History of Rocketry and Astronautics

Proceedings of the Thirty-Fourth History Symposium of the International Academy of Astronautics

Rio de Janeiro, Brazil, 2000

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AAS History Series, Volume 30

A Supplement to Advances in the Astronautical Sciences

IAA History Symposia, Volume 20

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 2009

ISSN 0730-3564

ISBN 978-0-87703-549-7 (Hard Cover)
ISBN 978-0-87703-550-3 (Soft Cover)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

Chapter 7

Between a Rocket and a Hard Place: Episodes in the Evolution of Launch Vehicle Technology*

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Introduction

After four decades of effort, access to space remains a difficult challenge in the year 2000. While space transport services should not be measured by terrestrial standards, if the grand plans of space visionaries and entrepreneurs are to be carried out, there is a real need to move beyond currently available technologies. Unfortunately, the high cost associated with space launch from 1950–2000 has demonstrated the slowest rate of improvement of all space technologies. Everyone in space activities shares a responsibility for addressing this critical technical problem. The overwhelming influence that space access has on all aspects of civil, commercial, and military space efforts indicate that it should enjoy a top priority.[1]

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* Presented at the Thirty-Fourth Symposium of the International Academy of Astronautics, Rio de Janeiro, Brazil, 2000. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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Of course, a key element in the spacefaring vision long held in the United States is the belief that inexpensive, reliable, safe, and easy spaceflight is attainable. Indeed, from virtually the beginning of the 20th century, those interested in the human exploration of space have viewed as central to that endeavor the development of vehicles of flight that travel easily to and from Earth-orbit. The more technically-minded recognized that once humans had achieved Earth-orbit about 200 miles up, the vast majority of the atmosphere and the gravity well had been conquered and that people were about halfway to anywhere they might want to go.[2]

It seems appropriate to break down the development of launch vehicles into six major time periods, each characterized by specific technological challenges, political and economic environments, design priorities, mission objectives, and legacies and lessons (Figure 1). The discussion that follows traces this evolutionary process and offers observations about key issues affecting the process of technological innovation to the present.

Figure 1

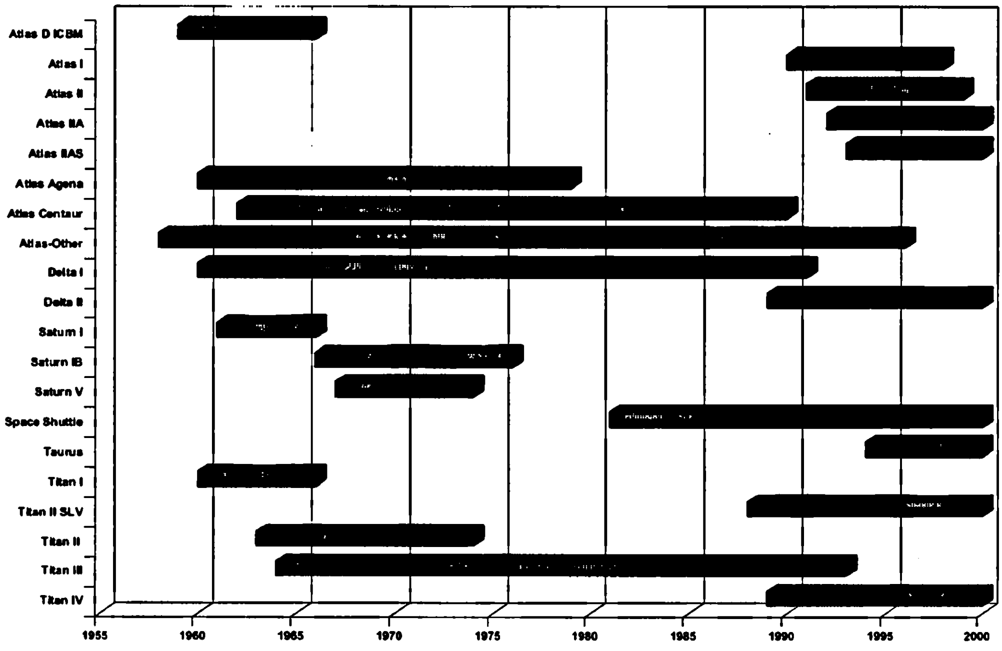
Time Period	Political/ Economic Environment	Mission Objectives	Technological Challenges	Design Parameters	Lessons and Legacies
Cold War Origins (1948–1956)	Cold War begins; Soviet Union viewed as technologically aggressive; crash rocket programs emerge; U.S. economy stable	Intercontinental ballistic missiles (ICBMs); spy satellites; scientific satellites; early warning	Everything; is flight in space even possible?; long-range rockets; satellites; guidance and control	Big, dumb boosters; thrust enhancement; launch reliability poor	Program management concept; large-scale approach; funding no obstacle
Height of Cold War (1957–1965)	Cold War heightens; funding increases; economy thrives in 1960s; head-to-head space race; sense that Soviet Union leads world	ICBM operations; ICBMs used for piloted flight; reductions of costs; long-duration missions; lunar exploration	Improved reliability and schedule; concentration on miniaturization; sustained long-duration operations; Apollo	Studies of reusability; greater reliability; increased time for operations	Validation of program management concept; large-scale funding investment

Cold War Confrontation Wanes (1966–1972)	Cold War moderates; sense that United States ahead in space race; Apollo continues; U.S. economy expands; Vietnam sours U.S. public on government activities	Little impetus for new military launchers; early warning system developed	Improved reliability and schedule; sustained long-duration operations; Apollo; continued miniaturization	Incremental reduction of cost and reliability of launch schedules	Continued validation of program management concept; large-scale funding investment
Visions of Routine Access to Space (1972–1985)	Space as U.S. province; Americans voice little concern for space issues; U.S. economy stagflates; little concern for Soviets	Emphasis on multiple payloads with launcher; make space transportation like aviation; cost reduction major emphasis	Reusability, single stage to orbit (SSTO), reduction of cost of access; continued miniaturization	Entirely new generation of launchers, older systems abandoned	Replacement of program management concept in favor of lead center approach; attempted standardization of all U.S. payloads for flight on Shuttle; attempted abandonment of all expendable launch vehicles (ELV)
Assuring Access to Space (1986–1989)	*Challenger* accident discredits NASA; ELVs reemerge; commercial markets emerge; U.S. deficit rages; Soviet Union collapses; Strategic Defense Initiative; loss of market to Ariane	Emphasis on multiple payloads with launchers; new ELV concepts; new military missions	Reusability; SSTO reemerges; reduction of cost of access; continued miniaturization	ELVs make incremental improvements and seek commercial payloads	Space access to be like aviation; spaceflight must pay; NASA less powerful, no longer can dictate policy
Commercial Space Access Begins (1990–2000)	Space viewed largely as marketplace; reevaluation of future military concerns about use of space	Emphasis on multiple payloads with launcher	Reusability, SSTO, reduction of cost of access; continued miniaturization; nanotechnology	Develop evolved EELVs, SSTOs	Commercial payoffs difficult; space access not self-supporting

Cold War Origins

The primary U.S. space launch capabilities were created only because of the challenge of an exceptionally desperate Cold War rivalry with the Soviet Union. Accordingly, the development and deployment of ballistic missiles, space-based intelligence-gathering capabilities, and the orbiting of scientific satellites into space were all critical to ensuring the national security of the United States (Figure 2).[3]

Figure 2: U.S. Launch Vehicles 1955–2000.



For the first eight years of the space age, the U.S. space effort operated and evolved in response to consistently focused governmental policy with the highest national priority. Then, the focus was on test and evaluation of ICBMs and on developing these systems into space launch vehicles, primarily to support the reconnaissance mission operated from Vandenberg Air Force Base (AFB) on the West Coast and the robotic spaceflight mission operated from Cape Canaveral on the East Coast. The initial development, test, and evaluation of ballistic missiles also drove the development for extensive tracking, telemetry collection, and precise photographic capabilities.

During this earliest period the United States began developing the principal launchers—the Atlas, Delta, and Titan—that are still in use. It is hard to believe in the year 2000, but the United States still relies on the descendants of these three ballistic missiles for the bulk of its space access requirements. Even though the three families of space boosters—each with numerous variants—have enjoyed incremental improvement since first flight, there seems no way to escape their beginnings in technology (dating back to the early 1950s) and their primary task of launching nuclear warheads.

The first-generation ICBM, the Atlas, was flight tested beginning 11 June 1955, and made operational in 1959. A second ballistic missile, the Thor, also dates from the 1950s, and under the name Delta, became an early workhorse in America's fleet of launchers. The Titan ICBM quickly followed the Atlas and Thor into service with the U.S. Air Force (USAF) in 1959 and remained on alert until the end of the Cold War at the end of the 1980s.[4]

Since these space launch vehicles began existence as national defense assets, they reflected both the benefits and liabilities of those origins. For example, the national defense requirements prompted the developers to emphasize development schedule and operational reliability over launch costs. Consequently, these vehicles were exceptionally costly both to develop and operate.

Indeed, the Dwight Eisenhower presidential administration poured enormous resources into the development of these first generation space access vehicles. As a measure of government investment, through fiscal year 1957, the government spent $11.8 billion on military space activities in 1957 dollars. "The cost of continuing these programs from FY 1957 through FY 1963," Eisenhower was told, "would amount to approximately $36.1 billion, for a grand total of $47 billion."[5]

In 1997 dollars, for comparison, this would have represented an investment of more than $228 billion. An investment of even 25 percent of that amount today would make possible an enormous advance of launch vehicle technology.

The Height of Cold War

The period between 1957 and 1965 might best be viewed as the height of the Cold War era and the age of the great race for space. Engaged in a broad contest over the ideologies and allegiances of the non-aligned nations of the world, space exploration was one major area contested. The Soviet Union gained the upper hand in this competition on 4 October 1957 when it launched *Sputnik 1*, the first artificial satellite to orbit Earth as part of a larger scientific effort associated with the International Geophysical Year.[6] The Soviet Union did not relinquish its apparent lead in the space race until the mid-1960s.

At the same time that the United States seemed incapable of conducting space operations effectively—notably during the failed launch of the Vanguard satellite on national television on 6 December 1957—the Soviet Union seemed to enjoy every success.

At the same time, successes in space fostered hubris within the Soviet Union not seen since the end of World War II in 1945 and never to be experienced again in that empire's history. It represented a high-water mark of success and Nikita Khrushchev's leadership exploited it to the fullest for the next decade. Thereafter, with high priorities given the effort by the Soviet leadership, the communist state's rocketeers led the way in one stunning success after another, as shown in Figure 3.

Figure 3: Soviet Firsts in Space, 1957–1965
The first living thing in orbit, the dog Laika, launched on *Sputnik 2* on 3 November 1957.
The first human-made object to escape Earth's gravity and be placed in orbit around the Sun, *Luna 1,* in January 1959.
The first clear images of the Moon's surface in September 1959 from *Luna 2.*
The first pictures of the far side of the Moon, October 1959, taken by the Soviet Union's *Luna 3.*
The first return of living creatures from orbital flight, two dogs sent into space by the Soviet Union in August 1960 aboard *Sputnik 5.*
The first human in space, Soviet Cosmonaut Yuri Gagarin, who flew a one-orbit mission aboard the spacecraft *Vostok 1* on 12 April 1961.
The first day-long human space flight mission, August 1961, made by *Vostok 2* with Cosmonaut Gherman Titov aboard.
The first long duration spaceflight, Cosmonaut Andrian Nicolayev spent four days in space aboard *Vostok 3,* August 1962.
The first woman in space, Soviet Cosmonaut Valentina Tereshkova, flew 48 orbits aboard *Vostok 6* in June 1963.
The first multi-person mission into space, *Voskhod 1*, carrying Cosmonauts Vladimir Komarov, Boris Yegorov, and Konstantin Feoktistov in October 1964.
The first spacewalk or extravehicular activity, March 1965, by Alexei Leonov during the *Voskhod 2* mission.

In those first 8 years of the space age, it looked as if the Soviet Union did everything right in space flight, and the United States appeared at best a weakling without the kind of capabilities that the command economy of the "workers' state" in the Soviet Union had been able to muster. The result was that the United States mobilized to "catch up" to the apparent might of its Cold War rival. As surely as the several crises in Berlin—the blockade and airlift, the wall—and the other flashpoints of competition, Sputnik served to fuel the antagonism and steel the resolve of both sides in the Cold War.[7]

Without question, notwithstanding genuine accomplishments in space by the United States, during those first years the Soviet Union held the edge. And it was Soviet rocket technology that allowed that to be the case. The large ICBM built by Sergei Korolev, the R-7, enabled the access to space so necessary to the long list of firsts piled up by the Soviet Union between 1957 and 1965.[8]

The United States worked hard to catch up to the Soviet Union in launcher technology during that period, and they did so by building on the ballistic missile accomplishments of the 1950s. As an example, combined with the Agena upper stage, last launched in 1967, the Atlas propelled some of the earliest space probes, such as Mariner and Ranger to the Moon and Mars. Another variant, the Atlas-Centaur, first flew in 1962 and underwent incremental improvements thereafter. It launched many of NASA's space probes to the planets and also launched numerous military and communications satellites.

For the first U.S. effort to orbit humans, Project Mercury, NASA also employed a modified Atlas rocket. But this decision was not without controversy. There were technical difficulties to be overcome in mating it to the Mercury capsule to be sure, but the biggest complication was a debate among NASA engineers about its propriety for human spaceflight.[9]

Most of the problems were resolved by the first successful orbital flight of an unoccupied Mercury–Atlas combination in September 1961. On 29 November the final test flight took place, this time with the chimpanzee Enos occupying the capsule for a two-orbit ride before being successfully recovered in an ocean landing. Not until 20 February 1962, however, could NASA get ready for an orbital flight with an astronaut. On that date John Glenn became the first American to circle Earth, making three orbits in the *Friendship 7* Mercury spacecraft. The flight had difficulties, and Glenn flew parts of the last two orbits manually because of an autopilot failure, and left his normally jettisoned retrorocket pack attached to his capsule during reentry because of the possibility of a loose heat shield.[10]

A second ballistic missile, the Delta, also became a workhorse in America's fleet of launchers. From 1960 to 1982 Delta underwent incremental improvements resulting in 34 separate configurations. The Titan ICBM, like Atlas and Delta, also underwent successive improvement during this era and was used to launch successive scientific, military, and a few commercial payloads.

The United States also undertook development of an entirely new space launch vehicle, the Saturn. NASA had inherited the effort to develop the Saturn family of boosters in 1960 when it acquired the Army Ballistic Missile Agency under Wernher von Braun.[11] By that time von Braun's engineers were hard at work on the first generation Saturn launch vehicle, a cluster of eight Redstone boosters around a Jupiter fuel tank. Fueled by a combination of liquid oxygen (LOX) and RP-1 (a version of kerosene), the Saturn I could generate a thrust of 205,000 pounds. This group also worked on a second stage that used a revolutionary fuel mixture of LOX and liquid hydrogen that could generate a greater ratio of thrust to weight. The fuel choice made this second stage a difficult development effort, because the mixture was highly volatile and could not be readily handled. But the stage could produce an additional 90,000 pounds of thrust. The Saturn I was solely a research-and-development vehicle that would lead toward the accomplishment of Apollo, making ten flights between October 1961 and July 1965. The first four flights tested the first stage, but beginning with the fifth launch the second stage was active and these missions were used to place scientific payloads and Apollo test capsules into orbit.[12] The next step in Saturn development came with the maturation of the Saturn IB, an upgraded version of earlier vehicle, and the mighty Saturn V Moon rocket developed in the latter half of the 1960s.

Cold War Confrontation Wanes

About 1965 the Cold War began to wane as a powerful motivator behind space activities. From the point where America began flying the Gemini spacecraft, and especially with the flights of Apollo (1968–1972), it became obvious that the United States led the world in rocket technology. Accordingly, the space race began to wane during that era, as the nation was consumed with issues other than crises with the Soviet Union, especially as it focused on the war in Vietnam.

Gemini had been conceived as a means of bridging the gap between the technological base required to land successfully on the Moon and that already in existence. NASA closed most of the gap by experimenting and training on the ground, but some issues required experience in space. Three major areas immediately arose where this was the case. The first was the ability in space to locate, maneuver toward, and rendezvous and dock with another spacecraft. The second was closely related, the ability of astronauts to work outside a spacecraft. The third involved the collection of more sophisticated physiological data about the human response to extended spaceflight.[13]

To gain experience in these areas before Apollo could be readied for flight, NASA devised Project Gemini. The two-person capsule was to be powered by the newly developed Titan II, another ballistic missile developed for the USAF. The Titan II proved difficult; it had longitudinal oscillations called the "pogo" effect because it resembled the behavior of a child on a pogo stick. Overcoming this problem required engineering imagination and long hours of overtime to stabilize fuel flow and maintain vehicle control. The fuel cells leaked and had to be redesigned, and an Agena target vehicle used for docking suffered costly delays. All of these difficulties shot an estimated $350 million program to more than $1 billion. The overruns were successfully justified by the space agency, however, as necessary in meeting the Apollo landing commitment.[14]

By the end of 1963 most of the difficulties with the Titan II had been resolved, albeit at great expense, and the program was ready for flight. Following two unoccupied orbital test flights, the first operational mission took place on 23 March 1965. Mercury astronaut Grissom commanded the mission with John W. Young, a Navy aviator chosen as an astronaut in 1962, accompanying him. The next mission, flown in June 1965, stayed aloft for four days and astronaut Edward H. White II performed the first U.S. extravehicular activity (EVA) or spacewalk.[15] Eight more missions followed through November 1966.[16]

If Gemini failed to convince anyone that the space race had been won by the United States, Apollo would. Using the Saturn IB, with more powerful engines generating 1.6 million pounds of thrust from the first stage, the two-stage combination could place 62,000-pound payloads into Earth orbit. The first flight on 26 February 1966 tested the capability of the booster and the Apollo capsule in a suborbital flight. Two more flights followed in quick succession. The first astronaut-occupied flight of the Saturn IB took place between 11 and 22 October 1968 when Walter Schirra, Donn F. Eisele, and R. Walter Cunningham made 163 orbits testing Apollo equipment.[17] Three more Saturn IB flights lofted astronauts to the Skylab orbital workshop in 1973–1974.

The penultimate launch vehicle of this family, the Saturn V, represented the culmination of those earlier booster development programs. Standing 363 feet tall, with three stages, this was the vehicle that could take astronauts to the Moon and return them safely to Earth. The first stage generated 7.5 million pounds of thrust from five massive engines developed for the system. These engines, known as the F-1, were some of the most significant engineering accomplishments of the program, requiring the development of new alloys and different construction techniques to withstand the extreme heat and shock of firing. The thunderous sound of the first static test of this stage, taking place at Huntsville, Alabama, on 16 April 1965, brought home to many that the John F. Kennedy goal was within technological grasp. For others, it signaled the magic of technological effort; one engineer even characterized rocket engine technology as a "black art" without rational principles.

The second stage presented enormous challenges to NASA engineers and nearly caused the lunar landing goal to be missed. Consisting of five engines burning LOX and liquid hydrogen, this stage could deliver 1 million pounds of thrust. It was always behind schedule and required constant attention and additional funding to ensure completion by the deadline for a lunar landing. Both the first and third stages of this Saturn vehicle development program moved forward relatively smoothly. (The third stage was an enlarged and improved version of the IB and had few developmental complications.)[18]

But even as the Apollo program achieved success, the NASA administrator terminated the Saturn V production line. With no large-scale space exploration programs envisioned beyond Apollo, there were no new missions requiring the booster's power. NASA's original order was for 15 Saturn V rockets. As early as 1968, the agency faced the issue of whether it would need more Saturn Vs, and decided to wait before ordering the long-lead-time components involved. In struggling in 1971 and 1972 to obtain approval to develop a new space transportation system, the Space Shuttle, NASA officials reluctantly decided that they had no choice but to give up hopes of preserving the two remaining Saturn V boosters for future use and of maintaining production capabilities for additional vehicles. NASA thereby took the action to end the Saturn family's production.[19]

At the same time, the American government sponsored continued maturation of the Atlas, Titan, and Delta launchers, but most of the payloads continued to support official operations. Movement beyond these first-generation launchers has remained a dream in the opening of space access to wider operations. Like the earlier experience with propeller-driven aircraft, the United States has sponsored incremental improvement of launchers for the last 40 years without making a major breakthrough in technology. Accordingly, America today has an efficient and mature expendable launch vehicle (ELV) launch capability that is still unable to overcome the limitations of the first generation ICBMs on which it is based. After more than four decades of effort, access to space remains a difficult challenge.

Visions of Routine Access to Space

In 1972, with the completion of the Apollo program, President Richard Nixon acquiesced in the decision to build the Space Shuttle, a partially reusable launch vehicle that sought to achieve the long-held vision of routine, reliable, low-cost U.S. access to space. This represented a major shift in the national priority for access to space: no longer would the United States be relying on ELVs based on original ICBM designs for most of its space access requirements. Instead the new national priority between 1972 and 1985 was to develop and operate the partially reusable Space Shuttle as the primary U.S. means of placing national security, civil, and commercial satellites into space.[20]

In 1972 NASA promoted to President Richard M. Nixon and the American people the idea of a reusable Space Shuttle as a means of reducing the cost to orbit. To conduct an aggressive space exploration effort, NASA officials declared in 1972, "efficient transportation to and from the earth is required." This could be best provided, they believed, with "low-cost access by reusable chemical and nuclear rocket transportation systems." Some NASA officials even compared the older method of using ELVs like the Saturn V to operating a railroad and throwing away the locomotive and box cars with every trip. The Shuttle, they claimed, would provide the United States with low-cost, routine access to space.[21]

At that time space observers calculated that a Titan IIIC cost $24 million to procure and launch, while each Saturn IB cost $55 million. Carrying 23,000 pounds to low Earth orbit (LEO), the Titan IIIC delivered its payload at a cost per pound of about $1,000. The Saturn IB cost about $1,500 per pound to deliver its 37,000 pound payload. It was these launch costs that NASA officials sought to reduce by the much heralded factor of ten.[22]

The Space Shuttle, therefore, became an attempt to provide "low-cost access [to space] by reusable chemical and nuclear rocket transportation systems."[23] George M. Low, NASA's deputy administrator, voiced the redefinition of this approach to the NASA leadership on 27 January 1970: "I think there is really only one objective for the Space Shuttle program, and that is 'to provide a low-cost, economical space transportation system.' To meet this objective, one has to concentrate both on low development costs and on low operational costs."[24] "Low cost, economical" space transportation became NASA's criteria for the program, and it was an effort to overcome a real-time problem of public perception about spaceflight at the time: that it was too expensive.[25]

NASA had originally intended to achieve cost effectiveness on the Shuttle through economies of scale, as late as 1984 estimating that it could fly as many as 24 missions per year. This has proven an unattainable goal. Instead, NASA might have cut operational costs by investing more money in cost-saving technologies at the beginning of the program. Dale D. Myers, who served as NASA deputy administrator in the post-*Challenger* era, suggested that reductions in the cost of flight operations might have been achieved "had the design team concentrated on operations as strongly as they concentrated on development."[26]

While the effort to achieve "low cost, economical" access to space was an appropriate goal for NASA, it eventually proved an embarrassment to the space program. So far, in spite of high hopes, the Shuttle has provided neither low cost nor routine access to space. The Space Shuttle—second to the Saturn V in both capability and cost—launches some 53,000 pounds of payload into orbit at a cost per launch of about $450 million. It is a high-end user, and the cost per flight is so astronomical that only the government can afford it. In addition, by January 1986, there had been only 24 Shuttle flights, although in the 1970s NASA had projected more flights than that for every year. While the system is reusable, its complexity, coupled with the ever-present rigors of flying in an aerospace environment, means that the turnaround time between flights requires several months instead of several days.

Since neither the cost per launch nor the flight schedule has met expectations, many criticized NASA for failing to meet the promises made in gaining approval of the Shuttle program. In some respects, therefore, a consensus emerged in the last decade of the 20th century that the Shuttle has been both a triumph and a tragedy. It remains an engagingly ambitious program that operates an exceptionally sophisticated vehicle, one that no other nation on Earth could have built at the time. As such, it has been an enormously successful program. At the same time, the Shuttle is essentially a continuation of space spectaculars, *à la* Apollo, and its much-touted capabilities remain unrealized. It made far fewer flights and conducted far fewer scientific experiments than NASA publicly predicted.[27]

While the Space Shuttle represented an enormously significant if unsuccessful attempt to lower the cost to orbit, the other major launchers of the United States—the Atlas, Titan, and Delta—worked to achieve greater economy through the use of mature technologies incrementally improved and efficient operations honed to a fine edge throughout time. Unfortunately, this approach has also failed to lower the costs of payloads to orbit. As shown in Figure 4, no current launch vehicle is able to achieve orbit at less than $3,000 per pound. Clearly this is unacceptable for the opening of significant space operations. Commercial human flight in space is often invoked as the ultimate goal—spaceplanes with the capability to move passengers to and from Earth orbit and around the globe—are commercially infeasible at the cost per pound shown here. For example, an individual and baggage totaling 220 pounds would have, at best, a ticket price of $733,260.

Under the national strategy of relying on the Shuttle, the Department of Defense (DoD) and NASA were to launch the remainder of their ELVs and then to fly only on the Space Shuttle. This represented a profound shift in the strategy of space access for the United States. In addition to the presumed shutting down of the production line for these other launch vehicles, the launching and processing facilities for ELVs atrophied. Instead, the focus headed toward on developing facilities and infrastructure to support only the Space Shuttle and ballistic missiles.[29]

Figure 4: The High Cost of Launch[28]
(FY 1993 Dollars)

Launch Vehicle	Pounds to LEO	Cost per Launch	Cost per Pound
Titan II	2,000–4,000	$40–$45 million	$10,000–$22,500
Delta II	5,000–11,000	$45–$50 million	$4,090–$10,000
Atlas II	12,000–18,000	$60–$70 million	$3,333–$5,833
Titan IV	30,000–50,000	$170–$220 million	$3,400–$7,333
Space Shuttle	53,000–56,000	$445 million	$8,036–$8,490

From 1972 to 1985, NASA continued to conduct launches of communications satellites on behalf of U.S. commercial and foreign customers in addition to those of foreign scientific satellites. As U.S. civil and military launch rates declined, launches of communications satellites steadily increased, rising to a high of nine launches in 1982. During this entire 13-year period, commercial launches accounted for 22 percent of all U.S. launches. When the Shuttle first flew in 1981, the Ronald Reagan presidential administration moved quickly to declare it operational and to empower NASA to manifest commercial payloads for it. The Shuttle first deployed commercial satellites in 1982, and by 1985 NASA had launched 11 commercial communications satellites on four Shuttle flights, and only three on Atlas-Centaur flights.[30]

While the U.S. government had mandated the phasing out of ELVs for its launches, manufacturers of these vehicles, in addition to some users, proposed continuing production and competing directly with the Space Shuttle and newly operational European Ariane launch vehicle. However the government's strategy to keep the Shuttle price low and Europe's support to keep the Ariane price even lower remained major impediments to their commercial success. Despite their hesitation, in February 1984, President Reagan signed Executive Order 12465 on "Commercial Expendable Launch Vehicle Activities," and Congress passed the Commercial Space Launch Act (CSLA) of 1984 establishing a licensing and regulatory regime for non-government launch activities within the Department of Transportation. This established the fundamental framework for the current law still in place today.[31]

The CSLA of 1984 recognized that U.S. ELVs would no longer be needed for government use in light of the national policy to rely on the Shuttle as the primary means of U.S. access to space. This law established the foundation and mechanisms necessary for U.S. companies to obtain use of, or even ownership of, these ELV-related facilities that were to become "excess or otherwise not needed for public use," and launch base and range support services from the USAF and NASA that were similarly no longer "needed for public use."[32]

This was never a perfect situation, for the Shuttle was shouldering, during the early Reagan years, the responsibility for all government launches and many commercial ones. It was, sadly, ill-equipped to satisfy these demands. Even with the best of intentions and with attractive payload pricing policies, the Space Shuttle remained what it had been intended to be in the first place, a research-and-development vehicle that would push the frontiers of spaceflight and knowledge about the universe. The desire for the Shuttle to be all things to all people—research-and-development aerospace vehicle, operational space truck, commercial carrier, scientific platform—ensured that it would satisfy none of these singular and mutually exclusive missions.[33]

These inherently competing goals, coupled with the reality of primitive reusable launch vehicle (RLV) technology, led to disappointment and disillusionment with the Space Shuttle. By 1985 NASA had learned a great deal about the limits of its own abilities as the Shuttle failed to deliver on its early promises, many of those promises of NASA's own making. Even so, NASA insisted on maintaining the Shuttle as the preeminent launcher for the United States, a position that became less tenable with every year of its operation.[34]

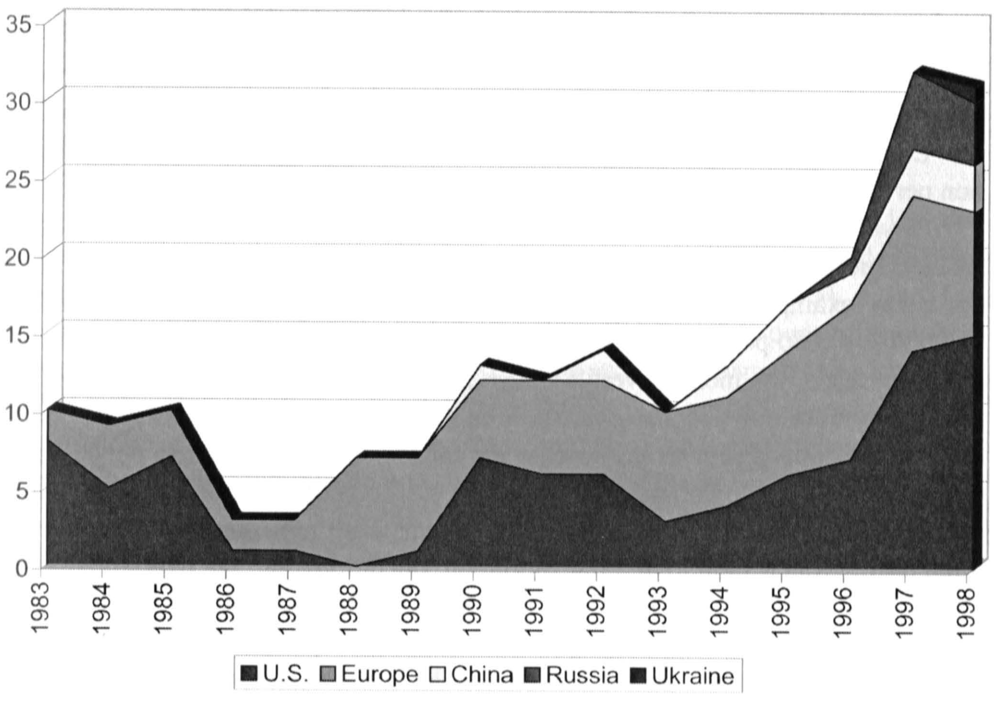
Assuring Access to Space

The loss of *Challenger* on 28 January 1986 changed everything. By mid 1986 virtually all U.S. space launch systems had experienced launch failures. In addition to *Challenger*, a Titan 34D-9 in May 1986 damaged both Titan launch pads at Vandenberg Air Force Base, and Delta and Atlas failures at Cape Canaveral called into question the possibility of the United States having *any* access to space, much less assured access. This series of failures led to serious concerns regarding the reliability and resilience of U.S. national access to space, which in turn led to another important shift in national policy for the future of space access.[35]

The *Challenger* accident reinvigorated the debate about the use of the Space Shuttle to launch all U.S. satellites. In August 1986, President Reagan announced that the Shuttle would no longer carry commercial satellites, a policy formalized in December 1986 in National Security Decision Directive 254, "United States Space Launch Strategy." A total of 44 commercial and foreign payloads that had been manifested on the Space Shuttle were forced to find new ELV launchers.[36]

For the next three years the U.S. government worked to reinvigorate the American ELV production lines and to redesign and modify satellites to be launched on ELVs instead of the Shuttle. The shift back to ELVs required additional government funding to fix the problems that had resulted from years of planning to retire these systems. As shown in Figure 5, the United States practically ceased commercial launch activities for several years, conducting just three commercial satellite launches (one just prior to the *Challenger* flight) for only 6 percent of U.S. space launches from 1986 to 1989.[37]

Figure 5: Commercial Launches by Nation.



During this period, however, two actions were initiated that enabled the emergence of a U.S. commercial launch industry. First, the DoD committed to purchasing a large number of ELVs as part of a strategy to maintain access to space using a mixed fleet of both the Space Shuttle and ELVs. This reopened the dormant U.S. ELV production lines at government expense and helped provide economies of scale necessary to enable U.S. companies to effectively compete against Ariane. Second, in 1988, Congress amended the CSLA to establish new insurance requirements whose effect was to limit liability for U.S. companies in case their launches caused damage to government property or third parties. The revised CSLA also established protections against government preemption of commercial launches on government ranges.[38]

As a result, the first U.S. commercial space launch took place in 1989—nearly five years after the CSLA was passed. Beginning in 1989, U.S. launches of commercial satellites were conducted by commercial launch companies (in most cases, the same companies providing launch services for DoD and NASA payloads as government contractors), not the U.S. government.

The development of new ELVs followed quickly. For instance, the most recent version of the Atlas, the IIAS, began flying in 1993 and could send 19,000 pounds into LEO at the "bargain" price of $105 million per flight, about $6,000 per pound. The three-stage Delta II entered operational service in 1989 and could place 3,190–4,060 pounds into orbit depending on configuration. Its cost was about $45–50 million per launch, about $12,000 per pound. The Titan IV, the only current operational version, is the largest and most powerful U.S. ELV in use. Capable of placing 39,000 pounds in Earth orbit, it cost more than $240 million per flight.[39]

Even so, the costs for space access remain exorbitant. The most modest space launchers placing relatively small satellites of less than 4,000 pounds into orbit, for example, still average some $25–$50 million per flight or about $10,000–$40,000 per pound depending on the launch system. The mighty Saturn V Moon rocket, the most powerful launch system ever developed, had a thrust at launch of 7.5 million pounds of thrust. It could place into orbit a massive payload of 262,000 pounds, but to do so cost an enormous $113.1 million per launch ($455 million in 2000 dollars). And those are just basic launch costs to orbit; they do not include the cost of satellite development, indemnification, boost to optimum orbit, ground support and transportation, operations, and the like.[40]

Space travel started out and remains an exceptionally costly enterprise. The best ELVs still cost something approaching $10,000 per pound from Earth to orbit. The result is that spaceflight remains an enormously costly business. No wonder that it has been the province of the government, a few high-end communications satellite companies, and other unique users, despite attempts to encourage further development of launch technology.[41]

Commercial Space Access Begins

An important policy shift occurred within the government space launch management structure in the early 1990s. From the beginning, responsibilities for ELV acquisition, development, and operations, in addition to the operation, maintenance, improvement, and modernization of the launch bases and ranges, resided in the acquisition and development arm of Air Force Systems Command (AFSC). In 1990 AFSC ceased to exist as an independent entity, and the USAF transferred access to space responsibilities from it to the operational arm under Air Force Space Command.[42]

Just as the U.S. Air Force shifted its space launch focus from "development" to "operations," the U.S. commercial space launch industry entered a period of growth and expansion. Between 1990 and 1994, commercial launch activities climbed back to their pre-*Challenger* level of around 20 percent of U.S. space launches conducted. For the next few years, U.S. commercial launch providers engaged in intense competition with Arianespace for leadership of the commercial launch industry. As the backlog of commercial payloads that had been delayed by the launch failures was flown out, an average of more than 12 launches per year were conducted from 1990 to 1994 (see Figure 5).

Recognizing the critical importance of space transportation to the U.S. national security, civil, and commercial space sectors, the Clinton presidential administration issued a National Space Transportation Policy in 1994. A key feature of the policy was that it established a clear division of responsibilities: DoD would oversee the ELV fleet, and NASA was given primary responsibility for RLV technology development and demonstration. Both agencies were directed to involve the U.S. commercial space sector, including state governments, as partners, participants, and investors in these programs. This policy formed the genesis for DoD's Evolved Expendable Launch Vehicle (EELV) program and for NASA's X-33, X-34, X-37, and X-38 RLV technology demonstrators.[43]

The EELV program emphasized the development of advanced Atlas and Delta launchers and the phase-out of the Titan rocket. In several versions, Atlas and Delta were to continue to be major U.S. launch vehicles for the foreseeable future. Beginning in 1995 the U.S. government began to phase the Titan out of the launch inventory. It had no commercial appeal, because of its price tag per flight, and its principal user, the DoD, was finding fewer payloads for it with every year. In the FY 1995 DoD appropriation, Congress included language that "terminates the Titan IV program after completion of the current contract" that provided for a total of 40 launches (with one spare) through 2003. This legislation called the Titan IV "excessively expensive" and foreswore the continuation of this launcher on grounds of cost. The Titan launcher will be extinct before 2005.[44]

Additionally, NASA charted a new course by placing greater responsibility for spaceflight operations with its private sector contractor, United Space Alliance (USA). Since 1995 USA increased performance by almost one third, cut ground processing time nearly in half, and reduced operating costs by more than one third when adjusted for inflation. NASA also invested about $100 million per year in Space Shuttle improvements to address safety and obsolescence, while USA has invested millions to improve Shuttle operations.[45] At the same time, NASA has invested heavily in the development of RLV technology with the X-33, X-34, X-37, and X-38 programs—all of them in partnership with industry.[46]

Driven by expanding market demand in the mid 1990s, the private sector also began making substantial investments in the development of new launch vehicles. For example, over the past six years, no fewer than nine start-up companies have emerged with the objective of building their own launch vehicle with little or no government involvement.[47] Partnerships with other aerospace organizations from other nations have also been the norm in the last decade of the 20th century. Following the end of the Cold War, U.S. aerospace companies formed a number of joint ventures with Russian and Ukrainian launch companies to provide launch services on former Soviet launch vehicles. Prominent among these new relationships is International Launch Services, a joint venture between Lockheed Martin and Russia's Khrunichev and Energia to market the Proton launch vehicle. Another is Sea Launch, a joint venture between Boeing, Ukraine's Yuzhnoye, Russia's Energia, and Norway's Kvaerner to launch a Zenit rocket from a launch platform in the middle of the Pacific Ocean.[48]

The Value of RLVs Versus ELVs

Many aerospace engineers believe that the long-term solutions to the world's launch needs are a series of completely reusable RLVs. A debate has raged between those who believe RLVs are the only—or at least the best—answer and those who emphasize the continuing place of ELVs in future space access operations. RLV advocates have been convincing in their argument that the only course leading to "efficient transportation to and from the earth" would be RLVs and have made the case repeatedly since the late 1960s.[49] Their model for a prosperous future in space is the airline industry, with its thousands of flights per year and its exceptionally safe and reliable operations. Since the advent of the Space Shuttle, NASA has been committed to advancing this model with Shuttle follow-on efforts.

One especially important effort for a next-generation RLV emerged during the Reagan administration when senior government officials began to talk about the "Orient Express," a hybrid air and spaceplane that would enable ordinary people to travel between New York City and Tokyo in about one hour. Such a concept was quite simple in theory, although enormously complex in reality. It required developing a passenger spaceplane with the capability to fly from an ordinary runway like a conventional jet. Flying supersonic it would reach an altitude of about 45,000 feet when the pilot would start scramjet engines, a more efficient, faster jet engine that has the potential to reach hypersonic speeds in the Mach 3 realm. These take the vehicle to the edge of space for a flight to the opposite side of the globe, from whence the process is reversed and the vehicle lands like a conventional airplane. It never would reach orbit, but it would still fly in space, and the result is the same as orbital flight for passengers but for less time. It would even be possible, RLV supporters insisted, to build such a spaceplane that could reach orbit.[50]

One of the most significant efforts to develop this reusable spaceplane was the National Aerospace Plane (NASP), a joint NASA/USAF technology demonstrator begun during the Reagan administration. Touted as a single-stage-to-orbit (SSTO) fully reusable vehicle using air breathing engines and wings, NASP never progressed to flight stage. It finally died a merciful death, trapped as it was in bureaucratic politics and seemingly endless technological difficulty, in 1994.[51]

NASA began its own RLV program after the demise of NASP, and the agency's leadership expressed high hopes for the X-33, a small suborbital vehicle that would demonstrate the technologies required for an operational SSTO launcher. This is the first of a projected set of four stages that would lead to a routine space faring capability. The X-33 project, undertaken in partnership with Lockheed Martin, had an ambitious timetable to fly by 2001. But what would happen after its tests were completed remained unclear. Even assuming complete success in meeting its research-and-development objectives, the time and money necessary to build, test, and certify a full-scale operational follow-on version has remained problematic. Who would pay for such an operational vehicle also remained a mystery, especially since the private sector has become less enamored with the joint project during the years and has eased itself away from the venture.[52]

There is also an understanding that the technical hurdles have proven more daunting than anticipated, as was the case 30 years ago with the Space Shuttle and more recently with NASP. Any SSTO, and X-33 holds true to this pattern, would require breakthroughs in a number of technologies, particularly in propulsion and materials. And when designers begin work on the full-scale SSTO, they may find that available technologies limit payload size so severely that the new vehicle provides little or no cost savings compared to old launchers. If this becomes the case, then everyone must understand that NASA will receive the same barbs from critics as had been seen with the Shuttle. They condemned NASA for "selling" the Space Shuttle program as a practical and cost-effective means of routine access to space and then failing to deliver on that promise.[53]

This is not to say that SSTO could never work or that the X-33 should not be pursued. It has always been NASA's job to take risks and push the technological envelope. But while the goal may be the development of a launch system that is significantly cheaper, more reliable, and more flexible than presently available it is possible to envision a future system that cannot meet those objectives. This is all the more true in a situation where breakthrough, revolutionary technologies do not emerge.[54]

Then there is an alternative position that suggests that the most appropriate approach to space access is through the use of throwaway "big, dumb boosters" that are inexpensive to manufacture and operate. While reusable rockets may seem to be as an attractive cost-saving alternative to expendables because they allow repeated use of critical components, such as rocket motors and structural elements, ELV advocates claim they offer a false promise of savings. This is because all RLV savings are predicated on maximizing usage of a small number of vehicles during a long period of time for all types of space launch requirements. Accordingly, cost savings are realized only when an RLV flies many times during many years. That goal is unattainable, they claim, because it assumes that there will be no (or few) accidents in the reusable fleet throughout its life span.[55]

The reality, ELV advocates warn, is that the probability of all RLV components operating without catastrophic failure throughout the lifetime of the vehicle cannot be assumed to be 100 percent. Indeed, the launch reliability rate of even relatively simple ELVs—those without upper stages or spacecraft propulsion modules and with significant operational experience—peaks at 98 percent with the Delta II and that took 30 years of operations to achieve. To be sure, most ELVs achieve a reliability rate of 90–92 percent, again only after a maturing of the system has taken place. The Space Shuttle, a partially reusable system, has attained a launch reliability rate of slightly more than 98 percent, but only through extensive and costly redundant systems and safety checks. In the case of a new RLV, or a new ELV for that matter, a higher failure rate has to be assumed because of a lack of experience with the system. Moreover, RLV use doubles the time of exposure of the vehicle to failure because it must also be recovered and be reusable after refurbishment. To counter this challenge, more and better reliability has to be built into the system and this exponentially increases both research and development and operational costs.[56]

Designing for one-use only, those arguing for ELV development suggest, simplifies the system enormously. One use of a rocket motor, guidance system, and the like, means that it only needs to function correctly one time. Acceptance of an operational reliability of 90 percent or even less would further reduce the costs incurred in designing and developing a new ELV. Indeed, many experts believe that reliability rates cannot be advanced more than 1.5 percent above the 90 percent mark without enormous effort, effort that would be strikingly cost inefficient.[57]

Some provocatively suggest that new ELVs should be designed with the types of payloads to be carried clearly in mind, accepting the risk inherent in a space launch environment where 90 percent reliability would be the norm. For expensive and one-of-a-kind scientific and military satellites, and expensive commercial spacecraft, spacecraft with a reliability rate and a higher price tag could be acceptable. But for most payloads, especially logistics supplies and the like, going to the International Space Station, reliabilities as low as 80 percent might be acceptable. And it goes without saying that for human spaceflights, NASA's longstanding goal of 99.99 percent operational reliability is not too high a goal to seek. The debate continues and will not end until a truly outstanding launch vehicle emerges that achieves what has been proposed and thereby quells critics.

Conclusion

Since the beginning of spaceflight more than 50 years ago, those who seek to travel in space have been, in essence, between a rocket and a hard place. The enormous release of energy made possible through the development of chemical rocket technology allowed the first generation of launch vehicles to free humankind and its robots from the constraints of Earth's gravity. It allowed the still exceptionally limited exploitation of space technology for all manner of activities important on Earth—communications, weather, global positioning, and a host of other remote sensing satellites—to such an extent that many individuals in the United States today cannot conceive of a world in which these technologies did not exist. This same chemical rocket technology made possible human flight into space, albeit for an exceptionally limited number of exceptional people, and the visiting of robotic probes from this planet to neighbors in the solar system.

These have been enormously significant, and overwhelmingly positive, developments. They have also been enormously expensive, despite sustained efforts to reduce the cost of spaceflight. One is to use rocket propulsion and, with new materials and clever engineering, to make a launcher that is not only recoverable, but also robust. The other is to use air-breathing launchers, and thus to employ the potentially large mass fractions that air breathing engines theoretically promises to build a robust launcher. Then there are other options still. Most launch vehicle efforts throughout the history of the space age, unfortunately, have committed a fair measure of self-deception and wishful thinking. A large ambitious program is created, hyped, and then fails as a result of unrealistic expectations, especially with regard to technical risk. These typically have blurred the line, which should be bright, between revolutionary, high-risk, high-payoff research-and-development efforts and low-risk, marginal payoff evolutionary efforts to improve operational systems. Efforts to break the bonds of this deception may well lead in remarkable new directions in future launcher development efforts. Only once that happens will humans be able to escape the nether world "between a rocket and a hard place."

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