introduced by a procedural change many years ago.
fewer components; the composite version has only two segment joints per motor, and greater nozzle control. Higher reliability was also achieved through the use of composite-cased motors included higher performance, lighter spent weight, and greater nozzle control. Higher reliability was also achieved through the use of fewer components; the composite version has only two segment joints per motor, as opposed to the eight joints for the segments and closures on the steel model.

Aerospace contributed substantially to the design of the composite-to-metal joint as well as to the propellant-grain design for the forward, center, and aft segments. Aerospace personnel participated extensively in all seven qualification motor firings. Working alongside the contractor and manufacturer, Aerospace provided expertise in the development of a comprehensive nondestructive evaluation program for the upgraded motor components. When production or qualification problems were encountered, Aerospace joined with the contractors to resolve the issues and continue processing. All the upgraded propulsion, structural, hydraulic, electrical, and avionics components were checked by Aerospace as part of the hardware acceptance review process. Equally important was the participation of Aerospace during the assembly and testing of the Titan IVB vehicle hardware at the launch bases.

With 12 of the 17 Titan IVB launches complete, the upgraded motors have flown successfully with predictable and consistent performance.

Composite Solid-Rocket Motor Cases

—Fred Buechler

After working with the steel-cased solid-rocket motors for the Titan III, 34D, and IVA vehicles for 25 years, Aerospace assisted the development and qualification of the graphite-epoxy composite solid-rocket motor upgrade. The primary advantages of the composite-cased motors included higher performance, lighter spent weight, and greater nozzle control. Higher reliability was also achieved through the use of fewer components; the composite version has only two segment joints per motor, as opposed to the eight joints for the segments and closures on the steel model.

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With 12 of the 17 Titan IVB launches complete, the upgraded motors have flown successfully with predictable and consistent performance.

The second of these Titan IV failures, the Titan IVB in April 1999, was separated from the first by just one successful Titan IV flight. In this instance, the cause of the failure was actually known within minutes: An incorrect constant in the control-system software caused radical roll errors, eventually resulting in a loss of control during the Centaur upper-stage flight. The erroneous constant resulted from simple human error (a misplaced decimal point). There were indications of this error before flight, but initial concerns were not adequately pursued; Aerospace’s traditional validation and verification role had been assigned to a subcontractor under the dictates of acquisition reform, so Aerospace was not required to check for such a transcription error. After the failure, the contractor, with Aerospace assistance, developed a process-proofing improvement plan that started with software but was ultimately applied to every critical analytical and test process employed on the Titan program. Aerospace also revisited its own software-validation process and developed improved processes to check mission software more rigorously. Thanks, in part, to these efforts, the basic Titans were returned to flight within a few weeks and the Centaur upper stage within a few months.

Titan in Reflection

By any standard, the Titan program has compiled a formidable track record, delivering into orbit hundreds of satellites that were ultimately able to perform their tasks as required. More than 360 Titans have been launched, with a total success rate of 86 percent. This figure is especially impressive because it includes the Titan ICBM (which did not need pinpoint accuracy to achieve effective deterrence). Without the ICBMs, the historical success rate jumps to 93 percent.

During every phase of the Titan’s evolution, Aerospace was there to provide invaluable technical support. By virtue of its objectivity and independence, Aerospace could apply its unique strengths and technical competence in all areas of space systems engineering, design, computational modeling, and simulation to establish high confidence of mission success. The Titan’s final launch in a few years will mark the close of a remarkable chapter in the history of rocketry and of Aerospace support for the nation’s most venerable launch system.

Acknowledgement

The author would like to thank Aerospace retirees Don Moses and John Bauer for their assistance and guidance during the research and preparation of this article.
Evolution of the Inertial Upper Stage

Though initially conceived as a short-term program, the Inertial Upper Stage played a critical role in ensuring U.S. access to upper orbits and beyond.

W. Paul Dunn

The Inertial Upper Stage (IUS) is a highly redundant and ground-commandable launch vehicle used to insert payloads into higher orbits than would be possible with just a primary booster. Throughout the years, the IUS has evolved to become an integral part of America’s access to space for both military and civilian sectors.

Initial Studies
The evolution of IUS began in 1969, when a presidential directive set in motion NASA and Air Force studies that led to development of the Space Transportation System (STS) and its principal vehicle, the space shuttle. As part of the early STS definition, NASA and the Air Force jointly studied several concepts for transporting payloads into higher operational orbits, especially the geosynchronous orbits used by most communications satellites. Physical limitations—such as the high propellant mass that would be required—prevent a standard booster from reaching these very high orbits. Rather than build a bigger booster, NASA and the Air Force focused on an upper-stage rocket as the most practical method available. Aerospace was integrally involved in these early studies, assessing the feasibility of cryogenically fueled orbit-to-orbit vehicles, piloted transfer vehicles, and modifications of existing upper stages such as the Centaur, Delta, Agena, and Transtage.

Based on these studies, NASA decided on a “space tug”—a reusable transfer vehicle that would tow satellites from an orbiting space platform to their final operational orbits. Such a project, however, would take years to complete. In the meantime, NASA and the Department of Defense (DOD) agreed to develop what was then called the Interim Upper Stage. This decision fostered a series of additional studies—including many at Aerospace—to determine the requirements, capabilities, and ultimate configuration of this temporary upper
In 1975, DOD proposed an expendable solid-fueled rocket because it would cost less to produce than a liquid-fueled vehicle. Independently, NASA also settled on a solid-fueled stage after determining that a liquid-fueled stage interfered with STS designs and could compromise the safety of the flight crew.

Aerospace assisted the Air Force through its source-selection process before establishing a program office in 1976. Several contractors proposed modifications to their existing rocket designs to meet the requirements of the new upper stage. Shortly before commencement of the program-validation phase, however, the Air Force introduced a new requirement: The IUS must be compatible not only with the space shuttle, but with the Titan 34D booster as well. The Titan 34D was the largest available expendable booster and was capable of placing larger and heavier payloads into orbit (military payloads tend to be more massive than civilian payloads). This capacity was important because of the competitive position it offered for commercial access to space and the security it offered for national defense. The Air Force also wanted to use the upper-stage avionics to guide the booster through its powered flight phase to improve reliability.

At the end of 1977, NASA abandoned its plans for a space tug, so the IUS program name was formally changed from Interim Upper Stage to Inertial Upper Stage (because it used inertial navigation). The prime contractor was selected, and full-scale development began in April 1978.

**Development Issues**

Aerospace worked to overcome several immediate challenges during development. Key requirements included a payload capacity of 2268 kilograms and reliability of 96 percent or better, all with minimal impact to the STS program. Also, the necessary support equipment had to be designed, and unique configurations had to be produced for NASA planetary missions. Numerous technical difficulties nearly scuttled the entire program. Significant problems occurred in the propulsion sub-system (e.g., case burst, tacky liner, soft and cracked propellant, nozzle delaminations), in the software (sizing and timing, guidance, redundancy management, failure detection and correction), and in the avionics (space-rated parts, redundancy, testing). Evolving definitions of booster loads and environments also threatened development, as did problems arising in the qualification testing of the support equipment. Compounding matters, significant differences arose in interpretations of contract and specification requirements, and a serious weight-growth problem prompted a drastic weight-reduction program. A Titan-specific interstage and extendable exit cone had to be added to maintain performance, and a destruct system had to be added to ensure launch-range safety.

This array of technical problems—coupled with various programmatic changes—led to schedule delays, higher costs, and, subsequently, two program restructurings. These delays, in turn, affected other aspects of the program. For example, the Tracking and Data Relay Satellite (TDRS) was to be the first NASA payload for the IUS, and the DSCS II and III communication satellites were to be the first for DOD; however, delays and scheduling conflicts caused uncertainty as to whether STS or Titan 34D would be the first IUS booster. Both would present exceptional challenges for a first-time launch. Requirements continued to shift and evolve, and the Interface Requirements Documents, safety protocols, and other procedures had to be worked out for the first time—under considerable scheduling pressure. Qualification testing was still going on in many areas for the STS version, and Independent Readiness Review Team findings led to several “fix before launch” concerns. Also during this period, NASA requirements for
From Lift to Release: the Stages of a Launch

In a typical IUS launch, a primary booster (such as a Titan IVB) powers the initial liftoff from the pad. Within a few minutes, the booster’s first-stage engine falls away and its second-stage engine kicks in, carrying the system to a low Earth or “parking” orbit. Soon thereafter, the IUS separates from the booster’s second stage and assumes control for the remainder of the powered ascent. About an hour later, the first-stage IUS solid-fueled rocket begins firing. The second solid-fueled rocket motor ignites toward the end of the ascent, followed by a coast phase, and finally, separation of the payload. The IUS can hoist a 2268-kilogram satellite into a geosynchronous orbit or heave a 3628-kilogram spacecraft out into the solar system.

System architecture of the Inertial Upper Stage, the most functionally redundant upper stage available and the only one that can be commanded from the ground during flight. Acronym key: TT&C—telemetry, tracking, and command; RIMU—redundant inertial measurement unit; TVC—thrust vector control; RCS—reaction control system; SRM—solid-rocket motor.

Planetary missions changed: The need for more accurate control dictated a three-axis stabilized configuration, which increased payload mass. Though problematic at the time, these demands led to several modifications to the IUS that now reflect its uniqueness as an upper stage. For example, the IUS first-stage motor can maintain continuous thrust for as long as 150 seconds—longer than any other solid-fueled upper-stage rocket developed for space applications. IUS is also the most functionally redundant upper stage available, and it is the only one that can be commanded from the ground during flight. To support this ground-command capability, Aerospace helped develop an array of contingency procedures to guide

The IUS measures about 5.18 meters long by 2.9 meters in diameter and has an overall mass of nearly 14,800 kilograms. Two slightly different versions are available, one for use with the Titan and one for the shuttle launcher. The IUS first-stage solid-rocket motor holds about 9700 kilograms of propellant and generates more than 188,000 newtons of thrust. The second-stage solid-rocket motor holds more than 2700 kilograms of propellant and generates more than 80,000 newtons of thrust.

The first-stage motor can maintain continuous thrust for as long as 150 seconds—longer than any other solid-fueled upper-stage rocket developed for space applications. Actual duration can be tailored to suit mission requirements.
rapid mission anomalies; moreover, the flight operations support team, which includes Aerospace personnel, conducts systematic simulation exercises to prepare for any eventuality during launch.

First Launches
The inaugural IUS launch, mated with a Titan 34D booster and a DSCS II/III spacecraft tandem, took place about five minutes after midnight on October 30, 1982, at Cape Canaveral Air Force Station in Florida. Aerospace provided technical support through its general offices and on-site launch personnel. Unfortunately, a loss of telemetry persisted for much of the flight—not surprising, perhaps, considering how many technical difficulties had to be overcome. Nonetheless, even though flying “blind” to Earth observers, the IUS completed its mission as planned because it was designed to fly autonomously by default, without commands from outside sources. After later analysis, the telemetry loss was attributed to a leak in the hermetic seal of a switch that routed radio-frequency signals to the IUS transmitting antennas. The leak allowed internal pressure in the switch to drop to a level where corona arcing occurred and caused switch failure.

Even with this problem out of the way, the second flight experienced difficulties that probably would have ended the mission for any other rocket. When a critical seal failed, the control system lost its ability to position the nozzle of the solid-rocket motor. The nozzle canted, causing the IUS to tumble through space along with the attached TDRS spacecraft. The lack of nozzle control was compounded by disruption of normal automatic mission sequencing as a result of unusually high cosmic radiation. Subsequent ground commands—possible only with the IUS—succeeded in separating the IUS from the TDRS, but the spacecraft was still tumbling. NASA was able to use the excess propellant on the TDRS to stabilize the spacecraft and eventually raise it to the desired geosynchronous orbit. Since then, the operational history of the IUS has been impressive, with 20 missions experiencing no significant anomalies. The lone exception occurred in April 1999, when the IUS stage-one component failed to separate normally from its stage-two component.

Aerospace also worked to make IUS as accurate as it is reliable, supporting a significant upgrade to the avionics for navigation, control, and guidance in 1999. To achieve this upgrade, the three original flight computer and inertial measurement units were redesigned into one chassis. This upgrade preserved the redundancy while modernizing the gyroscopic components from mechanical devices to more reliable ring laser devices and reducing overall mass by more than 45 kilograms. The flight software was also upgraded to employ more modern coding and other modifications. A single electronics unit, named the Flight Controller, incorporated all these changes. As a result, the IUS has since attained its highest level of orbit insertion accuracy.

Mechanisms
How do you launch a spacecraft with a 12-meter-diameter antenna via a 3.6-meter-diameter launch vehicle? How does a single launch vehicle support different spacecraft firmly enough to withstand launch forces, but gently enough to drop them into their correct orbits with a rotational speed no more than one-sixth of a clock’s second hand? Moving assemblies—or mechanisms—accomplish critical tasks such as these.

During launch, mechanisms help the launch vehicle shed excess weight. For example, many vehicles carry external solid-rocket motors that must be discarded once their fuel is used up. Release mechanisms and hydraulic actuators propel them away from the core vehicle.

Similarly, a launch vehicle’s internal fuel tanks are shed when their fuel is depleted. An explosive charge breaks the connection between a rocket’s stages, then compressed springs and guides help separate the spent stage.

Further into flight, as the atmosphere becomes negligible, the protective payload fairing becomes unnecessary, so it gets jettisoned. A continuous explosive charge or discrete pyrotechnic bolts break the connections between fairing segments. Then, hydraulic actuators team with open hinges, cams, or other mechanical apparatus to move the segments away from the launch vehicle without recontact.

The final separation is the payload release. One method for this is similar to a stage separation, where separation nuts release structural bolts joining the payload and rocket. Another method uses a clamped-band system, in which both bodies possess similar interface rings, and a band is tightened around their flanges. In this case, a bolt cutter or separation nut releases the band, thus allowing compression springs to impart relative velocity between the bodies.

Critical mechanisms such as these require stringent analysis to ensure proper design and operation. The Aerospace Corporation has developed specialized tools for static, kinematic, and dynamic analyses to predict positions, velocities, accelerations, and reaction forces for multiple rigid and flexible bodies. These computer-aided simulations model complex, three-dimensional separation mechanisms and events to verify that mechanisms will perform as intended.
End of an Era
Though conceived only as a stopgap measure, IUS became an indispensable part of the U.S. space program, achieving several notable distinctions. For example, it was the first upper stage to be used on the Titan IVA and B vehicles and the space shuttle and the first to provide upper-stage guidance for the Titan 34D. A number of NASA and DOD spacecraft have been carried aloft by IUS, including the Galileo probe, the Chandra X-ray Observatory, and the latest Defense Support Program satellites.

In 1997, organizational restructuring folded IUS into the Titan program and ended its stand-alone status. The last IUS on the manifest is expected to launch sometime in 2003. This final mission will bring to a close an important chapter in the history of space launch.

Acknowledgement
The author would like to thank R. K. Luke, A. R. Shibata, H. Sokoloff, A. E. Goldstein, and G. D. Jensen for their contributions to this article.

### Inertial Upper Stage Unclassified Flight History

<table>
<thead>
<tr>
<th>Tag no.</th>
<th>Booster</th>
<th>Date</th>
<th>Payload</th>
<th>Notes</th>
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<tr>
<td>IUS-2</td>
<td>Titan-34D</td>
<td>10/30/1982</td>
<td>DSCS II/III</td>
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<td>IUS-1</td>
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<td>IUS-3</td>
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<td>5/8/2000</td>
<td>DSP 20</td>
<td>Chandra Observatory</td>
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Key: DSCS—Defense Satellite Communications System; TDRS—Tracking and Data Relay System; DSP—Defense Support Program

DSP-16 and the IUS booster are checked out in the cargo bay of space shuttle Atlantis prior to release.
The Launch Verification Process

E. J. Tomei

The process used to independently determine launch system flight readiness is a capability unique to The Aerospace Corporation that has been employed for more than 40 years. It is based on a comprehensive technical assessment that is thorough in its attention to detail with total system coverage.

The Aerospace approach to launch-readiness verification is unparalleled in its breadth and depth. This comprehensive, end-to-end process extends from concept and requirements definition through flight operations: It entails the detailed scrutiny of hundreds, if not thousands, of components, procedures, and test reports; it draws upon independently derived system and subsystem models to objectively validate contractor data; it provides timely review through firsthand involvement in all aspects of the launch campaign; and it concludes with a thorough postflight assessment using independent analytical tools and independently acquired telemetry data to generate useful feedback and monitor performance trends.

Following is a brief description of some of the critical activities needed to complete the process for a given mission.

System Design and Qualification
Aerospace begins by verifying that overall top-level performance requirements are properly supported by lower-level systems and subsystems. Independent analyses validate dynamic loads and clearances, structural margins, thermal protection, and control stability.

At this point, design engineers review system, subsystem, and component qualification requirements to ensure that they provide adequate margins. Qualification testing is witnessed and documented, and the test results are evaluated to confirm that they meet system requirements. Such thorough qualification reviews apply to engines, solid motors, ordnance, controls, avionics, guidance, structures, and major subassemblies.

Milestone reviews must also be conducted, including a system requirements review, software design review, preliminary design review, and critical design review. Aerospace evaluates any changes with respect to the qualification baseline and may recommend requalification if the changes are severe or have been improperly implemented.

Manufacturing and Quality
The manufacturing process must also be reviewed to ensure that it can produce the final design. Quality-control processes are checked for compliance with standards and requirements.

After reviewing the results of initial production, Aerospace provides technical support to resolve problems with manufacturing techniques. This support can entail in-plant review of hardware and processes.

Hardware Verification
Even before hardware can be screened for defects, acceptance test plans and procedures must be reviewed to ensure that the test environments and pass/fail criteria can be trusted to screen out faulty components. Aerospace responsibilities in this area include witnessing selected acceptance testing of critical items and reviewing anomaly reports and corrective actions. Aerospace personnel also monitor failure investigations, and, in certain critical cases, augment them with independent investigations, which can include metallurgical analyses, material compatibility checks, electronic component testing, and contamination assessments.

An impartial and comprehensive system review verifies the flightworthiness of a launch vehicle and instills confidence in ultimate mission success.

This functional flow diagram outlines the primary elements of the Aerospace independent launch-readiness verification process. This comprehensive process extends from concept and requirements definition through flight operations and includes a postflight assessment using independent tools.
One particularly important task is the software “pedigree” review, which focuses on individual components and subsystems to establish that they were built and tested according to specification. This pedigree review includes a check of quality-assurance documentation to verify that the manufacturer followed the appropriate procedures, implemented engineering changes properly, justified any deviations adequately, and used valid criteria in selecting new processes or materials. The pedigree also includes an assessment of acceptance testing.

**Software Validation**

Every space launch requires mission-specific software that contains the instructions needed to get the payload from the launchpad to its intended orbit. Aerospace conducts an independent validation and verification of critical system software, especially pertaining to guidance, navigation, and control.

Validation of the launch system software typically requires the development of independent models and tools. Verification of flight software involves independent simulations in two phases using preliminary, then final, data from the dynamics analysis and mission design activities. These simulations ensure that programmers have implemented the correct trajectory and navigation algorithms in the autopilot software and have properly laid out the sequence of events to be followed during launch.

**Mission Planning, Verification, and Analysis**

A well-built launch system can still fail in its mission if it’s not properly integrated with its payload. Mission design analysis provides assurance that the launch system is capable of delivering the specific payload to its planned orbit with sufficient margin to guarantee mission success. Aerospace performs an independent analysis to verify adequate mission planning for all flight conditions. This involves examining system-level and integration requirements, confirming all mission-specific payload integration requirements to ensure that baseline reliability is preserved and new requirements have been met, and ensuring that all prior flight and test anomalies have been adequately resolved.

The mission analysis establishes that the flight trajectory and parameters are optimized for the specific payload, satisfy flight and safety constraints, and provide adequate margins for the radio-frequency link, power, propellant, and consumables. Dynamic loads must be analyzed to verify booster capability and compliance with the interface control document. Guidance, navigation, and control performance must also be analyzed for acceptable injection accuracy and control stability. Emphasis is placed on new hardware and software or new applications of established designs.

Other analyses—covering details such as aerodynamics, thermodynamics, vibro-acoustics, electromagnetic compatibility, radio-frequency interference, separation clearance, and contamination—verify operation within vehicle capabilities and interface control document specifications.

**Assembly, Test, and Preflight Readiness**

At the launch site, numerous tasks must be accomplished to prepare for launch. Aerospace assesses these processes to establish that they adequately support mission readiness and satisfy design requirements and operational constraints. Critical tasks and tests are witnessed and evaluated for compliance with requirements and procedures. Particular attention is placed on anomaly identification and resolution. Aerospace personnel support all major launch site tests and readiness reviews and provide technical corroboration for the test team.

**Launch-Readiness Verification**

Assuming all procedures have been properly documented and all test results fall within acceptable levels, Aerospace can now give its launch-readiness verification to the Air Force’s Space and Missile Systems Center (SMC). This document includes an overview of the launch verification activities, a listing of independent analyses and verifications, results of the pedigree review, a synopsis of lessons learned from similar missions, an explanation of anomaly review and resolution efforts, and an appraisal of launch-site processing adequacy.

The assessment culminates in a flight-worthiness determination and certification resulting from the launch verification process results in a tenfold reduction in risk. Probability of failure comparison: 33 percent versus 3.1 percent.
by SMC at a meeting known as the Flight Readiness Review. The objective is to ensure that the primary contractors, Aerospace, the spacecraft program office, and the launch programs agree that the launch vehicle and payload are ready to begin final launch operations.

**Countdown and Launch**

Aerospace personnel are “on-station” during countdown and launch, supporting launch decisions with the knowledge and experience gained during the launch verification process. Day-of-launch support also entails an independent review of launch placards, countdown anomalies, deviations and workarounds, and launch constraint violations. Any anomaly or deviation observed until liftoff may result in a reassessment of the vehicle’s launch readiness. If the launch is scrubbed, a new flight readiness assessment may be required before the countdown can resume.

Aerospace personnel also provide countdown and launch support via the Spacelift Telemetry Acquisition and Reporting System (STARS) room. From this facility, launch system technicians have access to a historical flight database via special computer and software tools, allowing independent evaluation of trends and mission-to-mission performance.

**Postflight Analysis and Lessons Learned**

Aerospace’s responsibility does not end when the launch vehicle finally leaves the pad. In fact, some of the most rigorous analysis happens after liftoff. For example, launch-system flight data are analyzed to independently assess vehicle performance, identify and assess flight anomalies, and update the data archives. Postflight analyses and reconstructions are used to perform trend analyses, capture lessons learned, and provide feedback for the next readiness assessment.

Postflight analysis of mission performance, for example, compares actual flight trajectory and performance characteristics to predicted values. Guidance measurements are processed to produce a trajectory profile and determine stage energy levels. Pressures, temperatures, atmospheric conditions, vehicle position, vehicle velocity, vehicle acceleration, aerodynamic drag, dynamic pressure, and timing of discrete events are used to evaluate vehicle performance during flight. Solid and liquid engine thrust, specific impulse, flow rates, pressures, temperatures, stage energy performance, system performance margins, mixture ratio, and propellant margin parameters are analyzed and compared to predictions.

Similarly, postflight analyses determine whether all components performed as expected. Measurements and data are compared with predictions and historical values, and deviations are logged, analyzed, and resolved.

Additional postflight analyses include review of radar, film, and video images collected during ignition, liftoff, and flight to determine flight behavior (particularly during staging events) to identify any anomalous conditions or sources of debris.

**Conclusion**

Aerospace’s end-to-end system review is a routine but critical part of every SMC launch. The impartial and independent launch verification provides assurance that all known technical issues have been resolved and that residual launch risks have been identified and assessed. When Aerospace signs off on its launch-readiness verification, SMC can proceed with strong confidence in ultimate mission success.

**Further Reading**


![Cumulative failure rate chart](chart.png)

Contribution of engineering errors to launch failures is relatively low on government programs. During the last decade, the rate of failures attributable to engineering errors on government programs was less than 3 percent, compared with nearly 15 percent for commercial programs.


S. C. Ruth, “Risk Roadmaps—A Bridge Between a Discipline and SE,” INCOSE Los Angeles Mini-Conference (Long Beach, CA, June 8, 2002).


Patents


A spacecraft system having two substantially similar reusable vehicles, one of which serves as a booster and the other as an orbiter, reduces the cost and complexity of reusable launch systems. The vehicles have identical flight-control and propulsion systems and identical payload bays for receiving mission-specific payloads—for example, a propellant tank for the booster and crew cabin for the orbiter. Each vehicle can be tailored to suit its flight function through the addition of standardized components; for instance, thermal protection might be added to the orbiter, but not to the booster. The use of an identical booster and orbiter reduces overall costs because only one stage of the multistage launch vehicle need be developed. The doubled production run reduces manufacturing cost through greater economy of scale. Launch operations are simplified because only one type of stage needs to be checked and refurbished after landing.

S. H. Choi, M. L. Leung, G. W. Stupian, N. Presser, “Electron Beam Lithography Method Forming Nanocrystal Shadowmask and Nanometer Etch Masks,” U.S. Patent No. 6,440,637, Aug. 2002. Precise, nanometer-scale shadow masks or photoresists for use during electron-beam lithography can be created from nanocrystals. The Langmuir-Blodgett process is used to form high-aspect-ratio lamellae or wire patterns of silver nanocrystals on the surface of water. The patterns are transferred onto resist-coated substrates as a Langmuir-Schaeffer film for producing the shadow mask. The nanostructure patterns are transferred to the

A covert tracking system uses a near-infrared beam to illuminate a tag concealed on a vehicle to produce an image that can be monitored by a near-infrared sensitive camera. This tracking method employs an optical quadrature waveplate attached to an automobile license plate as the hidden tag and alternating pulses of differently polarized light to enhance detection of the tag. Using commercial off-the-shelf equipment, this surveillance system offers an inexpensive method for law enforcement personnel to track suspect vehicles and cargo shipments moving through traffic.


To help overcome the problem of limited spectrum allocation for radio-frequency communications, this signal modulation method provides efficient frequency reuse within existing bandwidths. The generalized quadrature-product subcarrier modulation system enables the transmission of a quadrature multiplexed carrier modulation with one or more subcarrier signals in the same constant-envelope waveform. The process is suitable for efficient sine-wave and square-wave subcarrier modulations, including quadrature phase shift keying and minimum shift keying. Both direct and spread-spectrum quadrature multiplexed communications systems are appropriate. The quadrature subcarrier modulation enables the addition of new signals to the in-phase and quadrature-phase signals with spectral isolation while maintaining a constant amplitude waveform.


This technique improves the performance of interferometric antennas that measure the direction from which radio signals are received. The method resolves interferometric ambiguities for wide-field-of-view systems that require high angular accuracy and operation over wide bandwidths. In such designs, the individual interferometric elements are relatively small. According to this new approach, multiple antenna elements within the overall baseline provide a means by which to resolve the interferometric ambiguities that result because phase can be measured only over one cycle and the modulus cannot be determined. The antenna element spacings are configured to allow high probability of ambiguity resolution over a wide bandwidth. Additionally, radio-frequency combining techniques provide synthetic baseline values for further ambiguity resolution. This approach provides the system designer with a means of minimizing the number of interferometric elements—and hence cost and complexity—while having the assurance of correctly resolving the phase ambiguities with high probability.


Suitable for examining large arrays of solar cells, this inspection technique allows for high-speed optical inspection of specular or highly reflective surfaces. A contrasting patterned image is projected onto the specular surface, which reflects it at an angle to a camera that scans and records it. Defects and flaws in the specular surface cause distortion of the reflected pattern, which are relatively easy to discern. A video camera can be used to capture detailed surface imagery of individual devices. The data can be compared with previous scans to determine, for example, whether surface cracks have grown beyond acceptable levels. The system can be installed at a launch site to provide rapid remote inspections.


This patent relates to carrier-phase determination in frequency-hopped radio-frequency communication systems using Gaussian minimum shift keying, a form of continuous phase modulation. Unambiguous carrier-phase estimation is enabled through the use of zeroing channel bits and channel guard bits. The transmitter inserts these bits just prior to a known sync word during transmission of each frequency hop (the sync words are positioned arbitrarily within each hop). The inserted bits force the cumulative data phase to zero. The receiver detects these inserted bits and thus can determine the carrier phase. Once the carrier phase is known, the second data portion of the frequency hop can be demodulated, and during a second demodulation pass, the first data portion can be demodulated.


This invention pertains to the field of communications, and more specifically to the Viterbi algorithms that are commonly used to demodulate received radio signals. It describes a method and processing system for estimating the likelihood ratios for input symbols and determining a soft-decision metric for each one. The process entails: computing trellis-branch metrics based on a received sample sequence; updating initial-state metrics with a Viterbi algorithm; constraining trellises such that only state transitions caused by an input value associated with a particular trellis are allowed; executing the Viterbi algorithm on the constrained trellises for a finite number of steps; and computing likelihood ratios by taking a difference of a maximum-state metric for each trellis with a maximum-state metric of a reference trellis.


Systems that employ arrays of cell elements—such as heating, pyrotechnic, thermionic, or field-emitter elements—generally need to selectively address and activate them. Electrically addressable arrays of elements typically require extensive connections that necessitate complicated routing during semiconductor processing. This new approach offers a simpler alternative: An address element—including a polysilicon resistor, which functions as a heating element, and a blocking diode, which prevents current from reaching unaddressed elements—is selectively addressed using row and column address lines in a thin-film structure having a minimum of address lines and layers. The resistor heater element is well suited for igniting an individual fuel cell in a thin-film microthruster array. The isolating diode allows for individual addressing of micron-sized pyrotechnic elements, cells, or other microelectromechanical devices. The addressing method also enables selective interrogation of individual pyrotechnic cells to determine whether or not they have been ignited.


This patent describes a method of addressing individual cells in an array. An address element—including a polysilicon resistor, which functions as a heating element, and a blocking diode, which prevents current from reaching unaddressed elements—is selectively addressed using row and column address lines in a thin-film structure having a minimum of address lines and layers. The resistor heater element is well suited for igniting individual fuel cells in a thin-film microthruster array.


This method of addressing individual cells in an array can be used in the design of a large array of microthruster cells, each containing heat-sensitive combustible propellant, that can be individually addressed and ignited without...
damaging neighboring cells. The method addresses and interrogates specific cells having at least one resistor (which functions as a heating element) and one blocking diode (which prevents current from reaching unaddressed elements). The resistor is connected to a primary addressing line and the diode is connected to a secondary addressing line. The cells are selectively addressed using these row and column address lines. A thin-film structure can be thus created with a minimum of address lines and a minimum of polysilicon layers.


This solar collector employs a two-tiered approach to achieve greater efficiency than previous designs. The collector uses traditional reflective or refractive optics to concentrate collected sunlight along a primary axis while a spectrum splitter sends sunlight along a secondary axis. The first axis can use traditional Fresnel lenses, curved prismatic Fresnel-type lenses, or mirrors. The spectrum-splitting axis can be perpendicular to the first axis of concentration. This solar concentrator and energy converter provides high concentration ratios and conversion efficiency using an array of horizontally disposed bandgap-optimized photovoltaic cells.


A flexible space-qualified thin-film solar cell can be produced with a thermally emissive layer for heat rejection. A clear, thermally emissive coating (such as clear polyimide) is deposited directly upon a thin film to form a flexible thin-film solar cell. This cell can be deposited on another thermally emissive coating, which serves as a substrate during semiconductor processing. The associated interconnects and power-processing electronics are integrated into this polymer substrate, forming a flexible printed circuit board. The resulting flexible thin-film solar cell can be illuminated on the top and eject heat from both top and bottom. The cell is suitable for forming a solar-cell array covering a curved surface such as a PowerSphere nanosatellite.


This power-tracking system maximizes the power deliverable from an energy source, such as a solar array. It uses increasing, decreasing, and steady states controlled by a set-point signal modulated by a dither signal. This allows for stabilized regular power tracking during periods of low demand and maximum power tracking during periods of high demand. For systems involving several power sources, multiple sets of parallel-connected converters and maximum-power trackers can be coupled in parallel using shared bus and control signals for fault-tolerant equalized power conversion.

When used with multiple solar arrays—which can have quite different characteristics—some trackers can actively regulate maximum power flows from arrays that have deficient power while the remaining trackers are inactive. This is possible because the remaining solar arrays provide sufficient power to allow dc-dc converters to regulate the load voltage.


Determining the spin-axis attitude of a spinning space vehicle has been traditionally accomplished using a combination of sun and Earth-horizon sensors. This approach offers an alternative for vehicles orbiting below the GPS constellation. An antenna pattern null is created to receive signals from at least three visible GPS satellites, which function as pseudo stars for reference. The new sensor system includes a GPS receiver, a conventional sum and difference hybrid, and two 1/4-wave-plate patch antennas.


This patent describes a system for determining the spin-rate and spin-axis attitude of a space vehicle in Earth orbit below the GPS constellation. A pair of 1/4-wave patch antennas forms an antenna pattern null for receiving signals from at least three GPS satellites. Placed side by side on the space vehicle, the two antennas create an overlapping gain pattern with sum and null midway between them using a conventional 180-degree hybrid. The sum signal is used for conventional GPS signal detection and reception and for space-vehicle navigation. The difference signal serves as a time reference for determining the spin rate and is also used to determine azimuth angles for the GPS satellites for computing the spin-axis attitude of the spacecraft.


This device can be used to identify the glass-transition temperature of a composite material after fabrication, thereby verifying that the material has cured completely. The system includes a pointed probe that penetrates the sample. A heater raises the sample’s temperature high enough to induce a phase change from solid to semisolid. A thermocouple measures the temperature while a motion transducer measures the amount of probe penetration, which will increase sharply at the glass-transition temperature. A portable version can be used in the field to test the glass-transition properties of various composite materials, including those used in buildings and bridges. Used in conjunction with other nondestructive evaluation techniques, the system can check structures over the course of many years to verify their continued stability.
W. Paul Dunn, Principal Director, Launch Systems Analysis Directorate, joined Aerospace in 1977 and has led the work on a number of vehicle systems, including medium launch vehicles, the Inertial Upper Stage, other upper stages, propulsion systems, vehicle systems integration, and launch systems analysis. Among his many honors is the Distinguished Graduate Award from the University of Texas at Austin in 1993, the highest award given by the College of Engineering. Dunn earned a B.S. in civil engineering at UT, an M.S. in civil engineering at California State University, Los Angeles, and an M.B.A. from California State University, Dominguez Hills (wpaul.dunn@notes.aero.org).

Art Falconer, Principal Director, Titan Launch Verification, is responsible for ensuring Titan systems have been independently verified as flightworthy and ready for launch. He has more than 37 years of experience with launch vehicles, and for the past 16, has supported the Titan program in the areas of vehicle design, qualification, test, satellite integration, and launch operations. He has a B.S. in mechanical engineering from the University of California, Berkeley, and has been with Aerospace for 23 years (arthur.m.falconer@notes.aero.org).

Richard A. Hartunian joined Aerospace in 1960, establishing the aerophysics department in the Aerodynamics and Propulsion Research Laboratory. He served as general manager of the Reentry Systems Division from 1968 to 1976, when he was named vice president of Space Launch Operations. During his nine years in that position, he certified 130 launches of Atlas, Delta, and Titan vehicles and was responsible for Aerospace support of Air Force contributions to the space shuttle program. He received a B.S. in physics from Rensselaer Polytechnic Institute and a Ph.D. in aeronautical sciences from Cornell University. He was elected a fellow of AIAA in 1983 (richard.a.hartunian@notes.aero.org).

Ray F. Johnson, Vice President, Space Launch Operations, is responsible for Aerospace support to Air Force launch programs, including Titan II, Titan IV, Delta II, Pegasus, Inertial Upper Stage, and the Evolved Expendable Launch Vehicle, as well as the Air Force Space Test Program. He also has responsibility for the company’s launch operations at Cape Canaveral and Vandenberg Air Force Base and operations in support of the Space Test Program at Kirtland Air Force Base. Johnson holds a B.S. in mechanical engineering from the University of California, Berkeley, and an M.B.A. from the University of Chicago. He is a senior member of AIAA and has been with Aerospace since 1987 (ray.f.johnson@notes.aero.org).

Jimmy F. Kephart, Project Engineer, System Engineering, Western Range Directorate, has performed many environmental assessments for launch programs at Vandenberg Air Force Base, including the West Coast Space Shuttle, Titan IV, and EELV. Among the numerous space studies and proposals he has supported are site selection for the Texas Space Commission and evaluation of Kirimati Island for the Japanese J-II New Century. A major in the Air Force before joining Aerospace in 1991, Kephart worked on research and development for the Gemini program, the Manned Orbital Laboratory, West Coast Space Shuttle, and various satellites and ballistics. He is a graduate of the Industrial College of the Armed Forces and holds an M.S. in aerospace engineering from the Air Force Institute of Technology (jimmy.f.kephart@notes.aero.org).

E. J. (Joe) Tomei, Chief Engineer for Space Launch, Space Launch Operations, is responsible for horizontal engineering across all launch programs. Previously, he served as chief engineer for the EELV program and principal engineer for plans and analysis for Space Launch Operations. Tomei joined Aerospace in 1979 on the West Coast Space Shuttle program, serving as development and operations director for Space Launch Complex 6 until 1988. He provided testing and launch support for the first two shuttle missions from Kennedy Space Center. Tomei has an M.S. in aerospace engineering from the University of Southern California (edmardo.j.tomei@notes.aero.org).

Joseph F. Wambolt, Principal Director, Western Range Directorate, manages Aerospace activities in support of DOD space-launch programs at Vandenberg Air Force Base. Since joining Aerospace in 1960, he has held many managerial positions in launch-vehicle systems. His organization received the Aerospace Program Recognition Award for the Delta Program in 1992 and for the Atlas E/F Program in 1995. He shared The Aerospace President’s Award in 1990 for program management, and in 2000 received the company’s highest award, The Aerospace Trustees’ Distinguished Achievement Award, for his management and technical leadership. Wambolt has a B.S. in chemical engineering from Northeastern University, Boston, and an M.S. in business administration from California State University, Dominguez Hills (joseph.f.wambolt@notes.aero.org).

The Crosslink editorial staff. From left to right: Steven R. Strom, Robert Wright, Gabriel Spera, Donna Born, Jon Jackoway
This chart shows the lineage of major U.S. space launch vehicles. Many trace their roots to the V-2, brought back from Germany after World War II. Previously, the United States had been developing rockets, such as the Corporal, but none was as sophisticated as the V-2.

The postwar period saw the birth of the Army's Aerobee and Bumper (the first two-stage rocket) and the Navy's Viking sounding rockets. Viking was chosen as the first stage and Aerobee as the second stage for the Navy's Vanguard rocket. Vanguard later lent components and systems to Thor and its successor, Delta, as well as to the small Scout rocket and the Air Force's Atlas. Scout was America's first solid-fuel launch vehicle capable of putting a satellite into orbit; it took its first stage from the Navy's Polaris missile and upper stages from Vanguard. Polaris technology would also find its way into Minuteman ICBMs. Minuteman technology is now used to build small launch vehicles such as Pegasus and Minotaur.

Another early weapon program led to the Navaho cruise missile. Although the Navaho program did not last long, its legacy was significant. The Navaho booster engine, adapted from the V-2, was used in the development of Atlas, Redstone, Jupiter, Thor, and Titan I.

Atlas D, the first operational ICBM, was deployed in 1959. These missiles were later refurbished as space launch vehicles. Atlas gave way to the Atlas II family, which gave rise to Atlas V, one of two boosters in the Evolved Expendable Launch Vehicle (EELV) program.

The Thor ballistic missile program began in 1954. Although its airframe design was new, some of Thor's subsystems were borrowed from Atlas, including the guidance system and the Navaho-based booster engine. The Air Force soon began adding upper stages to Thor, creating Thor-Able, Thor-Able Star, Thor-Agena, and Thor-Delta—or simply Delta, as it came to be known.

Delta was first launched in 1960 using a second stage borrowed from Vanguard. Solid-rocket motors, derived from Scout, were added a few years later. Today, Delta IV is one of two boosters in the EELV program.

In 1961, the Army's Redstone rocket carried the first American into space. The Redstone, given two upper stages, became Jupiter C, later renamed Juno I; its liquid-propellant main-stage engine came from Navaho. A Jupiter C placed the first U.S. satellite into orbit. Juno I and the Jupiter ballistic missile combined to form Juno II. Redstone, Jupiter, and Juno led to the Saturn series, culminating in the massive Saturn V.
The first Titan ICBM was deployed in 1962. Development of Titan II began the same year. Many variants of Titan III emerged, including the IIC and 34D, whose solid motors were derived from Minuteman. The seven-segment Titan IIIM, conceived but never built for the canceled Manned Orbiting Laboratory, later resurfaced as Titan IV.

Centaur was the first American high-energy, liquid-hydrogen/liquid-oxygen rocket. Until 1974, Centaur was used exclusively with Atlas. It was later used with the Titan III and IV boosters and contributed to the Saturn series.

Propulsion system concepts and technologies from Saturn V and Titan III were applied to the space shuttle, whose main engines in turn contributed to the RS-68 engine used on Delta IV.
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