Crosslink

Rocket Science

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On the cover: An Atlas V blasts off from Cape Canaveral. The Atlas V and the Delta IV are the two rockets in the Air Force's EELV program. Design by Karl Jacobs.

From the Editors

Launch is hard—hard on your nerves, hard to get right, hard to get out of your system. Even after decades of practice, the launch vehicle community is challenged by each new attempt to send a payload into space. This is partly because of the high performance, low margins, and numerous hazards involved, but it is also because of the low production and flight rates, which profoundly affect how launch gets done. Thus, each launch is unique, replete with its own risks and rewards.

Minimizing risk—or at least managing it—is a primary mandate, especially for launches dealing with national security space. Aerospace has applied considerable resources to understanding the sources of risk and mitigating them enough to instill confidence in mission success. Propulsion systems, for example, are responsible for most launch failures, and Aerospace has worked hard to identify potential engine hazards and establish consistent and reproducible methods of testing for them. Flight software is entrusted with the critical job of steering the rocket into space; Aerospace has developed tools to optimize launch trajectory and verify software code while enhancing the sensors that tell the vehicle where it is and where it's going. Intensive effort has also been applied to generating accurate models of the dynamic forces that threaten the vast array of critical components and structural elements.

The age of the Evolved Expendable Launch Vehicle has arrived; yet numerous groups in the public and private sectors are already pursuing the next big leap in launch technology. They need the services of knowledgeable and unbiased experts to help coordinate their efforts and chart the best course forward. A new mandate for NASA, for example, could profoundly affect the strategy for securing cheap, reliable, and responsive access to space for national defense initiatives. Aerospace is helping these groups strike the optimal balance between risk and return with the goal of maximizing the potential benefit for all stakeholders.

Throughout the years, Aerospace has developed new technologies and honed its engineering expertise to reflect changing mission objectives, management philosophies, and launch procurement strategies. With an institutional memory exceeding 40 years and a growing repertoire of custom design and analysis tools, the company remains in a unique position to guide the country's space-launch initiatives well into the coming century. We hope this issue of *Crosslink* will provide some insight into the diverse technical challenges of spacelift and serve as a launching pad for further investigation.

In the Spirit of Opportunity

NASA's Jet Propulsion Laboratory (JPL) recently landed mobile scientific instruments or "rovers" on the surface of Mars. The first of the two rovers left Cape Canaveral aboard a Delta II rocket and safely touched down six months later on January 3, 2004. The second arrived three weeks later.

Aerospace was involved in this historic mission at varying levels since its beginning, roughly four years ago. "It is our first example of participation on a JPL project from inception into operations," said Dave Bearden, Systems Director of Aerospace's NASA/JPL Advanced Programs Office. Aerospace was part of a team supporting diverse areas, such as requirements management, general systems engineering, selected redundancy studies, risk management, mission visualization, subsystem peer reviews, launch vehicle mission planning, mission design and operations review, analysis of surface-to-orbit communi-

nication links, test anomaly resolution, and cost and schedule evaluations.

Aerospace's Satellite Orbit Analysis Program, for example, played a role in the spacecraft trajectory design. "We ran visualizations that showed basically the launch and the travel to Mars and the entry, descent, and landing on to the surface," said Bearden. Texture maps—representations of the geologic features on the planet—made the program even more useful in targeting certain landing areas.

Communicating with an instrument on the surface of another planet is obviously tricky. As Bearden explained, the rovers have two ways of sending signals to Earth—they can use a direct low-data-rate link, or relay their signals through other satellites orbiting the planet (the Mars Global Surveyor, Odyssey, and Mars Express). The relay method achieves much higher data rates. "We did some modeling where we looked at opportunities for communications from

orbiting assets to the rovers based on different places the rover might land and where the spacecraft might be," said Bearden. Based on these models, the communications team could make recommendations about nudging the satellites one way or another to optimize communications.

Aerospace work in risk and cost management for this project could have wider applications, Bearden said. "We developed some risk management processes and tools like failure modes and effects analyses for the rovers, and those are the types of things that are readily brought back and applied to national security space," he said. An Aerospace risk study found that while the Mars Rovers were reasonably well-funded, the time available for development was less than half the historical norm for success. An Aerospace tool known as CoBRA (Complexity-Based Risk Assessment) is being adapted for broader applicability to military satellite systems.

A 2020 Vision of the Moon

The White House in early January announced an ambitious plan to establish a human presence on the moon as a stepping-stone to an eventual piloted mission to Mars and beyond. Pete Aldridge, former president of Aerospace, will chair a special commission of private- and public-sector experts to advise the President on its implementation.

According to the plan, the space shuttle will remain in service only until 2010, the deadline for completing work on the International Space Station. It will be replaced by a new type of spacecraft, the Crew Exploration Vehicle. Flight tests will begin in 2008, and the first flights with an onboard crew will begin no than 2014. The vehicle will be capable of transporting astronauts and cargo to the space station after the shuttle is retired, but its main purpose will be to carry astronauts to other bodies in space. The vehicle will begin ferrying

International Launch Services photo by Carlton Bailie

astronauts to the moon as early as 2015 to establish a base there for further human exploration of the cosmos by 2020. Robotic missions, beginning in 2008, will scout the lunar surface to prepare for human outposts.

The full implications of the proposal for organizations such as Aerospace are not entirely clear. John Skratt, Principal Director of Space Launch Projects, remarked that "the nature of our technical support may not change (independent assessment, testing in the labs, modeling and simulation, special technical support, requirements analysis and management, etc.) but the application will be different. The challenge will be to make the shift happen in a smooth and timely manner."

Notably absent from any description of the initiative, said Skratt, is "exactly how we will launch the payloads necessary to fulfill whatever the plan will be. The suggestion is the continued use of expendable launch vehicles, both domestic and foreign," he said, adding, "My guess is that the issue of what the launch system will look like initially and downstream will be the basis of vigorous future debate."

Lidar Calibrates Sensor on Orbit

The Defense Meteorological Satellite Program (DMSP) has a new tool for predicting weather that could affect ground combat operations. The Special Sensor Microwave Imager/Sounder (SSMIS) is a multifrequency passive microwave sensor that is designed to enhance and extend DMSP microwave imaging and sounding capabilities. Aerospace played a key role in conceiving and developing the new instrument and is now verifying operation following launch of the first SSMIS on DMSP F-16. SSMIS aligns temperature and water-vapor readings within the same view of Earth and uses a conical scan, providing a constant angle of incidence at Earth's surface. This

is expected to increase resolution and accuracy of sounding information used in weather forecasting. Aerospace lidar measurements were recently used to confirm that key temperature and water-vapor channels are responding correctly and that calibration of most sounding channels is accurate.

"Lidar is the only profiling method capable of meeting the accuracy and altitude range requirements needed to confirm SSMIS capabilities," said John Wessel, Distinguished Scientist in the Electronics and Photonics Laboratory. The lidar methods employed are based on Rayleigh and Raman scattering of light, he explained. In lidar, a laser emits optical pulses up into the atmosphere, and light is scattered back to the receiver by atmospheric molecules. The amplitude of the elastically scattered

light (Rayleigh scattering) is proportional to atmospheric density at high altitudes. The density measurement can then be converted into temperature. Light is also scattered at Raman-shifted wavelengths, corresponding to vibrational frequencies of atmospheric constituents. Raman scattering can be used to measure water vapor in the troposphere when wavelength-selective elements are used to discriminate the water-vapor signals. Round-trip times are recorded for the signals, providing range profiles for temperature and water vapor. Radiative transfer calculations are performed on the lidar profiles, providing accurate simulations of radiances expected from the SSMIS microwave channels. These can then be compared to the actual profiles derived from SSMIS.

Robert Farley and Shaun Stoller deployed the Aerospace/DMSP lidar at Barking Sands, Kauai. Wessel analyzed the lidar data to produce atmospheric water-vapor and temperature profiles, and Ye Hong applied a custom radiative transfer code to them. This code converted the measured atmospheric profiles into the brightness temperatures that SSMIS was expected to observe during overpasses of the lidar site. The results agreed well with SSMIS brightness temperatures for most channels, although two channels were found to exhibit biases that may require revision of SSMIS calibration coefficients. A second campaign is underway, said Wessel, with a goal of improving measurement statistics and extending upper atmospheric temperature profiles over the range sensed by the highest altitude temperature channels of the new upper atmospheric sounder.
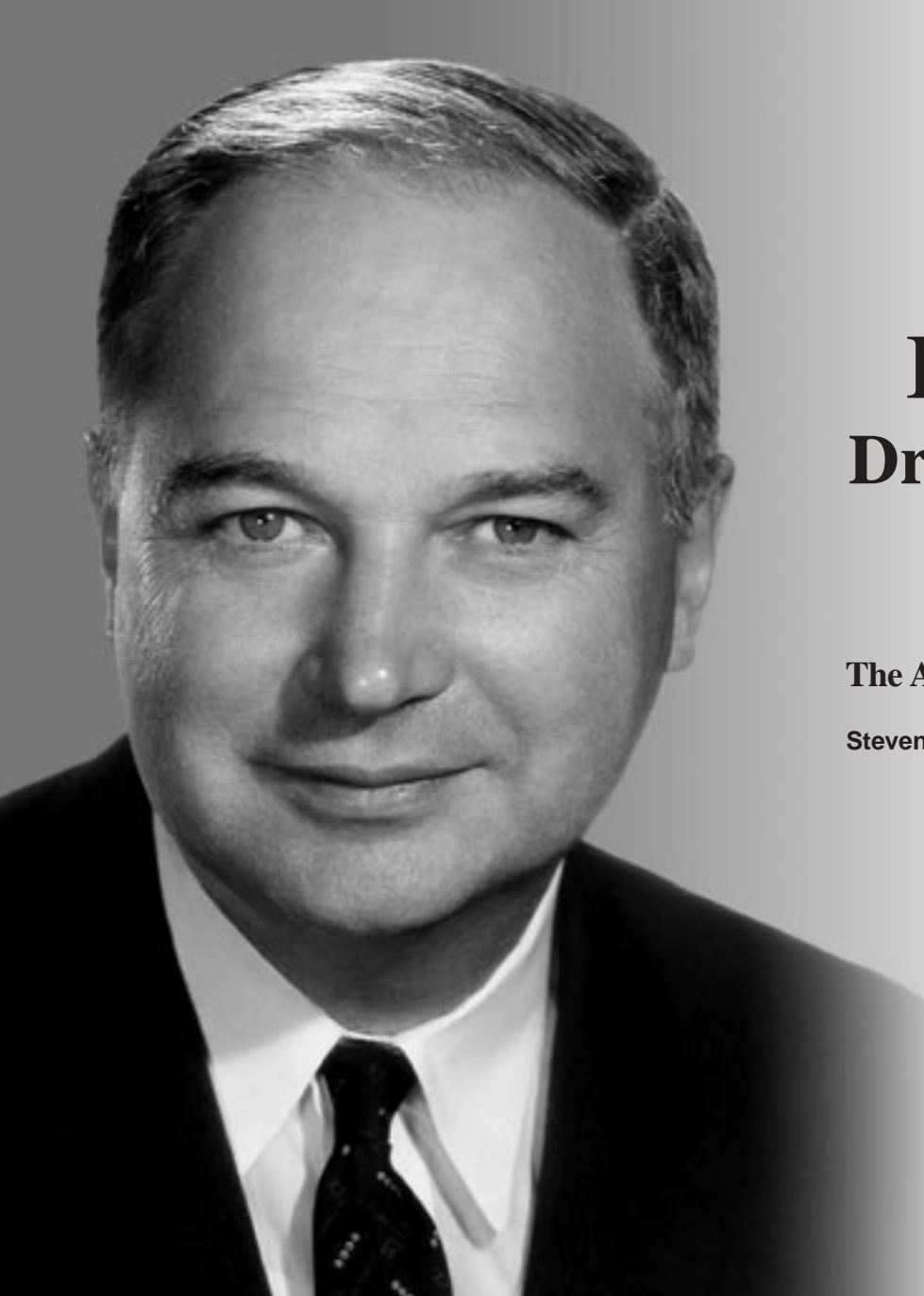
Aerospace began developing lidar calibration facilities for heritage microwave sensors in 1993 and has performed sensor calibrations for five DMSP satellites.

Ultrasound Technique Clears Rocket Motors for Flight

A nondestructive evaluation method developed at Aerospace helped pave the way for a successful launch of the Delta II rocket that carried the GPS IIR-10 satellite into orbit. In some rockets, the nozzle exit-cone liners are manufactured by wrapping composite tape around a metal mandrel to form plies at a specific angle relative to the nozzle centerline. The ply angle determines a critical trade-off between thermal conductivity and erosion rates. If the ply angles are too high or too low, nozzle structural components will overheat, causing the exit cone to fail. Unfortunately, checking ply angles is extremely difficult in completed nozzles. So, when several of the graphite-epoxy motors on the Delta II were suspected of having aberrant ply angles, the Air Force asked Aerospace to investigate.

Eric Johnson, Associate Director of Materials Processing and Evaluation, explained that the Aerospace technique involves measurement of the ultrasonic pulse-echo delay as a function of nozzle station. The delay times are compared with a nozzle-specific ply-angle lookup table that is developed by modeling the liner material as a transverse isotropic solid with fitting parameters determined via an ultrasonic through-transmission measurement. Working on the launchpad, Aerospace acquired data for the nine GPS IIR-10 nozzles. The results showed that the ply angles were within acceptable limits. The contractor is in the process of developing an automated nozzle scanner that will incorporate this inspection method. At the Air Force's request, Aerospace recently completed a similar inspection of the nine nozzles slated for the GPS IIR-11 mission, Johnson said.

VISION AND INTEGRITY:
Dr. Ivan A. Getting
1912–2003

**President,
The Aerospace Corporation, 1960–1977**

Steven R. Strom

The Aerospace Corporation lost its founding president and one of its most ardent advocates when Dr. Ivan A. Getting died October 11, 2003. From the company's founding in 1960 until his retirement in 1977, Getting's name was virtually synonymous with Aerospace. A brilliant visionary, he contributed to the world in ways that extend far beyond the company. Just last year, he shared the prestigious Draper Prize for his contributions to the development of the Global Positioning System, now recognized as one of the greatest aids to navigation in centuries.

Getting's accomplishments have been cited numerous times in the flood of obituaries that chronicled his life: the development during World War II of the SCR-584 radar tracking system, which intercepted German V-1 rockets fired at England and saved thousands of lives; his oversight of the production of transistors while serving as vice president of Raytheon, the first time this was done on a commercial basis; his contributions in 1956 to the Project Nobska study, which recommended the development of a submarine-based ballistic missile that ultimately became the Polaris; and major contributions to the Mercury and Gemini space programs during his first years as president of Aerospace. These are just a few of his outstanding achievements.

Nonetheless, Getting was most proud of the role he played in the formation of The Aerospace Corporation. In the company's formative years, Getting, more than anyone else, established the culture of uncompromising excellence that still endures more than four decades later. Under Getting's direction, Aerospace became a close and valued partner of the Air Force in the development of national security space systems. Max Weiss, who organized the Electronics Laboratory in 1961 and retired as Engineering Group Vice President in 1986, recalls that it was Getting's "absolute dedication to the importance of laboratory research at Aerospace" that "made the company much more effective as a trusted advisor to the government." Getting took time to mentor the younger members of the Aerospace staff, and Weiss noted that his delight in doing so, combined with his "passion for excellence," his good sense of

humor, and his "vision and integrity," helped "set the tone for Aerospace, which made it a pleasure to work there."

In addition to his support for Aerospace's technical and scientific operations, Getting was a strong advocate for continuing education in the development of the Aerospace workforce, and not just in science and mathematics. During his tenure as president of the IEEE in the late 1970s, Getting helped establish the organization's History Center. He was, in his own words, "a strong supporter of the role that history has to play in any organization." He was also a great admirer of *Crosslink*, and felt that the magazine played a vital role in explaining to the outside world the importance of Aerospace activities. Just three days before his death, he contributed to the article on the Dyna-Soar program that appears in this issue.

Getting's innovative contributions extended to matters that most folks at Aerospace take for granted, including the design of the main corporate campus in El Segundo. Getting closely followed the planning of new facilities for Aerospace, which began in 1963, making sure that the buildings were well designed and well lit and

the grounds nicely landscaped to "create an environment that would help to foster the creative thinking of Aerospace employees." He often worked late into the night with the architects and designers to ensure that the Aerospace buildings would be conducive to the company's overall mission.

Getting's brilliant mind was active right up to the time of his death. George Paulikas, former executive vice president, remembers that "he had a seemingly unbounded curiosity in matters scientific and technical. I recall that talking to him about a technical subject in 1961, or 2001 for that matter, was an invitation to discover how much you really knew—like a graduate school oral exam!" Max Weiss ably summarized Getting's long career and the qualities for which he will be remembered: "He was an extraordinary figure of the 20th century, a brilliant scientist and engineer, a great leader of men and women, a major force in the defense of our freedom during World War II and the Cold War, a dreamer of dreams who willed them into reality, and above all a wonderful human being." 🪐

Jurassic Technology:

The History of the Dyna-Soar

Steven R. Strom

During its brief existence, the nation's first space plane fostered research and technology that influenced space efforts for years to come.

When NASA announced in the spring of 2003 that its next major project would be the design and launch of an orbital space plane, many in the space community sensed that the nation's space program had come full circle. An Air Force program to develop a similar orbiting space plane, the Dyna-Soar, was the first in the nation's history to result in the manufacture of hardware. The Dyna-Soar program was truly a pioneering effort, and although it was canceled in December 1963 without achieving flight, it fostered research that was later applied to the development of the space shuttle and other U.S. space systems.

A largely forgotten aspect of this advanced program is that The Aerospace Corporation, under the direction of the Air Force, was responsible for general systems engineering/technical direction (GSE/TD) for the Dyna-Soar's proposed Titan booster—including modification of Launch Complex 20 at the Atlantic Missile Range. As with other early space programs, Aerospace personnel would ultimately make important contributions to the Dyna-Soar program prior to its cancellation.

Early History

As early as 1951, the Air Force began preliminary conceptual studies for a hypersonic, suborbital boost-glide vehicle. Various concepts were proposed throughout the 1950s, ranging from the initial bomber-missile concept to a rocket-bomber to a boost-glide vehicle. By 1957, virtually in tandem with the Soviet launch of Sputnik I, the Air Force had refined and consolidated these competing concepts into a system development plan for the newly named Dyna-Soar (from "dynamic ascent" and "soaring flight"), which was now seen as a follow-up to the experimental X-planes, including, most notably, the X-15. The initial version of Dyna-Soar called for a suborbital hypersonic vehicle that would be launched by a modified Titan I (the country's first two-stage ICBM, first launched in early 1959). Although some early proposals had envisioned the Dyna-Soar as an orbital vehicle, emphasis had shifted to the glider's suborbital capabilities, partly because of the booster's thrust limitations, and partly because of President Eisenhower's belief that the American manned space effort should be directed by a civilian agency. In fact, work on the Dyna-Soar program was to include assistance from the National Advisory Committee for Aeronautics, which later became NASA.

The Dyna-Soar program was approved in 1958, and in June, contracts were awarded for development of the system, vehicle, and modified Titan booster. The Air Force's Wright Aeronautical Development Center would direct the program, but the Air Force Ballistic Missile Division (AFBMD) would oversee the booster and launch-complex development, with Space Technology Laboratories (STL) assuming the role of GSE/TD for the Titan. Dyna-Soar was designated Program 620A by the Air Force. Disputes over the exact role of Dyna-Soar continued throughout the life of the program, many of which were never resolved. Whether it was a research vehicle, a military space system, or a combination of the two was always a divisive issue within the Department of Defense and even within the Air Force. Despite these differences,

many in the Air Force viewed the Dyna-Soar as their best hope for ultimately acquiring a manned presence in space.

A Boost from Aerospace

STL's GSE/TD responsibilities were reassigned to Aerospace following its formation in 1960. The Dyna-Soar program office, part of the Engineering Division, was among the first program offices formed at Aerospace. Under the direction of Walter Tydon, it was divided into four technical departments: Airborne Systems, Ground Systems Equipment, Product Assurance, and Test Planning and Evaluation. Aerospace, as a contractor for AFBMD, was responsible for providing technical direction to AFBMD's associate contractors to ensure the necessary design changes and modifications to the Titan I booster and its ground support equipment, including the launch facilities. Technical direction also extended to the integration of the booster subsystems and the launch complex as well as oversight of the actual launch operations.

The development plan went through numerous changes, and by late 1960, had been divided into three distinct phases. The Aerospace program office was specifically directed to assist with the first phase, research and development of the glider and its associated systems. Airdrops of an unpiloted glider from an airplane were scheduled for mid-1963, and an unpiloted glider launch using the Titan I was planned for late 1963. The final step of phase one included 14 piloted suborbital flights, which were scheduled to begin in early 1964 and conclude in 1966. Phase two involved the actual launching of the Dyna-Soar craft into orbit, while phase three would involve the development of weapons systems that could be used by the Dyna-Soar vehicle. The piloted flights were scheduled to land at four different sites, including one near Fortaleza, Brazil.

At first, Aerospace primarily carried through on decisions previously made by STL. Soon, however, Aerospace began making unique contributions through participation in several important Air Force studies. For example, when the weight of the vehicle increased following the addition of an acceleration rocket, the Air Force asked Aerospace to reevaluate the Dyna-Soar's booster requirements. Following these investigations, Aerospace recommended that the more powerful Titan II be used as the booster. Subsequently, in January 1961, the Air Force announced its decision to switch to a modified Titan II.
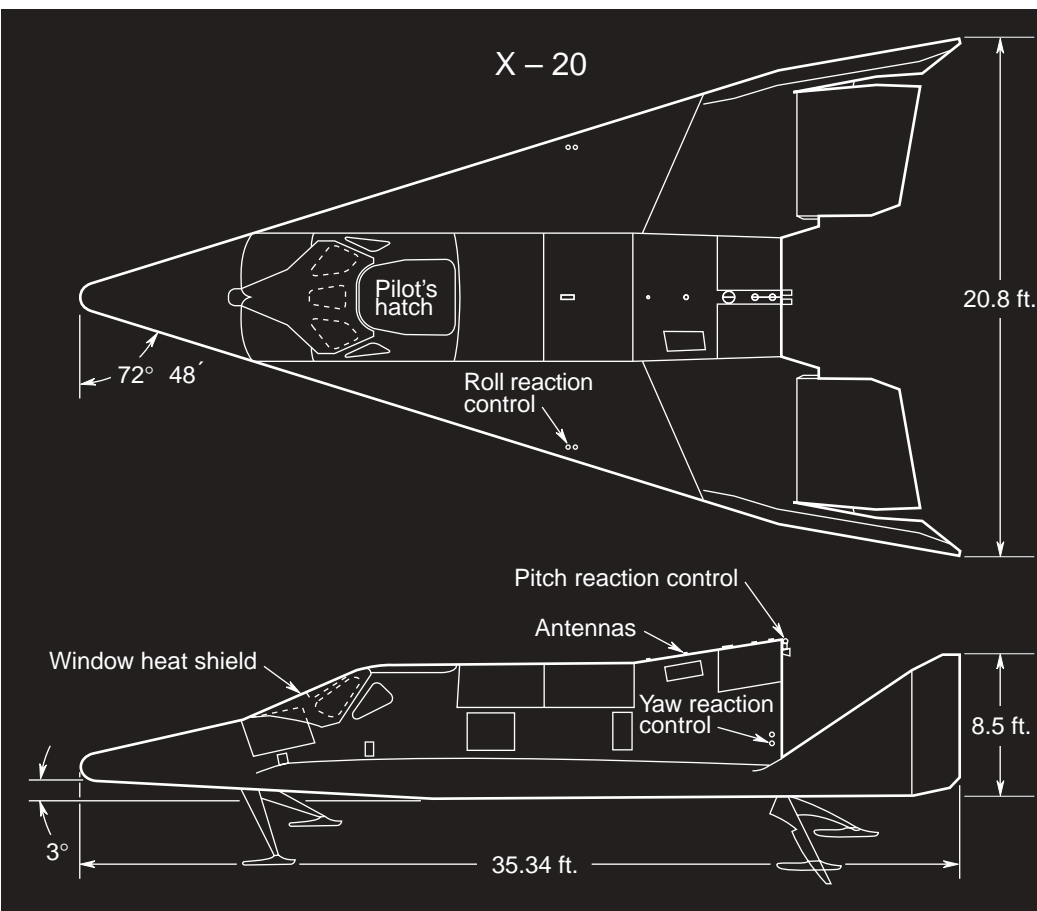
Aerospace had also been involved in an Air Force study known as Phoenix, which sought to determine the type of space launching system best suited to meet the needs of future space weapon applications. This study coincided with the new effort to develop a Titan II launch vehicle, and Aerospace Dyna-Soar personnel were able to use the Phoenix study's closely allied knowledge base for their own research.

One of the first studies conducted by the Dyna-Soar team after the adoption of the modified Titan II was an investigation of whether the launch vehicle should use an inertial guidance system, a radio guidance system, or a combination of the two. Ultimately, Aerospace concurred with the contractor that an all-inertial system would be most effective because it freed the missile from any reliance on a ground-based guidance system.

Too Big to Support

The Dyna-Soar program office continued to grow at Aerospace, but by the summer of 1961, there were already indications that it might be phased out before long. To begin with, the increasing weight of the Dyna-Soar was forcing the Air Force to seek an even larger booster. The Soviets, meanwhile, had been launching a series of satellites, each more massive than the previous one. The Vostok I capsule, which carried Yuri Gagarin on his historic orbital flight in April 1961, weighed more than five tons—more than three times the mass of America's Project Mercury capsule. While little was known about the Soviet booster, it was obviously far more powerful than any U.S. rocket. Gagarin's flight was a prominent topic among the Dyna-Soar planners at this time, and many wanted to speed up the Dyna-Soar program by eliminating the suborbital phase altogether, focusing instead entirely on orbital flights. Work at Aerospace was specifically geared toward the suborbital segment, so unless the office received new directives, it would no longer have a viable mission.

In light of the vehicle's growing weight requirements, the Air Force asked Aerospace to evaluate two competing proposals for a new, more capable Dyna-Soar booster. Aerospace recommended further modifications to the Titan II—specifically, the use of strap-on solid motors for the first stage. This booster was later renamed Titan III, and by the end of October 1961, the Air Force was touting it as the new launch vehicle for Dyna-Soar and for other future

X – 20

Pilot's hatch

72° 48′

Roll reaction control

20.8 ft.

Pitch reaction control

Antennas

Window heat shield

Yaw reaction control

8.5 ft.

3°

35.34 ft.

When the Dyna-Soar grew too heavy for a standard Titan II, Aerospace recommended the addition of two strap-on solid rocket motors.

Artist's conception of the Dyna-Soar separating from a Titan booster.

military space launches. On October 16, Tydon noted "the strong possibility of the activation of the Titan III program" and pointed out that the expertise earned by members of the Dyna-Soar office "would benefit the Aerospace efforts on Titan III." In November, the Air Force opened a new program office, known as Program 624A, to support the new booster. That same month, Aerospace announced that it was ready to provide GSE/TD to the Titan III development effort.

Once again, the Dyna-Soar program experienced a major revision. In retrospect, one might say that the technology was developing faster than the original schedule, fueled by the intensive space race. Thus, as expected, the Air Force announced in December that all suborbital flights employing the Titan II booster had been eliminated. The developmental program would concentrate on orbital flights using an "improved booster" (i.e., the Titan III). The first piloted flight was projected for August 1965. All flights would last one orbit and land at Edwards Air Force Base. At the urging of Defense Secretary Robert McNamara, the Air Force changed the program's official designation to X-20, highlighting its lineage from the well-known X-15. Nevertheless, the Air Force continued to use the Dyna-Soar name for public references, and both names were used, sometimes interchangeably and sometimes together, for the remainder of the program's life.

Shifting Focus

With the cancellation of suborbital flights, the Aerospace program office found itself without a mandate. By the end of January 1962, Aerospace had reassigned its Dyna-Soar personnel to other offices, primarily the Titan III effort. Although the lifespan of the Aerospace Dyna-Soar program office was relatively brief, Aerospace employees had made a number of contributions toward the effort to develop an adequate booster for the Dyna-Soar vehicle. In addition to its study recommending the Titan II, Aerospace contributions included the solving of difficult telemetry and guidance problems for the Titan II, the introduction of a systems engineering approach in the design of the Dyna-Soar booster configuration, overall system launch planning, development of a system to monitor the Dyna-Soar's malfunction-detection system, studies of the Titan's aerodynamics, and the establishment of reliability criteria for the Dyna-Soar booster system and its subsystems.

Despite the closure of its Dyna-Soar program office, Aerospace continued to support the program indirectly during the final two years of the Dyna-Soar effort. In addition to ongoing assistance from its Program 624A office with the Dyna-Soar booster, Aerospace also had responsibility for developing launchpads 40 and 41 to accommodate the modified Titan III. The Dyna-Soar program itself was coming under increased scrutiny by Defense Secretary McNamara, who was troubled by the program's lack of clear focus and direction. That summer, yet another schedule was released, this time with the addition of multiple-orbit flights.

Many in the Air Force remained optimistic that the Dyna-Soar could survive in some form, despite McNamara's reservations. When a mockup of Dyna-Soar was rolled out for public inspection in Las Vegas in September 1962, it quickly grabbed the attention of American space enthusiasts. The futuristic look of the space plane supported the optimistic attitude that Americans had toward new technology in the 1960s. By contrast, the blunt-nosed capsule used by the Mercury astronauts looked rather pedestrian. The advanced design of the Dyna-Soar glider is one of the major reasons for its lingering appeal. Writing in *Reader's Digest*, John G. Hubbell enthusiastically reported that the Dyna-Soar symbolized the best aspects of the American space program. The Dyna-Soar, he wrote, "looks like a cross between a porpoise and a manta ray…. It is a manned space glider—and one of the most important things to have happened in aviation since the Wright Brothers' first flight." During the Las Vegas rollout, the six Air Force pilots selected to fly the Dyna-Soar missions were also presented to the public for the first time.

A model of the Dyna-Soar captured the public's imagination when it was unveiled in 1962.

Dyna-Soar Extinction

Although the Air Force was beginning to make progress on the public relations front, the Dyna-Soar program was coming under greater threat. By the beginning of 1963, the Air Force was under pressure from DOD to provide a better rationale for the program's continued existence. In late January, Secretary McNamara announced a review of the Dyna-Soar, Gemini, and Titan programs to determine which vehicle would best serve the needs of future military space systems. McNamara again raised questions about the program's viability in March during a tour of contractor facilities. In June 1963, engineer Jack H. Irving reported McNamara's growing concerns to the Aerospace Board of Trustees. He pointed out that McNamara was particularly unhappy that "not enough attention has been directed to the specific military missions to be performed." Another program revision was announced in September, but by then it was probably too late to save the Dyna-Soar program, as McNamara had perhaps already made up his mind about its future.

On December 10, 1963, McNamara held a press conference to announce the cancellation of the Dyna-Soar program. At the same time, he revealed that the Dyna-Soar effort would be replaced by the Manned Orbiting Laboratory (which eventually spawned the largest Aerospace program office before it, too, was canceled in 1969).

An Enduring Legacy

Despite its cancellation, the legacy of the Dyna-Soar lives on. For example, many of the space shuttle's design elements and operating capabilities were derived from Dyna-Soar, including its rocket/glider configuration, its ability to land on a runway, its cargo bay, and its reusability. In addition, the extensive wind-tunnel tests conducted for the Dyna-Soar fostered new research methodologies used for several subsequent programs.

Perhaps the program's principal legacy is that in its drive to create a better booster for the Dyna-Soar, the Air Force developed a superior space launch vehicle, the Titan III. According to Ivan Getting, the first president of Aerospace, "Dyna-Soar was a remarkably far-sighted program. Aerospace was on the cutting edge of space research, as it was with the Mercury and Gemini programs." A recently published NASA inventory of American X-vehicles aptly summarizes the primary achievement of the Dyna-Soar program: "Very few vehicles have contributed more to the science of very high-speed flight—especially vehicles that were never built."

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The Suborbital Bomber

The origins of the Dyna-Soar program can be traced to concepts advocated by the German scientist Eugen Sänger as far back as the early 1930s, when he first proposed the development of boost-glide hypersonic aircraft. Sänger envisioned spaceflight as the next logical development in aviation, and he continued his design studies for a winged hypersonic vehicle for the remainder of the decade. The studies of Sänger and his fellow scientist (and future wife) Irene Bredt caught the attention of German military authorities, but the outbreak of World War II forced the Germans to focus their available resources on proven, rather than hypothetical, weapon systems.

As the war continued, desperation forced German military authorities to reconsider Sänger's ideas with the hope of developing a breakthrough weapon that might turn the war in Germany's favor. At one point, Sänger proposed to the German high command that a skip-glide plane capable of bombing New York City be built. Launched into a suborbital trajectory, the plane would have "skipped" along Earth's atmosphere, dropped its four-ton bomb load on New York, and glided back to its launch site in a series of decreasing bounces. Fortunately for the Allies, there was not enough money, resources, or time to construct the Sänger-Bredt "Silverbird." When American scientists obtained access to Sänger's research after the end of World War II, many of them became aware for the first time of the real possibility of creating a space plane that could function much like a conventional aircraft in outer space. As knowledge of Sänger's work spread through the U.S. military, many Air Force planners came to believe that the outcome of the next major conflict might well be decided in the near-Earth or space environment.

U.S. Air Force

That's Why They Call It
Rocket Science

Why is it so hard to launch a rocket into space with absolute assurance of success?

Edward Ruth

We've all seen the images. The silver and white rocket is thrusting majestically across the sky. It seems the very embodiment of power and technology and the fulfillment of an age-long dream of reaching the heavens. Suddenly, something goes terribly wrong. The rocket seems to tear itself apart and in an instant is transformed from an icon of humanity's great achievement to a scattering of high-tech trash raining down from the sky in flaming bits.

In the early days of spaceflight, this scenario was all too familiar, as one launch attempt after another ended in failure. Today, after nearly 45 years of development, launch systems have grown reliable enough to permit civilians and other non-career astronauts to fly in space on a somewhat routine basis. The experience and expertise of The Aerospace Corporation has helped the U.S. Air Force attain some of the highest launch success rates in the world. Still, even with these achievements, each launch requires a dedicated team of experts working many hours to achieve success—and even then, too many launches come to a tragic end.

Why don't modern launch systems have the same reliability as other comparable

technologies? Is there something about the fundamental physics behind launch vehicles that makes them inherently challenging to operate? What's so hard about launch systems that the expression "it's rocket science" is still used to signify a difficult activity?

The Rocket Equation

To answer these questions, we need to look at the engineering of launch vehicles, beginning with the so-called "rocket equation," which shows what parameters affect launch vehicle design and what impact they have on launch system reliability.

The rocket equation states that the velocity imparted to a payload by a given rocket stage can be found by:

$$\Delta v = gI_{sp}\ln(M).$$

Here, Δv is the change in velocity, and g is the gravitational constant (i.e., the groundward acceleration caused by Earth's gravity, 9.8 meters per second per second). The quantity M, the mass ratio, is the ratio of the mass of a fully fueled rocket stage (including any upper stages and payload) to its mass without fuel. The specific impulse, I_{sp}, is a measure of engine performance.

To get better performance from a rocket stage, we must increase either the specific impulse or the mass ratio. Today, the best engines can achieve a specific impulse on the order of 450 seconds, and this is probably about the best we are ever going to see from a chemical rocket. Specific impulse is mainly determined by the chemistry of the propellants, and it seems likely that after decades of experimenting, we are already using the most energetic propellant combinations that are technically useful.

This limitation on specific impulse leaves mass ratio as the only parameter that can be modified to improve performance. Mass ratio is simply a function of how much propellant can be loaded into the lightest possible structure—a property known as structural efficiency. The more efficient the launch vehicle is, the lighter it will be without fuel. A modern rocket stage will be 10 to 20 times more massive when it is fully fueled then when it is empty.

Failed launch of a Titan IV carrying a National Reconnaissance Office payload on August 12, 1998. The vehicle was lost at an altitude of 5330 meters, approximately 39 seconds into flight. Electrical transients in the power supply caused the guidance computer to reset, thereby losing attitude reference. Upon power recovery, the guidance system, responding to erroneous attitude information, commanded a maneuver that exceeded the vehicle's structural limits.

U.S. Air Force

Balancing Mass and Safety

The implications of the rocket equation can be summed up in this one simple fact: A high-performance rocket must be extremely light when empty. Unlike designers of highway bridges, nuclear reactors, or other large terrestrial structures, the rocket designer does not have the luxury of using more material than is needed to satisfy the minimum design requirements. Every item on the stage—engines, electronics, thermal protection system, etc.—must be as light as possible. Otherwise, the gross liftoff mass will become impractically large. This means that every part must be just strong enough to withstand the stress of flight and no more. Therefore, every part of a rocket is so close to its breaking point that any imperfection or flaw can lead to catastrophe.

This need for minimum design margins is a particular concern for the propulsion systems, which generate extremes of pressure, temperature, shock, and vibration. Rocket engines represent a significant fraction of the overall mass of the empty rocket stage, so they must achieve a high thrust-to-weight ratio to lift themselves—and the rest of the rocket and payload—into orbit. Given their high-energy output and low weight, it's not surprising that the propulsion systems are to blame in the majority of launch vehicle failures.

Complex Physics

The designer's job is further complicated by the specialized physics underlying the load-generating phenomena on the vehicle. The physics of launch vehicles involve such disciplines as aerodynamics, heat transfer, and combustion chemistry. These are difficult branches of engineering, and solutions to problems in these areas are often known only approximately, and then obtained only at great expense.

A good example of this complexity can be seen in determining the transient aerodynamic loads on the launch vehicle caused by a transonic flow over its exterior. The transonic flow regime—which is reached as the vehicle's velocity approaches and overtakes the speed of sound—is particularly difficult to model. There are no closed-form mathematical solutions to the complex equations governing the physics of transonic motion. Solutions can only be obtained using computationally intensive techniques that must be verified by testing in large and costly wind tunnels. Often, true measurements are only obtained in flight, and sometimes only after many flights.

Despite these challenges, the designer must ensure that an expendable launch vehicle will work right the first (and only) time it is used. Yet, problems with a launch vehicle might only become apparent when its components—including the software—are operated together as a complete system. Frequently, important system-design characteristics such as the aerodynamic loads or heat-transfer rates can only be
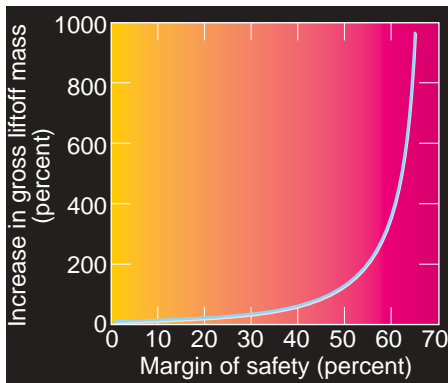
Simple graph plotting an increase in wall thickness of a rocket propellant tank versus an increase in the launch vehicle's gross liftoff mass. As wall thickness increases, the margin of safety goes up—but so does the mass. The curve is exponential, so a small improvement in margin of safety causes a large increase in liftoff mass.

determined with sufficient fidelity in flight. Simply put, the only way to thoroughly test an expendable launch vehicle is to expend it in a launch.

The Limits of Reliability

Putting it all together, we can summarize the designer's primary difficulties: Expendable rockets have minimal design margins, are governed by complex physics, and cannot be completely tested before flight. The launch vehicle designer must achieve as lightweight a structure as possible with only approximate knowledge of the loads it will encounter in its first and only flight. That modern rockets have achieved their current level of reliability is a testament to the dedication and skill of the teams that design, build, and launch them.

Have we reached the limit of launch vehicle reliability? We certainly have not. For one thing, there is a growing understanding that it is okay to sacrifice some performance in exchange for increased robustness. If we can accept an increase in gross liftoff mass while still getting the same payload into the desired orbit, then we can use significantly more mass to enhance structural durability.

There are, of course, practical limits to how much performance can be sacrificed while maintaining a launch system that is both affordable and operable. An increase in mass implies an increase in manufacturing cost. Historical expendable launch vehicle data suggest that hardware costs range from 50 to 75 percent of total launch costs, and all launch vehicle cost-estimating tools assume that mass and unit hardware costs are positively correlated. Therefore, limiting mass (beyond that which is necessary
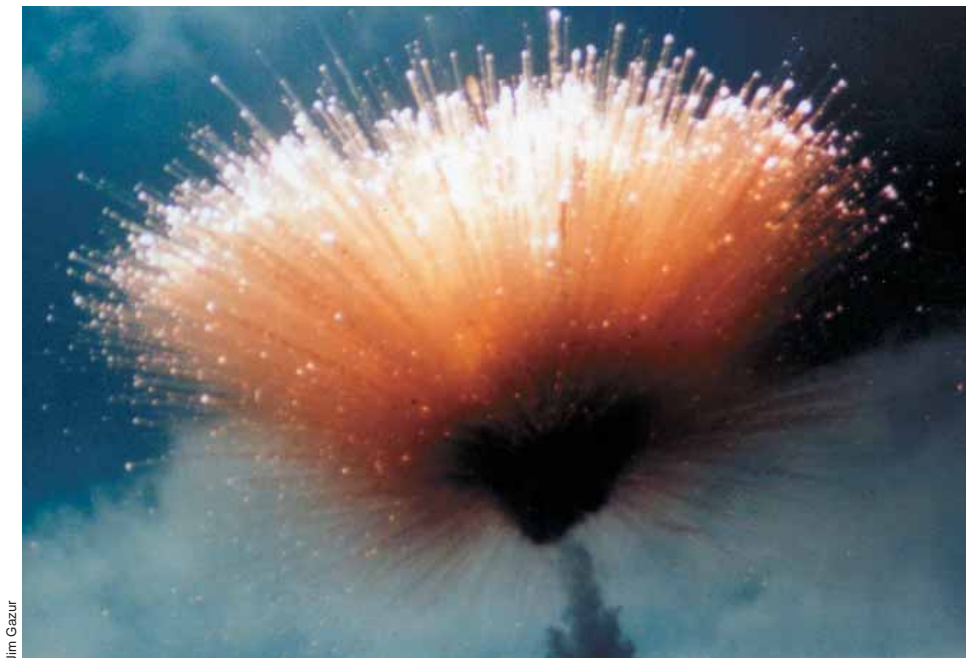
This Delta II rocket failed during a 1997 launch of a GPS IIR satellite. Approximately seven seconds after ignition, one of the solid rocket motors developed a long split in its casing. The motor exploded about five seconds later. The casing failure prompted the first-stage automatic destruct system. The second stage, third stage, and payload separated, but remained largely intact. Flight controllers then sent destruct commands to control the disintegration of the vehicle. These commands destroyed the second and third stages, which in turn released the payload fairing with the payload largely intact. The payload and fairing exploded on impact with the ground. Fortunately, there were no injuries.

to provide acceptable margins) makes the system more affordable. Larger vehicles are more difficult to erect and launch, requiring larger cranes, bigger trailers, and more extensive hardware in general.

Recall also that the rocket equation is exponential. Thus, a small increase in safety margins leads to a large increase in gross liftoff mass. In fact, if safety margins are increased too much, liftoff mass approaches infinity! At a certain point, an increase in reliability simply becomes impractical.

What's Next

As we move into the age of reusable launch vehicles, we move away from the paradigm of launch vehicles as ammunition—hardware used once, then discarded. A reusable vehicle can be flown repeatedly and, possibly, recovered from an aborted launch intact so flaws can be detected and corrected before the next flight.

Reusable launch systems may be able to take advantage of air-breathing propulsion, in which a rocket uses air from the atmosphere as oxidizer, rather than carry an oxidizer onboard. This scenario could provide a vastly improved specific impulse and thus a reduced emphasis on high mass ratios, with their attendant decreased margins.

Reusable systems may finally allow us to achieve launch-system reliability on a par with that of commercial aircraft. Until then, though, our launches really will remain rocket science. ♄

Driving Home the Point

Launch system designers base their designs on the best data available—but sometimes, the best data are just good estimates. True measurements of the launch environment can only be obtained in flight, and that's hardly an option at the design stage. The inherent risks of this design approach were driven home on one occasion when a faulty part caused an anomaly in a vintage launch system. The anomaly was only discovered when a part of the rocket part fell back to the launch site, landing on top of a parked car belonging to a member of the launch team! The failure most likely occurred because the actual aerodynamic loads encountered in flight were higher than what the original designers had calculated using the tools available to them at the time. The piece had probably failed on multiple flights and may have caused other unsolved problems; however, because the empty stages always fell into the ocean and were never inspected after launch, no one knew there was a problem with this part.

Launch Vehicle Propulsion

Rocket engines have evolved over the course of several decades. Research at Aerospace has helped make valuable improvements in performance, cost, and reliability.

Jeff Emdee

In 1920, *The New York Times* responded to a scientific paper in which Robert Goddard, the father of modern rocketry, discussed the possibility of sending a rocket to the moon. The *Times* editorial stated that Goddard's ideas were all wrong and that rockets could not reach the moon because there was "nothing for a rocket to push against in outer space." Of course, Goddard was correct, and in 1969, just after the launch of the Apollo 11 moon mission and 24 years after Goddard's death, the *Times* issued a belated retraction.

The technology underlying the propulsion systems that power today's rockets is being pushed to new limits. The analytical tools that Aerospace and contractors use to design and analyze engines have made significant improvements in speed and fidelity, but the hardware itself has evolved slowly compared with that of other high-tech industries. Characterized by extreme power density (enough pumping power to empty a swimming pool in 25 seconds) and severe temperature gradients (up to 3600 Kelvin), propulsion systems are understandably difficult to design with high

reliability. Challenges have included reducing propulsion system mass to allow more room for payload, pushing propellant combustion performance closer to the theoretical maximum, and increasing reliability to make launch vehicles as dependable as aircraft. The future holds promise in these areas, but to appreciate the changes taking place, one must first be familiar with the basic physics of rocket propulsion.

Rocket Science

To understand what Goddard knew in 1920, one must go back to the 17th century

Reaction

Action
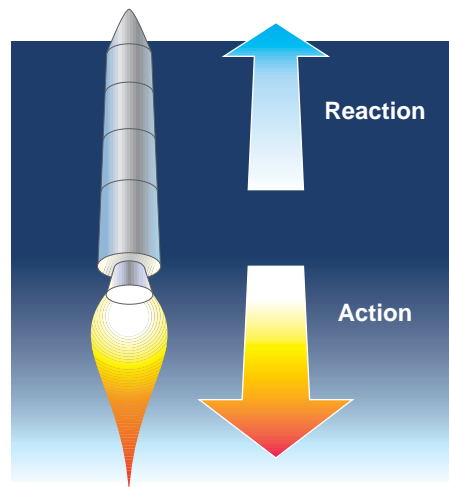
and Isaac Newton's three laws of physics. The first law is simple enough: Objects at rest will stay at rest and objects in motion will stay in motion, in a straight line, unless acted upon by an unbalanced force. The second law describes the relationship between force, mass, and acceleration—that is, an object will accelerate when a force is applied to it. The third law—for every action there is an equal and opposite reaction—explains why rocket propulsion works in a vacuum. The simplest way to think of this is in terms of someone on a small boat jumping onto a nearby dock. When the sailor leaps for the dock, he moves forward. His action imparts a force, or reaction, to the boat, sending it in the opposite direction. Disregarding friction, the acceleration of the boat is proportional to the mass of the boat and the force imparted to it.

In a rocket, propellants are burned in a combustion chamber and the combustion products are exhausted through a nozzle. The individual exhaust molecules can be thought of as little sailors jumping from the rear of the rocket at very high velocity. Although each molecule may not weigh

much, its individual action imparts a small reaction to the rocket and accelerates it forward, just like the small boat in the example. When one ton of combustion products exit the rear of a rocket at supersonic speeds—every second—they can generate enough force, or thrust, to push the rocket into space.

Typical launch vehicle propulsion systems generate thrust through the combustion of a fuel and an oxidizer. By definition, a rocket propulsion system does not rely on the oxygen in the atmosphere. Liquid-fueled engines use liquid propellants—such as kerosene and liquid oxygen—which must be rapidly pumped into the combustion chamber at a suitable mixture ratio. Solid rocket motors, often used to supplement liquid-fueled engines, burn propellants that are held together in a solid rubber-like binder. Liquid-fueled engines typically provide more thrust per kilogram of propellant, but they're also more complex because of the turbomachinery involved. Solid rocket motors are generally lower performing but are self-contained propulsion devices, which makes them suitable for smaller rockets or strap-ons with minimal integration.

Liquid Engine Power Cycles

Liquid engines can be categorized according to their power cycles—that is, how power is derived to feed propellants to the main combustion chamber. The most common arrangements include the gas-generator, staged combustion, expander, and pressure-fed cycles.

The selection of one power cycle over another must be made after careful design trades are considered. In design studies, Aerospace engineers use weight codes and power balance models developed in-house to make these trades. In-house design codes are used in many cases because Aerospace is in a unique position to employ a diverse set of contractor data to calibrate and correlate the models, making them more accurate than public codes.

The power balance models are used to simulate the engine pressures, temperatures, and pump speeds. The flow rates and pressure drops are balanced to produce a working design complete with dimensions of major components such as the pumps and chambers. The engine mass is then calculated using the pressures, temperatures, geometry, material strength properties, and appropriate factors of safety. Often, advanced lightweight materials are inserted into a concept design to judge the benefit of using these materials against the development risk of creating, testing, and certifying them. In the final analysis, the engine mass, performance, and cost are traded to best meet the program needs.

Propulsion Today: An Evolutionary Approach

The U.S. rockets flown today evolved from the ICBM fleet deployed around 1960. The Delta IV and the Atlas V—the two rocket families in the Air Force's Evolved Expendable Launch Vehicle program—trace their roots to the original Thor and Atlas missiles. The Delta IV's main engine, the RS-68, is based on a gas-generator cycle with lessons learned from the shuttle program. One of the reasons for this evolutionary approach is purely financial; the cost of developing and certifying a large booster engine can easily exceed $500 million, so risk must be managed carefully.

Liquid-Fueled Engines

Some of the more prominent liquid-fueled engines used in the United States today include the RS-68, the RL10, the RD-180, and the space shuttle main engine.

RS-68. The Delta IV RS-68 employs a gas-generator cycle using liquid hydrogen and liquid oxygen. It's the first new engine designed and built in the United States to fly since the 1970s. At 3310 kilonewtons vacuum thrust, it's also the most powerful hydrogen/oxygen system in the world. Still, the goal of this design was not to incorporate advanced technology. The commercially developed engine was designed with cost as an independent variable and as such used existing technologies to minimize risk.

In the past, engines for the ICBM fleet and the space shuttle had strict performance requirements; cost was often considered secondary. Propulsion technology was pushed to its limits to meet program goals. The Delta IV program chose high performing hydrogen for its fuel instead of the kerosene used in the Delta II and Delta III so that it could meet its payload performance requirements with a relatively inexpensive, low-technology engine. The RS-68 chamber pressure is only about half that of the space shuttle main engine. As a result, the engine is relatively large at 5.2 meters tall. This is a disadvantage in terms of mass, but an advantage in terms of manufacturing because large tolerances can be used in the design. The main pump housings use castings rather than machined and welded parts, a decision that increased mass but reduced cost. Also, the engine's ablative composite nozzle extension weighs more than a sheet-metal nozzle or cooled nozzle would. This nozzle was selected in a design trade that pitted manufacturing cost against performance. The result is a new engine with a cost-competitive design.

RL10. The RL10 family of rocket engines has been around since the early 1960s. This expander-cycle engine was the first hydrogen-

Power Cycles

Liquid engines can be categorized according to their power cycles—that is, how power is derived to feed propellants to the main combustion chamber. Here are some of the more common types.

Gas-Generator Cycle. The gas-generator cycle taps off a small amount of fuel and oxidizer from the main flow (typically 3 to 7 percent) to feed a burner called a gas generator. The hot gas from this generator passes through a turbine to generate power for the pumps that send propellants to the combustion chamber. The hot gas is then either dumped overboard or sent into the main nozzle downstream. Increasing the flow of propellants into the gas generator increases the speed of the turbine, which increases the flow of propellants into the main combustion chamber (and hence, the amount of thrust produced). The gas generator must burn propellants at a less-than-optimal mixture ratio to keep the temperature low for the turbine blades. Thus, the cycle is appropriate for moderate power requirements but not high-power systems, which would have to divert a large portion of the main flow to the less efficient gas-generator flow.
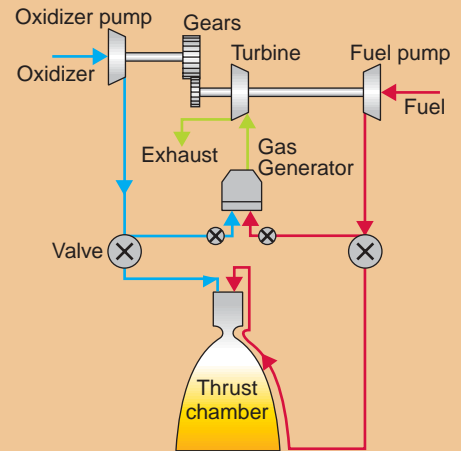
Staged Combustion Cycle. In a staged combustion cycle, the propellants are burned in stages. Like the gas-generator cycle, this cycle also has a burner, called a preburner, to generate gas for a turbine. The preburner taps off and burns a small amount of one propellant and a large amount of the other, producing an oxidizer-rich or fuel-rich hot gas mixture that is mostly unburned vaporized propellant. This hot gas is then passed through the turbine, injected into the main chamber, and burned again with the remaining propellants. The advantage over the gas-generator cycle is that all of the propellants 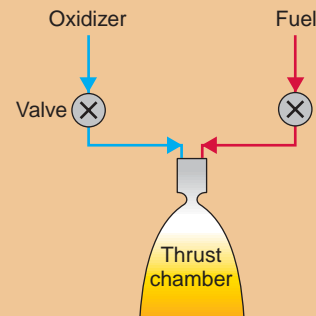are burned at the optimal mixture ratio in the main chamber and no flow is dumped overboard. The staged combustion cycle is often used for high-power applications. The higher the chamber pressure, the smaller and lighter the engine can be to produce the same thrust. Development cost for this cycle is higher because the high pressures complicate the development process.
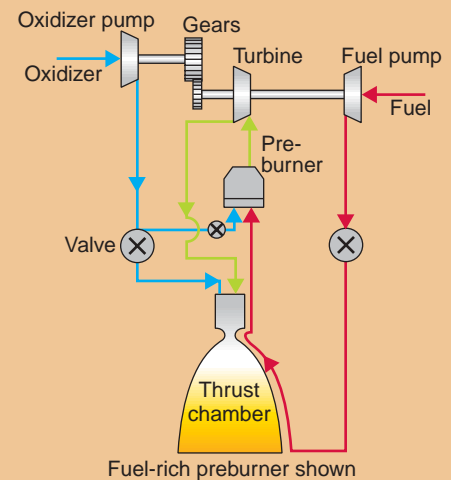
Expander Cycle. The expander cycle is similar to the staged combustion cycle but has no preburner. Heat in the cooling jacket of the main combustion chamber serves to vaporize the fuel. The fuel vapor is then passed through the turbine and injected into the main chamber to burn with the oxidizer. This cycle works with fuels such as hydrogen or methane, which have a low boiling point and can be vaporized easily. As with the staged combustion cycle, all of the propellants are burned at the optimal mixture ratio in the main chamber, and typically no flow is dumped overboard; however, the heat transfer to the fuel limits the power available to the turbine, making this cycle appropriate for small to midsize engines. A variation of the system is the open, or bleed, expander cycle, which uses only a portion of the fuel to drive the turbine. In this variation, the turbine exhaust is dumped overboard to ambient pressure to increase the turbine pressure ratio and power output. This can achieve higher chamber pressures than the closed expander cycle although at lower efficiency because of the overboard flow.
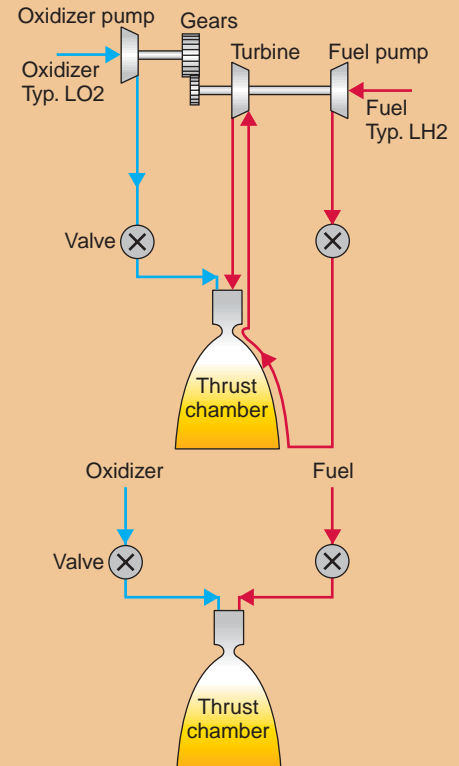
Pressure-Fed Cycle. The simplest system, the pressure-fed cycle, does not have pumps or turbines but instead relies on tank pressure to feed the propellants into the main chamber. In practice, the cycle is limited to relatively low chamber pressures because higher pressures make the vehicle tanks too heavy. The cycle can be reliable, given its reduced part count and complexity compared with other systems.

(Diagram: Gas-Generator Cycle — labels: Oxidizer pump, Gears, Turbine, Fuel pump, Oxidizer, Fuel, Exhaust, Gas Generator, Valve, Thrust chamber)

(Diagram: Staged Combustion Cycle — labels: Oxidizer pump, Gears, Turbine, Fuel pump, Oxidizer, Fuel, Pre-burner, Valve, Thrust chamber. Fuel-rich preburner shown)

(Diagram: Expander Cycle — labels: Oxidizer pump, Gears, Turbine, Fuel pump, Oxidizer Typ. LO2, Fuel Typ. LH2, Valve, Thrust chamber)

(Diagram: Pressure-Fed Cycle — labels: Oxidizer, Fuel, Valve, Thrust chamber)

The Delta IV RS-68 main engine is the world's most powerful hydrogen/oxygen engine. At 100 percent power level, the engine produces 3.3 meganewtons of thrust. The turbopumps can pump more than 815 kilograms per second of propellant into the combustion chamber when operating at full power. The engine can also be throttled to 57 percent power to meet mission trajectory needs. Three RS-68 engines will power the Delta IV heavy launch vehicle.

powered engine to fly in space and the first to be restarted in space. At 20 Kelvin, liquid hydrogen is a difficult fuel to handle but offers superior performance. Developed initially from a turbopump planned for a top-secret hydrogen jet program, the RL10 has gone through numerous design upgrades. Few people are aware that six RL10s were used to power the Saturn I second stage. The RL10 was also a critical part of the missions that launched the Voyager and Cassini interplanetary spacecraft. The RL10 now powers the second stage for both the Atlas and Delta family of vehicles. The RL10B-2 used in the Delta III and Delta IV produces 110 kilonewtons of thrust and has a large, lightweight carbon-carbon nozzle—the largest in the world. The large nozzle expands the supersonic exhaust gas to extremely high velocities, yielding the highest performing chemical engine ever built. The RL10A-4-2 found in the Atlas III and Atlas V, which generates

99 kilonewtons of thrust, employs a new redundant electronic ignition system that improves reliability for the critical start sequence. The engine's restart capability is used to propel payloads the final distance to parking orbit, insert payloads into geosynchronous transfer orbit, and circularize the final geosynchronous orbit.

Space Shuttle Main Engine. The hydrogen-powered space shuttle main engine is the only reusable passenger-rated engine in use today and was the first U.S. engine to use the staged combustion cycle. This cycle was chosen because of its ability to generate the high 206 bar chamber pressure needed to efficiently propel the shuttle orbiter. The development program was at times quite difficult. Many times, turbomachinery would explode during a test, or a valve would disintegrate after a few short seconds of testing as a result of catastrophic oxygen fires. Several of these problems arose because the program was pushing technology at the same time it was being implemented. For example, engineers were subjecting materials to high-pressure hydrogen for the first time and witnessing new problems such as hydrogen embrittlement. In addition, engineers struggled with pump cavitation phenomena that were never seen before. In the end, the space shuttle main engine saw more than 100,000 seconds of test time. As a result, the engine has been remarkably reliable in flight. In fact, the fleet of engines has been fired more than 300 times with only one engine shutdown in flight—and that was caused by a faulty sensor reading.

RD-180. The Russian RD-180 engine is also a staged-combustion engine using kerosene and liquid oxygen. This engine uses an oxygen-rich preburner, unlike the fuel-rich preburner used in the shuttle engine, to produce 255 bar chamber pressure. Kerosene is easier to handle but lower performing than hydrogen and produces soot and coking products that can clog chambers and turbines. The oxygen-rich preburner eliminates concerns over turbine soot and enables a higher chamber pressure to partly compensate for the performance shortfall; however, the hot oxygen-rich gas requires special coatings to keep the metal components from burning.

Solid Motors

Solid rocket motors have been in use for centuries as small rockets and fireworks. In the early 1960s, Aerospace helped pioneer the use of solid motors on large launch

The RL10 engine propels the Delta IV and Atlas V upper stages to their final orbit for payload delivery. Capable of generating 110 kilonewtons of thrust, the Delta IV RL10B-2 shown here has a large carbon-carbon nozzle extension with an exit-to-throat-area ratio of 285:1. The large nozzle increases the specific impulse, or fuel efficiency, of the engine, enabling higher vehicle performance. The nozzle extension can be seen glowing red during a qualification engine firing.

vehicles with the addition of strap-on motors for the Titan III rocket. An even larger version of this multisegment motor design concept is used on the space shuttle. These strap-ons provided the additional thrust-to-weight performance needed at liftoff. The solid motors on the Evolved Expendable Launch Vehicles are the latest in the solid motor design history.

Atlas V. The solid rocket motor used on the Atlas V launch vehicle is the largest monolithic (single segment) solid motor in the world. It measures 1.5 meters in diameter by 19.5 meters long and produces 1130 kilonewtons average thrust. The Atlas V can accommodate up to five solid rocket motors, each weighing 46,500 kilograms fully loaded. Each motor has a fixed composite nozzle. Although it is a new motor, much of its heritage technology comes from the Peacekeeper and Minuteman missile programs, including the filament-wound graphite-epoxy case.

Delta IV. The Delta IV GEM-60 motor is an evolution of the GEM (Graphite Epoxy Motor) family. The 34,000-kilogram GEM-60 is a 1.5-meter-diameter motor more than 16 meters long, cast as a single segment. The motor case is filament wound by computer-controlled winding machines using high-strength graphite fiber and epoxy resin. The Delta IV GEMs are ignited on the ground to optimize performance. The average thrust of each motor is 850 kilonewtons. The Delta IV can employ up to four GEMs with movable or fixed composite nozzles.

Aerospace has developed new analytical tools to help evaluate solid rocket motor operation and performance. These tools include ignition transient models, ballistic models, and thermal-structural models. The ballistic model is used to predict motor pressure and the propellant-grain burn-back profile as a function of time. This tool is used to gain confidence that the performance specification can be met with the full range of operating temperatures and propellant properties. For the Atlas V solid rocket motors, new advances were required in the transient modeling to predict the three-dimensional flow patterns at ignition. Three-dimensional computational fluid dynamics can be rather intensive and time consuming. Aerospace developed new techniques that allow the 3-D flow to be represented by integration of multiple 2-D flow fields. The results of these models were used to predict the thermal-structural behavior of the Atlas V solid rocket motor.

The Atlas V solid rocket motor provides additional liftoff thrust for the Atlas V Evolved Expendable Launch Vehicle. The motor, shown here during one of the horizontal ground firings, makes use of Peacekeeper and Minuteman technologies.

Solid Propellants

Solid propellants come in two types: double-base and composite. Double-base propellants have oxidizer and fuel in the same molecular compound. They tend to be more explosive and have lower specific impulse than composite propellants, which are more commonly used. In composite propellants, the fuel and oxidizer are separate but intimately mixed together. The organic fuel material is initially in a liquid or semiliquid form; it gets mixed with a solid oxidizer, typically ammonium perchlorate, and cured to produce a solid binder.

Powdered aluminum is often mixed with the binder. The burning aluminum particles increase overall energy and performance while improving combustion stability. Propellants are often quoted in terms of their solid loading—that is, the percentage of propellant (by weight) that is solid ammonium perchlorate or aluminum. Typical loadings are 80–88 percent solids. In addition to oxidizer and fuel, solid propellants also contain a small amount of additives that help with the curing process.
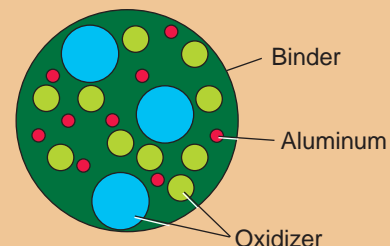
Advances are being made in the areas of smokeless propellants, formulations with low infrared signature, high-energy additives, and formulations that are less prone to combustion instability. For example, scientists are working on a new propellant made up solely of nitrogen atoms. The energy release from such a compound can be quite high and at the same time have a low infrared signature.

In evaluating GEM motors, Aerospace developed unique inspection tools to gain confidence in motor designs and margins. These inspection tools include processing of ultrasonic signals to verify manufacturing integrity of the composite materials. Aerospace has also drawn upon the experience and expertise in motor manufacturing from multiple Air Force programs to improve reliability. In examples like these, additional confidence is gained through Aerospace's independent efforts.

What the Future Offers

The Air Force and NASA are funding several efforts to push launch vehicle propulsion technology to new levels. The Integrated High Payoff Rocket Technology program, for example, is using a phased approach to increase performance and reliability while reducing cost. To support this program, Aerospace is conducting trade studies, design evaluations, and source selection activities.

One important initiative within this program is the Integrated Powerhead Demonstrator. The goal of this effort is to demonstrate a highly reusable engine with less mass, more reliability, and higher performance than the space shuttle main engine at lower cost. To reach these challenging goals, the engine will use a new cycle, known as the full-flow staged combustion cycle.

As noted in the sidebar on page 15, the staged combustion cycle uses propellant efficiently and can generate high chamber pressures. Today, staged combustion cycles use either fuel-rich preburners (e.g., the space shuttle main engine) or

Model of the Integrated Powerhead Demonstrator being developed by the Air Force Research Laboratory and NASA. The engine will provide higher power at more benign conditions than the space shuttle main engine by using both a fuel-rich preburner and an oxygen-rich preburner.

The Integrated Powerhead Demonstrator technology program completed successful tests of several components in the last year, including the oxygen turbopump, the fuel turbopump, and the two preburners. The hydrogen preburner test unit shown above simulated operating conditions of the engine and provided hot fuel-rich gas for the fuel turbopump testing. The hot gas temperature for this preburner is about 800 Kelvin compared to more than 1000 Kelvin for the comparable component on the space shuttle main engine. The lower temperature translates into longer operating life for the turbopump turbine blades or can be used as margin for higher-power expendable engine applications.

oxidizer-rich preburners (e.g., RD-180) to generate the gas that drives the turbine. The Integrated Powerhead Demonstrator uses both types of preburners: A fuel-rich preburner drives the fuel pump and turbine, and an oxidizer-rich preburner drives the oxygen pump and turbine. There are several advantages to this arrangement.

First, all of the propellants are burned in the preburners, thus providing more mass flow for turbine drive power than the conventional staged combustion cycle. This additional power can be used to increase the chamber pressure and produce a smaller engine; alternatively, the preburner temperature can be reduced to provide the same power at lower temperatures. The lower turbine temperatures translate into longer turbine blade life—often the limiting factor on reusable engine life.

The second advantage is that the use of oxidizer-rich gas in the oxidizer turbine and fuel-rich gas in the fuel turbine eliminates the need for a complex propellant seal for the pumps. There is little risk with leaking liquid fuel into a fuel-rich gas or liquid oxygen into an oxidizer-rich gas. In contrast, the fuel-rich staged combustion cycle must use sophisticated purges and multiple seals in the oxidizer pump to prevent any liquid oxygen from leaking into the hot fuel-rich gas. A similar situation must be avoided in the oxidizer-rich cycle on the fuel pump side. The elimination of this failure mode increases system reliability.

Other reliability improvements are being pursued in design and manufacturing. For example, the pumps use hydrostatic bearings instead of ball bearings. Hydrostatic bearings allow the pump shaft to ride on a cushion of fluid instead of another hard material, thereby increasing the life of the pump. The Integrated Powerhead Demonstrator will be the first engine to successfully start and restart with these new bearings. In addition, modern design tools are being employed to gain a better understanding of the design margins and to ferret out potential failure modes during development.

Finally, the Integrated Powerhead Demonstrator program is developing new materials to be compatible with the oxidizer-rich hot gas. Steel alloys would burn in the hot gas generated by the oxidizer preburner, which can operate at pressures greater than 400 bar. Coatings and platings could be used to protect the steel, but these are not always amenable to long engine life. Therefore, nickel-based super alloys were created and tested until the right combination of compatibility and machinability was found.

NASA is now testing the pumps and preburners. The program has shown remarkable success, given the technical hurdles it had to overcome. Next year, the full engine system will be hot fired. Once the system is demonstrated, the technology risk will be reduced for future full-scale development programs. Aerospace has helped the Air Force with the early design evaluation, providing systems engineering expertise throughout the design process.

The Air Force is also working on technologies to improve upper-stage propulsion
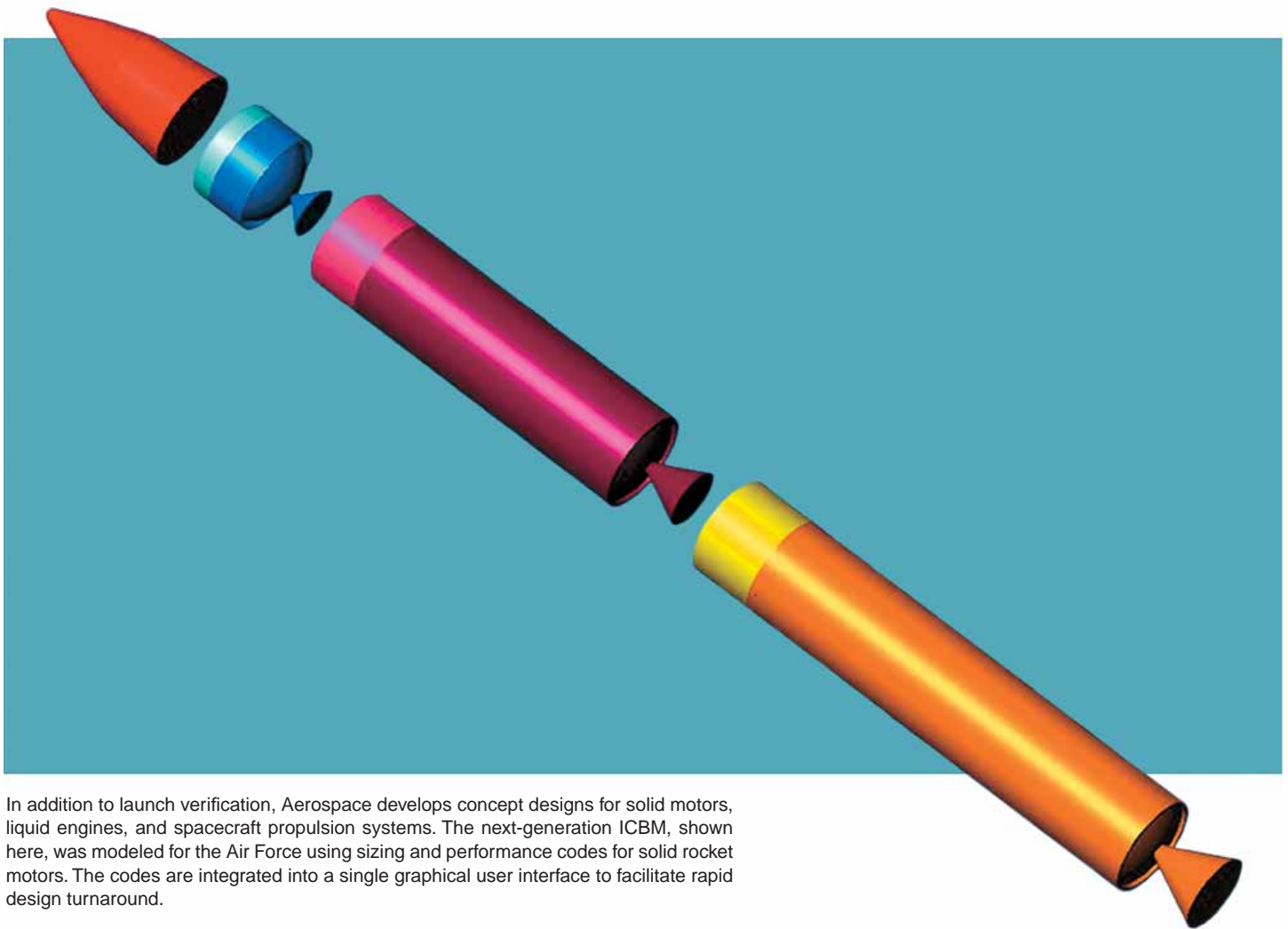
In addition to launch verification, Aerospace develops concept designs for solid motors, liquid engines, and spacecraft propulsion systems. The next-generation ICBM, shown here, was modeled for the Air Force using sizing and performance codes for solid rocket motors. The codes are integrated into a single graphical user interface to facilitate rapid design turnaround.

in general and the expander cycle in particular. Because the expander cycle uses heat from the combustion chamber to vaporize the liquid hydrogen that drives the turbine, the turbine power is dependent on the efficiency of the heat transfer. In the past, brazed steel tubes or slotted liners were used for the chamber cooling circuit. Both have drawbacks in manufacturing and heat transfer. Aerospace is supporting research geared toward improving the heat transfer while maintaining appropriate thermal margins. Chamber technologies under consideration include advanced copper alloys to enhance the heat transfer and new manufacturing techniques that reduce mass and production costs.

Also critical to the expander cycle is the hydrogen fuel pump. The fuel pump provides only 15 percent of the total propellant mass flow rate but can account for 80 percent of the horsepower requirements. Thus, inefficiencies can drive up size and weight. New high-speed turbopumps are being designed with a monolithic shaft, pump, and turbine rotor to decrease part count and increase reliability. Aerospace is a member of the government team pursuing this technology and is developing tools to assist in the design process. In addition, a systems engineering approach is being used to eliminate failure modes and produce a more reliable engine system.

In the solid motor area, advancements are being made in new high-strength composite fibers for lightweight motor cases and improved low-erosion nozzle materials and energetic propellants. Recently, the Air Force demonstrated a test motor that used these new materials to reduce system inert mass by 15 percent and improve payload capacity by almost 30 percent. These performance improvements result in cost savings of more than 30 percent in dollars per kilogram to orbit.

Other solid motor efforts are focused on developing modeling and simulation tools to aid future design efforts. Improvements are being pursued in the area of two-phase-flow particle models, performance prediction tools, and motor mass fraction models. Aerospace has developed motor sizing and performance codes that permit trade-offs in the design of future missiles for the ICBM fleet and for the Missile Defense Agency. These codes are used with graphical interfaces to seamlessly integrate results from performance models and weight models to develop rapid concept designs for proposal evaluation.

Conclusion

Propulsion systems are quite literally the driving force behind any effort to get a payload into space. Advances in engine technology have helped the Evolved Expendable Launch Vehicle program realize significant gains in performance and cost. As the launch community looks forward to the next generation of systems, Aerospace tools and expertise will continue to play a central role in the development of more affordable and reliable launch technologies.

Loads Analysis for National Security Space Missions

A rocket launch is an extremely stressful event—and not just for the people involved. Aerospace has helped define a rigorous design and verification process to ensure that launch vehicles and spacecraft will withstand the severe forces encountered during launch and ascent.

**A. M. Kabe,
M. C. Kim, and
C. E. Spiekermann**

During liftoff and ascent, a launch vehicle and its payload experience severe forces that cause structural deformations and vibrations. The vibrations will increase the deformations, which in turn produce internal loads and stresses in the launch vehicle and spacecraft structure. For most of the structure, these internal loads and stresses will represent the principal design requirements, dictating how strong the structure must be.

Designing launch vehicles and spacecraft to withstand these loads (and verifying that they can) is a complicated process, involving numerous organizations and diverse technical disciplines. Structural loads are a function of the dynamic properties of the entire launch vehicle and spacecraft system; but the integrated system cannot be tested prior to flight because of its size and complexity. Moreover, every substructure contributes to the dynamic properties of the

The Boeing Company

Liftoff of a Delta IV, one of the rockets in the Air Force's Evolved Expendable Launch Vehicle program. Data from this flight have been archived in Aerospace databases that also include flight data from past Atlas and Titan launch vehicle families. These data will support future validation and verification efforts.

system overall, so design changes in one element can result in load changes in all elements, and modeling errors in one place can cause load prediction errors in others. Also, neither the launch vehicle organization nor the spacecraft organization has control over the other's design, so neither can control the entire process.

As a result, the design and verification of launch vehicle and spacecraft structures requires a multidisciplinary, collaborative process that begins during the earliest phases of a program and does not end until the vehicle is launched and postflight data have been analyzed. The process is typically referred to as the load cycle process, and Aerospace has played a pivotal role in its development and current form.
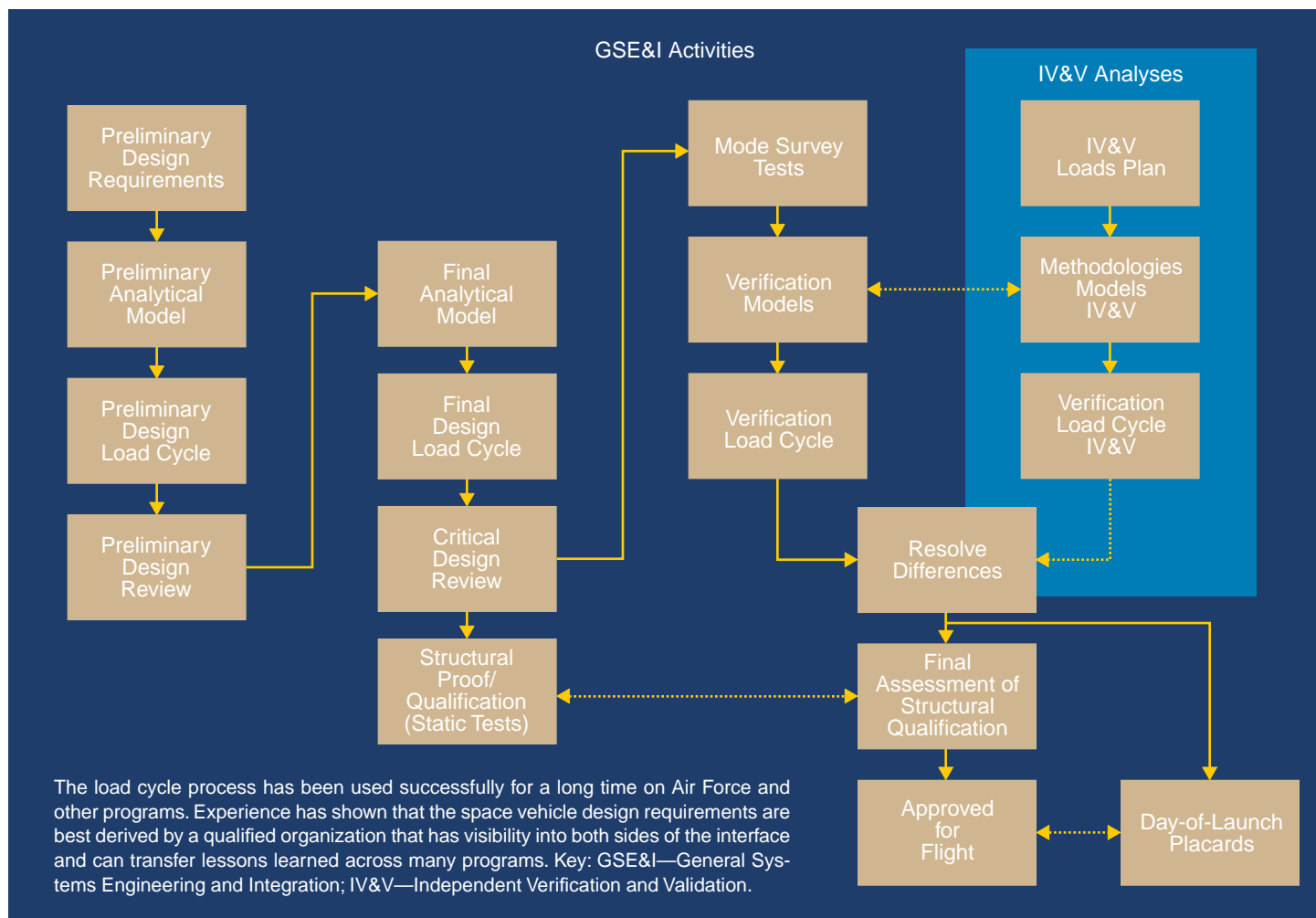
The Load Cycle Process

The spacecraft design process begins with an initial estimate of loads based on past experience with similar launch configurations. These preliminary design load factors are used to size the load-carrying structure, and insight into both sides of the launch vehicle/spacecraft interface can be of considerable value in their development.

Once the preliminary design and corresponding drawings of the spacecraft are complete, they can be used to create an analytical finite-element model. This model is in turn used to derive the structural dynamic model and internal load recovery equations. The structural dynamic model is used to calculate responses, and the load recovery equations are used to convert these responses to internal loads, stresses, and deflections. The spacecraft organization sends this information to the launch vehicle organization for use in the preliminary design load cycle.

The preliminary design load cycle is the first of several such load cycles (three is typical). For each, the launch vehicle organization develops models that correspond to liftoff and the various phases of ascent. Typically, six to twelve distinct events are considered. For each event, the spacecraft model is coupled to the corresponding launch vehicle model to form a unique coupled-system model. At this point, the dynamic properties of the launch vehicle and the space vehicle merge to form the system-level properties. The launch

vehicle organization will have developed distinct methodologies to analytically model the physics of each event as well as custom computer programs to numerically solve the equations of motion. The computed system responses are used with the load recovery equations (which can exceed 10,000 equations) to establish launch vehicle and spacecraft internal loads. The spacecraft loads are sent back to the spacecraft organization, and the launch vehicle loads are sent to the appropriate area of the launch vehicle organization for structural margin assessment.

The spacecraft organization will assess the preliminary design against the just-computed loads as part of its preliminary design phase. Areas with negative margins are redesigned, and any configuration changes are implemented. The drawings and the finite-element models are updated to reflect these changes, and the entire loads analysis process is repeated. After the final design load cycle, a structural assessment will confirm that the structure has adequate margin against predicted loads. The design can then be released for manufacturing.

The load cycle process has been used successfully for a long time on Air Force and other programs. Experience has shown that the space vehicle design requirements are best derived by a qualified organization that has visibility into both sides of the interface and can transfer lessons learned across many programs. Key: GSE&I—General Systems Engineering and Integration; IV&V—Independent Verification and Validation.

Flight Data Analysis

Aerospace plays a significant role in analyzing flight data for each national security space launch. During liftoff and ascent, sensors mounted on the launch vehicle continuously measure critical parameters such as acceleration, external pressure, internal engine performance, propellant tank pressure, temperature, thrust-chamber pressure, and guidance and navigation performance. These parameters vary with flight time—some of them quite rapidly. Acceleration, for example, can oscillate up to several thousand times each second.

Launch vehicle organizations, as well as Aerospace, have developed specialized time-series data analysis techniques to process and analyze the data. An onboard sampling process converts the analog measurements to digital time histories. These digital time histories are transmitted to ground stations which forward them to the appropriate organizations for postflight analysis.

To establish cause and effect among observed parameters, the launch team must resolve time differences to fractions of a millisecond—a task made difficult by errors inherent in telemetry acquisition and processing. Further complicating the analysis is the nonlinear and nonstationary nature of the underlying physics, which limits the applicability of standard time-series analysis techniques. Consequently, Aerospace continues to develop new data-analysis methods that address these issues.

Flight data analyses help support postflight data assessments, anomaly investigations, and research geared toward improving launch vehicles and their payloads, and the analysis methodologies used to predict loads and other performance parameters. On the day of launch, telemetry data are transmitted from the launch site, either Cape Canaveral or Vandenberg Air Force Base, over dedicated lines to the Spacelift Telemetry Acquisition and Reporting System (STARS) facility at Aerospace. Nearly instantaneous telemetry data are acquired, processed, and stored in the telemetry database and made available for cursory analyses and more involved postflight data assessments. The assessments include comparing the measured quantities to historical data and to preflight and postflight analytical predictions.

—B. H. Sako
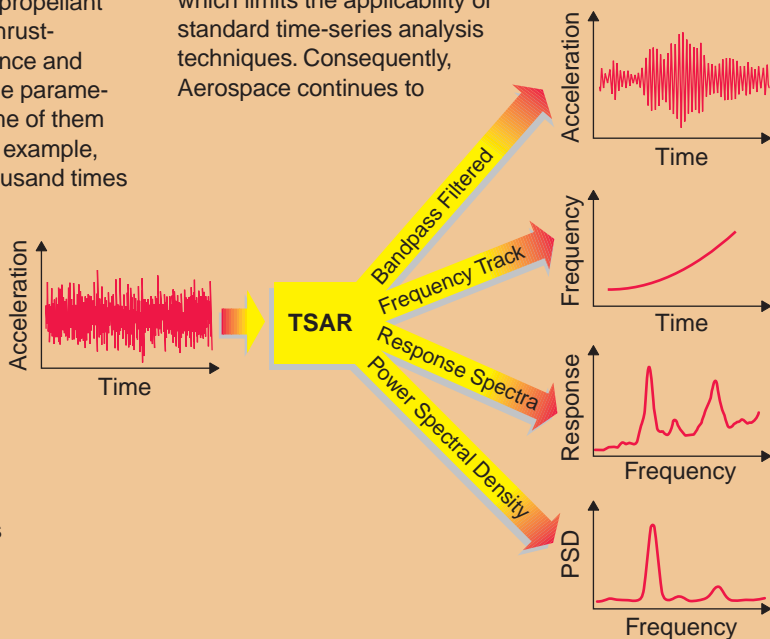
The Time Series Analysis Resource (TSAR) program was developed at Aerospace and is used routinely to analyze flight data. As this picture illustrates, time series data can be looked at in many different ways.

Once the spacecraft has been manufactured, numerous tests are performed in support of the last prelaunch loads analyses that verify the flightworthiness of the system. The testing can be performed on actual flight hardware, dedicated structural test articles, or a combination of the two. Mode survey tests, for example, are used to measure the structural dynamic properties of the spacecraft. (The launch vehicle organization will also perform mode survey tests on dynamically complex substructures such as the upper stage and fairing.) The data from these tests are used to adjust the finite-element models that will form the basis of the upcoming verification load cycle. In addition, data from these tests are often used directly as part of the dynamic models. The mode survey test is typically followed by static strength tests, in which the design-phase loads are applied to the actual hardware to establish empirically the structural capability.

The verification load cycle provides a final check on the adequacy of the launch vehicle and spacecraft structural designs. The loads analysis methodologies and analysis data, if not verified during previous verification load cycles, will also be independently validated and verified. Aerospace has performed this validation and verification function for numerous Air Force programs, and has developed loads analysis methodologies, procedures, and computer codes for the Atlas II, Atlas V, Delta II, Delta IV, Titan II, and Titan IV families of launch vehicles.

After the validation, an organization such as Aerospace will also perform independent loads analyses to verify that the predicted loads are error free. The spacecraft loads are then sent back to the spacecraft organization for final flightworthiness assessment. The validated launch vehicle loads are used in a similar assessment of the launch vehicle.

The procedures and data used in the loads analyses are continually being refined and improved as flight data become available. During liftoff and ascent, a relatively large amount of data is collected for postflight analysis. Data of interest include acceleration at various locations, external pressures on the vehicle skin, engine chamber pressures, autopilot commands, and engine actuator displacements. These data are analyzed to detect any anomalous behavior and are then used to refine the analysis methodologies and models. Data from several flights are typically needed to refine the loads analysis procedures enough for routine use. For this reason, Aerospace maintains extensive databases that include data from flights of the Atlas II, Atlas IIAS, Atlas IIIB, Atlas V, Delta II (6925 and 7925), Delta IV, Titan II, Titan IVA, and Titan IVB launch vehicles. One sophisticated flight data analysis tool, the Time Series Analysis Resource (TSAR), was developed at Aerospace and is used routinely to analyze flight data. Often, the data are available for real-time assessment at Aerospace as the launch vehicle lifts off the pad and flies to orbit.

Loads Analyses

The structural dynamic models used in the load cycle process are developed by coupling structural dynamic models of substructures. Typical substructures include the spacecraft, upper stage, fairing, interstage adapters, propellant tanks, liquid-fueled engines, and solid rocket motors. A launch configuration model will often consist of several dozen substructure models,

each of which may have been developed by coupling still other substructure models. A spacecraft bus and its payloads, for example, are typically modeled as separate substructures, often by different organizations.

Analytical structural dynamic models are developed from structural finite-element models. Finite-element models are detailed and relatively large; millions of equations are not unusual. To be useful in loads analysis, these large models must be reduced in size to those equations (typically tens of thousands) that are required to describe the kinetic energy (motion of all the mass, including fluids) of the system as it vibrates. They can then be converted into structural dynamic models by computing the normal, or natural, modes of vibration.

The normal modes of vibration are the patterns of motion in which a lightly damped, linear-elastic structure can vibrate. When a structure vibrates in a normal mode, all points undergo harmonic (periodic) motion, reach their maximum values at the same time, and pass through their static equilibrium point at the same time. Associated with each normal mode of vibration is a natural frequency and a certain amount of damping that will cause oscillations to decay. No matter how structural oscillations are initiated, the observable or measurable vibrations in a structure will be the superposition of the motions of the individual mode shapes.

Normal modes of vibration have unique properties that make them extremely useful in creating efficient system-level models. For example, they can be used to transform the substructure finite-element models into so-called mixed-modal/physical domain models. These models can be reduced in size and coupled to other models. Most large launch vehicle and spacecraft models are developed in this fashion. For example, a coupled launch system model is formed by combining the launch vehicle and spacecraft mixed-modal/physical domain models. The resulting equations are used to compute the mode shapes and associated natural frequencies and damping values of the coupled launch system.

Once the coupled-system modes are known, they can be used to develop the equations of motion that are solved to obtain loads. For lightly damped structures such as launch vehicles and spacecraft, natural modes are orthogonal to each other, which means that many modes can oscillate at the same time, but with little or no
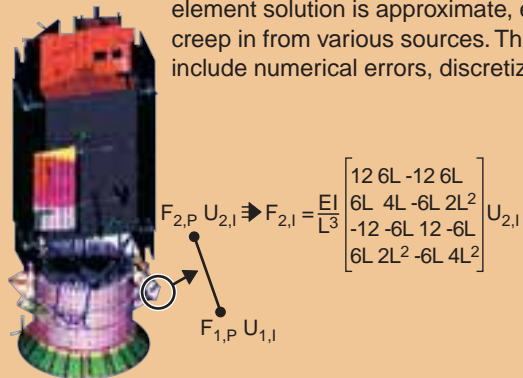
Finite-Element Models and Analysis

Finite-element models are an essential tool in the design and verification of launch vehicle and spacecraft structures. They are initially developed to define the force and deflection (stiffness) relationships needed to form loads analysis structural dynamic models. Then, once the working environment is defined in terms of forces, accelerations, and enforced displacements, they are used to determine the impact on structural integrity. The physical relationships between applied loads and displacements are governed by physics and empirical rules; however, the corresponding equations become impossible to solve for structures with complex shapes and boundary conditions. The finite-element method provides a way to generate numerical solutions. Essentially, it breaks a complex system down into a manageable (finite) number of elements. A curve, for example, could be drawn as a series of steps; the smaller the steps, the smoother the curve—but the more information required. In terms of loads analysis, the finite-element method approximates the continuous deformation of a structure, which is unknown, as a combination of mathematical shape functions defined over segments of the structure. In this way, an approximation to the deformation function can be derived by numerically solving a matrix of scale factors for the shape functions.

Modern finite-element tools simplify assembly of the matrix equations, but they still require significant engineering judgment. Often, the engineer needs to predict local stress for features that are only a few millimeters in size. If one were to subdivide a structure as large as a launch vehicle to this level of fidelity, the stress prediction would quickly become too complex for even the most advanced computer; many tens of millions of equations would be needed. Thus, depending on the scale of the feature of interest, more or less refinement may be needed.

In essence, the challenge in using the finite-element method is in understanding the inherent assumptions of the underlying theory and the assumed shape functions. In addition, because the finite-element solution is approximate, errors creep in from various sources. These include numerical errors, discretization

$$F_{2,P} \; U_{2,I} \Rightarrow F_{2,I} = \frac{EI}{L^3} \begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} U_{2,I}$$

$$F_{1,P} \; U_{1,I}$$

Finite-element model of a satellite. Colors represent different types of element. The finite-element method approximates the continuous deformation of a structure as a combination of mathematical shape functions defined over segments of the structure.

errors, theoretical simplifications, boundary condition errors, uncertainty in material properties, etc. Even the variability in manufacturing tolerances can lead to significant errors when dealing with precision structures. For this reason, finite-element models must be correlated with test data to ensure the validity of the predictions.

Because of the significant engineering judgment involved in developing finite-element models, Aerospace is intimately involved in the process for Air Force programs. With proper application, the finite-element method is a powerful analytic tool in the development of loads analysis models and the assessment of structural integrity.

—E. K. Hall II

interaction. This is a relatively difficult concept to visualize because the various modes of vibration are all determined by the same mass and stiffness properties of the structure. Because the modes are orthogonal, however, the equations of motion of a structure can be transformed into a modal coordinate domain in which their numerical solution is considerably simpli-fied. The total loads and accelerations, for example, are then obtained by summing the time-phased individual modal responses, which, for some events, can number as many as several thousand.

Liftoff Loads

The complexity of the loads analysis process can be illustrated by looking at one of the many critical events in the launch

Drawings

Launch Vehicle

Space Vehicle

Drawings

Mass Properties

Response Recovery Equations

Response Recovery Equations

Mass Properties

Stiffness Properties

LV Structural Dynamic Model

SV Structural Dynamic Model

Stiffness Properties

Damping Properties

Coupled SV/LV Loads Analysis Dynamics Model and Response Recovery Equations

Damping Properties

Solve Equations of Motion

Finite-element models are used to develop structural dynamic models along with the load recovery equations needed in the coupled launch vehicle/spacecraft loads analyses. Because of the classified or proprietary nature of many systems, the launch vehicle organization generally has little, if any, insight into the models used by the spacecraft organization—and vice versa.

sequence. Liftoff, for example, produces significant loads in both the launch vehicle and its payload. While the launch vehicle rests on the launchpad, the propulsion system—which may comprise any combination of liquid-fueled engines and solid rocket motors—ignites and generates thrust. If the vehicle is a "fly-away" type, it is allowed to rise freely as soon as the thrust overcomes the vehicle weight. If it is a "hold-down" type, a retention mechanism prevents it from lifting off while the engines build up thrust and computer systems verify the proper performance of the engines; this takes only a second or two. The retention mechanism is then released, any solid rocket motors are ignited, and the vehicle rises off the launchpad.

The ignition of liquid-fueled engines and solid rocket motors causes the system to oscillate and produce additional internal loads. Concurrently, the system undergoes a rapid change from being fully attached to the launchpad to being fully unconstrained and free flying. This change causes additional oscillations and internal loads. Also, ground winds and ignition overpressure pulses generate even more oscillations.

The prediction of liftoff loads requires complex mathematical simulations and computer codes that model the nonlinear forces associated with the launch vehicle's separation from the pad as well as the loading caused by engine ignitions, overpressure pulses, ground winds, and gravity. Models of the thrust forces must include the lateral forces caused by flow separation in nozzles, engine misalignments, and engine thrust offsets. Models of the ignition overpressure pulses must include the components emanating from the flame duct and from the exhaust port. Forces in propellant tanks caused by pressure fluctuations are also included, as are the fluctuating forces caused by thrust oscillation and engine actuator oscillation. The forces related to propellant motion in the feed lines can also be critical, especially during a launch abort.

## Atmospheric Flight Loads and Day-of-Launch Loads Analysis

Once a launch vehicle has lifted off the pad, it will rapidly accelerate, and can reach speeds greater than a few hundred meters per second while still in the atmosphere. These high speeds cause severe pressure on the launch vehicle skin, which in turn will cause the vehicle to deform and experience significant loads. As the launch vehicle approaches and passes the speed of sound, shock waves form on the vehicle and interact with the flow separation caused by geometry changes along the length of the vehicle. This interaction causes severe "buffet" vibration of the launch vehicle and spacecraft system. The launch vehicle may also encounter atmospheric turbulence or gusts, which can cause oscillations and increase loads. In addition, the launch vehicle control system, to maintain vehicle stability, will continually gimbal the engines. The side forces thus generated can also cause the vehicle to oscillate and produce internal loads.

Each of these atmospheric flight load contributors has a specialized analysis methodology requiring unique models. The methodology for analyzing atmospheric turbulence loads, for example, incorporates a control-system simulation, an aeroelastic model of the interaction between the launch vehicle structure and air (which is obtained by means of a wind-tunnel test), the structural dynamic model of the launch vehicle and spacecraft system, and representations of the atmospheric turbulence. Because of the complexity of the atmospheric flight events, each is analyzed separately, and the resulting response quantities, such as loads, are combined statistically.

Most of the loads analyses are performed well in advance of the launch date, but some are finalized just prior to launch. For most launch vehicles, reliability requirements can only be met by restricting the winds through which they are allowed to fly. This reduces launch availability, but the impact can be minimized by developing the launch vehicle steering profile using winds measured close to the opening of the launch window. In these cases, the actual winds and the resulting vehicle steering are not known until just before launch, so additional analyses are required to determine whether structural and performance limits (placards) would be exceeded if the vehicle were to launch.

These analyses typically begin several hours before the opening of the launch window and continue until the launch is either completed or scrubbed for the day. Wind speed and direction are typically determined with balloons that rise through the atmosphere. The measured wind profiles are used to derive the vehicle steering
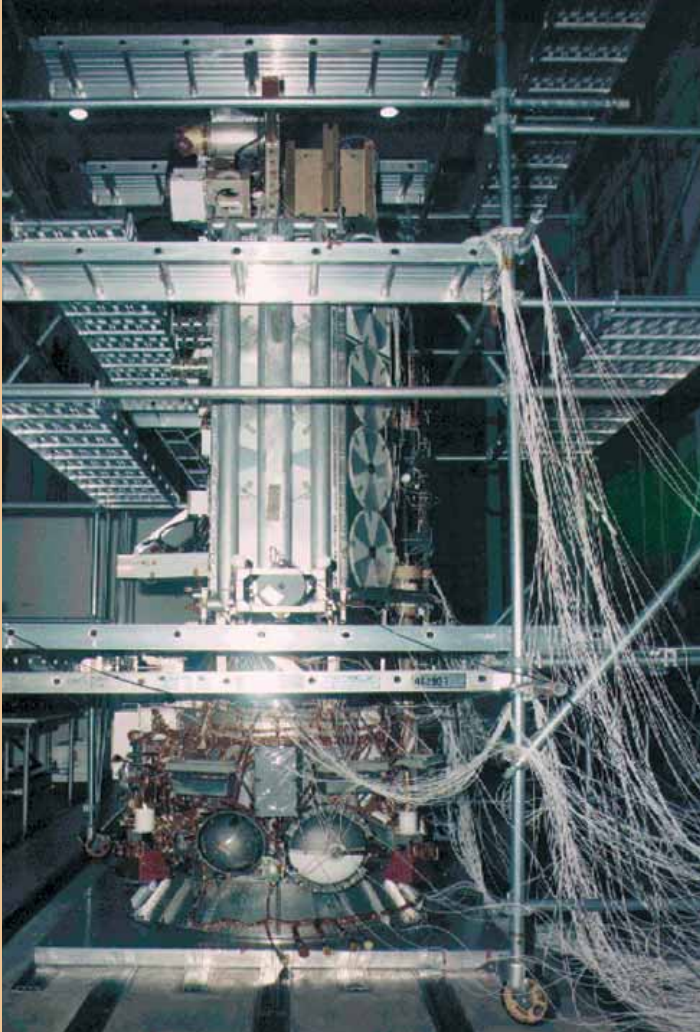
Mode Survey Tests

Mode survey tests establish the structural dynamic properties of spacecraft and complex launch vehicle components such as the upper stage and fairing. These measurements are used to adjust the analytical finite-element models that are, in turn, used to develop the loads analysis structural dynamic models.

Mode survey tests are typically conducted with multiple shakers that impart low-level random forces through tube-like stingers. Two to four shakers are usually positioned to impart forces at various locations on the test article. The imparted forces are measured with small force gages attached between the test article and the shaker stingers. System vibration is measured with sensitive accelerometers, and 300 to 500 accelerometers are not unusual for a mode survey test of a complex satellite structure. Time-series data analysis techniques are then used to compute transfer functions (which describe the mathematical relationship between system input and output) relative to each shaker as though the shaker forces were applied one at a time.

The locations of the applied forces and accelerometers must be chosen carefully to ensure that the test will generate adequate data. Aerospace has developed procedures for determining appropriate measurement locations. By automatically calculating factors such as mass-weighted effective independence and iterative residual kinetic energy, these methods have helped reduce the time required to conduct reliable mode survey tests.

Once the transfer functions have been computed from the measured data, optimization procedures are used to extract the normal or natural modes of vibration and their associated natural frequencies and damping values. Mode-X, a tool for extracting modal parameters from transfer function data, was developed at Aerospace to support mode survey tests on Air Force programs. Aerospace-derived parameters are often used to supplement contractor-derived parameters that eventually get used to adjust the analytical loads analysis models.

—J. A. Lollock

A satellite undergoing a mode survey test. The results are used to update the satellite's loads analysis model.

parameters. A trajectory simulation then "flies" the vehicle through the measured wind and computes loads-related data such as angle of attack, dynamic pressure, and Mach number as a function of flight time. These data are used to compute the static-aeroelastic (nonvibrating) component of the total load.

The static-aeroelastic load is then combined statistically, at all critical points along the vehicle trajectory, with the turbulence/gust, buffet, autopilot-induced, and dispersion loads, which will have been calculated in advance during the verification load cycle. The combined loads are compared to the allowable values at critical vehicle stations. If they are within acceptable limits, then the launch can proceed; if not, the launch is held, and the whole process—measuring the wind, performing the trajectory simulation, and computing the loads—is repeated until the vehicle is launched or the launch window closes.

Aerospace has been intimately involved in the development of the atmospheric flight loads analysis methodologies and their implementation in computer codes. For example, the time-domain buffet analysis approach, the Monte Carlo gust-analysis methodology, and the concept of using the structural dynamic model to perform static-aeroelastic loads analyses were developed at Aerospace and made available to the loads analysis community. In addition, the statistical approach used to verify the loads combination equations in the day-of-launch placard analyses was also developed at Aerospace. For Air Force launch vehicles, Aerospace is intimately involved in the development of the procedures and tools needed to perform the day-of-launch placard analyses. For the Titan IV vehicle, for example, Aerospace also performs the placard calculations independently on the day of launch and provides an independent launch recommendation.

Conclusion

The structural design and verification process is highly complex, involving various organizations and numerous technical disciplines. No single organization controls the entire process, so overall management is challenging. Further complicating the matter, the launch vehicle and spacecraft need to be treated as a single integrated unit, but such an integrated unit would be too large to test. Hence, mission planners must rely on copious analysis and substructure testing.

Aerospace plays a critical role in support of the structural design of national security launch vehicles and spacecraft. This includes independently validating and verifying the load cycle process loads analysis methodologies and procedures, many of which were developed at Aerospace alone or in close partnership with industry. In addition, Aerospace's cross-program involvement ensures that the structural design process remains equitable to the launch vehicle and spacecraft organizations. The high degree of structural reliability achieved by national security launch vehicles and spacecraft owes much to the load cycle process and the application of this process to each new system generation. 🪐

Mitigating Pogo on Liquid-Fueled Rockets

Interaction of a launch vehicle's propulsion system and structure can be a source of dynamic instability. Since the days of the Gemini program, Aerospace has been finding better ways to model and mitigate this potentially disastrous phenomenon.

Kirk Dotson

U.S. Air Force

Accelerations induced by pogo were a critical factor in the human-flight rating of the Titan II launch vehicle. Analytical investigations at Aerospace explained pogo occurrences and led to a successful resolution prior to the first Gemini mission.

Launch vehicles achieve thrust through the combustion of liquid or solid fuel in their rocket engines. In a liquid-fueled vehicle, the engine pumps propellants (fuel and oxidizer) through feed lines from their storage tanks to the engine's thrust chamber. Inevitably, the tanks, feed lines, and engine vibrate during liftoff and ascent. This vibration causes the flow of the propellants in the feed lines and engine to oscillate, leading to thrust oscillation. The resulting thrust oscillation can cause the structure to vibrate even more, which increases the fluid oscillations, which causes greater vibration, and so on in a progressive feedback loop. This represents a system instability, and the resulting oscillations can become extreme.

This dynamic interaction between the vehicle structure and the liquid propellants was first recognized during development of the Titan II in 1962. It had occurred on previous launch vehicles as well, but the phenomenon was not yet understood. The engineering community nicknamed the phenomenon "pogo" because it caused the launch vehicle to stretch and compress like a pogo stick. Pogo presented serious challenges for the developers of Titan II and remains a prime consideration in the design of launch vehicles today. Then, as now, Aerospace work on the pogo phenomenon has helped prevent potential mission failures.

Pogo and Gemini

The Gemini program followed the Mercury orbital missions and preceded the Apollo lunar expeditions. The primary goal of Gemini was to demonstrate the feasibility of a rendezvous of two or more spacecraft in orbit.

The Gemini capsule, designed to carry two astronauts, was to be launched on a modified Titan II ballistic missile. During its first development flight, the Titan II experienced pogo oscillation going from 10 to 13 hertz over a 30-second period during mid-burn of the first stage. At 11 hertz, this shaking reached a maximum of 2.5 g's at the payload. Superimposed on the steady acceleration, the force of this motion was excessive for military use and clearly unacceptable for an onboard crew.

NASA wanted to keep vibration levels below 0.25 g's to ensure the operational capability of the astronauts, although 1 g was tolerable in terms of the structural integrity of the Titan II. An engineering analysis suggested that the pogo interaction could be minimized by equipping the oxidizer feed line on each engine with an accumulator—essentially a container of gas that acts like a soft spring to reduce the fluid frequency well below the structural frequency and weaken the feedback. After achieving what appeared to be an adequate mathematical model of the phenomenon, the Titan development team installed the two accumulators on the eighth Titan II flight (N-11). This was the first attempt to mitigate pogo interactions for Gemini.

The result was unexpected and dramatic: peak vibration levels reached 5 g's—much worse than prior launches without pogo mitigation! Rather than suppress the pogo oscillations, the accumulator on the oxidizer line actually made them worse, triggering a premature shutdown of both engines that resulted in mission loss.

Pogo now became the top concern for the Gemini program. Clearly, the understanding of pogo was inadequate, and human-flight rating was in jeopardy.

Russ Underwood, Lockheed Martin

This Titan IVB rocket successfully launched a Milstar satellite in April 2003. Aerospace research limited the risk that liquid-fueled engine cavitation and dynamics would lead to system instability. The Aerospace and contractor team defined a mission profile that provided high confidence in mission success.

The Air Force asked Aerospace to step in as part of a Titan II improvement plan. The Aerospace team was led by Sheldon Rubin. He examined pressure recordings from static engine firings conducted a year earlier and identified the key missing element in the pogo model: cavitation—the formation of bubbles in the fluid at the inlets to both the oxidizer and fuel pumps. Like the gas in an accumulator, these cavitation bubbles served to lower the vibration frequency of the fluids in the feed lines. Because the bubbles at the fuel pumps were not recognized, the analyses had shown the fuel frequency to be well above the structural frequency. The oxidizer frequency appeared to be closer to the structural frequency, so that's where the accumulators had been installed. In fact, the cavitation bubbles caused the fuel frequency to fall close to the structural frequency as well. Without the oxidizer accumulators, the oxidizer feedback partially canceled the fuel feedback through phasing of their thrust contributions. When the oxidizer feedback was weakened, the net effect was a greater instability.

The Aerospace model incorporated the effect of bubbles at both the oxidizer and fuel pumps and showed that the addition of an accumulator in the fuel line of each engine was essential to eliminate pogo. With both fuel and oxidizer accumulators installed, a flight on November 1, 1963, showed a reduction of vibration levels to 0.11 g's. After two subsequent launches with accumulators also met the NASA limit, the Titan II was declared suitable for human flight, and the Gemini program went on to achieve its mission objectives.

Pogo After Gemini

Since then, Aerospace has been intimately involved with pogo mitigation for numerous other programs. In 1963, for example, Rubin's team described the Gemini experience in a joint technical panel held on Thor-Agena pogo. Until that time, the Thor program sought not to suppress pogo but to strengthen the payloads to endure the vibration. Years later, when analysis predicted an increased pogo for an extended version of the Thor-Delta (predecessor of the Delta launch vehicle family), Aerospace recommended the installation of an accumulator, which succeeded in suppressing pogo.

In 1964, Aerospace recommended a close-coupled configuration for oxidizer and fuel accumulators to improve their capability for the Air Force's Titan III. A new toroidal fuel accumulator was developed for Titan IIIB and used on all subsequent Titans. By 1967, new metal bellows accumulators were developed for Titan IIIM, as a result of extensive Aerospace involvement; these were first used on the third Titan IIIE and were standard on all subsequent Titan vehicles.

Apollo 6, the last unpiloted Apollo mission, exhibited a strong pogo oscillation. This craft was launched atop a Saturn V, the vehicle that would later carry the first astronauts to the surface of the moon. The pogo appeared during first-stage operation. Aerospace began an analysis for NASA, and concurred with a proposal to use trapped gas in the oxidizer prevalve to serve as an accumulator. Aerospace also recommended against an alternative proposal in which bubbles introduced near the tank outlet would be carried downstream to reduce the feed-line frequency. The accumulator approach was implemented on the first piloted flight, and pogo was permanently eliminated for the Saturn V first stage.

The five-engine second stage of Saturn V also experienced pogo, but the oscillations were concentrated at the center engine, so they were not felt by the astronauts. But on Apollo XII, the vibration at the center engine reached 8 g's and caused concern for the vehicle's structural integrity. Analysis predicted that the 15-g structural limit would not be exceeded, so no fix for pogo was implemented for Apollo XIII. But, as with the N-11 Gemini flight, the unexpected happened: Vibration levels reached 34 g's, causing premature shutdown of the center engine. The structure held together, and the mission was able to proceed using the four remaining engines. Again, NASA asked Aerospace to assess various prevention strategies. Aerospace supported the installation of a liquid-oxygen accumulator, which succeeded in suppressing pogo on all future Apollo flights.

In 1970, NASA published a monograph on pogo written by Rubin to be used for development of the space shuttle and subsequent vehicles. From 1971 to 1981, Aerospace conducted studies on space shuttle pogo suppression for NASA. The original space shuttle design called for an
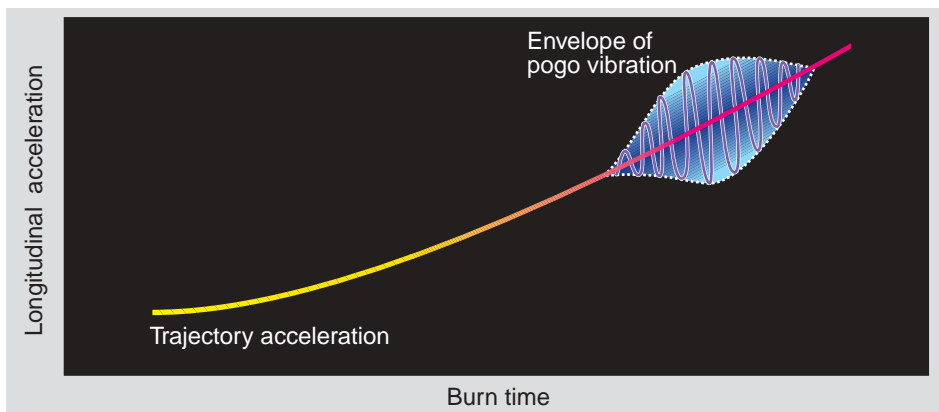
Depiction of pogo occurrence. Due to the time-varying structural dynamic properties of a launch vehicle, the structure-propulsion feedback is not sustained, but rather leads to a "blossom" in the launch vehicle's longitudinal response. This "blossom" occurs over a frequency range. Natural frequency is inversely proportional to the square root of mass; therefore, as propellants are consumed during flight, the natural frequency of the launch vehicle mode increases with respect to time. The maximum pogo response corresponds to close tuning of the structural and hydraulic frequencies.

What is Pogo?

Pogo—the self-excited vibration of a liquid-fueled rocket—arises from the inherent interaction of a flexible rocket structure with a fluid propulsion system. An occurrence of pogo can be detected in measurements of longitudinal acceleration, seen as a "blossom" of vibration superimposed on the steady acceleration. The oscillations grow, reach a maximum, and then recede.

The pogo oscillation typically falls in the range of 5–60 hertz (cycles per second) and tracks the slowly changing frequency of the vehicle's vibration. Accelerations up to 17 g's (zero to peak) have been observed at the interface between the launch vehicle and payload and up to 34 g's at an engine. Such high accelerations cause stress that may exceed the vehicle's structural limits and lead to ultimate mission loss. Pogo is a particular concern for piloted vehicles because, depending on the frequency, oscillations as low as 0.25 g's in amplitude can impair an astronaut's ability to read instrument panels.

Typically, pogo occurs when the natural frequency of a propellant feed line, which is primarily controlled by cavitation bubbles caused by the operation of an engine pump, comes close to a readily excited natural frequency of longitudinal structural vibration. A close matching of the propellant and structural frequencies is typically avoided by installing an accumulator in the feed line. The accumulator contains a volume of gas that acts like a soft spring to reduce the propellant frequency to well below that of critical structural frequencies.

accumulator at the usual location: upstream from the engine's liquid-oxygen inlet. Preliminary studies at Aerospace sought to understand the complexities of potential interaction and uncertainties, particularly in terms of predicting the degree of pump cavitation. These studies indicated that the optimal location for the accumulator was deep within the engine itself, near the high-pressure oxidizer pump inlet. This represented a new approach to pogo mitigation, and the proposal met with considerable resistance because of the major impact on the engine development test program and the difficulties in implementing an accumulator in a region of such high pressure. Nonetheless, the engine accumulator was implemented, and pogo was eliminated for the shuttle. This was the first vehicle cured of pogo prior to a need shown by flight.

In 1989, Aerospace developed an advanced pogo stability analysis code using a building-block formulation and an automated technique for extracting the vibration characteristics of the coupled structure-propulsion system. The code has been used for stability analyses of the Atlas and Titan upper stages, as well as for the Titan IV and Delta IV boost vehicles. The next version of the software is being broadened in analysis capabilities for the Evolved Expendable Launch Vehicle. The effort includes comprehensive review of the characterization of propulsion elements and the elimination of many restrictions and limitations in the existing codes.

Recent History

Even after 40 years, the potential for pogo continues to cause concerns. A recent flight
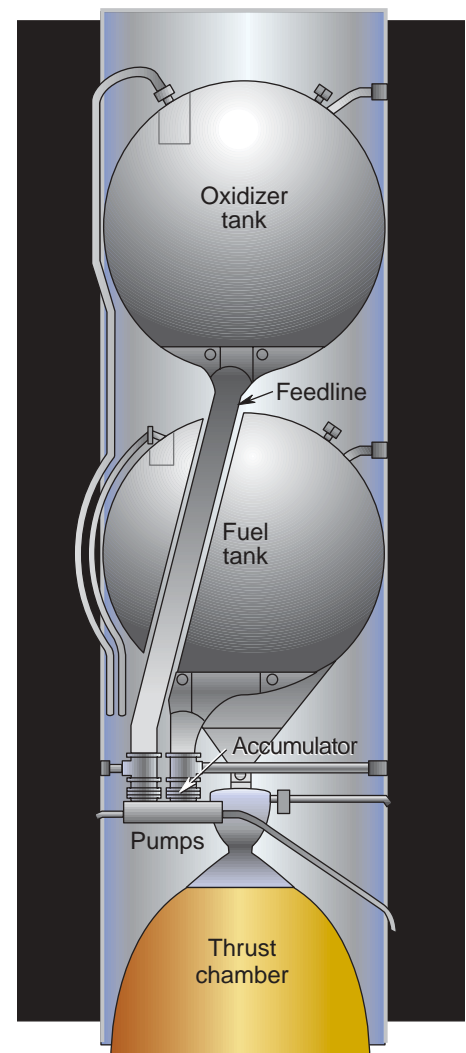
Schematic of propulsion system. The accumulator volume must be carefully selected to ensure that the hydraulic and structural frequencies are well separated during flight.

exhibited accelerations near the spacecraft interface that were significantly higher than those seen on a previous flight with a similar upper stage and spacecraft. Thus, as had happened with Saturn V, unexpectedly high responses were observed for similar missions without an apparent cause. This raised a concern for an upcoming Titan IV/Milstar mission, because the engine used on these previous flights would also be used, for the first time, on the Titan IV/Milstar mission.

Aerospace formed a multidisciplinary team to investigate the cause of the flight oscillations and to provide a risk assessment for the Titan IV/Milstar mission. The initial stage of the investigation revealed that a synchronization of the frequency, amplitude, and phase of the engine chamber pressure and structural response occurred during the earlier missions—which raised a concern that a pogo feedback loop

existed between the propulsion system and the launch vehicle/spacecraft structure.
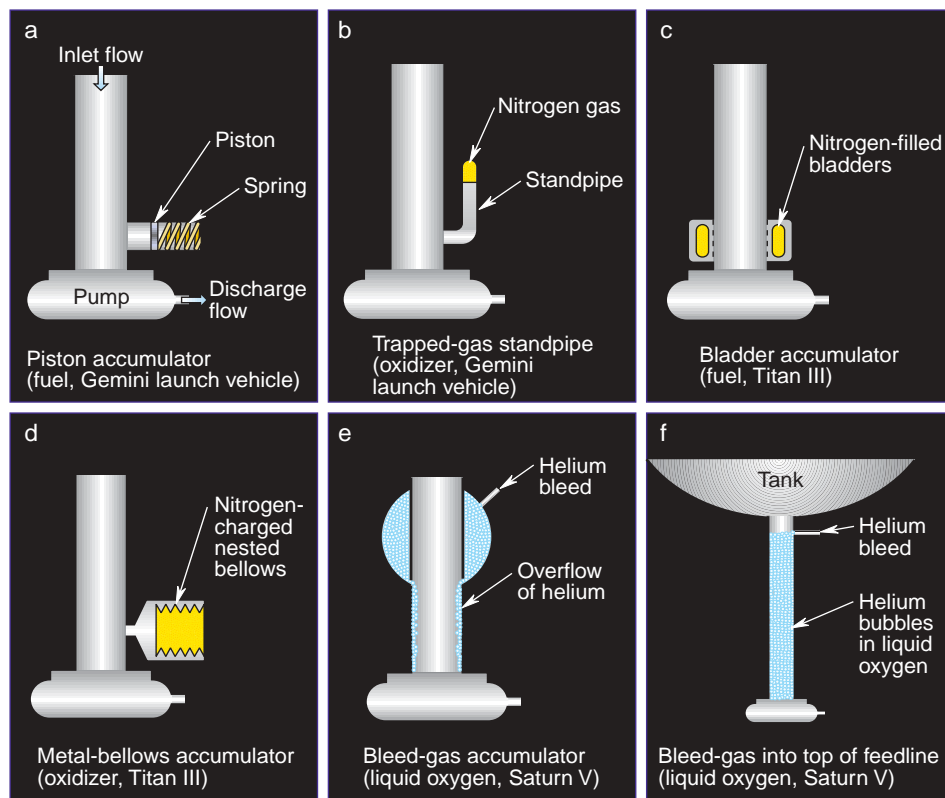
Aerospace and the contractor subsequently began an intensive effort to assess the pogo stability of the Titan IV/Milstar mission. Data from ground tests suggested that the engine oscillations could be associated with unsteady cavitation at the inlet of the liquid-oxidizer pump. That is, it was shown that the chamber pressure oscillations were most likely caused by cavitation bubbles at the pump inlet, which periodically formed and collapsed when the pump operated under a particular combination of inlet pressure, speed, and flow.

Equations for calculating pressure and flow oscillations across the pump interfaces existed for similar types of unsteady cavitation, but the equation coefficients were not known for the exact phenomenon that existed in this oxidizer pump. Moreover, the coefficients could not be identified from the available tests. Engineers combed through the existing literature and conducted pogo stability analyses to estimate the required parameters. The pogo model with the estimated pump parameters supported the hypothesis that the high accelerations on the earlier missions were caused by interaction of the launch vehicle/

space vehicle structure with the propulsion system during periods when the oxidizer pump was undergoing unsteady cavitation.

The pogo model with the best-estimated pump parameters predicted that the Titan IV/Milstar mission had the potential to experience instability if it flew as planned. In the worst case, a pogo response for the Titan IV/Milstar vehicle posed a potential for damage or even mission failure.

While developing the pogo stability model, the Aerospace and contractor team also worked to identify the operating conditions at which the unsteady pump cavitation occurred sufficiently to induce propulsion-structure interaction. From prior flight data, they established that the cavitation phenomenon only existed in a well-defined region of dimensionless pressure and flow parameters, and if these conditions were avoided, the risk of pogo during the Titan IV/Milstar mission could be effectively mitigated. The proposed mitigation procedure, therefore, involved controlling the propulsion system operation to avoid the cavitation-induced engine dynamic behavior. The mitigation was implemented, and the Titan IV/Milstar mission flew on April 8, 2003, without any evidence of pogo, successfully delivering the satellite into orbit.

Resonance

Nearly all objects tend to vibrate or oscillate when disturbed. Pluck a guitar string, for example, and it will oscillate at a particular frequency—known as its natural or harmonic frequency—based on factors such as thickness, tension, and length. Objects connected to the string, such as the guitar itself or the air inside it, can also start to vibrate at this frequency. Put a second identical guitar string next to the first, and it too will start to vibrate, even though it has not been plucked. This phenomenon is known as resonance—the tendency of an object to begin vibrating in response to a periodic force (in this case, sound waves) equal to or very near its natural frequency. The result of such resonance is an increase in amplitude or oscillation strength. For guitar strings, that means a louder sound; for rockets, that makes for a very bumpy ride.

Conclusion

From the early days of Gemini to the latest Milstar launch, Aerospace work on the pogo phenomenon has been instrumental in preventing catastrophic mission loss. Forty years of experience has shown that pogo is not an isolated phenomenon, but can affect launch systems as diverse as the Delta, Titan IV, and space shuttle. Even launch vehicles with a pogo-free flight history are not always immune. As the launch community transitions to the Evolved Expendable Launch Vehicle and other future systems, Aerospace will no doubt be called upon to use its expertise to help prevent pogo and ensure continued mission success.

Further Reading

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S. Rubin, *Prevention of Coupled Structure-Propulsion Instability (POGO)*, NASA SP-8055 (October 1970).

Schematics of accumulators that successfully suppressed pogo on various vehicles. The concept of introducing bubbles near the tank outlet (panel f) was proposed for the Saturn V first stage, but this approach was rejected in favor of the one shown in panel e. Inadvertent effervescing of nitrogen gas from the oxidizer exiting the first-stage tank on Titan IIIE-2 had previously led to pogo instability.

Launch Vehicle Guidance, Navigation, and Control

Getting a rocket safely from pad to orbit requires sophisticated, responsive flight software. Aerospace helps ensure that these mission-critical systems are fully qualified for the job.

N. A. Bletsos

A rocket's flight software (part of the avionics suite) has the difficult job of directing and controlling the vehicle from its initial position bolted down to the ground to its target location far above Earth. In modern rocketry, this is performed autonomously. To accomplish this challenging task, the flight software must correctly perform three basic functions: guidance, navigation, and control (GNC). Navigation is the process of determining the vehicle's position, velocity, and attitude in space. Guidance is the process of deciding how to steer to the desired target. Control is the process of implementing the guidance commands to achieve actual engine deflections or changes in thrust vector.

The Aerospace Corporation has historically been a major contributor to the development of launch vehicle GNC capabilities. In fact, in 1962, the Department of Defense commissioned Aerospace to design and develop the flight software for the Titan program, and this software has supported the program for more than 40 years. The unprecedented tasking of a federally funded R&D center as the prime contractor and developer has never been repeated; but Aerospace continues to support new and recurring launch programs through independent verification and validation, including modeling and simulation.

Navigation

Rocket navigation is managed by a device known as the inertial measurement unit or IMU, which is essentially an arrangement of accelerometers and gyros (rotation meters). An IMU operates on the same basic principle used for centuries by seagoing navigators—dead reckoning. Using this technique, the navigator would chart the speed and direction traveled from a known starting point to determine a new location, which in turn provided the starting point for the next computation. The process is a bit more sophisticated for launch vehicles: Given an initial position and velocity, the IMU integrates accelerations in three orthogonal directions to obtain velocity; this result is then integrated to determine a new position as a function of time. The process would be simple and accurate if not for four complications.

First, accelerometers measure physical accelerations, but cannot measure field-induced accelerations such as gravity, which has a real effect on the vehicle's position and velocity. To obtain the total acceleration, the IMU must combine the accelerometer measurements with modeled gravitational acceleration. Second, acceleration integrations must be performed in an inertially fixed nonrotating frame. In such a "working" frame, the integration process is simple; however, a launch vehicle experiences roll (rotation), pitch (nose up or down), and yaw (nose left or right) motions during its flight. Therefore, the IMU must somehow resist or compensate for these motions to maintain an inertially fixed frame of reference. Third, accelerometers and gyros—like any instruments—are intrinsically prone to error. Instrument biases, scale factors, and misalignments are common sources of errors. Finally, the IMU requires an initial state from which to navigate. Errors in initial position can contribute to initial attitude and velocity errors, so the initial state needs to be extremely accurate.

Aerospace has helped overcome many of these problems. For example, to enhance acceleration determination, Aerospace
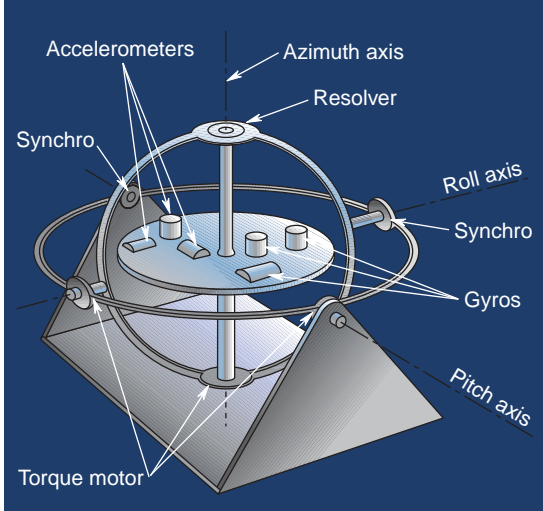
An IMU uses a coordinate frame to keep track of the accumulated motion. In the case of a strapdown system, the coordinate frame is computed. On the other hand, with a gimbaled IMU (shown here), the coordinate frame can be defined by the platform, which is held inertially fixed. The gyros on the platform sense any angular change and cause the torque motors to eliminate the rate, effectively holding the platform inertially stable. The accelerometers are free to integrate the translational motion without the complications of rotational motion.

evaluates calibration techniques and investigates anomalous instrument behavior. Aerospace has also examined techniques for precision modeling of local gravity.

To maintain an inertially fixed working frame, an IMU is typically designed to follow one of two main approaches. In the first, the accelerometers are mounted on a gimbaled platform held steady by servomotors that respond to gyro inputs. This type of IMU is known as a platform IMU. In the second approach, the accelerometers are allowed to rotate with the vehicle while gyros determine the change in attitude. In this case, the inertial working frame is a computational entity. This second type of IMU is known as a strapdown IMU, and it

has grown more popular with advances in computing power. To enhance IMU capability and applicability, Aerospace has been studying gyro technology in the lab, looking at both high-precision small-range gyros for platform applications and less precise large-range gyros for strapdown applications. Aerospace is also developing new gyro technologies and computational algorithms.

To assess the effects caused by sensor error, Aerospace has developed sophisticated simulation and error-analysis tools. One such tool, NavFil (Navigation Filter), evaluates the expected navigational accuracy of launch vehicles. The program reads in the nominal launch trajectory obtained from high-fidelity simulations and propagates the state-error covariance statistics using measured sensor-error statistics. A second statistical program, PRTORB, then computes the orbital dispersions for a given position and velocity error range, which is output from NavFil. The program generates a statistical population of perturbed orbits about the nominal. From this population, the sample mean, sample variance, probability density, and cumulative distribution function for each orbital element are determined. Tools such as NavFil and PRTORB help ensure mission success by determining the likelihood of navigation-related orbital constraint violations. In fact, when these tools indicate a substantial risk of such a violation, the contractor may choose to reoptimize the trajectory or seek a different IMU with higher performance.

Guidance

Guidance can be defined as the process of steering to generate a trajectory that will

achieve target conditions despite continuous changes in the launch vehicle and its environment. If the vehicle state and environmental conditions were exactly known and did not change, guidance would be a relatively simple matter, requiring only open-loop schemes. In practice, unknown system variations force the need for closed-loop guidance steering in which vehicle
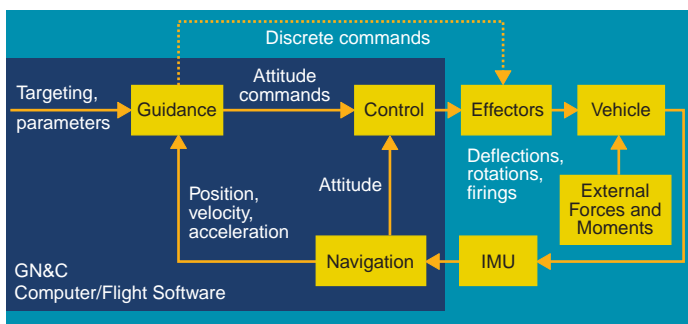
Guidance, navigation, and control functions are performed by the flight computer. A current navigation solution is computed using rates from the inertial measurement unit (IMU). Guidance uses the current navigated solution to determine the corrections that must be made to account for the vehicle's current location. The control system uses the commands from guidance along with high-frequency attitude information from the IMU to determine appropriate engine deflection angles.
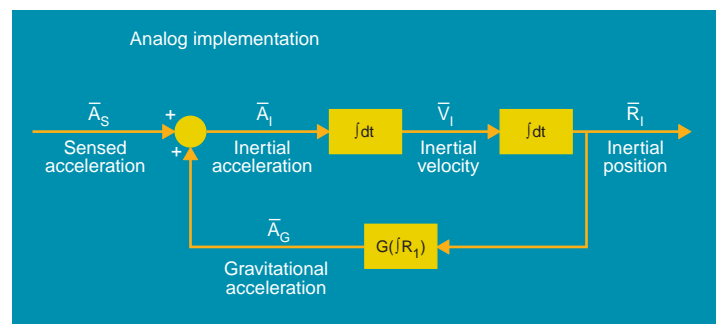
The navigation loop. The sensed acceleration (expressed in the working frame) drives the integrating loop from which position and velocity are determined. The attitude is determined by integrating the gyro data over time (in the case of a strapdown system) or by reading the gimbal angles (in the case of a gimbaled platform system). In the early days of launch vehicles, the gimbaled platform was extensively used. Today, strapdown systems, which are mechanically simpler but computationally more intense, are favored.

A typical launch trajectory. A launch vehicle operates in a wide range of environments, from the sea-level atmosphere to the near vacuum of space. The mass properties of the vehicle change continually during powered flight as fuel is used and discretely as components are jettisoned. The control and guidance systems must properly operate in all of these environments and must also account for the vehicle mass property changes to remain stable and on course to the targeted delivery point.

position and velocity are used as feedback in the guidance algorithm.

Guidance schemes are as varied as the systems they control. There is no generic guidance theory, but most mission-specific functions have three phases: atmospheric flight, exoatmospheric flight, and coast flight.

During atmospheric flight, the primary goal is to minimize aerodynamic loading and heating—that is, to prevent the vehicle from breaking or burning up. These atmospheric forces are a function of angle of attack; hence, a trajectory must be designed to minimize the angle of attack in the region of high dynamic pressure. This trajectory is typically designed prior to flight and input as open-loop attitude steering commands to the vehicle.

Exoatmospheric steering usually involves large closed-loop algorithmic solutions to the two-point boundary value problem—that is, how to get from point A to point B. Because of the computational complexity involved, real-time onboard optimization is rarely implemented. Various algorithms can be applied. For example, the Titan and Centaur vehicles use an iterative method to find a set of guidance parameters that satisfy the end condition for a guidance law given in functional

form. In contrast, the Inertial Upper Stage iteratively searches through all trajectories from the starting point to the target point until a suitable path is determined; this method is quite powerful but requires significant computational resources. On the other hand, the Delta employs a scheme that uses open-loop attitude commands and an open-loop trajectory-acceleration profile, determined a priori, as the basis for the steering; the system continually measures deviations from nominal and makes appropriate adjustments to the nominal commands.

Aerospace typically reviews and analyzes new or updated guidance algorithms. This involves independently implementing the proposed guidance scheme in a computer simulation to verify the algorithm convergence and targeting procedure. Using the flight software provided by the contractor (which includes the guidance algorithm), a large number of runs are made to stress the guidance function under dispersions to ensure that the flight software can safely operate and deliver the payload to the targeted orbit. The importance of this Aerospace activity was demonstrated recently when a contractor's initial guidance algorithm was found to be unstable under dispersions. A targeting parameter had to be modified to correct the instability.

Control

The basic purpose of the flight control system, or autopilot, is to maintain the vehicle attitude commanded by the guidance program. The autopilot senses the vehicle attitude via an inertial measurement system and commands the appropriate change in the engine thrust vector to achieve the commanded attitude. Design of the launch vehicle autopilot must satisfy three main, often conflicting, requirements: stabilize the vehicle, ensure adequate response to guidance commands while minimizing trajectory deviations, and minimize angle of attack to ensure structural integrity of the vehicle.

Vehicle stability is the primary and most difficult criterion to meet, and its design requirements are often contradictory to the speed of response of the autopilot. Vehicle stability is hampered by vehicle flexibility, which causes local elastic deflections that are sensed by the attitude and rate sensors used by the autopilot for attitude control. Minimizing the aerodynamic loads on the vehicle often requires a load-relief loop in the autopilot, which is typically a sensed lateral acceleration feedback loop that can cause deviations from the guidance commanded trajectory. Further complicating matters, the mass, aerodynamics, and slosh
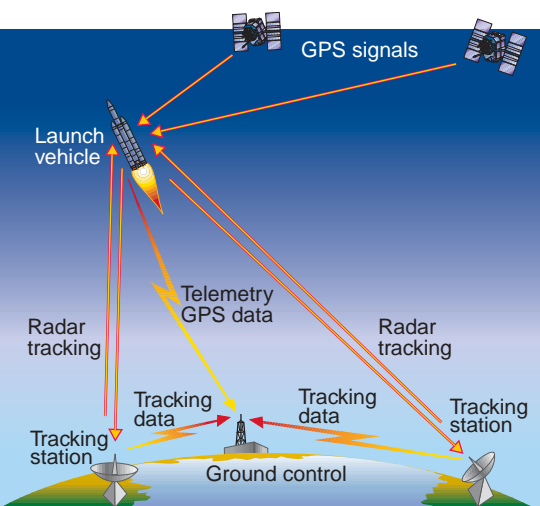
Range safety network incorporating GPS. Radar and IMU navigation data are currently used to verify that a launch vehicle is safely on course. With a GPS receiver on the rocket, a separate independent navigation measurement can be provided, virtually eliminating scrubbed launches caused by tracking-station failures.

and bending characteristics of the vehicle vary rapidly as propellant is consumed.

Because of these complexities, the design of the autopilot is performed in stages, beginning with highly simplified models. The process may be divided into four parts: point-mass determination of a reference trajectory; rigid-body autopilot design; slosh and flexible body design to determine filters, gyro locations, and stability characteristics; and nonlinear time-varying simulations to determine both stability and performance characteristics in the presence of wind.
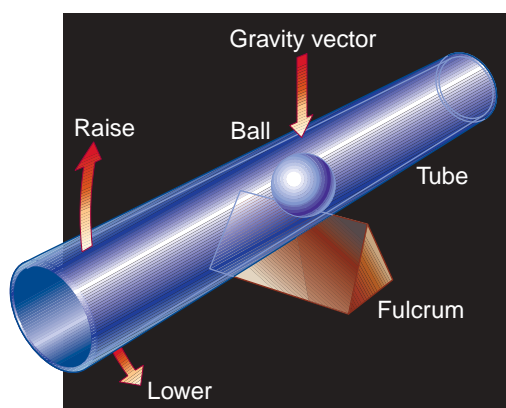
Leveling is the process of determining initial vertical orientation on the launchpad using measured acceleration data from the accelerometers in the IMU. The idea is comparable to taking a ball in a tube balanced on a fulcrum and finding the angle of the tube that causes the ball to remain balanced and stationary inside it. This gives local level in one direction. The process can be repeated in another direction to determine level relative to both north and east directions.

In the first phase, a reference trajectory is designed using a three-degrees-of-freedom simulation. During the second phase, the basic control gains are calculated. Because vehicle properties change over time, a "time-slice" design approach is used. This approach freezes the time-varying properties while making use of linearized vehicle equations of motion. The time slices are taken along various points in the trajectory, and the autopilot gains are linearly interpolated between them. This approach continues in phase three of the process, which considers slosh and flexible body dynamics. This is the most difficult and time-consuming phase of the design. When the third phase is complete, a nonlinear time-varying simulation is performed to ensure that the stability and performance of the autopilot are satisfactory. Iterations on each of these phases may be necessary before a final design is achieved.

Aerospace has developed tools for quickly analyzing vehicle stability under both nominal and off-nominal conditions, such as dispersed mass properties, aerodynamics, and flexible body parameters. These tools account for vehicle flexibility, propellant slosh, engine inertia, and engine actuator characteristics; they are used to assess the adequacy of the control system prior to launch and also to resolve anomalies seen during flight. These tools were critical in certifying a recent launch. Aerospace postflight analysis from an earlier mission found that the first structural bending mode frequency was significantly higher than predicted. This caused concern for a second mission scheduled to carry the same payload. Aerospace performed a stability analysis and showed that the autopilot could handle the frequency discrepancy in addition to the other modeled structural uncertainties. Thus, the autopilot was cleared for the mission.

Conclusion

The final responsibility for the success of a mission rests with the successful operation of the guidance, navigation, and control system. Aerospace has played a vital role in certifying these systems to ensure their accuracy and reliability.

The Aerospace role in GNC continues to expand. The corporation has initiated a series of independent research and development programs to evaluate and improve advanced GNC architectures, including the use of adaptive autopilots, integrated GPS/IMU navigation, and in-flight retargeting.

Alignment and Calibration

A launch vehicle's inertial measurement unit (IMU) is dependent on its precise knowledge of its initial position, velocity, and attitude. Small inaccuracies in the initial latitude can cause large initial velocity and attitude errors. Therefore, the location of a launch site must be carefully surveyed.

With the launch site location well known and the rocket on the pad, alignment can begin. Alignment is the process of precisely determining the IMU attitude. Generally, three techniques can be used: optical alignment, leveling, and gyro-compassing.

Optical alignment uses lines of sight to determine the initial twist, pitch, and yaw of the IMU. Leveling uses the accelerometers in the IMU to sense the direction of the plumb-line gravity vector. Gyro-compassing uses the gyros in the IMU to sense the direction of the Earth rotation vector. Optical alignment can yield highly accurate results, but requires human involvement, which is not always practical. Leveling and gyro-compassing can be performed automatically, but neither can fully determine IMU attitude. In practice, different techniques are combined, such as leveling with optical azimuth determination or leveling and gyro-compassing.

In addition to alignment, an IMU must undergo calibration to identify errors associated with the accelerometers and gyros. Before leaving the factory, the IMU is made to measure different known accelerations and spin rates. These measurements reveal any sensor errors (i.e., variations from the known values) so that the flight computer can compensate for them.

Vibrations, temperature changes, and mounting inaccuracies can cause the sensor errors to drift from their factory-calibrated values. When possible, the IMU is calibrated on the launchpad using the known Earth rotation rate and plumb-line gravity vectors as references.

In addition, Aerospace is supporting the Land Based Strategic Deterrent Analysis of Alternatives, a program to replace the current ICBM fleet of Minuteman and Peacekeeper missiles. The specifications levied upon the new system will necessitate the use of advanced technologies.

Acknowledgements

EELV:
The Next Stage of

U.S. launch capabilities continue to evolve to meet increasingly demanding space asset requirements. Aerospace is helping to ensure that the latest generation of advanced launch vehicles will lead a long and productive life.

U.S. Air Force

The end of the Cold War forced a retrenchment of many defense programs in the 1990s. Congress asked the Department of Defense to generate a plan for ensuring access to space despite increasing budgetary constraints. The resulting Space Launch Modernization Plan of 1994, developed with the participation of The Aerospace Corporation, presented various alternatives ranging from no change at all to a complete overhaul of the space-launch acquisition strategy. The Evolved Expendable Launch Vehicle (EELV) concept was ultimately chosen, as it offered the best approach for managing cost and risk.

The EELV program was designed to reduce the cost of government space launches through greater vehicle modularity, component standardization, and contractor competition. Aerospace helped develop system requirements that emphasized simplicity, commonality, standardization, new applications of existing technology, streamlined manufacturing capabilities, and more efficient launch-site processing. In fact, the EELV System Performance Requirements Document listed only three "key performance parameters." These stipulated specific mass-to-orbit requirements for each class of vehicle, design reliability of 98 percent at 50 percent confidence level, and standardization of the launchpads and payload interface.

The first Atlas V lifted off from Cape Canaveral on August 21, 2002. This launch marked the first operational use of a rocket designed under the EELV's joint Air Force/industry partnership.
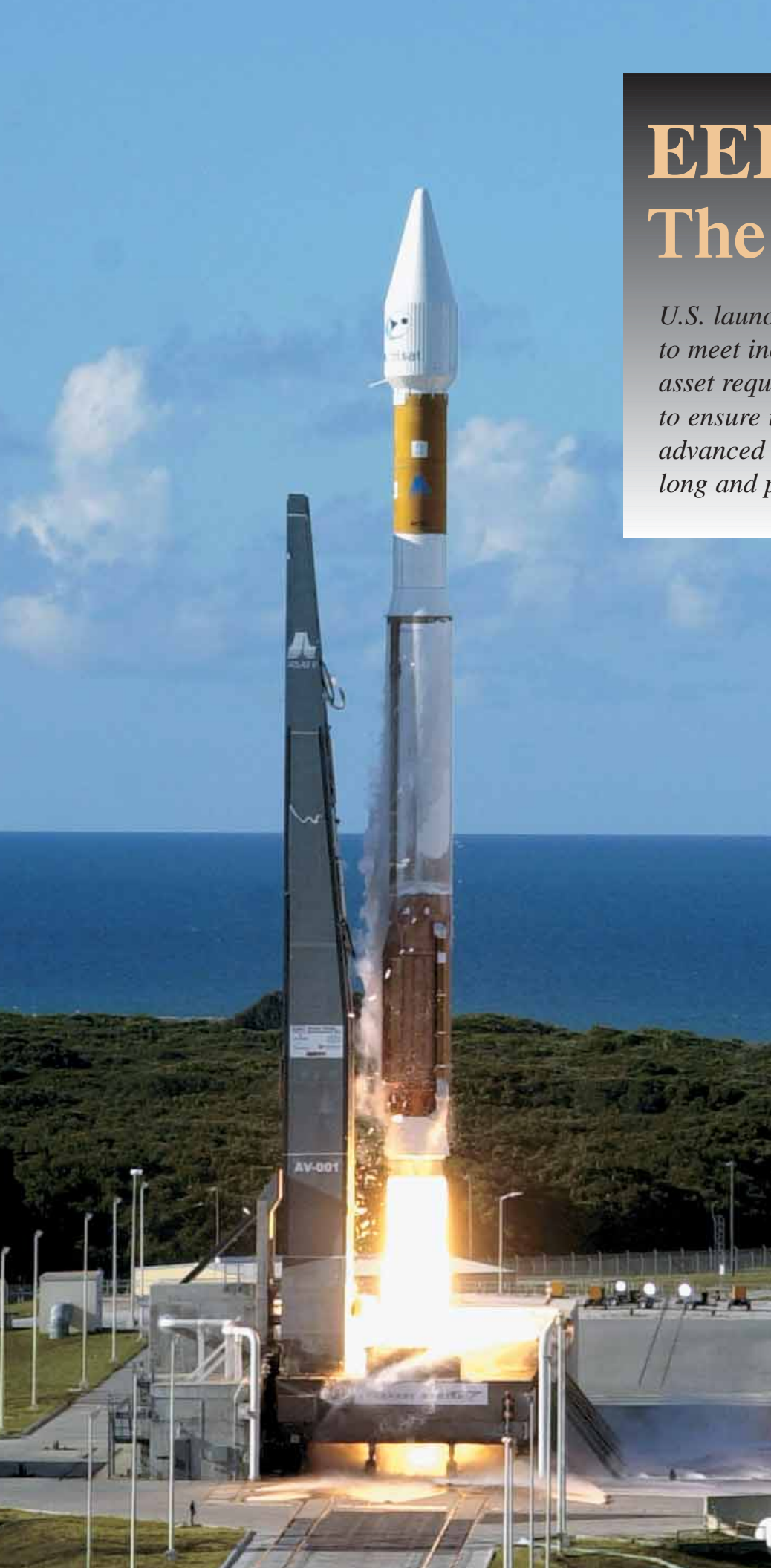
Space Launch

Randy Kendall

The program includes two families of launch vehicles—the Atlas V and the Delta IV—along with their associated infrastructure and support systems. Each is based on a two-stage medium-lift vehicle, augmented by solid rockets as needed to increase payload capability, and a three-core heavy-lift variant. Both have achieved notable successes in their first launches, but the EELV program is still in its infancy, and will need continued scrutiny to ensure that the anticipated gains in cost and reliability will be realized over the long term. In fact, Aerospace involvement in the program was initially limited, as the government sought to position itself more like a commercial customer; however, as the date approached for the first national security launch (for the Defense Satellite Communications System in March 2003), an increased emphasis on mission assurance prompted a return of Aerospace's traditional role in independent launch verification.

Atlas V Evolution

The Atlas V traces its roots to the Atlas ICBMs developed in the late 1950s, although its modern evolution begins with the Atlas IIA, introduced in 1992. The Atlas IIA featured a 3-meter-diameter pressure-stabilized booster tank powered by three liquid-oxygen/kerosene booster and sustainer engines producing 2.1 meganewtons of thrust at sea level. The rocket's upper stage—the Centaur II—was

This hot-fire ground test in October 2002 set the stage for the first flight of the Delta IV in November 2002. The Delta IV uses the first liquid-fueled rocket engine (the RS-68) designed, built, and flown in the United States in more than 20 years.

The Boeing Company

Atlas II/III Family

Atlas V Family
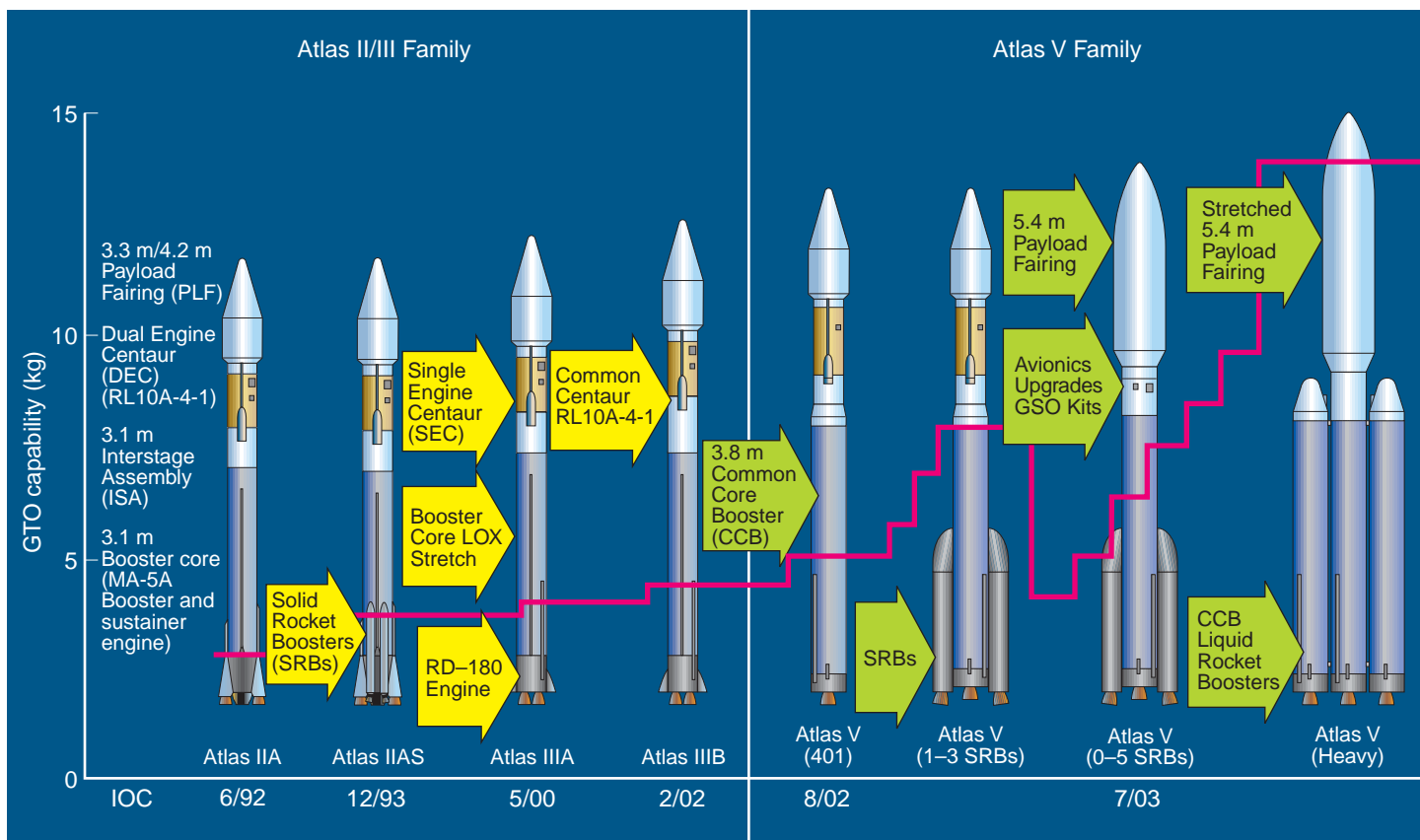
Atlas V vehicles carry a three-digit designation indicating the diameter of the payload fairing, the number of solid rocket boosters, and the number of Centaur engines. Thus, the most basic vehicle—the 401—would have a 4-meter fairing, no solid motors, and a single-engine Centaur. A 552 vehicle would have a 5-meter fairing, five solid rocket boosters, and a dual-engine Centaur. The heavy-lift vehicle consists of three cores strapped together.

also 3 meters in diameter and featured a dual RL10A-4 engine. The avionics that control the Atlas were located on the Centaur, with booster-specific components residing in an avionics pod attached to the outside of the first stage. In this configuration, the Atlas IIA could lift 3066 kilograms to a geosynchronous transfer orbit. The Atlas IIAS, introduced in 1993, used four solid rocket boosters to increase performance to 3720 kilograms to geosynchronous transfer orbit.

The next major Atlas variant, the IIIA, successfully flew on its first attempt in May 2000. This vehicle included the Russian-built RD-180 engine, which is also featured on Atlas V. Use of the RD-180 presented significant challenges for the government

The Atlas V prepares for its inaugural launch.

A still frame from the onboard video camera carried by the Atlas V during its inaugural launch. A jettisoned booster section can be seen falling away from the rocket toward Earth.
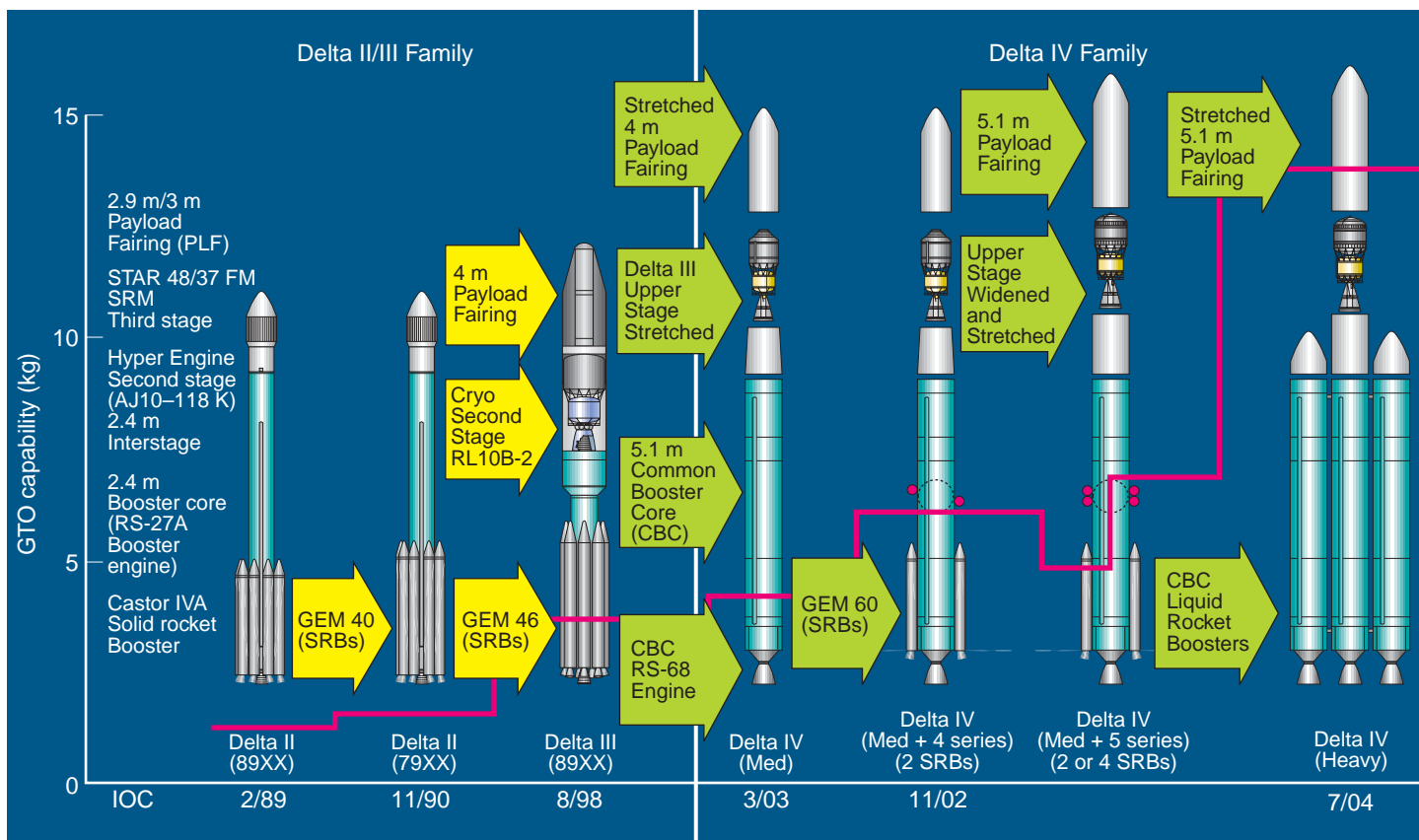
The Delta IV family includes three classes of vehicles. The medium-class vehicle has a Common Booster Core and a 4-meter-diameter upper stage and payload fairing. The medium-plus has two basic versions: one with a 4-meter-diameter upper stage and payload fairing and two solid motors, and one with a 5-meter-diameter upper stage and fairing and two or four solid motors. The heavy-lift vehicle consists of three cores strapped together.

and Aerospace in conducting flight verification activities because access to the engine's design and test data was restricted. (A U.S. coproduction capability is now being developed as a risk-reduction effort.) Fueled by liquid oxygen and kerosene, the RD-180 has two chambers fed by a common turbopump using a staged combustion cycle to deliver 3.8 meganewtons of thrust at sea level. To accommodate a higher mixture ratio, the liquid-oxygen tank was lengthened approximately 4 meters. The Atlas IIIA was also the first to use the Centaur III upper stage. In this configuration, the Atlas IIIA can lift 4060 kilograms to geosynchronous transfer orbit.

The Atlas evolution continued with the IIIB, first flown in February 2002. This vehicle introduced the Common Centaur upper stage, which can be flown with either single or dual RL10A-4-2 engines. The Atlas IIIB can lift 4500 kilograms to geosynchronous transfer orbit. The Centaur tanks on the Atlas IIIB were lengthened by approximately1.7 meters more than the IIAS; as a result, Aerospace recommended additional structural qualification testing, which is scheduled to be completed in spring 2004.

The Atlas V Family

The final step in the Atlas evolution was the introduction of the 3.8-meter-diameter Common Core Booster, which forms the basic building block of all Atlas V vehicles. Upgrades to avionics and redundant systems were also incorporated. The Atlas V core vehicles can be equipped with payload fairings measuring 4 or 5 meters in diameter; the 4-meter version can carry up to three solid motors, and the 5-meter version can carry up to five. A heavy-lift version, still in development, will consist of three Common Core Boosters strapped together. All variants use the same main engine, core booster, Common Centaur, and avionics. This commonality enables the Atlas V to support a wide range of missions and facilitates upgrade from one variant to the next if performance requirements increase. In fact, the Atlas V is the first Atlas that can support direct injection into geosynchronous orbit. The 4-meter vehicles can lift 4950–7620 kilograms to geosynchronous transfer orbit, the 5-meter series can lift 3950–8665 kilograms, and the heavy-lift vehicle will lift 12,650 kilograms.

Launch processing for the Atlas V centers on the "clean pad" concept at Cape Canaveral. The benefits of this approach include the ability to launch several Atlas V configurations from the same pad. The vehicle is fully integrated off-pad in a vertical position, including payload stacking and integrated testing. On the day of launch, the rocket is rolled to the pad on the mobile launch platform, where the propellants are loaded. The vehicle is then ready for countdown. There is no spacecraft or launch vehicle access at the pad, so any hardware problems require rolling the rocket back to the vertical integration facility. In fact, the second Atlas V flight had to do just that to allow replacement of avionics components; a successful launch followed within 24 hours.

Fewer Atlas V launches are scheduled for the West Coast, so the clean pad concept will not be used there. Rather, the Atlas V team is upgrading an existing Atlas III pad and will use a more traditional processing approach. This pad will accommodate the largest 5-meter vehicles, but not the heavy-lift version. Aerospace personnel who were involved with previous launchpad upgrades at Vandenberg are helping to support this activity.

A New Approach to Launch Acquisition

The Evolved Expendable Launch Vehicle (EELV) program sought to reduce the cost of military space missions by purchasing commercial launch services rather than launch-vehicle hardware, infrastructure, and operations support. The idea was to eventually eliminate the wide variety of expendable launch vehicles—Titan IV, Delta II, Atlas II, etc.—and have all defense payloads fly on one family of EELV rockets. That meant that the launch-pads and payload interfaces would all need to be standardized, and the rockets would have to employ a modular design to accommodate different payloads. Standardization would also allow the contractor to use the same systems for commercial launches, and thereby achieve economies of scale that are not typical of military launch programs.

The Department of Defense awarded $30 million contracts to four companies in August 1995 and then $60 million follow-on contracts to two companies in December 1996 with the goal of ultimately selecting just one. This strategy was based on the assumption that the commercial market could not support two launch systems; however, by 1997, the situation had apparently changed. The worldwide demand for commercial launches into geosynchronous transfer orbit was expected to reach 30–40 per year.

Given this robust commercial market, the government decided to revise its acquisition strategy and allow two contractors to proceed to the engineering, manufacturing, and development phase and receive Initial Launch Service contracts. The Defense Department competitively awarded a $500 million agreement in October 1998 to develop the Delta IV system and signed a $1.36 billion contract for 19 launches. The Atlas V system also received $500 million for development and a $650 million contract for nine launches.

This cost-sharing arrangement provided only partial funding for the development of the two launch systems. The balance would come from the contrac-tors themselves. In exchange, the contractors would retain ownership and control of all system designs and launch operations and could thus shape their development plans to support long-term corporate goals.

Along with this new acquisition strategy, the military had to rethink its traditional business approach and position itself more like a commercial customer. Consequently, EELV program managers adopted a new stance with regard to mission assurance, risk management, and overall program control. They replaced traditional government *oversight* with so-called *insight*, a project management style that allows in-line involvement but no actual direction.

No sooner had the Air Force changed its acquisition strategy than the environment changed again. First, the Delta III and Titan IV systems experienced significant failures in 1998 and 1999. As a result, the government formed a team, which included Aerospace, to investigate and evaluate potential systemic causes of failures across all launch systems. During the same period, the projected boom in the commercial market began to fizzle, drastically reducing the number of commercial missions that would occur before the first government missions, thereby diluting the risk reduction benefits that the government had anticipated.

As a result, additional mission-assurance steps were taken. For example, the Department of Defense allocated funds for a demonstration flight of the heavy-lift version of the Delta IV, scheduled for summer 2004. Such a demonstration was not originally necessary because the Delta IV was supposed to establish a track record with commercial launches before carrying any defense payload. The Department of Defense also revised its insight role to include more mission assurance. This was a significant step for Aerospace, which once again become a key contributor, providing launch verification and risk assessment for each mission.

—Pete Portanova

Delta IV Evolution

The Delta IV lineage also traces back to the late 1950s and has its origin in the Thor ballistic missile. The modern evolution stems from the Delta II, which completed its first mission—a GPS satellite launch—in 1989. Subsequent configurations have included the RS-27A liquid-oxygen/kerosene main engine on a core vehicle measuring 2.4 meters in diameter. The RS-27A provides only 0.9 meganewtons of thrust at sea level, so with a minimum gross liftoff mass greater than 100,000 kilograms (without solids), the Delta II requires strap-on solid rocket motors for liftoff. The second stage is powered by an engine running on N_2O_4 and Aerozine 50. For high-energy missions, such as a GPS transfer orbit or Earth escape trajectory, a third stage can be added with a solid rocket motor.

The next major development was the introduction of the Delta III with a 4-meter-diameter upper stage powered by an RL10B-2 engine. Fueled by liquid oxygen and liquid hydrogen, the RL10B-2 is similar to the RL10A-4 flown on the Centaur and includes an extendable nozzle. The Delta III uses a shorter and wider fuel tank than the Delta II to accommodate the larger upper stage and payload fairing; this design keeps the overall length roughly the same and allows the Delta III to maintain control authority and to maintain compatibility with existing facilities. In addition, slightly larger graphite-epoxy solid rocket motors are employed.

The heart of all Delta avionics is the redundant inertial flight control assembly; introduced in 1995, this assembly uses six ring-laser gyros and six accelerometers to provide complete redundancy in each axis. Capable of lifting 3810 kilograms to geosynchronous transfer orbit, the Delta III doubled the performance of the Delta II, allowing it to fly a much larger class of payloads. While its success record was not stellar, the Delta III was a critical step forward, enabling Delta to compete in the intermediate and heavy launch market. Although Delta III was an entirely commercial development, Aerospace participated in the anomaly resolution that followed the first Delta III failure in 1998 and performed independent validation of the modifications to the flight control software that was determined to be the root cause. Aerospace was also actively engaged in the anomaly resolution following the second

The Boeing Company

The Delta IV medium-plus configuration shown here includes the first stage, solid rocket motors, second stage, a 4-meter-wide composite fairing, and a simulated payload. In this photo, taken before the first launch of this rocket type, the tower has been rolled back for testing to ensure that the rocket and ground support equipment are compatible with the radio-frequency and electromagnetic transmitters.

The Delta IV Common Booster Core appears on all vehicles in the Delta IV family, with some tailoring of skin thickness to optimize weight as appropriate. The complete Delta IV family includes three classes of vehicles—medium, medium plus, and heavy. The medium vehicle comprises a Common Booster Core and a 4-meter-diameter upper stage and payload fairing. The medium-plus vehicle includes a version with a 4-meter-diameter payload fairing and two solid motors and a version with a 5-meter-diameter upper stage and fairing and two or four solid motors. The heavy-lift vehicle, similar to Atlas V, consists of three cores strapped together. The Delta IV medium can lift 4210 kilograms to geosynchronous transfer orbit, while the medium-plus variants can lift 4640–6565 kilograms and the heavy-lift vehicle can carry up to 13,130 kilograms.

The Delta IV system launches from two pads on the East and West coasts. The launchpads themselves are fairly conventional, with mobile service towers to provide protection from the environment and access to the vehicle and payload. The launch vehicle is processed off-pad in a horizontal position. The first stage is mated to the upper stage in the processing facility, and the vehicle is then rolled out to the pad and hydraulically rotated to vertical on the launch table. The encapsulated payload can then be hoisted and mated to the launch vehicle, followed by integrated system testing. On the day of launch, the mobile service tower is rolled back prior to propellant loading approximately 8 hours before launch.

Delta III failure that involved the RL10B-2 engine. Prior to the successful third flight, Aerospace personnel provided hardware review and software validation expertise.

The Delta IV Family

The final step in the evolution of the Delta IV brought the Delta III 4-meter-diameter upper stage to a new 5-meter-diameter Common Booster Core. The core's RS-68 main engine is the first liquid-oxygen/liquid-hydrogen main engine developed and flown in the United States since the space shuttle. It uses a gas generator cycle with a relatively low chamber pressure. Although it has significantly lower specific impulse than the space shuttle main engine, it produces almost twice the thrust and is much simpler and cheaper to produce. Aerospace provided significant support during the development and testing of this engine, including the resolution of several turbomachinery vibration issues.

Standard Payload Interfaces

Along with the improvements in performance, reliability, and operability, one of the most significant achievements of the EELV program was the development of a standard interface for all EELV payloads. The Standard Interface Specification was developed by a joint government-industry team

A Delta IV heavy-lift launch vehicle stands on the launchpad at Cape Canaveral. The first launch of this vehicle—constructed from three core boosters strapped together—is planned for early July 2004. The demonstration flight will contain a demonstration satellite configured to identify ascent conditions and their effect on future payloads.

A Delta IV medium-class rocket blasts off from Cape Canaveral in March 2003, carrying a Defense Satellite Communications System (DSCS) spacecraft to a geosynchronous transfer orbit. This was the first Air Force satellite delivered into orbit under the EELV program. Five months later, another Delta IV carried the final DSCS satellite into orbit.

with representatives from launch vehicle and space vehicle programs; Aerospace served as the technical coordinator. The document includes more than 100 requirements for all aspects of the launch vehicle/ spacecraft interface, including not only mechanical and electrical interfaces but also mission design requirements, flight environments, and ground interfaces and services.

While rigorous mission integration is still required, spacecraft that adhere closely to the specification can greatly simplify the process. The specification facilitates the dual integration of payloads to fly on both the Delta IV and Atlas V and also eases the transition of a spacecraft from one payload class to another. This is because all but 12 of the interface requirements are common across all medium, intermediate, and heavy-lift variants. The fact that both Delta IV and Atlas V provide the same standard interface is a significant improvement over the heritage systems, where moving from a

Delta II to an Atlas II or from an Atlas II to a Titan IV was highly complex, if at all possible.

The Next Steps
Both the Atlas V and Delta IV have successfully completed three out of three launches. Atlas V has flown three commercial communications satellites on the 4- and 5-meter configurations. Delta IV has launched two Defense Satellite Communications System spacecraft on medium vehicles and a commercial communications

All Atlas V 400 and 500 configurations use a stretched version of the Centaur upper stage used for Atlas III, which can be configured with single or dual engines depending on mission needs. The tank on the Common Centaur flown on Atlas IIIB and Atlas V is roughly 1.7 meters longer than that of the Atlas IIAS Centaur. The Common Centaur uses the RL10A-4-2 engine.

The third launch of an Atlas V rocket successfully carried the Rainbow 1 direct-broadcast television satellite into orbit from Cape Canaveral in July 2003. The Atlas V rocket was flown in its "521" configuration, meaning it was fitted with a 5-meter-diameter fairing and two solid rocket motors. The larger fairing was chosen to accommodate the satellite's extensive antenna array.

satellite on a medium-plus vehicle. On the day of launch, Aerospace personnel supported the government mission director by monitoring prelaunch and flight data from specialized facilities at the launch site and in El Segundo.

Although the commercial market remains weak, the EELV contractors have already been awarded 26 more government launch contracts, with up to 20 more expected to be awarded in summer 2004. While the expected cost efficiencies (based upon large numbers of commercial launches) have not yet materialized, the program is still meeting its cost-reduction goals—even with expected price increases in the next procurement round. The primary reason is that many of the payloads that can fly on an EELV intermediate variant would have required a much more expensive Titan IV vehicle in the past.

The program's next major challenge will be the Delta IV heavy-lift demonstration flight, scheduled for July 2004. The unprecedented flight of three 5-meter liquid-fueled cores through the atmosphere presents a number of structural dynamics and flight controls challenges, and Aerospace is working hand-in-hand with the Air Force and the contractor to ensure a successful mission.

Acknowledgement

Future Launch Systems

Fast, cheap, and reliable space launch capability would be a tremendous asset to defense, civil, and commercial organizations alike. Aerospace is helping to ensure that all options are given proper consideration— because the decisions made today will profoundly affect the launch community for many years to come.

Robert Hickman and Joseph Adams

Aerospace generated this concept design for a two-stage-to-orbit reusable launch vehicle as part of a series of vehicle evaluation studies.

I n the 46 years since Sputnik, the space age has seen progressive improvements in launch systems and corresponding enhancements in the services provided by space assets. Today's launch fleet routinely deploys sophisticated spacecraft for navigation, communication, meteorology, intelligence, surveillance, reconnaissance, and space exploration.

Though impressive, today's launch fleet is not without limitations. Launch costs and preparation times limit space applications to a handful of high-value services. A revolution in new space applications is possible, but would require a new generation of launch systems to reduce cost and preparation times. The Department of Defense and NASA have expressed interest in such "transformational" capability; but be-

fore pursuing such a system, three major interrelated questions must be answered.

First, what capabilities are envisioned for the system? The goals of the defense, civil, and commercial space sectors are different, and the degree to which common solutions can be developed will determine whether separate or joint programs are pursued. Second, what sort of system should be designed? The choice between an expendable and reusable system, for example, will depend on whether design techniques and manufacturing technologies can be improved enough to make reusable systems affordable. Third, what development strategy should be employed? The combination of risk tolerance, available budget, and timeframe of need will dictate whether developers seek radical advancements

through aggressive technology projects or accept a safer, more incremental approach.

Aerospace has been seeking answers to all these questions with the goal of charting a course to provide the greatest benefit for all stakeholders. Beginning in 1996, for example, Aerospace's Future Spacelift Requirements Study evaluated near- and long-term national space mission needs, traditional and emerging markets, and the technology needed to address such markets. That landmark study helped shape the debate about what sort of systems should be developed—a debate that continues today.

System Capabilities

The needs and priorities of the Defense Department do not always match those of NASA or a global telecommunications firm. Cargo mass, crew, orbit, and launch
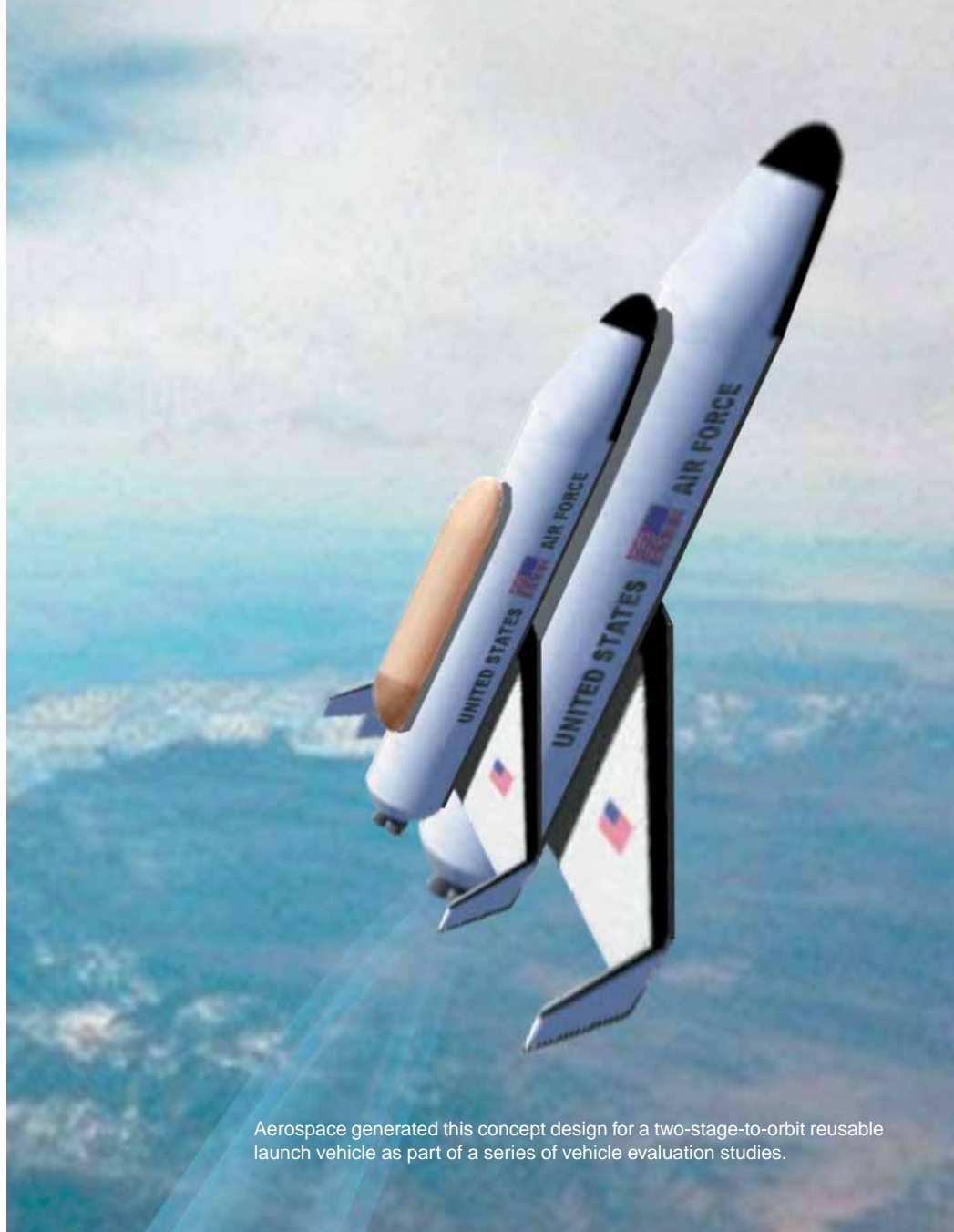
frequency requirements can vary considerably from sector to sector. Moreover, while all might agree on the need for high performance and reliability with low cost and risk, they might have widely different notions about what these concepts mean.

Defense Perspective

Defense launch systems are in the midst of a major transition. The heritage launch systems that served the nation's needs for decades are now being retired and replaced by a new generation of launch vehicle families under the Air Force Evolved Expendable Launch Vehicle (EELV) program.

These vehicles are adequate to support today's mission manifest of national security satellites; however, the Air Force has identified a need to launch tactical space missions that support war fighters in real time. These missions would allow global strike capability, rapid augmentation of satellite constellations, rapid replacement of compromised space assets, deployment of specialized space vehicles for combat support, and wartime protection of American space assets. The Air Force is clearly considering that future military engagements may require the launch of large numbers of payloads, each weighing less than 6800 kilograms, in just a few days.

Prosecuting a war in this manner would be impossible without launch responsiveness. Aerospace is assisting the Air Force Space Command in analyzing ways to achieve such "operationally responsive spacelift." At this point, efforts are still focused on formulating requirements, operational concepts, and design options.

Civil Perspective

In the course of more than 20 years, the space shuttle has launched more than a million kilograms of cargo and sent more than 300 people into space. After the start of operations, however, it became increasingly clear that the shuttle was difficult to operate, maintain, and upgrade. Also, the differing orbiter configurations made each flight preparation a painstaking ordeal.

In 1997, NASA commissioned a study of a second-generation single-stage fully reusable system to replace the shuttle. The result was the experimental X-33 space plane. The prototype—along with its full-scale version, VentureStar—sparked considerable interest within the commercial sector; but the X-33 couldn't overcome all the technological challenges associated with its design. Meanwhile, the projected market for broadband communications

satellites collapsed, deflating commercial interest and hastening the cancellation of not only the X-33 but the companion X-34 program as well.

As a result, NASA undertook an analysis of future systems that culminated in the so-called Integrated Space Transportation Plan. A major element of this plan was the Space Launch Initiative, a strategy to develop the architectural elements and associated technology for the shuttle replacement. Aerospace supported this initiative through requirements analysis and risk management techniques.

In the fall of 2002, NASA revamped its Integrated Space Transportation Plan by delineating three main building blocks. The first involved the Shuttle Life Extension Program, which considered how to keep the system flying until 2020. The second was the Orbital Space Plane, a vehicle that would initially serve as an escape craft for astronauts on the International Space Station. This would be followed a few years later by a crew transfer vessel launched atop an EELV. The third element was to

develop promising technologies identified through the Space Launch Initiative.

With this backdrop, the space shuttle Columbia flew its 28th and final mission, launching on January 16, 2003, and breaking up 16 days later on its return to Earth. A new plan announced in early 2004 calls for a return to shuttle flights and development of a space vehicle capable of carrying a crew to the moon and beyond.

Commercial Perspective

The traditional commercial launch market is focused principally on lofting communications spacecraft into Earth orbit. The global market for launch of these payloads, in terms of mass, is many orders of magnitude lower than for any other transport industry. Whereas the worldwide commercial launch market is less than half a million kilograms per year, commercial U.S. aircraft transport more than 1000 times that mass each day.

A methodology developed at Aerospace to explore launch costs suggests that the low flight rate required to support traditional communications spacecraft is not
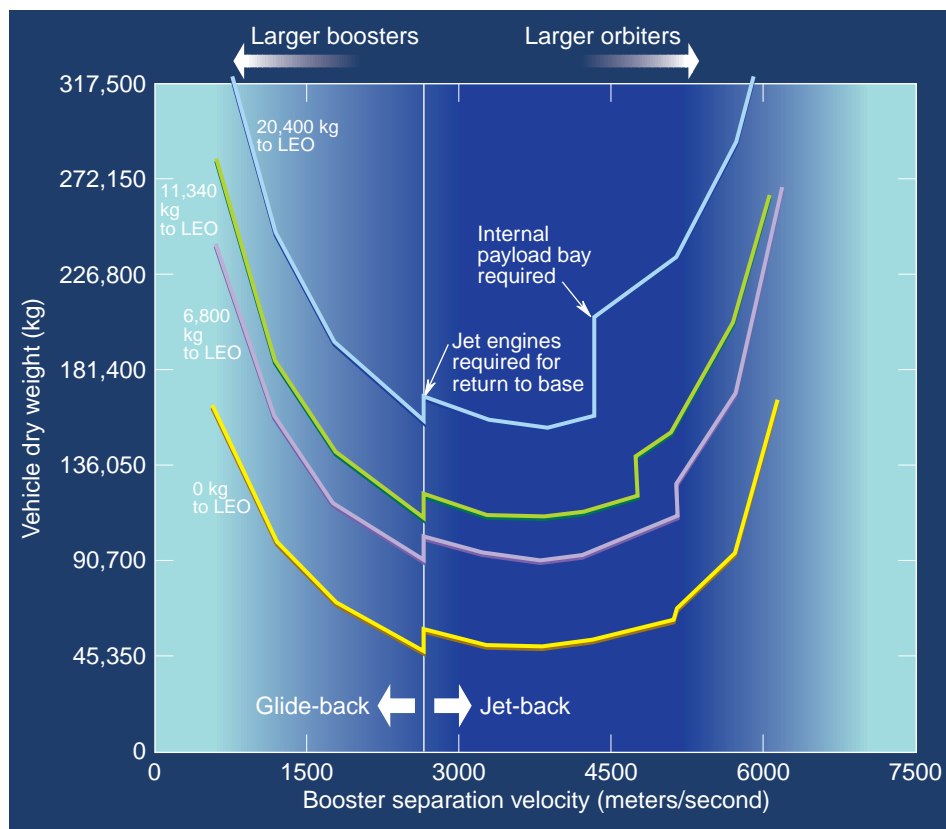
This graph depicts the relationship between dry weight and ideal separation velocity as it applies to two-stage-to-orbit reusable vehicles. An ideal separation velocity of approximately 2750 meters per second is roughly equivalent to Mach 4, after gravity and drag losses are accounted for. Below this separation speed, boosters can readily be designed to glide back to the launch base. Above this speed, jet propulsion is needed to fly the boosters home. Note that as one approaches the extremes of the curves, the weight relationship becomes very sensitive, which illustrates the difficulties in achieving single-stage-to-orbit vehicles. The design region for smallest (weight-optimized) vehicles is near the center of the curves.
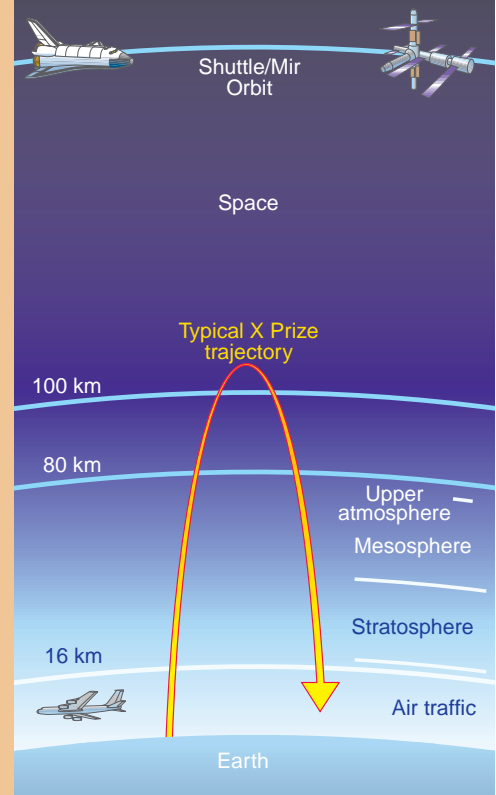
large enough, by itself, to justify large economic investments needed to achieve dramatically lower launch costs.

Nontraditional ventures may provide opportunities for profitable space launch businesses. Aerospace studies suggest that if launch cost could be reduced to between $50 and $225 per kilogram to orbit, a variety of nontraditional markets would open, thus providing an environment that would foster a viable growth industry. Examples include suborbital and orbital human transport, fast global freight and package delivery, space manufacture, and space solar power.

Recently, the commercial sector has witnessed an emergence of space launch development entrepreneurs. Partly spurred on by the X Prize competition, a number of entrepreneurs are investing commercial capital to develop suborbital and orbital space transportation systems. Their success or failure could have long-term repercussions on the commercial launch sector, hastening or delaying the introduction of a rapid-response space launch service.

System Design

ICBMs can launch in large numbers on short notice. To do so, they must be pre-processed and stored in a nearly launch-ready configuration. This methodology could also support the needs for responsive spacelift, but would require a massive launch and storage infrastructure and advanced production of the expendable launch vehicles. For reusable launch vehicles to be feasible, processing timelines must be shortened to less than four days; longer timelines will drive fleet size and processing facility requirements to unaffordable levels.

Determining how best to provide these capabilities requires an evaluation of each vehicle option's cost and technical risks. Aerospace has been applying considerable resources to do just that.

Expendable Vehicles

Expendable launch vehicles could probably support responsive tactical space needs, just as ICBMs do, but the cost would be prohibitive. Current launch costs range from $11,000 to $22,000 per kilogram of payload to low Earth orbit. The significant efforts of the EELV program have achieved moderate cost reductions, particularly for the heavy-lift vehicles, which use the same production line as the medium-lift versions. This commonality effectively provides the heavy-lift rocket with production rate advantages over the Titan IV and also permits the costs of engineering and logistics to be spread over a larger number of vehicles.

Still, further significant decreases in expendable launch vehicle cost are not anticipated. Some industry analysts suggest that technological breakthroughs will reduce cost, but typically, key aspects of such technologies are not well understood, which makes them risky. Air-launched systems are also often identified as solutions; but although air-based launchers can support all-azimuth launches, they do not impart a significant velocity increment, and so do not substantially reduce the amount or cost of the expendable hardware.

Conventional Reusable Vehicles

Reusable launch vehicles are commonly proposed as responsive and inexpensive alternatives to expendable rockets. Analogies to aircraft systems suggest that reusing flight hardware should substantially reduce cost.

According to Aerospace analyses, reusable launch vehicles that have been optimized for minimum dry mass have staging velocities (that is, the velocity at which the second stage deploys) roughly between Mach 10.5 and 11.5. In this case, the orbiter will be about half the dry mass of the booster. The mass of the reusable launch vehicle will grow steadily as the staging velocity deviates from this range. For example, if the staging velocity grows higher, the booster must be bigger to generate more thrust; if the staging velocity is lower, the upper stage will have to make up the difference to reach orbit. This is the problem faced by single-stage reusable launch vehicles. Single-stage vehicles are not practical without significant advancements in materials and propulsion technologies; however, two-stage vehicles are undeniably feasible, given the state of existing technologies.

A disadvantage of reusable launch vehicles is their relatively high initial costs.

Shuttle depicted for size comparisons only.

| Payload to LEO | Block 1
5,800 kg | Block 2
11,340 kg | Block 3
39,780 kg | Block 4
~72,575 kg |

This is an example of a notional spacelift architecture, designed by Aerospace to support a broad range of payloads, based on derivatives of only two vehicle elements.
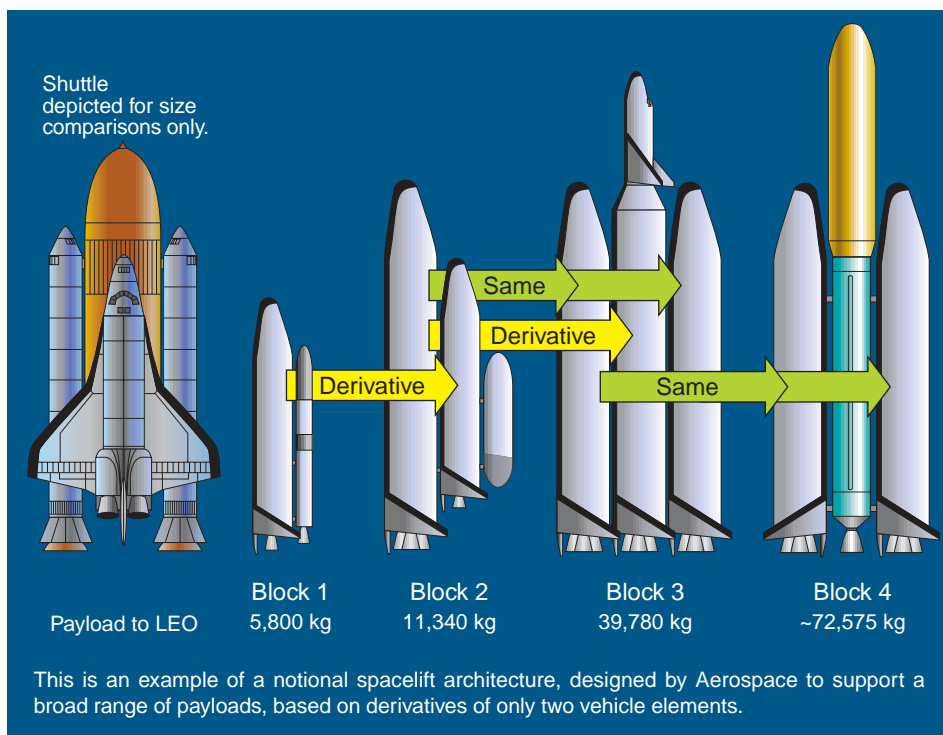
The combined cost of development, facilities, and fleet procurement will reach well into the billions of dollars, even for small fleets. For this reason, it may be impractical to develop completely separate reusable launch vehicle designs for defense, commercial, and civil communities. Rather, it will probably be more affordable to pursue modular development approaches to support the broad community. For example, derivatives of boosters and orbiters could be used in various configurations to support various payload classes. While the derivatives would not be identical to the original vehicles, they would possess common systems and components, thus reducing development and production costs. This commonality would also reduce the operational costs of logistics and sustaining engineering, which are major recurring costs.

Understanding the operability of such a system is crucial, as responsiveness will be the key defining characteristic of the next-generation launch system. Aerospace developed the Operability Design Model to estimate the maintenance and turnaround operations of future reusable launch vehicles. Using this tool, Aerospace determined that a new vehicle could improve operations one to two orders of magnitude compared with the space shuttle simply by implementing improved system designs, process improvements, and cutting-edge technologies.

Even with the industry's best operability analysis tools, experts agree that such estimates carry significant uncertainty. Credible estimates of turnaround time for the next reusable launch vehicle range from 2 to 10 days. This uncertainty is a problem for the Air Force, because it will affect how many vehicles and facilities are needed to accommodate a surge in demand (for example, during wartime). This affects cost sufficiently that the difference between a 2-day and 10-day turnaround may determine the ultimate choice between expendable or reusable launch vehicles.

Estimates of reusable launch vehicle production cost are also uncertain because the only actual data point is the space shuttle. The per-kilogram cost to build each orbiter was twice that of the Air Force's most expensive aircraft, the B-2 bomber. Were this to hold true for the next reusable launch vehicle, production costs would severely limit its affordability. There are, however, rational arguments suggesting the cost will be lower. For example, the shuttle was the first of its kind, and was never optimized to control production cost. The orbiters have life-support systems, and must be built to safeguard the lives of the crew. The shuttle features distributed, rather than modular, subsystems. The shuttle program did not have access to the latest materials and production technologies. All of these problems can be corrected or minimized by using modern designs, technologies, and

production techniques. Nonetheless, a factor-of-two uncertainty in production cost greatly affects the decision on expendable versus reusable launch vehicles.

Air-Breathing Reusable Vehicles

The appeal of air-breathing vehicles is that they get their oxidizer from the atmosphere, rather than carry it with them. Thus, they might, at least in theory, be smaller and less expensive than conventional rockets. Still, some fundamental issues need to be addressed.

For example, air-breathing rockets must sustain combustion at hypersonic speeds while producing positive thrust. This has not been demonstrated, although projections of potential hypersonic performance have been made using computational fluid dynamics models; however, these models must be calibrated with test or flight data to be credible, and wind tunnels cannot produce conditions to simulate hypersonic combustion beyond a fraction of a second.

The thermal environment presents another problem. The hypersonic combustion process generates extreme heat. Extended hypersonic flight within the atmosphere can generate thermal and aerodynamic loading many times greater than that of equivalent conventional rockets. Thus, successful development of hypersonic air-breathing rockets will require highly advanced high-temperature technologies for engines and reusable structural thermal protection.

A further limitation is that runways can support aircraft weighing no more than about 635,000 kilograms. This places a ceiling on the gross weight of air-breathing reusable launch vehicles, all of which must take off horizontally. Relatively small changes in hypersonic performance predictions could cause this runway limit to be exceeded.

Sometimes, the argument is advanced that because air-breathing rockets operate from runways rather than launchpads, their recurring operations costs and timelines will be closer to aircraft costs and timelines; however, good operability stems from several factors, including component accessibility, operating margins, and component design life. To enable robust turnaround, designers must allocate sufficient dry mass and vehicle volume to allow robust subsystems (which are heavier than less robust ones). Whether or not a combination of weight growth and runway limitations would force compromises in operability

and affordability remains an open question.

Thus, when one considers the theoretical nature of performance predictions, the advanced technological requirements, and the challenges for operability, it is clear that air-breathing concepts should be considered high risk well into the future.

Hybrid Vehicles

In its technical leadership role in the Air Force's Operationally Responsive Spacelift effort, Aerospace has also conducted analyses of hybrid reusable-expendable vehicles. These combine reusable boosters with expendable upper stages. The analysis suggests that such vehicles inherit an interesting combination of benefits from both elements.

Assuming optimal staging, at about Mach 7, hybrids expend about 35 percent of the hardware a comparable expendable rocket would expend. Thus, their recurring production costs are much lower. Also, the mass of the reusable booster stage for a hybrid is about 45 percent that of a fully reusable launch vehicle. Thus, development and production costs are significantly less. For these reasons, even relatively low launch rates could economically justify their development.

The hybrid vehicle also carries less risk than a fully reusable launch vehicle—primarily because it does not employ a reusable orbiter. Reusable orbiters present a difficult technical challenge, as they must survive on-orbit operations and reentry through Earth's atmosphere without significant damage. The reusable booster experiences a much less severe environment, resulting in fewer technical challenges and less risk.

Development Strategy

While many development strategies have been considered over the years, the Air Force and NASA both favor an evolutionary approach, focusing on incremental enhancements in capability. Both agencies also agree that ground and flight tests of a demonstration vehicle are critical—to reduce uncertainties regarding achievable production cost and responsiveness, to supply information needed to crystallize a

decision on an objective system, and to provide an affordable flight test bed to demonstrate design features and technologies needed to achieve various future technical objectives.

The hybrid is considered a relatively low-risk first step toward an operationally responsive spacelift capability, one with clear advantages over expendable and reusable launch vehicles. The performance of this hybrid will have far-reaching implications. According to Aerospace analyses, if the cost and responsiveness of the reusable booster turn out to be on the low end of predictions, then the Air Force and NASA might be better off pursuing a fully reusable launch vehicle. If instead middle to high-end predictions are demonstrated, then the Air Force would probably prefer the hybrid configuration.

Clearly, no first step in an evolutionary process can satisfy all the objectives of defense, civil, and commercial sectors. But the evolutionary approach establishes a low-risk process for building upon successes, ultimately supporting most or all spacelift needs. Once a substantial portion of nonrecurring reusable launch vehicle development costs are absorbed, then the recurring costs of operating commercial

reusable launch vehicles could be significantly lower than for modern expendable launch vehicle systems. Thus, development of a reusable launch vehicle system by NASA or DOD would offer opportunities to spin off commercial variants.

Future Technology

Properly focused technology development offers significant potential to increase system performance and reduce recurring cost. In fact, operability analyses performed by Aerospace identified the following technologies as particularly valuable for improving cost and operability in reusable launch vehicles: long-life components, nontoxic reaction-control systems, rugged thermal-protection systems, long-life propulsion systems, and autonomous health monitoring. All of these must be designed, of course, for quick turnaround—measured in hours rather than days or months. The only significant technology hurdle in this regard is the thermal-protection system. The proposed reusable-expendable hybrid demonstrator greatly mitigates this impediment.

The present technology base is adequate to achieve significant improvements in reusable launch vehicle responsiveness (compared with the shuttle). But by implementing an evolutionary development approach, even this capability can be incrementally enhanced via technology insertion at block upgrades. This will require that launch vehicles be designed to facilitate technology upgrades, employing modular systems (as in typical aircraft) rather than distributed systems (as in the shuttle). These are different methods of doing business for the government and for the spacelift industry. Implementation will be thorny—but in the end, it will determine how well risk is controlled and to what extent operability-enabling design features will be incorporated in the next generation of spacelift systems.

Acknowledgements

Modeling Operability

In the late 1980s, the launch community was investigating ways to provide heavy-lift capability with low launch costs and fast responsiveness. To help identify the factors that would achieve these goals, Aerospace developed the Operations Design Model.

Based on detailed studies of U.S. and international launch systems, the Operations Design Model used algorithms to estimate the recurring operations requirements, staffing needs, and cost for any particular expendable launch vehicle design. Inputs to the model included the size and mass of the vehicle, the kinds of subsystems involved, the safety factors to be implemented, planned level of certification testing, and other parameters related to design and development. The introduction of the model helped replace the "soft" analyses that were typical of the time with a more scientifically based methodology.

Later, during the National Aerospace Plane program, the Operations Design Model was upgraded to make estimates for reusable launch systems. Many in the program believed that because the plane would be a one-stage, runway-based vehicle that used air-breathing engines, it would have short turnaround times and relatively little maintenance between flights—similar to airliners or jet fighters. In fact, the Operations Design Model demonstrated that factors such as operating margins, thoroughness of certification testing, and technology maturity were far more significant than vehicle configuration and take-off mode.

The Operations Design Model has since become a critical piece of Aerospace's launch vehicle design methodology and was most recently used in the Operationally Responsive Spacelift Analysis of Alternatives for Air Force Space Command.

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Patents

W. F. Buell et al., "Method and System for Processing Laser Vibrometry Data Employing Bayesian Statistical Processing Techniques," U.S. Patent No. 6,672,167, Jan. 2003.

Developed as an alternative to FM-discriminator, spectrogram processing, and time-frequency techniques, a Bayesian statistical data-processing method improves the performance of laser vibrometry systems, which are used for noncontact measurement of an object's vibration. The method employs a statistical (Bayesian) signal-processing technique to process one or more mathematical models of an object's vibration along with laser vibrometry and other prior data for a system under observation. The method exhibits significantly improved performance in determining vibrational frequency, particularly when measurement time is limited to a few vibrational cycles. An iterative procedure then produces the full vibrational spectrum of the object under observation.

C. M. Heatwole, L. K. Herman, G. M. Manke, B. T. Hamada, "Fault Detection Pseudo Gyro," U.S. Patent No. 6,681,182, Jan. 2003.

Designed to improve the reliability and lifetime of flight systems, a software "pseudo gyro" can help detect failures in hardware gyros. The pseudo gyro operates as part of the attitude control and reference system. It provides accurate relative vehicular position and angular velocity by analyzing external torques and computing the momentum transfer between the satellite bus and its appendages. It can be used to monitor the performance of any number of hardware gyros, providing on-orbit checks of functionality and performance. It can identify gyros with anomalous performance and track long-term performance trends. It can identify anomalous performance in the hardware used to generate data for computation, such as stepper motors, encoders, angular-orientation sensors, tachometers, and reaction wheels. When used to supplement an attitude control system, the pseudo gyro enables higher reliability, longer service life, lower power consumption, and more accurate angular velocity rates within high-bandwidth operations

T. M. Nguyen, J. Yoh, C. C. Wang, D. M. Johnson, "High-Power Amplifier Predistorter System," U.S. Patent No. 6,680,648, Jan. 2003.

An adaptive system distorts an input signal before high-power amplification to compensate for undesired amplitude and phase distortion while reducing spectral regrowth. The predistortion ensures that the signal, when amplified, will maintain the same power spectrum after baseband filtering. Based on closed-loop feedback of the amplifier output, the system can change the amount of signal distortion and thus can linearize the output of a high-power amplifier having variable or unknown characteristics. The feedback is used to gauge the input and output signals in a complex form and at baseband. The adaptive predistortion processing algorithm can be implemented onboard a satellite.

G. E. Peterson, "Method and System for Controlling the Eccentricity of a Near-Circular Orbit," U.S. Patent No. 6,672,542, Jan. 2003.

This patent describes an efficient method for nudging a low Earth satellite into a "frozen" orbit—that is, an orbit that maintains the same perigee location in inertial space with nonvarying eccentricity. Frozen orbits facilitate satellite-to-satellite linkage, altimetry control, and collision avoidance. Changes in eccentricity are achieved through controlled burns at either the apogee or perigee of the orbit, depending upon the satellite's location. Burn targeting can be implemented, for example, via a controller that executes a stationkeeping algorithm that uses along-track burns to slowly change the eccentricity. These burns are conducted in concert with the normal along-track burns necessary to compensate for the effects of drag. Thus, the change in eccentricity is achieved without interfering with mission operations and without consuming additional fuel.

J. J. Poklemba, G. S. Mitchell, "Quadrature Vestigial Sideband Digital Communications Method," U.S. Patent No. 6,606,010, Aug. 2003.

A new communications technique known as quadrature vestigial sideband (QVSB) signaling makes more efficient use of bandwidth in transmitting digital data. When compared with conventional transmission formats, the QVSB technique can achieve twice the throughput capacity with relatively little degradation in the signal-to-noise ratio. This modulation scheme achieves its improved spectral occupancy by placing overlapping independent data streams on each of two quadrature carriers. This form of cross-coupled data signaling is akin to transmission with a controlled form of intersymbol interference. A quadrature-crosstalk, maximum-likelihood-sequence estimator implements a Viterbi decoding algorithm to unravel the intersymbol interference and provide estimated data sequence outputs with a low bit-error ratio. The receiver is a coherently aided demodulator structure, whose time- and phase-reference synchronization loops are aided by the data sequence output estimates.

E. Y. Robinson, "Spacecraft for Removal of Space Orbital Debris," U.S. Patent No. 6,655,637, Dec. 2003.

A spacecraft equipped with a grabbing mechanism can capture a piece of orbiting debris and remove it from orbit. The grabber uses inflatable articulating fingers that extend in various directions. Motors control tension lines that extend through loops in the fingers, pulling and releasing them as required to bend and secure them around the target object. An inflatable sphere or other high-drag device is then deployed to increase drag on an object in low Earth orbit, thereby pulling it slowly down into the atmosphere where it will burn up. For objects in upper orbits, this inflatable sphere can serve as a solar wind collector to gradually push them into disposal orbits; onboard thrusters can also be used for orbit removal and transfer of the object to the super synch galactic necropolis. The debris-removal spacecraft includes conventional components such as ranging sensors, navigation processors, and propulsion systems. It can be used as a single autonomous unit or bundled with others to remove multiple objects from orbit. This deorbit technique offers a simple alternative for attaching propulsion and guidance systems to space debris.

J. S. Swenson and R. C. Cole, "Method of Forming Patterned Metalization on Patterned Semiconductor Wafers," U.S. Patent No. 6,677,227, Jan. 2003.

Using standard processes, this method creates metalized via connections between semiconductor microcircuits and microelectromechanical systems (MEMS). It offers a process bridge between substrates containing CMOS devices and overlying MEMS and chemical sensor layers using foundry-incompatible materials. The CMOS wafer can have large-diameter and small features typical of foundries, but a MEMS shop doing this metalization does not need commensurate lithography equipment. An example starts with a CMOS wafer, with vias newly etched through the last insulation layer. New photoresist is developed away at vias and where wires are desired. Gold is deposited, with good step coverage. A thick planarization layer is spun on and etched back until only dimples remain filled. Etching removes the gold, except under the remaining planarization at vias and wires. The planarization and photoresist are then stripped away.

Contributors

### That's Why They Call It Rocket Science

Edward Ruth is Systems Director in the Space Launch Support Division with responsibility for Aerospace's civil and commercial space launch systems work. He has more than 20 years of experience in the development and operation of launch vehicles and their ground support systems, including the Atlas, Delta, Sea Launch, Kistler, Space Access, Pegasus, space shuttle, Taurus, Titan, Ariane 5, Proton, and H-IIA launch systems. His current focus is on supporting NASA's Safety Health and Independent Assessment organization in independent reviews of expendable launch vehicles. He has a Ph.D. in Aeronautics from the California Institute of Technology. He joined Aerospace in 1980 (edward.k.ruth@aero.org).

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Loads Analysis for National Security Space Missions
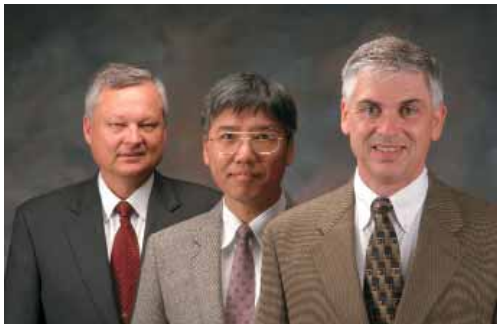
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Mitigating Pogo on Liquid-Fueled Rockets

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Nick Bletsos is Director of the Guidance Analysis Department in the Guidance and Control Subdivision, which focuses on all aspects of guidance, navigation, and control of launch vehicles. Bletsos joined Aerospace in 1979 to serve in the Guidance Analysis Department and later became Section Manager, Launch Vehicle Guidance and Control. He has led guidance and navigation studies and performance validation studies on several launch vehicle families. He holds a Ph.D. in Aerospace Engineering from the University of Michigan (nikolas.a.bletsos@aero.org).

EELV: The Next Stage of Space Launch

Randy L. Kendall, Principal Director, Mission Integration and Systems Engineering, Evolved Expendable Launch Vehicle (EELV) Division, is responsible for management and technical leadership of mission management and systems analysis on EELV. Core duties include synthesizing system and mission requirements, integrating system-level and mission-specific verification analyses, and guiding source selection planning and proposal evaluation for future EELV launch service acquisitions. He has been with Aerospace since 1988 and supported a variety of launch vehicle and spacecraft programs before joining EELV in 1997. He holds an M.S. in Aerospace Engineering from the University of Michigan and an MBA from California State University, Long Beach (randy.l.kendall@aero.org).

Future Launch Systems

Joseph Adams (left), Senior Project Leader in the Developmental Planning Directorate, provides expertise in the area of launch system operations and development. During his 17 years with Aerospace, he has assisted the development of launch system operability modeling and analysis techniques, databases, and technology evaluations. In various capacities, he has worked on every Air Force and NASA launch system and every new and experimental launch system development program, including the space shuttle, ALS, NASP, EELV, DC-X, X-33, X-38, and X-37 (joseph.d.adams@aero.org). **Robert Hickman** (right) is Director of the Advanced Spacelift and Force Application Directorate. He joined Aerospace in 1987 and has pioneered the development of system engineering tools to support the development of launch systems as well as analysis of integrated architecture systems. During the past four years, he has been the technical lead for Air Force advanced launch vehicle development and currently serves as the engineering lead for the Operationally Responsive Spacelift Analysis of Alternatives. He has an M.S. in Architecture and Systems Engineering from the University of Southern California. He is a member of the AIAA RLV program committee (robert.a.hickman@aero.org).
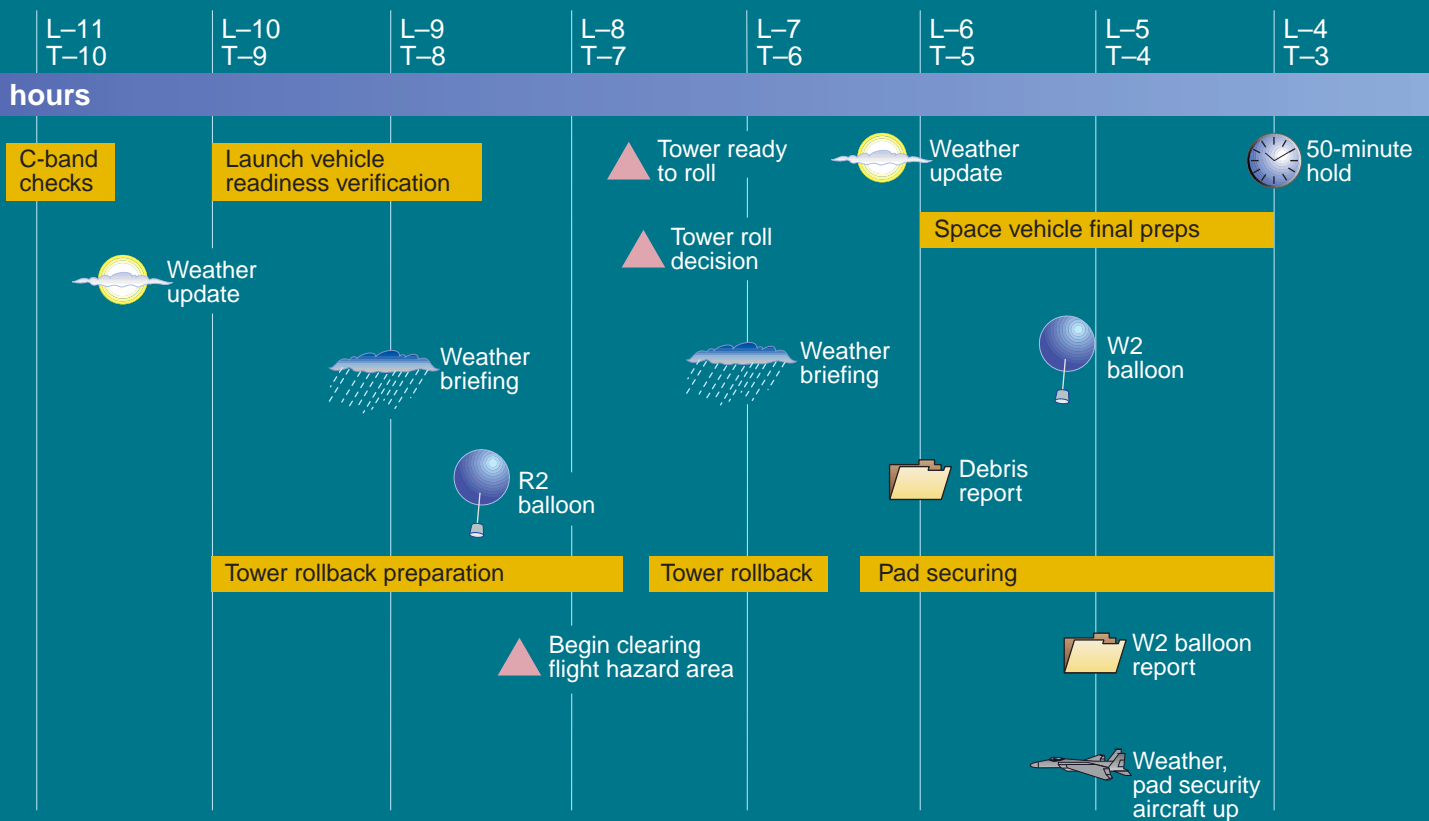
The *Crosslink* editorial staff.
From left to right:
Steven R. Strom, Donna Born,
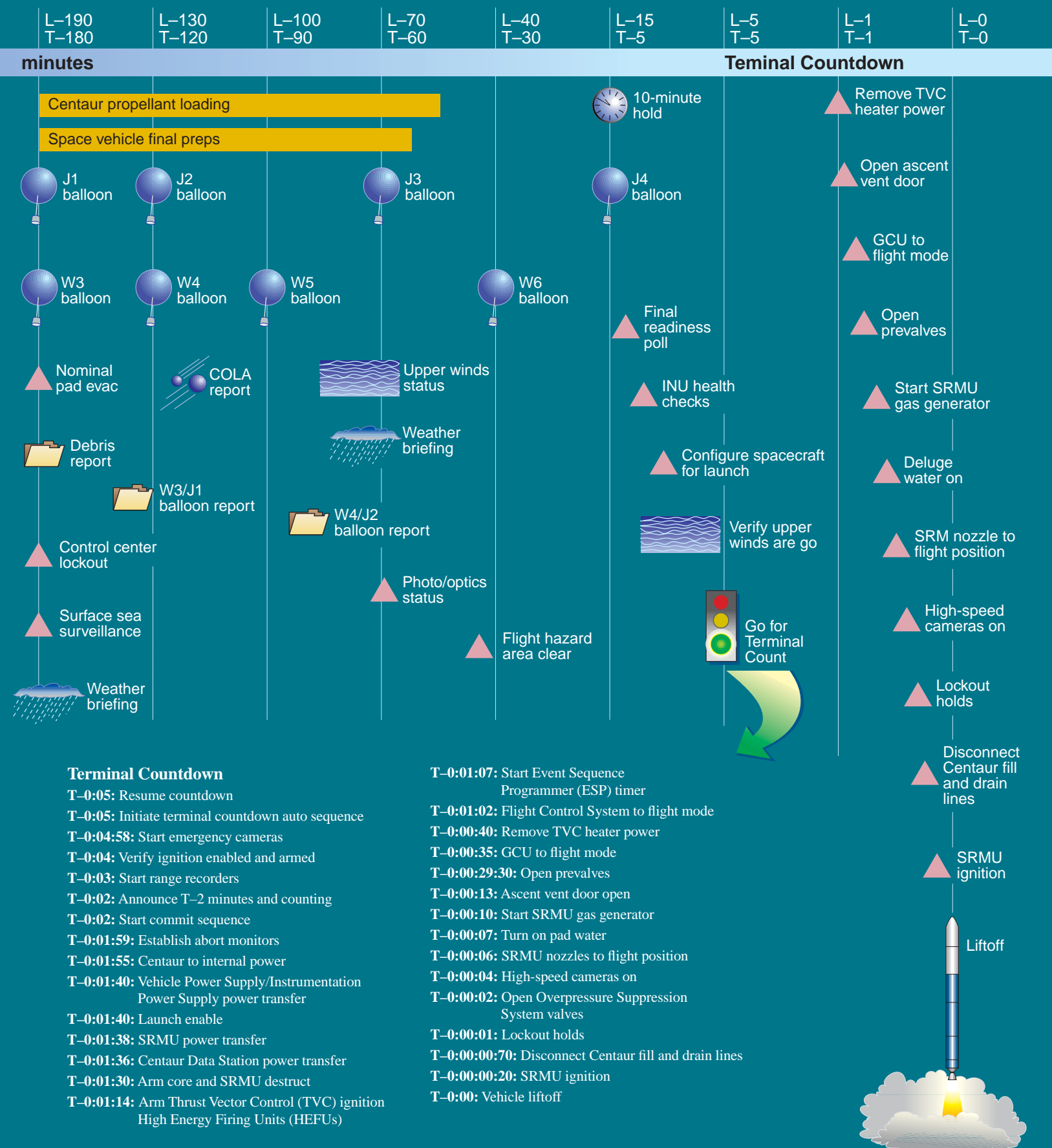Jon Bach, Gabriel Spera

L–11 T–10	L–10 T–9	L–9 T–8	L–8 T–7	L–7 T–6	L–6 T–5	L–5 T–4	L–4 T–3

hours

C-band checks

Launch vehicle readiness verification

Tower ready to roll

Weather update

50-minute hold

Weather update

Tower roll decision

Space vehicle final preps

Weather briefing

Weather briefing

W2 balloon

R2 balloon

Debris report

Tower rollback preparation

Tower rollback

Pad securing

Begin clearing flight hazard area

W2 balloon report

Weather, pad security aircraft up

This chart depicts the major launch countdown events for launching a Titan IV with a Centaur upper stage. The countdown is divided into phases and tasks but controlled by a single launch countdown procedure. The countdown begins with launch status preparations and includes manual activities and an automatic launch sequence. Countdown operations begin at L–26 hours; however, the final countdown begins at T–780. The countdown clock refers to two times, L-time and T-time. L-time shows the actual time remaining to launch, while T-time takes into account preplanned holds. Weather balloons are released periodically to measure winds in the upper atmosphere. Terminal Countdown starts at T–5 minutes. During this phase, control is transferred to the launch control computer.

T–25: 00: Countdown initiation
T–24: 55: Launch vehicle power on
T–22: 30: SRMU and core vehicle safing-pin removal
T–20: 30: Guidance nulls and gains
T–15: 30: Core vehicle pressure adjust
T–14: 00: Begin final closeout
T–13: 05: Comm checks and poll
T–13: 00: Final countdown initiation
T–12: 25: Range holdfire checks
T–10: 20: C-band open-loop checks
T–9: 50: Tower roll preparations begin
T–9: 50: Launch vehicle readiness begin
T–7: 50: Launch vehicle readiness complete
T–6: 50: Guidance Control Unit (GCU) to alignment begin
T–6: 35: Tower roll preparations complete
T–6: 35: Tower rollback begin
T–5: 40: GCU to alignment complete
T–5: 25: Tower rollback complete

T–5: 25: Tower securing and complex evacuation begin
T–3: 00: Pad securing and complex evacuation complete
T–3: 00: Planned 50 minute hold
T–3: 00: Centaur propellant loading begin
T–1: 13: Centaur liquid oxygen at 100 percent
T–0: 45: Centaur liquid hydrogen at 100 percent
T–0: 45: Range flight termination checks complete
T–0: 40: Final command receiver decoder checks
T–0: 10: Core pressurized to flight pressure
T–0: 10: Load countdown abort sequence
T–0: 09: Verify pulse beacon system on
T–0: 09: Programmable Aerospace Ground Equipment refresh and hardline TM monitor
T–0: 05: Planned 10 minute hold
T–0: 05: Load countdown sequence
T–0: 05: Winds update complete
T–0: 05: Inertial Navigation Unit health checks
T–0: 05: Readiness poll

L–190 T–180	L–130 T–120	L–100 T–90	L–70 T–60	L–40 T–30	L–15 T–5	L–5 T–5	L–1 T–1	L–0 T–0

minutes   **Teminal Countdown**

Centaur propellant loading

Space vehicle final preps

J1 balloon

J2 balloon

J3 balloon

J4 balloon

10-minute hold

Remove TVC heater power

W3 balloon

W4 balloon

W5 balloon

W6 balloon

Open ascent vent door

GCU to flight mode

Nominal pad evac

COLA report

Upper winds status

Final readiness poll

Open prevalves

Debris report

Weather briefing

INU health checks

Start SRMU gas generator

W3/J1 balloon report

Configure spacecraft for launch

Deluge water on

Control center lockout

W4/J2 balloon report

Verify upper winds are go

SRM nozzle to flight position

Surface sea surveillance

Photo/optics status

High-speed cameras on

Go for Terminal Count

Flight hazard area clear

Weather briefing

Lockout holds

Disconnect Centaur fill and drain lines

SRMU ignition

Liftoff

Terminal Countdown

T–0:05: Resume countdown

T–0:05: Initiate terminal countdown auto sequence

T–0:04:58: Start emergency cameras

T–0:04: Verify ignition enabled and armed

T–0:03: Start range recorders

T–0:02: Announce T–2 minutes and counting

T–0:02: Start commit sequence

T–0:01:59: Establish abort monitors

T–0:01:55: Centaur to internal power

T–0:01:40: Vehicle Power Supply/Instrumentation Power Supply power transfer

T–0:01:40: Launch enable

T–0:01:38: SRMU power transfer

T–0:01:36: Centaur Data Station power transfer

T–0:01:30: Arm core and SRMU destruct

T–0:01:14: Arm Thrust Vector Control (TVC) ignition High Energy Firing Units (HEFUs)

T–0:01:07: Start Event Sequence Programmer (ESP) timer

T–0:01:02: Flight Control System to flight mode

T–0:00:40: Remove TVC heater power

T–0:00:35: GCU to flight mode

T–0:00:29:30: Open prevalves

T–0:00:13: Ascent vent door open

T–0:00:10: Start SRMU gas generator

T–0:00:07: Turn on pad water

T–0:00:06: SRMU nozzles to flight position

T–0:00:04: High-speed cameras on

T–0:00:02: Open Overpressure Suppression System valves

T–0:00:01: Lockout holds

T–0:00:00:70: Disconnect Centaur fill and drain lines

T–0:00:00:20: SRMU ignition

T–0:00: Vehicle liftoff

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