NASA AERONAUTICS BOOK SERIES

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NASA's X-34 and the Quest for Cheap, Reusable Access to Space

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Prologue

Between 1992 and 1996, the American aerospace community vigorously explored the development of a post–Space Shuttle reusable space transportation system for the United States. This activity included studies by the National Aeronautics and Space Administration (NASA), scientific foundations, and the aerospace industry. Likewise, both the executive branch of the government, through the issuance of a White House Policy Space Transportation Directive, and the legislative branch, though the holding of congressional hearings and budget allocations to NASA and the Department of Defense, were deeply involved in the decision-making process. The new policy direction was aimed toward reestablishing the Unites States' competitiveness in the space launch vehicle development and launch area and in transferring much of this activity to the U.S. aerospace industry.

These developments served as the prelude to NASA's single-stage-to-orbit (SSTO), reusable launch vehicle (RLV) program that included the development of three technology test bed vehicles. The first of these vehicles was the DC-XA Clipper Graham, which actually was an upgrade to the original DC-X (Delta-Clipper Experimental) developed by McDonnell Douglas for the Department of Defense and subsequently transferred to NASA at the start of the Agency's single-stage-to-orbit program. The DC-XA Clipper Graham was followed by the X-33, which was intended to serve as a test bed vehicle for the subsequent development of a full-size reusable single-stage-to-orbit vehicle, and the X-34, which was intended as a technology test bed vehicle to demonstrate low-cost reusability and to conduct flight experiments.

These were all promising concepts, and prospects for developing a cheap, robust, reusable space lift system to supplant the already aging Space Shuttle seemed assured. But within a decade, such hopes had been dashed—all the more frustrating to program proponents and participants, who had contributed some remarkably creative engineering to support the bold conceptual visions underpinning each of these programs.

This book examines arguably the most elegant and promising of all of these, the NASA–Orbital Sciences X-34 Technology Testbed Demonstrator program, one ranking high on any list of the best research aircraft never flown. Indeed, in retrospect, it was a program that deserved greater support rather than precipitous cancellation. The two prototypes—only one of which flew, and then only on "captive carry" flight tests under a modified Lockheed L-1011 TriStar carrier aircraft—deserved far better fates than being reduced to incomplete hulks, left discarded on the eastern shore of Rogers Dry Lake, there to be baked under the harsh Mojave sun, blown about and buffeted by its hot desert winds, and flooded by sporadic desert cloudbursts. To trace how this program went from bright promise to dismal cancellation, it is necessary to begin in the early 1990s. It was a challenging time in American aerospace, as NASA confronted its space launch future (in the wake of the Challenger tragedy but before the Columbia catastrophe); it also was a time when the global patterns of space launch, combined with the rapid drawdown and national economic reinvestment that accompanied the end of the 40-year Cold War, were already eroding what had been America's preeminent position in space access.

The Space Shuttle was the world's first reusable space transportation system and inspired numerous national and international studies for successors, including the X-33 and X-34. Here, the Space Shuttle Endeavour lands at Edwards Air Force Base, California, on May 1, 1999. (NASA)

CHAPTER 1

NASA and the Post–Cold War Launch Vehicle Challenge

The abrupt end of the Cold War over the fall of 1989 greatly impacted the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), and the future of space launches. It resulted in a dramatic reduction in monies flowing to NASA and to the Department of Defense, which required trimmed-back efforts to develop new families and classes of space boosters. As Agency historians later reported, "money for new—and old—launch systems became hard to come by."[1]

Studies, Directives, and Congressional Hearings

In the early 1990s, the United States' dependence on the aging and increasingly costly and difficult-to-support Space Shuttle and on expendable boosters derived from the first generation of American ballistic missiles that were developed almost four decades previously fueled a crisis within the aerospace industry. This crisis resulted in numerous studies reassessing NASA's programs, goals, posture, and long-range plans, including readdressing existing plans for the redesign of Space Station Freedom (later to be named the International Space Station), making Space Shuttle safety and reliability improvements, and pursuing alternative transportation systems.

Agency personnel and others, both within and outside the Federal Government, aggressively pursued reducing the cost of space access to below that of large expendable launch vehicles such as the Titan III and IV, as well as semi-expendables such as the troubled Space Shuttle transportation system. Their energetic pursuit of alternative reusable launch vehicles (RLVs)—including the elusive and technically frustrating Holy Grail of SSTO—ultimately resulted in three major program efforts: the DC-XA Clipper Graham Vertical Take-Off and Landing (VTOL) demonstrator, the Lockheed Martin X-33 Advanced Technology Demonstrator, and the X-34. The evolution of the X-34—from its initial concept as the X-34 Reusable Small Booster, through the X-34 Orbital Sciences Corporation–Rockwell American Space Lines (which involved a small-payload X-34A launched from a Lockheed L-1011 and a larger-payload X-34B launched from a Boeing 747), to the much smaller, downsized Orbital Sciences X-34 Technology Testbed Demonstrator concept—is the subject of this book.

NASA's *Access to Space* Study

Most influential of the many analytical efforts NASA sponsored or undertook was the *Access to Space* study, undertaken by the Office of Space Systems Development in 1993 in response to a congressional directive in the Agency's fiscal year 1993 Appropriations Act to "assess National launch requirements, potential launch alternatives, and strategies to address such needs…to permit formulation of multiyear program plans."[2] *Access to Space* focused on "identifying long-term improvements leading to a space transportation architecture that would reduce the annual cost of space launch to the U.S. Government by at least 50 percent, increase the safety of flight crews by an order of magnitude [10 times], and make major improvements in overall system operability."[3]

The study examined three alternatives: upgrading the reusable Space Shuttle and the then-current expendable launch vehicle (ELV) fleet through 2030; developing a new ELV system using the latest technology and beginning a transition from the Space Shuttle and legacy ELV systems, starting in 2005; and developing a new reusable advanced-technology next-generation launch system, beginning the transition from the legacy Space Shuttle and ELV fleet, starting in 2008.[4]

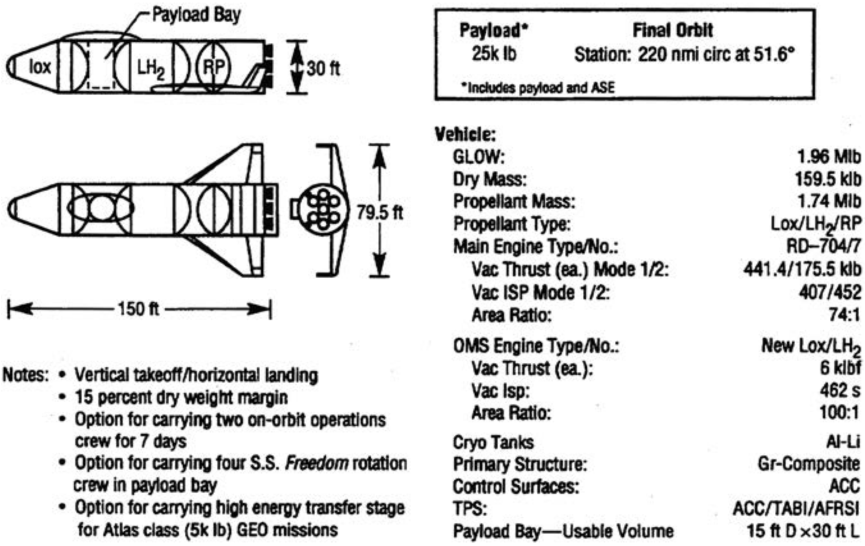
Each of the above options was analyzed by separate study teams using a common set of goals against which each option could be measured. Each study group covered the following categories in the order of their priority: a) the fundamental requirement of satisfying the national launch needs for NASA (crewed and uncrewed vehicles), the Department of Defense, and commercial companies, including the definition of payloads from small to Shuttle/Titan class and orbital destinations at all altitudes and inclinations, as well as destinations beyond earth orbit; b) the essential characteristics relating to improved crew safety by an order of magnitude, acceptable life-cycle costs (LCCs), vehicle reliability of at least 0.98, and environmental acceptability; and c) the desired features, including improving commercial competitiveness of launch vehicles, contributing to the industrial economy, enabling incremental development or improvements, and improving capability relative to current systems.[5] A common mission model was defined for the three study options; it included all U.S. defense, civilian, and commercial users covering the period from 1995 to 2030. This model was based on a conservative extrapolation of current requirements and planned programs but did not include future possibilities such as missions to the Moon or Mars.

The *Access to Space* study was directed by Arnold D. Aldrich, who was NASA's Associate Administrator for Space Systems Development. Aldrich was assisted by a senior-level steering group that periodically reviewed progress and provided advice. The steering group included members from NASA Headquarters and field installations, as well as from the Department of Defense, the U.S. Air Force, and the Office of Commercial Programs in the Department of Transportation. The leaders of the Option 1 Team were Bryan O'Connor from NASA Headquarters and Jay Greene from NASA's Johnson Space Center (JSC). The leaders for the Option 2 Team were Wayne Littles and Len Worland, both from NASA's Marshall Space Flight Center (MSFC). The leaders for the Option 3 Team were Michael Griffin from NASA Headquarters and Robert E. "Gene" Austin from MSFC.[6]

Each team analyzed a number of alternate vehicle designs and vehicle architectures. The Option 1 Team addressed Shuttle-based alternatives that included retrofitting the Space Shuttle by making evolutionary improvements and keeping the current expendable launch vehicle fleet. Ultimately, they recommended retrofitting the Space Shuttle.

The Option 2 Team studied the use of existing conventional technology. The team analyzed 84 configurations mixing different crew carriers, cargo vehicles, stage configurations, engine types, and a number of new vehicles. They narrowed the choice down to four primary candidates: 1) developing a new large vehicle and keeping the Atlas and Delta expendable launch vehicles plus the Horizontal Lander lifting body (the HL-42) and Automated Transfer Vehicle (ATV); 2) developing new large and small vehicles and keeping the Delta ELVs plus CLV-P (Crew Logistics Vehicle-Pressurized) for crew plus cargo; 3) developing new large and small vehicles and keeping the Delta ELVs, HL-42 plus ATV, and hybrid Space Transportation Main Engines (STMEs); and 4) developing new large and small vehicles and keeping the Delta ELVs, plus HL-42 plus ATV and RD-180/J-2S engines. They ultimately selected the new large- and small-vehicle alternatives that called for developing a new expendable 20,000-pound-payload launch vehicle to replace the Atlas; a new 85,000-pound-lift expendable vehicle to replace the Titan and the Shuttle; separate new cargo and crew carriers; and the single-engine Centaur upper stage. This alternative kept the Delta rocket as a cost-effective launcher for smaller payloads. Also, this alternative did not require new engine development but instead used the RD-180, which advocates claimed was simply a low-risk modification of the then-operational RD-170 engine. This alternative was deemed to generate the lowest operational costs for the Atlas-class missions, which were considered to have a high level of commercial interest.[7]

The Option 3 Team explored developing new technology using three alternatives: 1) single-stage-to-orbit all-rocket, both with and without ELVs;

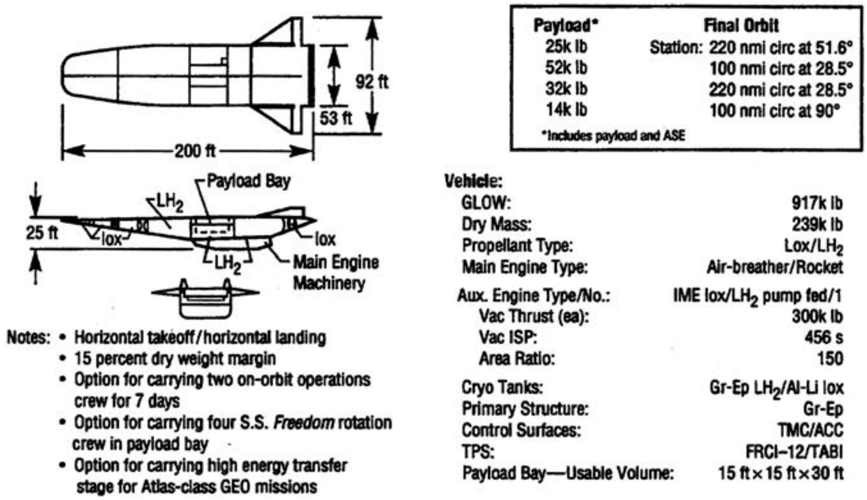


This is a reference single-stage-to-orbit logistical rocket vehicle, as depicted in the Summary Report of the NASA *Access to Space* study. (NASA)

2) single-stage-to-orbit air-breather/rocket without ELVs; and 3) two-stage-to-orbit air-breather/rocket without ELVs.[8] The team's design philosophy for the reference SSTO vehicle was to "maximize the lessons learned from the Space Shuttle program and apply the minimum technology required to allow for an operationally efficient vehicle."[9] They selected the fully reusable, all-rocket, single-stage-to-orbit vehicle. The recommended configuration for this vehicle called for a tri-propellant propulsion system, graphite-composite structure, aluminum-lithium propellant tanks, and an advanced thermal protection system (TPS) and subsystems. The team also noted that added margin could be attained by using graphite-composite fuel tanks instead of aluminum-lithium tanks.[10] The team selected rocket vehicles over air-breathing vehicles on the basis that they involved lower design-, development-, testing-, evaluation-, and technology-phase costs and risks, concluding that rockets "required less-demanding technology that would translate into a more quickly developed and less risky program."[11]

The study team likewise identified tentative characteristics for both single-stage and two-stage air-breather/rocket vehicles. The following diagrams show representative SSTO rocket and SSTO air-breathing vehicles.

Due to the high costs of operating the Titan expendable launch vehicle, the Option 3 Team recommended two versions of the single-stage-to-orbit alternative. The first version had a transverse payload bay measuring 15 feet in diameter and 30 feet long, unable to accommodate the largest of the Titan ELV-class



This is a reference single-stage-to-orbit logistical air-breathing vehicle, as depicted in the Summary Report of the NASA *Access to Space* study. (NASA)

missions, thus requiring continuing use of the Titan expendable vehicles for this alternative option. The second expendable launch vehicle recommendation had a 45-foot-long longitudinal payload bay that could accommodate all Titan payloads, provided that the payloads were somewhat downsized, and thus would not require continued use of expendable launch vehicles. The team noted that this second alternative was under serious consideration by the Department of Defense.[12] Option 3 subsequently spawned three separate development efforts, the DC-XA (Clipper Graham), the Lockheed Martin X-33, and the Orbital Sciences X-34 programs.

In making their selection of Option 3, the joint NASA and Department of Defense team recognized that a "culture change" in launch vehicle development, certification, and operations management would need to accompany the use of advanced technologies in order "to leverage them to the greatest extent possible." The team also noted that their "[v]ehicle concepts were designed for robust operational margins instead of performance capability, through the use of various advanced technologies."[13]

The Option 3 Team added that on the basis of the 1990 Modified Civil Needs Data Base, approximately 90 percent of all future low-orbit payloads would be less than 20,000 pounds and would measure less than 20 feet in length. "Delivery of these payloads (and their geosynchronous Earth orbit equivalent) was a primary driver in determining the payload size requirement of the advanced technology vehicle."[14] The team made a number of additional findings, including the following:

- Approximately 18 satellite delivery missions in the 10,000- to 20,000-class low-Earth orbit equivalent were to be conducted each year.
- A new liquid oxygen/liquid hydrogen (LOX/LH_2) upper stage would be required to transfer the largest payloads from low-Earth orbit to geosynchronous orbit, one approximately one-third the size of the venerable Centaur.
- Any recommended vehicle must be capable of delivering 150,000 pounds per year to the Space Station and returning 125,000 pounds to Earth.

Based upon previous flight experience and state-of-the-art avionics, the team concluded that any recommended vehicle must be capable of autonomous operations, although when required, the vehicle would need to have the capability of being operated on orbit by a two-person crew to enhance safety and perform nonstandard mission operations. In addition, the team believed the vehicle must have the capability to transport four additional crewmembers and associated payloads to the Space Station. Based on these payload requirements, they recommended a vehicle able to deliver a 25,000-pound payload to a 220-nautical-mile circular orbit, inclined at 51.6 degrees. On average, it would need to be capable of flying 39 flights per year to meet mission requirements, an average of one flight every 9 days.[15]

The Option 3 Team selected three launch vehicle concept designs for engineering and cost analysis. The team considered the three following concepts to be representative of the many fully reusable vehicle concept possibilities: 1) an all-rocket-powered single-stage-to-orbit (SSTO-R), 2) a combination of air-breather plus rocket-powered single-stage-to-orbit (SSTO-A/R), and 3) a combination of air-breather plus rocket-powered two-stage-to-orbit (TSTO-A/R).

In making their selection, the team stated that "[t]hese three concepts have been identified because they represent the largest range of candidate vehicle options in terms of technology requirements for reusable launch systems, and because government studies were already in progress to evaluate these concepts at the initiation of this study. It is emphasized that these concepts are intended to serve as representative vehicles for technology and operations evaluations and are not intended to serve as final concept recommendations. The use of advanced technologies is being considered to increase operability, margins, durability, and to enable full reusability."[16]

In their final analysis, the Option 3 Team determined that "the single-stage-to-orbit all-rocket vehicle meets the fundamental requirement established at the outset of the study to satisfy the national launch needs."[17] The team added that the focus of the study was to define a 25,000-pound-class launcher since approximately 90 percent of all future payloads would fall into this category, and that the advanced-technology vehicle would replace all Delta- and Atlas-class missions and meet Space Station logistics resupply requirements.[18] The findings also addressed operating-cost-saving issues, noting that the single-stage-to-orbit all-rocket vehicle operating cost was estimated to be approximately one-third of the Space Shuttle costs. They stated that this would be possible "through the use of a single, fully reusable airframe coupled with changes in the space launch operations culture."[19]

In regard to this "culture" reference, all three Option Teams recognized that "if large savings in annual costs were to be realized, new management, contracting, design, development, and, particularly, operations concepts had to be devised. The fundamental change required was that all phases had to be driven by efficient operations rather than by attainment of maximum performance levels. This, in turn, required maximizing automation and minimizing the number of people in the 'standing army' on the ground, as well as requiring redundancy, engine-out capacity, and robust margins in all subsystems."[20]

Subsequently, NASA's effort to change its model for doing business resulted in the Agency's controversial "faster, better, cheaper" policy, reviewed subsequently in chapter 2.

The *Access to Space* study concluded with the following recommendations:[21]

- Adopt the development of an advanced technology, fully reusable single-stage-to-orbit rocket vehicle as an Agency goal.
- Pursue a technology maturation and demonstration program as a first phase of this activity that also should include "a complementary experimental rocket vehicle technology demonstration flight program."[22]
- The technology, advanced development, and experimental vehicle programs should be coordinated with the Department of Defense.
- The Space Shuttle and the current expendable launch vehicle programs should be continued. The most beneficial and cost-effective upgrades should be considered for incorporation into these vehicles until the new single-stage-to-orbit vehicle becomes available.
- Although the focus of these recommendations is a technology maturation and demonstration program, additional studies should be conducted in parallel. They include system trade studies for the single-stage-to-orbit rocket vehicle configuration in order to guide the technology activities, and assessment of a fly-back reusable liquid booster concept for the Space Shuttle.
- The National Aero-Space Plane enabling technology program should be continued as a separate and distinct activity, as it contributes to future defense and civilian hypersonic aircraft programs, and it has potentially unique future mission applications.

From Earth to Orbit—An Assessment of Transportation Options

In addition to requesting NASA to undertake its *Access to Space* study reviewed above, Congress also requested the National Research Council (NRC) to conduct a separate study in 1992 to assess various space transportation options.[23] Members of the NRC are drawn from the National Academy of Sciences and two parallel organizations—the National Academy of Engineering and the Institute of Medicine. As part of the authority included in its 1863 Congressional Charter, the National Academy of Sciences has a mandate requiring the Academy to advise the Federal Government on scientific and technical matters. To undertake the study, the NRC established the Committee on Earth-to-Orbit Transportation Options, consisting of 13 members, who included college professors, aerospace industry representatives, and one member from a major securities brokerage firm. Joseph G. Gavin, former president of Grumman, served as chairman. The committee was assisted by a 21-member Aeronautics and Space Engineering Board. Duane T. McRuer, president and technical director of Systems Technology, Inc., served as board chairman.[24]

The committee's general finding regarding the challenge of reducing costs of access to space while increasing reliability and resiliency was that "the most binding constraint to achieving these goals is the way we do business—launch vehicle assembly, payload processing, and launch pad design and availability." The committee also noted that

> [l]ike much of the nation's terrestrial infrastructure, they are in a state of obsolescence and disrepair…. A clear imperative also exists to design vehicles and propulsion systems that do not need to be operated at the very limit of their performance. Together, the combination of more robust vehicles and a streamlined infrastructure holds the promise of more routine access to space and the benefits that would accrue in space science, national security, commercial enterprises, and the further exploration of space.[25]

The NRC provided Congress with a number of assessments, principal conclusions, and recommendations relating to launch vehicles and infrastructures, propulsion systems, technology, and specific programs then underway. These included:

Launch Vehicles and Launch Infrastructure

- *The United States should make a long-term commitment to new infrastructure and launch vehicles*. The committee noted that multiyear appropriations could be an important step toward this goal.

- *The United States should undertake extensive design of new East and West Coast launch facilities as soon as possible.* Existing facilities were deteriorating and becoming increasingly expensive to operate.
- *A 20,000-pound-payload-class vehicle should be the first of the proposed National Launch Systems (NLS) vehicles to be designed and built*. The NRC further recommended that the design and fabrication of this vehicle be coordinated with the construction of the new launch facilities. (The committee noted that this vehicle would be the least complex and least expensive of the proposed NLS vehicles and would be the most likely to have commercial as well as national security applications, adding that, based on NASA and Department of Defense projections, the 20,000-pound-payload requirement had the greatest growth potential and that this vehicle class would utilize most of the new technologies currently anticipated for the NLS vehicles.)
- *Investment in improvements for the Space Shuttle orbiter and its subsystems should continue*.
- *Reliability should have top priority in the design of new systems, even at the expense of greater up-front costs and lower performance*. The committee added that the cost of failure in terms of time, money, and national prestige far outweighed the costs of built-in reliability.
- *The United States should seek a one-third to one-half reduction in launch and operations costs in order for the United States to remain competitive in the launch vehicle market.* The committee added that this was second in importance only to reliability.

Propulsion

- *Development and qualification of the Space Transportation Main Engine (STME) should proceed immediately and vigorously.*
- *Efforts underway to improve the reliability, reduce the cost, and simplify production and refurbishment of the Space Shuttle Main Engine (SSME) should be continued.* Committee members recognized that the United States would have to rely on the Space Shuttle into the first decade of the 21st century. (The Space Shuttle made its last flight on July 8, 2011).
- *The growth of a family of vehicles would best be accomplished by using strap-on boosters that, to enhance reliability, would be designed to allow pad hold-down with engine shutdown capability, as well as to be throttleable*. The committee added that liquid, solid, and hybrid boosters could all be candidates as long as they incorporated the above attributes. They added, however, that a number of considerations favored liquid over solid propulsion systems because liquid rocket engines

enable a more flexible approach to modular clustering and are amenable to verification before launch. However, the most compelling reasons for the use of liquid rocket engines noted by the committee were throttleability and thrust termination, which enable first-stage booster designs to incorporate an engine redundancy capability. The committee added that hybrid motors might be able to meet these criteria in the future, but at that time, the technology was at a very early stage and needed to be advanced to the point where it could be evaluated.

- *A plan was needed to provide an array of engines with a range of thrust levels and propulsion system capabilities for all stages of future launch vehicles.* The committee added that the proposed STME could be used for the first stages of future launch vehicles and that the Rocketdyne F-1A and the current Russian RD-170 engines should be evaluated for liquid booster applications.
- *Active redundancy for fail-safe capability should be considered in the design of new launch vehicle first stages having multiple engines, in addition to pad hold-down and engine shutdown capability.*
- *The committee recommended increased emphasis on propulsion system tests, to include the whole propellant feed system, stressing that such should be a major aspect of any new launch system program*.
- *The committee believed that NASA should rely on the current redesigned solid rocket motor (RSRM) and that the advanced solid rocket motor (ASRM) program should be reconsidered.* The committee, however, added that the ASRM would enable future space launch systems to support the heavy payload end of NLS, although the committee found no compelling rationale for such use other than the fact that it might be introduced in a reasonably short time.
- *The committee endorsed continuing research to identify and understand potential detrimental environmental effects generated by launch vehicles.* The committee pointed out that data suggested that pollution due to combustion products from launch vehicles, at the anticipated frequency and scale, is not significant in comparison with other anthropogenic pollution on a global scale.

Technology

- *A greater investment in long-term technology must be made to build the technology base for future systems*. In this regard, the committee noted that decisions were hampered by the absence of research and development over the previous decade. They identified the following areas of technology as offering the potential for high payoff: manufacturing methodology; automatic docking procedures and methodology; modern, miniaturized guidance, navigation, and control; propulsion advances; propulsion system health monitoring and control; and ceramic and intermetallic composite materials.

- *Research and technology development with the goal of developing a new personnel carrier should be continued.*
- *An investment should be made in demonstrating the technology necessary to validate the engineering practicality of the hybrid rocket motor for large, high-thrust strap-on rocket applications.* Hybrid motors employ a liquid oxidizer with solid rocket fuel.

NRC Recommendations Regarding the DC-Y and X-30 NASP

The committee also made three recommendations regarding the DC-Y and another regarding the ailing X-30 National Aero-Space Plane (NASP). ("DC-Y" was the designation for an intended follow-on vehicle to the DC-X Delta-Clipper in the Strategic Defense Initiative Organization [SDIO] Single-Stage Rocket Technology Program.)[26] For the DC-Y Delta Clipper, the committee recommended that SDIO should

- continue a vigorous research and development effort directed at adding depth of detail design and analysis,
- examine the use of other already-existing engine or engines under development, and
- reconsider the value and timing of the proposed one-third scale model flight tests relative to the more critical need for demonstrating the adequacy of the required low-weight structure and heat protection.

For the NASP—behind schedule and growing in weight and complexity as engineers sought in vain to "close" the design—the committee noted that it had nevertheless been both "a stimulating and productive research and development program" urging that the materials and air-breathing hypersonic propulsion aspects of the program "deserve continuing and vigorous support."[27]

In a paper presented at the March 1992 American Institute of Aeronautics and Astronautics (AIAA) Space Programs and Technologies Conference, Air Force officers Lieutenant Colonel Pat Ladner and Major Jess Sponable noted—before the loss of the DC-XA Clipper Graham—that in addition to fully demonstrating the operational and cost objectives of the SSTO, the DC-Y would demonstrate three other technologies—qualification of a new main engine, reusability of cryogenic tanks, and durability of the thermal protection system.[28]

These represented the same goals as set for the X-34. In concluding their paper, the two officers reflected on what was needed for a successful SSTO program by noting the following:

Just as the 20th century ushered in an era of many different aircraft driven by both propellers and jets, the 21st century will see the introduction of many new types of launch systems. The issue facing the next generation of space launch systems is not expendable versus reusable, rocket versus scramjet [supersonic combustion ramjet] or even heavy versus medium lift payloads. The issue is how to build an affordable, reliable and diverse launch infrastructure able to support national versus single agency needs—21st century highways and bridges.

Simplicity, reliability, safety and lower costs are key attributes of single stage rockets that reflect the President's policy in NSPD-4. If these critical operational objectives can be demonstrated in a relatively low cost experimental prototype vehicle, SSTO rockets may open a multitude of commercial, civil and military applications. One of the last times such a consortium of national needs coincided was during the 1930s. The rapid move toward all-metal, more operable and lower cost aircraft culminated in the development of the DC-3.

Experimental prototype vehicles can be built quickly and at a fraction the cost of an operational system. However, whether or not the U.S. proceeds to build the prototype(s) needed to limit both risk and investment awaits a national decision. Although the SDIO can provide the environment for an informed decision based on its designs, it cannot build the "highway to space" alone. Leaders in both the government and aerospace industry must make that decision.[29]

The White House's National Space Transportation Policy

Following the studies reviewed above, the White House, on August 5, 1994, released a new National Space Transportation Policy directive (NSPD-4), drafted by the National Science and Technology Council and approved by President Clinton. The purpose of the policy statement was to set a "clear course for the nation's space program, providing a coherent strategy for supporting and strengthening U.S. space launch capability to meet the growing needs of the civilian, national security and commercial sectors."[30] The policy committed the United States to following a "two-track strategy of maintaining and improving the current fleet of expendable launch vehicles as necessary to meet civil, commercial, and national security requirements; and investing R&D [research and development] resources in developing and demonstrating next generation reusable space transportation systems with the potential to greatly reduce the cost of access to space."[31]

The new policy had four objectives:

- *Establish new national policy for Federal space transportation spending, consistent with current budget constraints and the opportunities presented by emerging technologies.*
- *Establish policy on Federal agencies' use of foreign launch systems and components.* The policy statement noted that with the end of the Cold War, it was important for the "U.S. to be in a position to capitalize on foreign technologies—including Russian technologies—without, at the same time, becoming dependent on them. The policy allows for the use of foreign components, technologies and (under certain conditions) foreign launch services, consistent with U.S. national security, foreign policy and commercial space guidelines in the policy."[32]
- *Establish policy on Federal agencies' use of excess U.S. ballistic missile assets for space launch, in order to prevent adverse impacts on the U.S. commercial space launch industry.* As the statement noted, "The policy obliges the government to fully consider commercial services as part of the decision-making process and imposes specific criteria on the use of excess assets."[33]
- *Provide for an expanded private sector role in the Federal space transportation R&D decision making processes.* "In contrast with previous national policy on space transportation, this policy specifically directs the Departments of Transportation and Commerce to identify opportunities for government-industry cooperation and to factor these into NASA's and DoD's implementation plans."[34]

The directive designated the Department of Defense as lead agency for the improvement and evolution of the U.S. expendable launch vehicle fleet and for the development of the appropriate technology. NASA was assigned responsibility for reusable launch vehicles, including improvement of the Space Shuttle system, focusing on reliability, safety, and cost effectiveness and, in the longer term, developing the technology and demonstrating the next generation of reusable space transportation systems. This included the controversial and technically challenging SSTO concept. NASA was to focus its investments on technologies to support a decision no later than December 1996 on whether to proceed with a flight demonstration program, which would, in turn, provide the basis for deciding by the year 2000 whether to proceed with a new launch system to replace the aging Shuttle fleet. In retrospect, these goals were overly ambitious, given the many other fiscal demands and priorities of the Clinton administration.

The directive assigned the Department of Transportation and the Department of Commerce the responsibility for identifying and promoting innovative arrangements between the U.S. Government and the private sector, including state and local governments. The Department of Defense and NASA were directed to plan for the transition between space programs and future launch systems in a manner that would ensure continuity of mission capability and accommodate transition costs. They also were directed to combine their expendable launch service requirements into single procurements, when such procurements would result in cost savings or otherwise accrue advantages to the Government.[35] Finally, the policy directive noted that "[i]t is envisioned that the private sector could have a significant role in managing the development and operation of a new reusable space transportation system. In anticipation of this role, NASA shall actively involve the private sector in planning and evaluating its launch technology activities."[36]

NASA and the Winged-Body RLV Concept

From April 1994 to January 1995, NASA and several of its industry partners conducted a study to analyze the winged-body single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) concept. The stated primary objectives of the overall studies were to develop a better technical understanding of three different design concepts—winged-body, vertical-lander, and lifting-body—and a consistent set of ground rules for an applicable upper stage. A consistent set of ground rules was necessary in order to perform an equitable comparison of the three different concepts that were based on different ground rules and assumptions. The analytical results of the study also were intended to establish the targets required for the technology program. The study team believed that once a standard set of ground rules and assumptions was established, the pros and cons of each concept could be weighed to furnish answers to fundamental questions relating to system weight (always a critical and sensitive issue), technology targets, and requirements change or "creep." The study team asked these questions, among others:[37]

- How well do NASA's preliminary sizing tools predict vehicle performance?
- Are all issues correctly understood?
- Are the right technologies being pursued?
- Is emphasis being placed on the right technologies?
- How can NASA measure the technology maturation?
- How would requirements impact size, engine choice, and required materials?

Initial Analysis

Based on the availability of data, the winged-body (WB 001) concept was the first established reference configuration, to be followed by the vertical-lander and later the lifting-body, which the study noted remained to be determined due to continuing development of a configuration for that concept. The evolution to a WB 002 configuration and corresponding technology targets had, as of the January 1995 report date, only been completed for the winged body concept. This delay in covering the other two concepts may have caused the unfortunate political controversy reviewed below.

The initial study requirements and goals were derived primarily from the NASA *Access to Space* study, and they stressed the ability to achieve missions accomplished by the older Delta, Atlas, and Space Shuttle launch systems. Conceptual mission parameters were as follows:

- Be able to transport 25,000 pounds to the International Space Station.
- Possess a 7-day maximum mission duration.
- Be able to launch and land at the same site, with no downrange abort sites.
- Be capable of autonomous ground and flight operations.

The upper stage was assumed to be an expendable stage that would not require rendezvous and docking capability. In addition, since it would be used primarily for geosynchronous orbit (GEO) and planetary missions and not to deliver payloads to the Space Station, it would be required to ignite only once in a parking orbit and not during the launch vehicle ascent profile. The study team selected the 25,000-pound weight limitation after learning that space commerce advocates were interested in having a vehicle with a capability of delivering 20,000 to 25,000 pounds to a due-east low-Earth orbit (LEO).[38]

As already noted, the initial analysis completed as of the January 1995 report date was limited primarily to the winged-body concept. In regard to this concept, the report made several important observations. First, the winged-body vehicle is very sensitive to weight growth. The data indicated that every 1-pound increase in subsystem dry weight would result in approximately a 3- to 4-pound increase in overall vehicle weight; additionally, as the vehicle becomes larger, its sensitivity to weight growth increases. Accordingly, a winged-body vehicle resulting from this analysis would weigh approximately 350,000 pounds. Also, once a design was established, weight growth on a winged-body vehicle would have to be kept within the planned allocation in order to avoid having to totally redesign the vehicle. A second important finding was that the winged-body concept design tools utilized to provide initial sizing of the reference vehicle proved to be fairly accurate. Finally, the report cautioned:

> Since any SSTO vehicle is highly sensitive to weight growth, a very aggressive technology program is required to enable reducing the weight to various subsystems, using fewer engines, and, in general, keeping the vehicle to a reasonable size. Toward this end,

> designs using lightweight materials, such as composite tanks and lightweight TPS [thermal protection system] (or materials not requiring a separate TPS) and propulsion systems with high I_{sp} [specific impulse] and thrust/weight ratios should be the primary focus of the technology program.[39]

The winged-body study was not universally hailed and thus quickly came under increasing criticism. Both congressional lawmakers and advocates within the space industry expressed reservations, fearing that the study's conclusions were biasing NASA's future effort toward a complex winged launch vehicle like the Space Shuttle. Though Marshall Space Flight Center engineers defended their study by stressing that it covered various vehicle concepts, officials at NASA Headquarters promptly directed Marshall's engineers to stop further work. At the same time, the Agency stressed that it still wanted to give the space industry a free hand in conceptualizing their designs and that it certainly did not want to define the design as closely as it had in the early days of the Space Shuttle design competition.[40] For their part, Marshall's hardworking engineers resented Headquarters' overly defensive reaction, particularly the implication that they had attempted to bias the design process. One engineer, Robert E. "Gene" Austin, responded, "I don't think the group that generated the report had any ulterior motive except they wanted to get some technology information out to the people working this program for their use."[41]

The NRC Undertakes a Further RLV Study

As a follow-up to the NRC's 1992 study, NASA requested the National Research Council to "assess the reusable launch vehicle (RLV) technology and test programs in the most critical component technologies." The NRC qualified its study by noting that the report "does not address the feasibility of an SSTO [single-stage-to-orbit] vehicle, nor does it revisit the roles and responsibilities assigned to NASA by the National Transportation Policy. Instead, the report set forth the NCR committee's findings and recommendations regarding the RLV technology development and test program in the critical areas of propulsion, a reusable cryogenic tank system (RCTS), primary vehicle structure, and a thermal protection system (TPS)."[42] The committee concluded:

> Materials considerably lighter than those currently used for the tanks and primary structures are required because reaching orbit with an SSTO vehicle (using current technologies) requires that 90 percent of the vehicle's total mass at launch be propellant. In the propulsion area, a significant improvement in the thrust-to-weight (T/W) ratio (sea level) of the engines is necessary—compared to

> the T/W ratio of the two existing large-thrust liquid oxygen/liquid hydrogen engines, the Russian RD-0120 [used as the core engine of the Soviet-era Energia booster] and the U.S. Space Shuttle Main Engine (SSME). Achieving orbit with the required payload is only part of the challenge that has been undertaken in the NASA/industry RLV program. The other, equally important challenge is to demonstrate a system that is capable of achieving a lower cost per launch and be clearly competitive with other launchers worldwide. In the case of the SSTO and maximum reusability, all of the components for the vehicle primary system structures, the cryogenic tanks, the thermal protection system (TPS), and the propulsion system must first be developed. Then it must be demonstrated that these components are reusable with minimal inspections or replacements for at least 20 missions and a have a lifetime of at least 100 missions.[43]

"We Have To Move Beyond the Shuttle": Congress and the RLV Issue

On May 16, 1995, the U.S. Senate's Subcommittee on Science, Technology, and Space held a hearing on the future of American space launches. It brought together key members of Congress, along with representatives of NASA, industry, the aerospace community, and academia. Together, they presented their views on NASA's aging Space Shuttle and the emerging reusable launch vehicle program.

The hearing quickly got down to the essentials of the RLV issue. In his opening statement, Senator Conrad Burns (R-MT), subcommittee chairman, noted that

> [a]s great as the Shuttle has been, all agree it will soon start to outlive its usefulness. The Shuttle operates on 1970s technologies, less sophisticated than our average commercial airplane. Moreover, the Shuttle costs over $400 million per launch to fly.… The challenge before NASA is to make the current Shuttle more cost-effective *while also planning for a post-Shuttle future*.[44]

In the House, Representative Dana Rohrabacher (R-CA), a keen and enthusiastic student of American aerospace, agreed that "if we are going to have cheap and regular access to space, if we are going to be the leader in launch technologies, we have to move beyond the Shuttle." In an extensive statement, he invoked returning to "the old idea of X-vehicles" and praised NASA for seeking stronger partnerships with private industry. Rohrabacher detailed the program for his congressional colleagues, noting the relevant differences between and merits of the DC-XA, X-33, and X-34, and concluded by stressing that the key was "the X-33 itself. Like the X-1 and X-15 experimental planes of the past," he said, "the X-33 will push the state-of-the-art and make possible a whole new generation of commercially developed and operated SSTO launch vehicles."[45]

NASA Associate Administrator John Mansfield briefed Congress on the need and purposes of the reusable launch vehicle, stressing that it was "a fast-paced program, tightly funded, with an aggressive, small management team," and "different" in that it was a "government-industry partnership" with both partners "putting money on the table." Out of this, NASA hoped, would come a decision "early in the next century to build a money-making, large-scale launch vehicle that will take the place of most or all of our expendable launch vehicles and will provide us that long-sought, cheap and reliable access to space, access to space that will allow us to build large-scale industrial facilities in space, access to space that will allow us to have many people constantly in near-Earth orbit, engaged in commerce and science and preparing us to move to the planets. It is only by having large-scale access to low-Earth orbit at low cost that low-Earth orbit will ever be a frontier to exploration of the universe."[46]

In his written statement, Associate Administrator Mansfield noted that the National Space Transportation Policy, as revised by the President in August 1994, envisioned the U.S. private sector playing a greater role in developing and operating next-generation launch vehicle systems. Doing so would require NASA to undertake a technology review enabling a decision to proceed with a subscale RLV flight demonstrator program no later than December 1996. That program, in turn, would enable a shared Government-industry decision by decade's end on whether to proceed with a full-scale operational RLV. Accordingly, in the interim, NASA had to mature technologies required for next-generation launch systems; demonstrate an ability to achieve low development and operations cost; and reduce technical risk to levels sufficient to attract private investors to support development and operation of next-generation launch systems. Mansfield recognized that the RLV program was "uniquely challenging," and to achieve both its technical and business objectives, the program had to take an approach that was "nothing short of revolutionary in NASA's way of doing launch systems development."[47]

This new approach included working in an unusually close partnership with industry; in particular, over the previous year, the Agency executed over a dozen cooperative agreements with industry to cost-share and manage various aspects of the RLV effort. Mansfield told Congress, "We are mounting a vigorous and extremely fast-paced five-year program of technology development centered around a balanced program of ground-based and flight-environment testing—emphasizing smart light-weight, reusable, robust advanced components; high margins, low change-out engines; automated take-off and landing;

small ground crews; low maintenance; and rapid launch turnaround times."[48] That "balanced program" consisted of the DC-XA, the X-33, and the X-34 (see Table 1.1). The X-34 here was the early concept of the program and was terminated in early 1996; it should not be confused with the X-34 as recast after March 1996, which continued through the final termination of the program.

Jerry Grey, a longtime space advocate who served as the Director of Aerospace and Science Policy for the American Institute of Aeronautics and Astronautics (AIAA), the largest professional aerospace science and engineering society in the world, also submitted a statement. In it, he endorsed the program, its emphasis on reducing developmental risk (and thus encouraging private investment in space launch), its emphasis on Government-industry partnering as then pursued in Europe and Japan, and the teaming of the small two-stage X-34 with the larger X-33. He noted that the X-34 "would provide NASA with a valuable early testbed for X-33 technologies and also opportunities to test outside the X-33 envelope. It is the X-15 of the 1990s."[49]

"If an SSTO configuration proves able to meet both performance and operational goals, it should certainly be chosen," Gray wrote. "But defining

Table 1.1: The DC-XA, X-33, and X-34 in Context

Vehicle	First Flight	Purpose
DC-XA VTOL Demonstrator	Mid-1996	To test advanced technologies such as composite graphite tanks and intertank structures, as well as hydrogen leak-detection sensors.
X-33 Advanced Technology Demonstrator	July 1999	To build upon results of ground-based component testing, the DC-XA, and the X-34, and integrated SSTO-based vehicle components, operations, reliability, and business-management aspects. Assumed White House go-ahead no later than December 1996. Cost-shared with industry; intended to form the basis for scaled-up post-2000 next-generation commercially built and operated RLV systems. (The X-33 quickly became the centerpiece of NASA's RLV effort).
X-34 Small Two-Stage Winged Booster	Late 1997	To validate less costly, more operable components and demonstrate industry-led management as well as the economics of reusability. Cost-shared with NASA's contribution capped at $70 million and industry providing more than an equivalent amount.

the optimum configuration is a major objective of the X-33 program. NASA and industry should pick the system that offers lowest cost, highest reliability and best operational features, whether it turns out to be SSTO, boosted, two-stage[,] or uses drop tanks. The last thing we need," he warned[,] "is yet another launch system that has to squeeze out every last ounce of performance the way our present launchers do. Every blue-ribbon panel has agreed we need a robust, low-cost vehicle with conservative design margins. That goal could be prejudiced if the vehicle is constrained to a pre-determined configuration."[50]

John M. Logsdon, the founder-director of George Washington University's Space Policy Institute (a training ground for many space executives), excoriated the Government-industry space community for its failure to move rapidly beyond the Shuttle, noting that America "has lost two decades of launch-related R&D while Europe, Japan, and Russia have developed and are putting into operation modern launchers." The "biggest failure," he believed, "is that 23 years after the approval of Shuttle development, the United States still has not begun to develop next-generation transportation systems." He contrasted the history of space launch to the history of commercial aviation, noting that "[b]y 23 years after the beginning of the flight of the [Douglas] DC-3, we were flying [Boeing B-] 707s, with a number of systems in between." He advised that "[i]f we are going to be a leading spacefaring nation, we must address the space launch issue [and, to that end] both the X-33 and X-34 programs are steps in the right direction," adding somewhat wistfully, "I hope that we can avoid repeating that experience and [resist] the temptation to try to make a single system all things to all people."[51]

In questioning the witnesses, the subcommittee probed the relationship between the proposed X-33 and X-34. NASA's John Mansfield justified pursuing both by emphasizing each synergistically benefited the other, noting "the X-34 vehicle would allow us to demonstrate reusability, the durability of these composite structures and the automatic control mechanisms, and the thermal protection system at the earliest possible date. That data will be very useful for the X-33 program. So in summary, they are different in scale, one is larger [the X-33], one is smaller [the X-34]; they are different in time, one is earlier [the X-34], and one is later [the X-33], but they are similar in that they demonstrate the technologies needed for the full-scale vehicle."[52] Logsdon seconded Mansfield, noting that while the X-34 and X-33 were "fundamentally different programs," with the X-34 at most "launching 1,500-pound payloads into space, and the X-33, which will be the workhorse launching 20,000-pound cargo," there was a beneficial synergy between them. "Since we have done nothing for 20 years," he concluded, "I applaud the fact that we are beginning now to do something at both ends of the spectrum."[53]

Potential Program Problems and Conflicts

In May 1995, the U.S. Congress's Office of Technology Assessment identified a number of space policy issues for Congress to consider as it debated the funding, oversight, and legislative requirements of the new space transportation policy. The report, which was prepared for the House Committee on Science, was the work of a 24-member advisory panel consisting of representatives from 14 aerospace companies, 4 universities, 3 consultants, and one each from a foundation, investment firm, and a retired NASA engineer. Ronald Brunner, Director for Public Policy Research at the University of Colorado, chaired the advisory panel, and Christopher M. Waychoff served as staff project director. Orbital and Rockwell International, as well as Lockheed Martin and McDonnell Douglas, each had a representative on the panel.[54]

The panel's report examined the new National Space Transportation Policy outlined in the White House announcement on August 5, 1994. The report also reviewed the implementation plans of the Department of Defense, NASA, and the Departments of Transportation and Commerce. The panel identified a number of issues, as well as potential problems and conflicts, including the ones summarized here:

Lack of Consensus on U.S. Policy Goals

The panel noted that the U.S. space transportation and industrial base was in "a period of tumult and uncertainty brought about by the end of the Cold War, a constrained fiscal environment, and a pending shift in responsibilities from the public to the private sector." The report noted that most observers agreed that reducing costs and improving reliability were important objectives but added that it might be difficult to achieve lower costs "without a clearly articulated, long-term plan supported by adequate funding." In this regard, the panel added that the Office of Technology Assessment had previously noted that "until the nation chooses *what* it wants to accomplish in space, and what the U.S. taxpayer is willing to pay for, neither the *type* nor number of necessary launchers and facilities can be estimated with accuracy." They added that "[t]he Administration has outlined some broad national space goals, such as achieving the International Space Station [but] has not made clear…how specific goals relate to each other." The panel likewise cautioned that many Government and industry officials were skeptical and that "[t]hese officials point out the previous commitments to new space transportation systems that failed to produce operational vehicles despite less severe budget constraints (e.g. the National Launch System, the Advanced Launch System, the Air Force Space Lifter, the Shuttle C, the Shuttle II, and the National Aero-Space Plane)."[55]

Government Demand Dominates the Space Transportation Market

The panel noted that "[t]he U.S. government and industry remain tightly entwined through R&D and procurement contracts, federal regulations, and the need for licenses, despite the rise of commercial space launch markets…. Moreover, some launch providers are reluctant to take the steps necessary to make their launch operations more commercially price-competitive, because the changes might conflict with government requirements or the government might demand similar savings."[56]

Competing Interests Make Common Strategy Difficult

Another difficulty identified by the panel was that even though all members of the space transportation technology and industrial base recognized the critical need to reduce the cost of space transportation, they were faced with differing interests that make it difficult to agree on a common strategy. For example, whereas NASA wanted to replace its aging Space Shuttle fleet with a new, low-cost RLV in the medium launch class, most industry representatives wanted to focus on the development of medium, reusable vehicles designed to recapture lost worldwide commercial market share, and small launch vehicle producers and selected space scientists wanted to maintain U.S. leadership in small launch vehicles.[57]

Space Transportation Funding and Division of Responsibilities

The panel noted that the administration had taken a step toward reducing conflicts and redundancies by placing the Department of Defense in charge of expendable launch vehicles development and NASA in charge of continued Space Shuttle operation and RLV development. Furthermore, each organization had initiated programs to address costs. This would necessitate increased coordination between DOD and NASA, but conflicts over how to handle the development of new space transportation systems would most likely occur.[58] The panel added, however, that

> [a]t present, it appears that resolution of these conflicts will be achieved via negotiation between DoD and NASA on a case-by-case basis, possibly with some mediation by a third party within the executive branch. Such negotiations may succeed in satisfying both DoD and NASA, but could fail to account for interests of all relevant parties, especially those in the private sector.
>
> Such negotiations could also lead to programmatic redundancies. In the absence of central authority or leadership, DoD and NASA may discount potential redundancies and simply continue to promote those projects that best address their own organization

> requirements. As a result, hard space transportation policy choices may go unmade. The panel added that even a central authority to resolve differences might not work because "[g]iven the considerable bureaucratic and political weight of DoD and NASA, competing organizational interest could potentially override the wishes of a central authority. Furthermore, existing legal and organizational obstacles may prevent the level of interagency and private sector coordination sought by a central authority."[59]

In addition, the panel pointed out that DOD and NASA had collectively proposed a sizable number of new space transportation technology initiatives and that these had added their own complexity and challenges, noting that "[w]hile this multitrack approach may reduce the overall risk of pursuing new space transportation systems, it may also lead to potential conflicts and redundancies and higher overall costs. For example, development of a commercially competitive EELV [evolved expendable launch vehicle] by DoD could undercut NASA's effort to commercialize a follow-on X-33 by reducing the incentive for private investors to fund a technically risky RLV."[60]

The panel also referenced both the potential value of the original X-34 concept to the larger, more complex X-33 and, ironically, the risk that X-34 itself might be abandoned as being too "operationally" focused. "As for NASA's dual-track RLV development strategy, they concluded, "the Agency believes that early X-34 test flights could positively affect X-33 development by steering it toward or away from certain technologies. Moreover, proponents note that the X-34 could generate significant benefits for the government, industry, and consumers of space-based services if its target of threefold cost reductions for launching small payloads are achieved. Critics, however, have suggested canceling the X-34 program, arguing that it is geared toward developing an operational vehicle, not an experimental vehicle, and that its cancellation would not affect the technological success of the X-33 program."[61] It should be noted that the X-34 program referenced above related to the first "large X-34" program, as opposed to the follow-on X-34 that called for a much smaller technology test bed demonstrator.

The panel raised specific issues relating to the X-33 by noting that some analysts thought that the program was geared too closely to the development of a vehicle to get to the Space Station rather than toward the development of a fully SSTO technology demonstrator. Other critics suggested a competitive fly-off for competing concepts in order to decrease the possibility of selecting the wrong technology. They also believed that a fly-off would raise the likelihood of increasing competition in the domestic vehicle launch industry. A downside of this strategy was that a larger near-term budget than currently planned would be needed. There also was concern over whether NASA has adequately defined the criteria for judging the success of the X-34 program.

Finally, the panel questioned whether DOD payloads would be available during the early testing of a commercial RLV, noting that "NASA and its commercial partners will need a sufficient number of payloads to both prove the reliability of RLV technology and attract potential investors. DoD officials, however, do not wish to repeat their negative experiences with the Space Shuttle and are, therefore, hesitant to contribute DoD payloads to the RLV until it is proven. Unless NASA and its industry partners can entice other payloads to fly aboard an RLV, DoD's reliance could potentially drive up the price of launching payloads on the RLV."[62]

Use of Foreign Technology

The panel noted that the use of foreign technologies in U.S. space transportation systems could "improve the efficiency of U.S. launch systems, assist U.S. access to space, and improve U.S. competitiveness in the international space transportation market… [and that] Russian hardware and space transportation skills can fill important gaps in U.S. capabilities." The panel concluded that the U.S. also might benefit from European space transportation technology. They added that U.S. national security demanded that the United States maintain a viable launch capability and technology base. In regard to foreign technology, the panel stated that "[t]he simple purchase of either vehicles or launch services appears to be less attractive than joint ventures, co-production of vehicles and/or systems, and analogous business arrangements, as ways of harmonizing these different interests."[63]

Following the conduct of the above studies, NASA was now ready to move forward to the conversion of the DOD DC-X Delta Clipper to the NASA DC-XA Clipper Graham and to the design and fabrication of the X-33 and X-34 vehicles. But first, it should be noted that the United States was not the only country working on the development of SSTO and reusable launch vehicles.

Foreign Interest in Reusable Launch Vehicles

In addition to NASA's reusable launch vehicle and single-stage-to-orbit programs, a number of other countries, including Japan, Russia, the United Kingdom, Germany, and, most recently, China, were undertaking their own studies and vehicle development work. For example, five aerospace engineers in Japan noted in their April 2001 AIAA paper that the National Aerospace Laboratory of Japan (NAL) had initiated studies of the spaceplane concept, including SSTO vehicles, and had worked on the development of required hypersonic technology bases since 1987. They added that the NAL

> will continue the study of the A/RCC (Air-breather/Rocket Combined Cycle) engine powered spaceplane concept [and that] wind tunnel tests should be planned to provide aerodynamic forces and moments of the vehicle [and that] CFD [computational fluid dynamics] analysis will support further understanding in detailed aerodynamic performance around the spaceplane.[64]

Japan's National Space Development Agency (NASDA) actually launched a development program, the H-II Orbiting Plane Experimental (HOPE-X), hoping to test it in 2005. The HOPE-X was "focused on the establishment of the reentry technologies of unmanned winged vehicles…." The main objective of this program was to establish the R&D plan for future Japanese launch vehicles. Several prior flight experiments had already been successfully conducted. However, due to a number of successive launch failures of expendable vehicles, the Government halted the HOPE-X program in August 2000, concentrating instead on the development of a new space transportation R&D plan.[65]

In Russia, V. Lazarev, of the Tsentral'nyi Aerogidrodinamicheskiy Institut (TsAGI, the Central Aerohydrodynamic Institute, which is Russia's equivalent of the NACA/NASA), in agreement with other aerospace engineers, identified the problems associated with reusable hypersonic vehicles, including thermal loading, selecting materials, increasing the payload mass fraction, and defining a rational service life for a reusable launcher on the basis of the cost criterion at various reliability levels. In regard to serviceability, he noted that "[a]lthough the structure of reentry vehicles with a low L/D [lift-to-drag] ratio (e.g., Soyuz, Progress) and high L/D ratio (e.g., Space Shuttle, Buran) has proven its serviceability, it cannot be a prototype for the structure of airspace planes and launch systems, because it is strictly oriented to one motion regime and requires serious repairing work after each flight." Lazarev added, however, that a "highly effective structure of hypersonic aircraft can be developed as a result of joint activity of specialists in the field of materials, production engineers and designers." He qualified this statement by adding, "[I]n the conditions when there are many different concepts of future hypersonic aircraft, while the demand for them is relatively limited and the cost of each concept is high, the decision of main research centers of the world to favour developing hypersonic technologies over full-scale designs seems reasonable." Lazarev concluded by stating that the "[h]igh costs of initial materials, manufacturing processes[,] production and experimental facilities and a considerable volume of scientific work dictated by the multitude of different possible vehicle concepts and technical solutions, make an international co-operation of various scientific and design organizations highly desirable."[66]

In his 1992 AIAA paper, which preceded NASA's single-stage-to-orbit and RLV programs, D.E. Koelle of Deutsche Aerospace provided the following background summary:

> The key problem in the past was performance, resulting in four-stage or three-stage launch vehicles. The introduction of liquid hydrogen/liquid oxygen for upper stages reduced the number of stages required for LEO [low-Earth orbit] to two, and today we are working towards single-stage vehicles.
>
> There is still much discussion of whether SSTOs are feasible. This concept doubtless represents the ultimate solution, however, beyond feasibility it must be economically competitive also.
>
> The optimum system solution also depends on the transportation task. In the same way we find different types of vehicles on ground like cars, busses and trucks, there are different optimal concepts for space transportation.... In parallel we see the advent of winged launch systems (as suggested by the late Prof. [Eugen] Sänger already in 1932). The air-launched Pegasus on the one hand, as well as re-entry gliders like the Shuttle Orbiter or the European Hermes Project on the other hand can be considered as forerunners of future two-stage and finally eventually single-stage winged vehicles.[67]

In the United Kingdom, Reaction Engines Limited has been working on development plans for the Skylon reusable launch vehicle. According to the company, the Skylon is "an unpiloted, reusable spaceplane intended to provide reliable, responsive and cost-effective access to space."[68] In regard to China's developmental effort, while few details are available, popular literature suggests that China is developing an experimental vehicle resembling the X-34. Reputedly named Shenlong ("Divine Dragon"), it is intended for air-launch from a modified Xian H-6 bomber (the Chinese-produced derivation of the Soviet-era Tupolev Tu-16 Badger), in the same fashion that the United States' North American X-15 was air-launched from a Boeing NB-52 Stratofortress.

In early 2001, Teal Group analyst Marco Antonio Cáceres commented on the reusable launch vehicle programs then underway worldwide by noting that

> [t]here are roughly a dozen reusable launch vehicle (RLV) development efforts worldwide, including a few Russian and European programs for which there [is] little information. Most of these programs are not much farther along than the concept design

> phase. Some, such as Rotary Rocket's *Roton* program, have actually come up with a demonstration vehicle that has flown.
>
> What seems clear right now is that there are no proposed RLVs that are…close to being operational. All of these programs lack funds to complete technology testing and build full-fledged flight models, much less fleets of vehicles. NASA's Space Shuttle is still the only RLV family on the market, and chances are that it will remain so for the foreseeable future.
>
> The downside to the Shuttle is obviously the fact that it is so expensive to operate and maintain—somewhere in the neighborhood of half a billion dollars per mission. If cost was not such a major issue, NASA would probably not be so preoccupied with searching for a replacement.[69]

Proceeding from Studies to Testing

In 1995, commenting on the many studies that addressed the development of single-stage-to-orbit and reusable launch vehicles, Delma C. Freeman and Theodore A. Talay, from NASA's Langley Research Center, and Robert E. "Gene" Austin, from NASA Marshall, noted that

> [c]ost-effective, reliable space transportation is a major focus of current government and commercial launch industry efforts. The paths to this goal range from incremental improvements to existing launch systems, including the current fleet of expendables and the Space Shuttle, to new systems that hold the promise of opening the space frontier to a variety of new industries. In the latter case, numerous studies in the past have examined many new and, in some cases, innovative concepts for achieving cost-effective space transportation. Estimates of performance, greatly reduced costs, and airplane-like operations must first hold up to the rigors of detailed analysis. Confirmation of results requires proceeding to technology and test programs.[70]

Eventually, NASA *did* proceed with the development and testing of two single-stage-to-orbit test bed vehicles (the DC-XA and X-33) and one reusable test bed vehicle (the X-34), which, abandoned in its initial form in 1996, later emerged Phoenix-like in smaller form.

Endnotes

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40. Martin Burkey, "MSFC to steer clear of X-33," *The Huntsville Times* (May 18, 1995): B1–2.
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47. Ibid., pp. 12–15.
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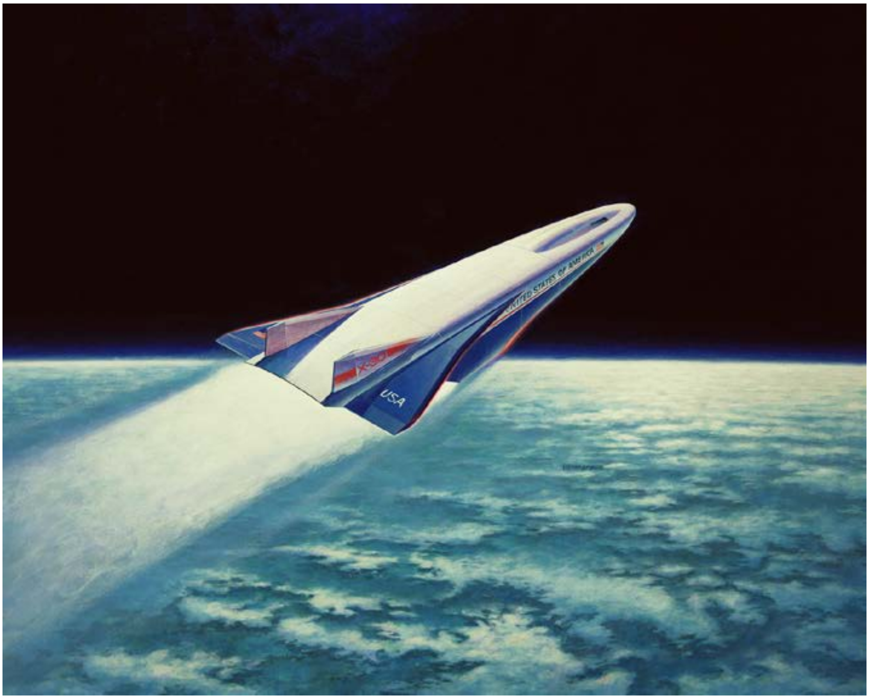


Even though ultimately unsuccessful, the National Aero-Space Plane (NASP) program constituted an important predecessor SSTO RLV design effort to the studies of the 1990s. (NASA)

CHAPTER 2

Three Pathways to Space

The X-34 represented the culmination of a study effort that had spawned what were, in effect, three separate pathways to space. These were defined and examined through an Agency-wide Reusable Launch Vehicle (RLV) Technology Program reflecting both NASA's internal influences and external ones from outside the Agency.

The Reusable Launch Vehicle Program

NASA's Reusable Launch Vehicle (RLV) Technology Program grew out of the *Access to Space* study, congressional action, and the National Space Transportation Policy (NSTP) signed by President Clinton on August 5, 1994. The program constituted a de facto partnership between NASA, the United States Air Force, and private industry to develop a new generation of single-stage-to-orbit (SSTO) reusable launch vehicles. The SSTO/RLV program was committed to the development of new operations and component technologies, as well as the establishment of an industry-Government relationship designed to bring significant changes to the space launch industry.

This program included three separate experimental vehicle programs:

1. the Delta Clipper–Experimental Advanced (DC-XA, an outgrowth of the DC-X),
2. the X-33 Advanced Technology Demonstrator, and
3. the X-34.

Over its evolution, the X-34 progressed from an initial two-phase program (the proposed X-34A and X-34B) into a final "downsized" Orbital Sciences X-34 Technology Testbed Demonstrator (X-34 TTD), ultimately pursued by NASA. These distinctions between variants are important to make, and unless otherwise stated, the discussion in this chapter is primarily on the initial two-phase X-34A/B concept for the X-34, and not the "ultimate" X-34 TTD, which is discussed subsequently.[1]

In addressing the historical context of this "next generation" of both military and research X-planes (including the X-33 and X-34), noted aviation editor George C. Larson wrote in the Smithsonian Institution's prestigious *Air and*

Space Magazine in June 2000 (while the X-33 and X-34 programs were well underway) that

> New research aircraft are being announced at a rate that hasn't been seen since the post–World War II period, when the X-1 became the first in a distinguished lineage of craft designed predominantly for a single purpose: exploration of high-speed aerodynamics. During the late 1940s and throughout the 1950s, new shapes featuring swept wings, variable wings, tiny wings, and nearly no wings at all flew at speeds ranging from Mach 1 to more than Mach 6 and ventured out into the fringes of space.… Now a new generation of vehicles will take it from there.
>
> …The highly focused research of the new craft, most of which are designed to prove various concepts, does not depend on onboard humans. And humans are increasingly unnecessary as more powerful avionics, navigation systems, and flight control computers are being matched up with lighter and more durable materials for reentry heat shields, as well as radical new methods for maneuvering without the use of traditional control surfaces such as elevators, ailerons, and rudders. This trend is being echoed in military aircraft design, which is also increasingly turning to remotely piloted vehicles.
>
> …The first generation of research craft were designed solely to conduct research in aerodynamics. The latest generation are combining high-speed research in aerodynamics and spaceflight with exploration of a realm that research aircraft have never probed before: economics. Reduced size and weight, smart avionics that replace the pilot, new low-cost materials that resist high-Mach heat—all signs point to a future in which performance remains the foremost goal, but affordability runs a close second.[2]

The importance and interrelationship of the three separate vehicle programs were reviewed in NASA's Delta Clipper rollout press release that noted that "[t]he knowledge and experience acquired in developing and test flying the DC-XA will be used by NASA and an industry partner in development of the X-33, a larger advanced technology demonstrator." The press release likewise referenced the importance of the X-34 program by stating that "[t]he X-34, a small technology vehicle to be developed and flight tested by 1998, also will contribute valuable data to the X-33 program, which in turn could lead to a national, industry-led decision to develop a commercial reusable launch vehicle early next century."[3]

The overall program objectives common to all three demonstrators included

1. development of an integrated systems test bed for advanced technologies;
2. demonstration of capabilities in realistic ground and flight environments for a next-generation system;
3. demonstration of operability, maintainability, and reusability required for a next-generation system;
4. demonstration of rapid prototyping; and
5. demonstration of the ability to perform "faster, better, cheaper."

An additional objective that applied specifically to the X-33 program was the demonstration of a mass fraction scalable to full-scale single-stage-to-orbit use.[4] Two of the RLV programs, the X-33 and X-34, were conducted under NASA's new management concept popularly known as "faster, better, cheaper."

A New Way of Doing Business—the "Faster, Better, Cheaper" Concept

Following his appointment as NASA Administrator in 1992, Daniel S. Goldin initiated a widely heralded "faster, better, cheaper" management program intended to "revolutionize the structure of NASA."[5] Its objectives were "to cut costs, take greater risks, and dispatch [robotic] spacecraft that actually flew."[6] Proponents of the initiative also sought to achieve economy without significant reductions in reliability. These objectives were to be achieved through changes in technology and management. For a project to be included as part of the "faster, better, cheaper" initiative it had "to have a substantially reduced cost ceiling, to be placed on a compressed development schedule, and to have someone with executive responsibility in NASA designate it a 'faster, better, cheaper' project."[7]

The concept represented a major cultural change—indeed a veritable reversal—compared to how NASA had previously operated, with the exception of some of its constituent Centers, such as the then-Dryden Flight Research Facility (now Armstrong Flight Research Center), which had a record of promoting and executing some remarkably sophisticated research projects quickly and economically. As a result, the new management initiative met with significant bureaucratic resistance within the Agency. Prior to the "faster, better, cheaper" management initiative, NASA had relied primarily on a systems-management approach drawn largely from the defense acquisition world, which was based on what had worked in the 1950s and during the Apollo era, an era of big projects, lofty goals, and robust funding. But it is a veritable natural law that, over time, organizations tend to become both more complex and bureaucratically moribund, developing an internal sclerosis and sluggishness.

In NASA's case in the early 1990s, this involved ever-larger staffs, the involvement of multiple Centers, more testing, longer time schedules, and higher costs, and all at a time when the Agency was facing arguably the most serious funding stringencies and management challenges of its history. Under Dan Goldin, space historian and policy analyst Howard E. McCurdy, noted, "'[f]aster, better, cheaper' became the primary means of testing whether alternatives to formal systems management could be made to work."[8] The change in management techniques—emphasizing, as McCurdy put it, the "dynamics that arise in small, cohesive project teams" (such as Lockheed's legendary "Skunk Works")—started a controversy within the Agency that lasted throughout the time period of the initiative and well beyond as well.[9]

Having decided to boldly go where no Agency administrator had gone before, Goldin was undeterred by any naysayers and enthusiastically embarked upon his "faster, better, cheaper" quest.[10] Commenting in 1995 on the Agency's experience over the previous two years of pursuing this new way of doing business with a significantly reduced budget, he stated:

> The accomplishments we have made over the past two years to reinvent our programs have allowed us to absorb significant cuts in our budget. We have initiated the first steps by reducing our five-year budget plan by 30 percent since 1993. Now we have an opportunity to continue reinventing NASA as an institution, which will result in even further savings to the American taxpayer and help reduce the deficit for future generations…. The result is a new blueprint for the future of our Agency. The plan we will follow defines five areas that the Administration, the Congress, and the American people have come to recognize as NASA's mission. These strategic enterprises include: Mission to Planet Earth, Aeronautics, Human Exploration and Development of Space, Space Science, and Space Technology. With these programs as a foundation, we now enter the second phase of reinventing NASA. This means we're going to revolutionize the structure of NASA—our workers, our relationship with contractors, and our facilities. In a word, *everything.*[11]

The projects under Goldin's initiative, including the X-33 and X-34 (though not the inherited DC-X/XA), started with great success. Between 1992 and 1998, 9 of the 10 "faster, better, cheaper" projects were successful. Only one project failed (the Lewis Earth Observation Satellite), and another one was canceled (Project Clark). A drastic change in fortunes for NASA's "faster, better, cheaper" projects came in 1999, however. The Wide-Field Infrared Explorer (WIRE), which was a cryogenically cooled telescope, failed in March due to the premature separation of the vehicle's protective cover; the Mars Climate

Orbiter failed in September; and the Mars Polar Lander and Deep Space 2 (carrying twin microprobes named Amundsen and Scott in honor of explorers Roald Amundsen and Robert Falcon Scott) failed in December.

In total, 16 "faster, better, cheaper" projects were undertaken between 1992 and January 2000; all of the missions involved small vehicles, and most of them were designed to test new technologies. Of these projects, six of the missions (38 percent) resulted in some sort of failure.[12]

The extent to which the "faster, better, cheaper" initiative impacted the above failures is debatable. Many critics of the initiative claimed that it was "too much, too cheap, too soon" and that perhaps one could expect to attain one or two of the "faster, better, cheaper" goals, but not all three. But program proponents responded that there were many successes and that most of the failures had resulted from mistakes that either would not have been detected under different management techniques or that had not been detected due to improper application of the "faster, better, cheaper" procedures. (Indeed, a special assessment team reviewing the failure of the three Mars missions concluded that the "faster, better, cheaper" approach was an effective concept that should be continued).[13] A 2010 assessment of the lessons learned from NASA's "faster, better, cheaper" initiative noted that

> [A] closer examination of NASA's FBC [faster, better, cheaper] reveals an admirable record of success, along with helpful and illuminating lessons for anyone involved in developing and fielding high-tech systems. Far from an embarrassing failure or proof that program managers must 'pick two,' the FBC initiative actually improved cost, schedule, and performance all at once. NASA's experience provides an insightful organizational roadmap for sustaining mission success while respecting constraints of time and funding.[14]

Whatever the position one takes, the "faster, better, cheaper" management construct must be kept in mind as one examines the emergent RLV program, and NASA's many other 1990s activities.

NASA and OMB Agreement on Initial Single-Stage-to-Orbit Program Criteria

NASA and the Office of Management and Budget (OMB) entered into an agreement on December 30, 1994, which set criteria for the decisions to proceed to a Phase II and Phase III of the single-stage-to-orbit program. Agency and OMB authorities established criteria in accordance with an earlier 11-point agreement between NASA and OMB signed on November 25, 1994.[15]

The Phase II decision was "contingent on four programmatic criteria as well as two enabling technical and two enhancing technical criteria, all of which are supported by numerous specific technical metrics at the project and task level during Phase I."[16] Phase II included the DC-XA Delta Clipper, the X-34, and the preliminary design concept for the X-33. The DC-XA program criteria stressed demonstrating, "by maintenance of run-out budget projections, that a jointly funded, Government/industry project team can design, develop, and integrate advanced technology components (including cryogenic tankage and primary structure) into an experimental flight system within budget."[17] (Intriguingly, the agreement noted that actual flight testing was not required in order to satisfy this criterion). Overall, NASA and OMB stressed, the X-34 program was to demonstrate that the partnership of a co-funded, industry-led Government/industry project team could "successfully show consistent progress toward the development of an advanced technology demonstrator with commercial application to the space launch market."[18]

Vertical Visions: The DC-X/XA Delta Clipper/Clipper Graham

The NASA DC-XA Delta Clipper was an advanced version of the earlier DC-X that the Ballistic Missile Defense Organization (BMDO) tested as part of its single-stage-to-orbit space access program. The name—DC-X—was meant to consciously recall the immensely successful Douglas DC-1 transport that had spawned the DC-2 and DC-3 that revolutionized global air transport in the mid-1930s. The DC-X was a one-third-scale, suborbital version of a proposed United States Strategic Defense Initiative Organization (SDIO) single-stage launch vehicle designated the DC-Y. (As is traditional in American designation schemes, X indicates an experimental system, while Y indicates a prototype of a possible production system).

The planned BMDO program involved three phases:

- Phase I: awarding contracts to study the various types of potential SSTO vehicles.
- Phase II: awarding the contract to fabricate the DC-X.
- Phase III: the fabrication and flight testing of the DC-Y.

The mission of this program "was to demonstrate the practicality, reliability, operability, and cost efficiency of a fully reusable rapid turnaround single-stage rocket, with the ultimate goal of aircraftlike operations of RLVs."[19] The program was designed to use existing technology and systems to demonstrate the feasibility of building RLVs for suborbital and orbital flight that could fly into space, return to the launching site, and to be ready for the next mission within 3 days.

Development and Flight Test

McDonnell Douglas Space Systems Company of Huntington Beach, California, won the Phase I SDIO competition with a single-stage concept, funded under contract SDIO84-90-C-0030, receiving $59 million in August 1991 to fabricate the DC-X Delta Clipper. The name reflected both the company's extraordinarily successful Thor-Delta rocket and the 19th-century commercial clipper ships that opened new sea routes to international trade.

Prior to selecting the final concept, the McDonnell Douglas team evaluated three different conceptions for a single-stage reusable, safe, and reliable launch system that had a fast turnaround time between flights:

1. Horizontal takeoff and landing (HTOL);
2. Vertical takeoff and horizontal landing (VTO-HL); and
3. Vertical takeoff and landing (VTOL).

McDonnell Douglas selected the vertical takeoff and landing concept with nose-first reentry. This selection was based on their findings that a VTOL vehicle represented the lowest cost to acquire and operate, had the least sensitivity to uncertainties in predicted weight and performance, and had operational flexibility (For details of this concept, see Table 2.1).

The concept study team identified two issues associated with the Delta Clipper operating concept: 1) transitioning from a nose-first reentry attitude to a base-forward landing and 2) making a vertical powered landing. The study team noted optimistically that "unique technology issues associated with nose first reentry followed by vertical landing have been resolved by ground test and simulation."[20] In addition, they concluded that "the VTOL configuration has advantages over horizontal landing designs in terms of lateral loads during abort maneuvers and reduced sensitivity to winds and gusts during landing."[21]

DC-X proponents hoped it would lead to a future single-stage-to-orbit reusable launch system, the VTOL McDonnell Douglas DC-XA, shown in this conceptual depiction. (NASA)

Table 2.1: DC-X Delta Clipper Specifications[22]

Width	13 ⅓ feet at base, conical shape
Height	40 feet
Weight (empty)	20,000 pounds
Weight (with propellants)	41,600 pounds
Propellants	LOX and liquid hydrogen (LH_2)
Propulsion	Four Pratt & Whitney RL-10A5 rocket engines, each engine throttleable from 30 percent to 100 percent; each engine gimbals from +8 to –8 degrees
Thrust	13,500 pounds static thrust each
Reaction controls	Four 440-pound-thrust gaseous oxygen, gaseous hydrogen thrusters
Guidance, navigation, and control avionics	Advanced 32-bit, 4.5-mips computer; F-15 navigation system with ring laser gyros; F/A-18 accelerometer and rate gyro package; global positioning satellite P/(Y) code receiver; digital data telemetry system; radar altimeter
Primary contractor	McDonnell Douglas

Beginning in 1993, the DC-X (officially designated as the SX-1, for Spaceplane Experimental) underwent a series of tests conducted by the United States Air Force's Phillips Laboratory at Kirkland Air Force Base in New Mexico as part of the BMDO's Single Stage Rocket Technology Program.[23]

The DC-X was not itself an operational vehicle capable of orbital flight but instead was a test bed vehicle to demonstrate the feasibility of suborbital and orbital RLVs. The design emphasized "simplified ground and flight operations, vehicle maintenance, rapid turnaround, and operational characteristics that would also be relevant to future orbital vehicles."[24]

Between August 18, 1993, and July 7, 1995, the DC-X completed eight test flights at the U.S. Army's White Sands Missile Range (WSMR) in New Mexico. The first test flight lasted 59 seconds and verified flight-control systems and vertical-landing capabilities. Two additional flights followed during 1993; two were flown in 1994; and a final three flights were flown in 1995. The longest, on June 20, 1994, lasted 136 seconds. During the next flight (the fifth) on June 27, 1994, a ground equipment explosion ripped a 4- by 15-foot hole in the vehicle's aeroshell, causing the ground controller, former astronaut Charles "Pete" Conrad, to activate the DC-X's "autoland" computer abort program. The vehicle made a successful intact abort landing, an aerospace first.[25] Commenting on this flight, Air Force Lieutenant

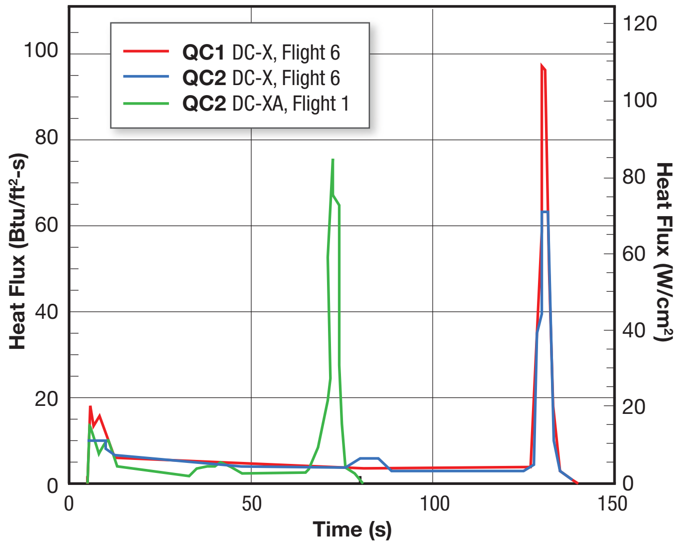
Colonel Jess Sponable, BMDO's Single Stage Rocket Technology program manager, stated:

> This anomaly resulted in successful demonstrations of several important firsts: executing the autoland sequence demonstrating an "aircraft-like" abort mode; landing on the gypsum, demonstrating the ability to land future SSTO vehicles virtually anywhere; and demonstrating the system's toughness and robustness, since the DC-X continued to fly despite the aeroshell damage.[26]

The final DC-X flight, on July 7, 1995, reached an altitude of approximately 8,800 feet and demonstrated the vehicle's turnaround maneuver. On this last flight, the vehicle's aeroshell cracked during landing, damaging the vehicle and ending the flight tests of the DC-X.[27]

Despite its somewhat ignominious conclusion, the DC-X's test program had achieved some notable technical accomplishments. These included demonstrating engine differential throttling for flight control, using gaseous oxygen/hydrogen reaction control thruster modules, and achieving engine performance that, together, would enable maneuvers necessary following reentry. Also, the goal of conducting ground operations with a small number of people was achieved, although the objective of rapid system turnaround—that is, flying, recovering, readying, and flying again, like a commercial airliner or military transport—was not achieved.[28]

In May 1994, NASA was designated as the lead agency for the SSTO program and the Department of Defense was designated as the lead agency for expendable rockets. Accordingly, in July 1995, the Department of Defense transferred the reusable DC-X program to NASA. The vehicle had been returned to McDonnell Douglas for conversion to the DC-XA, which became one of the three vehicles in NASA's SSTO/RLV program. During the rollout ceremony for the refurbished NASA Delta Clipper, Dan Dumbacher, NASA's Marshall Space Flight Center DC-XA project manager, stated that "[t]his is a radically different vehicle from the DC-X that flew last year in tests conducted for the Air Force.... Many technology innovations have been introduced to the vehicle and when we test fly it this spring we'll be writing a new page in the history of space transportation systems." The new technology included a composite hydrogen tank made of graphite-epoxy composites that weighed 1,200 pounds less than the aluminum tank used for the DC-X. Additional new technologies included a Russian-built aluminum-lithium alloy liquid oxygen tank; a composite intertank connecting the hydrogen and oxygen tanks; and an auxiliary propulsion system consisting of a composite liquid hydrogen feedline and valve and a liquid-to-gas conversion system in the flight-control system.[29]



The DC-X and DC-XA programs returned valuable information both on the behavior of VTOL rocket systems and on the unique thermal protection challenges faced by such craft. Here is a plot of heating results from tests of ceramic thermal protection systems affixed to the base heat shield of the two vehicles from NASA TM-110430. (NASA)

The DC-XA rolled out on March 15, 1996, and arrived at White Sands on March 22. The five planned flights were to "focus on the basic functionality of the DC-XA system and its readiness to conduct regular flight operations," including vehicle verification, validation of its control hardware and software, the operational utility of its 3-person control center and 15-person support team, and the readiness of the DC-XA for operational turnaround and subsequent flights.[30]

The vehicle had two engine tests on May 4 and 7 and completed four of the five planned test flights between May 18 and July 31. The first flight was on May 18, when it flew for 62 seconds, reaching an altitude of 801 feet, and transiting laterally for 350 feet before landing. The aeroshell caught fire during the extended landing approach, causing minor damage that was quickly repaired. During the second flight on June 7, the DC-XA flew for 63.6 seconds. It attained an altitude of 1,936 feet and transited laterally for 590 feet before landing. The third flight, on June 8, came after a 26-hour turnaround and also set a duration and altitude record (142 seconds and 10,302 feet, respectively).

The DC-XA took off on its fourth flight on July 31. By this time, NASA had changed the name of the DC-XA from Delta Clipper to Clipper Graham in honor of Lieutenant General Daniel O. Graham, an outspoken advocate of ballistic missile defense and American space supremacy who had recently died.[31] At first all went well, and the DC-X reached 4,100 feet, including maintaining control during a pitchover maneuver and then returning to a vertical orientation for its descent. As the DC-X touched down from its 140-second flight, one of its four landing struts failed to extend, pitching it over. The subsequent impact broke up its internal tankage and plumbing, released the remaining volatile propellants and triggered a catastrophic series of three explosions over the next 90 seconds.[32]

Noted space historian Andrew J. Butrica described the fiery *Götterdämmerung* that followed: "The first explosion ignited the composite shell and the avionics rack.… Then a second explosion of liquid oxygen from the aluminum-lithium tank rocked the mishap scene.… About one minute after the second explosion, the hydrogen tank blew up and scattered aeroshell and hydrogen tank composite material over the accident scene."[33]

Following the loss of the DC-XA/Clipper Graham, NASA appointed a five-member accident board, chaired by former astronaut Vance Brand, to investigate the mishap. Following a 5-month investigation, the Brand board released its findings in January 1997, concluding that

> [t]he primary cause of the vehicle mishap was that the brake line on the helium pneumatic system for landing gear #2 was not connected. This unconnected brake line prevented the brake mechanism from being pressurized to release the brake and resulted in landing gear #2 not extending. The vehicle became unstable upon landing, toppled onto its side, exploded and burned.[34]

The board identified the following contributing causes and lessons learned:

- Design of the system for gear stowage required technicians to break the integrity of the helium brake line after integrity had been already verified. No other check was conducted to re-verify the integrity of the system after disconnection and reconnection of the line was completed.
- Landing gear stowage was never identified as a critical process. No special steps were taken to ensure the readiness of this system for flight.
- During the gear stowage process, there was no record of checking off steps or evidence of cross-checking or work by another person.
- Distraction or interruption of the mechanical technician during gear stowage operations may have contributed to the non-connection of the brake line.[35]

The Board made the following recommendations:

- Critical procedural steps should be identified during systems design and flagged as critical in vehicle operations procedures. Then, independent verification of all critical steps should be performed during execution of operations procedures.
- NASA should perform a handover design review when any program is transferred from another agency.
- The "rapid prototyping" philosophy was cited as a rationale for employing minimal written procedures. The concept should be revisited from an operations perspective.
- Prelaunch processing documentation and data tapes should be kept as historical records for each flight at least until a mission is completed and degree of mission success is understood.
- Up-to-date hazardous materials information should be supplied to the appropriate hazardous response agencies at the start of any flight program in the future.[36]

While not numbered as a cause of the mishap or specifically listed as a "lesson learned," the report did mention two other points that subsequently impacted the X-34 TTD program. The report noted that the DC-XA was a "single string" design (hence susceptible to catastrophic destruction from a single failure of a non-redundant system) and that there was "just one flight test vehicle" so that when the first was lost, the program thus came to an immediate end. Learning from this, NASA contracted for two X-34 TTD test vehicles, not just one. Indeed, later NASA authorized a third, which was in the process of being assembled when the program ended.

In commenting on the DC-XA mishap report, Gary E. Payton, NASA Deputy Associate Administrator for Space Launch Technology, noted that the "Lessons learned from the Board's report and the observations and recommendations made will play an important role in the Agency's continuing Reusable Launch Vehicles activities. In the X-33 and X-34 programs, for example, cost reduction and efficient reusability will continue to be our major objectives, along with safety and reliability that the proper mix of automation and human control can deliver."[37]

The loss of the DC-XA Clipper Graham raised significant issues, including the following:

- disagreement over assigning blame for the loss of the vehicle;
- arguments over management and operations, including whether sufficient staffing had been allocated to the flight testing;
- concerns about the implementation of McDonnell Douglas's rapid prototyping guidelines;
- concerns regarding flight-control checklists and procedures;

- concerns over the single string design and the building of only one test vehicle;
- disputes over whether to build another DC-XA vehicle or to switch attention and funding to the X-33;
- disputes about the awarding of the industry cooperative contracts; and
- discussion of the impact of NASA's "faster, better, cheaper" concept.

These issues, especially given that the DC-XA was the only one of the three NASA program vehicles ever to fly, lasted beyond NASA's decision to concentrate on the X-33 and not to rebuild the DC-XA Clipper Graham.[38] Orbital Sciences and Rockwell International noted the following benefits derived from the DC-XA in their first X-34 program: composite fuel tank; composite intertank structure; composite feedlines; inertial navigation system (INS) and Global Positioning System (GPS) satellite navigation system; automated flight planning; streamlined flight/ground operations; X-vehicle use at White Sands Missile Range; and rapid prototyping.[39]

Failure To Launch: The X-33 Advanced Technology Demonstrator

With the loss of the VTO-VL DC-XA Clipper Graham, NASA's SSTO efforts turned toward the X-33, a VTO-HL lifting body. David Urie, director of the Lockheed Skunk Works, had been working on a lifting body SSTO RLV concept for a vehicle capable of flying into Earth orbit to rescue crews from the Space Station. This concept led to the X-33.[40] The primary objective of the proposed X-33, as outlined in NASA's 1994 Implementation Plan for NSPD-4, the National Space Transportation Policy was to "prove the concept of a reusable next-generation system by demonstrating key technology, operations, and reliability requirements in an integrated flight vehicle."[41] As initially planned, the X-33 program was to consist of the three following phases:

- Phase I consisted of the concept definition and design, which had begun in March 1995 and was planned to last for 15 months, during which time the maturity levels of a wide range of proposed technologies were to be demonstrated.
- Phase II included the fabrication and flight testing of the X-33 vehicle, which was to begin by the end of 1996 and be completed by the end of the decade.
- Phase III was planned to be the actual commercial development of a next-generation space launch system, leading to the development of an operational NASA RLV by 2005.[42]

Phase I for the X-33 program was a $24 million concept definition and design study that extended from early 1995 through May 1996. For this phase, three industry design teams were selected—Lockheed Martin, Rockwell International, and the McDonnell Douglas-Boeing team. Each of the companies was an American industrial stalwart with a distinguished record in air and space. Lockheed's secretive Skunk Works had pioneered such exotic aircraft as the U-2, the Mach 3+ SR-71 Blackbird, and the F-117 Nighthawk, the so-called "stealth fighter." Martin had produced the Titan I and II intercontinental ballistic missiles (ICBMs) and the heavy-lift Titan III and IV ELVs. McDonnell had built America's first and second inhabited spacecraft, the Mercury and Gemini, as well as two pioneering rocket-boosted hypersonic test vehicles, the Alpha-Draco and ASSET. Douglas had designed the revolutionary DC-3, the D-558-2 Skyrocket (the first Mach 2 airplane), and the Thor intermediate-range ballistic missile (IRBM) which spawned the firm's subsequent Delta and Thor-Delta launch vehicles. Boeing had produced a legendary series of bombers, chief among which were the B-17 Flying Fortress, B-29 Superfortress, B-47 Stratojet, and B-52 Stratofortress, as well as the milestone B-707, B-727, and B-747 jetliners and the Minuteman ICBM. Rockwell had inherited the North American Aviation legacy, which included the P-51 Mustang, F-86 Sabre, X-15, Apollo, B-1 strategic bomber, and, of course, the Space Shuttle.

In responding to the X-33 solicitation, each company produced a distinctive design: Rockwell a relatively conventional delta-winged RLV, McDonnell Douglas-Boeing a tail-sitting DC-XA-like VTO-VL approach, and Lockheed Martin a fattened delta-winged lifting body with twin vertical fins and aerospike propulsion.

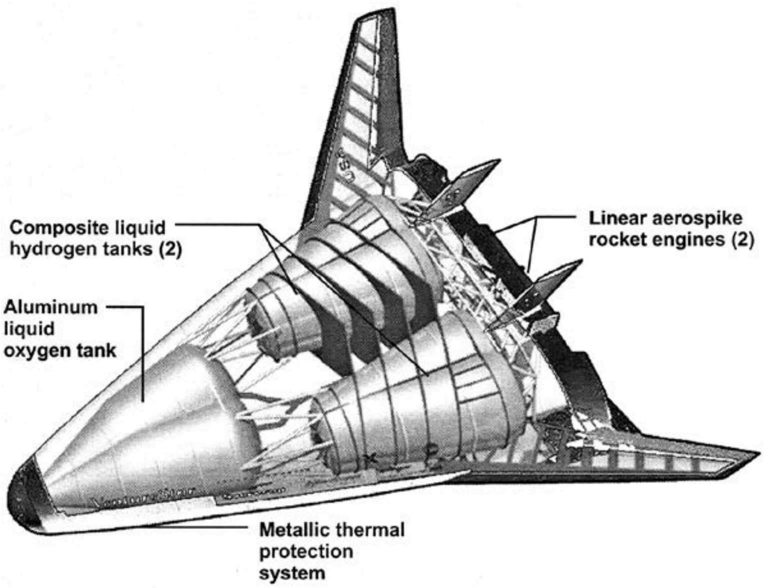
In July 1996, Vice President Albert Gore announced that the Lockheed Martin Skunk Works team, designated as lead contractor following the Phase I study, had been selected to proceed to Phase II: building and flying a subscale X-33 Advanced Technology Demonstrator.[43] Their industry partners included Rocketdyne (engines), Rohr (thermal protection systems), Allied Signal (subsystems), and Sverdrup Corporation (ground support equipment). Assisting this team were NASA Centers and Department of Defense laboratories. The cooperative agreement between NASA and Lockheed Martin was valued at approximately $1.16 billion ($941 million from NASA and $220 million from Lockheed Martin) over a 42-month time period and included 15 suborbital test flights to Mach 15—high hypersonic, but not the Mach 25+ required for orbital insertion.[44]

At an international conference in Norway in 1995, D.C. Freeman, Chief of NASA Langley's Space Systems and Concepts Division; fellow Langley engineer Theodore A. Talay; and Robert E. Austin, an aerospace engineer at NASA Marshall, outlined the technology test plans for the X-33. The three noted that

These were the three candidates for the X-33 Phase I design concepts from 1995. They are (L to R) the Rockwell winged RLV, the McDonnell Douglas-Boeing VTO/VL RLV, and the Lockheed Martin lifting body RLV. (NASA)

For the X-33 and follow-on RLV configurations, technology development efforts will demonstrate relative merits of state-of-the-art composite materials for application in wing and/or aero-surfaces, intertanks, and thrust structures. Issues to be addressed include estimating the material property, life cycle, manufacturing, inspectability and repairability of composite materials. The objective is to meet weight, reuse, cost and operations requirements for X-33 and RLV configurations. Intertank, thrust structure, wing panel or aerosurface test articles will be constructed and integrated with TPS (if required), health monitoring, and attachment subsystems and tested. Additional coupon and subscale testing will be used to quantify weight, strength, producibility, inspectability, and operability characteristics. The documented results are necessary to validate analytical tools applicable to both X-33 and full-scale RLV configurations.[45]

This is the proposed—but never built—Lockheed X-33 VentureStar.



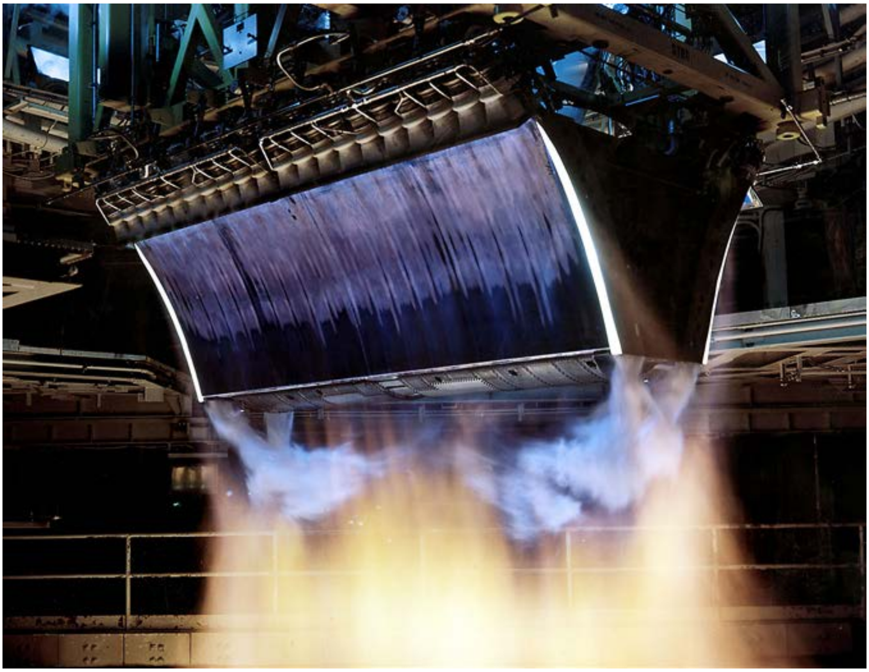
Here is the internal layout of the proposed X-33 VentureStar. The composite liquid hydrogen tanks and linear aerospike engines proved critical weaknesses in the system's overall concept. (NASA-GAO)

The X-33 was a just-over-half-scale (53 percent), suborbital advanced technology lifting body demonstrator intended to lead to a full-size RLV, the Lockheed Martin VentureStar. The VentureStar hopefully would reduce the cost of placing objects in orbit from $10,000 to $1,000 per pound, achieving this in part by having a structural mass fraction of less than 10 percent of the full-scale RLV's anticipated empty weight (see Table 2.2).[46] Program planners hoped the VentureStar would have just a 7-day turnaround time, reduced to just 2 days in an emergency. Due to cost considerations, NASA planned for only one X-33 vehicle. After the X-33 passed an agency critical design review, Lockheed Martin began fabricating the small demonstrator on October 31, 1997. Unfortunately, because of a number of problems, NASA later canceled the program when the vehicle was only 75 percent complete.[47]

Table 2.2: X-33 ATD and VentureStar Comparative Specifications[48]

	X-33 ATD	VentureStar
Length	66 feet, 7 inches	127 feet
Wingspan	72 feet, 5 inches	128 feet
Surface area	1,561 square feet	2,945 square feet
Height	19 feet, 4 inches	36 feet, 6 inches
Gross weight	289,000 pounds	3,300,000 pounds
Empty weight	75,000 pounds	212,000 pounds
LEO payload	N/A	59,000 pounds
Range (endurance)	20 minutes	Orbital
Maximum altitude	316,800 feet	LEO
Maximum speed	Mach 15	Mach 25

The X-33 was autonomously piloted and would have launched vertically like a rocket and landed horizontally like an airplane. It would have been powered by two linear aerospike rocket engines, an experimental design that replaced the conventional "bell" of a rocket engine with a curved linear wedge. This design effectively used atmospheric pressure to "form" the other half of the wedge, controlling the expansion of the exhaust flow emerging from the engine. It thereby achieved performance efficiencies unobtainable by a "fixed bell" exhaust in a manner analogous to the controllable pitch propeller, which, in the 1930s, had proven more efficient than a fixed-pitch propeller.[49] NASA planned a series of 15 test flights from Edwards Air Force Base, the first, of just 450 miles, to Dugway Proving Grounds in Utah. Subsequent longer flights of 950 miles would extend from Edwards to Malmstrom Air Force Base in Montana.[50]



An XRS-2200 twin-linear aerospike rocket engine is shown undergoing testing at the NASA Stennis Space Center. (NASA)

The X-33 would test or employ a number of specific technologies intended for future RLV programs, including reusable cryogenic propellant tanks, composite primary structures, thermal protection systems, improved propulsion systems, and new system operations protocols. The development of large-scale, flight-weight reusable cryogenic tanks was considered one of the most challenging tasks for the X-33 vehicle. The first step toward achieving this goal was the graphite composite liquid hydrogen tank developed for the DC-XA. The DC-XA tank (which weighed 1,200 pounds less than the DC-X tank and yet provided the same strength as an aluminum tank), represented the first reusable composite tank to fly on a rocket. An important associated goal included the research, development, and testing of both internal and external types of cryogenic tank insulation.[51]

Composite primary structures represented another important technology needed for the X-33, and, indeed, both it and later RLVs were intended to demonstrate the merits of composites for wings and other aerosurfaces, for intertanks, and for structures to take the thrust loads of their engines. Composite structures offered the potential for significant weight savings. For example, the DC-XA composite intertank represented a 300-pound weight

Researchers at the NASA Hugh L. Dryden Flight Research Center (now the Neil A. Armstrong Flight Research Center) fly a small radio-controlled model of the X-33, air-dropped from a mother ship, to acquire basic handling qualities and performance data. (NASA)

savings over the original DC-X structure. As part of the X-33 program, NASA Langley conducted tests designed for "estimating the material property, life cycle, manufacturing, inspectability and repairability of composite materials" for use on reusable launch vehicles. These tests were designed to validate the analytical tools applicable to both the X-33 and full-scale RLV configurations. In 1998, at the Dryden Flight Research Center, researchers test-flew a small model of the X-33 to gain basic information on its low-speed performance, a research methodology the Center had employed since the earliest days of lifting-body and hypersonic vehicle tests in the 1960s.[52]

Thermal protection system (TPS) tests probed the durability and reusability of TPS materials in launch and reentry environments. The X-33 used a three-level "hot structure" approach. Radiative panels fabricated from carbon-carbon (used on the Mach 25+ Space Shuttle orbiters) took the highest thermal loads; Inconel nickel alloy (used on the Mach 6+ X-15s) protected from moderate loads; and titanium (used in the Mach 3+ SR-71) sufficed for the lowest thermal loads. In June 1998 a NASA Dryden research team mounted a number of TPS panels on a test fixture that Center pilots then flew on NASA's F-15B Aerodynamic Flight Facility aircraft. The F-15B reached an altitude of 36,000 feet and a top speed of Mach 1.4 during the tests.[53]

Overall, the objective of the TPS testing was to develop a thermal protection systems capable of flying a minimum of 100 missions with an order of

Here is a Dryden Flight Research Center McDonnell Douglas F-15B with the X-33's proposed thermal protection system affixed on a special test fixture, cruising over R-2508 at the Edwards Air Force Base flight-test range in May 1998. (NASA)

magnitude reduction in maintenance and inspection requirements as compared with the high-maintenance Space Shuttle TPS system.[54] Though the Shuttle was not directly connected to the X-33 development program, NASA affixed sample Inconel and titanium radiative panels on the Shuttle Endeavour, flying them on mission STS-77 in May 1996, although the temperatures they encountered were only approximately 1,000 °F.[55]

The objective of the propulsion system part of the X-33 program was to investigate the performance and operational characteristics of its proposed aerospike engine installation, including achievable thrust-to-weight ratios, robustness, operability, ease of inspection, and affordability. Researchers undertook detailed trials to understand the performance and operations of liquid oxygen and liquid hydrogen-burning aerospike engines for use on RLV configurations, such as the J-2S and a new Rocketdyne RS-2200. Testing included an extensive effort to characterize the aerodynamics of the integrated lifting-body/aerospike X-33 using a 5-percent scale model of the lifting-body configuration in the supersonic wind tunnel at the Air Force's Arnold Engineering Development Center at Tullahoma, Tennessee.[56]

As well, NASA researchers at Dryden installed a special Linear Aerospike Research Experiment (LASRE) on a Mach 3+ Lockheed SR-71A Blackbird. The experiment consisted of a scaled 20-percent linear aerospike engine with eight thrust cells mounted like a vertical fin on a special 40-foot "canoe" installed on

A Dryden Flight Research Center Lockheed SR-71A Blackbird flew with a special linear aerospike experiment (LASRE), although it only achieved "cold" non-ignition flow. (NASA)

the top of the Blackbird's aft fuselage. Researchers hoped that the experimental installation—which would effectively turn the Blackbird into a latter-day Ford Tri-Motor—could be tested in flight, burning liquid oxygen and hydrogen. NASA completed the first of several LASRE flights on October 31, 1997, though, as this mini-program turned out, it never flew a "hot-fire" research mission. Serious oxygen leaks from manufacturing flaws precluded operating the engine in other than a "cold" mode, e.g., pumping propellant through the cells to acquire data on flow rates and characteristics.[57]

The technology area relating to operations included the enhancement of health maintenance systems and advanced avionics, such as the development of automated flight controls. The primary operations goal was to develop and demonstrate technologies that would permit automation and reduce staff requirements associated with between-flight maintenance, the launch complex, and ground-based flight operations support. A primary goal in the avionics area was to shift more of the mission control from the ground to the flight vehicle. These goals represented the first time within the space launch program that a "detailed reliability, maintainability, and supportability (RM&S) approach" was used. This RM&S concept was planned to be used throughout the entire X-33 and X-34 programs.[58]

To the casual eye, by the late 1990s, it seemed that the X-33 program was moving well along. A Critical Design Review (CDR) held at Dryden drew 600 attendees who, over 5 days, examined the program minutely and gave

The X-33 Launch Complex that Sverdrup Corporation built on the Edwards AFB test range in anticipation of the onset of powered flight tests. (NASA)

it generally positive reviews.[59] Sverdrup Corporation was finishing a launch complex for the X-33 on the Edwards range complex in anticipation of the program's first experimental flights. Called Area 1-54, it covered almost 104 acres in the center of which were 22,000 square feet of facilities consisting of the launch pad, a shelter, office trailers, cryogenic storage tanks for liquid hydrogen and liquid oxygen, and high-pressure storage for gaseous nitrogen and helium.[60]

But the X-33 program was already experiencing alarming development problems. Like the X-30 NASP before it (another SSTO approach, but an air-breather, not pure rocket), the X-33's weight steadily grew, lowering its anticipated performance. The maximum hypersonic Mach number officially dropped from 15 to 13.8, but unofficially was just Mach 10, raising fears the X-33 might not even be able to reach Malmstrom following a launch from Edwards. The revolutionary aerospike engines encountered their own development difficulties delaying the program beyond its planned rollout date of November 1998.[61]

In addition to its steady weight growth and resulting drop in performance, the X-33 experienced a critical failure of its hydrogen fuel tank on December 23, 1998. While in an autoclave, an inner wall of the tank delaminated over 90 percent of its area and another wall separated from its frame. These failures raised questions regarding the adequacy of the inspection procedures and the design of the tank and resulted in further delays.[62] The problems with the composite hydrogen fuel tank extended back to at least July 1998, when fabrication difficulties had caused a schedule slip from July 31 to September 2, 1998. Then, on September 27, the team noted that one of the X-33's two tanks experienced the loss of a cure cycle, causing a 30-day fabrication setback (the other tank cured satisfactorily).[63] Though the Lockheed Martin team pressed ahead with composites for the X-33 subscale demonstrator, the problems with the composite hydrogen tanks caused them to switch to aluminum tanks for the planned full-size VentureStar. The latter project, still a paper concept, had grown alarmingly over three years, from a planned 2.2 million pounds in 1996 to 3.3 million pounds in 1999, a bad sign.[64]

By mid-1999, first flight for the X-33 demonstrator had slipped 16 months, to July 2000. (It soon slipped even further, to 2003). Representative Dana Rohrabacher (R-CA), Chair of the House Subcommittee on Space and Aeronautics, requested that the General Accounting Office (GAO) review the program. GAO gave at best a lukewarm endorsement, recommending NASA establish "performance targets for the X-33 Program that establish a clear path leading from the X-33 flight-test vehicle to an operational RLV and show progress toward meeting the Agency's objective of significantly reducing launch costs."[65]

Then, fatally, in November 1999, another composite tank delaminated and fractured. In response to this latest setback, Lockheed Martin proposed replacing the X-33's composite tanks with aluminum, thereby removing one of the major rationales behind the X-33 program. Although the X-33 program briefly lingered on, NASA refused to throw more good money after bad. (By this point, NASA's investment in the X-33 program already totaled $912 million and Lockheed Martin's investment totaled $357 million, both sums being well beyond the $220 million total program costs originally forecast.) These practicality and financial factors doomed the X-33. On March 1, 2001, NASA announced that the Agency would no longer fund the ailing X-33 program.[66] Lockheed, having found that investors were cool to investing in the VentureStar program, then ended its own participation in the program.[67]

In retrospect, Lockheed and NASA took too big of a step in using a new and unproven composite fabrication method to manufacture the propellant tank. Gary E. Payton, now NASA's Deputy Associate Administrator for Space Transportation Technology, noted that the X-33 attempted a new honeycombed composite construction propellant tank, while the DC-XA had successfully used a multilayered cross-layering approach. He added that, for X-33, perhaps fabricating two tanks, each using a different method, would have provided a better chance at success.[68] Looking back, Richard DalBello, who was then Director of Aeronautics and Space in the Office of Science and Technology Policy (OSTP) during the Clinton administration, noted that

"I learned a very important lesson: policy never trumps physics. You can say whatever you want, but if you can't do it, it won't happen. We just didn't have the technology."[69] It was as good and succinct an epitaph as any.

Out from the Shadows: The X-34 Technology Testbed Demonstrator

The demise of the DC-XA and X-33 cleared the path for the third vehicle in NASA's RLV initiative, the X-34 Technology Testbed Demonstrator.

There were actually two separate X-34 programs, as well as an Orbital Sciences pre-X-34 program. The Orbital program, which led the company to approach NASA regarding the X-34, ran from February 1991 until early 1994. This program never extended beyond the concept stage.

The first X-34 program, undertaken pursuant to an industry cooperative agreement, ran from March 1995 until terminated in August 1996.

The second X-34 program, later designated as a project following a program restructuring in November 1998, was a contract awarded to Orbital, with NASA support, to build a downsized X-34 Technology Testbed Demonstrator.

The history of these efforts is covered in the following chapters of this book.

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Deputy Director of the Central Intelligence Agency (CIA), and from 1974 to 1976, he served as Director of the Defense Intelligence Agency (DIA). Among other decorations, Graham received the Distinguished Service Medal, the Distinguished Intelligence Medal, and the Legion of Merit. In 1981, Graham established the High Frontier Society, a policy organization intended to study and promote defense systems in space. He vigorously supported routine access to space, which led NASA to rename the Delta Clipper in his honor. For his views on space defense, see Lt. Gen. Daniel O. Graham, USA (ret.), *We Must Defend America: A New Strategy for American Survival* (Chicago: Regnery Gateway, 1983), passim.

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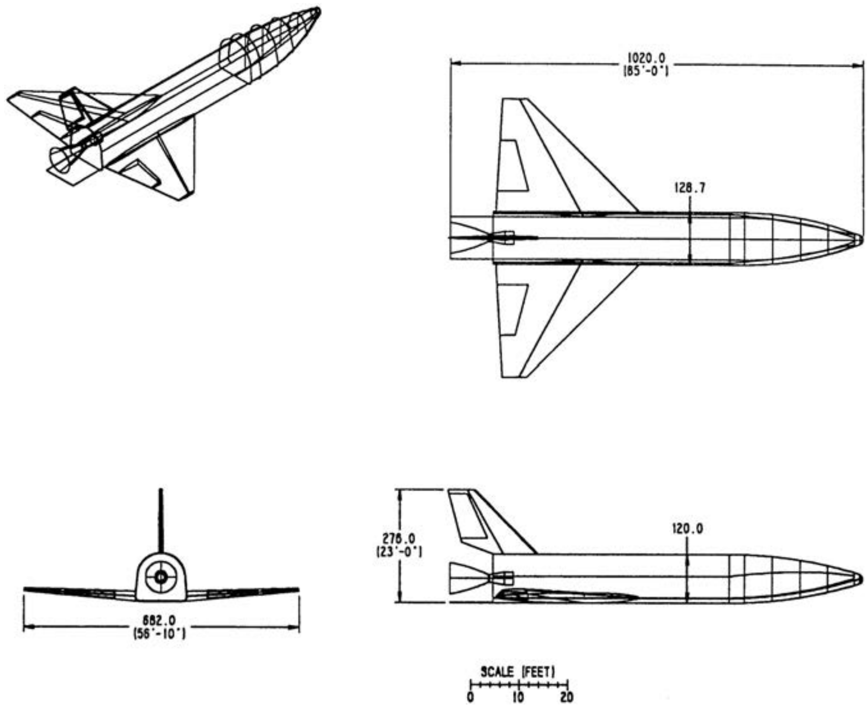


The X-34 RLV as originally conceived by Orbital and Rockwell's joint design team, June 1, 1995. (OSC)

CHAPTER 3

The “First” X-34: A Prequel

In 1982, David W. Thompson, Bruce Ferguson, and Scott Webster teamed to form Orbital Sciences Corporation (OSC), a new aerospace company headquartered in Dulles, VA. Aerospace startups have a spotty record of success, but thanks to energetic leadership, insightful management, rigorous selection of company personnel, and a thorough understanding of the space business, Orbital flourished. By 1990, its engineers had developed the solid-fuel Pegasus air-launched expendable booster, an impressive hypersonic winged three-stage rocket that was capable of placing satellites weighing up to 1,000 pounds into low-Earth orbit.

This is the first Orbital Sciences Corporation Pegasus winged booster on a captive-carry flight under NASA’s Boeing NB-52 Stratofortress mother ship, November 1989. (NASA)

Pegasus made its first flight in 1990, launched from Dryden's already-venerable Boeing NB-52 mother ship, the same launch aircraft that had dropped the X-15 and the M2-F2/3, HL-10, and X-24A/B lifting bodies. Orbital procured a former Air Canada Lockheed L-1011 TriStar jetliner, modified it as a launch ship, and then used it for Pegasus's commercial space launches. The Pegasus booster proved a winner, also becoming a booster for another NASA hypersonic test program, the scramjet-powered X-43, which established Orbital's reputation as a solid competitor and player in the space launch business. However, Orbital's leadership had their eyes on yet another goal: developing an air-launched reusable space launch system.

Orbital's Early Progression Beyond Pegasus

Even as Pegasus made its first flights, Orbital engineers were examining launch cost-reduction potential possible with reusable launchers in the 500- to 1,000-pound payload category. Company studies had already indicated that a hybrid configuration consisting of a reusable booster and an expendable vehicle would result in significant cost reductions, when balancing the costs of development and flight operations, as well as reductions in costs of expendable hardware. Orbital engineers concluded that "These studies also indicated that such an approach, named at the time Hypersonic Suborbital Reusable Booster (HSRB), had the potential to reduce the fully-amortized specific cost to orbit by a factor of two to three over Pegasus, and that a total investment of about $150M would be required."[1] Orbital's Project MALIBOO (manned air-launched intermediate booster) sprang out of this early effort.

Project MALIBOO: Orbital's First Concept for an RLV

The team working on Orbital's Project MALIBOO (Manned Air-Launched Intermediate Booster) included Antonio L. Elias of Orbital, C.C. Johnson with Space Industries, and Maxime "Max" Faget, a private consultant and retired NASA senior executive who had been Director of Engineering and Development at the Manned Spacecraft Center (later the NASA Lyndon B. Johnson Space Center). Johnson and Faget were legends in the space flight community, being two of the principal NASA designers of the Mercury, Gemini, and Apollo spacecraft. Both had also played key roles in advancing concepts for what became the Space Shuttle.

These three individuals developed the outer mold line for a concept RLV vehicle. They then requested Burt Rutan, the legendary founder of the Rutan Aircraft Factory (later Scaled Composites), to assist on the wing design and the arrangement of the internal components and to draw more detailed plans for the rocket plane and a carrier aircraft. Between 1992 and 1994, Rutan drew six iterations of the proposed vehicle, which were designated as 205-1 through 205-6. Elias credited Rutan with ingeniously solving a major carrier aircraft problem by opting to employ a configuration using twin fuselages, thus leaving the center area open for carrying a rocket or rocket plane, and not requiring the craft to be carried under a wing, or, less optimally, under the fuselage. (Scaled Composites subsequently followed this approach on the White Knight One and White Knight Two launch aircraft for the SpaceShipOne and SpaceShipTwo projects). Elias added that in designing airplanes, most designers want to have components located near the center of mass, which would interfere with carrying the second-stage RLV vehicle on the aircraft. While Project MALIBOO never got beyond the concept stage, it led to Orbital approaching NASA, and that, in turn, led to its participation in the first X-34 program.[2]

Orbital's and Rockwell's Emerging Interest in a Joint Venture

Orbital continued to recognize both the need for a reusable launch vehicle and the financial hurdles that had to be overcome in developing such a vehicle. In addressing the need for an RLV, Orbital's president, David W. Thompson, noted that "[w]e made an early determination that if we want low cost, we have to go to a high degree of reusability." The company, however, recognized the cost obstacle as reflected by Antonio Elias, Orbital's director of advanced projects, who added that engineering and industry studies indicated that the most economical solutions still stopped short of full reusability.[3]

Having relied on NASA for technical and analytical assistance since the earliest days of its Pegasus program, Orbital turned again to the Agency when contemplating the possibilities and potentialities of future RLVs. This approach was based on NASA's earlier assistance during testing and operation of Orbital's Pegasus winged booster. Orbital also thought that NASA might be interested in being a partner in the development of a commercial space vehicle and, as noted by Thompson, "the climate was right for a different way of doing business."[4]

Finally, due to the expense and challenge of undertaking such a project alone, Orbital decided to seek a major aerospace company as a partner in any such venture. Accordingly, in the fall of 1994, Orbital approached Rockwell to determine if the company had a mutual industry interest in participating in what was to become the X-34 reusable small booster (RSB) program. As a result, in February 1994, Orbital and Rockwell signed a Memorandum of Agreement for the two companies to jointly respond to NASA's Cooperative Agreement Notice. This was followed by a February 1995 joint proposal to participate in the X-34 program. NASA selected the Orbital and Rockwell team and the cooperative agreement was signed on March 30, 1995.[5] Hailing the program start, the editors of *Aviation Week & Space Technology* commented, "Developing a financially viable X-34 will be an early tryout of the reusable launch vehicle (RLV) concept the U.S. hopes will return it to leadership in commercial space transportation. For an aerospace industry faced with atrophy of its traditional government customer, the X-34 project will eventually stress a launcher in a grueling and still largely unfamiliar test regime—the free market."[6]

Gary E. Payton, then NASA's Deputy Associate Administrator for Space Transportation and Technology, proved a key figure in advancing the program. Payton, who thought that the X-33 should be supported by a smaller technology demonstrator, contacted the USAF's Air Force Materiel Command (AFMC) at Wright-Patterson AFB, in Dayton, Ohio, to request the next available X vehicle number, which turned out to be the X-34.[7]

NASA Marshall Briefs the Industry on X-33 and X-34

Prior to the issuance of the formal Cooperative Agreement Notice, NASA Marshall presented an X-33 and X-34 overview briefing on October 19, 1994. It was shared with industry representatives from Aerojet, Allied Signal, Fiber Material, Martin Marietta Aerospace Division, McDonnell Douglas (MD-D), Pratt & Whitney (P&W), Pennsylvania State University, Rocketdyne, Rockwell International (RI), and Refractory Composites Inc. The briefing reviewed the program objectives; potential X-34 attributes; launch vehicle perspectives; NASA funding; program assumptions; and the cooperative agreement definition, features, notices, and schedule.

The briefing identified the following X-34 RSB program objectives:

1. Stimulate the development of a reusable commercial launch capability for low-Earth orbit payloads that would significantly reduce costs.
2. Demonstrate technologies applicable to future launch vehicles, including design, follow-on use of the vehicle as a test bed, and low-operating costs with rapid turnaround.
3. Demonstrate that an industry-led industry-Government partnership can accomplish the previous objectives within 30 to 36 months and within a fixed Government budget.
4. Start the test flights in mid-1997, demonstrate orbital delivery capability in early 1998, and conduct two special NASA missions in late 1998 and early 1999.[8]

The desired and/or potential attributes of the X-34 RSB as presented are shown in Table 3.1.[9]

Table 3.1: X-34 RSB Desired and/or Potential Attributes

Commercial	Technical Demonstrator	Technical Test Bed
Low-cost launcher for: • Low-cost operations • Rapid turnaround • Simplified maintenance and payload integration • Simple interfaces • Rapid investment return available by 1998	• Autonomous ascent, reentry, and landing • Integrated vehicle health management • Modern avionics • Composite structure • Reusable LOX tanks • Engine/vehicle turnaround • Durable insulation and TPS maintainability of systems	• Hypersonic environment • Alternative TPS • Avionics systems tests • Reentry profile environment variations • Environment and air data instrumentation • Extension of the flight operations envelope

NASA Marshall noted the Agency had a number of smaller, cheaper, faster type payloads to support up to perhaps six flights per year if the launch cost were reduced to about $5 million per launch for a 1,000-pound payload. Also, the Department of Defense was launching 3 to 4 satellites per year in this class at this time. NASA and the DOD thus presented an opportunity for a Government-industry joint effort to develop this capability for the benefit of both parties.[10]

NASA's X-34 "Should Cost" Price Model Estimates

In March 1994, as preparation for the program, NASA Marshall's Engineering Cost Office developed a "should cost" estimate of what later became the X-34 RSB, although at the time, it was simply designated as a hypersonic reusable vehicle (HSRV). The office estimated that the program would cost $380 million (in 2016 dollars, equivalent to $618 million) using "traditional" estimation techniques including a Government cost model and adoption of best commercial practices.[11] At the same time, the Engineering Cost Office attempted an estimate based on an analysis of Orbital's Pegasus program. This estimate was based on technical data supplied by Orbital and the Government cost model. These results were then used to calibrate the Government cost model to reflect Orbital's ways of doing business based on the ratio of Pegasus's actual costs to the Government model estimate. This process resulted in a reduced estimate of $169 million. This was very close to the $150 million proposed cost estimated by Orbital. Cost-per-flight estimates also were made. These ranged from approximately $5.7 million (Orbital's ways of doing business) to $8.8 million (the Government's cost estimate). Orbital's best then-current estimate was $5.25 million per flight.[12]

NASA and Orbital divided the program funding between them. NASA funding would total a fixed amount of $70 million, broken down by fiscal year as follows: $10 million (1995), $30 million (1996), $15 million (1997), $10 million (1998), and $5 million (1999). Industry had to match at least 50 percent of Government funding. Program assumptions were to 1) fabricate two flight vehicles, plus spare parts and other necessary equipment; 2) include necessary test articles, ground tests, and test facilities costs; 3) include effective use of NASA personnel and facilities; and 4) include adequate performance, cost, and schedule margins.[13]

The briefing emphasized that the Government was not the customer but was a partner to stimulate technology and commercial development. Finally, NASA set a tight schedule for the Cooperative Agreement Notice (CAN 8-2) as follows: industry comments on the draft CAN were due by November 2, 1994; the planned CAN release date was November 15; proposals were due on or about January 6, 1995; and the planned awards were to be announced by February 28.[14] The actual release date was January 12, and the submission deadline was February 24. The selection was announced on March 8, and the agreement was signed by Orbital on March 30, 1995.

Formalizing the Program

NASA's Criteria for the Decisions To Proceed Beyond Phase One

On January 13, 1995, John E. Mansfield, NASA's Associate Administrator for Space Access and Technology, forwarded the decision criteria for advancing to phases II and III of the Reusable Launch Vehicle Program to NASA's Advisory Council[15] (NAC) for review. The decision criteria were established in accordance with an 11-point agreement between NASA and the Office of Management and Budget signed on November 25, 1994. Before proceeding to Phase II, certain technologies were "to be demonstrated through small scale experimental testing.… Analytical results derived from these demonstrations [would] enable the design of the full size system." The Phase I technology to be demonstrated included reusable cryogenic tanks, vehicle primary structures, thermal protection systems, and propulsion systems.[16]

The Phase II decision was contingent on four programmatic and four technical criteria (two enabling and two enhancing), all of which were to be supported by numerous specific technical metrics at the project and task levels during Phase I. Included in the programmatic requirements were the DC-XA and X-34 programs, "which support the belief that small, industry-led Government/industry projects teams are an efficient management tool for the rapid prototyping of advanced space launch technology. The X-34 program was expected to demonstrate during Phase I—through projected program run-out and operational costs—progress toward the timely fielding of a commercially viable space launch system, which significantly reduces the price of launch in its payload class."[17]

The Phase III decision was dependent "on business and operations plans, specific technical metrics, and programmatic criteria. Included in the technical criteria [were] the demonstration, through the X-33 project (focused on rocket based single-stage-to-orbit (SSTO) feasibility), that low-cost access to space is technically feasible and that operational costs for such a vehicle are acceptable." The two programmatic requirements were "1) the X-33 and X-34 programs have demonstrated that cooperative Government/industry technology development programs can be both successful and efficient, and 2) acceptable business arrangements have been reached which will facilitate the development and operation of the next generation of space-launch systems."[18]

The NASA Advisory Council (NAC) reviewed the above agreement and, while generally supportive of the Reusable Launch Vehicle program, raised six issues, two of which are reviewed here, along with the responses from Gary E. Payton.[19]

> *Issue raised*: We [NAC] remain concerned that a completely reusable SSTO system may not be the best choice and that NASA is not considering alternatives to SSTO in sufficient depth and breadth to provide a rational basis for selecting a[n] SSTO launch system even if the X-33 program indicates that it is technically feasible.
>
> *Response*: This Presidentially approved policy [Presidential Decision Directive NSTC-4] dictates that we pursue a technology development and flight demonstration program oriented to an end-of-decade decision concerning the feasibility of rocket powered SSTO technology. This development path was deemed to be the most stressing, technologically, but holds the greatest promise for reductions in the cost of space launch. Furthermore, this approach does not preempt a decision to use a TSTO [two-stage-to-orbit] architecture should SSTO technology be too difficult or too costly to achieve. A decision to pursue a more limited TSTO would delay the potential benefits of SSTO systems for decades. Our ability to deliver a TSTO system is not in question, even with today's technology, and resources to develop technology in support of TSTO, separate from SSTO, would be a wasted effort.[20]
>
> *Issue raised*: …NASA should develop a Government user payload model that could be expressed in terms of ranges for flights per

> year and payload weights, incorporating requirements of DOD, NASA, and other Government agencies.
>
> *Response*: The private sector's ability to survey and estimate potential markets far exceeds the Government's capability to validate a portion of this market…. In an industry-led program, industry must feel a sense of ownership. This means ownership of the vehicle design, confidence in the marketplace, and dedication to satisfy that marketplace.[21]

Payton concluded the memorandum by noting that

> [i]n summary, we fear the NAC, by and large, either does not accept, or has not been exposed to, the change in culture that this program is attempting to inculcate. The era of Government-specified designs, Government guaranteed mission models, and never ending Government studies has stalled the advance of technology and emasculated the launch industry. The RLV program aims to rectify this. The Nation is on the verge of losing this industry. A few of us over the next few years can reverse this loss, but only by focusing the meager resources available on the highest value development and by continuing to stress the overwhelming benefits of a lean and commercially driven industry.[22]

The NASA-Industry Cooperative Agreement

The first X-34 Small Reusable Booster program was undertaken pursuant to a Government-industry cooperative agreement satisfying the Chiles Act (31 U.S.C. § 6305) cooperative agreement requirement that the program have substantial involvement between the Government and non-Government participants. The requirement was formulated in order to stimulate private-industry development rather than simply to acquire a product.

The development stimulation requirement was to be fulfilled through the following objectives: 1) maturing the technologies required for the next-generation space launch system; 2) demonstrating the capability to achieve low development and operational cost, including rapid launch turnaround times; and 3) reducing technical risk in order to encourage private investment in the commercial development and operation of the next-generation space launch system. The substantial-involvement requirement was to be fulfilled by industry's agreeing to fund at least 50 percent of the activity cost, industry's providing management and technical leadership, and NASA agreeing to participate beyond mere funding or management. A National Performance

Review conducted under the direction of then-Vice President Gore triggered an additional requirement calling for NASA to direct between 10 and 20 percent of its budget to partnerships with industry.

The X-34 Cooperative Agreement Notice (CAN) solicited proposals to "enhance U.S. Commercial Space Launch competitiveness" and outlined nine project objectives:[23]

1. Develop a small reusable or partially reusable booster with potential commercial application at a reduced launch cost of a factor of approximately three.
2. Demonstrate technologies applicable to future reusable launch vehicle systems.
3. Develop and demonstrate reusability and operability concepts.
4. Begin test flights in late 1997.
5. Demonstrate orbital delivery by mid-1998.
6. Conduct two technology test bed flights beginning in late 1998.
7. Produce flight data to support validation of hypersonic flight environments.
8. Demonstrate that an industry led joint industry/Government funded partnership can successfully develop a new booster within three years.
9. Facilitate the transfer of new technology and operational concepts to other U.S. industrial and Government organizations.[24]

The CAN required that each proposal contain two crucial attachments—Attachment A (Responsibilities) and Attachment B (Payment Milestones). The Responsibilities attachment delineated the specific responsibilities of both Government and industry, which in the case of the X-34 program placed the industry partner in the primary management role, with NASA basically acting as a subcontractor.[25] The Payment milestone attachment provided the precise dollar amount that the Government would pay, which in the case of the X-34 agreement could not exceed $70 million ($60 million in cash and $10 million of in-kind services). Furthermore, at any one time, Government funding must be matched by industry funding, thus clearly limiting Government funding liability. NASA had the task of assuring fiscal responsibility for the spending of the Government's share of the program funding. The Government funding was a fixed amount, leaving the industry parties responsible for any cost overruns.

Three industry proposals (from Orbital Sciences, Space Access, and Kelly Aerospace) were received on February 24, 1995. The proposals were evaluated and the source selection made within 10 days, and the cooperative agreement—including definition of terms and conditions, roles and responsibilities of each party to the agreement, and funding commitments—was signed on March 30, 1995. Officially, the agreement under contract number NCC8-75 was between Orbital Sciences Corporation of Dulles, Virginia, and the George C. Marshall Space Flight Center but unofficially, in effect, included Rockwell.

Frederick Bachtel, Deputy Director of NASA's Space Transportation Division, noted that the evaluation process was accomplished in such a short time due to handling the evaluation process electronically. Approximately 200 engineers were at NASA Marshall for the evaluation process. The engineers were divided into sub-teams that considered the different issues, such as thermal protection systems, propulsion, and structures. Each sub-team had a computer on the network and could input information directly on the computerized evaluation forms. The forms were then passed up the selection chain electronically in a "faster, better, cheaper" exercise.[26]

The agreement, to run through September 30, 1999, provided for substantial NASA participation and sharing of resources throughout the project. The agreement also provided for dual periodic review (at least annually) of actual versus planned resource contributions in order to verify that each party was making reasonable efforts. In addition, the recipient was required to submit quarterly reports containing a summary of costs incurred, budgeted costs of the work performed, and the projected costs of work to be performed. An important additional provision stated that if all resources were expended prior to the end of the contract, then the parties had no obligation to continue and could cease work on the project. The parties, however, could extend the expiration date if additional time was required to complete the milestones at no increase in Government funding. In regard to the precise funding amounts, the agreement provided for NASA external funding of $58,731,000 [$92.9 million in 2016]; NASA internal "in kind" funding of $11,269,000 [$17.8 million in 2016]; and contractor funding of $99,763,395 [$157.8 million in 2016]. Payments were to be made based on the completion dates of each milestone. Any commitments exceeding the $70 million [$111 million in 2016] Government funding amount were the responsibility of the contractor. The cooperative agreement stipulated Antonio Elias, of Orbital Sciences, as program manager.[27]

Payments were to be made based on the completion dates of 15 milestones (see Table 3.2). The milestones represented an ambitious time schedule pursuant to NASA's "faster, better, cheaper" operational guidelines then in effect.

Table 3.2: Milestone Tasks, Dates, and Payments for the "First" X-34[28]

	Milestone Tasks	Completion	Payment*
1	Completion of the structural configuration, L-1011 vs. 747 carrier plane decision, booster engine decision, and market demand assessment.	05-01-95	$3.00 million
2	Industry/NASA agreement that the configuration and sizing details required to support detailed design; long lead parts ordering; any necessary development tests, including the booster vehicle, orbital vehicle, carrier aircraft; and integration.	06-15-95	$5.11 million
3	Design freeze—boost vehicle airframe configuration and detailed design sufficiently mature to proceed with airframe structural fabrication; airframe structural fabrication started.	11-01-95	$10.00 million
4	Joint venture/NASA agreement on system configuration and detailed design sufficiently mature to proceed with system parts ordering, manufacture, and assembly.	03-01-96	$10.00 million
5	Completion of LOX tank qualification and arrival of LOX tank at integration site.	06-01-96	$5.458 million
6	The primary structural components of the fuselage, payload bay, and wing assemblies are completed in preparation for the core structural tests.	11-01-96	$5.00 million
7	Test of core structure in accordance with the test documentation including axial thrust loads, distributed aero body loads, L-1011 captive carry loads, landing loads, and corresponding data analysis to identify structural capability.	01-01-97	$3.00 million
8	Successful completion of ground vibration test and corresponding data analysis to identify structural capability.	03-01-97	$3.00 million
9	Captive carry test of the airframe in accordance with test documentation, including the taxi test, runway test, low-speed flight characterization, and high-speed flight characterization.	06-01-97	$1.339 million
10	Approach and landing test of the airframe in accordance with test documentation including X-34A and L-1011 communication, umbilical disconnect, drop, minimal approach and land, short approach and land, and long approach and land.	11-01-97	$4.00 million

Table 3.2: continued

	Milestone Tasks	Completion	Payment*
11	Successful completion of static firing of the propulsion system installed in the boost vehicle for verification of function capability.	03-01-98	$2.00 million
12	Successful completion of suborbital flight test.	06-01-98	$2.00 million
13	Orbital flight test of one vehicle in accordance with test documentation and completion of the other vehicle's integration.	09-01-98	$0.573 million
14	Successful completion of first development test flight.	12-01-98	$3.00 million
15	Successful completion of second development test flight.	06-01-99	$1.251 million
		Total	**$58.731 million**

*Note: $1.00 in 1995 monies is approximately $1.69 in 2020.

A provision in Attachment A to the cooperative agreement called for the production and integration of two booster vehicles designated as BV-1 and BV-2. They were to involve "serial component fabrication, serial airframe assembly, and serial subsystem integration so that lessons learned from the first vehicle build can be applied to the second." As noted in Table 3.2, the core structure test was to be completed in late 1996 (BV-1 vehicle). This was planned to occur prior to subsystem integration on the second airframe in order to enable the incorporation of any needed structural modification.[29]

In commenting on the cooperative agreement selection process, Daniel S. Goldin noted that "[t]he innovative 'fast track' procurement process resulting in these selections is a true harbinger of how the 21st-century 'faster, better, cheaper' NASA intends to conduct its business:" as if to prove his point, over the next 2 months, NASA issued both the X-33 and X-34 Cooperative Agreement Notices, industry responded with its proposals, and the Agency made its selections.[30]

The Orbital Sciences Corporation—Rockwell Joint Proposal

On February 24, 1995, Orbital and Rockwell submitted a joint proposal for an industry-Government cooperative agreement to develop, test, and operate the X-34 small reusable launch vehicle. Interestingly, each company submitted a separate cover letter rather than a jointly executed single document. Orbital's February 22 letter noted that "[w]e recognize that the X-34 program is a critical pathfinder for future reusable vehicles (RLV), both as a demonstrator of important technologies and operational methods and as a model for industry-led, NASA-assisted development partnerships."[31] Rockwell's letter, which was dated one day earlier, noted that "We view X-34 as an outstanding opportunity for industry and Government to pioneer new ways of doing business, demonstrate needed technologies for future reusable launch vehicles, and strengthen the competitive position of the U.S. space launch industry.[32]

Rockwell added that:

> NASA's and Rockwell's experience in hypersonic flight and reusable space operations from highly reliable systems like X-15 and Space Shuttle, coupled with OSC's small launch system experience from Pegasus and Taurus and "faster, better, cheaper" capabilities for small satellites, provide an unprecedented team for X-34. Our program approach takes full advantage of the complementary strengths of each team member to achieve our primary goals of using X-34 as an operational launch system that significantly reduces the cost of launching small payloads and demonstrating key RLV technologies and operational practices on an accelerated schedule. In addition, we take full advantage of the results and ongoing work under Rockwell's existing RLV cooperative agreements with NASA Centers on integrated propulsion technology, reusable cryogenic composite tanks, graphite composite primary structures, and lightweight durable TPS. Over the past six months, Rockwell has performed an in-depth technical, business and risk assessment for the X-34 program. Our results indicate that the risks are manageable and the economic returns are adequate to make this a sound business venture.[33]

Orbital and Rockwell's Joint Venture

The cooperative agreement also recognized that Orbital was intending to enter into a joint venture with Rockwell International Corporation (RI). The new commercial joint venture entity was named American Space Lines (ASL), and after formation, the cooperative agreement would be modified accordingly. Orbital and Rockwell would own approximately equal shares in ASL, with Orbital serving as the managing partner. The American Space Lines board of directors consisted of D.W. Thompson and J.R. Thompson, representing Orbital, and K.M. Black and R.G. Minor, representing Rockwell. D.W. Thompson was designated as president. The structure and key personnel are shown in Table 3.3.

Table 3.3: American Space Lines Key Personnel by Position and Areas of Responsibility[34]

Position/Area of Responsibility	Individual	Affiliation*
President	D.W. Thompson	Orbital
X-34 Project Manager and Principal Investigator	Antonio L. Elias	Orbital
Deputy Project Managers Orbital and NASA	Drew Hays	Orbital
	James W. Kennedy	NASA
Systems Engineering Subproject Managers	Bryan Sullivan	Orbital
	Richard Cervisi	Rockwell
Mechanical Systems	G. Harris	Orbital
Avionics	David Steffy	Orbital
Thermal Protection System	R.L. Figard	Rockwell
Booster Propulsion	M. Ventura	Rockwell
Integration, Test, and Operations	T. Dragone	Orbital
Vehicle Design and Development	William Wrobel	Orbital

The Orbital-Rockwell team would be complemented by the technology base and development and test capabilities of six NASA Centers—Ames Research Center (ARC), Dryden Flight Research Center (DFRC), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC).

NASA's, Orbital's, and Rockwell's Objectives for the Program

NASA, Orbital Sciences Corporation, and Rockwell International each had separate objectives for jointly participating in the X-34 program. These objectives complemented each other and, taken together, were intended to result in the successful design, fabrication, and testing of the X-34 vehicle. NASA's objectives were to

1. stimulate United States commercial space transportation competitiveness through technology development, leading to major reductions in vehicle launch costs;
2. develop new technologies and flight operations concepts, including addressing certification and regulatory requirements; and
3. experiment with, refine, and demonstrate new ways of doing business, including more effective use of Agency capabilities and resources, especially in a constrained-budget environment.

NASA's objectives would be considered fulfilled if the design, development, and testing (DD&T) of the system were deemed to be successful.

Orbital Sciences' objectives were to

1. stimulate growth in Orbital's principal market—microspace—by reducing the very significant transportation-to-orbit cost burden,
2. develop the next-generation product in the company's Pegasus/Taurus line of small launchers in order to maintain Orbital's market share in small satellite launch services in the face of increasing domestic and overseas competition, and
3. expand its overall knowledge and technology base.

Rockwell International's objectives were to

1. effect a leveraged, reduced-cost entry in the new commercial launch services market and
2. enhance its technology base for similar, larger products.

The industry partnership's final objectives would be considered fulfilled only after the system reached profitable commercial operational status. Thus the industry objectives extended beyond the time limits of the cooperative agreement. Accordingly, the X-34 would be applied specifically to the DD&T aspects of the program, intended to achieve several objectives:

1. Develop and flight-test a small (1.0 to 1.5 times Pegasus payload class), mostly reusable launch system providing
   a. significant reductions in launch cost (the goal was a 3:1 reduction in dollars per pound to orbit compared to Pegasus);
   b. the capability of flight-testing new RLV technologies, either by embedding them into the design ("embedded technologies") or flying them as piggyback experiments or upgrades in dedicated technologies demonstration flights; and
   c. a demonstration of cost-reducing reusability and operability concepts in actual orbital launch operations.
2. Begin flight tests in late 1997.
3. Demonstrate orbital launch capability in mid-1998 and conduct two dedicated suborbital technology test/demonstration flights in addition to the test flights required for development and qualification of the launch system.
4. Demonstrate that an industry-led, joint Government-industry–funded partnership could successfully accomplish the development of a new, reusable booster within 3 years with a fixed Government funding profile.
5. Transfer the lessons learned to other U.S. industry and Government organizations.[35]

It was hoped that the DC-XA Clipper Graham, which was the first of the three RLV program vehicles, would provide a number of benefits to the X-34 program. These planned benefits included a composite fuel tank, a composite intertank structure, composite feedlines, an Inertial Navigation System (INS) and Differential GPS, automated flight planning, streamlined flight/ground operations, X-vehicle use of the White Sands Missile Range, and rapid prototyping.[36]

An Optimistic Program Start

A March 31, 1995, article in *Aerospace Daily* noted that Orbital's and Rockwell's American Space Lines joint venture "wants to be launching 18 to 20 small satellites a year by 2005 on the commercial vehicle that derives from the X-34 prototype…[and that this number] would represent about two-thirds of the smallest launch market that the joint venture executives hope will emerge if they can cut the cost to put a satellite into low-Earth orbit by a factor of three, a market roughly double the 15 worldwide launches a year in the 500-to-3,000-pound payload class that exists today [1995]." The article added that "[t]o get the cost down, engineers from Orbital, Rockwell, and NASA have sketched a vehicle that would reuse about 94% of its hardware, throwing away only a small orbital vehicle powered by a relatively cheap liquid oxygen/kerosene rocket engine NASA will develop in-house based on work already done at Marshall Space Flight Center."[37] *Aerospace Daily*'s editors further noted that "[f]lying the X-34 from the top of the 747 [Space Shuttle carrier aircraft], instead of dropping it from the bottom of the L-1011 [Orbital's Pegasus rocket carrier vehicle] gives engineers room to design a more circular [in cross section] vehicle with the size and power to carry the heavier payloads, [Antonio] Elias said. The L-1011-launched 'X-34A' configuration would be able to take 1,200 pounds to LEO with a 76,300-pound gross weight. The 'X-34B,' flying from the 747[,] would weigh 108,500 pounds and be able to deliver 2,500 pounds to LEO."[38] In regard to engines, the article added that the joint venture was studying a number of engines in the 85,000-pound up to nearly the 200,000-pound power class, including Russian engines and the Rocketdyne MA-5 engine for use in the reusable primary vehicle. The expendable orbital vehicle was planned to use the Fastrac engine being developed at NASA Marshall.[39]

The optimistic start was confirmed just 3 months later in a June 27, 1995 X-34 program non-advocate review finding that, following 18 months of preliminary design and trade studies and just 3 months after the joint venture's authority to proceed, the X-34 program was progressing to a "mature and well understood baseline."[40] The review concluded that the program was clearly focused on its two primary objectives—low-cost access to space and the development of an advanced technology demonstrator. There were two additional findings:

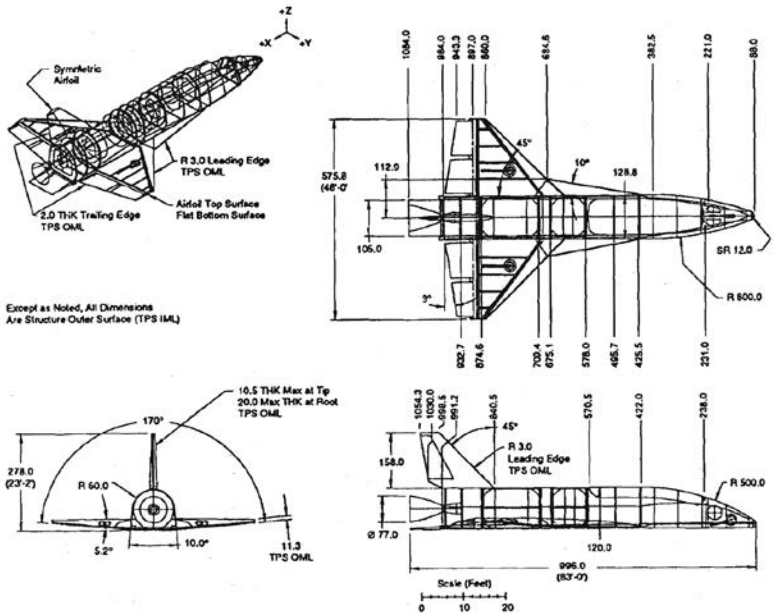
1. Even though cost targets were low compared to traditional models, the budget was based on Pegasus rocket actual costs, contained a 13-percent reserve, was well within the cost limit necessary to sustain industry involvement, and closely complied with the Performance Measurement System.
2. While the schedule baseline was tight, it was consistent with previous Orbital and Rockwell programs, was well thought out with major predefined milestones and risk mitigation measures, and closely complied with the Performance Measurement System.[41]

In regard to the industry-led-Government-sponsored partnership, the review found that the plan was working well, was motivational for all involved, was organized to succeed, and was fully supported by industry and Government senior management. The review also found that management tools were streamlined and provided effective controls. Overall, the review concluded that the "X-34 was an integral part of the overall RLV technology maturation process."[42]

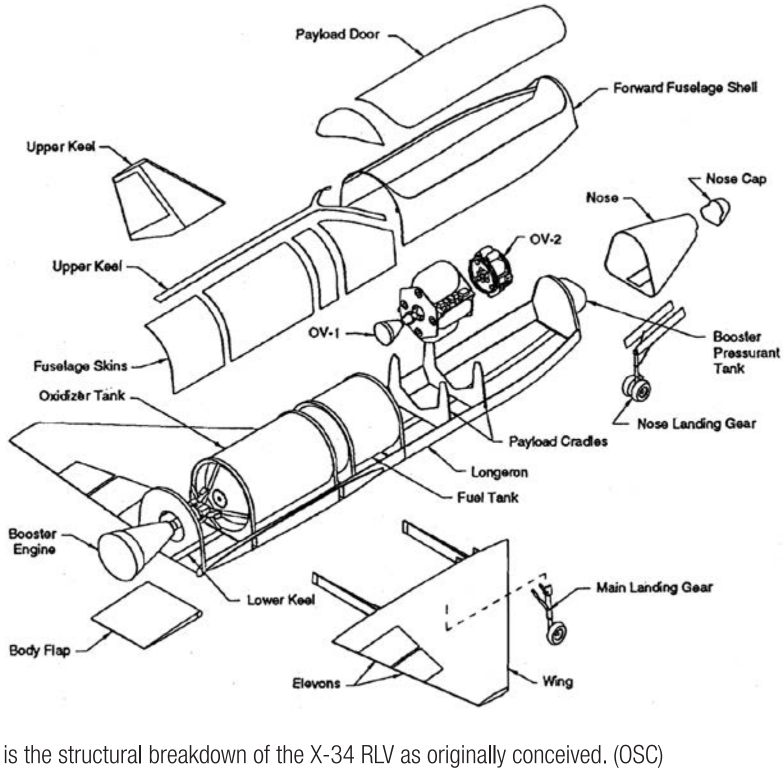
The First X-34: Design, Performance, and Planned Test Program

As noted previously, the Orbital–Rockwell American Space Lines team considered two design options, designated the X-34A and the X-34B. The X-34A was the smaller of the two, and thus could fit under Orbital's L-1011 launch airplane. It had an elliptical cross section, with a width roughly twice its height. Following studies on the potential payload market, Orbital opted for a larger variant, one having greater payload capability, and this became the X-34B. Since the X-34B was larger than the X-34A, it was both too large and too heavy for launch from the L-1011. Thus, Orbital turned to NASA's Boeing 747 SCA.[43] The X-34 vehicle design actually went through at least 13 iterations before emerging as a finalized design.

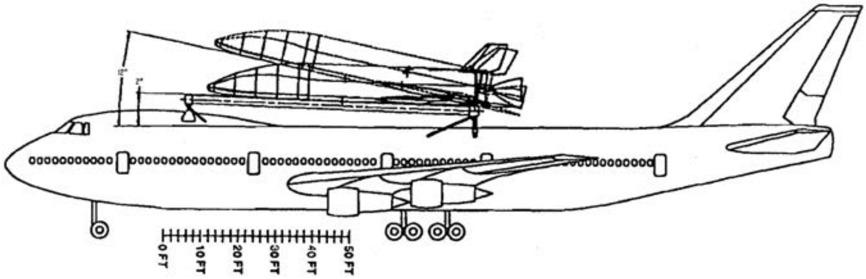
Orbital planned two suborbital and one orbital demonstration flight tests for the X-34 test vehicle. The technology demonstration flights were initially scheduled for December 1998 and June 1999, with an orbital demonstration flight planned for September 1998. Additional flights could be scheduled at a cost of between $2 and $3 million per flight. Since the upper stage would not be on the tested vehicle, more room would be available to accommodate the desired experiments. The flight profiles were tailored to generate relevant environments for testing promising reusable launch technologies. Piggyback technology tests were also considered, as well as other possible follow-on test



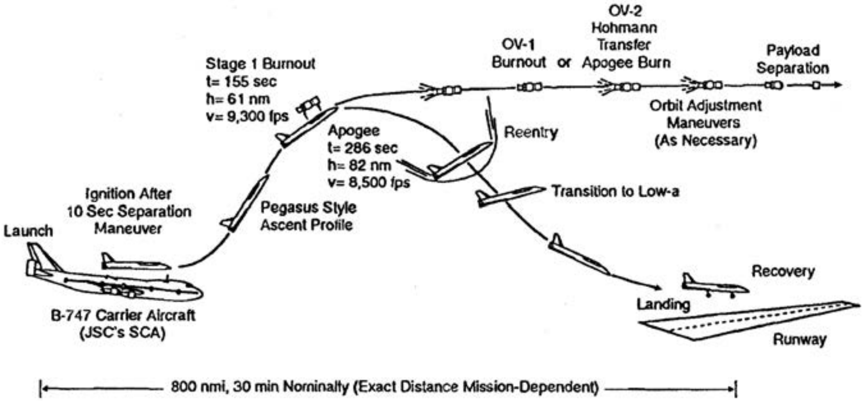
Here are the initial X-34 space booster configuration and dimensions, circa 1995. (OSC)



This is the structural breakdown of the X-34 RLV as originally conceived. (OSC)



The proposed mating of the X-34 RLV to the NASA JSC Boeing 747 Shuttle Carrier Aircraft shows a 12-degree launch separation angle of the X-34 for release from the SCA. (OSC)



This is the mission concept of an X-34 RLV air-launched from the SCA on a satellite insertion mission. (OSC)

bed missions. This combination of testing the orbital vehicle and using test bed technologies was later determined to be undertaking too much, thus contributing to having a separate smaller vehicle designed specifically as a technology test bed vehicle. This desire for a separate test bed small demonstrator was a factor in going forward with the follow-on X-34 vehicle.[44]

Planned Mission Performance of the X-34A and B

The X-34A was intended to launch about 800 nautical miles (nmi) from its recovery site and be released from its L-1011 at 35,000 feet. Following a 5-second drop, its engine would ignite. Over a 3-minute engine burn, the X-34A would boost into the upper atmosphere like the Pegasus, climbing to over 300,000 feet, having gained 12,000 feet per second (fps) in velocity since its launch. It would then open a cargo bay door on its underside,

An October 1995 depiction of an X-34 RLV shows it releasing a satellite payload, which will then boost into orbit. (OSC)

disgorging a combined 11,200-pound kick-stage and orbital payload. The X-34A would continue climbing, reaching an apogee of approximately 575,000 feet before beginning a reentry at an angle of attack of 40 degrees. During reentry, it would sustain stressing peak heating rates and aerothermal structural loads, although less than those experienced by the contemporary Space Shuttle as it reentered from orbit velocity. After decelerating to supersonic speeds, the X-34A would glide to a landing on a conventional runway using GPS-cued guidance, touching down at 120 knots and braking to a stop within 3,000 feet of rollout. Meanwhile, in space, the released kick-stage/orbital payload would have ignited, accelerating the 1,200-pound payload a further 13,600-fps, sufficient to achieve a 100-nmi LEO at an inclination of 28 degrees. If necessary, the kick-stage could circularize the orbit as well. The total duration of a mission, from launch to landing, would be approximately 20 minutes.[45]

The engine planned for the booster for the first concept X-34A was to have 85,000 pounds of thrust and use kerosene (conventional military JP-4 jet fuel, not space-rated rocket propellant) and liquid oxygen. The two engines initially considered for use on the X-34 were a modified Rocketdyne MA-5 Atlas ICBM sustainer engine and—reflecting the end of the Cold War—the Russian NPO Trud NK-32/39.[46]

The second concept vehicle, the X-34B, which would be launched from the top of a NASA 747, would weigh 108,500 pounds, compared with 76,300 pounds for the X-34A. The length of the X-34B was planned for 88 feet, with a wingspan of 50 feet. By comparison, the X-34A was planned to have a length of 72 feet with a 34-foot wingspan. Launching from the 747 would have required the carrier plane to descend steeply immediately following the drop to maintain a safe separation distance from the X-34. Two different propulsion options were considered for the X-34B—the Rocketdyne RS-27, favored by Rockwell, and the Russian NPO Energomash RD-120, favored by Orbital and NASA. The first captive-carry test was initially set for mid-1997, followed by a suborbital flight and finally an orbital flight set for mid-1998.[47] In a May 24, 1995, note to NASA's Administrator, Gary Payton advised Goldin that "[t]he X-34 partnership has formally agreed to the configuration that will fly off the 747/Shuttle carrier aircraft [X-34B]." In the same note, however, Payton advised Goldin that "Rockwell and Orbital have not yet agreed to the propulsion system."[48] Indeed not: engine selection for the X-34, as will be seen, would become the program's most controversial feature.

Mid-Course Perspective: Participant Observations After 6 Months

Antonio Elias, Drew Hays, and James Kennedy made several observations based upon the first 6 months of program operations.

> From our experience so far, we believe that, in order to work, such a partnership must have the following characteristics:
>
> - It must be a true partnership, capitalizing on the relative strengths of each organization to result in a more efficient and productive team—not a customer-client relationship.
> - There must be little or no Government oversight: the relationship must be built on Trust and Common Goals—Industry and NASA's objectives must be complementary. Each team member's participation must be viewed as being leveraged by the others' investment.
> - The Government must produce a "Real Product"—not simply supply money. This requires, however, that NASA must deliver on schedule and within costs.
> - The program must be cost effective, expedient, and maximize the participants' incentives: this points to a more commercial, rather than government-style approach. In addition, if the outcome is to have a credible commercial viability it must be industry led. However, this also implies that industry must also be the prime investor.

Finally, the three engineers concluded their observations by noting that

> [f]or initiatives, like the X-34, where both government and industry objectives can be met, and where no deliverable goods or services are required by the government, a partnership based on a Cooperative Agreement can be an attractive alternative to conventional contracting. X-34 is a first attempt to demonstrate this at a scale of a new flight vehicle development. We must wait for the completion of the program to tell if it has been successful.[49]

Terminal Descent: The Collapse of the First X-34 Development Effort

In retrospect, there is a hopeful, almost wistful, tone to the observations made about the first 6 months of the X-34 program, a desire that perhaps this program would be different from other NASA efforts and would proceed smoothly and relatively conflict-free on to flight and further success. But shortly after these observations were reported, disagreement over which engine to use surfaced publicly in the aviation media. On November 6, 1995, *Aviation Week*'s journalists reported that "NASA has suspended [on November 2, 1995] the X-34 reusable winged booster effort because the industry partners…are demanding that a Rocketdyne engine be used instead of the Russian power plant first planned for the small launcher." The article added that "Whether or not the X-34 project survives, it seemed likely late last week that the flap would give a black eye to the new style government-industry partnerships upon which NASA is staking much of its future."[50]

Arguments over engine choice centered on payload capability (which was lower with the Rocketdyne engine), comparative flight experience (the Rocketdyne engine had 125 flights, the RD-120 just 25), and certitude of availability (the Rocketdyne was American-made while the RD-120 engine was Russian-made).[51]

As well, the program was under criticism from Marshall Space Flight Center executives for failure to meet design milestones: Mark Stiles, X-34 contracting officer at Marshall, told journalists for *Aerospace Daily* that Orbital and Rockwell had failed to meet milestones for freezing the airframe design and choosing between different configuration options and that the issue was "broader than just the engine."[52] Indeed, on November 2, 1995, NASA had issued the suspension notice shutting down the program for 14 days "to allow time for the agency to review progress in the program" because the program had missed the two milestones mentioned above. Orbital and Rockwell worked quickly to resolve the issue, and NASA lifted the suspension in less than a week.[53]

Buy Russian or Go American? The X-34's Engine Controversy

The engine controversy had been simmering for weeks and came to a head at an October 23 meeting between the partners and NASA representatives. NASA wanted the higher-performance Russian NPO Energomash RD-120, used as the second stage on the Russian Zenit rocket and then being marketed in America by Pratt & Whitney. Rockwell argued, and not without very good reason, that the lower-performance Rocketdyne RS-27 engine used on the Delta rocket was a better choice, given the political instability then wracking the former Soviet Union. Indeed, Rockwell reportedly threatened to leave the partnership if the Rocketdyne engine was not selected.[54] NASA threatened to withdraw from the program and was persuaded to continue only after direct intervention from the White House's Office of Science and Technology Policy (OSTP). Lionel Johns, associate director for technology in OSTP, informed Gary Payton that NASA would have to work with Orbital and Rockwell to resolve the engine dispute.[55] The controversy lasted into late November, when, in a series of telephone conferences, Payton, Michael Griffin (of American Space Lines, and future NASA Administrator), and Robert Minor (president of Rockwell Space Systems Division) tentatively agreed to use the Russian engine.[56]

But this shorthand summary is hardly adequate to address what was a more complex controversy, and thus some background and further explanation are warranted. Just prior to the conflict's eruption, NASA had released policy and guidelines for the use of foreign technology in the RLV program, stating in part: "The RLV technology development and demonstration program may seek to take advantage of all beneficial components and technologies, both foreign and domestic, in developing United States next-generation space transportation systems. Foreign participation in X-33 and X-34 projects will be undertaken on a company-to-company contractual basis and will be conducted with the policy and guidelines in this document."[57]

The guidelines outlined several points:

1. Foreign participation must provide clear net benefits for the achievement of the program's technical and business objectives.
2. U.S. Government funds may be used for the manufacture or acquisition of flight-ready foreign component technology but cannot be used for foreign-based RLV development of foreign technology, unless specifically exempted by the NASA Administrator.
3. The use of foreign technology must not threaten the successful execution of the program in either its developmental or operational stages.

4. Due consideration must be given to fostering United States competitiveness and safeguarding national security interests throughout the life of the program.
5. Close consultation must be maintained with NASA and other appropriate agencies on all aspects of foreign participation.[58]

Prior to the release of the foreign technology guidelines, Payton, in a May 25, 1995, note to Daniel S. Goldin, detailed the growing engine controversy and provided his recommendation regarding which engine to use. Payton stated that "[t]he partnership has formally agreed to the configuration that will fly off the 747/Shuttle carrier aircraft…[but that] Rockwell and Orbital have not yet agreed to the propulsion system."[59] The price for two Rocketdyne RS-27 engines was $20 million [$32 million in 2016]. But United Technologies Corporation's (UTC) Pratt & Whitney was offering what Payton wrote "appears too good to be true." It would furnish a mockup for testing, plus two RD-120 engines (each guaranteed for 20 firings), at no up-front procurement costs, but at a cost of $100,000 [$158,000 in 2016] per flight, which would be reduced to $75,000 [$119,000 in 2016] per flight by the 40th X-34 mission. Also, P&W would absorb the $10 million [$16 million in 2016] design, development, test, and evaluation (DDT&E) estimated costs to integrate the RD-120 into the X-34. Payton explained Pratt & Whitney's largesse by noting to Goldin that "United Technologies presence in Russia is huge ($250 million on contract and 15,000 employees) and this is a comparatively small investment on their part to crack the near-monopoly Rocketdyne has on U.S. space launch propulsion."[60]

While noting that the major question revolved around the acceptance of foreign technology on the X-34, Payton recommended, "My preference is to go with the superior business deal. By accepting Pratt's offer, we are saving $20 million on a program whose total government and industry costs are approximately $180 million. With Pratt standing behind the guarantee and with a stockpile of spares, it makes little sense to go with the terribly more expensive offer from Rocketdyne."[61]

Buttressing Payton's recommendation was a technical comment from NASA Dryden which weighed in on the engine controversy on October 27, 1995, adding that ASL's selection of the Rocketdyne engine for the X-34 "provides an engine with significantly less performance."[62] Thereafter, Dryden's reports offer an interesting perspective of the wind-down of the program. Within 2 weeks of the previously mentioned status report, the November 9, 1995, report added that "last week, Thursday, Dryden was directed to stop work on the X-34 program because Headquarters deemed the program suspended. However, the decision to cancel the program was turned around, and Dryden was directed to begin work again last Friday."[63] The January 16, 1996, report noted that "[a]n engine decision (Rocketdyne vs. Russian RD-120) has still not been made by NASA Headquarters. It is anticipated that this issue will be resolved next week."[64] Dryden's Activity Report submitted on January 26, 1996, stated that "OCS issued a stop-work order to the Centers for the X-34 last week. Word is that a small team is looking to down-scale the vehicle to an L-1011 launched configuration."[65]

As noted earlier, Orbital was having second thoughts about the larger X-34B favored by Rockwell and agreed to by Orbital. Orbital's leadership were particularly concerned about the cost of the X-34B, as well as a lack of a potential commercial market. Then there were the technical concerns regarding the risk of a collision launching from the top of the NASA 747. These concerns caused Orbital to move in favor of a smaller vehicle like the X-34A or scaled-down X-34B that would be launched by dropping the vehicle from the underside of Orbital's L-1011.[66]

The White House and NASA Attempt To Resuscitate the Program

A November 3, 1995, memorandum from the Office of Science and Technology Policy to Goldin outlined both the office's concerns about deviating from the original program objectives and the office's desire for NASA to try to resolve the differences between Orbital and Rockwell. The memorandum also gave an indication that disagreement on which engine to use was a factor endangering the continuation of the program and that NASA was at least somewhat involved in the dispute. The policy office expressed concern that the program was changing the focus by developing a low-cost operational vehicle as opposed to the original objectives, as reviewed in the following paragraph in the memorandum:

> We are concerned with NASA's apparent change in the X-34 program's main objectives. We approved the program last year as a *technology program* that would: 1) demonstrate advanced technologies and efficient operations applicable to a future low cost launch system; 2) help prove the economies of reusability; and 3) demonstrate that new ways of doing business in an industry-led format could reduce costs and development time—and meet these objectives in a timely fashion in order to contribute to the X-33 program and, ultimately, to a RLV decision. An added bonus to the program would be if through industry's cost share, the X-34 would become an operational vehicle that could better enable agency needs. Recent statements by the NASA RLV program team, however, have focused narrowly on developing a

low cost operational vehicle. From that perspective, we can understand why the agency is concerned about the industry's engine selection and its potential implications for cost and performance. However, if the program is truly a technology program, as we understand it to be, we should not be as concerned about those attributes—that should be a business decision that industry is in the best position to make and invest in. The government's concern should be mainly on whether the program can meet the three objectives listed above."[67]

The Office of Science and Technology Policy was particularly concerned about the implications a program collapse would have on the larger goal of forging public-private partnerships, noting that

> This program is a critical pathfinder for the agency in demonstrating that NASA can make an industry-led program work. Our impression, however, is that both NASA and the two industry partners are not trying hard enough to make this new partnership work. We strongly urge NASA to exhaust all possibilities to make this program succeed before taking any precipitous action to terminate the program. With industry's cost share nearly twice that of government's, NASA should not withdraw from the partnership without strong cause and clear violations of negotiated terms. NASA, in cooperation with other X-34 partners, needs to develop objective criteria to determine how changes to program objectives will influence NASA's continued support for this program."[68]

Finally, OSTP expressed concern regarding the impact any failure of the X-34 program might have on the longer-term X-33, reminding NASA that

> [w]e believe, as we are sure you do, that success of the X-34 will enhance overall administration, congressional and public support for the X-33 program. Failure to master the challenges of government–industry cooperation in this relatively modest program could complicate our much bolder X-33 program. Also, we believe that significant cost sharing must be provided by industry for the X-33, just as industry has done on the X-34. We view cost sharing as an important barometer for gauging industry interest in the value of the project and their intent in making this an industry-led program, not just a status quo government-contractor

> relationship. We fear, however, that the failure of the X-34 partnership will discourage needed investments from industry in the X-33.[69]

Ironically, as events turned out, the reverse might actually have occurred—the failure to complete the X-33 might have played a role in the termination of the X-34 program.[70]

"We're Going Back to the Drawing Board"

By now, the X-34 was threatened by more than its engine choice. The X-34B was growing in weight and complexity, and Orbital and Rockwell differed in their approach to the future of the program. Should it be designed to meet cost goals or performance goals? Alarmed at how rapidly it was burning through its financial reserves, the smaller Orbital favored cost; the larger and more financially powerful Rockwell favored capability. As well, Orbital still had not settled on a final configuration, having encountered, as Orbital senior vice president Antonio Elias put it, "unexpected weaknesses in the technology available to us."[71] For its part, Rockwell saw uncertainty. John McLuckey, Rockwell's chief operating officer for aerospace, bluntly stated, "Frankly, we saw some vacillation over what the best configuration was, such that we did not think we had a successful arrangement for executing the program."[72] *Aviation Week & Space Technology* was reporting that the X-34 project was once more "in jeopardy," with NASA Administrator Goldin warning both Orbital and Rockwell that they had to quickly resolve their differences, pointedly adding that he was "not going to wait months."[73]

Clearly, the partnership was unraveling, and it soon came completely apart. Again, Dryden's perspective is informative. The February 5, 1996, report added that "[a] written stop-work order was received by the project office on Wednesday, January 31. Copies were sent to Dryden Directors and X-34 team members. OSC has started their process of re-evaluating new potential vehicle configurations and new program approaches."[74] Finally, the February 9, 1996, report noted that "[t]he project was notified by telecom on Wednesday, February 7, 1996, that the OSC/Rockwell/NASA partnership was dissolved and the X-34 program was canceled."[75] In reality, it lingered for two further weeks. On February 15, Orbital, pursuant to Article 17(b) of the cooperative agreement, suspended the X-34 joint venture program while the company reviewed possible courses of action that it could take under the agreement. On February 23, Orbital notified NASA that "[w]e have completed that review, and after required discussions with NASA, are revoking the Agreement pursuant to Article 17."[76]

After the expenditure of approximately $15 million [$23 million in 2016], both Orbital and Rockwell went their separate ways to sort out lingering financial obligations between them.[77] The primary reason for Orbital's final decision to terminate its participation in the first X-34 program appears to have been concern over the commercial viability of the proposed vehicle. Ironically, it had been a detailed review that Orbital undertook during the temporary NASA suspension that led officials to conclude that the X-34, as originally envisioned, would not be economically viable from a commercial business standpoint. An unnamed Orbital official remarked afterward that "[w]e're going back to the drawing board…. [X-34] was not meeting our financial or technical goals. It was a business decision."[78]

The termination of the first X-34 raised issues regarding the Government-industry business model used for both the X-33 and X-34 programs. Goldin noted that both the Government and the industry shared blame for not making the necessary investment to lower launch costs below $10,000 per pound. He added, however, that industry was spending hundreds of millions of dollars on the Air Force evolved expendable launch vehicle (EELV) competition to upgrade the current fleet of United States expendable rockets but was unwilling to make credible investments in reusable vehicle programs such as the X-34. (In its defense, it may be said that the Air Force at this time was, of course, on a sustained 24/7/365 wartime footing—and had been since August 1990—and had far more serious funding issues to consider than finding money for RLVs.) Goldin also noted that if the industry was not willing to make the necessary investment, then NASA would convert the program to a "Government-type program." But, as OSTP had noted in its memo to Goldin, in this case, Orbital and Rockwell had made an extraordinary corporate commitment to the X-34—their cost-share was nearly twice that of the Government's—and thus they could hardly be faulted on that score.[79] For his part, Gary Payton took at least some comfort in having had the program canceled as quickly as it was, stating that

> If the X-34 had been a conventional government contract with no industry financial participation, we probably would have reached the same decision, but maybe two years from now after all of the government money was gone. So the fact that industry was contributing their own money to this forced a very, very tough decision very, very early.[80]

Finally, in a June 12, 1996, prepared statement submitted to the House Subcommittee on Space and Aeronautics, Goldin explained that the first X-34 program had combined "NASA's need for early technology demonstration with industry's need for a commercially viable small launcher." He added, however, that "[u]fortunately, our industry partners determined that the current economic viability of the program could not justify their investment and they withdrew." Goldin further advised that "NASA's objectives for the [follow-on] X-34 to be a technology demonstrator *and pathfinder for X-33* remain unchanged" (emphasis added).[81]

Some Lessons Learned from the First X-34 Program

Delma C. Freeman, Jr., Director of NASA Langley's Aerospace Transportation Office; Theodore A. Talay, a Langley aerospace engineer; and R. Eugene Austin, the X-33 program manager; identified a number of lessons learned from the initial X-34 program. There was the difficulty of combining a technology demonstrator with a commercial development program. Then, there was the schedule, with a requirement to fly by 1998, which limited any flexibility in schedule margin and hindered making major configuration changes to meet commercial needs. Another challenge was the administrative requirement to have all teaming agreements (including provisions regarding authorities, responsibilities, and decision-making processes) in place before NASA signed off on the cooperative agreements. In regard to the X-34, the three engineers added that significant schedule time was lost due to resolving disagreements between industry partners while the program was underway. These also led to configuration changes and missed milestones.[82]

Phoenix from the Ashes: The Birth of the "New X-34 Initiative"

The X-34, which might otherwise have disappeared into the mists of aerospace history, now witnessed a near-miraculous metamorphosis. After the termination of the first X-34 program by the two industry partners, and following White House intervention, NASA decided to use the remaining program budget funds to pursue a revised RLV that shared many of the original X-34 program goals but was contracted along more conventional lines, with a more modest performance.[83] Within 1 month of cancellation, Dryden's activity report of March 4, 1996, noted that Marshall Space Flight Center already had plans for a "new" X-34 underway and hoped to define within 3 weeks a $62 million [$95 million in 2016] program for "a 30,000- to 50,000-pound, Mach-8 vehicle that will be air launched from a B-52 and land at Edwards."[84] For its part, Orbital had already started planning for a smaller-scale suborbital-technology RLV test bed vehicle based on its X-34 experience.

On March 27, 1996, NASA issued Research Announcement NRA 8-14, soliciting proposals for the development of a second version of the X-34 for technology demonstrations and for flight-related experiments that would be conducted on the new vehicle. The new proposed X-34 was intended to be an integral part of NASA's overall reusable launch program and to enable "a flight demonstration that was, from a performance standpoint, between the DC-XA vehicle and the X-34 single-stage-to-orbit precursor vehicle."[85] The design, aerodynamic modeling and testing, fabrication of the vehicle and its component systems and subsystems, proposed flight testing, and termination of this second program are discussed subsequently.

Endnotes

1. Antonio L. Elias, Drew Hays, and Jim Kennedy, "Pioneering Industry/Government Partnerships: X-34," paper presented at AIAA Space Programs and Technologies Conference, Huntsville, AL, September 26–28, 1995, AIAA 95-3777, p. 1.
2. Antonio Elias, interview by the author, Orbital Sciences Corporation, Dulles, VA, June 19, 2013.
3. "X-34 To Be Acid Test For Space Commerce," *Aviation Week & Space Technology* (April 3, 1995): 44–45.
4. Ibid., p. 48.
5. David W. Thompson and Kent M. Black, Orbital Science's and Rockwell International Corporation's proposal to NASA for a "Cooperative Agreement for an industry-led, Government-assisted development of a small reusable launch vehicle (X-34) for commercial and research applications" (February 21–22, 1995), file folder 435, box 16, NARA accession no. 255-04-0645, NASA History Program Office, HRC. See also Heppenheimer, *Facing the Heat Barrier*, pp. 261–262, in which it is stressed how Orbital needed the financial reserves Rockwell could bring.
6. "X-34 to be Acid Test for Space Commerce," *Aviation Week & Space Technology* (April 3, 1995): 44.
7. Gary E. Payton, telephone interview by the author, April 21, 2014. X-aircraft designations are officially coordinated through and assigned by the United States Air Force.
8. NASA Marshall Space Flight Center. "Reusable Launch Vehicle Program Experimental Demonstrators: X-33 & X-34," industry briefing, October 19, 1994, Slide 1A-1214, NASA George C. Marshall Space Flight Center History Office.
9. Ibid., Slide 1A-1216. See also Elias, Hays, and Kennedy, "Pioneering Industry/Government Partnerships," pp. 1–3, and "NASA Cooperative Agreement Notice: Reusable Launch Vehicle (RLV) Small Reusable Booster—X-34," CAN 8-2, January 12, 1995, Appendix A (Technical Description), George C. Marshall Space Flight Center History Office.
10. Ibid., slide 1A-1215.
11. Michael E. Vanhook memo to Jim Kennedy, "X-34 'Should Cost' Documentation Relative to X-34 RLV Decision Criteria," March 20, 1995, file folder 541, box 20, NARA accession no. 255-04-0645, NASA Historical Reference Collection, NASA History Program Office.
12. Ibid.

13. NASA Marshall Space Flight Center. "Reusable Launch Vehicle Program Experimental Demonstrators: X-33 & X-34," industry briefing, slide 1A-1219.
14. Ibid., slide 1A-1292.
15. The NASA Advisory Council is an independent group of scientists and aerospace experts who provide external guidance to NASA's Administrator; see *http://www.nasa.gov/offices/nac/home/index.html*, accessed February 2, 2014.
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37. "Orbital/Rockwell Target as Many As 20 X-34 Launches a Year In 10 Years," *Aerospace Daily*, 173, no. 62 (1995): 485–486.
38. Ibid.
39. Ibid., p. 486. See also B. Iannotta, "Russian Power for X-34?," Space News (June 26–July 2, 1995): 1, 28. *Space News* also noted Antonio Elias' interest in building an additional X-34 to test a supersonic combustion engine (scramjet) to velocities exceeding Mach 17. This would have been a most worthwhile endeavor had it been pursued but would have required extensive redesign to properly integrate the scramjet into the vehicle.
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44. Ibid.
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53. "NASA Lifts X-34 Suspension After Parties Agree To Settle Issues," *Aerospace Daily* (November 6, 1995): 214.

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63. "XP Highlights, November 9, 1995," X-34 subsection, History Office, Armstrong Flight Research Center, Edwards, CA.
64. "Code P Highlights, January 12, 1996," X-34 subsection, History Office. Armstrong Flight Research Center, Edwards, CA.
65. "Report of Dryden Activities, Week Ending January 26, 1996," X-34 subsection, Office of History–Armstrong Flight Research Center, Edwards, CA.
66. Antonio L. Elias, interviews by the author, Orbital Sciences Corporation, Dulles, VA, January 9, 2013, and June 19, 2013.
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79. Joseph C. Anselmo, "As Rockwell and Orbital Bail Out Of X-34, Goldin Hammers Industry To Be Bolder. Contractors indicate willingness to take financial risks," *Aviation Week & Space Technology* (February 19, 1996): 20–21. The OSTP memo is Skip Johns and T.J. Glauthier memo to Daniel Goldin, "Status of X-34 Program," 3 November 1995.
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81. Daniel S. Goldin, "Statement to the House of Representatives," June 12, 1996, NASA HRC, Headquarters History Office, Washington, DC.
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84. "Code P Highlights, March 4, 1996," X-34 subsection, Armstrong History Office, Edwards, CA.
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Orbital's design concept for the X-34 Technology Testbed Demonstrator is shown in this June 1996 artwork. (OSC)

CHAPTER 4

Orbital Gets a Second Chance

Following the termination of the first X-34, NASA used its remaining program funds to try again, contracting with industry for a suborbital RLV demonstrator but scaling-back the program's scope compared to the original X-34's ambitious program. Even so, the planned replacement X-34 vehicle still had to achieve many of the original goals established previously.

Resuscitating the X-34

Having the opportunity to "resuscitate" the X-34 program led to a number of recommendations as to what to include in the "new-old" program. Presciently, Frederick Bachtel, NASA's Deputy Director of the Space Transportation Division, recommended ensuring that the revised X-34 and X-33 complement but not compete with each other, as competition might lead NASA "to cancel one or the other if they are too similar."[1] He recommended a "meaningful" first flight, one that would be "more than an unpowered drop test," as had been undertaken with most X-series rocket airplanes such as the X-15 and X-24, indeed, even back to the original X-1. He thought any new X-34 should have enough similarities to the earlier X-34 effort to warrant retaining the X-34 designation, recognizing that using a new one "would not look good for NASA or the RLV program."[2] It should be "a true reusable X-plane with clear research and technology development goals," even at the risk of reduced industry cost-sharing because of the lack of an immediate commercial application.[3] Bachtel recommended that NASA "acquire the X-plane as government owned and subsequently operate as a test bed for government led and sponsored research," adding, "Industry can take the vehicle design, modify as required, and develop a commercial vehicle on their own. The first phase would thus be government led and funded (the X-plane) and the second phase industry led and funded (commercial application) as contrasted to the current X-34 program where we tried to combine the two phases into one activity with one design."[4]

Overall, Bachtel emphasized that a renewed—even if downsized—X-34 would constitute a most valuable tool, suitable for use "as a hypersonic research test bed for vehicle technologies (TPS, etc.) for propulsion technologies (RBCC [rocket-based combined cycle], Aerospike, etc.) and for any other applicable hypersonic research identified," and suitable for research on such issues as "avionics, composite structures, automated and autonomous launch, flight, and recovery operations, rapid turnaround, operable cryogenic systems, and other possible demonstrations such as fly back booster systems (e.g. subsonic fly-back and recovery) or other recovery schemes which may be developed."[5]

In one major respect, however, Bachtel diverged from what program advocates wished, suggesting that NASA "get off the carrier aircraft," arguing that air-launch presented issues with aerodynamics, flight control, propellant management of fuel and oxidizer in essentially "horizontal" tanks (including both "ullage," the tendency of fuels and oxidizers evaporate and/or leak, and their tendency to shift and slosh under load, changing loadings and location of the craft's center-of-gravity), and abort issues (particularly how to furnish enough pressure to jettison propellants rapidly in the event that the X-34's engine failed to start, so that the vehicle could be safely recovered). None of these, he wrote, were "insurmountable," but they did "require time and money to resolve."[6] Thus, he warned, "If we are to fly in two years on a minimum budget it doesn't make sense to start out handicapped."[7] Most of his recommendations were accepted either in whole or in part for the restructured X-34 program—but there was never any doubt the X-34 would be air-launched, as with the X-15 before it.

NASA's Invitation to Industry

On March 27, 1996, NASA issued research announcement NRA 8-14, inviting proposals for a technology demonstrator that, in capabilities and performance, fell between the subsonic DC-XA and the suborbital X-33 vehicles. The overarching intent remained the same as in the first X-34 program—namely, to reduce the cost of access to space from $10,000 per pound of payload to $1,000 per pound of payload. Announcement NRA 8-14 called for testing key technologies "by building a test bed technology demonstration vehicle, as well as providing RLV technology flight experiments." The X-34 effort was to be an accelerated fixed-budget program; innovative ideas are sought in all areas of research to enable meaningful technology demonstrations within the limited budget and schedule constraints." The announcement also contained an option/renewal provision, which was subsequently awarded for additional flight test demonstrations "averaging 2 per month over a period of 1 year after completion of the initial test flights." Finally, the announcement identified the "expected program funding" at $60 million [$92 million in 2016] for the vehicle portion and an additional $2 million [$3 million in 2016] for the experiments. The technical and mission requirements for this resurrected X-34 RLV, now designated the X-34 Technology Testbed Demonstrator (TTD) are listed in Table 4.1.[8]

Table 4.1: Technical and Mission Requirements for the Resurrected X-34 TTD[9]

Primary	Subsidiary
I. Readily enable integration of new technologies and test articles with adequate margins to enable performance growth to test these new technologies.	—
II. Be capable of 25 test flights over a period of 1 year.	—
III. Be capable of autonomous flight operations, including return and landing to a designated landing site.	—
IV. Be capable of demonstrating vehicle safe abort (such as engine-out, propellant dump, and landing).	—
V. Demonstrate subsonic and hypersonic technologies throughout its flight profile.	1. Be capable of operations in expected RLV-type environments and conditions such as landing in cross winds of up to 20 knots and subsonic flight through rain and fog.
	2. Be capable of powered flight to at least 250,000 feet.
	3. Be capable of eventually attaining Mach 8 or above.
VI. Demonstrate, or be capable of demonstrating through subsequent upgrades, advanced technologies applicable to future reusable launch vehicles. The design is expected to incorporate some embedded RLV technologies which may include but are not limited to:	1. Composite structures such as aero surfaces, primary airframe, and thrust structures
	2. Composite reusable propellant tanks and cryo insulation
	3. Composite propulsion system lines, ducts, and valves
	4. Advanced operable thermal protection systems (TPS) including operable leading edge TPS materials
	5. Advanced low-cost avionics including integrated GPS/INS and rapid low-cost flight software development tools
	6. Integrated vehicle health monitoring techniques with advanced sensors and software algorithms

Table 4.1: continued

Primary	Subsidiary
VII. Be capable of attaining an average recurring flight cost of about $500,000 and should demonstrate routine operations with a small workforce.	—
VIII. Be capable as a low-Mach number test bed for advanced propulsion technologies that may be installed as an optimal main propulsion system, as an attached experiment, or as a deployed free-flyer and may include but are not limited to:	1. Rocket-based combined cycle (RBCC) engines
	2. Plug nozzle rocket engines
	3. Pulse detonation wave rocket engines
	4. Dual expansion engines
IX. Guidelines for use of foreign technology:	1. Foreign participation must provide clear net benefits to the achievement of the program's technical and business objectives.
	2. Federal funds may be used for manufacture or acquisition of flight-ready foreign component technology but may not be used for foreign-based RLV development of foreign technology unless specifically exempted by the NASA Administrator.
	3. Importation of foreign technology must not threaten the successful execution of the program, both in its developmental and operational phases.
	4. Due consideration should be given to fostering U.S. competitiveness and safeguarding national security interests throughout the life of the program.
	5. Close consultation should be maintained with NASA and other appropriate U.S. Government agencies on all aspects of foreign participation.

Orbital Submits Its Proposal for a Follow-On X-34 TTD

On May 10, 1996, Orbital submitted its proposal "to develop, test and operate a small, fully-reusable vehicle with the objective of demonstrating technologies and operating concepts applicable to future Reusable Launch Vehicle (RLV) systems."[10] The proposal added that Allied Signal Aerospace, Oceaneering Space Systems, the Charles Stark Draper Laboratory, and six NASA Centers and other Government facilities supported Orbital. Orbital mentioned their benefits from lessons learned over the previous 2 years, as well as the over $12 million invested on predecessor programs, including the hypersonic suborbital reusable booster (HRSB), the small booster technology demonstrator (SBTD), and the X-34B. Orbital identified its related experiences, including the development of its Pegasus and Taurus vehicles and the firm's experience in working with NASA Centers on the X-34B. The proposal described how the X-34 would be scaled down from the company's first program X-34B design and would now be comparable in size to Orbital's Pegasus XL winged expendable booster. In addition, the proposed vehicle would use the NASA Marshall Fastrac engine.[11]

The proposal also addressed some specific issues, including air launch, fabrication of two airframes, aerodynamic database, operations, software development, and the Government-industry working relationship, as described below:

1. *Air launch*. In its proposal, Orbital claimed that unlike a ground-launched vehicle, an air-launched X-34 could operate from several launch sites and make full use of the unique advantages of each flight-test range, adding that "[u]sing a fly-out, shoot-back approach, preflight and post-flight processing are conducted at the same facility, reducing facility cost, turnaround time and operations cost." Orbital added that their L-1011 carrier aircraft, which was already certified for Pegasus and Pegasus XL, "yields the lowest modification and operations costs and provides long-range, all weather capability needed for conducting unlimited X-34 operations."[12]
2. *Fabrication of two airframes*. Orbital proposed to build two primary fuselages, which would reduce the fabrication schedule risk because Orbital would conduct development and qualification testing with one vehicle while assembling, in parallel activity, the first flight vehicle. They added that the first vehicle could be upgraded to flight status at a later time, thus "mitigating program risk due to catastrophic failure."[13]
3. *Head start on aerodynamic database*. Orbital noted the necessity of having a valid aerodynamic database at contract award, adding that Orbital, during its proposal effort, had "validated and extended the [first program] X-34B wind tunnel aerodynamic database, providing a head start for the X-34 program schedule." The proposal added that the "*X-34B aerodynamics database is well-understood and assures low program risks in aerodynamics*." [Emphasis in original].

4. *Design for operations*. The company claimed that "[l]ow-cost rapid turnaround operations are embedded in every aspect of our system design, from specification of line replaceable units (LRU) for avionics and mechanisms, to processing requirements for propulsion and TPS, to development of automated tools for post-flight vehicle assessment."[14]
5. *Software development.* Orbital proposed to "minimize cost and schedule for X-34 software development by using code from and experience gained on the Pegasus, Taurus, and X-34B RLV programs." As an example of their demonstrated capability, Orbital pointed out that they had used the same flight software on two entirely different vehicles—the air-launched Pegasus and ground-launched Taurus boosters—and that only minor changes would be required to adapt this software for use on the X-34.[15]

The proposal also addressed the critical issue of mission failure that haunted NASA and persisted throughout the X-34 program. Orbital said that its robust vehicle design and experience in autopilot design from its air-launched Pegasus vehicle reduced the possibility of catastrophic failure. The company added that the "air-launch concept is inherently low risk as most systems are checked-out during captive carry and the mission may be aborted at any time prior to drop."[16] As an additional protection against catastrophic failure, Orbital proposed to retrofit and test the backup airframe that, in event of loss of the first vehicle, could be placed into service after the cause of failure of the first vehicle was identified and corrected.[17]

Orbital submitted its proposal less than a month later. NASA opened negotiations with the company to finalize a contract. Orbital faced competition for the contract from a mix of established (and in some cases legendary) firms, lesser-known start-ups, and a few hopeful wannabes: Lockheed Martin's Skunk Works, McDonnell Douglas, Northrop Grumman, Rockwell International, DuPont Aerospace, Pioneer Rocket Plane, Space Access, and Truax Engineering. That Orbital, first, was selected for further negotiation and, second, finally won was both a tribute to the excellence of its design and to the commanding leadership of Michael Griffin, then chief of Orbital's Advanced Systems Group (and who eventually served as NASA Administrator from 2005 to 2009). On August 28, 1996, NASA selected Orbital to receive a 30-month performance period contract, marking the official resurrection of the X-34. Afterward, Griffin stated that "[t]he program has the same name, but it's a different program…. It's kind of like the classic case of jacking up the license plate and sliding a new car underneath."[18]

The differences between the first X-34 and the follow-on second program reflected the very different intent of the two programs. The first, as Jack Levine, as NASA's first X-34 program manager, stressed, "combined in one vehicle a technology demonstration objective with development of a small reusable booster for potential application to low-cost commercial launch vehicles for small payloads."[19] The second, as Gary Payton emphasized, was just a technology testbed and thus "not tied to potential commercial applications."[20] The distinction drove differences in size, performance, and technology between the "first" and "second" X-34s. There also, of course, were significant differences between the X-34 and X-33, in terms of configuration, capability, propulsion, and intent, and it is to these that this study now turns.

Basic Differences Between the X-33 and the X-34 TTD

To those not involved with the two programs, the X-33 and X-34 seemed, at first glance, to be similar, even duplicative, programs. NASA and the manufacturers (Orbital for the X-34 and Lockheed Martin for the X-33) were at pains to point out both their differences and the synergistic benefits of having each (though neither was dependent for its survival on the other).

In September 1996, Jack Levine noted that "[the] X-34 is considerably smaller and lighter than X-33. It is capable of hypersonic flight to Mach 8, compared with the X-33's Mach 15. "Consequently, it is considerably less expensive and simpler to develop, to operate, and to modify for flight experiments. It has different embedded technologies and a different operational concept. We expect it to make perhaps twice as many flights as X-33, and be adaptable for frequent and diverse experiments. In short, X-34 will be a productive complement to X-33 and a valuable contribution to RLV [studies]. The flight testing will focus on RLV-type operations, the embedded technologies, and technology test articles to be carried as experiments."[21] At the end of the year, an anonymous note-taker spelled out more explicitly the following differences and relationships between the two programs:

- The X-34 program called for a more modest vehicle as compared with the X-33, which was designed to investigate the application of a larger number of more advanced technologies.
- The X-34 was designed to fly more routinely than the X-33, thus pushing the envelope in a different direction that included low-cost, efficient turnaround operations. The explicit goal of the X-34 was a fast turnaround rate at a cost of less than $500,000 per flight [$768,000 in 2016]. The X-34 also would have a much lower nonrecurring price tag.

- The X-34 was designed as a Mach 8 winged vehicle compared with the Mach 15 X-33 lifting body. This resulted in the X-34's not needing the same kinds of materials and structures as the X-33.
- The X-33 was pushing the propulsion technology envelope much further than the X-34 in the area of high performance. The X-34 was pushing for reduction of production fabrication costs.
- The X-34 used a carrier aircraft and had different ascent guidance algorithms, whereas X-33 was ground-launched.[22]

It should also be added that the X-33 was designed to lead to a single-stage-to-orbit vehicle, while the X-34 was intended as a reusable launch vehicle and experiment flight host. Accordingly, failure of the X-33 should not have impacted continued X-34 development—which, alas, it did.

The restart of the X-34 got off to a fast pace with the following tasks completed between March 27 and December 17, 1996—just a little less than 9 months:

- March 27: NASA Research Announcement NRA 8-14 issued.
- May 10: Proposal receipt due date.
- June 6: Orbital Sciences selected to start negotiation.
- August 28: Contract awarded to Orbital Sciences.
- September 27: System Requirements Review completed.
- October 15: Main propulsion system requirements package delivered.
- November 4: Transonic Wind Tunnel test completed.
- December 6: Initial loads document completed.
- December 17: Outer Mold Line freezes.[23]

Among the many challenges facing the restarted X-34 program were its composite primary structure, thermal protection system, and propulsion system, as well as the fabrication and durability of its reusable cryogenic tanks. While the composite liquid hydrogen tanks in the DC-XA Clipper Graham were the first such tanks to fly on a rocket, they were but a first step. A paper presented at the 47th International Astronautical Congress in 1996 noted that the design and fabrication of "large-scale, flight weight cryogenic tanks using suitable tank and insulation materials [constituted] the most challenging aspect of reusable vehicle design."[24] Composite structures were not as well understood as more conventional metal materials, and much work remained before engineers could adequately estimate their material properties, life-cycle utility, manufacturing issues, and ability to be inspected and repaired.[25] In particular, there was a lack of available data to estimate the durability, and hence reusability, of thermal protection system materials in launch and entry environments.[26]

This is an artistic conception of the Orbital X-34 Technology Testbed Demonstrator during a Mach 8 hypersonic glide. (NASA)

NASA Kicks Off the X-34 TTD Program

In April 1996, NASA's leadership announced plans to downsize its Headquarters and to transfer over 200 positions to the Field Centers. This announcement was followed in October 1996 by major NASA-wide restructuring. As part of this restructuring, Agency executives disbanded the Office of Space Access and Technology (OSAT, Code X), which had responsibility for the Agency's Reusable Launch Vehicles program, returning its functions to the Office of Aeronautics and Space Transportation Technology (OASTT, Code R), and thus relocating the X-33 and X-34 programs to it. Payton, previously in charge of Code X's Space Transportation Division, now assumed leadership of two new divisions within OASTT, Space Transportation Technology and Space Transportation.[27] Thus, the restructured X-34 program would be pursued in an equally restructured NASA.

NASA formally launched the second X-34 in August 1996, with Jack Levine giving an overview of the scaled-down program on August 8. He noted that the initial phase included building the vehicle and conducting two powered flights—the first flight planned for not later than September 30, 1998, with the second to be completed by January 31, 1999. The flight-test option for the X-34 was to undertake 25 flights in 1 year and to test both embedded technologies and carry-on experiments. The planned capabilities for the vehicle were to fly to an altitude of at least 250,000 feet, reach a speed of Mach 8 plus (Mach 3.8 initial phase), have low-cost operations (small workforce, nominal 2-week turnaround, with surge capability of two flights in 24 hours), and test integrated health monitoring. The X-34's environmental operational requirements included being able to land in rain, fog, or crosswinds and, if necessary, make a safe abort (flight termination or landing at alternate site). The key technologies to be tested included a composite primary and secondary airframe; composite reusable propellant tanks, cryogenic insulation, propulsion system elements; advanced thermal protection systems and materials; low-cost avionics, including integrated GPS/INS systems; rapid low-cost software development tools; flush air data system; and a new, low-cost NASA-built rocket engine.[28]

The contract Orbital received was for a firm fixed price, overseen by NASA Marshall as the Center with primary program management responsibility. Industry subcontractors included Allied Signal Aerospace (control actuators and hydraulic pumps), Oceaneering Space Systems (thermal protection blankets), Draper Laboratory (entry guidance and flight software), Vermont Composites, Aurora Flight Sciences, R-Cubed Composites, Lockheed Martin, Michoud Assembly Facility, Litton, OR Computers, and AP Precision Hydraulics. Government involvement included NASA's Ames, Dryden, Kennedy, Langley, and Marshall Centers; the Air Force at Holloman AFB; and the White Sands Missile Range complex.[29]

In late September 1998, NASA X-34 program director John R. London III, accompanied by G.M. Lyles from NASA Marshall, journeyed to Melbourne, Australia, to present a program update at a meeting of the International Astronautical Federation (IAF). There, before an audience of the world's leading astronautics practitioners, they reviewed three primary areas of focus and a number of specific technical goals of the program. The first focus area involved the planned testing of embedded RLV technologies. This was intended to include the first flight testing of a composite RP-1 (kerosene) propellant tank as well as the first demonstration of a reusable liquid oxygen and RP-1 propulsion system. Another planned technology test involved the X-34's autonomous navigation and landing system, which was very similar to the system on the X-33, thus providing testing of this system before the first planned flight of the X-33. The second area of focus involved low-cost operations and a quick vehicle turnaround time that was hoped to demonstrate a $500,000 [$740,000 in 2016] per-flight cost and an annual launch-rate capability of 25 flights with a surge capability for two flights within a 24-hour period. This would be obtained through the use of a small workforce to operate an integrated mobile ground operations center and an aircraftlike propellant loading system. The third focus area involved testing a host of experiments.[30] Back in America, London noted that "the Number One goal for us technologically with X-34 is to demonstrate low-cost operation.... We're trying to follow in the footsteps of the work that was done by the DC-X and DC-XA programs that really broke a lot of new ground in the area of low cost operations, with small numbers of people involved in the actual processing and launch and rapid turnaround of the vehicle." He added hopefully, "So we're going to try to continue to push the football down the field."[31]

The X-34 Hosted-Experiments Program

In response to NASA's first requests for hosted experiments, the Agency accepted 27 proposals and rejected 6. Requests came from seven different U.S. companies, two NASA Centers, and two foreign companies. The proposals fell into the following four categories:

1. Thermal Protection Systems (TPS)	18 experiments
2. Guidance, Navigation, and Control (GN&C)	3 experiments
3. Propulsion/Auxiliary Power Units (P/APU)	3 experiments
4. Structural Instrumentation (SI)	3 experiments

Altogether, NASA budgeted $2 million [$3 million in 2016] for X-34 experiments.[32] Although NASA evaluators judged all 27 proposals as worthwhile, budget limitations eventually resulted in their only selecting seven: five collectively from Boeing and McDonnell Douglas, and one each from Daimler-Benz and Alenia.[33]

Assigned X-34 Task Agreement Relationships

Orbital and NASA each had an X-34 program manager, with the Orbital program manager held accountable to the NASA program manager. Over the program, Orbital had two different program managers—Robert E. Lindberg, Jr. (also Orbital vice president and X-34 program principal investigator), and G. David Lowe.[34] NASA had four managers, beginning with Jack Levine, followed in sequence by John R. London III, Michael D. Allen, and finally Mark Fisher. In addition, Steven D. Creech served as NASA's first onsite X-34 resident manager (March 1998–March 1999) at Orbital's Dulles, Virginia, facility, followed by Anthony M. "Tony" Springer. Prior to Creech's appointment, the position of resident manager was not officially designated because Jack Levine was located at NASA Headquarters and was able, as NASA program manager, to handle the duties of both positions.[35] The onsite resident manager was responsible for the day-to-day activities and contractor interfaces with Orbital. After another NASA realignment, in October–November 1998), the X-34 *program* officially became a *project*. Consequently, its *program* managers then became *project* managers. Even so, the words "program" and "project" appeared interchangeably in internal NASA communications and reports and in non-NASA media articles through the end of the X-34 endeavor.

Orbital and its Government partners each had so-called "Task Agreement" (TA) relationships, as follows:

- NASA Marshall had a total of 28 separate TAs, including responsibility for Federal Aviation Administration frequency procurement; main propulsion system definition, analysis, and design; Fastrac engine; vendor procurement support.
- White Sands Test Facility system testing support; flight-test support; and base heating analysis.
- NASA Langley had 17 separate TAs, including preliminary vehicle trajectory analysis; preliminary aerodynamics; aerodynamic database development; wind tunnel models and tests; flying qualities assessment; GN&C development and flight support; and Schlieren and phosphor imaging.
- NASA Ames had 12 separate TAs, including design, test, analysis, and manufacture of the silicone-impregnated ceramic ablator tiles (SIRCA) leading edge thermal protection system tiles and blankets; tile tooling, nonrecurring engineering (NRE), and fabrication; and TPS flight-test support.
- NASA Dryden had five separate Task Agreements, including ground vibration testing, captive carry Federal Aviation Administration (FAA) certification, flush air data sensors, and video chase support.
- Holloman Air Force Base had a total of 15 separate TAs, including safety plan support; systems test support; antenna pattern testing; fuel and liquid oxygen handling support; and horizontal test stand modifications.
- White Sands Missile Range had a total of eight TAs, including an environmental impact statement to be conducted with Holloman AFB, hazardous procedures support, and range approval and support.
- White Sands Test Facilities had 11 separate TAs, including test support and expendables; fuel and liquid oxygen handling equipment; static fire testing, and safety plan support.[36]

Early Concerns over Costs and Schedule

From the very beginning of the X-34 program restart, NASA attached great importance to avoiding cost overruns and schedule slippage. For example, NASA's contracting office raised "serious concerns regarding cost and schedule conditions which exist less than 6 months after contract award and are endangering successful completion of the contract."[37] In regard to cost overruns, NASA noted that Orbital "for the period ending December 31, 1996, projects a Latest Revised Estimate of $59,773,568 [$91,678,329 in 2016], which exceeds the firm-fixed-price basic contract amount by $3,632,984 [$5,572,127 in 2016]…[and that this] "apparent problem is exacerbated by anticipated significant increases in subcontract amounts over initial estimates, delays in definitizing [sic] subcontract awards, schedule stretch-outs, and substantially increased burdened labor rates under the contract as a result of recent restructuring within OSC." NASA's contracting office added that "[t]he projected date for the first flight of January 15, 1999, is already beyond the goal of September 30, 1998, and contractual delivery date of November 21, 1998, which contained two months of schedule margin…[and that the] projected flight dates are unacceptable, and there is serious concern that the schedule may further erode."[38]

Keeping Congress in the Loop: NASA's March 1997 Progress Report

On March 12, 1997, Dr. Robert E. Whitehead, NASA Associate Administrator for Aeronautics and Space Transportation Technology, testified before the U.S. House of Representatives Subcommittee on Space and Aeronautics regarding NASA's FY 1998 budget request for the Agency's Space Transportation Technology Enterprise that included $20 million in funding for the X-34 program. He reminded legislators that "it is not NASA's job to build operational vehicles, either for aviation or space transportation. It *is* NASA's job to reduce the technology risk enough so that industry can produce vehicles for use by both government and commercial sectors. To this end, NASA conducts enabling, precompetitive, risk reducing research, along with some focused technology validation and demonstrations."[39]

Applying this research, Whitehead told the Rohrabacher subcommittee, both supported NASA mission requirements and improved U.S. economic competitiveness. "Leading the world in flight—in the air as well as in space—has a profound impact on our Nation: socially, economically, and politically," he said, adding, "And now, more than ever, we in government are being asked to ensure the relevance of our national investments. The value of NASA's work to the U.S. taxpayer is the extent to which we add to the economic well-being and security of this country for future generations."[40]

Specifically referring to the X-33 and X-34 programs, Whitehead emphasized that "[t]he X-33 and X-34 programs were initiated in direct response to the National Space Transportation Policy with the primary goal of reducing launch costs by a factor of ten," optimistically offering the bright prospect that the two would "develop promising advanced technologies which, once demonstrated, can be quickly transferred to commercial use. NASA," he proclaimed, had "incorporated a commercial focus from early technology planning through program implementation and evaluation," including forming "innovative partnerships" strengthening "the alliance between industry and government, thus eliminating unfocused technology and assuring alignment with National needs," specifically furnishing a base of knowledge "required to enable a decision on whether or not to proceed with development of a low-cost next-generation launch system around the end of the decade."[41] He argued that such data could only come through flight testing because "The 'threat of flight'…forces advanced vehicle concepts and related technology efforts, such as the X-33 lifting body, to become more integrated and to place additional focus on system technology demonstration."[42]

Whitehead added that the first step had already been taken by the DC-XA, and now it was the X-34's turn. Phase I of the reconstituted X-34 program included vehicle design, manufacturing, and checkout (including two flight tests). This phase was planned as a 30-month program, with the first flight planned to take place in late 1998 from White Sands Missile Range. A Phase II option (subsequently exercised) after the basic contract had been fulfilled added a further 25 flight tests over a 12-month period. These flights would cover a range of conditions and would be conducted from multiple launch and landing sites including, initially, Kennedy Space Center. NASA set a per-flight cost goal of $500,000 to fulfill the low-cost-per-launch program objective. As well, Whitehead informed his listeners, a second X-34 had been added to the program in order to enable a more robust flight program. Summing up, Whitehead concluded optimistically (given the Agency's earlier concerns over schedule slip and cost) that

> [t]he X-34 program is proceeding as planned, is working toward a system design review in May of this year [1997] and begins major hardware delivery this summer. Fabrication of the fuselage, propellant tanks, wings, pressure tanks and actuation systems has been initiated. The X-34 is also building on technology initially developed in the ASTP program [Advanced Space Transportation Program] by continuing advancement of the "Fastrac" engine. The Fastrac and related propulsion subsystems will fly on the maiden voyage of the first fully-integrated powered X-34 flight. Critical design review (90% design completed) will be completed in April. Hardware fabrication continues in support of turbomachinery, thrust chamber, and other subsystem testing beginning later this month.[43]

Further Restructures and Realignments

In another 9 months, however, on December 24, 1997, NASA abruptly restructured the program, the first major modification to the program since its Phoenix-like rebirth in August 1996. The restructuring addressed two major program concerns—reducing risks and adjusting the anticipated launch dates.[44]

Restructuring for Risk Reduction

The first priority in the risk review area was to reduce the risk to the first flight. Having already slipped from September 30 to November 21, 1998, and then to January 15, 1999, it was now rescheduled for March 11, 1999. The decisions included

- adding more hardware, including hardware for a second vehicle;
- changing the first flight to an unpowered drop flight;
- adding new tests to reduce uncertainties;
- moving the dates for the second flight and static test; and
- adjusting how the A-1 ground test vehicle, A-2 flight vehicle, and A-3 (added) flight vehicle would be used in the program.[45]

The program realignment necessitated adding new Task Agreements, as well as realigning the existing agreements; rearranging the scope of the program by adding to the list of Government furnished equipment (GFE); allowing for the addition of a third vehicle (A-3, the second flight vehicle); realigning deliverables to the new dates; and ensuring that program personnel worked to the same schedule and milestones. The realignment came at a price of approximately $20.5 million ($18 million for Orbital and $2.5 million for NASA) [respectively, $30.7 million, $27 million, and $3.75 million in 2016].[46]

The Restructured X-34 Program Budget

With the additional realignment funds noted above, the X-34 program budget, including funds already spent and projected expenditures for fiscal years 1998 through 2001, totaled $156.7 million. Orbital's work was now budgeted at $69 million, and the Fastrac engine was budgeted at $30.9 million. The annual allocations by fiscal year are shown in Table 4.2.[47]

Realigning the X-34 Program Office

In November 1998, NASA's Office of Aeronautics and Space Technology (OAST) realigned the space transportation program assigned to Marshall "to provide consistency in the distinction between programs and projects and to add a new program for Future-X. Consequently, OAST declared, "the X-34 program is now considered a project under the new Future-X Pathfinder

Table 4.2: X-34 Program Budget (in Millions of Dollars) by Fiscal Year[48]

Activity	Prior to FY98	FY98	FY99	FY00	FY01	Total
Fastrac	11.92	9.50	7.61	1.90	—	30.90
Orbital	29.60	18.62	20.49	0.26	—	69.00
Task assignments	4.79	4.46	3.16	—	—	12.40
Technology demonstration pool	—	—	2.20	5.80	2.00	10.00
Flight tests option 1	—	—	1.58	11.71	1.48	14.80
MSFC program management	0.60	1.40	0.98	0.32	0.24	3.50
HQ	1.75	0.70	1.57	0.89	0.20	5.10
Total	**50.51**	**39.17**	**39.00**	**22.00**	**6.00**	**156.70**

program."[49] John R. London, who had been the X-34 program manager, now became director of Marshall's Future-X Pathfinder Office, and Mike Allen became X-34 project manager.[50]

Mitigating Risk: NASA and Orbital Perspectives

Risk mitigation was a prominent feature of the X-34 program, reflecting changes in the Agency's attitude toward risk in the wake of the Challenger disaster in 1986. It became more so in the 1990s, after a well-publicized series of expensive NASA failures involving space vehicles attracted media attention (and it would arise again, after the turn of the 21st century, with the tragic loss of a second Shuttle, Columbia, during its return to Earth). It had surfaced first in 1987, regarding the future use of NASA's successful AD-1 Oblique Wing Technology Demonstrator for a follow-on NASA joined-wing program.[51] The aircraft was not used due to concerns over its airworthiness. NASA Ames Research Center Director Dr. William Ballhaus, Jr., complained (quite rightly) to NASA Headquarters that

> Whether we care to admit it or not, the current post-Challenger environment will not allow NASA to take risks particularly with flight vehicles. NASA cannot survive many more flight accidents. *This is really a sad situation for NASA. If you are not taking some*

> *risks, you are not taking big enough steps. You are not challenging the technology.* If this situation continues, we will have to rely on someone else like ACA [NASA's industry partner in the joined-wing program] or DARPA [Defense Advanced Research Projects Agency] to take the risks and make the breakthroughs. *A sorry state of affairs*.[52] [Emphasis added.]

There was, of course, a difference between accepting the risk associated with an inhabited flight vehicle and the risk associated with an uninhabited one (though an out-of-control or disintegrating uninhabited vehicle could itself become a deadly missile to any in its way).

In January 2000, which was well into the X-34 program and just after a string of highly publicized NASA mission failures, Orbital's Antonio Elias proposed "a framework for the analysis and evaluation of mission success risks for reusable launch vehicles (RLVs), assessment of the impact (cost/benefit) of risk mitigation alternatives, and its application to reducing X-34 risks."[53] Elias grounded his evaluation in three assumptions:

- Mission success risk areas include design, interface, and specification mistakes; hardware failures; and operational errors.
- Some risks are higher during the early developmental flights, while other risks dominate during the operational and mature phases of the program.
- The nature of mission success risks is different for reusable launch vehicles as compared with spacecraft and expendable launch vehicles.

He concluded that the history of flight failures for both expendable launch vehicles and remotely piloted vehicles revealed root causes of the failures that could be grouped into categories sharing one or more common features. Analyzing and understanding these causes would ease the complex challenge of evaluating risk mitigation. Elias classified mission success risks into the three categories that he designated as "A, B, and C."[54]

> *Category A—Design Problems*: The risks in this category manifest themselves early in the flight program, typically in the first flight. Examples of these problems were the Pegasus XL STEP 1 (F6) lateral autopilot instability, the Ariane V (F501) software overflow bug, and the Delta 3 (D3-1) structural mode/autopilot interaction problems.[55] Elias noted that the root causes of problems in this category involved design errors, including specification errors; analysis, such as incorrect aerodynamic coefficients (Lockheed/Boeing Tier III Minus) second flight instability; testing or test specification errors (Athena 1 Ring Laser Gyro

power supply arcing failure due to insufficient altitude testing); and early or first-time operational errors.[56] Elias identified the common characteristics of this risk category as follows: "[T]hey appear on early flights; occurrence probability is highest on first flight; and once identified and remedied, they seldom, if ever, reoccur. Analyses of these failures indicate that a more thorough analysis, documentation, and discipline are often stated as risk mitigation factors."[57]

Category B—Statistical Problems: Elias identified the risks in this category as "random hardware failures, environment statistics and 'one of a kind' operational or maintenance problems." He noted that a random hardware failure situation exhibits an increasing probability of failure with time, which can be measured by a component mean time between failures (MTBF) method. Classical tools to analyze these situations include single point of failure analysis, reliability block diagrams (RBDs), and failure modes and effects criticality analyses (FMECAs). Approaches for mitigating random failures "include increased component reliability (increased component MTBF), system level redundancy (increased system MTBCFs [mean time between critical failures]) and, for multiuse systems, adequate maintenance." Elias added that random failures "are very likely to become a major factor for RLVs [and that] it would be interesting to tabulate the number of non-spacecraft related (EDVs [EELV-derived vehicles] and UAVs [uninhabited aerial vehicles]) flight failures actually caused by MTBF problems."[58]

In regard to environmental risks, Elias noted that "less common are causes where an environmental risk is known, a knowledgeable risk decision is made, and 'bad luck' causes flight failure. These problems, common in wartime military operations, are historically rare for launch vehicles because of the very conservative nature of space operations, and are normally addressed via placards and flight rules. However, in an experimental program such as X-34 where exploration of the flight envelope is central to the objectives of the program, conscious and deliberate environments [sic] risk-taking may be unavoidable, and more sophisticated risk-mitigation strategies may have to be developed."[59]

Finally, for Category B situations, Elias noted that "one-of-a-kind maintenance or operational errors, such as the inadvertent flight termination activation of the [Northrop Grumman] Global

> Hawk Vehicle 2 UAV[60] in March 1999, exhibit a statistical behavior similar to random failures, even if they involve procedures and not hardware."[61]
>
> *Category C—Age Problems:* This category includes hardware aging and loss of corporate memory. Elias concluded that hardware aging "is likely to become a significant issue with multiple-use RLV." Likewise, Elias noted that "Loss of corporate memory problems are those associated with relatively long-lived programs, especially those that have gone through periods of reduced or no activity, and the operating team's group skills have deteriorated or even been lost…. A good example is the April 1999 failure of the DSP-19 Titan IV/IUS launch caused by improper thermal wrapping of a separation connector. The original design, dating to 1978, did not include key information on how the separation connector worked so that when thermal wrap was installed in the connector, it disabled the separation mechanism. Obviously, the technicians that had assembled that connector on previous successful flights had done 'the right thing' in spite of the lack of documentation."[62]
>
> Elias added that the common characteristic of Category C problems "is that the probability of occurrence of any given one is essentially zero during the early history of the program, becoming proportional to time after a certain instant[….] Mitigation of these risks after discovery, if implemented (usually an economic decision) leads to the 'resetting' of the event's probability."[63]

Unfortunately, while not yet apparent at the time Elias wrote his white paper, the X-34 program was itself to provide another example of the loss of corporate memory: its proposed Fastrac engine was the first new NASA-built rocket engine since the building of the Space Shuttle Main Engine (SSME) 25 years earlier.[64]

In summarizing the impact of the above three categories of potential problems, Elias noted that, as the result of compounding Category A, B, and C flight failures, "design failures dominate the early part of the flight program, statistical failures dominate the middle part of the program, and unmitigated aging failures dominate the latter part of the program."[65] He concluded his white paper with the following recommendation for the X-34:

> We recommend that a *flight failure analysis* of the X-34 program be carried out based on both top-down (failure tree)

> and bottoms-up [failure modes and effects criticality analyses] (FMECA) approaches, and incorporating a comparative review of the lessons learned from a database of launch vehicle failures and UAV and experimental aircraft accidents…. At the vehicle level, this analysis should incorporate the MPS [main propulsion system], Avionics and Hydraulic System [failure modes and effects analyses] (FMEAs) that have already been performed on the X-34 vehicle, as well as additional FMEAs for the main engine and system level (FMECA). [Emphasis in original.]
>
> This analysis should compare each known ELV, UAV and X-vehicle failure (as well as the single Shuttle flight failure, relevant Shuttle "near-misses," DC-XA, etc.) with the X-34 program and design for applicability. If applicable, the X-34 design and/or programmatics will be evaluated for its effect on the postulated failure (low, medium, or high probability). For each medium to high probability of flight failure mechanism, a possible risk mitigation path or paths will be identified. Each path will then be rated with respect to its likely effectiveness (risk reduction potential), schedule impact, cost, and secondary effects (e.g. loss of research objectives).[66]

The issue of risk mitigation was to resurface throughout the X-34 program and would eventually play a significant role in the termination of the program before the first unpowered drop fight or powered flight could be made. We turn now to the specifics relating to the design and fabrication of the X-34; its aerodynamic testing and modeling; its Fastrac engine and main propulsion system and subsystems; its planned flight testing; continued program/project evaluation; and, finally, the decision to terminate the X-34 before it could rocket into space.

Endnotes

1. Frederick "Rick" Bachtel note to Gary Payton, "Points to Consider for X-34 Restructure and/or Replacement Resolution," undated, X-34 files, NASA HRC.
2. Ibid.
3. Ibid.
4. Ibid.
5. Ibid.
6. Ibid.
7. Ibid.
8. *NASA Research Announcement Soliciting Proposals for the Period Ending May 10, 1996 (1st Cycle) (TA1), July 1, 1996 through May 9, 1997 (2nd Cycle) (TA2)*, NRA 8-14, pp. ii, A-1, and A-4–5 (March 27, 1996).
9. J.R. London III and G.M. Lyles, "X-34 Program Status," paper presented at the 49th International Astronautical Congress, Melbourne, Australia, September 28–October 2, 1998, IFA-98-V.4.04, p. 1.
10. Orbital Sciences Corporation, "Proposal for the X-34 Technology Demonstration Vehicle," submitted to the Marshall Space Flight Center in response to NASA Research Announcement 8–14, May 10, 1996, cover page abstract, Marshall Space Flight Center History Office.
11. Ibid., cover page abstract and p. 10.
12. Ibid., p. 1.
13. Ibid.
14. Ibid., p. 2.
15. Ibid., p. 24.
16. Ibid., A-10.
17. Ibid., pp. A-10–A-11, quotation from p. A-10.
18. Joseph C. Anderson, "NASA Gives Orbital Second Shot at X-34," *Aviation Week & Space Technology* (June 17, 1996): 31.
19. Jack Levine, "X-34 Technology Demonstrator Vehicle," September 12, 1996, attachment to presentation given at the AIAA 7th International Spaceplanes and Hypersonic Systems & Technology Conference (Norfolk, VA, November 18, 1996), p. 1, NASA Marshall Space Flight Center History Office.
20. "NASA Invests in X-34 Rescue Programme," *Flight International* (April 3–9, 1996): 23.
21. Jack Levine, "X-34 Technology Demonstrator Vehicle," p. 2.
22. Anon., "X-34 Meeting Notes," December 11, 1996, box 23, file folder 698, NARA accession no. 255-04-0645, NASA HRC.
23. John Hudiburg, "Reusable Launch Vehicle Program: X-34," undated, p. 4, file folder 698, box 23, accession no. 255-01-0645, NASA HRC.

24. Delma C. Freeman, Jr., Theodore A. Talay, and R. Eugene Austin, "Reusable Launch Vehicle Technology Program," paper presented at the 47th International Astronautical Congress, Beijing, China, October 7–11, 1996, IAF 96-V.4.-1, p. 7.
25. These all were, incidentally, major challenges in the early days of stealth aircraft, such as the Lockheed F-117A strike aircraft and the Northrop (later Northrop Grumman) B-2A Spirit bomber.
26. Freeman, Talay, and Austin, "RLV Technology Program," p. 9.
27. Rumerman, *NASA Historical Data Book,* vol. 7, p. 32.
28. Jack Levine, "NASA X-34 Program Kickoff Presentation," August 8, 1996, pp. 3–10; NASA "Lead Center PMC Presentation," in Space Transportation Program, X-34 Program file, Marshall History Office, February 17, 1998, p. 5.
29. Levine, "NASA X-34 Program Kickoff Presentation."
30. London and Lyles, "X-34 Program Status," p. 2.
31. Anon., "NASA Takes Option For 25 X-34 Flights; Engine Test Imminent," *Aerospace Daily* (December 21, 1998): 34.
32. Ibid.
33. London and Lyles, "X-34 Program Status," p. 2.
34. *NASA Research Announcement*. It is noted in Appendix B that "The principal investigator is responsible for supervision of the work and participates in the conduct of the research regardless of whether or not compensated under the award."
35. Stephen Creech, telephone interview by the author, April 14, 2014.
36. NASA "Lead Center PMC Presentation," pp. 25–30.
37. Stephen P. Beal, letter to Orbital Sciences Corporation, "Contract NAS8-40887, X-34 Cost and Schedule Issues," February 25, 1997, record file no. 18559, Box 2. NASA HRC.
38. Ibid.
39. Hearing before the Subcommittee on Science, House of Representatives, 105th Cong. (March 12, 1997) (statement of Robert E. Whitehead, Associate Administrator for Aeronautics and Space Transportation Technology, National Aeronautics and Space Administration).
40. Ibid.
41. Ibid.
42. Ibid.
43. Ibid.
44. "NASA Lead Center PMC Presentation," p. 10.
45. This was consistent with previous NASA—and Dryden/Edwards—practice, going back to the Space Shuttle, the lifting bodies, and the X-15 before that, all the way to the original Bell XS-1, which had launched the whole X-series.

46. "NASA Lead Center PMC Presentation," p. 10.
47. Ibid., p. 24.
48. Ibid.
49. A.G. Stephenson memo, "Program Office Realignment," November 18, 1998, box 5, record file no. 18562, NASA HRC.
50. John R. London III, telephone interview by the author, March 17, 2014. A "Pathfinder" designation indicated a lower-cost project; a "Trailblazer" designation signaled a higher-cost, larger project.
51. Discussed in the author's book *Thinking Obliquely: Robert T. Jones, the Oblique Wing, NASA's AD-1 Demonstrator, and its Legacy* (Washington, DC: NASA SP-2011-602, 2011).
52. William F. Ballhaus, Jr., memo to NASA Headquarters, June 11, 1987, folder 8, box L1-5-4, NASA Armstrong History Office, Edwards, CA.
53. Antonio Elias, "White Paper on X-34 Mission Success Risk Evaluation and Options: A Program Overview," January 20, 2000, p. 1, X-34 Program Office Files, 1995–2001, box 2 of 7, reference number 18559, NASA HRC.
54. Ibid.
55. All widely employed ELV systems.
56. Tier III Minus was a tailless stealthy Lockheed remotely piloted reconnaissance system called Dark Star that proved uncontrollable on its second flight; the program was subsequently cancelled.
57. Elias, "White Paper on X-34," p. 2.
58. Ibid., p. 3.
59. Ibid., p. 4.
60. In 1999, the second prototype Northrop Grumman Global Hawk remotely piloted reconnaissance aircraft was inadvertently destroyed by an erroneously sent destruct signal. The signal detonated a destruct package on the Hawk, which crashed north of Edwards AFB. The accident was a sobering one, for the "drone" was the size of a commercial Boeing 727 airliner and could have caused great damage, injury, and even death had it crashed in nearby California City or Mojave.
61. Elias, "White Paper on X-34," p. 4.
62. Ibid., p. 5.
63. Ibid., 5–6.
64. Michael D Allen, interview by the author, October 16, 2012, Marshall Space Flight Center. Michael Allen was a NASA Marshall X-34 program director. He identified the training of a new generation of engineers and technicians as perhaps the most important accomplishment of the Fastrac engine project.
65. Elias "White Paper," p. 6.
66. Ibid., p. 7.

The X-34 A-1 Structural Test Article on Rogers Dry Lake, April 16, 1999, showing its distinctive high-fineness-ratio fuselage and double-delta planform. (NASA)

CHAPTER 5

Designing and Building the X-34

The X-34 Technology Testbed Demonstrator vehicles incorporated features and lessons learned from previous programs, including the X-15, the Space Shuttle, the DC-X/XA, and the first X-34. This chapter reviews the design and fabrication of the X-34 vehicles, the vehicle description, the mission profile, influences and project-driving factors, the Orbital team that fabricated the three test bed demonstrators, risk mitigation, and preparation for flight testing.

An X-34 Design Primer

The X-34 drew on previous company experience with the Pegasus launch system and benefited from technology developed for the Rockwell Space Shuttle Orbiter, including lessons learned from operating that much larger and more complex system. For example, the ascent trajectory and performance targets for the X-34 were similar to those of the first stage of the Pegasus rocket.[1] Also, the cost, schedule, and performance requirements of the X-34 required Orbital to draw heavily from the first program X-34 configuration for the aerodynamic design of the vehicle, "which in turn extensively utilized data and design experience generated from the Space Shuttle program."[2]

The X-15 as an X-34 Analog

Orbital also drew upon lessons learned from the earlier Mach 6+ X-15, which, like the X-34, was a hypersonic air-launched boost-glider, though a piloted, not an unpiloted, system. Indeed, as noted by Anthony "Tony" Springer (then-Resident Manager and, subsequently, NASA's Alliance Development Manager for Aerospace Technology), the X-15 constituted a veritable analog for the X-34.[3] The X-15, which flew from 1959 through 1968, was the most successful of all American post–Second World War rocket research aircraft programs, attaining Mach 6.70 and an altitude of 354,200 feet, figures that remained unsurpassed for winged transatmospheric aircraft until the first flight of the Space Shuttle Columbia in April 1981. A comparison, shown in Table 5.1, indicates the many similarities between the X-15 and the X-34.

Table 5.1: The X-15 and the X-34[4]

Category	Characteristic	North American X-15	Orbital X-34
Dimensions	Length	50.75 feet	57.8 feet
	Wingspan	22.3 feet	27.7 feet
	Wing planform area	200 square feet	357 square feet
	Aspect ratio	2.5	2.14
	Sweepback degrees	25	45
Weights	Launch weight	31,275 pounds	47,725 pounds
	Landing weight	12,971 pounds	~18,500 pounds
	Usable propellant weight	18,304 pounds	~29,000 pounds
Control system, launch parameters, and actual or anticipated flight performance	Primary flight control	Piloted	Autonomous
	Reaction control system	Hydrogen peroxide	Nitrogen
	Launch aircraft	Boeing NB-52	Lockheed L-1011
	Launch altitude	~45,000 feet	~38,000 feet
	Launch speed	Mach ~0.80	Mach ~0.70
	Landing speed	200 knots	200 knots
	Max Mach	Mach 6.70	Mach 8.0
	Maximum altitude	354,200 feet	N/A
	Design altitude	250,000 feet	250,000 feet
Propulsion	Engine model	XLR99	MC-1 (Fastrac)
	Engine thrust at launch	50,000 pounds	64,000 pounds
	Launch thrust-to-weight	1.60	1.34
	Engine I_{sp}	230	310
	Oxidizer/fuel	LOX/anhydrous ammonia	LOX/RP
Structure	Primary structural material	Inconel-X nickel alloy	Composite material

There were many other comparisons that one could offer between the X-15 and the X-34. Both programs had overcome significant adversity including serious propulsion delays (in the case of the X-15, this had involved making its first contractor flights up to Mach 3 with two small X-1-legacy Reaction

The North American X-15 was an ambitious, piloted hypersonic boost-glider that routinely exceeded Mach 6 and altitudes above 250,000 feet. Here the third of the three X-15s, which had an advanced adaptive flight control system, accelerates after launch from a NB-52 mother ship. (USAF)

Motors Inc. XLR-11 rocket engines rather than the Thiokol XLR-99 which would take it into the hypersonic arena. As Springer noted regarding the development and testing of the X-15:

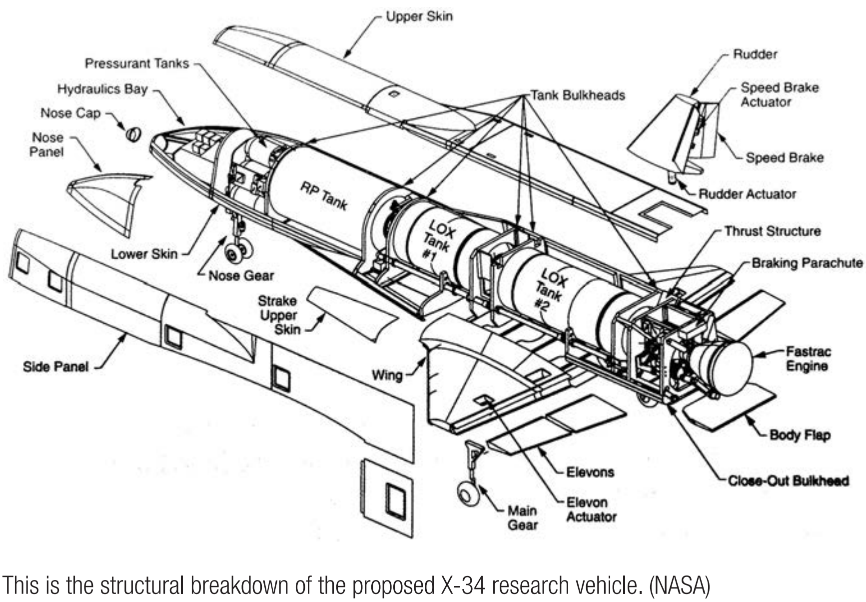
> Significant delays and cost overruns were encountered during the program, along with the damage and loss of aircraft, and the death of a pilot during flight testing. The X-15 program accepted the risks associated with experimental flight-testing, overcame adversity both technical and operational and succeeded in flying 199 flights over a span of 10 years. During this time the X-15 program accomplished the goals set forth at the start of the program. The X-15 program serves as a good analog for current expected experimental vehicle operations and cost due to similar nature of the programs and similarity in vehicle configurations. While the climate of the times and technology has changed the X-15 serves as a good starting point for current and future operational and cost estimates.[5]

Orbital aerospace engineers Henri D. Fuhrmann, John Hildebrand, and Tony Lalicata acknowledged the influence of the X-15 on the X-34 program when they wrote that "Whereas previous "X" programs have pushed the edge of the performance envelope, the X-34 program seeks to build on the experience garnered from vehicles such as the X-15 by matching or slightly exceeding performance with an order-of-magnitude reduction in development and operations cost."[6]

Orbital also benefited from consultations with NASA's John "Jack" McTigue and the Air Force's Johnny Armstrong. These two uniquely qualified NASA and Air Force engineers had worked at Edwards on the earlier X-15 and other rocket research airplanes, and between them had a combined eight decades of practical experience with supersonic and hypersonic boost-gliders. McTigue and Armstrong greatly assisted Orbital as it confronted various design issues, drawing upon their vast knowledge.

The X-34: Its Features and Details[7]

The X-34 had an all-composite primary and secondary airframe structure, the external skin of the vehicle consisted of sandwich panels that had graphite/epoxy skins over an aluminum honeycomb core. Aerodynamically, it had a high-fineness-ratio fuselage joined to an elegant double-delta wing, with a single all-moving vertical fin. The X-34 measured 58 feet in length, with a 28-foot wingspan, with an empty weight of approximately 18,500 pounds and a launch weight (fully fueled) of not quite 48,000 pounds. The trim fuselage lines, which transformed from a trapezoidal cross-section at the nose to a rectangular cross-section by the mid-body of the vehicle, housed a composite



This is the structural breakdown of the proposed X-34 research vehicle. (NASA)

RP-1 fuel tank, and two aluminum LOX tanks arranged axially (e.g., one behind the other) in the aft fuselage. (The location of the launch release housing for the attachment hooks on Orbital's Lockheed L-1011 mother ship drove the decision to use two oxidizer tanks instead of a single tank). Having three tanks, rather than a hindrance, offered the possibility of testing experimental tri-propellant propulsion systems.

A single all-moving vertical fin (incorporating a split speed brake) was mounted on the aft fuselage, the speed brake allowing the X-34 to modulate its lift-to-drag ratio and thus vary its approach during descent to landing, in similar fashion to the Space Shuttle. A ventral body flap assisted both longitudinal (e.g., pitch) control and helped shield the engine bay and exhaust bell from high-temperature flows during reentry.

At high angles of attack—"high AOA," or "high alpha" ("high α") in flight test shorthand—the X-34 relied upon 60-pound-thrust nitrogen gas reaction control system (RCS) thrusters for lateral (roll) and directional (yaw) control when the vertical tail became ineffective in the low dynamic pressure ("low q") environment found in the tenuous upper atmosphere. Eight thrusters were located in the tail section for pitch and roll control. Two thrusters that were also located in the tail section of the fuselage provided yaw control.

The X-34's double-delta wing (a configuration first pioneered in the 1950s by the Saab 210, a subscale test bed for Saab's J 35 Draken supersonic jet fighter) closely emulated that of the Space Shuttle. It had an inner strake sweep angle of 80 degrees, an outer wing sweep angle of 45 degrees, elevon-to-wing-planform ratios similar to that of the Space Shuttle, and a dihedral (fuselage-to-wingtip upsweep) angle of 6 degrees. However, the X-34 differed from the Space Shuttle in that it had a simple flat bottom airfoil section and a constant-radius wing leading edge for ease-of-manufacturing.[8]

Reflecting the era in which it was designed, the X-34 was a product of the computer age, with distributed avionics monitoring system health and performance. A flush air data system (FADS), furnished dynamic pressure, angle of attack, and angle of sideslip data, while the X-34's guidance navigation, and control (GNC) system employed a flight computer and a 3-axis inertial navigation system (INS) augmented with positioning information from the Global Positioning System (GPS) satellite navigation system. The central flight computer undertook primary flight control via three onboard utility controllers that interfaced with the main propulsion system (MPS), the attitude thruster reaction control system (RCS), and the conventional control surfaces and other subsystems. The landing gear, control surfaces (body flap, rudder, elevons, and speed brakes), and thrust vector control (TVC) actuators were controlled by a 3,000-pound-per-square-inch, absolute (3,000 psia) hydraulic system. The X-34 used simple batteries and electric motors in place of a more traditional auxiliary power unit (APU), which would have required hazardous propellants and more complex handling.

Table 5.2: X-34 Wing and Vertical Fin Dimensions and Layout[9]

Parameter	Wing	All-moving Vertical Tail
Area	357.5 square feet	33.0 square feet
Span	332.9 inches	75.5 inches
Aspect ratio	2.14	1.2
Sweep (LE)	45 degrees	40 degrees
Dihedral	6 degrees	N/A
Incidence	0	N/A
Mean aerodynamic chord	174.5 inches	64.5 inches

Table 5.3: X-34 Control Surface Areas and Maximum Deflection[10]

Control	Area	Maximum Deflection
Inboard elevon	14.5 square feet	–34.2 to +15.8 degrees
Outboard elevon	14.9 square feet	–34.2 to +15.8 degrees
All-moving vertical tail	33.0 square feet	± 30 degrees
Speed brake	11.0 square feet	–13.6 to 90 degrees
Body flap	22.3 square feet	–10 to 20 degrees

On the original X-34 program, Orbital had investigated various possible launch aircraft. These possibilities included a Burt Rutan-designed concept for a twin-fuselage launch aircraft that was similar in concept to the Rutan design later developed by his Scaled Composites Company in Mojave, California, for Virgin Galactic's Space Ship One and Space Ship Two. Orbital initially planned on using a 747 launch aircraft, separating the X-34B from the back of the 747 in a fashion analogous to how NASA had launched the Space Shuttle Enterprise from a 747 during the Shuttle Approach and Landing Tests (ALT) that were conducted in 1977 at the NASA Dryden Flight Research Center.

But the cancellation and then rebirth of the program, which resulted in a smaller X-34 vehicle, meant that Orbital could now utilize its ex-Air Canada Lockheed L-1011 Tristar airliner, which would drop the X-34 off launch adaptor on its underside from an altitude of 38,000 feet and at Mach

Orbital's L-1011 TriStar Launch Aircraft; note the aerodynamically faired launch adaptor for air-launched booster systems, such as the Pegasus visible on the underside of the fuselage. (RPH)

0.70. In case the X-34 got into trouble after launch, the vehicle had a two-phase flight termination system (FTS). Range safety monitors in Mission Control could shut down the engine (something that was impossible with a solid-fuel system, which, once ignited, burns until the fuel is exhausted); secondly, the monitors could send a signal that would trigger maximum elevon deflection, which would cause the X-34 to roll rapidly, sending it tumbling out of control.

X-34 Mission Profile

The X-34 was not restricted to using any particular test locale or venue, although it was naturally assumed that its flight test program (FTP) would begin at Edwards Air Force Base, which had a great 65-square-mile dry lakebed. While Dryden ultimately received the flight test program, the initial planned site was the White Sands Missile Range. The L-1011 carrier aircraft would take off and climb to the designated launch point, dropping the X-34 at an altitude of approximately 38,000 feet and a Mach number of 0.7. After its release, the X-34 would drop away for approximately 5 seconds so as to safely clear the L-1011 carrier aircraft. Then, once the X-34 had separated to a safe distance from the L-1011, the Fastrac rocket engine would ignite and burn for approximately 150 seconds, placing the vehicle on a trajectory to coast to its target altitude and speed of 250,000 feet and Mach 8. Following reentry, the vehicle would glide back to Earth, making an autonomous airplane-style landing at approximately 200 knots on a conventional runway.

The X-34 A-1 with its Lockheed L-1011 mother ship, on the ramp of the NASA Hugh L. Dryden Flight Research Center (now the Neil A. Armstrong Research Center), Edwards, California, in 2000. (NASA)

Orbital's X-34 Design: Philosophy, Influence, and Driving Factors

As Bryan Sullivan, Orbital's X-34 program chief engineer and Brian Winters, Orbital's X-34 propulsion lead, noted, "The X-34 program design philosophy encourage[d] sacrificing performance and mass fraction to achieve lower cost and faster turnaround. Operational philosophies include[d] the use of simplified procedures, small, well-trained crews, and flight data to verify functionality of the system prior to the next launch."[11] These were all essential aspects of reliable, rapid-turnaround, and reusable launch vehicle design. To this end, the X-34 incorporated a number of so-called "embedded technologies," as shown in Table 5.4.[12]

The DC-X and DC-XA Experience and Its Influence on the X-34

At first glance it might seem that the X-34 had little in common with the VTOL DC-X and DC-XA Clipper Graham. One was, effectively, a low-speed takeoff-and-landing demonstrator, and the other was a potential Mach 8 hypersonic boost-glider. In fact, however, Orbital benefited from the experience that McDonnell Douglas had with the DC-X/DC-XA, for it had demonstrated that

Table 5.4: X-34 Embedded Technologies

Technology	Advantages
Composite airframe and control surfaces	Lower mass, higher performance
Compartmented composite fuel tank	Lower mass, higher performance
SIRCA tiles and windward surface blankets	Simpler manufacturing, robust, lower reuse cost
Autonomous guidance using INS/GPS	Reduced avionics cost
Integrated vehicle health monitoring system	Faster turnaround, simplified maintenance
Aircraft propulsion fittings and cryogenic insulation	Lower cost, reduced operations
Fastrac engine	Lower manufacturing cost

one could successfully undertake design development of a low-cost, quick-turnaround boost system. As well, it had pioneered some technologies, such as composite valve/feed lines and differential throttle/control techniques, applicable to other systems. It had taught a more sobering lesson, as well—namely the weakness of building but a single test vehicle: once it had crashed, the program was over. Thus, Orbital planned from the outset for a minimum of two X-34s, and later, with NASA approval, secured authorization for a third (of the three, only two were intended for flight).[13]

Orbital engineer Brian Winters, in a professional short course on liquid rocket propulsion that he taught for the American Institute of Aeronautics and Astronautics, enumerated the following additional lessons learned.[14]

- System integrity should not be violated after a system is verified for flight unless integrity can be re-verified after reconnection.
- Critical processes should be verified based on appropriate fault tree analysis, and/or critical items lists. "A second set of eyes should verify the results of critical steps and assure proper system configuration before closeout of an area. A second set of eyes will be employed on all critical field site operations, and a closeout inspection by a third set of eyes will be conducted prior to compartment closeout."[15]
- Near misses should be documented and their causes corrected.
- A procedural step should not contain too many tasks and tasks defined as critical should be divided into separate steps. All field site procedures should be written so they can be completed in one shift and each procedure should clearly show the prerequisite procedures required.

- There should be a disciplined way of physically checking off steps in each procedure.
- A designated leader on the launch pad team should be responsible and accountable for task completion. Launch pad technicians should be on a recorded communication net around a large vehicle for improved communications in order to document the start and completion of each procedural event and to flag anomalies.
- In the design phase of a project, attention should be given to vehicle access for maintenance.
- Operations aspects of rapid prototyping deserve special consideration in order to make sure that safety and reliability of vehicle preparation operations are not violated. The Orbital engineer noted "X-34 continues a long history of rapid prototyping at Orbital. The lessons learned on each program are being incorporated into the operations aspects of the X-34."[16]
- Documentation, data tapes, and recorded voice tapes should be retained as historical records for each flight at least until a mission is completed and the degree of success is understood.
- The project should ensure that hazardous response groups are provided with up-to-date hazardous materials information at the start of the program.

Driving Technical Factors

As Orbital engineers Henri Fuhrmann, John Hildebrand, and Tony Lalicata noted in 1999, cost, schedule, performance, and technical risk were the factors that "drove the design of the X-34."[17] They further noted that the fast-paced and tightly scheduled program "dictated a concurrent engineering approach in which the design and analysis of the vehicle were conducted in parallel with fabrication and testing [and that as a result, this] required compromise and an appropriate balance of schedule and technical risk."[18] While, as mentioned previously, it drew upon experience with the double-delta planform of the Space Shuttle, its wing differed significantly in its airfoil shape. It was "quite different from that of the Shuttle Orbiter," the three engineers added that the airfoil had to have a flat bottom and a constant diameter leading-edge radius on its outer-wing panels, for ease of manufacture, as well as be thick enough to house the landing gear and its actuators. "The result," they noted, "is a flat-bottomed airfoil with high upper surface camber and varying spanwise thickness-to-chord ratio from 9.2% at the sweep break point to 13.4% at the wing tip."[19]

Understanding the thermal environment that the X-34 would encounter was of crucial importance and Orbital drew on NASA research at Langley and

The X-34 A-2 shown with its double-delta wing, the graphite/epoxy composite skin structure, and portions of the thermal protection system blanket overlay, March 17, 2010. (RPH)

Ames, employing computational fluid dynamics (CFD), experimental, and engineering methods to design the X-34's TPS within just 7 months. As well, the X-34 benefitted from the extensive investment in thermal protection systems made by NASA, the Department of Defense, and the aerospace industry in the four decades separating the era of the X-15 and the Orbital vehicle; the X-34 benefited in particular from the experience of the Space Shuttle.[20] As a result of its thermal analysis, X-34's TPS system consisted of a combination of ceramic tiles located on the nose and wing leading edge (where the aerodynamic heating would be most severe), and blankets elsewhere (the type depending on the anticipated heating environment). In addition, Orbital varied the thickness of the upper surface TPS insulation blankets to accommodate the higher heating loads anticipated on the upper (leeside) wing surface near the wing leading edge.[21]

Design Freeze, Detail Development, and Vehicle Fabrication

Orbital and a team of Government and industry representatives successfully completed a three-day Critical Design Review in May 1997. As a consequence, the design was now considered "frozen," having achieved a "system design freeze" (SDF) indicating that the design had met NASA's goals and objectives, had acceptable risks, that all "action items" were recorded and assigned, and that any subsequent design changes were likely to have minimal impact on cost and schedule.[22] This review basically anchored the design of the X-34 systems, including structures, guidance, navigation and control, avionics, thermal protection systems and main propulsion systems, thus allowing the program to proceed forward with fabrication of the vehicle. Commenting upon the design freeze, Robert Lindberg (Orbital's vice president, who served as the company's first X-34 program manager), noted that the design freeze was the most important X-34 program milestone achieved to date.[23]

Orbital's press release noted that all major subcontractors had been selected and had started work. The major "subs" and their responsibilities are shown in Table 5.5.

Table 5.5: X-34 Major Subcontractors and Their Responsibilities

Subcontractor/Center	Responsibility
Allied Signal Aerospace	Actuators, controls, and pumps
Draper Laboratory	Reentry and landing guidance algorithms
Oceaneering Space Systems	Thermal protection system
Vermont Composites	Fuselage
Aurora Flight Sciences	First wing
R-Cubed Composites	RP-1 fuel tank and second wing
SAAB	Landing gear
Spincraft	LOX tankage
Marshall Aerospace	Modifications to L-1011 mother ship

Other subcontractors included the Advanced Composites Group, Litton, SBS Embedded Computers, and Avica. NASA Centers involved included Langley (aerodynamics), Marshall (Main Propulsion System and the Fastrac engine), Ames (TPS tiles), and Dryden (flight testing).

Fabricating the X-34's Fuselage and Wing

Orbital used an innovative low-cost method to construct the fuselage and wing of the X-34 vehicles; as the company summarized it:

> Tooling [for the fuselage] was established on which the lower skin panels were located and bonded together. Bulkhead simulators were then positioned at the appropriate locations. The upper panels were installed and bonded together. Next the side-panels were

> installed and holes were drilled through the skins using bushings installed in the bulkhead simulators. The bulkhead simulators were then removed, the actual bulkheads were installed, and the panels were screwed to the bulkheads. This provided a very stiff structure at minimal cost.[24]

The external skins of the X-34 consisted of sandwich panel construction with graphite/epoxy skins over an aluminum honeycomb core. The wings and rudder had traditional multispar construction with the spar caps embedded within the lay-up of the skin panels.[25]

For fabrication of the upper and lower wing, molds were constructed and the skins were laid up in the molds and cured. Next, a grid assembly of spars and ribs was assembled and bonded to the lower skin. Finally, the upper skin was bonded to the grid assembly, completing the assembly of the wing. Once the construction of the wing was completed, it was tested and the wing was then integrated to the fuselage and load tests of the entire vehicle were performed. To conduct the load tests, a load test cage was constructed around the vehicle. Hydraulic actuators then applied 125 percent of the flight load to the vehicle.[26]

The X-34's Use of Composites

From the beginning of the RLV effort, NASA had strongly encouraged contractors to employ composites to the greatest possible extent to achieve the requisite vehicle mass fraction desired in future full-scale reusable launch vehicles. As a consequence, the X-34 was a 95 percent composite vehicle, employing composite parts and structure furnished by various subcontractors including Vermont Composites, Aurora Flight Sciences, and R-Cubed Composites.[27] Orbital selected LTM45EL composite-resin material for its tensile, shear, compression, and inter-laminar properties, processing flexibility, and value. LTM45EL could be oven-cured rather than cured in an autoclave and did not require spliced joints. But it had to be used quickly, lest the resin cure so rapidly that it lose tack and thus lose its ability to form a reliable bond or lay-up. Additionally, Orbital employed 34-700WD standard modulus graphite unidirectional tape for the vehicle structure, stiffer T800WD intermediate modulus graphite unidirectional tape for the fuselage longerons and wing spar caps, and CF302 standard modulus 2×2 twill fabric for curved and bolted structures.[28]

The X-34 was designed for possible service life up to 100 missions, which meant that structural fatigue issues, a problem for conventional aircraft that flew thousands of flight hours over years of service, was not an issue. Even so, being a design that used graphite/epoxy—as opposed to traditional aluminum—as its primary airframe material, the X-34 posed special technical challenges for the Orbital design team. Adding to this technical challenge was the "somewhat unique" thermal environment encountered by the X-34's structure while in flight, because its peak structural heat-soaking occurred not during the high skin-temperature reentry, but afterward, when it was well into its terminal glide back to landing.[29]

As Orbital engineers Thomas L. Dragone and Patrick A. Hipp noted in 1998:

> The ceramic thermal blankets and tiles that cover the vehicle create a significant lag between the time when the peak heat flux is applied to the vehicle and the time when the structure reaches its maximum temperature of 350-deg. F.… The peak structural loads on the vehicle occur shortly after drop from the L-1011 carrier aircraft, when the vehicle is cold-soaked below freezing as a result of the extended captive carry flight to the launch point. Maximum heating and secondary loads occur during entry when the structure has warmed to nearly room temperature again. This heat soaks into the structure and causes the peak structure temperature to occur several minutes later during thermal maneuvers, when the loading on the structure is much lower.[30]

The X-34's Propellant Tanks

Altogether, the design of the X-34's tankage was one of the most challenging and ingenious aspects of its overall design. The X-34's RP-1 (kerosene) composite-structure pressurized fuel tank consisted of a three-compartment, unlined, filament-wound 63-inch-diameter tank, with its internal flows controlled by valves and vents. The two aluminum liquid oxygen tanks were of similar design, but differed from each other in their internal layout, with the forward tank having three compartments and the aft tank having four.[31] Launch acceleration loads, combined with inherent rapid propellant consumption, forced special design considerations to prevent the X-34 from either going out of trim from fuel sloshing aft-wards within the tanks or experiencing fuel starvation from uncovering internal ports and drains. Design considerations were also needed to prevent a forward "migration" of the center-of-gravity following engine burnout. The residual fuel had to be prevented from flowing forward under the forces of longitudinal deceleration. Otherwise, the X-34 would get so nose-heavy that it could not maintain its requisite reentry angle of attack, experiencing higher aerothermodynamic loads and thus being inevitably lost.[32]

The X-34's Thrust Structure

To absorb the acceleration loads of powered flight, the X-34 had a cruciform-shaped, sandwich-panel thrust structure. The engine gimbal block attached to four composite sandwich panels which, in turn, were attached to the four corners of the aft fuselage structure via metallic fittings. The cruciform panels also were tied into a transverse bulkhead to provide additional stiffness.[33]

The X-34's Power Buses

The X-34 had four groups of electrical buses for powering various subsystems. These were organized as avionics, telemetry, transient, and hydraulics:

- Avionics: critical subsystems and components
- Telemetry: telemetry and noncritical subsystems
- Transient: noise-generating components
- Hydraulics: hydraulic motor controllers[34]

The first three power subsystems consisted of 28-volt lithium-ion batteries that were turned on and off by power transfer modules (PTMs) in the utility controllers. Each bus had its own PTM, with each PTM capable of independently switching four separate switches on each bus. Prior to launch, except for certain safety-critical components, external power was provided from the L-1011.

The X-34's Vehicle Telemetry Downlink

As detailed in Table 5.6, the X-34 acquired both analog and digital data that was multiplexed via a main encoder unit (MEU) and telemetered via S-band to Mission Control:

Table 5.6: X-34 Analog and Digital Data Acquisition Architecture

Data Type	Acquisition System	Source
Analog	Three encoders (one master, two remote)	Strain gauge Pressure Temperature
Digital	Flight computer	Utility controller-1 Utility controller-2 GPS receiver INS Radar altimeter FADS

The X-34's Electronic Ground Support Equipment

The X-34's electronic ground support equipment (EGSE) allowed vehicle testing and verification of overall system functionality. It included the equipment listed below.

- A console PC to monitor the initial health of the flight computer and to load code to the flight computer.
- A flight simulator (RTSIM Computer) to allow vehicle simulations to be run by supplying simulated navigational information to the flight computer.
- A telemetry PC to receive raw telemetry from the X-34's telemetry encoder, log the data to disc, and display the data in a graphic format.
- The L-1011 (carrier aircraft) simulator to simulate functions such as power control switching, valve controls, separation switches, and the input/output of data.
- Internal power battery simulators that would simulate internal batteries in order to allow for long test times without cycling the flight batteries.
- External GPS antenna located on the roof of the buildup area, to transmit a strong GPS signal to the vehicle's receiver for verification testing.[35]

Guidance, Navigation, and Control Subsystem

The guidance, navigation, and control (GNC) subsystem consisted of an outer guidance loop, which generated commands to send through a steering algorithm, then through command filters, and then on to the flight control system (FCS). The FCS subsequently calculated required control inputs to achieve guidance objectives, while maintaining the requisite stability.[36] The guidance commands would have varied depending on the flight phase of the vehicle, based either on predefined tables or on algorithms that were based on Space Shuttle-rooted energy-management techniques.

As the main engine fired during the ascent, a guidance roll command would be calculated to eliminate heading errors in the X-34's trajectory. During this phase, longitudinal (e.g., pitch) guidance commands would have been obtained from tables. At main engine cutoff, the calculation of lateral (e.g., roll) guidance commands would be terminated and the X-34 would ballistically coast to apogee with its wings level, with trim maintained (if necessary) by its on-board RCS system. The use of generated guidance commands would restart upon the initiation of atmospheric entry to ensure a safe vehicle recovery by not exceeding thermal, structural, and touchdown constraints. Orbital summarized entry guidance in a report, saying that:

> The entry guidance is designed to steer the vehicle onto a nominal entry trajectory that is divided into three distinct phases: *gliding*

return to launch site (GRTLS), *terminal area energy management* (TAEM), and *approach and landing* (A/L). GRTLS involves flight at a high angle of attack to dissipate the kinetic energy of the vehicle as it descends into the atmosphere. The three sub-phases of GRTLS are GRTLS alpha recovery (or alpha hold), GRTLS Nz [normal acceleration] hold, and GRTLS alpha transition. The alpha recovery sub-phase commands the vehicle to fly with wings level at a high angle of attack (typically 25 degrees). When the sensed normal acceleration reaches a specified threshold, the Nz hold sub-phase is initiated to force the vehicle to follow a pre-defined normal acceleration profile. Once the altitude rate exceeds a prescribed level, the alpha transition phase is initiated. This phase commands the angle of attack to decrease linearly and thus provide a smooth transition to atmospheric flight. Alpha transition guidance also provides a commanded roll angle to reduce heading errors in the vehicle trajectory.

Terminal area energy management (TAEM) guidance is initiated when the vehicle slows to a specified Mach number. TAEM flies the vehicle along a predetermined energy over weight (E/W) profile as a function of the range to the runway. In practice, the energy state of the vehicle is controlled by flying an altitude, altitude rate, and dynamic pressure profile.

Approach and landing (A/L) guidance transitions from the pre-final phase of TAEM to approach and landing once a set of conditions on altitude, dynamic pressure, flight path angle, and cross-range are met. Under nominal conditions, A/L guidance will initiate at an altitude of 10,000 feet but the transition can take place as low as 5,000 feet under extreme circumstances. The goal of A/L guidance is to direct the vehicle along a predetermined altitude and velocity trajectory to touchdown on the runway. [37]

Flight Control Software

The flight control software was scheduled by a dispatcher that coordinates all activities in the X-34 code. This included the execution of attitude calculations, the acquisition of sensor data required for guidance and control subroutines, the selection and execution of appropriate guidance and control functions, and the command filtering and processing. The aerodynamic and TVC autopilot controlled the X-34 during ascent and entry using a blended combination of elevon, aileron, rudder, and main engine actuator commands. This autopilot function also was capable of employing closed-loop body-flap commands. The reaction control system (RCS) autopilot controlled the X-34 via commanding nitrogen thrusters to fire at high altitudes, where the dynamic pressure ("q") is too low to allow for the exclusive use of aerodynamic control surfaces. Finally, upon landing, the rollout autopilot, activated immediately after the main gear touchdown, provided control until the vehicle came to a complete stop on the runway. A rollout cross-range autopilot steered the vehicle to the runway centerline using rudder and nose gear commands.[38] For navigation subroutines, the X-34 employed a fixed-gain navigation filter using measurements from the inertial navigation system (INS) and Global Positioning System satellite navigation (GPS) to maintain an accurate estimate of the vehicle position.[39]

Hydraulics and Landing Mechanisms

The X-34's hydraulic system provided the hydraulic power—3,000 pounds-per-square-inch (psi) nominal—necessary to operate the vehicle's control surfaces (the elevons [combined elevators and ailerons for pitch and roll control], the split speed brake on the rudder [a pivoted all-moving vertical fin], and the body flap), engine thrust vector control, main landing gear and doors, nose landing gear and door, steering, brakes, and the flight termination system. The hydraulic system consisted a flight control actuator system, the hydraulic power system, and the flight termination system.[40]

Flight Termination System

The X-34 had a unique, non-explosive, flight termination system consisting of two helium bottle assemblies connected to two actuator servo manifolds. In the event of receiving a termination command, the bottles pressurized the hydraulic system to drive the port elevons to hard-over upward deflection, and the starboard elevons to hard-over downward deflection, sending the X-34 into a no-lift high-rate roll and forcing the errant vehicle "to essentially follow a ballistic path."[41] (It is likely that the employment of this system would likewise have led to vehicle breakup in the lower atmosphere as flight loads increased and the rapid rotation led to inertial coupling, possibly triggering a fatal vehicle tumble.)

Operations Team and Mechanical Ground Support Equipment (MGSE)

The Orbital X-34 operations team was responsible for handling and servicing the X-34 vehicle once it left Orbital's Dulles integration facility. This team also coordinated the shipment of the vehicles. The X-34 was transported in two pieces—the wing and the fuselage. The wing was transported on a lowboy truck, which had a bed that was approximately two feet off of the road surface and was tilted to the side to reduce the wing's height. The fuselage was bolted to an extended-length flatbed truck. In addition to transporting the vehicle, the operations team also developed the ground support equipment

The Orbital mission operations vehicle (MOV) shown with the X-34 A-1 during ground navigation trials at the NASA Dryden Flight Research Center, July 20, 2000. (NASA)

(GSE) necessary to handle the vehicle in the field. This equipment included the transportation mate trailer (TMT) and the engine installer. The TMT was used to transport the X-34 under the L-1011 for mating. The X-34 rode on air-bearings, which allowed for the very fine adjustment of its position and azimuth to easily line up with the L-1011 hooks. An operator controlled the vehicle position and attitude through a pneumatic control station mounted on the TMT.[42]

Once the vehicle was in the field, the operations team continued the servicing and maintenance of the X-34. The team would have performed the final closeouts and system testing as well as the turnaround operations between flights. Had the X-34 been flight-tested, the operations team would have overseen the mating of the X-34 to the L-1011 and the loading of the gasses and propellants onto the X-34 vehicle. In addition, the team would have facilitated "safing" of the X-34 following flight by using the mobile operations vehicle (MOV), which was a mobile facility that could interface with the X-34 vehicle. The MOV had telemetry reception and decommutation capabilities and was designed to control the X-34 systems through an umbilical that would have been connected after landing. The MOV also was designed to provide purge gasses in order to minimize internal vehicle heating as well as to prevent RP-1 and LOX from intermingling in the engine's interpropellant seal. The MOV had a tow-bar to enable movement of the X-34, control cables, power cables, and helium/nitrogen supplies.[43]

The Orbital Corporate Culture: Observations and Reflections

In an interview with the author, Bryan Sullivan, who served as the chief engineer and technical director for Orbital's X-34 program, recalled that approximately 100 Orbital employees worked on the management, design, and fabrication teams for the X-34. He added that most of the Orbital engineers were young and worked well together. As an indication of the interest and dedication, Sullivan pointed out that most of these engineers and technicians stayed with Orbital and now comprise a core of expertise to the company.

Orbital's design group was organized into the following eight teams:

- Propulsion (Brian Winters, team lead)
- Structures (Gary Harris, team lead and Tom Dragone, wing lead)
- Landing Gear and Mechanisms (Bob Kozero, team lead and tow test series lead)
- Aerodynamics (Henri Fuhrmann, team lead and NASA Langley liaison)
- Thermal Protection System (John Hildebrand, team lead)
- Avionics (Jamie Fernandez, team lead)
- Guidance, Navigation, and Control (Mike Ruth, team lead)
- L-1011 Carrier Aircraft (Todd Ruckert, team lead)[44]

In addition, Sally Richardson served as Systems Engineering manager, and Frank Bellinger served as manager of Integration and Operations. In this role, Bellinger also drafted and negotiated the Task Agreements associated with flight test range and facility use agreements and was part of the proposal writing team for Orbital's participation in the second X-34 program.[45]

Captain Troy Pearson, an Air Force officer detailed to Orbital for a 10-month tour as part of the service's Education with Industry (EWI) program, provided an overview of how the team worked together to overcome problems and stay on schedule.[46] In a piece that he wrote for Orbital's *Space Talk*, Pearson reflected that "[i]f the actions of the X-34 team are any indication of how Orbital conducts its business, the company definitely has a bright future." He continued:

> The X-34 team's management acumen was demonstrated last fall when a bulkhead, part of the basic vehicle frame, failed during a system test, rather than accepting a schedule slip of more than two months, the entire team approached the problem with its usual success-oriented attitude, taking the opportunity to move the program forward on several fronts. The structures group quickly analyzed the failure and replaced the broken bulkhead with a slightly modified one planned for the second X-34 vehicle. At the same time, all of the subsystem groups were encouraged to

> accelerate their detailed design efforts to enable an earlier integration of subsystems into both the first and second vehicles.[47]

He concluded that "One of the most impressive things about this team is how the program managers truly empower everyone to get the job done in the most effective and efficient manner," noting that "managers…allowed each subsystem group to meet those objectives in its own way," and did not hesitate to provide workers with sufficient resources to accomplish their job. In one case, this had increased Orbital's drawing release rate by no less than 500 percent.[48]

The Continuing Quest to Mitigate Program Risk

As the X-34 program moved ahead, NASA personnel still had concerns over safety and risk. If Orbital built just one vehicle and something happened to it then the program would effectively count to naught. While every precaution could be taken to ensure that the systems on a single X-34 vehicle were as reliable as possible, flight test history had numerous examples of where the unexpected had led to the loss of even highly reliable and system-redundant designs. Thus, as time went on, an increasing number of individuals advocated for at least two X-34s.

NASA Approves a Second X-34 Flight Vehicle

On December 13, 1996, NASA approved a charter establishing an X-34 Backup Flight Vehicle Study Team. The team included members and advisors from NASA's Ames, Dryden, Marshall, Langley, Kennedy, and Johnson Centers, the Unites States Air Force, and the X-34 program office. Dryden's Robert Meyer was appointed team chair. The team issued an Interim Report on February 13, 1997, and a follow-up report on March 5 of that year.[49] It had as its objective "to develop technical, schedule and cost information required as a partial basis for decision on procurement of a second X-34 flight vehicle."[50]

The enabling charter clearly indicated that NASA was already amenable, even inclined, toward procuring a second X-34:

> Procurement of a second flight vehicle for backup and for flight test redundancy is being considered… [the] primary decision factor will be the backup/redundancy benefit. However, if the second vehicle also provided enhanced capability for additional flight testing in support of RLV and other research and technology objectives, its value would increase considerably…. The study team considerations will focus on a potential second vehicle that

> would be essentially a duplicate of the first, with no major structural changes. Minor modifications may be possible if important, as would additional necessary instrument or data provisions.[51]

The team identified nine potential risk hazards for the single-string X-34 vehicle, and also addressed the desirability of having a second vehicle in order to reduce the risk to the program mission. For each hazard, the team noted the cause, effect, planned risk reduction action, and probability of occurrence, including the severity of the occurrence. The team constructed a matrix to plot the risk using five categories: 1) risks likely to occur frequently; 2) risks likely to occur several times in the program; 3) risks likely to occur sometime in the program; 4) risks unlikely to occur; and 5) risks that were extremely improbable. Within each of these categories, the level of severity was identified as *catastrophic* (loss of vehicle), *critical* (serious damage to vehicle), *degradation to the program*, and *safe*.

NASA Enumerates Likely X-34 Failures

The team identified nine hazards constituting potential failures.[52]

> *Hazard 1: Aerodynamic Loss of Control.* The first identified potential cause of failure was if the aerodynamic models used in the control system design did not adequately predict the stability and control characteristics of the vehicle. The effect would be "Loss of control of vehicle in critical stage of flight (launch, high Mach, landing, etc.)." The planned risk reduction action was "Use of conventional planform, with relatively known aero characteristics [and] wind tunnel testing of vehicle with supporting computational analysis." The current status probability of occurrence was rated as *unlikely*.[53]

> *Hazard 2: Failure of Flight Control System (FCS) Hardware*. The second potential identified cause was the failure of a single FCS component of the single string system. For this hazard, the team listed several risk-reduction options A) design redundancy management in the currently planned single-string system; B) install a flight recovery system; C) implement an uplinked remotely piloted vehicle system as backup; D) conduct additional reliability testing; and E) design and implement a redundant flight control system. The team listed the current status probability of occurrence as *likely to occur sometime in the program*, again causing the catastrophic loss of the vehicle. Using option A, option C, and

option D did not change the probability rating. With option B, the rating still was *likely to occur sometime in program*, but the severity level was reduced to *critical*. Option E reduced the rating to *unlikely to occur*.[54]

Hazard 3: Failure of Flight Control System (FCS) Software. The potential identified cause was either missing a software or a hardware failure mode or a reliability issue, which would result in the loss of control. For this hazard, the team listed three risk reduction options: A) additional ground testing of the FCS system; B) adding a flight recovery system; and C) implementing an uplinked remotely piloted vehicle system as backup. The current probability of occurrence was *likely to occur sometime in the program*, causing the catastrophic loss of the vehicle. Using both option A and option C did not change the probability rating. With option B, the rating still was *likely to occur sometime in program*, but the severity was reduced to *critical*. Option E reduced the rating to *unlikely to occur*.[55]

Hazard 4: Failure of Autoland System. The potential identified cause was the failure of the algorithms to function as anticipated or the failure of the autoland hardware to operate properly. The impact of this failure would be the departure of the vehicle from controlled flight, the inaccuracy of vehicle touch down, or roll out. For this hazard, the team listed three risk-reduction options as follows: A) demonstrate autoland system prior to first flight on a piloted test bed; B) conduct the first series of landings on a lakebed; and C) provide a remotely piloted capability as backup. The current probability of occurrence was the *likely to occur sometime in the program* scenario that would cause the catastrophic loss of the vehicle. Using option A and option C moved the estimated risk to the *unlikely to fail* category. With option B, the rating still was *likely to occur sometime in program*, but the severity level was reduced to *critical*.[56]

Hazard 5: Thrust Loss in Ascent. The potential identified cause was failure due to engine or main propulsion system problems. The impact of this failure would be the loss of control of the vehicle, resulting in loss of vehicle due to lack of intermediate abort capability. For this hazard, the team listed three risk-reduction options as follows: A) design the center of gravity control system and the fuel dump system to maintain the center of gravity within controllable limits; B) install a flight recovery system; and C) provide an intermediate abort capability. The current probability of occurrence was the *likely to occur sometime in the program* scenario that would cause the catastrophic loss of the vehicle. Using any of the three options still left the estimated risk rating as *likely to occur sometime in program*, but the severity was reduced to *critical*.[57]

Hazard 6: Diminished Thrust in Ascent. The potential identified cause was the same as Hazard 5—failure due to engine or main propulsion system problems. The impact of this failure, if the landing site is unobtainable, was "termination of vehicle," since intermediate abort capability was not available. For this hazard, the team listed two risk reduction options as follows: A) design an intermediate abort capability; or B) install a flight recovery system. The current probability of occurrence was the *likely to occur sometime in the program* scenario that would cause the catastrophic loss of the vehicle. Using either of the two options still left the rating at the *likely to occur sometime in program* level, but the severity was reduced to *degradation of the vehicle*.[58]

Hazard 7: Failure of Rocket Engine to Light at Launch. The potential identified cause was the failure of the rocket engine to light after launch due to system component failure. The impact of this failure would have been landing at the abort site, causing *loss of mission*. For this hazard, the team risk reduction plan was to develop a flight plan at the launch point that had an adequate abort site. The current probability of occurrence was the *likely to occur sometime in the program* scenario that would cause *degradation of the vehicle*.[59]

Hazard 8: Structural Failure. The potential identified cause was the failure of the composite structure due to limited experience with advanced structure or a manufacturing error. The impact of this failure would have been inflight damage to critical structure, resulting in serious damage or loss of control of the vehicle. For this hazard, the team risk reduction plan was "Proven structural margins and construction techniques [and] [g]round testing of structure (proof tests)." The current probability of occurrence was the *unlikely to occur* scenario.[60]

> *Hazard 9: Failure of Thermal Protection System*. The potential identified cause was the failure of the TPS to "provide adequate thermal protection to the vehicle, due to flawed thermal analysis or mechanical failure of TPS." The impact of this failure would have been "Damage to critical structure or systems result[ing] in serious damage or loss of control of vehicle." For this hazard, the team risk reduction plan consisted of a combination of ground testing of TPS, previous experience with similar TPS, and expansion of the flight-testing envelope. The current probability of occurrence was the *unlikely to occur* scenario with a *critical* severity rating. This level remained at the *unlikely* level after taking the proposed risk reduction action, but with the lower *degradation* resulting probability.[61]

The study team made the following recommendations for a backup vehicle (and for the first flight vehicle, if possible):

- Provide pilot intervention through remotely piloted vehicle capability at least in the terminal area.
- Implement redundancy management into current single string flight control system where possible.
- Provide for a parachute recovery system.
- Conduct additional verification and validation of the flight control system.
- Design a CG (center of gravity) control system to maintain CG within controllable limits throughout the flight envelope.
- Provide immediate abort capability.

Recommendations for the first flight vehicle:

- Demonstrate an autoland system on a piloted test bed prior to the first flight.
- Consider schedule modifications that would include inert drop tests (approach and landing test-glide only, no engine used) as early in the schedule as possible.
- Conduct early landings on the lakebed.
- Consider removing the second LOX tank during early flights.[62]

Following up on its continued interest in risk mitigation, NASA modified its X-34 contract with Orbital to approve fabrication of a second flight vehicle in January 1998. Mike Allen, then NASA Marshall's X-34 deputy program manager, commented on the decision, stating that "[t]he purpose of a second vehicle is to reduce risk to the X-34 program [noting that] one of the lessons we learned from the Clipper Graham [DC-XA] program is that it is desirable to have a second flight vehicle available, especially if it can be acquired at a relatively low cost."[63]

Having now approved a second flight vehicle, NASA also expanded the program's test objectives, including the addition of more unpowered testing to the flight profile, and providing greater flexibility in demonstrating various technologies. With two vehicles, repetitive flights could be conducted at the same time without delays due to the time-consuming refitting of the larger technology testing projects.

NASA also increased its original $50 million Orbital contract (in addition to the $10 million in NASA funds that were in direct support of the program) by allocating an additional $7.7 million for the purchase of long lead-time hardware, including a new wing, fuselage, avionics set, hydraulic pump and actuator system, plus other needed items. In addition, NASA approved $2 million more for wind tunnel testing and a second leading-edge thermal protection system. Two funding options, which NASA expected to be exercised, provided $8.5 million in funding for the purchase of shorter lead-time hardware, including navigation systems. Another option, totaling $1.8 million, was added for assembly and the integration of parts into component subsystems.[64]

In late 1998, NASA also exercised an option for Orbital to add 25 additional test flights during a 12-month period following the two initially contracted test flights (see Appendix 1). This option added an additional $10 million to the program, with Government organizations performing $4.7 million of the additional work.[65]

By this time, Orbital was fabricating three X-34 airframes—designated as A-1, A-2, and A-3. The A-1 was originally intended only as an inert test bed to validate the primary structure through static load and ground vibration tests, to verify interfaces with the L-1011 carrier aircraft, and to receive FAA certification for the L-1011 to carry the X-34. To this end, the A-1 had to match the mass and inertia values of the full flight vehicle. After the mass simulators and test instrumentation were installed in the A-1 at Orbital's headquarters in Dulles, Virginia, the company would ship it to NASA Dryden for subsequent ground testing, including a ground vibration test to verify the accuracy of predicted structural modes and stiffness before carrying it on captive carry flight tests with the L-1011 mother ship. This was, planners initially thought, the only time the A-1 would ever fly, but that plan soon changed.[66]

In contrast to the captive-only A-1, the A-2 and the A-3 were both intended for powered flight. Both would complete the same static load test as the A-1 vehicle in order to validate manufacturing quality. The A-2 airframe was intended to be the first X-34 to fly, and thus to have the full complement of systems onboard. In accordance with Edwards' rocket airplane (and Space Shuttle) tradition, the first flight was planned to be an unpowered inert drop from the L-1011 to serve as a "dress rehearsal" to verify the launch procedures and the X-34/L-1011 mating. Orbital concluded "this strategy reduces risk to the program by validating vehicle systems prior to operating the propulsion system," noting that it was consistent with "the approach and landing tests performed with the Space Shuttle Enterprise."[67] Upon successful completion of the unpowered flight test, Orbital would install the Fastrac engine and then begin a series of progressively more demanding ground tests at Holloman AFB to "confirm the design and operation of the propulsion system."[68] The A-3 airframe was planned to follow the same path as the A-2, with the exception of the static propulsion test series at Holloman AFB.

X-34 Prepares for its First Flight Tests

In February 1999, Orbital completed the fabrication and manufacturing checkout of the X-34 A-1, shipping it across the country from Orbital's Dulles facility in two separate trucks—one carrying the fuselage and the other carrying the wing. Its arrival at Dryden marked the transition from the design and fabrication phase of the program to the flight test phase.

By that summer, Orbital had completed wind tunnel testing, assembly of the requisite aerodynamic database, autopilot, LOX and RP tanks qualification, navigation system flight tests, static loads qualification testing, L-1011 carrier plane modifications, and ground vibration tests. Integration of flight tanks for the A-2 vehicle were underway, with a captive carry test planned for early June 2000, and the approach and landing tests scheduled to commence in the fall of 2000. Engine static firing tests were scheduled after the approach and landing tests.

But changes were yet again underway. In August 1999, NASA, at the recommendation of John R. London, requested that Orbital upgrade the A-1 vehicle so that it could be used for unpowered flight tests, redesignating it the X-34 A-1A.[69] This decision to upgrade the vehicle made up for months of lost time while the flight test locations were being reviewed. The estimated $2 million upgrade enabled the A-1A to be used for high-speed tow tests and unpowered flight and landing tests. This would permit the A-1A and A-2 vehicles to undertake some testing in parallel, leading proponents to believe they could recover 3 to 6 months of schedule slippage. The upgrade, to be made at NASA Dryden, included adding full flight hydraulics and avionics systems. The A-1A, however, would not have an engine or main propulsion system. If not able to fly like an eagle, the A-1 at least was no longer a flightless dodo. For its part, the A-2's powered flights were now scheduled to start in the summer of 2000.[70] As the fall of 1999 approached, it seemed X-34 would at last take to the air.

Endnotes

1. Henri D. Fuhrmann, John Hildebrand, and Tony Lalicata, "Aerothermodynamic Overview, X-34," *Journal of Spacecraft and Rockets* vol. 36, no. 2 (1999): 153.
2. Ibid.
3. Anthony M. Springer, "The X-15 as an Analog to Expected Experimental Vehicle Operations and Costs," paper presented at the AIAA/NAL-NASDA-ISAS Space Planes and Hypersonic Systems and Technologies Conference, Kyoto, Japan, April 24–27, 2001, A01-28085 and AIAA 2001-1904, pp. 1–8. See also Brian Winters, Orbital Sciences Corporation, "Liquid Rocket Propulsion—Evolution and Advancement II," an AIAA short course PowerPoint presentation at 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 24, 1999, p. 41, box 5, reference number 18562, NASA HRC.
4. Based primarily upon data in Springer, "The X-15 as an Analog."
5. Ibid., p. 1.
6. Fuhrmann, Hildebrand, and Lalicata, "Aerodynamic Overview, X-34," p. 153.
7. This discussion is based extensively upon R. Bryan Sullivan's and Brian Winters "X-34 Program Overview," paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, AIAA 98-3516, passim; Bandu N. Pamadi, Gregory J. Brauckmann, Michael J. Ruth, and Henri D. Fuhrmann, "Aerodynamic Characteristics, Database Development and Flight Simulation of the X-34 Vehicle," paper presented at the 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10–13, 2000, pp. 2–3, AIAA 2000-0900; Richard Kutyn, "X-34 Technology Test Bed Vehicle Baseline Flight Test Program: Program Introduction," briefing memo, December 12, 1996, p. 10, box 3 (1996–1997), reference number 18560, NASA HRC.
8. Fuhrmann, Hildebrand, and Lalicata, "Aerodynamic Overview, X-34," pp. 153–154.
9. Ibid.
10. Ibid.
11. Sullivan and Winters, "X-34 Program Overview," pp. 1–2.
12. Winters, "Liquid Rocket Propulsion," p. 36.
13. Only one of the two initially planned vehicles was planned to fly. The first vehicle (A-1) was primarily a ground test article that was also used for flight tests to certify the L-1011 mating with the X-34. This vehicle was later upgraded to become the A-1A, which was capable of unpowered free-flights. See chapter 8 for more details.

14. Winters, "Liquid Rocket Propulsion," pp. 37–40.
15. Ibid., p. 38.
16. Ibid.
17. Fuhrmann, Hildebrand, and Lalicata, "Aerodynamic Overview, X-34," p. 153.
18. Ibid. As an example of the aggressive cost and schedule requirements, the three Orbital engineers noted that the outer mold line was frozen just 2 months after NASA and Orbital signed the X-34 contract, and that only 5 months later, the aerodynamic heating analysis was completed.
19. Ibid.
20. Roger D. Launius and Dennis R. Jenkins, *Coming Home: Reentry and Recovery from Space* (Washington, DC: NASA SP-211-593, 2011), pp. 185–219, 234–235.
21. Fuhrmann, Hildebrand, and Lalicata, "Aerodynamic Overview, X-34," p. 159.
22. Jim Cast, Dom Amatore, and Baron Beneski, "X-34 Systems Design Freeze Completed," NASA press release 97–107, May 22, 1997; NASA X-34 Program Board, "X-34 Program System Design Freeze," June 4, 1997, pp. 6–7, box 3 (1996–1997), reference number 18560, NASA HRC.
23. Brian Winters, "Orbital Concludes Systems Design Review of X-34 Reusable Launch Vehicle," Orbital Sciences press release, May 22, 1997; Cast, Amatore, and Beneski, "X-34 Systems Design Freeze Completed."
24. Orbital Sciences Corporation, "X-34 Technology Demonstrator Summary," pp. 20–22.
25. Ibid.
26. Ibid.
27. Each furnished the composites for a specific application: Vermont for the fuselage, Aurora for the wing, and R-Cubed for the split speed brake on the vertical fin and the wing's combined pitch-roll elevons.
28. Thomas L. Dragone and Patrick A. Hipp, "Material Characteristics and Joint Testing on the X-34 Reusable Launch Vehicle," paper presented at the Society for the Advancement of Material and Process Engineering (SAMPE) Fall Technical Conference, San Antonio, TX, October 20–24, 1998, *SAMPE Journal* (September–October 1998): 9–11.
29. Ibid., p. 8.
30. Ibid.
31. Ibid., pp. 24–25.
32. Ibid.
33. Ibid., p. 25.
34. R.H. Champion, Jr., and R.J. Darrow, Jr., "X-34 Main Propulsion System Design and Operation," paper presented at the 34th AIAA/ASME/SAE/

ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, AIAA 98-4032, p. 36.
35. Ibid., pp. 37–38.
36. Ibid., p. 40.
37. Ibid., pp. 40–41.
38. Ibid., pp. 41–42.
39. Ibid., p. 42.
40. Ibid., p. 43.
41. Ibid., p. 44.
42. Ibid., p. 45.
43. Ibid., p. 47.
44. Bryan Sullivan interview by the author, January 9, 2013, and e-mail exchange May 24, 2013.
45. Frank T. Bellinger, telephone interview by the author March 6, 2014, and e-mail exchange June 13, 2014.
46. Capt. Troy Pearson, USAF, "The X-Files Part 2: An 'Alien among us,'" *Space Talk* [internal publication of the Orbital Sciences Corporation] (1999): 14. The article stated, "EWI officers are stationed at companies for 10-month tours to learn best commercial practices first hand and to develop more effective management and technical skills. In return, companies gain not only the participant's immediate expertise, but also the support of decision-makers in the Air Force who have an in-depth understanding of industry's objectives, problems and modes of operation. Orbital has hosted at least one EWI officer for each of the last six years."
47. Ibid.
48. Ibid.
49. NASA X-34 Backup Flight Vehicle Assessment Team, *Interim Report to Project* (February 13, 1997); NASA X-34 Backup Flight Vehicle Assessment Team, *Report to Branscome Committee* (March 5, 1997), pp. 14–22, box 3 (1996–1997), reference number 18560, NASA HRC.
50. Jack Levine memo to Dryden Flight Research Center, "Charter developed for the X-34 Backup Flight Vehicle Study Team" (December 13, 1996), box 3 (1996–1997), reference number 18560, NASA HRC.
51. Ibid., Enclosure 1.
52. NASA X-34 Back-up Flight Vehicle Assessment Team, *Interim Report to Project*, pp. 14–22.
53. Ibid., p. 14.
54. Ibid., p. 15.
55. Ibid., p. 16.
56. Ibid., p. 17.
57. Ibid., p. 18.

58. Ibid., p. 19.
59. Ibid., p. 20.
60. Ibid., p. 21.
61. Ibid., p. 22.
62. Ibid., p. 25.
63. Jim Cast, "NASA Commits to Second Vehicle for X-34 Program," NASA press release #98-11 (January 13, 1998).
64. Ibid.
65. Rumerman, *NASA Historical Data Book*, vol. 7, p. 84.
66. Sullivan and Winters, "X-34 Program Overview," pp. 2–3.
67. Ibid., p. 3.
68. Ibid.
69. John R. London III telephone interview with the author, March 17, 2014.
70. Joseph C. Anselmo, "NASA Revamps X-34 Testing, Adds Third Flight Vehicle," *Aviation Week & Space Technology* (August 30, 1999): 28.

The X-34 A-1, together with the Boeing X-40A (left, back), and the MicroCraft X-43 scramjet mockup (left, front), shown on exhibit at the NASA DFRC RLV Technology Exposition, June 22, 2000. (NASA)

CHAPTER 6

Aerodynamics Modeling, Testing, and Thermal Protection

Between 1996 and October 1999, a team of 8–10 aerospace engineers and technicians at NASA's Langley Research Center and at Orbital Sciences Corporation developed the X-34's aerodynamic database, undertaking extensive aerodynamic and aerothermodynamic analysis, modeling, wind tunnel testing, and simulation.[1] Additionally, Orbital aerodynamicist Henri Fuhrmann ran tests using a Lockheed Martin tunnel, and one at the Calspan Corporation in Buffalo, New York.[2]

This chapter reviews NASA Langley's extensive wind tunnel facilities, where X-34 models were tested and special issues were addressed; wind tunnel models that were constructed and tested; aerodynamic and aero-heating testing procedures that were employed; computational fluid dynamics (CFD) programs that were exploited; the formulation of the initial and final aerodynamic database; and the flight simulation of X-34 reference missions. The thermal protection system work undertaken at NASA Ames and NASA Langley is reviewed as well, as is Orbital's contribution to the aerodynamic database.

Langley Wind Tunnel Facilities Supporting the X-34 Program

Models were tested in Langley's subsonic, supersonic, transonic, and hypersonic wind tunnels. These included Langley's low turbulence pressure tunnel, a 14-by-22-foot subsonic tunnel, a 16-foot transonic tunnel, unitary plan wind tunnels, and five upgraded hypersonic tunnels.

NASA Langley's Wind Tunnels: A Characteristics and Capabilities Review

The Langley low turbulence pressure tunnel is a single-return, closed-throat pressure tunnel that can be used to test models for Mach numbers ranging from 0.15 to 0.30. The tunnel can be pressurized from 1 to 10 atmospheres to vary the Reynolds number and thus attempt to better match the flow characteristics of the real aircraft with those on the wind tunnel model. A pitch/roll mechanism is used to set model attitude, and Mach numbers are determined from measured values of total and static pressures.

The Langley 14-by-22-foot subsonic tunnel is a closed-circuit, single-return, atmospheric tunnel with a maximum speed Mach 0.7. The maximum Reynolds number is 2.1×10^6 per feet, although aerodynamicists generally use Mach number to reference velocity.

Langley's 16-foot transonic tunnel is a closed-circuit, single-return, continuous-flow atmospheric tunnel that uses air as the test medium. The normal test Mach number ranges from 0.3 to 1.3; the angle of attack can be varied up to 25 degrees; and the Reynolds number varied from 2.0 to 4×10^6 per foot.

Langley's unitary plan wind tunnel is a continuous-flow, variable-pressure, closed-circuit pressure tunnel that has two separate test sections—test section leg 1 for low Mach number (1.46 to 2.86), and test section leg 2 for high Mach number (2.3 to 4.6). Each test section measures 4 by 4 feet and is 7 feet long. The angle of attack capability ranges from –12 to +22 degrees and higher if dogleg (modified model attachment) stings are used. (The sting is the structure that attaches the model to the tunnel floor and measurement system. If the sting is "bent" at a certain angle, a higher angle of attack range can be obtained before interference with the tunnel wall is reached.)[3] Reynolds numbers range from 1.0 to 4.0×10^6. This tunnel is capable of operating from near vacuum conditions to a pressure of 10 atmospheres.[4]

Due to renewed interest in hypersonics related to the X-30 NASP program's emphasis on air-breathing single-stage-to-orbit systems, NASA Langley made major modifications, upgrades, and enhancements to its Aerothermodynamics Facilities Complex in the late 1980s and early 1990s. Aerothermodynamics, which encompasses aerodynamics, aero-heating, fluid dynamics, and physical processes, is a critical research area for all space vehicles.[5]

Langley's complex includes five hypersonic blow-down-to-vacuum conventional-type wind tunnels that complement each other. Three different test gases (dry air, helium, and tetrafluoromethane-CF_4) are used as the flow media, enabling a wide range of Mach number and Reynolds number combinations. Each test facility is designated by a set format regime in the following order: 1) the size is given in terms of the nozzle exit diameter or height (e.g., 20-inch), 2) the Mach number (e.g., Mach 6), and 3) the test gas used (e.g., tetrafluoromethane-CF_4).

The five tunnels are as follows:[6]

> **20-inch Mach 6 CF_4 tunnel.** This wind tunnel generates a normal shock density ratio similar to that experienced during the

hypervelocity portion of reentry into Earth's atmosphere, or other planetary atmospheres. An important capability of the CF_4 tunnel is its ability to simulate the high-density ratio aspect of a real gas such as occurs in flight. The density ratio produced in conventional-type hypersonic wind tunnels that use air as the test gas is approximately 6, and with those that use helium it is only 4, while it is 12 for CF_4 gas at Mach 6. The CF_4 tunnel's basic components are the CF_4 storage trailer, high-pressure CF_4 bottle-field, pressure regulator, salt-bath storage heater, dual filtering system, settling chamber, nozzle, open-jet section, diffuser, aftercooler, vacuum system, and CF_4 reclaimer. Models are supported at the nozzle exit by a hydraulically driven injection/support mechanism enabling the angle of attack to be varied from –10 degrees to +50 degrees and angle of sideslip from –5 degrees to +5 degrees. The injection time can be varied from approximately 0.5 seconds for heat-transfer tests to 2 seconds for force and moment tests.[7]

20-inch Mach 6 tunnel. This is a blow-down wind tunnel that uses dry air as its test gas. Models are mounted on the injection system, located in the housing below the closed test section. There is a computer-operated sting support system capable of moving the model through an angle of attack of –5 degrees to +55 degrees and angles of sideslip of 0 degrees to ±10 degrees. For force and moments tests, the injection time is adjusted to 1.2 seconds with a maximum acceleration of 2 g's. Heat-transfer tests can be as rapid as 0.5 seconds. Models can be tested in this facility and in the 31-inch Mach 10 tunnel in order to examine compressibility (Mach number) effects. This wind tunnel also enables engineers and technicians to examine boundary layer transition from laminar to turbulent flow on various aerospace vehicle concepts.[8]

15-inch Mach 6 high temperature tunnel. The basic components of this tunnel include an 865 square foot bottlefield; a 5-megawatt AC resistance heater through which air flows; a 5-micron in-line filter; a pressure regulator; a settling chamber; an axisymmetric contoured nozzle; a walk-in open-jet test section; a hydraulically driven injection/retraction support mechanism, for which the angle of attack can be varied from –10 degrees to +50 degrees and sideslip between ±10 degrees; a variable area diffuser; an aftercooler; and a vacuum system shared with the 31-inch Mach 10 tunnel.

> **31-inch Mach 10 tunnel.** Although designed as a blow-down start, continuous-running tunnel, this facility operates in the blow-down mode. Models are supported on a hydraulically operated, sidewall-mounted injection system. The models can be injected to the nozzle centerline in less than 0.6 seconds and the angle of attack can be varied from –10 degrees to +45 degrees with a straight sting. The slideslip range is ±5 degrees and a computer controls both the angle of attack and the yaw.
>
> **22-inch Mach 15 to 20 helium tunnel.** This facility is an intermittent closed-cycle, blow-down tunnel that uses high purity helium (less than 40 parts per million impurities). The helium test gas does not require heating for Mach numbers less than approximately 28. The tunnel components include a high-pressure storage system designed for 5,000 psia (pounds per square inch, absolute), an in-line electrical resistance heater capable of heating the gas to a maximum temperature of 1,100 degrees R (Rankine scale), a 5-micron in-line filter, and a settling chamber. The flow is expanded through a 0.622-inch-diameter throat and an axisymmetric contoured nozzle that is designed to provide Mach 20 flow at the exit into a contoured test section that is 11.6 feet long and a maximum diameter of 22 inches. There also is a second nozzle designed for Mach 15. Typical run time is 30 seconds, but run times as long as 60 seconds have been achieved. The flow conditions produced by this facility can simulate entry flight Mach and Reynolds numbers, providing viscous interaction parameters for a variety of entry vehicles.[9]

These five facilities covered a Mach range from 6 to 20, a Reynolds number range from 0.05 to 25.0 × 10^6, and a normal shock density ratio from 4 to 12. They were used extensively in aerodynamic and aerothermodynamic testing of the X-34, facilitating its design and also furnishing significant benchmarking data. They provided the capability to run a number of tests, including force and moments, pressure, heat transfer, and thermographic phosphors (an optical acquisition method using a two-color relative-intensity phosphor thermography technique).

X-34 Wind Tunnel Testing: Issues, Models, and Methods

Aspects of the X-34 that required extensive research were the shifts in center of gravity that would occur during flight; the effects of variation in vehicle angle of attack during the powered portion of the flight; and the X-34's anticipated aerothermal environment and, consequently, the design requirements of its thermal protection system (TPS).

X-34 Special Issues in Flight Dynamics, Aerodynamic Heating, and Safety

After the X-34 was dropped and the engine ignited, the center of gravity would initially move aft to the 432-inch reference point (measured from the fuselage nose) during the ascent phase and then move forward to the 414-inch point at the end of the ascent phase. The vehicle's center of gravity would remain at 414 inches for the remainder of the flight back to Earth.[10] The shift in the center of gravity reflected the manner in which the LOX/RP-1 propellant is consumed. The ratio of fuel (RP-1) to oxidizer (LOX) and the higher density of the LOX compared to RP-1 caused the center of gravity to move aft and then forward during the course of the burn.

Just as important was the shift in the aerodynamic center as the X-34 accelerated. To balance the vehicle, the aerodynamic center needed to coincide with the center of gravity. Thus, as the X-34 accelerated, maintaining proper balance required deflecting the control surfaces to shift the aerodynamic center back to a stable balance point. The aerodynamic center first shifts forward as the vehicle accelerates supersonically, then aft during hypersonic flight, and then forward once again at subsonic landing. Therefore, calculating the relative position of the aerodynamic center and the center of gravity during the length of engine burn time is vitally important.[11]

During the initial phase of the X-34's assent, the vehicle would reach an angle of attack of approximately 13 degrees so the X-34 would climb rapidly out of the lower layers of the atmosphere, which would keep the aerodynamic loads as low as possible. The angle of attack would then decrease and remain in the 5- to 10-degree range for the rest of the assent. On the return, the X-34 would maintain an angle of attack of approximately 25 degrees for the hypersonic phase of the descent, which would minimize the increase in the temperature of the vehicle during this period of severe aerodynamic heating. For the remainder of the descent the angle of attack for the X-34 would decrease as the vehicle decelerates to low subsonic speeds. The X-34 would then land on a conventional runway at the speed of Mach 0.3.[12]

Orbital's aerodynamicist Henri Fuhrmann identified a number of other problems faced by the aerodynamics team including: a) scheduling problems (the team was under tight time constraints and actually continued follow-up testing after the X-34 time freeze and while the vehicle was under construction); b) model design and fabrication; c) the X-34's high landing speed; d) the fact that the vehicle was designed for landing, but had to go through the entire flight regime; and e) safe operation from the L-1011. Resolving the problem of safely separating the X-34 from the L-1011 in both nominal and emergency situations required a substantial amount of wind tunnel testing and separation analyses to verify that no “adverse recontact” would occur during separation. The X-34 tail had less than 7 inches axial clearance and 2 inches lateral clearance in the fin box. To provide sufficient margin, Orbital, in an interesting example of concurrent engineering, cropped the top corner of the vertical stabilizer, which solved the problem. Fuhrmann noted that, surprisingly, the notch had very little effect on the aerodynamics of the vehicle.[13]

X-34 Wind Tunnel Model Types and Purposes

Four different scale models were used for the aerodynamic testing of the X-34, depending upon the tunnel in which they were tested. They are described below.

- The test model used for low subsonic, freestream, and ground effects testing in the 14-by-22-foot tunnel was a 10 percent scale model of the X-34 Outer Mold Line (OML). This test model had remotely activated elevons, body flap, and rudder.[14] The freestream tests were conducted for landing gear fully retracted and doors closed (clean configuration) and for the landing gear-extended configuration. The ground effects tests assess the changes in the vehicle’s aerodynamic characteristics when it is flying within one-half of its wingspan above the ground, as it would during the final seconds of flight prior to landing. These tests were made both with and without the landing gear extended. The X-34 had two main landing gear doors per landing gear and one nose gear door. When the nose gear is down and the door is open, the configuration becomes aerodynamically asymmetric—that is, with the lowered door acting like an off-centerline (and possibly destabilizing) ventral fin. Therefore, tests needed to be made for various combinations of main gear and nose gear extended and retracted and doors open and closed in order to cover the various gear deployment sequences during approach and landing.[15]
- The X-34 test model for the 16-foot transonic and unitary plan wind tunnels was a 0.033-scale model (3.3 percent of the size of the full-scale vehicle) of the X-34 OML geometry.
- The X-34 test model used for the 20-inch Mach 6 tunnel tests was a 0.0183 (1.83 percent of the size of the full-scale vehicle) OML geometry.[16]
- The X-34 test model used for the 31-inch Mach 10 tunnel was a 0.013-scale model (1.3 percent of the size of the full-scale vehicle) of the X-34 OML geometry.[17] There also was an early version of the OML that was tested in the Langley low turbulence tunnel and the Lockheed supersonic tunnel. This provided early design data that was later validated with the higher fidelity tests.[18]

Table 6.1: X-34 Full-Scale Vehicle Compared to X-34 Tunnel Models

Dimension	Full Scale X-34	.033 Model	.018 Model
Wing area (square feet)	357.5	11.9167	6.5477
Wing chord (inches)	174.5	5.8167	3.1960
Wing span (inches)	332.5	11.0833	6.0897
Length (inches)	646.9	21.6540	11.8978

Table 6.1 provides the dimensions for the full-scale X-34 compared to the two primary wind tunnel test models, the 0.033 model tested in the Langley 16-foot transonic, and the 0.018 model tested in the 20-inch Mach 6 tunnel.[19]

The models described in Table 6.1 were made of aluminum and/or stainless steel, and control surface deflections were achieved by use of individual brackets. Rudder deflections were set by use of a locating pin, while the speed brakes were attached to the aft section of the tail. A partial engine bell was fabricated and tested for each model.

Ceramic force and moment models with phosphors also were fabricated for aerothermodynamic testing. These models can be made in about an order of magnitude less time than stainless steel models. C. G. Miller, of NASA Langley, noted that: "Although not a total success, due primarily to the lack of surface fidelity in critical aerodynamic surfaces, lack of precise determination of transfer distances, and challenges associated with precision alignment of the strain-gauge balances, preliminary findings were nevertheless encouraging." Miller also added that "significant advances were made in the fabrication of precision ceramic models for aero-heating studies.… [and that] Attempts to refine/enhance fabrication of ceramic and high-temperature resin force and moment models will continue in an effort to reduce the time to generate hypersonic aerodynamic information for assessment/optimization phases of the aerothermodynamic process: i.e., reduce design cycle time."[20]

Thermographic Phosphors

One of the optical acquisition methods used for the X-34 tests was the two-color relative-intensity phosphor thermography technique, which used ceramic wind tunnel models that were coated with phosphors that fluoresced in two regions of the visible spectrum when illuminated with ultraviolet light.

The fluorescence intensity images of the illuminated phosphor model exposed to a hypersonic stream were acquired by a color video camera. Temperature mappings were then calculated for portions of the model within the field of view of the camera utilizing the green and red camera outputs. The resulting intensity images were then converted to temperature mappings through use of a temperature-intensity calibration of the phosphor coating. This calibration was valid over a range from 22 to 170 degrees Celsius (532–800 °R).

Finally, heat-transfer rates were calculated at every point on the image (globally on the model) from time-sequenced images taken during the wind tunnel test. Data acquisition was performed with PC-based video-acquisition systems and color solid-state video 3-CCD (charge-coupled device) cameras that digitized the phosphor fluorescence intensity images, which were then transferred to UNIX workstations for data reduction. The large volume of data was analyzed using the NASA Langley developed I-HEAT (Internet-based Heat Evaluation and Assessment Tool) workstation-based image package that could reduce the data to global heat transfer images within minutes. NASA Langley also used a new methodology known as EXTRAP whereby global phosphor thermography wind tunnel data could be extrapolated to flight heating levels.

From these two techniques, calculated surface temperatures and heat transfer rates were made for the X-34 Technology Testbed Demonstrator using a Navier-Stokes solver known as LAURA (Langley Aerothermodynamic Upwind Relaxation Algorithm). In regard to the X-34, comparison of calculated surface temperature and heat transfer rates to extrapolated data were determined to be in good agreement. Additional techniques used at the Langley facilities included infrared emission, flow visualization, and flow field surveys.[21]

Initial Tunnel Testing

Three series of wind tunnel tests exploring the early design of the X-34 were conducted at Langley in the fall of 1996. Experimental data from these tests were used to refine the early predictions that shaped the initial X-34 aerodynamic database. These findings were updated during the initial expanded aerodynamic testing phase, and finally actual wind tunnel test data was used to produce the final aerodynamic database that was completed in October 1999.

Interestingly, the aerodynamic databases for both the X-33 and X-34 were almost exclusively drawn from wind tunnel testing as opposed to computational fluid dynamics (CFD), which was complementary in nature. This was largely because the X-34 was intended to explore the lower hypersonic environment (up to Mach 8), and not the high hypersonic environment above Mach 10, for which CFD analysis and prediction is more useful and for which performing wind tunnel, shock tube, and associated testing is more challenging.[22] Langley's C. G. Miller put tunnel testing and CFD in perspective, noting that, for the X-33 and X-34, there were:

> two primary reasons for the dominance of wind tunnel testing over CFD for these programs. Once models and associated hardware are available, wind tunnels provide huge quantities of aerodynamic performance information over wide ranges of attitude (alpha, beta), control surface deflections, individually and in combination, and flow conditions in a relatively short period of time and with a high degree of credibility based on decades of previous experience. The second reason is available wind tunnels cover the flight regimes for the X-33 and X-34 nicely, in that the maximum flight Mach number for X-33 is expected to be around 10 and to around 7 for the X-34. [However, he noted that] the contribution of CFD increases significantly above Mach 10, or so, where reacting flow-fields influence aerodynamic characteristics. In the generation of [Mach 10+] aero-heating data bases, CFD was an equal and synergistic partner with wind tunnel testing.[23]

Expanded Tunnel Testing and Analysis

Freestream and ground effect tests were conducted in the 14-by-22-foot wind tunnel using the 0.1 scale model of the X-34. These tests were made for both configurations—landing gear fully retracted with doors closed and landing gear extended. The ground effects tests were made both with and without the landing gear extended. The ground effects data was obtained for separation heights ranging between 0.3 and 2.5 times the wingspan. Due to limitations imposed by the fast-track pace of the X-34 program, pressure measurements and flow visualization tests were not performed on any of the three models.

The Aerodynamic Preliminary Analysis System (APAS), which is an interactive computer code developed jointly by NASA Langley and Rockwell in the early 1980s, was the preliminary computer code method of analysis used to provide a quick estimate of complete aerodynamic characteristics of aerospace vehicle configurations, including the X-34, ranging from subsonic to hypersonic speeds. APAS run times are in the order of minutes, thus enabling aerodynamic characteristics of a given aerospace configuration to be generated in a matter of hours, as opposed to several days or weeks required by higher fidelity methods. In the subsonic and low supersonic regimes, APAS utilized a combination of slender-body theory, source and vortex panel distribution, and empirical viscous and wave drag estimating methods. Fuselage-type components are analyzed by the slender body theory while the lifting surfaces such as wings and tails are analyzed by a panel method using distributions of linear sources and vortices.

The subsonic and low supersonic analysis in APAS was performed by the unified distributed panel (UDP) code. For the high supersonic and hypersonic speeds, APAS utilizes the Mark III Hypersonic Arbitrary Body Program (HABP). This code uses the same geometry model as used for the subsonic and low supersonic analysis. NASA Langley engineers relied upon the APAS computer codes, for they furnished good results for longitudinal aerodynamic coefficients at subsonic and supersonic and were particularly good for hypersonic speeds. The pitching moment coefficient, however, might sometimes differ from high fidelity wind tunnel tests or CFD methods, especially for configurations with long fuselages and with aft center of pressure locations.

The Langley engineers noted that for these configurations, empirical adjustments to APAS usually resulted in satisfactory predictions of the pitching moment coefficient. Finally, at transonic speeds, the APAS predictions are known to differ from wind tunnel test data. The APAS predictions of lateral/directional aerodynamic coefficients were generally considered to be of the first order of accuracy. Side force and rolling moment coefficient predictions are considered to be satisfactory for wing-body type configurations such as the X-34. The yawing moment coefficient, however, can have significant errors, especially for body dominated configurations.[24]

The X-34 Aerodynamic Data Base and Mission Trajectory Analysis

As NASA Langley aerospace engineers Bandu N. Pamadi and Gregory J. Brauckmann noted, formulation of a reliable aerodynamic database is crucially dependent upon the formulation of a realistic aerodynamic model, one that "represents the physics of the problem" and accounts for all variables.[25] To accomplish this, NASA Langley formulated aerodynamic coefficients both in free flight (i.e., the vehicle freed from ground interference and influence) and in ground effect. These tests formed the framework for building the initial aerodynamic database for the X-34 for Mach numbers ranging between 0.3 and 9.0, with closely spaced values in the transonic range. The data was formulated for varying Mach speeds, angles of attack, and elevon and aileron deflections. The data was presented in the form of aerodynamic total and incremental data tables, so that the user could evaluate each of the terms appearing in the free flight and ground effect aerodynamic models and then sum all of the terms to get the desired aerodynamic coefficients.

Initial Formulation

The first version of the aero database was developed using APAS. The APAS results were made using available wind tunnel data at the Mach 0.2 and Mach 6.0, including data obtained from the first X-34 program. For other Mach numbers, past program experience with vehicles similar to the X-34

(Space Shuttle and other wing-body configurations) was used to adjust the APAS predictions.

This database was then updated as wind tunnel test results from the X-34 program became available from the 16-foot transonic tunnel, the unitary plan wind tunnel, and the 14-by-22-foot subsonic tunnel tests. The APAS results were replaced with the actual wind tunnel test data. At some Mach numbers (for example, Mach 1.1 and Mach 1.4), where data was required but wind tunnel test data was not available, smooth interpolations using the MATLAB analytical program were made in order to obtain the aerodynamic coefficients.

Finally, for hypersonic Mach numbers greater than 6, where wind tunnel data was not initially available, APAS was used to adjust the Mach 6 wind tunnel for Mach numbers between 7 and 9. (At the time, the Mach 10 tests on the X-34 were still in progress at Langley). Pamadi and Brauckmann summarized the Langley team's initial findings:

> We have presented an overview of the wind tunnel tests, aerodynamic analyses, and the process of development of the preflight aerodynamic database of the NASA/Orbital X-34 reusable launch vehicle from subsonic to hypersonic Mach numbers. This aerodynamic data is provided for both free flight and flight in ground effect and covers the complete range of Mach numbers, angles of attack, sideslip and control surface deflections anticipated in the entire flight envelope of the X-34 vehicle. This aerodynamic data is in a form suitable for flight control system design. A typical control history based on the application of the present aerodynamic database shows that the [X-34] vehicle has satisfactory control capabilities at all the points along the nominal flight trajectory.[26]

X-34 Tunnel Data Updating and Refinement

In a later follow-up paper presented at the AIAA's 38th annual Aerospace Sciences Meeting held in Reno, Nevada, in January 2000, NASA Langley aerospace engineers Bandu N. Pamadi and Gregory J. Brauckmann, joined by Orbital engineers Michael Ruth and Henri Fuhrmann, updated the team's findings regarding the completion of all of the planned wind tunnel testing, and the final update of the aerodynamic database that was accomplished in October 1999, by which time the X-34 A-1 had already arrived at Dryden.

This updated analysis resulted from replacing the initial APAS results with the wind tunnel test data as the new data on the X-34 models became available. The teams made the following observations regarding the aerodynamic characteristics:

- *The X-34 vehicle would not encounter stall up to a 21-degree angle of attack in the subsonic and supersonic range and up to a 40-degree angle of attack at hypersonic speeds.* The vehicle is unstable at low speeds (M = 0.30) in pitch at low angles of attack; exhibits a pitch up tendency at around a 9-degree angle of attack; and then exhibits a stable break with further increase in angle of attack. The X-34 becomes more stable at transonic and supersonic speeds and the angle of attack at which pitch up occurs also increases. At hypersonic speeds, the vehicle becomes unstable due to the increasing lift developed by the forward parts of the fuselage and exhibits a tendency for a stable break at high angles of attack. The aerospace engineering team noted that this type of variation in pitching moment coefficient is typical of wing-body configurations at hypersonic speeds.
- *At low subsonic speeds, the vehicle has a lift-to-drag ratio as high as 8 at low angles of attack.* However, as Mach numbers increase, the lift-to-drag ratio decreases and assumes values ranging from 1 to 2.
- *Elevon effectiveness decreases rapidly at supersonic and hypersonic speeds.* However, at a 20-degree angle of attack, the downward deflected elevons still retain their effectiveness up to Mach 10.
- *The body flap effectiveness decreases at supersonic and hypersonic speeds for angles of attack of 6 degrees.* At a 20-degree angle of attack, the downward deflected body flap retains effectiveness up to Mach 10.
- *At angles of attack of 6 and 20 degrees, aileron effectiveness decreases at supersonic and hypersonic speeds*. At an angle of attack of 20 degrees, the downward deflected ailerons retain their effectiveness up to Mach 10.
- *Rudder effectiveness increases at transonic speeds, but decreases rapidly at higher Mach numbers.* At an angle of attack of 20 degrees, the rudder is virtually ineffective above Mach 5. In these situations, the X-34 must use the reaction control system (RCS) for directional control.
- *The increment in drag due to speed brake is accompanied by an increase in pitching moment that can augment the pitch control.* The loss of rudder and speed brake effectiveness at high angles of attack and high Mach numbers is due to the immersion of these surfaces in the low-pressure wake of the fuselage and wings.
- *At an angle of attack of 6 degrees, the X-34 is stable in roll up to approximately Mach 1.7, but beyond 1.7 the vehicle becomes unstable in roll.* At an angle of attack of 18 degrees, the X-34 is stable in roll at all Mach numbers, except around Mach 1.0, due to the increasing stabilization effect provided by the wing dihedral. At an angle of attack of 6 degrees, the vehicle is directionally stable up to Mach 1.5, but

is unstable above Mach 1.5. At an angle of attack of 18 degrees, the vehicle becomes directionally unstable at all Mach numbers.

- *Landing gear deployment leads to a more nose down pitching moment up to 12 degrees angle of attack and then the trend reverses at higher angles of attack.* The incremental coefficients correspond to approximately a 0.5 degree of elevon deflection. In addition, the vehicle experiences significant asymmetry in the variation of pitching moment coefficient with sideslip and a loss of directional stability due to landing gear deployment. The asymmetry in the variation of pitching and yawing moment coefficients with sideslip is due to the X-34 having a single nose gear door.
- *When the vehicle is in ground effect, the incremental lift and drag coefficients are positive, whereas the pitching moment increments are negative.* This is expected because in the presence of the ground, the strength of the wing tip vortices diminishes leading to a general reduction in downwash along the wingspan. Also, the elevons and body flap were found to be more effective in the presence of ground compared to those in free flight.
- *The wind tunnel test Reynolds numbers for the X-34 model, based on mean aerodynamic chord, range up to 2×10^6, whereas corresponding full-scale flight Reynolds numbers range up to 40×10^6.* The test Reynolds numbers match the flight Reynolds numbers only for a segment of hypersonic descent. Elsewhere, the flight Reynolds numbers are orders of magnitude higher than the wind tunnel test Reynolds numbers. To evaluate the impact of this finding on the pitch trim, which is of critical importance during unpowered descent, Langley engineers conducted a limited exercise using various computational fluid dynamics codes (CFD). The CFD results for Mach 2.5, 4.6, and 6.0 agreed well with the wind tunnel test data, but the CFD for Mach 1.05 and 1.25 predicted about 10 percent more nose-down pitching moment coefficient compared to the wind tunnel test data. Also, two CFD codes were run at Mach 1.05 for the flight Reynolds numbers with a turbulent boundary layer. These limited results indicated that the Reynolds number still has some influence and the flight vehicle is likely to experience a slightly higher nose-down pitching moment than predicted by the wind tunnel tests and hence the data in the aero database. This increment in nose down pitching moment approximately corresponds to about 2 degrees of up elevon deflection.[27]

X-34 Flight Trajectory Analysis

The "nominal" trajectory of the actual X-34 was described by Gregory J. Brauckmann, NASA Langley aerospace engineer: "On ascent, the X-34 maintains a low angle of attack, around 5°, except in the initial transonic phase just after drop. Here the vehicle pitches to a higher angle of attack (~13°) to rapidly establish a steep flight path angle to pull the vehicle out of lower atmosphere as quickly possible. [During reentry] the angle of attack is initially maintained at 25° and then is progressively lowered. For this trajectory, the maximum Mach number is 7.2 at an altitude of 250,000 feet. The Reynolds number…is based on free stream conditions and the mean aerodynamic chord."[28]

Beyond this general framework, the X-34 team evaluated four different X-34 Design Reference Mission (DRM) trajectories, each of which provided critical design requirements for the vehicle. These trajectories (designated as DRM 1, 2, 3, and 4) were also used to define envelope expansion strategies and to plan flight test range resources. Each represented a different flight condition: DRM 1 was a typical low Mach powered flight; DRM 2 was a maximum engine burn Mach 8 flight; DRM 3 was a no-engine ignition abort; and DRM 4 was a nominal unpowered approach and landing flight.

The DRM 1, 2, and 3 trajectories were generated using the Program to Optimize Simulated Trajectories (POST) analytical methodology, and the DRM 4 trajectory, which includes the landing phase, was generated using the Orbital Sciences-developed Pegasus six degree of freedom simulation analytical methodology. Aerodynamic uncertainties, including Reynolds number effect, were not considered in any of the four simulations. Monte Carlo simulations incorporating aerodynamic and other uncertainties were not covered, though such simulations were underway in support of the flight certification program. Pamadi, Brauckmann, Ruth, and Fuhrmann detailed each trajectory:

> **DRM 1 Trajectory.** "The DRM 1 is representative of the first powered (low Mach number) flight of the X-34 vehicle. After separation from the L-1011, the vehicle begins a pull-up to engine ignition attitude. The engine is ignited and the vehicle continues a 2g pull up maneuver. The maximum dynamic pressure attained during this flight is about 600 lb./sq. ft. The engine burn is cut off at a point when about 50% propellants are still remaining in the tanks. At this point, the vehicle dumps the remaining propellants and glides back to execute a standard approach and landing."[29] In this simulation, the maximum altitude reached is approximately 115,000 feet; the maximum Mach number reached is about 3.6; and the angle of attack goes up to approximately 14 degrees during the pull-up following the drop. The thrust vectoring (engine

gimbal angle) of about 15 degrees in pitch plane is commanded initially during the ascent in order to augment the pitch control. The commanded elevon deflection reaches approximately –20 degrees when the vehicle is descending at around a Mach 3 speed. A –2 degree elevon deflection to trim is commanded to compensate for the vehicle's experiencing more nose-down pitching moment. The commanded body flap deflections go up to –7.5 degrees during the initial part of the ascent and for the rest of the trajectory the body flap deflection remains at –10 degrees. The center-of-gravity position at drop is approximately 404 inches from the nose of the vehicle. As reviewed above, the center of gravity on the X-34 would initially move aft to about 430 inches and then move forward about 393 inches and then again move back to about 417 inches and remain at that position.[30]

DRM 2 Trajectory. "The DRM 2 is representative of a full engine burn to propellant depletion and vehicle reaching the designated altitude of 250,000 ft and target speed of Mach 8. The sequence of separation, engine ignition, and pull up are similar to the DRM 1. During this flight, the vehicle spends some time outside the atmosphere—dynamic pressure less than 1 pound per square foot (1 psf)—and performs an entry at 25° angle-of-attack. The RCS is used during the high-altitude flight for lateral/directional control. The vehicle then follows the standard approach and landing flight path. Stagnation temperatures during entry can reach 2,000 °F. Envelope expansion flights will fill the gap between the low Mach DRM 1 flight and the maximum Mach 8 DRM 2 mission."[31] In this situation, the X-34 attains its target altitude of 250,000 feet and target speed of Mach 8 at around 220 seconds, and then starts its unpowered descent with an angle of attack of about 25 degrees. The commanded elevon deflections reach about -16 degrees while the vehicle is passing through supersonic/transonic speeds. As in DRM 1, the center of gravity moves aft initially due to consumption of LOX from forward tank and then forward due to depletion of aft LOX tank. The center of gravity then remains at approximately 414 inches when all the propellants are depleted and engine burn out occurs.

DRM 3 Trajectory. "The DRM 3 is an abort trajectory to deal with engine failures. Should the main engine fail to ignite after separation, a DRM 3 abort mission would be initiated in which

> propellants are immediately dumped and an approach and landing to the abort site is conducted. As the full propellant load is dumped, the center of gravity can vary greatly. The DRM 3 abort mission is not a planned flight, but would only occur in case of engine ignition failure."[32] In this situation the altitude and Mach number steadily decrease following the initiation of the abort maneuver. The commanded elevon deflections reach up to –20 degrees towards the end of the descent. Even though these elevon deflections are significantly high, they are still within permissible limits. The commanded speed brake deflections reach up to 80 degrees at the beginning and towards the end of the mission. The speed brake deflections are not commanded during DRM 1 and 2 examples. The initial aft center of gravity movement is followed by the forward movement, and then the remaining constant of around 420 inches, are caused by the sequential dumping of the RP and LOX propellants.[33]
>
> **DRM 4 Trajectory.** "The unpowered approach and landing test (DRM 4) will constitute the first unpowered flight of the X-34 vehicle. After release from the L-1011, the unfueled X-34 acquires the approach flight path and conducts a standard approach and landing …It is observed that the vehicle lands around an angle of attack of 8 degrees. The commanded elevon, body flap and speed brake deflections are within limits as in DRM 1 to DRM 3."[34]

Afterward, Langley and Orbital engineers concluded that "[t]he aerodynamic data in the database is provided for both free flight and flights in ground effect and covers the complete range of Mach numbers, angles of attack, sideslip and control surface deflections expected in the entire flight envelope of the X-34 vehicle. The variations of the trajectory parameters and control time histories for the four design reference missions, which are representative of the X-34 flight test program, indicate that the vehicle performs these missions satisfactorily and the commanded control deflections are within the permissible limits at all points along these flight trajectories."[35]

Several other items should be mentioned before reviewing the lessons learned, including the debts the X-34 owed to the Space Shuttle. For example, the wing planform of the X-34 was leveraged from the Space Shuttle. This allowed aerodynamicists to use some Shuttle aero data, but more importantly the Shuttle control surface hinge moments allowed Orbital to size the X-34 actuators and structural design. The all-moving vertical stabilizer with split-speed brake was the "first of its kind and is aerodynamically interesting." While the split surface acts as a speed brake, it is actually more important for pitch control during the transonic condition. Also, the thermal protection blanket thickness varied on the X-34 wing, creating a different airfoil shape. While this was ultimately included in the high-fidelity wind tunnel model, it involved a tradeoff between thermal protection, weight, and aerodynamic shape. Finally, the aerodynamic team noted that the "uncertainty band that should be used with the prediction is sometimes more important than the actual aerodynamic or thermal prediction." To address this issue, the team worked hard to make sure that they "bounded the aerodynamics and the heating as much as possible without being too conservative." Orbital's Henri Fuhrmann added, as one of the X-34 lessons learned, that he has applied this rule ever since, noting that the "uncertainty bands are more important than the nominal predicted values." [36]

X-33 and X-34 Aerothermodynamic Lessons Learned

Testing by Langley Research Center's Aerothermodynamics Branch supporting both the X-33 and X-34 efforts generated a database on aerothermodynamics that had value far beyond either of the two programs themselves. It generated not only a "synoptic of lessons learned" useful throughout the physical sciences communities, but also furnished, as C. G. Miller noted, "a guide/reminder for future programs requiring extensive aerothermodynamic information," both on the details of the field itself, and also on its organization and practice. As Miller saw it, lessons were learned in six particular subject areas:[37]

> **Personnel:** Experienced aerothermodynamicists who have worked on similar programs should be blended with junior aerothermodynamicists who have not yet learned what is impossible and are eager to learn and to try new approaches, etc. The advantages provided by such a blending have been demonstrated in numerous programs, yet this approach is not always utilized.
>
> Aerothermodynamicists and systems analysis engineers responsible for the initial vehicle concept, for applying engineering codes and interpolation procedures to populate the aerodynamic and aero-heating data bases, and for generating flight trajectories should work closely together from the beginning to the end of the program. Experienced aerothermodynamicists often will identify deficiencies in initial concepts, thereby allowing system analysis engineers to iterate on the concept prior to its entering the aerothermodynamic process…. Such an exchange can save considerable time and resources…. Personnel working guidance, navigation and control (GN&C) issues should also be brought

into the aerothermodynamic process early, as they are the ultimate customer for aerodynamic measurements and predictions. Likewise, designers of the thermal protection system (TPS), who are customers for aero-heating measurements and predictions, should be included.

It is imperative that experimental and computational aerothermodynamicists work together from the beginning to the end of the program. The ultimate creditability of the aerodynamic and aero-heating information is achieved when independently performed wind tunnel measurements and CFD predictions for wind tunnel cases are compared and found to be in excellent agreement over a range of attitude and flow conditions. Wind tunnel measurements and CFD predictions are highly complementary and together provide accurate aerothermodynamic information throughout the flight trajectory; i.e., across the subsonic to hypersonic regimes. There is a tendency of computationalists to bypass comparing CFD predictions to wind tunnel measurements and to apply CFD only to flight conditions…. Knowledge of the strengths and weaknesses of both disciplines allowed the strengths to be systematically combined and optimized.

It is important to have experimental and computational aerothermodynamicists working aerodynamic issues and those working aero-heating issues establish strong lines of communication. Often, "anomalies" observed in aerodynamic force and moment measurements can be explained by the detailed surface information achieved in experimental aero-heating studies. Detailed studies of shock-shock interactions, flow separation-reattachment phenomena, boundary layer transitions, etc. via aero-heating measurements are beneficial to aerodynamicists in explaining force and moment trends.

The same team of experimental aerodynamicists should test across the subsonic-to-hypersonic speed regimes, as opposed to different teams testing at subsonic, transonic, supersonic, and hypersonic conditions. The continuity and flexibility provided by a single team testing across the speed regimes is believed to outweigh the collective outputs of specialists in each regime that must be coordinated and assembled into one story.

Facilities: It is imperative for most all aerospace vehicle concepts that transonic aerodynamic information be obtained early in the program, such that subsonic, transonic, and hypersonic information is used concurrently in the optimization of OMLs to achieve desired flying characteristics across the entire speed regime, from high altitude hypersonic conditions to approach and landing. In most cases, the credibility of the experimental aerodynamic data base is enhanced considerably with the simulation of flight values of Reynolds number based on appropriate full-scale vehicle dimensions. Generally existing hypersonic wind tunnels within NASA and the United States Air Force simulate flight values of Reynolds number, for a given Mach number, and provide a sufficient Reynolds number range to produce fully laminar and equilibrium turbulent boundary layer/shear layer flow about the test article.

Models: The major contributor to the failure to meet wind tunnel schedules and the corresponding milestones for delivery of aerodynamic data was delays in design and fabrication of metallic force and moment models…. In Phase I of the X-33 program involving aerodynamic assessment and optimization of three industry concepts in parallel with the X-34, all models tested in these fast-paced programs were fabricated in-house at the LaRC and were delivered on time and within cost. This success was achieved by assigning a high priority to the X-33 and X-34 programs and the Fabrication Division operating numerical cutting machines 24-hours per day 7 days per week. Modifications to model components to enhance aerodynamic performance were generally performed in a day or two, and often overnight. Metallic model fabrication began to be outsourced about the time that Phase II of the X-33 program was initiated. The impact of model delivery delays and the testing of models without verification of the accuracy of OMLs due to insufficient time was substantial. The time associated with fabrication of metallic models represents the major contribution to total time to perform an experimental aerodynamic test in a wind tunnel.

Instrumentation: Protecting strain-gauge balances from adverse thermal gradients during a run in the heated flow of a hypersonic wind tunnel, or accurately compensating for such gradients proved to be quite challenging. Although the balances were water cooled, heat conduction through the stainless steel walls of the model and/or the sting/blade support and into the balance compromised accuracy…. Minimizing the contact surface of the balance with the model provided the best protection against unacceptable temperature gradients and proved successful in most cases. Credible aerodynamic data was obtained, but only after many repeat runs, comparison of runs for which the angle of attack was increased with run time to those where alpha was decreased, soak runs where alpha was held constant for the entire run, and so forth. Needed is a fully temperature compensated strain-gage balance and/or improved methods for balance cooling or protection of the balance from heat conditions.

The Langley developed phosphor thermography technique… was heavily utilized for the X-33, X-34, and a number of other programs and performed in an outstanding manner. This technique for measuring global, quantitative aero-heating distributions on models truly revolutionized the aerothermodynamic process and is indeed "better, faster, cheaper" than previously used techniques…. One new capability with this technique is to extrapolate heating distributions measured on a model in a hypersonic wind tunnel to flight values of vehicle surface temperature…and to do so immediately following a tunnel run. The accuracy of this extrapolation of ground-based data to flight has been substantiated with comparisons to CFD predictions for both wind tunnel conditions and flight conditions for the X-34.

Testing Techniques and Procedures: All force and moment models, including those for benchmark studies, should be designed and fabricated for configuration building (i.e., each component attached to the basic body or fuselage may be removed and replaced with a section contoured to the basic body) as opposed to being fabricated in one piece. Models with configuration buildup capability are, naturally, required in the assessment and optimization phases of the aerothermodynamic process and should also be employed in the benchmark phase.

If successfully developed and applied, nonintrusive, optical-video based, global surface pressure measurement techniques for heated and unheated wind tunnels should be utilized in future studies similar to X-33 and X-34. These techniques will be faster, better, and cheaper than conventional ESP [tools that enable simulation] systems and provide detailed information in critical areas on the model; i.e., in regions of shock-shock interactions, flow separation-reattachment (including the entire leeward surface), etc.

Because of the long lead time in the design and fabrication of a force and moment model or pressure model with jets at various locations to simulate reaction control system (RCS) interactions by blowing of various gases, this important phase of the aerothermodynamic study should be initiated just prior to or immediately following the freezing of OMLs.

Computational Fluid Dynamics: CFD contributed significantly to the development of aero-heating data bases for X-33 and X-34, addressed specific, localized phenomena such as shear layer impingement on the X-33 engine modules, and played a complementary role in the development of aerodynamic data bases which required full tip-to-tail solutions. Through these applications to complex configurations over wide ranges of flow conditions and attitude, CFD capabilities increased considerably as codes were modified to enhance accuracy, increase speed, and provide new capabilities such as RCS interactions, full wake solutions, etc. Extensive comparisons were performed between the two primary Navier-Stokes solvers for hypersonic flows used within NASA, namely the Langley developed LAURA code and the commercially available GASP code from Aerosoft, Inc., in which strengths and weaknesses were identified.... Most importantly, confidence in using CFD to provide aerodynamic and aero-heating data for aerospace vehicles was increased appreciably by comparisons of CFD predictions to wind tunnel measurements and code to code. These comparisons provided a better understanding of what physical and numerical models to use...in futures applications.

From X-33 and X-34 experiences in aerothermodynamics, it is strongly recommended that computational and experimental aerothermodynamicists work together in the development of both aerodynamic and aero-heating data bases. The strengths of CFD and ground-based testing are complementary and, used together, provide a better product. Due to expected advances in CFD in the future, particularly in reduced times required to run full Navier-Stokes solvers tip-to-tail, and to dedicated computers for a given program, the time will come when CFD plays a dominant role in the development of aerothermodynamic data bases. However, for the next decade, it is believed that vehicle designers will rely primarily on wind tunnels for subsonic-to-low-hypersonics (i.e., Mach 0.1 to 10) aerothermodynamic information and on CFD predictions for hypersonic-hypervelocity flows (i.e., Mach numbers in excess of 10).

Developing the X-34 Thermal Protection System

The NASA Ames Research Center was assigned the responsibility to design, analyze, and fabricate the Thermal Protection System (TPS) for the X-34 vehicle nose-cap, wing leading edges, and rudder leading edge. The nose-cap and leading edges were protected by low thermal conductivity silicone impregnated reusable ceramic ablator (SIRCA) tiles, a ceramic/organic composite that has a fibrous silica substrate impregnated with silicone that could survive a heat flux as high as 200 W/cm^2 (watts per square centimeter).[38] The fuselage was protected by different types of reusable blankets bonded to the vehicle's skin.

The TPS work by NASA Ames was performed under a Task Agreement executed on April 29, 1996. This agreement assigned specific tasks to Orbital and Ames. Ames's responsibilities, with the necessary input from Orbital, included local aerothermal loads analysis, base heating analysis, tile design, tile analysis, tile tooling, tile fabrication, TPS component testing, TPS flight test support, thermal blanket design, aerothermal analysis, testing, and installation support. The identified Ames points of contact were Grant Palmer (local aerothermal loads analysis and base heating analysis), Huy K. Tran and Jerry Ridge (tile design), Frank Milos (tile analysis), Huy K. Tran and Dane Smith (tile tooling and tile fabrication), Mike Hinds (TPS component testing), and Rex Churchward (TPS flight support). The Orbital point of contact was Tom Dragone.[39] Some of the above personnel assignments were changed by a later contract modification.

The Ames Task Agreement was valued at approximately $4 million. The work was accomplished over a period of at least 2 years, and the Ames TPS team key personnel included the program manager (Huy K. Tran), eight team leads, one full-time systems engineer, and one part-time system engineer. Oceaneering fabricated the TPS blankets. Forrest Engineering (Southern California) and Impact Engineering (San Francisco Bay area) assisted Ames on the fabrication of the SIRCA ceramic tiles.[40]

NASA Langley, as noted above, in addition to extensive wind tunnel testing, also carried out significant TPS aerothermal analysis for the X-34. The Langley effort concentrated primarily on the blanket areas of the vehicle. Some immediate areas of concern that surfaced were

> roughness-induced turbulent heating, the design of the interface between the tile and blanket systems, potential areas of shock impingement and shock interactions, use of blankets in the high-dynamic pressure regions of deflected control surfaces, the zone of transition of the fuselage cross section from circular to square, and the vortices which will likely emanate from the strake fuselage juncture[41]

Selecting a TPS system that utilized thermal blankets and ceramic tiles, however, allowed Orbital to take advantage of a technology previously demonstrated on the Space Shuttle, along with the subsequent developments that improved the operational characteristics of these TPS materials. An advantage of the flexible blankets was that they could be adhesively bonded to a nonsmooth surface. In addition, they were considered to be fairly tolerant of the "over temperatures" that might be associated with heating uncertainties.[42] The leeward-side thermal protection blankets varied in thickness along the chord since insulation requirements were more severe toward the leading edge. This factor, combined with manufacturing requirements, led to a wing design with a "sufficient low-speed lift-to-drag ratio and adequate supersonic and hypersonic handling characteristics while meeting structural and thermal design and manufacturing goals."[43] The blankets chosen for the leeward side had more design flexibility for blanket type and thickness and had the highest temperature and insulation properties with high thermal protection margins. Because of these factors, NASA Langley's aerodynamic heating analysis focused on obtaining maximum leeward heating environments. The windward surface of the X-34 was protected by constant-thickness TPS blankets. This was dictated by outer mold line requirements and cost constraints.[44]

NASA Ames performed detailed heating analyses of the elevon hinge line and cove area and Orbital performed similar heating analyses of the back side of the speed brake and body flap hinge line. Sealing and protecting these areas required a degree of "engineering judgment and novel approaches [and] In general, conservative assumptions were made in areas where data do not exist."[45]

In reviewing NASA Langley's aerothermal analysis and testing, research engineers Kathryn E. Wurster, Christopher J. Riley, and E. Vincent Zoby noted the "methodology [including wind-tunnel testing and computational fluid dynamics] by which the aerothermal environments for the X-34 [were] predicted in sufficient detail to allow design of the TPS such that the survivability, as well as the reusability, of the flight vehicle [was] ensured to a high degree of certainty." The compressed schedule for the X-34 posed a particular challenge, Wurster, Riley, and Zoby acknowledged that its anticipated 2-and-a-half–year span from the date of the awarding of the final contract to first flight constituted a "remarkably short time frame" to design the vehicle, order materials, manufacture components, test the engine, build ground facilities, address anticipated operational issues, assemble the X-34, modify its L-1011 mother ship, and ready the program for flight. "The extraordinary pace of this program," they noted, "required that the thermal environments be generated in parallel with design of the vehicle and development of the flight profile."[46]

Table 6.2: X-34 "TPS 101"—A Summary Overview[47]

Thermal Protection System Anticipated Operational Environment	Type	Max. Expected Temp.
	Leading edge	2,100 °F
	Lower surface blankets	1,700 °F
	Upper surface blankets	1,400 °F

TPS Type and Material		Max. Heat Flux	Max. Temp.	Location
Silicone impregnated reusable ceramic ablator (SIRCA)		175 BTU/square foot	2,500 °F	Nose cap
				Wing leading edge
				Vertical fin leading edge
High heat blankets (HHB)	Silica fabric over silica batting, with a hard ceramic coating	20 BTU/square foot	2,000 °F	Lower surfaces
				Rudder
Low heat blankets (LHB)	Silica batting	10 BTU/square foot	1,500 °F	Upper forward fuselage
Flexible reusable surface insulation (FRSI)	Silica coated Nomex™	2 BTU/square foot	700 °F	Upper wing surface
				Upper aft fuselage

Note: TPS designed for a 50-flight service life. As well, the X-34 had an engine heat shield with the aft vehicle closeout covered by a flexible thermal "boot" as employed on ELVs.

X-34 TPS Blankets, Tiles, and Applications

The X-34 employed a combination of blankets and tiles to protect the system from heat impingement and thermal entry into the structure, summarized in Table 6.2. These blankets and tiles are listed below.

Reusable Blankets (three types). These were bonded to the vehicle's skin by a Momentive Performance Materials, Inc. RTV-560 silicone rubber compound bonding agent.

1. *Flexible reusable surface insulation* (FRSI) consisted of Nomex™ flame-resistant felt coated with RTV. It was capable of multiple exposures up to 700 degrees °F; this covered the upper wing and upper aft fuselage.

2. *Low heat blankets* (LHB) consisted of silica batting and was able to repeatedly withstand temperatures to 1,500 °F. This covered the upper forward fuselage.
3. *High heat blankets* (HHB) consisted of silica fabric over silica batting and with a hard, gray ceramic coating. This covered the lower surfaces and the rudder. Again, the X-34 benefited in its use of these materials from their previous employment on the Space Shuttle program, though in some respects the X-34 used upgraded materials.[48]

Silicone Impregnated Reusable Ceramic Ablator (SIRCA) tiles, which are able to withstand temperature cycles up to 2,500 °F with minimal ablation and surface char, were employed on the wing and rudder leading edges and nose, were mechanically attached to the vehicle structure, and the fastener holes were then covered with SIRCA plugs.[49] As an aside, attaching the wing tiles was the most difficult TPS challenge to overcome, given the requirement that tiles, if damaged, be replaced within the 24-hour turnaround time between flights desired for the X-34. Program engineers met this challenge by using smaller-size (12 inches) SIRCA blocks and by designing wing connectors that could be quickly removed and replaced. The tiles and blankets were tested on two or three Dryden support aircraft flights to ensure that the tile connector system and blanket material worked. A second significant problem encountered involved the interface of the SIRCA tiles between the wing leading edge and the fuselage. Working out the attachment procedure also solved this problem.[50]

A closeout thermal protection system composed of metal and ceramic materials was employed to protect various seals, articulating elements (such as flight controls and doors), and penetration areas.

1. A flexible blanket closed out the interface between the engine and aft bulkhead of the X-34. The blanket attached to a metallic collar around the nozzle of the engine and to a composite flange on the aft bulkhead of the vehicle.
2. Elevon and body flap closeout employed thermal isolators located on the hinge flanges in order to prevent heat flow from entering the composite structure. Metallic wiper seals and rub plates closed out the elevon ends and prevented airflow around the control surfaces.
3. For the landing gear and umbilical door seals, the X-34 employed Nextel 312 ceramic sleeving with batting as a thermal seal between TPS blankets on the landing gear door interface.
4. Speed brake and rudder aft spar closeout was achieved through the use of Inconel edge protectors and hinge isolators that prevent heat flow in the rudder composite structure in a manner similar to the closeout of the elevon bays. The inner surfaces of the speed brakes

and the rudder's aft spar have stainless steel radiation barriers that mechanically attach to the structure.

5. Ground support equipment (GSE) fitting flight closeout plugs included covers for jack points, wing and fuselage assembly fittings, and umbilical door release locations that were either metallic plugs that had sufficient thermal mass to prevent excessive temperatures from impacting the structure or, for areas where the heat loads were higher, the plugs were covered with high or low heat blankets, depending upon anticipated temperatures.[51]

X-34 Thermal Protection Driven by Mission Profile Requirements

The mission profile of the X-34 created unique internal thermal control requirements. Prior to launch, components had to function on the ground at sea level conditions and also in unpressurized compartments at 39,000 feet. The X-34 then had to survive engine ignition, ascent heating and depressurization, reentry heating and repressurization, and finally post-landing heat soak conditions when the interior of the vehicle would be considerably hotter than the ambient outside temperature at its recovery site.

Keeping its sensitive avionics cool posed a special challenge. As Orbital reported, thermal control was achieved through both passive and active measures. Passive measures included use of fans, heat sinks, free convection, surface coatings, insulation, isolators, conductive pads, etc. Active measures included use of thermostatically controlled heaters and nitrogen purges, the latter furnished prior to launch from umbilical gas lines running from the L-1011 carrier aircraft to the rocket vehicle. Nitrogen purging ensured that the interior of the X-34 was both inert and dry, and also furnished convective cooling of the S-band transmitter, rudder avionics, and the engine bay. Nitrogen purging also ensured that the LOX and RP-1 would not prematurely mix in the engine turbopump. Purging would begin during ground servicing and fueling prior to taxi and continue until just 2 minutes prior to launch.[52] Batteries powering the hydraulic system had thermostat-controlled heaters, foam insulation, and a Mylar outer layer.[53] The X-34's aluminum LOX tanks employed multilayered polyimide foam/Mylar insulation developed jointly by Orbital APG and AVICA-Meggit Aerospace. The main fuel line running from the RP-1 tank through the cold environment in the forward and aft LOX tank bays and on to the engine bay was wrapped with aluminized Mylar in the LOX bays to minimize heat transfer.[54] The engine bay had thermal control to maintain engine components above –40 °F prior to ignition, to prevent freezing of the RP-1 fuel. The engine bay thermal control also employed an aluminized fiberglass thermal curtain (maintained in place by aircraft grade Velcro), gaseous nitrogen purging of the aft bay, and aluminized Mylar over all the inner engine bay surfaces.[55] The system design on the X-34 vehicle required the TPS insulate to be within 50 °F of the 350 °F temperature limit of the vehicle structure. This requirement meant that the thermal analyses had to show that the X-34 structure never exceeded 300 °F. As Henri D. Fuhrmann, John Hildebrand, and Tony Lalicata reported in the AIAA's *Journal of Spacecraft and Rockets*, the 50 °F margin was used "to account for trajectory dispersions, TPS fabrication anomalies, and uncertainties in heat transfer and soak-back rates."[56]

Endnotes

1. Henri Fuhrmann, interview by the author, January 9, 2013.
2. It should be noted that the shape of the X-34 was frozen well before this wind tunnel testing was conducted, thus causing the aerodynamicists to depend, to a considerable extent, on "experience, conceptual design tools, and the initial low fidelity wind tunnel test." Quote from Henri Fuhrmann, e-mail to the author, April 16, 2013.
3. Ibid.
4. Bandu N. Pamadi, Gregory J. Brauckmann, Michael J. Ruth, and Henri D. Fuhrmann, [hereafter Pamadi et al.] "Aerodynamic Characteristics, Database Development and Flight Simulation of the X-34 Vehicle," paper presented at the 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10–13, 2000, AIAA 2000-0900, p. 4.
5. C. G. Miller, "Development of X-33/X-34 Aerothermodynamic Data Bases: Lessons Learned and Future Enhancements," Paper 32 in NATO Research and Technology Organization, *Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment*: Papers presented at the Symposium of the RTO Applied Vehicle Technology (AVT) Panel, Ottawa, Canada, October 18–21, 1999 (Neuilly sur Seine, Fr: RTO/NATO Report RTO-MP-035, 2000), p. 1.
6. J. R. Micol, "Langley Aerothermodynamic Facilities Complex: Enhancements and Testing Capabilities," paper presented at the 36th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 12–15, 1998, AIAA 98-0147, pp. 1–2. See also J. R. Micol, "Hypersonic Aerodynamic/Aerothermodynamic Testing Capabilities at Langley Research Center: Aerothermodynamics Facilities Complex," paper presented at the 30th AIAA Thermophysics Conference, San Diego, CA, June 19–22, 1995, AIAA 95-2107, passim; and C. G. Miller, "Hypersonic Aerodynamic/Aerothermodynamic Testing Capabilities at Langley Research Center," paper presented at 17th AIAA Aerospace Ground Testing Conference, Nashville, TN, July 6–8, 1992, AIAA 92-3937, passim.
7. Ibid.
8. Ibid.
9. Ibid.
10. Bandu N. Pamadi and Gregory J. Brauckmann, "Aerodynamic Characteristics and Development of the Aerodynamic Database of the X-34 Reusable Launch Vehicle," paper presented at the International Symposium on Atmospheric Reentry Vehicles and Systems, Arcachon, France, March 16–18, 1999, NTRS ID 19990047600, p. 3.

11. Information provided to the author by Orbital aerodynamicist Henri Fuhrmann in an interview with the author, 9 Jan. 2013 and an e-mail to the author, April 16, 2013.
12. Pamadi et al., "Aerodynamic Characteristics, Database Development," p. 3.
13. Henri Fuhrmann interview by the author, January 9, 2013.
14. Ibid.
15. Pamadi and Brauckmann, "Aerodynamic Characteristics and Development of the Aerodynamic Database," pp. 3–5.
16. An earlier .018 scale model was fabricated prior to this one based on the Outer Mold Line (OML) of an earlier geometry. The primary difference was the inclusion of the thermal protection system (TPS) blanket geometry of the later model. This TPS resulted in aft-facing ramps on the upper surface of the wing and aft-facing ramps in the nose region. The ramps were due to different thicknesses of thermal blankets.
17. Pamadi and Brauckmann, "Aerodynamic Characteristics and Development of the Aerodynamic Database," p. 4–5; Pamadi et al., "Aerodynamic Characteristics, Database Development," p. 4.
18. Information on testing of an earlier version of the outer mold line was provided to the author by Orbital aerodynamicist Henri Fuhrmann in an interview on January 9, 2013, and a follow-up e-mail on April 16, 2013.
19. Gregory J. Brauckmann, "X-34 Vehicle Aerodynamic Characteristics," *Journal of Spacecraft and Rockets* 26, no. 2 (1999): 229.
20. Miller, "Development of the X-33/X-34 Aerodynamic Data Bases," p. 4.
21. Micol, "Langley Aerothermodynamic Facilities Complex," pp. 7–9.
22. Ibid., pp. 1–2.
23. Ibid.
24. Pamadi and Brauckmann, "Aerodynamic Characteristics and Development of the Aerodynamic Database," pp. 5–6.
25. Ibid., p. 6.
26. Ibid., pp. 6–17 (quotation from 17).
27. Pamadi et al., "Aerodynamic Characteristics, Database Development," pp. 5–11.
28. Brauckmann, "X-34 Vehicle Aerodynamic Characteristics," p. 2.
29. Pamadi et al., "Aerodynamic Characteristics, Database Development," p. 12.
30. Ibid., p. 13.
31. Ibid.
32. Ibid., p. 14.
33. Ibid.
34. Ibid.
35. Ibid., p. 15.

36. Henri Fuhrmann, e-mail to the author, April 16, 2014. He notes: "Uncertainty bands are basically the high and low uncertainty value for any aerodynamic parameter. This would take into consideration wind tunnel to flight uncertainties such as Reynolds number effects, changes in the as-built configuration, unknowns in certain shock interactions, and other unknown-unknowns. So, given a nominal prediction for parameters like lift, drag, and moments, an upper and lower uncertainty band needs to be accounted for in loads and GNC design."
37. Miller, "Development of X-33/X-34 Aerothermodynamic Data Base," pp. 2–7. Following quotes are drawn from these pages, inclusive.
38. Grant Palmer and Susan Polsky, "Heating Analysis of the Nose Cap and Leading Edges of the X-34 Vehicle," *Journal of Spacecraft and Rockets* 36, no. 2 (1999): 199.
39. T. Castellano, "OSC Task Negotiated 4-29-96," Task Agreement provided to the author by Huy K. Tran, NASA Ames X-34 TPS program manager.
40. Huy K. Tran, interview by the author, December 23, 2013.
41. Kathryn E. Wurster, Christopher J. Riley, and E. Vincent Zoby, "Engineering Aerothermal Analysis for X-34 Thermal Protection System Design," paper presented at 36th Aerospace Sciences Meeting and *Exhibit, Reno, NV, January 12–15,* 1998, AIAA 98-0882, pp. 3–4.
42. Ibid.
43. Henri D. Fuhrmann, John Hildebrand, and Tony Lalicata, "Aerothermodynamic Overview, X-34," *Journal of Spacecraft and Rockets* 36, no. 2, (1999): 153. See also Brauckmann, "Vehicle Aerodynamic Characteristics," pp. 229–239.
44. Fuhrmann, Hildebrand, and Lalicata, "Aerothermodynamic Overview, X-34," p. 154.
45. Ibid., p. 159.
46. Wurster, Riley, and Zoby, "Engineering Aerothermal Analysis for X-34 Thermal Protection System Design," pp. 1, 4.
47. Jennifer Henry, "Reusable Launch Vehicles," February 16, 2000, folder MSFC X-34 Program Office, file box 6, record 18563, NASA HRC; Fuhrmann, Hildebrand, and Lalicata, "Aerothermodynamic Overview, X-34," p. 153.
48. Fuhrmann, Hildebrand, and Lalicata, "Aerothermodynamic Overview, X-34," p. 153.
49. Orbital Sciences, "X-34 Technology Demonstrator Summary," p. 17.
50. Huy K. Tran, interview by the author, December 23, 2013.
51. Ibid., p. 18.
52. Orbital Sciences, "X-34 Technology Demonstrator Summary," p. 20.

53. Ibid., p. 29.
54. Ibid., p. 29–30.
55. Ibid., p. 30.
56. Fuhrmann, Hildebrand, and Lalicata, "Aerothermodynamic Overview, X-34," pp. 153–154.

The NASA MC-1 Fastrac 60,000 pound-thrust liquid fuel rocket engine was intended for the X-34 research vehicle. (NASA)

CHAPTER 7

The Fastrac Engine: Heart of the X-34 Program

Throughout the history of flight, propulsion has been a critical pacing factor determining the schedule, performance and, often, ultimately, the success or failure of a program. Not without reason has the engine—whether in an airplane or launch vehicle—been commonly referred to as the "heart" of the system. In the case of the X-34, its "heart was an imaginative liquid-fueled rocket engine burning a mix of liquid oxygen and RP-1 (kerosene) propellants, the so-called "Fastrac." This chapter reviews the Fastrac project's origin, project objectives, initial design and development, start-up work, engine operation and characteristics, project development team organization, alternative engine considerations, and accomplishments and lessons learned. Details on the X-34's Fastrac engine components and subsystems, as well as an overview of the X-34's main propulsion system, are reviewed in Appendix 2.

Origin of the NASA Fastrac MC-1 Engine

The NASA Marshall Space Flight Center's Fastrac engine—which later was officially designated as the MC-1 (Marshall Center-1) engine by Marshall Chief Propulsion Engineer Robert Sackheim—did not originate with the X-34 Program. Instead, its origin can be traced to NASA Administrator Daniel S. Goldin's "faster, better, cheaper" challenge, which resulted in a challenge to Marshall to produce a new engine that, employed in a new launch system, could demonstrate the value of his new management approach. Consequently, in November 1994, Marshall assembled a team to undertake its conceptualization, design, and development.[1]

As a final project summary closeout report by the Marshall Center noted, Administrator Goldin had tasked the Huntsville rocketeers "to produce a new kind of engine and a new kind of transportation system that could demonstrate this new approach. He wanted to not just test new systems but also to fly them, and quickly. Breaking paradigms was expected and occasional mission failures along the way would be tolerated, per Mr. Goldin."[2] The team's work evolved into the Advanced Space Transportation Program (ASTP) in 1995. The ASTP program goals "included lowering the cost and increasing the reliability of space transportation (engines, propulsion systems, and vehicles) through strategies aimed at an array of launch market segments including 100–200 lb [payloads] to LEO [low Earth orbit], Shuttle-class payload missions to the space station, and more," the project's closeout report further stated that

> [f]or the smallest payload class, the strategy was to create a market by creating a low-cost access to space capability. It was believed that a launch market could be created for universities, research institutes, and small companies if a capability of $1.0–1.5M [million] per launch could be established in this payload class…. Mr. Goldin approved ASTP, including its strategy to develop this market segment. Strategy implementation centered on a new launcher concept called Bantam, which had a goal of flying within 2–3 years to demonstrate boost technologies for 100–200 lb payloads at costs that could achieve under $1.5M per launch as a market developed and mission traffic expanded.[3]

Even before ASTP and formulation of the Bantam concept, engineers in NASA Marshall's Propulsion Laboratory and Materials & Processes Laboratory were exploring the idea that "a rocket engine could be designed with drastically fewer parts and built using standard and fewer industrial manufacturing materials and methods." They wanted to make the parts "more robust, maintainable, and accessible by making them beefier and simpler." In addition, NASA Marshall engineers were experimenting with turbomachinery consisting of fewer parts as well as experimenting with composite rocket nozzles and simple injectors. This work included experimenting with the Simplex turbopump and the 40,000-pound thrust chamber. The NASA engineers also were expressing interest in commercial off-the-shelf (COTS) hardware for use in rocket engines. The above efforts led the Engine Systems Branch of the Marshall Propulsion Laboratory to begin, in 1995, an in-house effort to design, build, and test bed engine system demonstrator.[4]

Soon after NASA made the decision to rebid the X-34 contract, interest arose in using the Fastrac engine in the X-34 Technology Testbed Demonstrator. This led to discussions between NASA Marshall and Orbital that resulted in the signing of a Memorandum of Agreement (MOA) on August 22, 1996, following the Preliminary Design Review of the Fastrac engine. Orbital Sciences had utilized the Fastrac engine in their proposed vehicle configuration and subsequently negotiated Task Agreements with NASA Marshall for the Center to develop an engine with spare nozzles for development and initial flight testing of the X-34. The MOA was signed by the reusable launch vehicle project manager (Rick Bachtel), the Advanced Space Transportation Program (ASTP) project manager (Gary Lyles), the X-34 program manager (Jack Levine) and the Low-Cost Booster Technology (LCBT) Project manager (Jan Monk).[5]

As noted in Marshall's MC-1 project termination closeout report:

> The idea was to deliver and test an engine system as quickly as possible, demonstrating a rapid development cycle. Then, as X-34 and Bantam requirements matured and manufacturing and test experience produced lessons learned, the engine project would undertake a block change in design and test it. The vehicles' schedule and requirements would determine whether they would fly the baseline Fastrac design or wait for a block change.[6]

The scope of the work outlined in the agreement called for the LCBT project "to provide the engine design and interface definition for the X-34 design effort [and to] conduct a development program to provide a producible flight engine design, demonstrated fabrication capability with an approved vendor list, and a flight production unit configured for the X-34 vehicle." The X-34 program assumed the "responsibility for procurement of additional engines and shipping containers from commercial vendors for the option phase of the X-34 Project." The LCBT project would loan "the engine shipping container and any engine specific checkout equipment required at the launch site." The X-34 program would provide its "own unique mechanical ground support equipment…for engine handling and installation in the X-34 vehicle." Finally, the X-34 program agreed to "utilize the basic engine design currently in development and shall not impose additional requirements other than the X-34 unique requirement of a horizontal start at an altitude of greater than 30,000 feet."[7]

The Memorandum of Agreement contained the scope of the project, interface requirements, verification overview, support requirements, funding provisions, management and reporting requirements, and the nominal engine configuration and performance requirements.[8]

MC-1 Fastrac Engine Development Project Objectives

The stated objective for the NASA-led Fastrac MC-1 engine project was to demonstrate a low-cost turbopump-fed rocket engine that could be utilized for both reusable and expendable launch systems. In order to obtain the lower cost projections, the project team used a simple engine system design employing a gas generator, a reduced number of parts, commercial manufacturing techniques, and commercial off-the-shelf components. Key elements of the cost savings objective were the use of a one-piece silica-phenolic and graphite-epoxy chamber/nozzle, a simple approach to turbopump design and fabrication, and simplified injector and gas generator components. In order to minimize complexity and reduce costs, Fastrac system components were combined in a simple open-loop control system. NASA's goal was to mature both the component and system-level technologies to a level that could be transferred to the aerospace industry with minimal technical and economic risks.

Another key objective of the Fastrac engine project was to demonstrate "that a largely government team at the Marshall Space Flight Center could design, develop, and test major aspects of a large liquid bipropellant rocket engine. By coupling Fastrac to the X-34 effort, Marshall was in a position to also [initially] design the X-34 main propulsion system as a completely government led in-house enterprise."[9]

Principal users of these technologies were both traditional and emerging space access providers. NASA hoped that the new fabrication technologies would enable emerging aerospace companies to be cost competitive by reducing fabrication and testing infrastructure requirements, leading to increased competition and lower rocket engine costs. NASA planned to demonstrate the Fastrac engine in flight tests on the X-34 and also to make the engine available for use in the Bantam flight demonstrations.[10] NASA estimated each Fastrac engine would cost approximately $1 million, at least a one-fourth cost reduction over similar engines. In addition to powering the X-34, NASA hoped the Fastrac engine could be used in other launchers designed to boost payloads weighing up to 500 pounds at a substantially lower price.[11]

Fastrac in the Context of Other Large Liquid-Fuel Rocket Efforts

In May 1998, *Aviation Week & Space Technology* reporters informed the trade bible's readers that

> [k]ey rocket engine tests getting underway will accelerate the development of three revolutionary propulsion systems for the NASA X-33 and X-34 winged booster test beds and the Boeing Delta 4 evolved launch vehicle. [They] are the first large rocket propulsion developments conducted in the U.S. in more than 20 years. The last major rocket engine program was the space shuttle main engine (SSME) development of the late 1970s. The new programs are rejuvenating propulsion work at the NASA Marshall Space Flight Center, Huntsville, Ala.; NASA Stennis Space Center, Bay St. Louis, Miss.; and the U.S. Air Force Research Laboratory's Propulsion Directorate at Edwards AFB, Calif.[12]

The engine projects included NASA Marshall's 60,000-pound thrust oxygen/kerosene Fastrac engine (later designated as the MC-1 Fastrac); the Boeing/Rocketdyne RS-2200 oxygen/hydrogen linear 500,000-pound thrust aerospike engine; the Boeing/Rocketdyne RS-68 oxygen/hydrogen 650,000-pound liftoff thrust (and 750,000 pounds at altitude) first-stage engine for the Delta 4 EELV (roughly 50 percent more powerful than the Space Shuttle Main Engine); and—another cutting-edge program in the planning stage—Boeing/Rocketdyne's 900,000-pound thrust oxygen/kerosene engine intended for use in liquid strap-on fly-back boosters.

These Fastrac engine development efforts were spawning establishment of new rocket propulsion companies, including Barber-Nichols Inc. of Arvado, Colorado, and Summa Technology Inc. of Huntsville, Alabama.[13] As well, *Aviation Week & Space Technology* pointed out that a number of modification programs were underway. These included the Pratt & Whitney RL-10 being upgraded with a new French SEP composite nozzle for the Delta 3 rocket; Atlantic Research Corporation testing the Agena 2000 bipropellant rocket engine intended for use on Lockheed Martin Astronautics' EELV program; and Russia testing the NPO Energomash RD-180, derived from the RD-170 used on the Zenit booster, and, as well, being adapted by Pratt & Whitney for Lockheed Martin's EELV.[14]

Initial Fastrac Engine Design, Characteristics, and Development

The Fastrac engine design started before the Bantam and X-34 vehicle and mission designs were well defined. As a result, the initial design had to be based on a number of preliminary assumptions and parameters derived by the project team based on what the team thought might be needed. As the project progressed and final vehicle and mission design requirements were more clearly discerned, changes in engine design were incorporated in "block" fashion. As an initial assumption, engine hardware was predicated on a "point design" burning a mix of RP-1 and LOX, using a gas generator-based propulsion system.

Engine control was an open loop operated by an electronic control sequencer. The ablative nozzle size was based on NASA Marshall's in-house manufacturing tooling limitations that limited the nozzle area ratio to 30:1, which would be the area ratio for the air launched X-34. The area ratio for the planned Bantam ground launch was 15:1. The nozzle size, combined with a 40,000-pound thrust chamber test result, justified a 60,000-pound vacuum thrust target level. The engine power head layout was initially only 15,000–24,000 pounds-force thrust due to the short length of an upper stage rocket, which was the initial intended use of the Fastrac engine. The original planned turbopump assembly was an in-line configuration with turbine, RP-1 pump, inter-propellant seal package, and LOX pump stacked together. The power balance model was based on the nozzle size limited by the tooling capabilities, test results from the 40,000-pound thrust chamber, and inputs from the turbomachinery designers. The power balance model provided the component designers with the necessary detailed pressures, temperatures, flow rates, and other engine steady state-run parameters required to design the details of the components and plan for hardware testing.[15]

The MC-1 Fastrac Propulsion Test Article and Horizontal Test Facility

A Propulsion Test Article (PTA) is the test platform constructed to test an engine. The MC-1 Fastrac PTA, like the initial design of the Fastrac engine, likewise was a point design concept due to lack of specific vehicle or mission definitions. The Fastrac owed much to the vertical-launch Bantam concept, which, as John R. London noted, "reached the point of launch system development, with two of the four designs employing the Fastrac engine [and that] one of the four concepts was [a] partially reusable [vehicle concept] by [the] Pioneer Rocketplane [company]."[16]

Thus, like Bantam, the Fastrac PTA included a vertical engine orientation with the nozzle pointed down with engine gimballing to ±5 degrees. The maximum thrust capability was 120,000 pounds, which could accommodate the possibility of a block change to a larger thrust engine. The propellant tanks were sized for an estimated 155-second full duration steady state burn even though the Bantam and X-34 requirements had not yet been determined. The PTA was designed to accommodate an aluminum LOX tank on the bottom, a composite RP-1 tank on top, a tank pressurization system, propellant and pressurized fuel feed systems, propellant flow-meters, and a thrust measurement system. The PTA and engine were designed to be controlled by a modular architecture avionics system that included a propulsion checkout controller, a propulsion system controller, and a drive electronics assembly plus associated harnesses and sensors.

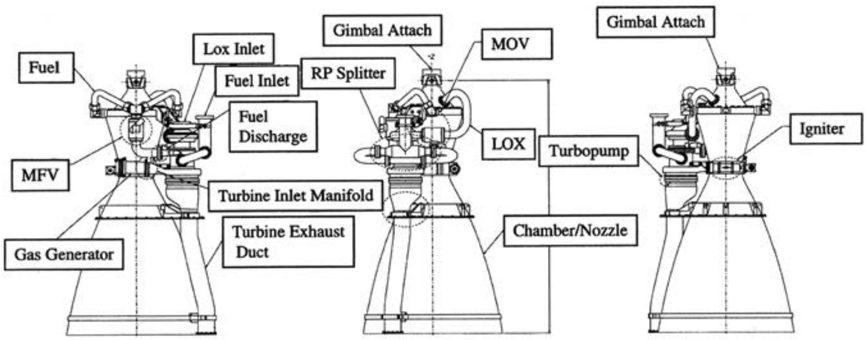
Marshall's MC-1 project termination report noted that "the Bantam architecture studies were examining many concepts with wide ranging technology challenges, and they moved away from the concept being manifested in the PTA. The Bantam project never gained a strong footing with any of its architectures and eventually ended without implementation. However, Bantam had given birth to the PTA concept, which was maturing in design and hardware. PTA design and construction continued based on the point design that had been derived from the early Bantam concept."[17]

With the end of the Bantam concept—which required a PTA that could accommodate a vertical ground launched rocket—a PTA was modified to accommodate the air launched X-34, which required a horizontal test orientation. The project team also had to assess and implement other PTA changes in order to make the test site usable as a horizontal test facility (HTF) for the X-34's MC-1 Fastrac engine. The B-2 test stand at the Stennis Space Center in Mississippi was modified to conduct horizontal engine testing required for the air-dropped X-34. It consisted of the five following subsystems: 1) strongback, 2) LOX tank, 3) RP-1 tank, 4) main propulsion system, and 5) avionics. Writing at the time, engineers reported that it "has the capability to anchor system analysis models for feedline flow and pressure loss, pressurization, and vent analysis, as well as overall propellant utilization analysis. The avionics and MPS for PTA have the capability, however, to test the engine at a range of operating conditions and is instrumented for flow measurement as well as three-axis thrust measurement, thereby allowing for the determination of I_{sp} [specific impulse, a measure of engine efficiency]."[18]

The major requirements of the PTA were as follows:

1. Provide a LOX/RP PTA (PTA-1) that incorporates low-cost technologies and demonstrates their operation in ground tests;
2. Provide measurements necessary for estimation of 60K FE [Fastrac engine] specific impulse [I_{sp}];
3. Provide avionics for command, checkout, control, and data acquisition of the PTA-1 and 60K FE; and
4. Provide a safe operating environment for the testing of the FE and other propulsion system components.[19]

The design of the horizontal test facility was primarily determined by X-34 program needs. The Fastrac engine could be mounted nearly horizontally on the HTF, which was capable of validating design of the X-34's LOX and RP-1



This is the component breakdown of the Fastrac engine. (NASA) feedlines and simulating the cold conditions (–55 °F) the X-34 would encounter at its 38,000-foot launch altitude. While the X-34 was planned to fire its Fastrac engine for 155 seconds, the HTF allowed longer duration static firings up to 250 seconds to confirm design margins and nozzle life.[20]

Overview of the NASA MC-1 Engine Operation

The Fastrac engine was a much simpler engine because it used fewer parts than previous American-made rocket engines. The reduced number of parts resulted from selecting technologies and design concepts that use simpler manufacturing and assembly processes. Another design feature that simplified the engine was its avionics system, itself typically a sophisticated and expensive aspect of the engine. The avionics to operate the Fastrac engines were supplied by X-34 and were only to be used to open and close valves. The thrust and mixture ratio was set during ground calibration as opposed to rocket engines, in which the avionics continually modify the amount of propellants flowing into the chamber as changes in thrust are detected by the onboard computers. The Fastrac engine also avoided complex plumbing by using an ablative cooling process, which cools the chamber by charring or scorching its inside surface as the engine heats. In addition, layers of silica-phenolic composite material formed a liner inside the chamber. This liner would decompose to prevent excessive heat buildup. With the exception of the ablative chamber nozzle and the hypergolic (i.e., self-igniting) ignition cartridge, nearly all of the parts were reusable.[21]

The Fastrac engine was only the second American-made engine of 29 new rocket engines developed in the previous 25 years.[22] As noted above, the design of the Fastrac Engine was originally undertaken for use in the low-cost booster technology (LCBT) project and later was baselined as the rocket engine for the X-34 Technology Testbed Demonstrator. Later in the X-34 program/project, the official designation of the Fastrac engine became the MC-1 (Marshall Center-1), although the name "Fastrac" continued in both common and technical usage.

NASA Marshall employees Richard O. Ballard (MC-1 test and evaluation lead) and Tim Olive (performance analyst) provided the following overview description for operation of the MC-1 Engine.[23]

> The MC-1 Engine is a pump-fed liquid rocket engine with fixed thrust and gimballing capacity…. The engine burns a mixture of RP-1 hydrocarbon fuel [kerosene] and liquid oxygen (LOX) propellants in a gas generator (GG) power cycle. Propellants are tapped from the engine propellant lines, and are burned as a fuel-rich mixture in a GG to power a turbine that rotates an in-line

turbopump assembly. Both propellant pumps use a single-stage centrifugal impeller and the turbine is single-stage also. The fuel pump and main fuel injector use a dual-entry configuration to reduce flow velocity entering the component. Turbine exhaust gas is routed overboard via a turbine exhaust duct routed alongside the engine nozzle. The chamber/nozzle is built as one piece with ablative liner and composite overwrap. The main injector uses 2-on-2 LOL [LOX-on-LOX][24] impinging elements with fuel file cooling orifices drilled at the injector faceplate periphery. With the exception of the ablative thrust chamber, all components on the engine are reusable.

The engine uses a combination of electro-pneumatic and solenoid valves to control engine operation. The valves are designed to be either fully opened or fully closed. Helium is the working fluid in the pneumatic system. The two main propellant valves, the main oxidizer valve (MOV) and the main fuel valve (MFV), are controlled by separate solenoid pilot valves. Four remaining electro-pneumatic valves, the gas generator oxidizer valve (GGOV), gas generator fuel valve (GGFV), main fuel purge valve (MFPV), and oxidizer bleed valve (OBV) have built-in solenoid pilot valves. The remaining valves, the igniter fuel valve (IFV), fuel bleed valve (FBV), oxidizer purge valve (OPV), and the gas generator LOX purge valve (GLPV) are direct-acting solenoid valves. Seven check valves are also used to isolate the pneumatic system from the propellant systems…. The engine operates at one rated power level, nominally 60,000 lbf at vacuum for the 15:1 area ratio nozzle configuration [planned for the Bantam program], and slightly higher for the 30:1 nozzle [planned for the X-34]. Thrust and mixture ratio are open loop controlled by setting fixed orifices in the engine propellant lines during engine calibration testing. Therefore, variations in engine propellant inlet conditions cause engine performance variations. Electrical commands for engine start and shutdown are issued by an electronic controller external to the engine.

The MC-1 uses two ignition systems for engine start, one for the main chamber and one for the GG [gas generator]. Following spin-up of the turbopump from the vehicle…helium spin-start system, main chamber ignition is accomplished by injecting TEA/TEB [triethylaluminum/triethylborane] hypergol from the piston-actuated reloadable cartridge" into the combustion chamber.[25]

Table 7.1: MC-1 Fastrac Nominal Engine Configuration[26]

Area ratio	30:1
Area exit diameter	47 inches
Engine length	90 inches
Engine dry weight	1,125 pounds
Start attitude	Horizontal
Start altitude	Greater than 30,000 feet
Engine life (excluding chamber/nozzle)	7 starts
Chamber/nozzle life	150 seconds

Table 7.2: MC-1 Fastrac Nominal Performance Requirements (Rated Conditions)

Vacuum thrust	60,000 pounds-F
Engine mixture ratio	2.18
Vacuum I_{sp}	310 seconds (achieved value was less than 310 seconds)[27]
Oxidizer minimum NPSP	TBD
Fuel minimum NPSP	TBD

Table 7.3: MC-1 Fastrac Engine General Requirements

Design Points	Technology/Property/Quantity
Engine configuration	Gas generator derivative
Recurring cost goal	$1 million
Weight goal	1,870 pounds (at 30:1 area ratio)
Thrust (vac.)	60,000 pounds-f vac.
Engine start	Vertical at sea level; horizontal at 38,000 feet
Fuel	RP-1
Oxidizer	LOX
Burn time for flight	Approximately 155 seconds
Gimbaling	Yes 10 degrees at 5 degrees/s
Reusability	7 uses minimum

In June 1997, NASA's Systems and Reliability Office completed its preliminary study to predict the reliability of the Fastrac Engine and X-34 main propulsion system. The study predicted an engine reliability of 0.99615, which represented a risk of 1 in 260, based on the Space Shuttle Main Engine, J-2 engine, and the MA-5 engine "flight and test data adjusted for environment." For the MPS predictability, the three following mission scenarios were considered: 1) nominal burn time only (150 seconds); 2) nominal burn time plus chill-down (450 seconds); and 3) nominal burn time plus chill-down and propellant jump (810 seconds). Each mission scenario was considered using two different databases—industry data only and Space Shuttle and industry data combined. The worst-case scenario was number 3 with industry data only. The predicted risk for this situation was 0.99832, which represented a risk of 1 in 595. The predicted reliability for the engine and worst case main propulsion system combined was 0.99448, which represented a risk of 1 in 181.[28]

On August 14, 1997, NASA announced that the X-34 Fastrac engine had recently passed a number of critical tests, including evaluation of "the engine's thrust chamber assembly at high pressure almost identical to flight conditions." George Young, Fastrac engine chief engineer at the time, noted that "[t]he thrust chamber assembly performed as designed, which is another indication that the Fastrac is an engineering breakthrough." Young added, "Marshall engineers developed this engine in a much shorter-than-usual design cycle at significantly lower costs than a typical rocket engine." Danny Davis, manager of the low-cost technologies project, noted that "[t]hese successful test firings of the thrust chamber mark a major milestone in the progression to low-cost space propulsion."[29]

By December 1997, 80 percent of the design had been completed. In March 1998, a manufacturing review was held with Orbital Sciences Corporation and NASA's Marshall Space Flight Center that resulted in some design changes to bring about a better match with the manufacturer's preferences, reduce costs and weight, and improve operational and assembly time requirements. At that point, the X-34 vehicle was being integrated into the static stand at Orbital in preparation for testing. As of that time, the first powered flight was scheduled for late 1999. The verification requirements specified an engine start at a horizontal attitude of ±20 degrees at an altitude of 35,000 feet ±5,000 feet, and main stage performance duration of 155 seconds.[30]

While the X-34 Authority to Proceed directive was issued by NASA in August 1996, the Main Propulsion Design Team was not fully staffed until late February 1997. At this point the design team was concurrently working conceptual layouts and updates based on results of the structural model and other analyses. The two-fault tolerance analysis, operations analyses, and component specifications were initiated during this time in order to ensure that

Marshall Space Flight Center Director Arthur Stephenson (standing in dark suit, hand on body of X-34 model, under sculpture) poses with members of the Advanced Space Transportation Program (ASTP), NASA Marshall's "New Rocket Team," on July 14, 1999. (NASA)

requirements were properly impacted on the design and that the design centered on the use of off-the-shelf-hardware. The X-34 main propulsion system (MPS) Design Review was held in March 1997 and the system design freeze occurred in May 1997. During this freeze review time, a contract modification was made to add a nonpowered flight and to extend the MPS design date from September 1997 to May 1998.

Teamwork and Partnerships

NASA relied on internal and external teamwork and partnerships to pursue development of the Fastrac engine. In particular, the Agency had a wide-ranging construct of teams functioning out of the Marshall Space Flight Center at Huntsville, Alabama, working with colleagues at the Stennis Center and other NASA Centers (such as Dryden) as necessary. As well, of course, the Agency drew on its partnerships with a broad group of contractors and subcontractors in its pursuit of this engine.

Marshall Space Flight Center's Fastrac Engine Development Teams

In a review of Marshall's work on the Fastrac engine (FE) and the Propulsion Test Article (PTA), Center engineers Mark F. Fisher and Michael R. Ise noted changes that had occurred in the two decades since NASA had developed the Space Shuttle Main Engine in the 1970s, noting that "the physics of rocket engine development," and the challenge of "weight and performance" generated "a delicate balance between cost, weight, performance, reliability, manpower, and schedule," one requiring that "new management practices" be developed. To that end, NASA's Advanced Space Transportation Program (ASTP) at MSFC had organized the Low-Cost Technologies (LCT) project office.[31]

Fisher and Ise were particularly pleased with the Propulsion Test Article (PTA), a Marshall-designed propulsion system test bed capable of testing various engine components, including feed lines, tanks, and engines working together. The planned engine would be the 60,000-pound engine thrust level Fastrac engine. The engineers noted that the 60,000-pound thrust level was selected "because it provides a relevant environment for testing of low-cost options and is a reasonable design growth of the work already accomplished by previous technology efforts." After the test bed components were tested, other hardware would be substituted for the test components enabling the PTA to be fired.[32]

The Fastrac engine development engineering and technical staff at NASA Marshall was organized into product development and component development teams. Each team was comprised of all necessary disciplines needed to design, analyze, fabricate, and test all hardware within each team's area of responsibility. In addition to NASA employees, the teams also included contracted support from vendors assisting on the project. Each team was authorized to develop its applicable test articles within guidelines established in the team's project plan. Each product development team lead was responsible for coordinating their activities, determining product requirements, establishing the various tasks to be done, setting work schedules, determining verification requirements, identifying and resolving issues to be addressed within or across the teams. In addition to team leads, each team also had a project manager and chief engineer.[33]

The X-34 Fastrac engine development staff resources were divided into the four following primary teams: 1) Systems Product Development, 2) System Integration, 3) Engine Product Development, and 4) Avionics and Electrical Systems Product Development Team.

The Systems Development Team was responsible for developing the Propulsion Test Article and the horizontal test facility propulsion components, tankage and structures, support structure, coordinating integration of avionics, and test integration with the Stennis Space Center. This team, which also had responsibility for the safety and quality aspects of the test article, had the four following component development teams:[34]

1. Main Propulsion: This team was "chartered to develop low-cost solutions to launch vehicle propellant delivery, pressurization, fill, drain, and vent requirements."
2. Tankage Structures: This team was "chartered to develop low-cost solutions to launch vehicle structural requirements."
3. Support Structures: This team was "chartered to design and fabricate the support structure" for the Propulsion Test Article.
4. Horizontal Test Facility (HTF) Team, which was "chartered to develop HTF per requirements stated in the project plan and in the HTF Facility Requirements Document (FRD)."[35]

The Systems Integration Team was "responsible for interface control, including definition, documentation, and verification. The team [was] also responsible for mass properties, weight statements, and configurations control, including the development of the plan as well as assisting the PDTs [Product Development Teams] in the implementation and control of the documentation and drawings."[36]

The Engine Development Team was responsible for developing the Fastrac Engine in accordance with the requirement guidelines and other project requirements, including system engineering, design, analysis, design integration, and test integration of the engine. In addition, this team was responsible for the safety and quality aspects of the engine.

The Engine Product Development Team drew on four component development teams.

1. Turbomachinery Team: This team was "chartered to develop low-cost solutions to turbomachinery."
2. Thrust Chamber Assembly Team: This team was "chartered to develop low-cost solutions to chamber/nozzles, injectors, and main chamber igniters."
3. Gas Generator Component Team: This team was "chartered to develop low-cost solutions to GG's [gas generators] and GG igniters."
4. Lines, Valves, and Actuators Team. This team was "chartered to develop low-cost solutions to engine lines, valves, and actuators…."[37]

The Avionics and Electrical Systems Team was responsible for developing a low-cost solution to propulsion avionics for the Propulsion Test Article. Experiments included the propulsion controller, ground check-out computer, drive electronics, including engine and main propulsion system valves and thrust vector control, and the software and sensors. In addition, this team also was responsible for developing engine instrumentation and cable harnesses.[38]

The Product Development Team (PDT) and the Component Development Team (CDT) were supported by professionals knowledgeable in structural dynamics, stress, thermal analysis, performance analysis, quality, safety, manufacturing, and testing, among other areas. The management approach gave team leaders great leeway in both technical and administrative decision-making. In noting the teams' working relationship, the project termination closeout report said

> [t]here would be no prime contractor for the engine. Instead, the in-house team was not only to lead the development but also do most of the actual work associated with the development of the components and the engine system. This was a radical departure for [NASA] Marshall. It was the first turbopump fed liquid rocket engine system ever to be developed in-house by the Marshall center. The Marshall team of engineers had a lot to prove and they were excited for the opportunity to be challenged. Morale was high even though schedule pressures were dominant at every level on the project. The project team responded with enthusiasm, rolled up their sleeves, and went to work, often working long hours for months on end to do whatever it took to make it happen. The project began to gain momentum as line organizations provided manpower and insight but agreed to allow the PDT/CDT organizations to function with a high degree of autonomy.[39]

The Product Development Teams also included NASA personnel from the Stennis Space Center, where some of the Fastrac engine testing occurred at the Center's reactivated B-2 test stand that included a second position for horizontal engine testing required for the air-dropped X-34. Commenting on development team working relationship, Mark F. Fisher and Stennis engineers Richard F. King and Donald J. Chenevert, noted that

> [f]rom the inception of the project, it was realized that a close working relationship with the test site would be required to meet the aggressive schedule. The project chose to utilize the integrated Product Development Team (PDT) approach for the hardware development. It was soon clear that the test facility engineering and operations personnel would be key players and, as such, were included in the PDT design structure…. This multi-center, in-house design team is somewhat unique in the author's experience, but it was found to be enabling in order to meet the schedule requirements of the project. The results were very exciting:

> Center and organizational lines blurred and a true team spirit arose. MSFC [NASA Marshall] design reviews had active and numerous participation by SSC [NASA Stennis] engineering and operations personnel. SSC facility design and activation included participation by MSFC personnel. In addition to the reactivation of a test stand that had been dormant for 15 years, the team was able to design and construct the interfaces, mechanical, fluid and electrical to meet the test requirements of the project.[40]

Following completion of the development phase of the project and after the fabrication of several engines, the overall project team considered changing the team organization from teams centered on products and development to teams centered on the core processes associated with completing testing, modifying the design, and supporting flight integration. While an official reorganization was never formalized, the teams actually operated under the core processes structure throughout the last year of the project. "These teams were responsible for core processes associated with system engineering and integration, operations and flight integration support, requirements and verification, testing and evaluation, design and analyses, hardware and logistics, and information systems."[41]

NASA's Industry Partners on the Fastrac Engine

On July 30, 1999, NASA contracted with Summa Technology, Inc., of Huntsville, Alabama, to assist on the assembly of the Fastrac engine. NASA and Summa signed an $11 million, 28-month, competitively awarded contract for "Summa to build three new Fastrac flight engines for the X-34 technology demonstrator and utilize one additional flight engine already under contract." The contract covered engine hardware, engineering support, refurbishment for 22 planned powered flights, engine hot-fire acceptance testing at NASA Stennis, logistics and spare parts, and monitoring engine performance during and after the flight tests.[42]

Summa made some parts and contracted with Barber-Nichols, Inc. (BNI) of Arvada, Colorado, for turbopump manufacturing. NASA also fabricated some parts and provided them to Summa. Valves were bought from Allied Signal (now Honeywell), Marotta Scientific Controls Inc., and Circle Seal. Thiokol manufactured nozzles at a NASA Marshall facility and Metals Research manufactured main injectors in Guntersville, Alabama.[43]

Barber-Nichols was founded by Bob Barber and Ken Nichols in 1966. BNI specializes in the design and production of turbomachinery. The company's products include compressors, fans, pumps, turbines, generators, motors, and controllers for aerospace, cryogenic, defense, and energy applications. BNI also provides engineering consulting and contract manufacturing services. Barber-Nichols entered the space launch industry in 1996 and has become a world leading developer of rocket engine turbopump technology. BNI was NASA's industry partner in the design and building of the turbopump for the Fastrac LOX /RP-1 Engine. In addition to the X-34, Barber-Nichols has worked on a number of other rocket projects, including working with Rocketdyne to design and build the turbopump for the Bantam LOX/RP-1 rocket, which was another example demonstrating BNI's cutting edge turbopump expertise; designing and producing the Merlin Turbopump for the SpaceX Falcon launch vehicle; collaborating on the design of the LOX/Hydrocarbon Turbopump for Northrop Grumman's one million pound-thrust TR107 engine; designing, manufacturing, assembling and testing of the H2O2/Kerosene turbopump for Northrop Grumman's 30,000 pound-thrust TR108 engine; designing the core and upper stage LOX turbopumps for Lockheed Martin's hybrid 300,000 and 60,000 pound-thrust Falcon rocket engines; designing the LOX/methane turbopump for Applied Astronautics' 60,000 pound thrust HyFIRE engine; manufacturing of the LOX/LH2 turbine nozzles for the 745,000 pound-thrust RS-68 engine; and collaborating on the design of the LOX/LH2 turbopump for an Air Force Research Laboratory's 40,000 pound-thrust demonstrator engine.[44]

MC-1 Fastrac Slippage Forces Consideration of the Rocketdyne MA-5

The initial timeline stated that the deadline for delivery of the Fastrac engine to Orbital for flight-testing in the X-34 was March 1999, with the first flight scheduled for August 1999.[45] Slippage from this timeline was the major factor that caused both NASA and Orbital to consider alternative engines for the initial powered flight-testing of the X-34.

In a September 12, 1996, presentation, Jack Levine, NASA's first X-34 program manager noted that the X-34 could be useful in testing different engines. Levine stated that

> [a]lthough propulsion is not an X-34 technology objective, the use of an existing low-cost, relatively low-performance engine such as the Fastrac provides another useful demonstration opportunity, particularly with respect to future small reusable launch vehicles…. We are considering the possibility of preparing a modified version of the Atlas MA-5 sustainer engine as an alternate, both for additional operability experimentation and for risk mitigation in the event of delay in Fastrac delivery. In addition, since the modular X-34 design permits easy engine removal and replacement, it may be adaptable for subsequent testing of more

> advanced propulsion technologies such as rocket based combined cycle, plug nozzle, pulse detonation wave rocket, and dual expansion engines.[46]

The MA-5A Sustainer engine was an updated version of Rocketdyne's liquid propellant, pump-fed MA-5 engine, which dated to General Bernard Schriever and the earliest days of the Air Force's Atlas intercontinental ballistic missile (ICBM) program in the mid-1950s. As Rocketdyne reported in 1996, the MA-5A "consists of a two-chamber booster engine and a separate sustainer engine. The booster engine subsystem has been increased from 377,500-pound thrust to 423,500-pound thrust by use of higher rated, flight-proven RS-27 engine components. The sustainer engine (which was the engine studied for the X-34) of 60,500-pound thrust remains unchanged from the MA-5. The MA-5A engine system is used to power the new generation of Atlas II, IIA, and IIAS, launch vehicles." Table 7.4 shows the specifications for this engine system.[47]

Table 7.4: X-34 MA-5A-Derivative Sustainer Engine Specifications

Type	Liquid propellant/pump-fed
Propellants	LOX/RP-1
Thrust	60,500 pounds
Specific impulse (I_{sp})	296 seconds
Run duration	368 seconds
Mixture ratio	2.27:1
Chamber pressure	736 psia
Area ratio	25:1
Weight	1,035 pounds
Dimensions	97 in long; 48 in wide (bell diam.)

As early as October 1996, Orbital Sciences examined the possibility of using the MA-5A engine as an interim alterative to the Fastrac engine. The study, completed under a NASA Marshall purchase order, included the four following tasks:

1. define the MA-5A design requirements on the X-34;
2. assess the impact of the design requirements on the X-34 vehicle;
3. define the issues and technical risks; and
4. evaluate the cost and schedule of using the MA-5A.[48]

For each area examined in the study, two installation options were considered: using only the MA-5A engine and, second, the potential for accommodating both the Fastrac and MA-5A engines in the same X-34 vehicle design. The first option had the advantage of eliminating the need to refit the propulsion system back to the Fastrac engine, thus resulting in significant cost savings. The second option had the advantage of solving the scheduling problem associated with the Fastrac engine, while retaining the capability to integrate the Fastrac engine into the X-34 at a later date. Both options were based on the assumption that the MA-5A engine could be delivered by June 1, 1998. The study took into account the fact that the main engine affects almost all vehicle disciplines on the X-34, including its structures, main propulsion system, guidance-navigation and control, avionics, hydraulics, thermal protection system, and operations.

The study indicated that the X-34 would require a number of modifications in order to accommodate both engines, listed below.

- Engine interface. The two engines had greatly differing interface requirements (the connection of the engine to the airframe structure). However, designing structural adapters that could mate with the engine on one side and with the airframe on the other side could solve this problem.
- Thrust vectoring. The thrust vector actuators—which provide the means to orient the exhaust nozzle in a particular desired direction—represented a much more difficult problem. The actuator attach points were in dramatically different locations on the two engines, and the longitudinal position of the actuators also were different for each engine. The engineering team concluded that solving the actuators issues would have a significant impact on costs, weight, and potentially on aspects of the X-34 schedule.
- Tubing and propellant feed lines. Both engines had a comparable number of tubing connections between the main propulsion system and the engine, but the location and function of these connections varied between the engines. This would require the fluid utilities to be designed for removal and modification in order for the X-34 to be able to accommodate both engines. The propellant feedline design would require modification.
- Nozzle geometry. The engine nozzle geometry was also different in each engine, which would force the modification of the base heat shield and thrust section boot, and that, in turn, would have significant impact to accommodating both engines.
- Engine start systems. The Fastrac engine used a helium spin-start that tapped into existing helium storage tanks, while the MA-5A engine used a dedicated liquid start system, which required two additional

tanks that stored LOX and RP-1 for use during startup. In order to accommodate both startup systems, an additional secondary support structure would be needed, which would bring with it a corresponding weight impact.

- Thrust load factors. Each engine had different load factors. The higher thrust of the MA-5A engine would result in an increased structural load to the X-34 vehicle, which would necessitate strengthening the X-34 structure. In order to accommodate the higher-thrust engine, significant impacts to the X-34 structural design would be required. Due to the cost impact of making the required modifications, the study recommended that if the MA-5A were incorporated, that it function at a reduced 60,000 pounds force at vacuum thrust level, the same as the slipping Fastrac.[49]

Besides these, there were other differences, including characteristics involving engine shutdown, flight operations, ground support, and turnaround maintenance.

Another important factor weighed by the Orbital study team was engine reliability, and in this parameter, the proven MA-5A had an advantage over its younger rival. X-34 Fastrac program requirements specified an engine reliability of 0.999 in order to support the main propulsion subsystem reliability requirement of 0.995. The engineers noted, however, that to date the Fastrac engine testing had not demonstrated the required reliability level. By comparison, the study team added that the MA-5A engine had an extensive history of operation and database to support a reliability of 0.984 at a 90 percent confidence level and a demonstrated success rate of 99.6 percent. They added that the MA-5A engine could be modified to meet X-34 mission requirement with minimal testing or analysis and posed little risk to affecting these reliability numbers (see Table 7.5).

As a consequence, the OSC engineering team report concluded:

> The MA-5A feasibility study revealed that the modified MA-5A Sustainer engine is a viable alternative as the main engine on X-34. Two significant modifications are required to the main engine. First, the thrust level must be reduced. Trajectory analysis showed that the MA-5A current thrust level resulted in an unacceptable dynamic pressure to the vehicle structure. Therefore, reduction of the MA-5A to the current Fastrac engine thrust level is required. Any increase in vehicle thrust will impact the current vehicle structural design. The Fastrac engine thrust level is what X-34 is currently designed for and providing this thrust results in minimum vehicle impacts. The second significant modification is the

Table 7.5: X-34 MA-5A Integration Benefits and Requirements

Benefits	Requirements
Demonstrated engine operations	Reduce MA-5A thrust level
Demonstrated reliability figures	Increase gimbal capability
Potential for 15 flights (versus 7 for Fastrac)	Reduce weight to 1,384 lb (including start system)
Engine removal between firings not required	Modify for horizontal start
Large database with interfaces known	Modify for altitude start
Lower weight and smaller moments of inertia	Achieve 15+ flight engine life
Start sequence well defined	LOX chill-down requirement
Purge sequence well defined	
Electrical interfaces well defined	
Environments well defined	
Maintenance well defined	

> gimbal requirement. The MA-5A Sustainer engine must increase its current gimbal requirement to ±8°. This may require significant modifications to the gimbal block design.[50]

As a result of this review, at the end of October 1996, Orbital recommended baselining the MA-5A engine at a reduced 60,000 pound-foot thrust level, recommended against the dual engine option as it would result in a $8.2 million cost increase to the program and a significant schedule slip, and urged NASA to make "a prompt decision to minimize costs impacts and proceed with design activities towards the appropriate engine installation."[51]

Just weeks later, on November 18, 1996, at a public presentation at the AIAA 7th International Spaceplanes and Hypersonic Systems & Technology Conference, NASA X-34 program manager Jack Levine bluntly stated "[f]or additional operability experimentation, *and for risk mitigation in the event of delay in Fastrack* [sic] *delivery*, we are considering also preparing a hybrid version of the already proven Atlas MA-5A sustainer engine, modified for horizontal start at altitude and for increased control gimbaling."[52] [Emphasis added.]

It should be noted that both of these came to pass more than 4 years later: first, slippage in the Fastrac schedule and, second, concerns over whether the Fastrac engine could (or even should) be used for the powered technology experiment flights. As will be examined subsequently, these factors contributed to the eventual termination of the X-34 program.

A Russian NK-39 Engine for the X-34 A-3?

In the wake of end of the Cold War, NASA Marshall also considered an upgraded Russian NK-39 engine—at least at the study stage—for Orbital's X-34 A-3. It offered much higher thrust, a throttling capability, and full reusability. The NK-39 option, however, would have required significant engine modification and redesign of the X-34 main propulsion system and possibly would have required additional changes on the structure of the vehicle. Further studies to assess impacts and program cost were to be made by Aerojet and Orbital with a decision due before May 1998.[53]

Earlier Concerns Regarding the Fastrac Engine

Between August 27 and 29, 1997, NASA conducted a review of the Fastrac engine development work "because the Fastrac engine is several months behind schedule and the cost[s] are higher than original budgets." The scope of the review included cost, schedule, program management, engine tests, and performance issues. The review team consisted of five individuals including three from Langley, one from NASA Headquarters, and one from Phillips Laboratory.[54] The team's findings were presented to NASA Headquarters on September 16, and October 2, 1997.

In regard to costs, the current estimate for the Fastrac, which originally was estimated as an additional "in-kind" NASA commitment of $10 million, now totaled $35.65 million broken down by fiscal year as follows: FY96 ($4.48 million); FY97 ($14.15 million); FY98 ($13.33 million); and FY99 ($3.69 million). Of this total, $9.2 million was for projected needed "risk mitigation" ($7.33 million projected for FY98 and $2.39 for FY99).[55] The review noted that the Fastrac "Project started as a Technology Demonstrator ($17.5M), became part of X-34 ($18.9M), additional $6M (rec'd 1/97) & $10.8M (requested) for Risk Mitigation."[56] In regard to the risk mitigation costs, the team responded to a NASA question by noting that

> [t]he risk mitigation element ($10.99M) is required in order to provide a suitable engine for the X-34 and has been considered new scope rather than growth. Again, this requirement should have been identified when the X-34 project committed to the Fastrac engine." The team concluded that, "overall the project cost estimate appears reasonable at the total and recurring costs [projections].[57]

In regard to schedule, the review team found that there had been overall schedule slippage with "significant schedule concerns." The thrust chamber assembly fabrication was behind schedule and casting problems continued to delay the turbopumps, which would propagate slips into engine development.[58]

As part of their review, the special assessment team was asked to respond to a number of specific questions. The first question asked about how much of the additional requested funding was necessary. The team responded by noting that $10.9 million of the $16.8 million would be used for risk mitigation involving the purchase of additional hardware and an increased ground test program. $3.1 million would be applied to "programmatic changes." $1.62 million would be held in reserve and the team estimated that "this level of reserve is too low considering the magnitude of the work remaining."[59] In regard to the mitigation funds, $5,083,629 was allocated for additional hardware and $4,832,100 was for the Stennis Space Center activity.[60]

Another question related to the "interaction" between Orbital and the Fastrac engine team. The assessment review team noted that while the situation had significantly improved over the previous 9 months, Orbital has been disappointed in several areas, including the two following: a) high engine design margins have adversely impacted the X-34 design; and b) the need to remove the engine between flights is impacting the X-34 goal for rapid turnaround. The assessment team added, "OSC [Orbital] commented that their relationship with MSFC [NASA Marshall] has been different from the relationship they would expect from a commercial company." This led to a follow-up question regarding the team's view of the Orbital/NASA relationship. The team responded that "[i]n the judgment of the review team, there is an actual conflict of interest which arises because the prime X-34 contractor (OSC) reports to an organization which is also a major supplier to the prime."[61]

Continued Schedule Slippage

In a March 1998 white paper, Danny Davis, NASA Marshall project director for low-cost technologies, noted that the Fastrac project had accrued a schedule delay of about 6 months due to various technical reasons primarily associated with development of the turbopump.

Turbopumps have always proven a challenge to rocket engine development, for they are inherently high-risk: any failure can have catastrophic consequences. Delays in developing a planned turbopump in the 1940s delayed flight-testing of the first American supersonic airplane, the Bell XS-1 and, in fact, forced its modification before flight to use a high-pressure nitrogen blow-down fuel feed system that cut its anticipated high-Mach performance by almost half.[62] In the case of the X-34, a combination of difficulties with casting of the pump housings and manufacturing errors imposed serious delays.

Table 7.6 summarizes the milestone slippages for the MC-1 Fastrac engine.[63]

Table 7.6: MC-1 Fastrac Milestone Slippage Summary

Milestone	Original Date	Revised Date	Reason for Slip
Authorization to proceed	Apr. 1996	Apr. 1996	No slippage
PDR	Aug. 1996	Aug. 1996	No slippage
CDR	Apr. 1997	Apr. 1997	No slippage
Delta CDR	Nov. 1997	Jun. 1998	Nozzle failure, turbopump delays
Turbopump test	Aug. 1997	Apr. 1998	Casting development, loss of LOX impellers, Facility mishap during TCA test
Engine hot fire	Jan. 1998	Aug. 1998	Turbopump delay
Engine delivery to X-34	Oct. 1998	Mar. 1999	X-34 contract modification
X-34 powered flight	Dec. 1998	Aug. 1999	X-34 contract modification

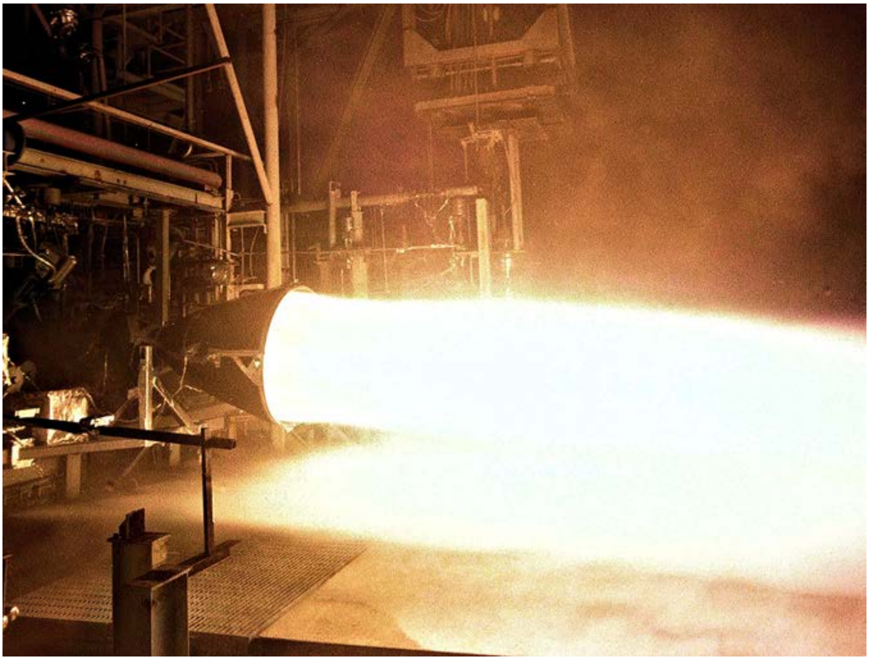
Davis noted that due to this slippage "significant slack" now existed in the program schedule, because of moving the planned first (drop) flight of the X-34 from September 1998 to August 1999. The first Fastrac engine was scheduled for delivery to NASA Stennis Space Center in June 1998 for hot-fire tests in August 1998. Three additional engines were in the fabrication process to support later development tests, and procurement planning for three other engines, including one more development engine, the X-34 flight engine, and one spare contingency engine was in progress. The cost per engine also was expected to decline from $1,100,000 million to $350,000 due to lower line production costs and the infusion of supporting low cost component technologies. Overall, Davis concluded that

> [t]he Fastrac Engine Project has made remarkable progress. MSFC [NASA Marshall] has developed and demonstrated several extremely low cost engine components with other component demonstrations and system level tests imminent. More importantly, this activity has spawned a new breed of engineers that now have hands-on experience from design concepts through test development, and eventually to delivery and acceptance of the final product. This engineering workforce is well equipped

> to transfer technology and assist industry in problem resolution on any number of rocket related issues. This workforce is a more informed and discriminating buyer and producer for the government. This activity and related technology projects have inspired industry to develop new low cost paradigms. Several emerging companies are taking advantage of the low cost technology transfer to position themselves to compete in the launch service industry. Traditional rocket engine companies are reporting substantial improvement in design-to-cost efforts. The Fastrac Engine Project is an example of appropriate application of government resources to provide technologies that minimize risk for U.S. companies and provide leadership that inspires industries to answer the challenge of low cost access to Earth orbit.[64]

A Brief Bright Spark: The First Fastrac Engine Hot-Fire Tests

In March 1999, NASA's Stennis Space Center completed the first full-engine hot-fire testing of the Fastrac rocket engine. The test, which ran for 20 seconds, demonstrated the operation of the complete engine system. Danny Davis, manager of NASA Marshall's Low Cost Technologies Project, noted that "[t]his



The Fastrac Engine during a hot firing at the NASA Stennis Space Center. (NASA) is an exciting time as we transition from testing individual pieces of the engine to hot-fire testing of the full engine." This was the start of up to 85 full-engine tests scheduled at Stennis during 1999.[65]

On May 14, 1999, Stennis Space Center engineers and technicians successfully completed the first 155-second firing—the planned burn time for the X-34 vehicle—of the Fastrac engine. An additional 16 full-firing (155-second) tests, plus 2 additional firings at 1.5 times full-duration, were planned for completion in 1999.[66] NASA engineer Robert H. Champion noted that the successful hot-firing tests proved the flight readiness of the Fastrac engine and that the engine could have integrated into the X-34 for drop and powered flight-testing at the time of project terminated. In commenting on the termination of the X-34 project, Champion added that while NASA has had many successful programs, the Agency has carried through with very few vehicle launch programs.[67]

Writing on the Wall: the MC-1 Fastrac Independent Assessment Review

Despite the optimism so evident to program participants in 1998 and the successful firings of the engine at Stennis, Fastrac continued to slip, as did the X-34 program as a whole, and NASA formed a Fastrac Independent Assessment Team to review the program. In March 2000, just preceding the June 2000 X-34 project restructuring, NASA's leadership received its findings. The team prepared a sobering report, having found "a number of issues/risk areas."[68]

The team noted the following "Top Level Observations," identifying the following accomplishments, as well as several problems.

- The X-34 Project to date had provided a learning platform for multiple "Generation 2" directions regarding both people and tools.
- Significant progress had been made given the constraints dictated to each project.
- The Fastrac engine design approach was established prior to a firm definition vehicle.
- The Project Office had been "inhibited by resource limitations, contractual arrangements, and organizational structure."
- There was limited communication between project teams.
- Recent failures indicated a "need for increased emphasis on mission success criteria."
- The scope of the development was underestimated at the start of the project and the Fastrac flight certification requirement was not well defined.
- Current schedules were unrealistic.[69]

At this point, as Marshall's MC-1 engine closeout report subsequently noted, the MC-1 engine project underwent "a change in philosophy from the more spartan "faster, better, cheaper" to that of ensuring mission success."[70]

MC-1 Fastrac Program Closeout and Final Lessons Learned

Fastrac never flew, and the program ended with the X-34. Nevertheless, program participants could take pride in what they had accomplished. Today, for program participants, it still remains a fond memory, with many adherents still debating what might have been, like the X-34 airframe it was intended to power.

Fastrac accomplishments included 57 engine tests, 42 hot-fires, and only 11 premature cut-offs, all of which were admirable by the standards of experimental rocketry. Overall, the engine accumulated 888 seconds of test time (equivalent to about six full-duration X-34 flights), including 732 seconds at the highest power level. During this testing, the engine confirmed that it could be reused as designed, and was, in fact, proof-fitted into an X-34 vehicle.[71]

Marshall's Thumbnail Assessment of Fastrac's Program Accomplishments

Marshall, with a proprietary interest in the Fastrac program, took great pride in noting the following accomplishments of its Fastrac project, some of which influenced subsequent efforts such as Space-X:

- Marshall proved the concept of a low-cost rocket engine, built by nontraditional commercial suppliers.
- ATP [Authority to Proceed] to first engine delivery occurred within in 28 months.
- Five complete engines were assembled, as were 50 ablative nozzles.
- Fifty-seven complete engine system hot-fire tests were undertaken with no major failures.
- Four new engine test systems were constructed and activated.
- An engine was fit-checked in the X-34 vehicle.
- Acceptance/calibration were tested on the first flight-quality engine.
- A short development cycle was demonstrated.
- You engineers were provided with valuable in-house DDT&E [design development test and evaluation] experience.
- Barber-Nichols was developed into a successful turbomachinery design and manufacturing business.
- Open-source design documentation and drawings were provided to multiple companies at their request.
- Space-X was started with Fastrac turbopump design for their first Merlin engine including using Barber-Nichols as their supplier/vendor.[72]

Marshall's Project Termination Closeout Report

The most extensive recounting of the final lessons learned is contained in Marshall's encyclopedic *MC-1 Engine Project Termination Closeout Report* prepared in 2001 in order to document the Fastrac engine project for future reference.[73] A team of 24 engineers, technicians, and project staff, identified as primary authors, conscientiously prepared this admirable report.[74] The details presented in this report serve both as an indication of the high degree of interest that project personnel had in preserving their record of accomplishments and in providing recommendations and lessons learned for use in future projects.

The list of 37 "lessons learned" presented below represents selected "high point" lessons learned and observations drawn from the very extensive and detailed list of approximately 190, including their supporting "corollaries."

1. In-house, hands-on technology demonstration projects are vital to sustain the [NASA Marshall] Center's engineering excellence at the leading edge of technological development and should be continued.
2. A program/project must have adequate budget, schedule, workforce, and reserves committed to it.
3. The right skill/experience-mix is essential to actually achieve the reality of a robust project systems engineering capability.
4. To enable effective project control, a sound work breakdown structure must be developed and implemented as a first step after mission definition.
5. Failure investigation activity is itself organizationally anomalous; it requires conscientious attention to ensure optimal organizational and team success—beyond just the determination of incident cause and recommended mitigation activity.
6. Major design reviews should be based on design maturity and not a calendar-based milestone schedule.
7. Never underestimate the level of effort required to activate a test stand (existing or new) and resolve test preparation issues.
8. To realize the benefits of empowerment, push decision-making authority as low as you can for as long as you can.
9. The [NASA Marshall] Center has some serious cultural issues that impede the ability to honestly communicate and exercise sound project decision-making.
10. The Center has a systemic problem with growing effective project managers/leaders.
11. Don't change horses in midstream; but if you must, the change process strategy development and implementation must be impeccable to succeed.

12. Sound Government-to-contractor working relationships are fundamental to the ultimate success or failure of a program. Clear communication of expectations (roles, responsibilities, authority, processes, architecture, etc.) between MSFC and their contractors and vendors is paramount.
13. A project needs to spend an adequate amount of time defining and flowing down requirements, with deliberate and methodical technical interchange meetings held frequently thereafter to work any problems.
14. While a primary goal, and a substantial (critical) portion of mission success, absolute safety is unrealistic; mission success can still be achieved despite breaches in safety.
15. Never underestimate the commitment in time and resources required to effectively communicate to the project team members.
16. Project manager visibility/involvement at the workforce level, however difficult to achieve, is imperative to sustaining team morale and esprit de corps.
17. Project maturity prompts an exponential growth in documentation: commit to a single, centralized project-level information clearinghouse and associated resources to maintain its currency.
18. To sustain the team and its foundation of trust, share good news and bad news equally.
19. Definition of a clear, unambiguous organizational structure, with sub-element charters and clearly delineated and communicated organizational roles, responsibilities, and limits of authority, is key to the organization's ultimate success.
20. A project's chief engineer must be in place—this individual is indispensable in focusing all project technical issues and rendering clear technical decisions.
21. The importance of implementing a sound, comprehensive configuration management system cannot be overstated.
22. Transition of design engineering to operations engineering must be done over an extended period of time to include having ops [operations] engineering deeply involved in the project's design and test phases. Appropriate staffing must be available in ops engineering to allow for this transition.
23. Sustaining the team's morale and working relationships are absolutely essential to product success.
24. Allowing the design organization reasonable authority to override customer requests based on sound engineering judgment is a prudent measure.
25. Don't believe vendor COTS [commercial-off-the-shelf] specifications.

26. The design organization should require a formal work request for each new item, with requirements included.
27. Cost and schedule should not override good, viable engineering and design decisions.
28. Expect problems with vendors (i.e., valves) when there is no long-term commitment or vision of a bigger piece of the pie.
29. Take a lot of photographs.
30. Keep track of details in an informal (continuity) notebook.
31. Justify decisions in writing.
32. Keep all fabrication paperwork.
33. Keep the engineers close to fabrication.
34. Once the contract is negotiated, both contractor and Government contracting officers must become more "team players" and serve the needs and requests of their respective program managers.
35. The project's implementation of sound risk mitigation strategies (prudent use of redundancy; test-as-you-fly/fly-as-you test: oversight vs. insight; efficient, competent, independent reviews) was severely compromised as a result of requirements instability/creep and the workload/resource disconnects.
36. Safety and mission assurance (reliability, quality and maintainability) must be an integral part of the project from inception, and if factored into the project phases later, results in either considerable redesign, or acceptance of higher risk, or both.
37. The project must adequately scope the needs for spare hardware or suffer the very serious programmatic risks of being spare poor.[75]

Finally, the multiple authors of the Marshall *MC-1 Engine Project Termination Closeout Report* noted the less-tangible benefits and accomplishment of the Fastrac effort: "In addition to the tangible development program results," they wrote that

> numerous intangible results came out of the program. These include the opportunity for NASA engineers to experience being at the core of an engine development program with direct authority and responsibility over hardware decisions; the learning associated with direct hands-on participation in a development program; and a better understanding of the trials of real systems engineering and the responsibility of technical and programmatic decision making. Such learning/professional growth cannot be gained in seminars, nor learned from books. How to successfully fabricate rocket engines using non-traditional manufactures is another beneficial program experience. NASA/

> MSFC will apply this MC-1 wisdom to next generation propulsion technology development.[76]

Wistful Moment: NASA Recognizes the Fastrac Engine Team

In May 2000, NASA's Office of Aerospace Technology awarded Marshall's Fastrac engine team for "developing technology aimed at reducing the cost to launch a pound of payload from $10,000 to $1,000 by 2010." NASA's press release noted that

> Fastrac is a 60,000 pound-thrust engine fueled by a mixture of liquid oxygen and kerosene. It's less expensive than similar engines because of an innovative design approach that uses commercial, off-the-shelf parts and fewer of them. Common manufacturing methods are used, so building the engine is relatively easy and not as labor-intensive as manufacturing typical rocket engines. Each Fastrac engine will initially cost approximately $1.2 million—about one-fourth the costs of similar engines.... As the first engine developed in-house by engineers at the Marshall Center, Fastrac leapt from the drawing board to full-engine testing in less than three years—a much faster than usual design cycle for rocket engines. Full-engine, hot-fire testing began in March 1999 at NASA's Stennis Space Center, Mississippi. In May 1999, the complete engine system was tested for the first time at full power for 150 seconds, the length of time it will be required to perform during an X-34 flight. System level testing is being conducted now at Santa Susana Field Laboratory in Ventura County, California, while component testing continues at the Marshall Center.[77]

In announcing the award to the Marshall Center Fastrac team that designed and developed the engine, NASA acknowledged its industry team, including Summa Technology, Inc., of Huntsville, Alabama; Allied Signal, Inc., of Tempe, Arizona; Marotta Scientific Controls, Inc., of Montville, New Jersey; Barber-Nichols Inc., of Arvada, Colorado; and Thiokol Propulsion, a division of Cordant Technologies Inc., of Salt Lake City, Utah. Whatever satisfaction all the recipients of this singular honor could take in receiving it was tempered by a sobering reality: The whole X-34 program was seriously endangered, and not expected to survive. How it got there is subject of the next chapters.

Endnotes

1. John R. London III, e-mail to the author, July 15, 2014.
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3. Ibid. [ITAR document]
4. Ibid., 6. [ITAR document]
5. NASA, Advanced Space Transportation Office, "Memorandum of Agreement between the X-34 and LCBT Project for Delivery of the Fastrac Engine," August 22, 1996, box 2, (1995–2001), no. 18559, accession no. 255-01, NASA Headquarters History Office, Washington, DC.
6. *MC-1 Engine Project Termination Closeout Report*, MSFC-RPT-3195, p. 10. [ITAR document]
7. NASA Advanced Space Transportation Office, "Memorandum of Agreement Between the X-34 and LCBT Project," p. 2.
8. Ibid., pp. 3–4.
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11. Jim Cast and June Malone, "X-34 Fastrac Engines Passes Critical Tests," Press release #97-178, August 14, 1997.
12. Craig Couvalt, "Rocket Propulsion Tests Aimed at X-33, X-34 and Delta 4," *Aviation Week and Space Technology* 148, no. 18 (May 4, 1998): p. 51.
13. Ibid.
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19. Ibid., p. 5.
20. Ibid., pp. 9–10.
21. NASA, "Fastrac Engine—A Boost for Low-cost Space Launch," NASA Fact Sheet #FS-1999-02-002-MSFC, February 1999. The chamber

nozzle's interior liner would abate from the intense heat of combustion inside the chamber, requiring its replacement after each flight.

22. Ibid.
23. Richard O. Ballard and Tim Olive, "Development Status of the NASA MC-1 (Fastrac) Engine," paper presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 16–19, 2000, AIAA-2000-3898, pp. 1–2.
24. LOX on LOX is where a stream of LOX exiting the injector impacts another such stream. The impact causes the liquid to disperse more efficiently and result in efficient burning of the propellants. Information provided by Bryan Sullivan of Orbital Sciences Corporation in an e-mail to the author, May 6, 2014.
25. See also "Microgravity Research Program," NASA Fact Sheet # FS-1997-08-006-MSFC, 2; and NASA, "Fastrac Engine—A Boost for Low-cost Space Launch," NASA Fact Sheet #FS-1999-02-002-MSFC, February 1999, p. 2.
26. NASA Advanced Space Transportation Office, "Memorandum of Agreement between the X-34 and LCBT Project," p. 4.
27. Bryan Sullivan, e-mail to the author, May 6, 2014.
28. Fayssal M. Safie, memorandum to Jack Levine, "X-34 Main Propulsion System (MPS)/Engine Reliability Prediction," June 20, 1997, box 2, (1995–2001), no. 18559, accession no. 255-01, NASA Headquarters History Office, Washington, DC.
29. Jim Cast and June Malone, "X-34 Fastrac Engine Passes Critical Tests," NASA press release #97-178, August 14, 1997.
30. NASA Advanced Space Transportation Office, "Memorandum of Agreement Between the X-34 and LCBT Project,"p. 4.
31. Mark F. Fisher and Michael R. Ise, "Low-Cost Propulsion Technology at the Marshall Space Center—Fastrac Engine and Propulsion Test Article," paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, AIAA-98-3365, p. 1.
32. Ibid., pp. 1–4, the quotation is on pp. 3–4.
33. Ibid., pp. 2–3.
34. Ibid., p. 3. The quotes that follow are from this document.
35. HTF referred to the horizontal position of the test stand that would simulate the X-34.
36. Ibid.
37. Ibid.
38. Ibid.
39. *MC-1 Engine Project Termination Closeout Report*, MSFC-RPT-3195, pp. 10–11. [ITAR document]

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43. Ibid.
44. See the Barber-Nichols website at *http://www.barber-nichols.com*, accessed on September 4, 2012.
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The X-34 A-1 is being readied for a lake bed tow test, July 20, 2000. (NASA)

CHAPTER 8

Captive-Carry, Ground Tow, and Planned Powered Testing

Testing the X-34 involved extensive planning, including setting priorities, selecting appropriate test sites, receiving FAA certification of the L-1011 carrier aircraft with the attached X-34 vehicle, developing environmental impact statements, and resolving risk mitigation issues. The core aspects of the actual flight test program—tow tests, unpowered drop tests, and planned powered flight tests, including flights to conduct experiments—also needed addressing. Among these, site selection was a very early and significant problem from both a technical and political standpoint, forcing a series of changes and schedule slippage that, in turn, contributed to the demise of the overall X-34 program. Risk mitigation decisions, which are covered in detail in chapter 9, were the final blow from which the X-34 could not recover. The site selection and risk mitigation issues dragged on long enough for the plans to fly the X-34 Technology Testbed Demonstrator to end before the drop or powered testing could even begin.

The Importance of Ground and Flight Demonstrations

Flight-testing has always marked the culmination of the aerospace development process. In 1896, shortly before his death in a gliding accident, German pioneer Otto Lilienthal wrote "One can get a proper insight into the practice of flying only by actual flying experiments…. It is in the air itself that we have to develop our knowledge."[1] In 1901, Wilbur Wright, more famously, compared flying to riding a fractious horse, noting "if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial."[2] In 1967, testifying before the Senate Committee on Aeronautical and Space Sciences, NASA Administrator James E. Webb said:

> Flight-testing of new concepts, designs, and systems is fundamental to aeronautics. Laboratory data alone, and theories based on these data, cannot give all the important answers…. Each time a

> new aircraft flies, a "moment of truth" arrives for the designer as he discovers whether a group of individually satisfactory elements add together to make a satisfactory whole or whether their unexpected interactions result in a major deficiency. Flight research plays the essential role in assuring that all the elements of an aircraft can be integrated into a satisfactory system.[3]

It was in the spirit of all three sentiments that NASA and Orbital embarked upon the X-34's flight test program. NASA Marshall's Stephen A. Cook stressed the importance of flight demonstration to all three of the reusable launch vehicle program's alternative approaches, the DC-XA, X-33, and X-34, writing "Flight demonstration is a key and integral part of the overall RLV technology program. It is clear that flight demonstration will force the real technology development issues to surface early in the program, thus minimizing technical issues during the costlier full-scale development phase." He identified the objectives common to all three RLV programs as

- providing an integrated systems test bed for advanced technologies;
- demonstrating capabilities in realistic ground and flight environments of a next-generation program;
- demonstrating the operability, maintainability, and reusability required for the next-generation program;
- demonstrating rapid prototyping; and
- demonstrating the ability to perform "faster, better, cheaper."[4]

Cook added that

> [t]o commit to specific component technologies for both the flight demonstrators and the full-scale operational vehicle, it is necessary to demonstrate that components have robust and well understood design margins relative to the applications of which they are intended. Thus, the ground test program will entail cycling of the candidate components under realistic environmental conditions to establish the acceptable number of flight cycles before deterioration, or failure of the components will occur. The flight test demonstration program [will] be implemented to identify component and system integration issues in the RLV program that are unresolved by ground test and to confirm the environments that are employed in the ground tests.[5]

The X-34 Commences Its Flight Test Program

On April 19, 1999, *Aviation Week & Space Technology* reporter Joseph C. Anselmo reported on a "quandary" facing X-34 program planners, writing that

> The space agency had planned to stage initial flights of the X-34 reusable launch vehicle out of Holloman AFB this summer. The unpiloted, air-launched vehicle was to be dropped from an L-1011 aircraft based at Holloman. In later tests, the X-34 was to return and land on a runway at the base to demonstrate its autonomous landing system. But acting Air Force Secretary F. Whitten Peters recently informed NASA Administrator Daniel S. Goldin that the tests would have to be conducted elsewhere. "When we fly [X-34], everything else has to be shut down, and it would interfere with their operations," Goldin said last week. The Air Force's wing of stealthy F-117 strike aircraft are based at Holloman. Peters also expressed concern about potential noise and environmental impacts from the X-34 tests. NASA responded to Peter's concerns by tentatively planning to shift the tests to Edwards AFB, Calif. But that decision was then put on hold when Peters agreed to reconsider his stance after receiving protests from New Mexico's congressional delegation. "We're kind of on the sidelines right now," said Gary E. Payton, NASA's director for space transportation technology. "It's up to the Air Force." NASA has instructed its X-34 contractor, Orbital Sciences Corp., to stop preparing for the tests until the issue is resolved.[6]

X-34 Program Priorities

NASA established the four following priorities for flight-testing the X-34 Technology Testbed Demonstrator.

1. Demonstrate safe flight test operations. Prove that the X-34 vehicle can fly safely by gradually expanding the envelope from captive-carry to tow testing to unpowered drop flights to System Propulsion test to powered flights.
2. Conduct sustained operation rate demonstration. Demonstrate a 25-flights-per-year capability by conducting 6 flights at approximately Mach 4.5 within 3 months, with a maximum turnaround time of 14 days (may include one 24-hour turnaround).
3. Envelope expansion. Expand the flight envelope up to Mach 8 and an altitude of 250,000 feet, and demonstrate embedded technologies.

4. Demonstrate industry experiments. Integrate and fly technologies' experiment profiles.[7]

X-34 Flight Test Plan Overview

Planners envisioned testing the X-34 over several different ranges, including the White Sands Missile Range in New Mexico and the NASA Dryden Flight Research Center at Edwards AFB, both of which had long and distinguished histories involving rocketry, rocket research aircraft, and the drive into space. Powered flights by the X-34 would have required a flight path of approximately 500 miles. The initial schedule provided for five unpowered flights at the White Sands Missile Range. The carrier L-1011 aircraft would launch from Holloman Air Force Base and fly up-range, dropping the X-34 A-1A at Mach 0.7 and an altitude of 35,000 feet. The X-34 would then glide to a landing at White Sands Space Harbor. Following the unpowered flight tests of the X-34 A-1A vehicle, the second vehicle (X-34 A-2), which was under construction, would be transported to NASA Dryden for tow testing and powered trials. There was an earlier test-flight plan developed by Orbital engineer Frank Bellinger, which called for using Dryden from the beginning. According to Bellinger, however, Dryden was consumed with planning for flight-testing of the X-33, which was a far bigger program for Dryden. (The X-33's launch site was already under construction by Haystack Butte, on the eastern portion of the Air Force Flight Test Center's broad range. Bellinger then switched to preparing plans for using Holloman AFB and White Sands Missile Range for initial flight test.[8] The final testing site later returned to Dryden where, as proposed by Bellinger, it would have been in the first place.

On December 18, 1998, NASA announced that it had exercised an option for 25 additional flights during a 12-month period. The contract was valued at more than $10 million, with Government organizations performing an additional $4.7 million in work.[9] By June 1999, NASA and Orbital had established an X-34 Flight Test Planning Group (FTPG) to address X-34 flight-test issues including, most importantly, the testing locations. This group apparently was formed after termination of the original White Sands Missile Range/Holloman AFB flight test plan. The FTPG was co-chaired by Jeff Sexton, from NASA Marshall, and Curt Shoffner, representing Orbital. FTPG membership included NASA Marshall, Orbital, NASA Dryden/Air Force Flight Test Center, Kennedy Space Center, Marshall Environmental Office, as well as participants from the Federal Aviation Administration. In his June 8, 1999, briefing to Gary Payton, Jeff Sexton addressed the flight-test location issues and options, noting that the then current plan called for a) performing envelope expansion at Dryden/Edwards AFB up to Mach 5, b) then conducting operations demonstrations at Kennedy and

Cape Canaveral Air Station (CCAS) for flights between Mach 4 and 4.5, and c) completing the envelope expansion up to Mach 8, as well as the technology experimental flights, at Dryden/Edwards AFB. However, due to what Sexton termed as “recent concerns regarding the X-34 test flight location” the three following scenarios were evaluated: 1) conduct all flight operations at Dryden/Edwards and Kennedy/CCAS; 2) revert to previous baseline of White Sands/Holloman and Kennedy/CCAS; or 3) conduct flight operations at all three locations.[10] Sexton provided the following additional details for the three options.

- **Option 1** (all operations at Dryden/Edwards and Kennedy/CCAS). This envelope expansion plan included 18 to 19 planned flights at Dryden/Edwards, plus three unpowered flights, a tow test series, and a system hot-fire test. Sexton identified this course of action as the best technical option due to Dryden’s and Edwards AFB’s experience and expertise, and because of the lake bed infrastructure for landing margins and future midrange abort. Also, since this flight plan used the existing approved X-33 corridor, satisfying the environmental impact concerns would be easier. The sustained operations rate and surge would be tested by 8 to 9 Kennedy/CCAS demonstration flights. Sexton estimated the cost of the option 1 plan would be approximately $10 million.
- **Option 2** (revert to previous baseline of White Sands/Holloman and Kennedy/CCAS). Under this option the flight tests series would include 3 unpowered flights, system static hot-fire tests, and 4 to 6 envelope expansion flights up to Mach 2.5 conducted at White Sands/Holloman AFB. The remaining 18 to 20 flights would be conducted at Kennedy/CCAS. Under this option, the sustained operation rate demonstrations would be limited to not more than Mach 2.5 and this flight envelope would take place without the benefit of a lake bed landing margin and future midrange abort. Also, this corridor raised FAA concerns due to heavy commercial air traffic. The cost impact of option 2 was estimated at $7 million.
- **Option 3** (conduct flight operations in all three locations). Under this option, 4 powered flights and 3 unpowered flights would be conducted at White Sands/Holloman AFB. There would be 18 or 19 envelope expansion flights, including technology experiment flights, flown at Dryden/Edwards AFB. There would be 8 or 9 sustained operations rate and surge demonstration flights undertaken at Kennedy/CCAS, including repetitive Mach 4 to 4.5 flights from Beaufort, South Carolina, to the Shuttle Landing Facility in Florida. The cost impact was estimated at $18 million.[11]

Sexton also offered details about the current plans to complete the envelope expansion up to Mach 8, as well as other plans for technology experimental flights.

- **Flight Envelope Expansion to Mach 5.** There were 8 to 10 envelope expansion flights up to Mach 5 planned, which would use a stair-step approach starting at Mach 2. Limited maneuvers were planned for each flight to characterize vehicle response for pitch doublets at various Mach numbers and altitude, rudder doublets, aileron doublets, speed brake effectiveness, and body flap effectiveness. These flights also would verify propellant dump and the reaction control system, and would have prepared the ground operations crew for follow-on sustained operations rate demonstrations.[12]
- **Flight Envelope Expansion to Mach 8.** This powered flight, which was planned for the A-3 vehicle, was designed to expand the flight envelope up to Mach 8. This included 1 shakedown flight at Mach 2.5, 5 flights at Mach 5, 1 flight at Mach 6 to compare with the A-2 vehicle Mach 5 flights, and 1 maximum Mach and altitude flight. Where possible, the flights would be co-manifested with experiments.[13]

Testers were cognizant of the challenges attending any envelope expansion flights and enumerated some in an undated NASA planning proposal. These included the following:

- the X-34 is a fully autonomous hypersonic vehicle;
- the X-34 has many "binary" systems;
- there is very limited test time on each flight;
- there is limited airspace/alternate landing fields;
- the vehicle is launched from a carrier aircraft; and
- there are a limited number of flights scheduled.

Among the many parameters having to be assessed during expansion were drop conditions, Mach number, dynamic pressure, altitude, aero coefficients, control effectiveness, ground controllability, landing distance, heat flux, total heat, reaction control system, power on/off characteristics, engine firing time, and propellant dump system. Each of these parameters would need to be tracked during flight-testing in order to identify available design limit margins. The flight envelope was divided into five regions: separation, subsonic, in ground effect, less than Mach 4.0, and greater than 4.0. Within each region, certain characteristics would need to be determined, and deemed satisfactory, prior to advancing to the next region of the envelope.[14]

Beyond this, they noted the following points:[15]

- **Autopilot:** In addition, the autopilot will be forced to handle all situations; the data must be analyzed following each step to ensure the trends are as predicted; due to preprograming, only one build-up maneuver should be attempted per flight; the required data points for all characteristics in a particular part of the flight envelope should be achieved simultaneously; the program will have reduced risks, but will require a large number of flights; and the methodology also applies to the individual subsystems.

- **Autonomous Vehicles:** The advantage of an autonomous vehicle is that it allows the designer to do things that would not be tolerated if flown by a human pilot. The disadvantage is that a pilot has the ability to feel the plane and adapt to its characteristics. For example, a pilot can attempt to recover from an unanticipated problem while an autopilot simply performs the maneuvers it is programed to execute. Accordingly, the X-34 was required to have a high degree of mission flexibility, thus requiring a high degree of robustness of the autopilot.
- **Limited Test Time:** The X-34 would have had very limited time on each flight to perform dedicated testing. This is due to having a low lift-to-drag ratio resulting in high rates of descent, and to the vehicles high degree of power, which once extinguished could not be restarted. For unpowered flights the X-34 would have had approximately 90 seconds of dedicated test time between drop time and the acquisition of the glide slope. For powered flights, the flight conditions would have changed so rapidly that the X-34 could neither fly at a constant Mach number or dynamic pressure during ascent or reentry. After separation from the carrier aircraft, the vehicle would need to pull up to maintain a normal acceleration of 2.0 g until reaching a designated flight path angle. This maneuver was designed as a compromise between high dynamic pressures and aero loads and would have provided no room for anything other than carry along experiments. During reentry, the X-34 would have been limited by an angle of attack profile that would have provided adequate temperature protection, but only subtle changes to these profiles could have been made during these two phases of flight, thus limiting the remainder of the flight to performing dynamic maneuvers or experiments.[16]
- **Binary Systems:** X-34 binary systems included the main propulsion system, flight controls, flight termination system, and separation from the carrier aircraft. All of these would have needed to work well on the first use in order prevent loss of the vehicle. This would have required adequate ground testing and/or analysis to be performed on each system. Also, as many of these systems as feasible should be tested while the vehicle is in captive-carry in order to reduce the risk of losing the vehicle.[17]
- **Airspace Constraints:** Operational airspace should be a by-product of the required mission and not a limitation imposed on good test

practice. After complete analysis/simulation of each mission, the vehicle mission would need to be adapted to the appropriate test range.

- **Separation from Carrier Aircraft:** Numerous constraints on design of both the vehicle's geometry and performance exist due to launching the X-34 from a carrier aircraft. During captive-carry, the rudder of the X-34 is inside an unpressurized box (fin-box) constructed within the belly of the L-1011. Clean separation from the aircraft requires that the vehicle's 76-inch rudder would not contact the fin-box during drop. The first separation was planned to be performed at preset conditions determined to give the largest fin-box clearance. The result of this first drop would then have been compared to the simulations and adjustments to elevon preset angles made for the subsequent flight. The Mach number and altitude combination at time of separation would impact the maximum altitude and Mach number the X-34 could achieve.[18]
- **Envelope Expansion:** Each envelope expansion would need to be performed on all systems simultaneously. Each system would need to be advanced at a steady pace even though it might mean flying similar conditions repeatedly and adjustments resulting from earlier flights would need to be incorporated and tested prior to proceeding with the expansion. Each flight would increase the auto flight database building the reliability and robustness of the system.[19]

Flight-Testing Delays Due to Uncertainty over Location

The launch options for the X-34 far exceeded those of the Space Shuttle, Atlas ELV, and the planned X-33. Being smaller, less complex, and air launched from a mother ship, the X-34 could be launched in higher winds, in inclement weather, and over a wide range of geographic locations, and with fewer people than any of these other vehicles. Key parameters included the following:

- **Site winds:** The Space Shuttle was limited to launching in winds of under 10 knots, and the Atlas ELV and the X-33 were limited to launching in winds of under 20 knots. In comparison, the X-34 could launch in winds of up to 20 knots, with a plan to increase this limit up to 40 knots.
- **Site rain:** The Space Shuttle, the Atlas ELV, and the X-33 were limited to clear-weather launches, while the X-34 was planned to be able to launch in moderate and even heavy rain. Orbital backed away from this plan, however, because of concerns that the thermal protection material would not survive a significant and continued impact of rain at high speeds.[20]

- **Launch location:** The Space Shuttle was limited to launching from Kennedy Space Center, while the Atlas ELV could be launched from either Kennedy or Vandenberg AFB in California. The X-33 was planned to launch from the Air Force Flight Test Center. In contrast, the X-34 (as discussed previously) could be launched from many locations.
- **Launch personnel:** The personnel for the Space Shuttle numbered in the thousands, the Atlas ELV and the X-33 in the hundreds, and the X-34 in the tens.[21]

But having said this, choosing the X-34 launch site was not without controversy. Following Dryden's apparent initial lack of interest in the X-34 previously noted by Frank Bellinger, plans for powered flight test of the X-34 turned to launching the vehicle from Holloman AFB in New Mexico and landing the craft at the Army's White Sands Missile Range in New Mexico. The use of Holloman AFB, however, soon became uncertain due to Air Force concerns over safety, environmental issues, and Air Force training missions.

In a March 26, 1999, letter to NASA Administrator Daniel Goldin, F. Whitten Peters, who was then the Acting Secretary of the Air Force, expressed his "serious concerns regarding NASA's proposed X-34 testing and operations at Holloman Air Force Base." Peters noted that "adding X-34 testing activities and constraints place both Air Force operations and X-34 efforts in jeopardy." The Air Force activities included F-117 Nighthawk stealth fighter aircraft operations by the 37th Tactical Fighter Wing, and Luftwaffe F-4F Phantom II training activities. (Holloman was a center for German air force fighter-crew training as part of the United States' commitment to the North Atlantic Treaty Organization, or NATO.) Peters also noted that Holloman was then involved in a number of environmental lawsuits, and that operations of the X-34 would potentially add to these. Holloman was also involved in the highly controversial Realistic Bomber Training Initiative, which was causing concern in eastern New Mexico. Peters added, however, that he was committed to supporting the X-34 program and wanted to explore the potential for relocating the X-34 testing to Edwards AFB in California, noting that Edwards "not only has a long history of hypersonics and high-altitude testing, but also has various extant facilities and capabilities which might be brought to bear."[22] This letter marked the beginnings of a political controversy over the location for testing the X-34 that swiftly pitted the congressional delegations of New Mexico and California against one another.

The New Mexico congressional delegation was pushing for testing at Holloman AFB that would also involve the Army's White Sands range in New Mexico, while California representatives were backing Edwards AFB as the test-flight location. This dispute received significant press coverage. NASA was caught in the middle and received advocacy letters from both states' congressional representatives. The controversy engendered public comment as well; one example of this was a May 8, 1999, editorial published in the *Southeast Kern Weekender* of Tehachapi, California (a mountainous community located approximately 35 miles northwest from Edwards). The editorial summed up the political dispute:

> Just where that test flight will take place was not decided as top NASA officials and others gathered at the NASA Dryden Flight Research Center here. The decision is at the heart of a battle between politicians in New Mexico, who want testing to take place at Holloman Air Force Base, and California, whose lawmakers favor Edwards.
>
> California Congressman William Thomas (R-Bakersfield), whose district included Edwards, joined with 25 Congressional colleagues, including the state's two U.S. Senators, in a letter to NASA Administrator Daniel Goldin asking that the X-34 flight testing be conducted at Edwards.[23]

Four days later, on May 12, the *Antelope Valley Press* of Lancaster, California (located 25 miles southwest of Edwards), printed an Associated Press article adding that

> New Mexico's congressional delegation is making a pitch to keep an experimental rocket program in southern New Mexico. The five-member delegation plans to meet Wednesday with acting Air Force Secretary Whitten Peters, who has recommended moving the X-34 reusable rocket program from Holloman Air Force Base to Edwards Air Force Base. The delegation is protective of the small X-34 program because it gives New Mexico a foot in the door toward future reusable rocket efforts. "Keeping the X-34 in New Mexico bolsters our opportunity to successfully compete in the race for the lucrative commercial space market," said Rep. Joe Skeen…. "This program's like an acorn, and someday we want to grow an oak."[24]

Meanwhile concerns were being raised by NASA and Orbital regarding possible flight delays and increased costs while the issue of where flight-testing would take place remained unsolved.

Further complicating the situation was the consideration of also using the Kennedy Space Center. Under this tentative plan, the captive-carry tests would be conducted at Edwards with the first X-34 vehicle. The second X-34 vehicle would be shipped to White Sands for one drop test and at least one first flight test. Remaining flight-testing would take place at the Kennedy Space Center. This plan evolved when only two test flights were planned for the X-34. With the planned addition of 25 more flights, the plan changed to favor Edwards for the both the preliminary testing and for the developmental testing with some testing still planned for Kennedy. Dryden's David Bushman, one of the Center's X-34 managers, noted that the Center had been trying to get the X-34 flight testing, invoking its X-15 legacy and that the X-34 was like an X-15 but without a pilot. Bushman pointed out that despite each having a different mission—the X-15 was developed to initially explore the hypersonic flight envelope, while the X-34 was intended to examine how to reduce launch costs and to test new technologies for reusable launch vehicles—the X-15 and X-34 were similar in shape, size, and capabilities. He noted an additional advantage of flight-testing at Edwards AFB was that the X-34 could use the same flight track already planned for the X-33.[25]

In commenting on the problems at Holloman AFB, *Aviation Week & Space Technology*'s Joseph C. Anselmo noted that

> some program officials are secretly delighted because the size of the test range at Holloman would have limited the X-34 to speeds of Mach 2.5–3. Flying out of Edwards, the vehicle could be dropped over the Groom Lake test range in Nevada, enabling it to achieve peak [Mach 8.0] speed before being moved to Florida for weather-related tests.[26]

Commenting further on the dispute over using Dryden versus White Sands, Bushman noted that "[w]e here at Dryden with our experience with the X-15 and X-33…this is what we do."[27] X-plane flight-testing at Dryden appeared to be confirmed by NASA Administrator Daniel S. Goldin, during his April 2000 visit to Dryden, saying that, "Dryden needs to be the place to test X-planes…[and] there should be no ambiguity any longer…if it involves flight, Dryden needs to be involved from the beginning."[28]

The A-2 vehicle, which was originally planned to be used in New Mexico, was now planned to be shipped to NASA's Kennedy Space Center for a second set of flight tests. It was hoped that these tests, which were planned to reach speeds of approximately Mach 4.5, would demonstrate rapid turnaround flight operations as well as the capability to make crosswind landings and fly through rain. The remainder of the flight-testing would then be conducted at NASA Dryden using the A-3 vehicle. These tests were expected to expand the X-34's maximum capability of attaining speeds up to Mach 8 and altitudes up to

250,000 feet, while also testing additional reusable launch vehicle technologies as carry-on experiments. The ultimate testing goal remained reducing the cost of putting payloads into orbit from $10,000 to $1,000 per pound.[29]

FAA Certification of the L-1011 Carrier Aircraft

In his March 9, 2000, briefing to the Federal Aviation Administration, Mark Gamache, Orbital's L-1011 carrier aircraft program manager, outlined various safety provisions that Orbital would take to mitigate the risk posed to the L-1011 and its crew in carrying and launching the X-34. Two important areas that Orbital needed to address involved procedures to jettison the X-34 from the carrier aircraft, in both controlled and emergency situations, and the X-34's flight termination system. A controlled jettison would be necessary in hazardous situations on the X-34 or on carrier aircraft where the presence of the attached X-34 would not permit the L-1011 to land. An emergency jettison would be necessary in any situation on either the X-34 or carrier aircraft that placed the aircraft or crew at risk. In a controlled jettison situation, a checklist of tasks would be followed to remove power from the X-34, and the vehicle would then be jettisoned using normal release procedures. A controlled jettison would need to be coordinated with and approved by the range safety officer. In an emergency jettison situation, the aircraft commander was authorized to perform emergency jettison without prior authorization of range or ground personnel. Simulations of an immediate jettison of the X-34 in certain flight regimes indicated that the tail of the X-34 could make contact with the L-1011's fin box, but would not impact critical L-1011 systems.[30]

Preparing the X-34 Environmental Impact Statement

While all this was going on, NASA was tasked with another program requirement: the preparation of the X-34's Environmental Impact Statement (EIS). This task reflected a historic fact, namely, that concern over the environment had changed dramatically in the 40 years since the North American X-15 had first taken to the skies, carrying hazardous materials and flying on a flight profile across great swaths of territory. In the 1990s, environmental activists had succeeded in putting their imprint upon the Federal Government, and so the ease with which NASA and other agencies had conducted their research activities disappeared amidst a welter of often conflicting and challenging paperwork generating Environmental Impact Statements that, at times, threatened to prevent any reasonable testing at all.

In the case of the X-34, NASA was required to prepare an Environmental Impact Statement, because some of the test flights would overfly areas outside the boundaries of Government flight ranges. For example, the X-34 flight tests at Edwards AFB also would fly over parts of Nevada and Utah. These two states also were being evaluated for contingency landing sites. The first step in the EIS process involved publishing a notice of intent in the *Federal Register*, notifying the public of all potential flight paths for flying the X-34. Public meetings were then scheduled. Quite frankly, by the end of the 1990s, it was highly unlikely, even inconceivable, that NASA could secure approval to build and fly a sophisticated system like the high-risk experimental X-15 and fly it across the United States, given the changes in environmental law, policy, and the interest in local jurisdictions in what was happening above their heads. Certainly, that had been a major concern with the X-33, though its cancellation stemmed from other causes including design flaws in its propulsion tankage.[31]

Arrival of the First X-34 at NASA Dryden

The first X-34—the A-1 structural test article—arrived at NASA Dryden on February 24, 1999. The vehicle, which consisted of the X-34 airframe minus its engine and propulsion subsystems, was shipped from Orbital's Dulles, Virginia, facility in two separate trucks—one carrying the fuselage and the other carrying the wing. In commenting on shipping the X-34 A-1 to Dryden, Robert E. Lindberg, Orbital's vice president and the first X-34 program manager, noted that "[t]he shipment of the first X-34 vehicle marks the transition from the development phase of the program to the field test phase. When fully operational, the X-34 will validate and expand the high-speed and high-altitude

The X-34 A-1 Structural Test Article after delivery to the Dryden Flight Research Center, shown on the Dryden ramp on April 16, 1999. (NASA)

VIPs, Dryden workers, and other invitees inspect the X-34 A-1 at the official rollout ceremony, held at the Center on April 30, 1999. (NASA)

flight research last carried out by NASA's X-15 space plane more than 30 years ago."[32] Lindberg added that a team of 15 Orbital engineers and technicians would operate and maintain the X-34 test article during the tests undertaken at NASA Dryden.

Upon arrival of the vehicle, David Bushman, Dryden X-34 project manager, added that, "[w]e are excited to be part of the X-34 team. We are pleased to be able to make a contribution to this project that adds to Dryden's legacy in test flight."[33] Following its arrival at Dryden, the vehicle was to be assembled before undergoing ground vibration tests, which are conducted to ensure that there are no potentially hazardous vibrations during the test flights. The L-1011 also was scheduled for ground vibration tests both alone and while mated to the X-34. Following completion of the ground tests, the X-34 was planned to make up to seven captive-carry flights mated to the L-1011 in order to enable the FAA to approve modifications made to Orbital's L-1011 to carry the X-34. The certification flights were scheduled to take place at Edwards Air Force Base. [34]

Official Rollout of the X-34 Technology Demonstrator

On April 30, 1999, the X-34 was "rolled out" at NASA Dryden with much fanfare and optimism. The rollout was attended by various officials, including Daniel S. Goldin, NASA's Administrator; David W. Thompson, Chief Executive Officer of Orbital, and other company officers; Kevin L. Petersen, Director of NASA Dryden; and Major General Richard V. "Dick" Reynolds, the commander of the Air Force Flight Test Center. In addition, Vice President

Senior aerospace dignitaries sharing the podium at the X-34 rollout included (left to right) David W. Thompson, Arthur Stephenson, Daniel S. Goldin, Kevin L. Petersen, and Major General Richard V. "Dick" Reynolds. (NASA)

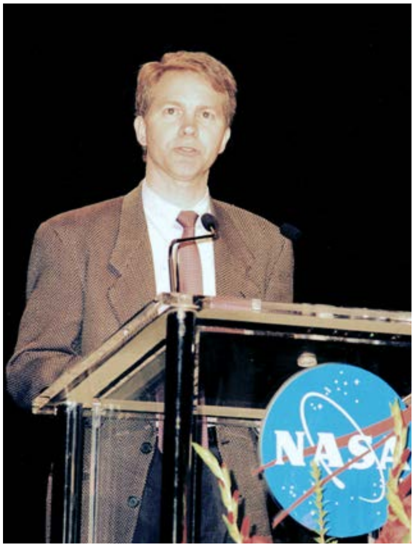
Albert Gore sent a videotaped message of congratulations, hailing the program and its potential contributions to America's commercial space future.[35]

During his remarks, Goldin said that "[t]he X-34 is the cornerstone of our efforts to show properly designed rocket vehicles can be easy and inexpensive to operate."[36] Gary Payton, now NASA's Deputy Associate Administrator Space Transportation Technology, added, "[i]n less than 3 years we went from a blank piece of paper to a prototype."[37] Antonio Elias, Orbital's Senior Vice President for Advanced Programs, noted, "[w]e are here today because we share a dream for a safe, affordable system that is as spontaneous as air travel is today."[38]

In his remarks, Orbital's Thompson directly addressed the potential of the program to lead to reduced cost-to-launch space payloads, stating that

> [b]y reducing the cost of launch services, space will be made more accessible to a wider group of commercial and government customers. With reduced launch costs, government budgets could support more frequent scientific or national security missions, and commercial users that provide services from satellites, such as voice and data communications or Earth imagery, could lower prices for their customers.[39]

NASA Administrator Daniel S. Goldin is speaking at the X-34's rollout ceremony on April 30, 1999. (NASA)



Orbital Chief Executive Officer David Thompson is speaking at the X-34's rollout ceremony on April 30, 1999. (NASA)

The X-34 test flights were planned to test many new technologies, including composite material structures, composite tanks, and new integrated avionics. The test flights also were planned to demonstrate "the ability to fly through inclement weather, land horizontally at a designated landing site, and safely abort during flight." The planned 27 test flights, to be executed within 1 year, also were intended to "demonstrate the program's ability to fly within 24 hours of its last mission, using a small ground crew."[40]

X-34 Pre-Flight Operations

An Orbital summary described what the preflight operations would have entailed:

> The X-34 vehicles are prepared for flight in a typical aircraft hangar. Transportable ground support equipment (GSE) is used to assist flight operations. Systems are checked out, pressurant gases are loaded, and the vehicle side panels/doors are closed. The vehicle is towed to the flight ramp, attached underneath the Orbital L-1011 carrier aircraft, and fueled with propellants. Once the propellant loading GSE is removed from the vehicle, the L-1011 taxies to the runway, takes off, and climbs to cruise altitude of 35,000 feet.[41]

NASA and Orbital X-34 test personnel at Dryden are modifying the X-34 A-1 for air launch, October 1999. (NASA)

X-34 Captive-carry Tests

The captive-carry flights were conducted to enable Orbital and the Federal Aviation Administration (FAA) to certify that the modification made to Orbital's L-1011 carrier aircraft, which carries Orbital's Pegasus rocket, was able also to safely carry the X-34 without posing any safety issues to the flight crew, the aircraft, or the people and property on the ground. UK-based Marshall Aerospace had modified the company's L-1011 so that the aircraft could be used for both Pegasus and X-34 missions.

In preparation for captive-carry flight testing, the X-34 was mated underneath the L-1011 on June 23, 1999, and underwent several days of preflight testing prior to its first captive-carry test on June 29.[42] This first test, however, was cut short due to an F/A-18 chase plane pilot noticing a vibration on two small fuselage skin panels located aft on the X-34. The vibration apparently was caused by the aerodynamic wake from the mated X-34, which caused the panel fasteners to come loose and allowed the two panels on the right and left sides of the aircraft to vibrate. The vibrations were noticed when the carrier aircraft had reached its top flight speed of approximately 350 knots. The test flight mission

Orbital's L-1011 TriStar mother ship lifts off from Edwards' Runway 04/22 on the X-34 A-1's first captive test flight, June 29, 1999. (NASA)

was ended when the X-34 was 1 hour and 50 minutes into its planned 2.5-hour flight and at an altitude of 16,000 feet of the mission's planned 30,000-foot test altitude. Program officials noted, however, that all systems appeared to be operating normally prior to mission termination.[43] The Dryden status report added that several test objectives were accomplished during this flight and that aircraft performance was evaluated at various speeds and altitudes. A simulated propellant release was accomplished using fluorescent dye and that the flight successfully checked "the electronic connections between the mated aircraft, data collection systems and the video camera system on the L-1011."[44]

The X-34 had its second captive-carry test of September 3, 1999, and on September 14, the X-34 completed its final captive-carry test of 1999. This flight, which lasted 8 hours, was to collect data on the performance of the mated configuration and validate the flight condition for the future test release of the X-34 from the L-1011 carrier aircraft. The remaining captive-carry tests were planned for late January 2000, following completion of the tow tests.[45]

Throughout the captive-carry testing, NASA Dryden Aerospace project reports identified the progress and accomplishments. These reports are highlighted below.[46]

> **July 2:** The X-34 first captive-carry flight was conducted on June 29. The flight was successful overall, but the L-1011 and

X-34 had to return to base without completing the planned flight cards due to the aft L-1011 panel vibration. Post-flight inspection revealed some fasteners missing and galled fastener holes on the panel. Orbital and Marshall Aerospace are analyzing the vibration causes and formulating repair plans.[47]

July 9: The X-34 team comprised of MSFC, Orbital, Marshall Aerospace and DFRC held discussions sessions regarding the in-flight anomaly of L-1011 panel vibration during the first captive-carry Flight. The team attributed the cause of vibration to the vortex generated by X-34. Because there was no instrumentation data to characterize the vortex, the team agreed to strengthen the internal structure of the area and install a set of instrumentation for the next captive-carry flight. Marshall Aerospace, L-1011 vendor, and DFRC will collaborate to implement the instrumentation requirement.[48]

July 23: Additional cracks were found in L-1011 panels below and aft of leading edge of right wing. The panels on the left wing do not have cracks but indicate higher than normal load. The analysis and repair are in work. This may postpone the second captive-carry flight, which is scheduled for July 30.[49]

September 3: The L-1011 captive-carry flight No. 2 has been successfully conducted for 4.5 hours, 9/3. No anomaly was indicated.[50]

September 10: The tech briefing for the upcoming L-1011/X-34 captive-carry flight No. 3 on 9/14 had been conducted on 9/9 successfully. This will be the last captive-carry flight for the remaining year in order to proceed with A-1 Upgrade. The rest of the captive-carry flights will resume in late January of year 2000 after the completion of tow testing of A-1A. The demate of X-34 is scheduled for 9/16.[51]

September 17: The L-1011/X-34 captive-carry flight No. 3 was successfully conducted on September 14. The X-34 vehicle A-1 was demated in hangar 1600 on September 16 and moved into hangar 4833 for retrofit. The L-1011 will leave this weekend and return by the end of January 2000 to resume the X-34 captive-carry flights.[52]

> **August 4, 2000:** Current plan is to reconfigure the A-1A from the tow test to captive-carry flight in order to finish the L-1011/X-34 FAA certification program.[53]

Upgrading the X-34 A-1 Vehicle for Unpowered Flight Testing

Following NASA's and Orbital's decision to upgrade the X-34-A-1 vehicle to unpowered flight-testing status, a task planning meeting was held on July 28–29, 1999, at NASA Dryden. The purpose of the meeting was to "understand the scope of the A-1 upgrade effort to enable development of the cost, schedule, and skills required."[54] Orbital had originally designed and built the first X-34 A-1 prototype as a structural test vehicle for the purpose of ground vibration testing and captive-carry flight-testing on Orbital's L-1011 carrier aircraft. The identified upgrade to flight test requirements were: 1) to enable "minimum necessary fidelity to conduct X-34 tow testing and unpowered glide flights"; 2) to ensure that critical data obtained from A-1 testing correlated to the A-2 vehicle flight testing efforts; 3) to use existing X-34 development procedures, processes and standards; and 4) not to allow the upgrade effort to impact the A-2 static hot fire and powered flight schedule. The team also noted that the A-1 tow testing was to occur at Dryden during calendar year 1999.[55] Orbital was assigned to lead the engineering effort, including providing the design and analysis work, engineering support, and undertaking the subsystem and system level testing. Orbital also was to provide all hardware and software, assign a task manager, and maintain overall responsibility for X-34 flight testing. NASA Dryden's responsibilities included leading the technician effort, providing the majority of the technicians needed for assembly of the modifications to the A-1, and assigning a task manager. No support contractors were to be used.[56]

On January 28, 2000, *The Dryden X-Press* reported that NASA and Orbital were now ready to start the unpowered tow testing of the X-34 A-1 vehicle, now upgraded and re-designated as the X-34 A-1A. Jeff Sexton, who was NASA Marshall's flight-testing and operations project manager for the Pathfinder program noted that "…we [have] added all the flight mechanisms—avionics and wiring, hydraulics, control surfaces, landing gear mechanism and flight software—needed for unpowered flight-testing [and that the upgraded X-34] A-1A is identical to the other flight vehicles except that it lacks the thermal protection system and propulsion system required for high speed, high-altitude flight."[57] In performing the upgrading, Sexton added that the effort "…definitely was a team effort with several organizations working elbow to elbow to put together the [X-34] A-1A…. [and that] It's been a real pleasure to see technicians and engineers from multiple government and industry organizations working together as a single team."[58]

X-34 Tow-Tests

In mid-July 2000, following completion of initial captive-carry tests, the X-34 started a series of 12 planned tow tests on Edwards' dry lake bed at Edwards Air Force Base, California. The tow-tests, which simulated the vehicle's roll-out after landing, were designed to verify the X-34's guidance and navigation systems, nose wheel steering, braking, rudder speed brake operation, and rudder steering. For the tow tests, most of the vehicle subsystems were powered on, including avionics and navigation, computer software, hydraulics, power system, mechanical systems, and internal thermal control (TCS). To accomplish the tests, the X-34 was towed behind a semi-truck for distances up to 10,000 feet and released at speeds up to 80 miles per hour. The vehicle was attached to the tow truck by a specially designed 500-foot cable. A radio link provided communications between the vehicle and the tow truck launch panel operator.

On July 20, the X-34 was towed twice and released at speeds of 5 and 10 mph. On July 24, the vehicle was towed two more times and released at 10 and 30 mph. In regard to these tests, Antonio Elias, senior vice president and general manager of Orbital's advanced program group, noted that: "We are pleased to begin another series of testing for the X-34 that will bring us one step closer to flight… [and that] "When completed, they will provide valuable data and help ensure the success of the flight program."[59]

As with the captive-carry tests, the Dryden Center Aerospace Project Reports noted the tow test activity as reviewed below.

> **February 14, 2000:** "A first Tow Test simulation was conducted on Tuesday February 8. Some anomalies with the A-1A interface and GSE [ground support equipment] were found and are being corrected. Also the procedures and checklist are being updated. There will be another Tow Test simulation in the hangar prior to the first lake bed Tow Test Operation."[60]
>
> **April 4, 2000:** "The flight simulation testing of A-1A for Tow Test had been completed last Friday. The newly serviced hydraulic batteries are installed in the forward bay this week."[61]
>
> **May 19, 2000:** "The X-34 A-1A Tow Test was performed yesterday, 5/18, on the lake bed 15. Unfortunately the test was aborted before the completion due to the inadvertently disconnected lanyard of the tow cable. Another anomaly discovered from the test was that the primary and secondary release pyros on the tow cable didn't respond to the "Fire" command. Post-test inspection

indicated no damage to the X-34 vehicle from the test anomaly. Orbital and DFRC engineering will be analyzing the test data and working on Problem resolutions next week."[62]

May 26, 2000: "DFRC and Orbital engineering are working on the resolution of the A-1A Tow Test anomalies. The tow cable pull test is under planning in order to characterize the cable behavior and requalify the design. The pyro, primary and secondary, failure was caused by the incorrect pin matings between the vehicle and test adaptor connectors. A redesign effort to eliminate the possibility of incorrect mating is in work."[63]

June 9, 2000: "On Monday, June 5th, the tow cable was tested successfully for the pyro separation using the current design of hard wiring. Then Thursday, June 8, another pyro separation test was conducted with the spuds installed on the cable. This test resulted [in] a hang-fire. The test team troubleshooted and found that the ground leads for pyro had contacted the metal pyro body and shunted the pyro firing. Retest is scheduled for next week."[64]

June 16, 2000: "The tow cable No. 2 has been completely tested this week. It was pulled to the maximum loading of 12,000 lbs. and the hard wired secondary pyro was fired to demonstrate the functionality at 6,000 lbs. During the second cable testing, the tug, MB2, which is the hold down point for the cable rolled over the chuck when the truck pulled about 14,000 lbs. in the attempt of reaching 12,000 lbs. loading. This caused minor damage to the cable. A heavier tug, T500, with better brake system was obtained and used for the remaining test."[65]

July 7, 2000: "The Tech Brief for the X-34 Tow System End-to-End Verification and Tow Test is scheduled for July 15 at 10:00 am tentatively."

July 28, 2000: "On July 24, the A-1A tow test was successfully conducted for the low speeds at 10 mph, 20 mph, and 30 mph. A Tech Brief was held on July 26 for the A-1A high-speed (beyond 30 mph) tow test."[66]

August 4, 2000: "The X-34 Project decided to defer the high speed tow test of A-1A based on the successful completion of

> low speed, 5 to 30 mph, tow test. Engineering obtained substantial test data to verify the guidance/navigation system, braking system, nose gear steering, and hydraulic system. Also, from the tow tests, engineering identified a few components that require modifications. Current plan is to reconfigure the A-1A from the Tow Test to Carry Flight in order to finish the L-1011/X-34 FAA certification program."[67]

On August 4, *Aerospace Daily* reported that the X-34 was slightly damaged in the tow test over the weekend when its nose gear wheels became entangled in the tow cable. The vehicle's on-board computer, however, released the cable, disengaged the steering mechanism, and braked the X-34 to prevent further damage.[68]

After completion of ground testing, the X-34 was planned to be attached to Orbital's L-1011 Stargazer in order to finish the captive-carry tests for FAA verification that the aircraft with X-34 attached was safe to fly. After completion of the FAA certification program, Orbital planned to conduct approach and landing flights at White Sands Missile Range, New Mexico. As reviewed above, the planned test site was switched from White Sands back to Edwards AFB and subsequently the X-34 was not flown at Edwards due to cancellation of the program.

What Might Have Been: Free Flights, Unpowered and Powered

While the X-34 project was terminated prior to unpowered flight testing, three unpowered flights were planned to be made by dropping the modified A-1A vehicle from Orbital's L-1011 carrier aircraft. Flight 1 was planned as a nominal energy straight-in landing approach and landing on a lake bed. This first flight was designed to verify X-34 Terminal Area Energy Management [TAEM], touchdown characteristics, separation of the vehicle from the aircraft verification, rollout logic, software mode change, and flush air data system (FADS) calibration. Flight 2 plans called for a turn to the final heading at a higher energy state at time of release followed by landing on a lake bed. Flight 3 planned for a straight-in approach at a higher energy level than flight 2. This flight was planned for landing on a hard runway. In addition, the third flight would have utilized speed braking for high energy dissipation and performed 10 degree pitch and aileron doublets.[69] In regard to the planned unpowered drop tests, Jeff Sexton, from NASA Marshall, stated that

> [t]hese glide flights will give us an understanding of how the X-34 separates from the L-1011 and its flight characteristics.... We

> will be able to test its control surface effectiveness, validate the flight software that controls guidance, navigation, final approach, touchdown and landing rollout without risking the two fully functional powered flight vehicles.[70]

Further Program Concerns, Complexities, and Considerations

As the X-34 moved hopefully towards its initial flight trials, a variety of other concerns, complexities, and considerations arose to plague planners seeking to move the program forward.

Powered Flight Schedule Slippage: While NASA had hoped to conduct the first X-34 powered flight test in August 2000, the flight scheduled was set back several months until late fall. John R. London III, X-34 and Pathfinder program manager at NASA Marshall, attributed the delay to a decision to conduct at least three static tests of the integrated engine and fuselage at Holloman AFB. This represented a change from the original plan that called for only one engine test. London also stated that additional engine stand test also would be conducted at Boeing's Rocketdyne Santa Susana facility near Los Angeles, California.[71]

NASA's Inspector General's X-34 Audit Report: NASA's Office of Inspector General's March 30, 2000 audit report raised serious issues relating to the planned flight testing of the X-34. The Office of Inspector General (OIG) noted that while the initial contract provided for two flights, NASA Marshall exercised an option on January 22 1999 to add 25 additional flights to the program. To accomplish these tests, NASA Marshall, as of October 1999, had separated the 27 flights into 4 segments: 5 unpowered flights; 7 first-powered envelope expansion flights; 7 "operability" flights, including one contingency flight; and 8 final maximum envelope expansion flights with experiments. They noted further that the parameters for the X-34 tests, as provided by the NASA agreement, included flight tests at altitudes up to 250,000 feet and speeds up to Mach 8 and "[i]n addition to testing RLV [reusable launch vehicle] technologies embedded in the X-34 vehicle and a variety of experiments, the project is to demonstrate 'aircraft like' operability, that is, quick turnaround averaging 2 weeks between flights with a 'surge' capability of 2 flights in 24 hours."[72]

In regard to the above mission-specific requirements, the OIG findings noted that

> the X-34 contract statement of work requires that the contractor [Orbital] develop requirements compliance verification methodologies, which permit the linking of NASA mission requirements

> to each test flight and to the verification process. However, the contractor has not yet completed verification methodologies or flight software on the Optional Flight Test Program because NASA has not yet established the mission-specific requirements for each flight test. Because Marshall had not determined the mission-specific requirements of the additional 25 flights, they were all identical 2.5 Mach flights without additional speed, altitude, or other performance mission requirements. The 25 "baseline" flights did not meet Project objectives, which include testing the X-34 at speeds up to Mach 8 and altitudes up to 250,000 feet. On November 14, 1996, Marshall negotiated modification No. 2 to the X-34 contract, which added a pool of 100,000 labor hours to the contract in anticipation of the additional contractor effort that would be required to develop necessary flight control software and to perform additional tasks to support mission requirements, once Marshall identified them. As of November 1999, Marshall still had not established the mission-specific requirements for each flight.[73]

The OIG also noted that each test flight costs NASA approximately $1 million and that NASA had not performed a cost-benefit analysis and had not revalidated flight-test requirements. NASA Marshall concurred with the OIG findings, and in January 2000 NASA Marshall provided mission-specific flight-test requirements to Orbital and stated that the X-34 project manager would ensure that flight requirements are revalidated.[74]

Air Force Interest and Equities in the X-34: If the contretemps over Holloman and Edwards seemed at first glance to imply the Air Force was not supportive of the X-34 program, such was far from the truth. Air Force hypersonic partisans at the Air Force Flight Test Center (AFFTC) at Edwards were among the field's most zealous supporters. Led by Johnny Armstrong, Edwards' most experienced and distinguished hypersonic flight tester, they welcomed the arrival of the X-34, and worked assiduously to ensure that the program would be a success. The AFFTC's Access to Space Office identified a number of considerations and concepts for flight-testing the X-34 at Edwards Air Force Base (EAFB). They identified the tests that NASA and Orbital planned to undertake for each X-34 vehicle and the unofficial schedule for conducting the tests. First, propulsion tests using the X-15 test stand would be conducted from January through May 2000, but the three planned test runs for 20-second durations were considered low compared to the X-15 experience. After these tests, five powered flights would be flown from May through October 2000. The briefing noted that the current program provided for Mach 2.5 flight tests using White

Sands and Holloman AFB with flights above Mach 2.5 launched on the East Coast and landed on NASA's Kennedy Space Center's Shuttle landing runway.[75]

The Air Force's conceptual test program for Edwards AFB called for initial glide flight launches over the AFFTC's Precision Impact Range (PIRA), with landings on Rogers Lake bed runways. This site was considered to have fewer issues for obtaining approval. Powered flights would be launched at increasing distances at Edwards in order to expand the Mach and altitude envelope. The launches would be near dry lake beds to provide for emergency landings in the event the engine did not light. All planned landings would be at Edwards. The X-34 flight termination system, which consisted of command flight control actuators to put the vehicle out of control, was identified as possibly needing extensive ground verification to satisfy range safety requirements. Sonic booms, which were likely to reach the ground during vehicle rotation to positive climb after launch and on landing approach at Edwards, were not expected to be a significant factor due to the relatively small vehicle size and the remote areas of operation.[76]

The Air Force studied a plan to use the X-15 site to support X-34 engine testing at Edwards AFB. The review identified four modifications that would be needed, including removal of the water deluge system, engine collar, instrument panels and fittings, and concrete flame trench. The study noted that with the exception of the water deluge systems, the modification could not be reversed following the X-34 engine testing.

Orbital's Follow-on LEO Vehicle Development Hopes

David Thompson hoped that the X-34 program would validate enough technology and operational methods to enable Orbital to develop a commercial space launcher based on the X-34. The Orbital team envisioned a follow-on vehicle that would be launched from the ground with a reusable first stage and, at least at the beginning, have an expendable upper stage. The upper stage would carry a payload weighing as much as 5,000 to 8,000 pounds at a projected cost of between $2,500 and $4,000 per pound (in 1999 dollars) to orbit. Thompson identified low-Earth orbit communications satellites as one particular market "target." Orbital officials estimated that developing such a spin-off vehicle would require an investment of a least $250 million. Thompson added that Orbital would decide whether or not to go ahead with the project in the second half of 2000, which was planned to be near the end of the X-34 flight test program.

In what turned out to be a prophetic statement for the X-34, *Aviation Week & Space Technology*, noting the end of the first X-34 program, had commented on hoped-for next-phase development.

> If such an idea seems like a case of déjà vu, that's because it is. When the [first] X-34 program began in 1995, it was a much more ambitious effort. NASA, Orbital Sciences, and Rockwell International planned to develop a commercial launcher two-thirds the size of the Space Shuttle. The jointly-funded, 140,000-lb. vehicle was to be made up of a reusable first stage and an expendable upper stage and carry 2,500 lb. payload to LEO.
>
> But the partnership fell apart in early 1996 after the companies determined they would not be able to make a profit given ballooning development costs. NASA took the money it had left over and recompeted [sic] the X-34 as a much smaller, suborbital technology demonstrator. It ultimately selected Orbital from nine bidders….
>
> Thompson said last week that if the new X-34 can demonstrate key technologies and operations in its flight tests, it will be easier for Orbital to justify an investment in the commercial follow-on—essentially picking up where it left off in 1996.[77]

Alas, this was not to be: NASA terminated the X-34 project before it undertook any powered test flights.

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68. Leslie A. Williams, "Tests to Begin on Modified X-34 Experimental Rocket Plane," NASA Dryden press release 00-03, January 5, 2000, p. 2.
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The X-34 A-1, shown here from an aft right-quarter perspective, is sitting on the Dryden ramp on April 16, 1999. (NASA)

CHAPTER 9
Whither X-34?

Late 1997 through 1999 constituted a period of initial program modification, evaluation, reassessment, and restructuring, followed by a NASA Office of Inspector General review through fiscal year 1999 that preceded final restructuring of the X-34 program. Included in the OIG evaluation and reassessment was an examination of the relative merits of using alternative engines, especially for the A-3 vehicle and for the experiment flights. In addition to these efforts, NASA, as it had throughout the preceding X-34 program, also conducted periodic Safety and Mission Assurance Reviews and received recommendations from the program's Technical Assessment Advisory Group (TAAG).

From Program Inception to Redirection

Early in the program, NASA determined that the X-34 program warranted a thorough formal review process "to assess progress with respect to technical and operational objectives within established programmatic and funding constraints." Accordingly, in 1996, NASA formed a five- to-seven-person Technical Assessment Advisory Group that was chartered to "receive its directions from, and make its recommendations to, the NASA X-34 Program Manager, who will provide the group with the necessary resources, information, logistical support, and access to facilities and personnel." The X-34 program manager also was to "provide the group leader with timely notification of planned reviews and meetings as well as copies of pertinent documentation and status reports."[1]

"The objective of the group [was] to strengthen program management's assessment of the X-34 program at several key points during its life, such as outer mold line freeze, system design freeze, and flight readiness reviews for the first hypersonic flight." The group's assessments were to "cover all elements of the X-34 program, including tasks being performed by industry and government suppliers, and develop opinions as to: the likelihood of meeting safety, cost, schedule, operational, and technical performance requirements; support activities; flight readiness; and risks NASA faces as it proceeds with these flights." Also, the planning of experiments and experiment integration was to be assessed by the group. The first meeting was scheduled for November

1996, with a report due within 7 days following each major review. A formal report to the NASA Program Management Council was scheduled for the spring of 1997.[2] One of the early Technical Assessment Advisory Group reviews was a December 17, 1996, participation in Orbital's Outer Mold Line Freeze. "Overall the group was very favorably impressed by the broad progress made in a very short time since the program was initiated." They did, however, provide review action recommendations, including the two listed below.

- *They advised that the engine/vehicle airframe integration analysis was incomplete and needed immediate attention.* The group recommended establishing an empowered integration product team to establish engine/airframe compatibility before the Outer Mold Line freeze occurs.
- *They advised that the margins on landing were too small and that an "in-depth re-look at integrated landing, slap-down, and rollout [was] needed before a freeze."* They added that the "plan to treat off-nominal conditions through computational fluid dynamics (CFD) raised new concerns."[3]

This review was immediately followed by an unfavorable evaluation report on December 23, 1996, covering Orbital's X-34 program safety and mission assurance documents. This review, which was conducted by NASA's Payloads and Aeronautics Division, recommended the following actions.[4]

- **Risk management.** "One of the most notable omissions in the OSC program is that of an overall risk management approach and plan for the entire X-34 program. The contractor should establish an overall risk management policy and approach which balances performance (technical, quality, reliability, and safety) with cost and schedule throughout the program. Such an approach must be defined up front and utilized in a concurrent engineering process throughout the program. Risk management implemented in this manner is absolutely mandatory for any program which has limited resources."[5]
- **Integration.** "Integration of the principle [sic] X-34 design, manufacturing, testing and flight certification milestones with the respective S&MA [Safety and Mission Assurance] activities is required during the various program phases. This information has not been provided. In particular, testing is not integrated across the project, and no overall test plan leading to flight certification is provided."[6]
- **Staffing.** "There is general concern regarding the S&MA staffing levels as currently planned by the contractor. Given experience from other flight hardware and flight test development programs, the expectation would be that OSC will not be able to provide adequate S&MA coverage to successfully accomplish the contract milestones."

The S&MA staff concluded by noting that "[o]ur assessment concludes that if the X-34 Program is executed in a manner depicted in the S&MA documentation, there cannot be a high expectation of success. Given our review of the X-34 Program S&MA documentation, it is recommended that the X-34 program be required to develop an adequate safety and mission assurance program which will positively contribute to the expectations for overall success."[7]

FY 1997: A Year of Accomplishment

Gary Payton listed several fiscal year 1997 (October 1996 through September 1997) X-34 program accomplishments.

- The first round of wind tunnel testing was completed in November 1996.
- The Outer Mold Line was frozen in December 1996.
- The tank design was enhanced with bulkhead to accommodate intact abort.
- A second round of wind tunnel testing was conducted between March and September 1997.
- The performance of the autopilot was verified in simulation.
- The main propulsion system PDR was completed in April 1997.
- The arc-jet testing blanket and leading edge ceramic materials were underway.
- The Fastrac engine CDR was completed in April 1997.
- The fuselage assembly had gotten underway in high bay in May 1997.
- The system design freeze completed in May 1997.
- Getting the Fastrac engine nozzle/chamber to start test firing at 60,000 pound thrust level was completed in July 1997.

NASA Executes the First Major X-34 Contract Modification

Just 3 months after Payton's assessment, NASA signed its first X-34 contract modification on December 24, 1997. This modification addressed two major areas—risk reduction and the realignment of power-flight dates. The first risk-reduction priority was to reduce risk for the first flight date. This was accomplished by providing for an additional flight vehicle, making a total of three vehicles now designated A-1 (test vehicle), A-2 (first flight vehicle), and A-3 (second flight vehicle). The addition of the second flight vehicle represented a "lesson learned" from the loss of the DC-XA Clipper Graham, which had no back-up vehicle. The cost of fabricating two vehicles while the production line was operating and parts still available was significantly cheaper than having to start all over again to build a replacement vehicle at a later date. Additional risk mitigation measures taken included changing the first flight to unpowered, moving the dates of the second flight and static test, adding additional new test series to reduce uncertainties, and adjusting the way the ground test vehicle (A-1) and the two powered flight vehicles (A-2 and A-3) were to be used.[8] The new "best possible" flight date was reset for March 11, 1999, and task agreements were adjusted or developed as necessary to accommodate the new schedule and additional flight vehicle.

NASA planners estimated the total cost of the contract modification at approximately $18 million for Orbital and $2.5 million for added Government tasks.[9] This increased budget allocation raised the total X-34 program budget estimate to $156.68 million, broken out as follows: Orbital Sciences, $68.97 million; flight testing, $35.71 million; Fastrac engine, $30.93 million; basic and C&V task agreements, $12.42 million; NASA headquarters "tax," $5.11 million; and NASA Marshall PMS, $3.54 million.[10]

An earlier NASA Fastrac Independent Assessment, published in August 1997, had presented project growth vs. time budget estimates from March 1996 through July 1997:

- Technology Demonstrator (March 1996): $17.5 million for PTA1, 4 Fastrac Engines (3 demonstration units and 1 spare), and 48 tests;
- X-34 at time of Memorandum of Understanding (August 1996): $18.9 million for the same activities outlined in item 1, plus verification;
- Addition of risk mitigation activities (January 1997): $24.9 million for PTA1, 7 Fastrac engines, horizontal PTA testing, additional analysis, additional castings, water flow test, back-up sensors, and 87 tests; and
- Addition of risk mitigation plus options (July 1997): $35.6 million for the same activities outlined in item 3, including cold box testing, issues with the X-34 avionics, and addressing "pogo" oscillatory issues stemming from potential combustion instability.[11]

February 1998: New Budget Estimates, Task Agreements, and a Warning

Just 2 months after the December 1997 contract modification, in February 1998, NASA submitted a new estimate for the X-34, totaling $156.7 million for the program, of which $30.9 million was for the Fastrac engine, and $69 million for Orbital.[12] The breakdown of Task Agreements by NASA Centers and Military Installations as of February 17 were as follows:

- Dryden (5 Task Agreements): Ground vibration testing, captive carry, FAA certification, flush air data sensors, and video chase support;
- Ames (12 Task Agreements): Design, testing, analysis, and manufacturing of the SIRCA leading edge thermal protection system tiles; arc-jet testing of TPS tile and blankets; tile tooling; fabrication; and TPS flight test support;

- White Sands Missile Range (8 Task Agreements): Environmental impact statement with Holloman AFB; hazardous procedures support; and range approval and support;
- White Sands Test Facilities (11 Task Agreements): Test support and expendables, fuel and LOX handling equipment, static fire testing, and safety plan support;
- Marshall (24 Task Agreements): FAA frequency procurement; MPS definition, analysis, and design; Fastrac engine and MGSE; vendor procurement support; flight test support; and base heating analysis;
- Langley (17 Task Agreements): Task management, preliminary vehicle analysis—trajectory, preliminary aerodynamics, aerodynamic database development, wind tunnel modeling and testing, flying qualities assessment, GN&C development and flight support, and Schlieren and phosphor imaging; and
- Holloman Air Force Base (15 Task Agreements): Safety plan support, systems test support, antenna pattern testing, fuel and LOX handling support, and horizontal test stand modifications.

The goals and program objectives remained the same under the first contract modification. The goal was still "to significantly reduce the cost of access to space" and program objective remained the development of a test bed vehicle for demonstrating key reusable launch vehicle operations and technologies. The three primary focus areas remained

1. investigation of new methods for low-cost operations;
2. development of new RLV technologies embedded in the X-34 vehicle design; and
3. the demonstration of "hosted" RLV and hypersonic experiments.

The embedded technologies still included

- composite primary and secondary airframe structures;
- composite reusable propellant tanks;
- integrated vehicle health monitoring system;
- advance operable TPS system, including leading edge materials;
- low-cost avionics, including integrated GPS/INS and Differential GPS;
- flush air data system; and
- a new low-cost rocket engine, the Fastrac MC-1 Engine.[13]

By February 17, 1998, NASA had received 27 proposals for the conduct of hosted experiments, including 21 from American companies, 3 from NASA centers, and 3 from two foreign companies. The proposals were grouped in the four following categories:

- thermal protection system (18 experiments);
- guidance, navigation, and control (3 experiments);

- propulsion/APU (3 experiments); and
- structural instrumentation (3 experiments).

The X-34 team estimated that this series of experiments would cost $2 million.[14]

The February 1998 contract modification, at least indirectly, noted potential problems using the Fastrac MC-1 engine, in effect a "yellow light" warning, and addressed the opportunity to "upgrade performance, flexibility, and operability" by using an alternative, the Russian NK-39, for the X-34 A-3 test vehicle. Marshall studies indicated that the Russian Khrunichev NK-39 was the best choice because it offered "much higher thrust, throttling, [and] full reusability," Though the NK-39 would have required significant engine modification and MPS redesign. Aerojet and Orbital were to assess the impacts and cost so a decision could be made before May 1998 on whether to purchase the NK-39 (another alternative was the firm's NK-31, discussed in the next section).[15]

Finally, the presentation noted the following additional issues: 1) the vendor encountered problems with tooling for manufacturing of the composite RP-1 fuel tank; 2) Orbital had changed vendors for fabrication of the second wing; and 3) the low-speed ground-effect tests had slipped due to late contractor deliveries.[16]

X-34 Alternative Engine Considerations

Internal NASA memos written over the late summer and early fall of 1997 indicate that both NASA and Orbital were by then considering alternative engines to the Fastrac. An August 14, memo from Robert E. Whitehead, NASA's Associate Administrator for Aeronautics and Space Transportation Technology, to J. Wayne Littles, Director of NASA Marshall, referenced a "back-up vehicle study that identified several interesting possibilities for future X-34 flight research." Whitehead added:

> Langley aerosciences researchers are particularly enthusiastic about a potential future modification, which could enable the X-34 to conduct flight research at higher altitudes and Mach numbers than are expected to be reached in the X-34 technology demonstration program. If this were so, it would greatly increase the future potential of the second flight vehicle.
>
> The optimism about increased performance is based on information from Aerojet about the Russian [Khrunichev] NK-31 engine. Aerojet describes the NK-31 as a developed and flight-ready reusable engine, throttleable over a broad thrust range up to a maximum thrust on the order of 90,000 pounds [Fastrac

> thrust was 60,000 pounds]. Although that level of performance is considerably more than necessary for the X-34 program itself, it could offer a number of advantages for follow-on research.
>
> The higher maximum thrust would permit hypersonic flight under flow conditions at which considerable uncertainty exists in computational analysis. The higher and variable thrust would provide for sustained flight under a variety of Mach number, Reynolds number, or dynamic pressure conditions. These flights could acquire research-quality data and correlate that data with wind tunnel, computational predictions, or flight data obtained by other means. Since much of the flying could be well below design maximum thrust, the performance margin and the engine's regenerative cooled nozzle might permit an extensive research program requiring only two or three engines.[17]

Whitehead concluded his memo by stating that "[t]he study cost is estimated at $200K, which I would be willing to support once it is clear that the study would not compromise accomplishments of 34/RLV program objectives. In that latter regard, I believe the study should be implemented by Orbital working with Aerojet."[18]

A follow-up note from Bachtel added that Littles spoke with Whitehead and agreed on a three-phase approach to conduct a suitable study:[19]

- *Phase 1:* NASA Marshall would assess existing engines such as the NK-31 to establish candidate engines that could be integrated into the X-34.[20]
- *Phase 2:* NASA Langley would assess "X-34 vehicle performance for the candidate engine(s) coming out of 1 above. This would include an assessment of vehicle-engine compatibility from a flight performance standpoint as well as the ability to enhance future aerosciences flight research."[21]
- *Phase 3:* Orbital would be tasked to conduct an in-depth assessment, if warranted by phases 1 and 2 findings, and eventually submit an implementation proposal. Bachtel proposed a four-person team with Alberto Duarte, of NASA Marshall, serving as team lead and undertaking most of the work. Two of the team members, John Hudiburg and Jimmy Lee, "would be consultants only to minimize impact to the baseline X-34 program."[22]

On September 23, Littles responded:

> I agree that enhancing the X-34 flight performance with as alternate engine, if available, could provide a valuable asset to this

> Agency for aeroscience flight research. Rather than task OSC to investigate alternate engine options, as you suggested, I believe it would be more prudent to perform a preliminary assessment in-house as outlined below. The X-34 program is currently in a critical phase, and the X-34 Program Office believes that initially involving OSC in this type of study would be disruptive to the program.[23]

Littles basically accepted the three-phase approach under the direction of Alberto Duarte, but assigned Davy Haynes to the team to coordinate the NASA Langley activities, and while the team could work with Orbital on a "noninterference" basis, Orbital would only be tasked to conduct a study if the team determined that "a feasible option is evident." Littles anticipated that the study would be completed by February 1998.[24]

On November 6, 1997, Littles reported to Robert Whitehead that, "the NK-31/39 appears to be a viable engine to provide increased performance for aeroscience research applications of the X-34 vehicle. It also appears to be a viable engine to serve as a backup for the Fastrac engine for X-34. Our future assessments will include both applications…. We are initiating a task with Orbital Sciences…to assess potential vehicle impacts for integrating the engine with the vehicle…. [Langley] will establish the viability of the X-34 vehicle/NK-31/39 engine combination to provide the environment required for potential research tasks."[25]

Several NASA Langley engineers also noted, from an aeroscience viewpoint, some possible advantages of using an enhanced propulsion system (such as the NK-31) for the X-34. Charles G. Miller from NASA Langley, pointed out in a note that "[f]rom aerosciences viewpoint, [the] most critical issue is *vehicle instrumentation* to measure surface (i.e., outer mold line (OML) temperature—time histories, surface pressures and vehicle forces and moments (i.e., aeroheating, aeroloads and aerodynamics respectively)."[26] [Emphasis in original.]

Testing requires numerous discrete measurements and sufficient accuracy to benchmark the data. Miller noted that using the NK-31 engine in the X-34 would enhance aeroscience knowledge by enabling the vehicle to fly higher (greater than 250,000 feet), fly faster (to Mach 10 and possibly higher), and to perform flight experiments—as opposed to simply flying the plane. Flying higher would expand the envelope to enter a noncontinuum, or rarefied flow regime, in which computational fluid dynamics is not applicable. Miller added that there were no facilities in the United States that could simulate this regime from an aerodynamic perspective and that flight data would be of tremendous value in bridging these regimes. This also would provide an opportunity to optimize reaction control system capabilities. In regard to flying faster, Miller noted that

> [a]t Mach 10, [the X-34 would be] beginning to enter real-gas regime where oxygen begins to dissociate and NO is formed. This early stage of dissociation in regions of high temperature (e.g., nose, wing leading edge, deflected control surfaces) coupled with vibrational excitation can alter pressure distributions (increase surface pressure in compression and significantly decrease surface pressure in expansion) on vehicle and thus alter aerodynamics (e.g., orbiter pitch-up anomaly). Also, real-gas effects alter heating…. Flying faster pushes the envelope for advanced TPS performance [and] [e]stablishes limits for blankets and for ceramic and, particularly, *metallic* TPS materials. TPS design is conservative as a turbulent boundary layer was assumed for entire trajectory. Thus, may be able to withstand laminar-heating levels at Mach 10 or beyond. Heat loads may be different story—may require thicker materials."[27]

Performing flight experiments and tests would have pushed margins to verify the accuracy of wind tunnel simulations and/or CFD predictions, and Miller added (in somewhat cryptic veritable stream-of-consciousness recital for non-specialists):

> Fly constant Mach number trajectory; expand range of Reynolds number both down into the laminar slip regime and up well into the hypersonic turbulent boundary layer regime. Fly constant dynamic pressure trajectory (is 1200–1500 psf possible for short duration?) as required for meaningful air-breathing experiments. Vary attitude (i.e., angles of attack and sideslip) aggressively to vary aerothermodynamic behavior (slender body at low alpha [alpha = angle of attack (α)]; moderately blunt body at high alpha) including shock-shock interactions (e.g., fuselage-wing shock [shock impingement on another shock]). Fly trajectories that provide well-defined "pure laminar" flow everywhere over vehicle, which is crucial for meaningful CFD validation. Fly trajectory whereby the boundary layer is laminar at high altitude-velocity, becomes transitional to turbulent at lower altitudes, and is boosted in velocity again to *re-laminarize*—a first in flight? Search for hysteresis at hypersonic conditions due to change in

> flow separation and reattachment, leeside vortices, and boundary layer—shear layer transition.[28]

In concluding, Miller wrote that

> These are ideas that floated to the surface in a 15–20-minute discussion by Ken Sutton, John Paulson, and I. As a last comment, the return to the aeroscience community would be enhanced by orders of magnitude if qualitative and particularly quantitative *global* surface measurements could be achieved. For example, if time histories of infrared emission images could be measured on the windward or leeward surfaces from which global surface temperatures could be inferred. The capability to perform such measurements may reside in other Government organizations. Wireless sensors offering increased numbers and flexibility over conventional measurement techniques would also greatly enhance the return. Can the X-34 be a test bed for the testing of such sensors?[29]

A May 20, 1998, Space Transportation Program overview of the NK-39 engine for potential use in the X-34 noted that the final engine report had been received from Orbital and Aerojet on April 30. The ground rules for the study included the following requirements:

- There should be no adverse effects on the first planned launch date of the X-34.
- Either engine must be able to be used on either vehicle.
- No changes to the Outer Mold Line of the vehicle should be made.
- The Fastrac engine would remain the prime means of propulsion for the first flight.
- All proposed changes and impact on the X-34 vehicle must be shown by subsystem to include cost and schedule, as well as technical considerations.[30]

The cost and schedule were requested for two different scenarios. The first was for the purchase of three engines (two flight-rated and one development) with Aerojet serving as a subcontractor to Orbital. The second was for the purchase of three engines with an option to purchase two more. A further indication of interest within NASA in using these engines for the X-34 was the following handwritten notation on the overview document: "Have Aerojet price the import of all 5 engines."[31]

Under this plan, Orbital was to provide

- the engine design for the vehicle to incorporate the Russian NK-39 engine;

- preparation of both vehicles to accommodate either engine;
- support for Aerojet in the development of the Interface Control Document for using the NK-39 engine in the X-34;
- the required hardware; and
- the analysis and engine support necessary to assure vehicle operation with the NK-39 engine.

Aerojet was to provide

- the arrangements for purchasing the engines;
- support to Orbital for integration of the engine into the vehicle;
- the Americanization of the engines (for example, new sensors, electronics, Pyro igniter, and solenoid valves);
- testing of the engines at Aerojet;
- transportation of the engines and ground support system; and
- flight support.[32]

The two primary technical issues for using the NK-39 were the "ability of Orbital to incorporate the changes needed with the limited manpower they have and hold schedule," and the detailed work that could cause delays in the build-up and scarring of both vehicles.[33] This detailed work included design of the new bulkhead, rework of the tress analysis that could impact vehicle design, rework of the heat shield, interface between the engine controller and the flight computer, and Aerojet's work assessing the different loads during flight and landing. The total cost, based on three engines, was estimated at $8.5 million for Orbital and $13.2 million for Aerojet.[34]

Program Status as of February 1998: A Summary Review

As part of the Lead Center presentation outlining the contract modification, NASA's Space Transportation Program staff outlined the current X-34 program status as follows.

- Over 850 hours of wind tunnel testing had been completed.
- Orbital had selected all major vendors.
- A system "design freeze" had been completed in May 1997.
- A new flight termination system concept had been approved by the test range.
- The fuselage skin panel assembly had been completed in October 1997.
- The arc-jet testing of TPS blankets and leading-edge tiles had been completed in December 1997.
- The tank simulators had been completed in December 1997.
- The static loads test fixture had been completed in December 1997.
- The main propulsion system Critical Design Review (CDR) had been completed in December 1997.

- The LOX qualification tank had been delivered for start of testing in February 1998.
- The nose landing gear had been delivered in February 1998.
- An [Environmental Assessment] had been initiated for Eastern Range operations in February 1998.
- Meyer II Team aeroscience experiments had been completed February 1998.

Soon after the completion of the first contact modification, NASA presented the X-34 program "lessons learned," which will be reviewed in the following section.

May 1998: First Compilation of Initial Lessons Learned

By May 1998, NASA was near the midpoint of the X-34 program, and was evaluating the lessons learned up to that point. In a presentation forwarded to Gary Payton by NASA's Program Office, the following lessons learned were noted:

- *Fixed-price contracts for programs having a tight schedule can create many management problems.* For example, the contractor might accept schedule if the contractor thinks it will avoid increased costs or the contractor might be reticent to commit additional resources to resolve schedule problems.
- *Small Government program offices work if they have the right personnel.* Program offices must be staffed with people who can work at different management paradigms from those they might have been taught. In addition, Government personnel must be willing to trust the contractor in more areas than in the past and the staff must have the support of management to resist the temptation of using traditional Government oversight processes and organizations.
- *Trusting the contractor to get the task done right will work provided the right contractor is selected.* In this regard, past performance of the potential contractor is an important consideration.
- *Selecting a small company is a double-edged sword.* The benefits are that they are more likely to be innovative and not tied to past practices that are part of the problem. The liabilities, however, are that they are less of a known quantity and might lack the resources to successfully complete the program.
- *Once management is committed to "faster, better, cheaper," they must stay the course throughout the life of the program*.
- *Use of Government personnel as subcontractors to industry contractors does work, but the Government personnel must follow the concept that industry, not the Government, is the customer*.

- *The Government program office must avoid placing itself in the middle between the industry prime contractor and the industry subcontractors.*
- *Government-furnished equipment will work, provided it is ready in a timely manner and managing technical interfaces between the Government and the industry contractors are avoided.*
- *Government-funded programs should not run in parallel to contractor development programs.*
- *The contract or cooperative agreement should have sufficient budget and detailed technical requirements provided up front in order to avoid costly and painful contract renegotiations downstream.*
- *The Government program office needs to be on site with the prime contractor in order to facilitate timely decisions and to maintain a proper level of oversight.*
- *Adopting contractor procedures and standards instead of passing down NASA requirements has worked well.*
- *Time should be taken to do a short-phase A/B study before initiating the development program.*
- *Milestones for payment have proven to be effective, but the milestones must be well-defined, measurable, and indicative of program progress.*[35]

May 1998: X-34 Safety and Mission Assurance Review

On April 7, 1998, Frederick D. Gregory, NASA's Associate Administrator for Safety and Mission Assurance Processes requested a 2-day meeting at Orbital "in order to review and discuss current X-34 program and S&MA [Safety and Mission Assurance] activities." The review was to "encompass NASA required plans and documentation as well as implementation of OSC flight assurance requirements." Gregory added that "[t]he review will also enable NASA to assume an advocacy role for third party indemnification of contractors conducting NASA X-program research and development activity."[36]

NASA's Office of Safety and Mission Assurance (OSMA) conducted the requested S&MA review in May 1998. The stated purpose of the review was "to assure public safety, exercise care in management of financial resources, and promote the likelihood of achieving mission success."[37] "The objectives of the S&MA review were to: attain *process level insight* into the X-34 Program; understand the S&MA and Risk Management processes employed by Orbital Sciences Corporation in the X-34 vehicle design, manufacture, and operation; understand the S&MA processes employed by NASA/MSFC [NASA Marshall] in the development of the FASTRAC engine; [and] understand S&MA issues related to the X-34 program."[38] The review staff included representatives from NASA Headquarters, program offices and Centers, the White Sands Missile Range, and the United States Air Force 45th Space Wing at

Cape Canaveral Air Force Station, as well as observers from NASA's Office of Inspector General and the Aerospace Safety Advisory Panel.

The review reaffirmed the following very detailed demonstration objectives and technologies of the X-34 program:

- Integration of new technologies
- 25 test flights over a period of 1 year
- Autonomous flight operations
- Safe abort capability
- Technology demonstration throughout the flight profile
- Subsonic and hypersonic flight
- Powered flight to at least 250,000 feet
- Speeds of up to Mach 8
- Advanced RLV technology demonstration
- Composite structures (aero, prime airframe, and thrust structures)
- Composite propellant tanks and cryo insulation.
- Advanced low-cost avionics (GPS and INS).
- Rapid low-cost flight software development tools.
- Integrated vehicle health monitoring.
- Ability to attain average recurring flight cost.
- Adaptable as low Mach number test bed (embedded, attached, or deployed), e.g., Rocket-Based Combined Cycle; Plug Nozzle; Pulse detonation wave; dual bell expansion engine.[39]

The S&MA review report likewise provided the following detailed list of X-34 key technologies:

- Composite primary and secondary airframe structures.
- Composite airframe including primary, aerosurfaces, and thrust structures.
- High margin structure designed to require minimal inspection, with modular design and numerous access ports for maintainability.
- Composite reusable propellant tanks, cryogenic insulation, and propulsion system.
- Advanced thermal protection systems and materials.
- Low-cost, low-weight thermal protection systems and materials on the leading edges and other critical heating areas.
- Low-cost flight proven avionics including differential GPS and integrated GPS/INS.
- Integrated vehicle health monitoring systems.
- Flush air data system.
- Platform for demonstration of "added on" or additional experiments.
- Low cost-to-manufacture engine [i.e., Fastrac].[40]

The report added that the original fixed-price contract was for $49,540,584, which included Government Task Agreements of $9,631,433 for performance through February 9, 1999. As of the June 1998 review, the budget with the latest change of scope modifications totaled $75,165,938, including $11,843,083 in Government Task Agreements.

Regarding the "faster, better, cheaper" aspect of the program, the S&MA review stated that

> the X-34 Program is an excellent example of the Better/Faster/Cheaper concurrent engineering environment where large formal board meetings (Configuration Control, Engineering Change, etc.) are replaced with more numerous small meetings, formal and informal, where design and manufacturing issues are resolved. The key to making this work is a central configuration management system, shared CAD [computer-aided design] tool suite, and a process [that] everyone seems to understand. The X-34 Program has three regularly scheduled weekly meetings which provide a relatively "short cycle" risk management/program management control process. The OSC [Orbital] FA [Flight Assurance] manager attends all of these meetings…. OSC does not have a formal risk-management plan for the X-34 program. However, all of steps of an adequate risk-management process are in place and functioning; these include risk identification, analysis, planning, tracking, controlling, and documentation and communication. Risk identification includes safety risks from the FMECA [failure modes and effects analysis], hazard analysis, and fault tree analysis provided by Flight Assurance; contact/schedule/cost/risks from Weekly Management Reviews; and current and potential risks from Weekly Management Reviews; and current and potential risks from Weekly Engineering Meetings.[41]

As noted, part of the program's ongoing review process included the Independent Technical Assessment Advisory Group that was formed at NASA Langley and was chaired by Darrell Branscome. In addition to participating in the December 1996 Outer Mold Line Freeze, the team also was involved in the System Design Freeze that followed in May 1997.

Another review team, chaired by Robert Meyer from NASA Dryden, evaluated risk-reduction approaches and assessed the merit of conducting the optional test program. This team also reviewed the X-34 aeroscience experiments and operations technologies opportunities. This review was completed in April 1998.

Finally, Orbital conducted a separate independent review of the X-34's wing design. Quartas Engineering performed this review, which took place between December 1997 and May 1998. The review team determined that the overall wing design was sound. Orbital also established an internal "Flight Assurance Advisory Board" that reported to Antonio Elias, Orbital's senior vice president. The purpose of this board was to advise Orbital "on issues of safety and mission assurance relative to the various flight projects…." In addition, Orbital formed another internal assessment team designated as the "Blue Team" that, to date, had "participated in each major program review (i.e., System Requirement Review, Outer Mold Line Freeze, and System Design Freeze)…." This team consisted of members from Orbital and NASA Marshall who were not directly involved in the X-34 program.[42]

The findings included the following:

> The review team found that key S&MA processes are in place, and are being implemented in a successful fashion. The team observed that the X-34 is innovative in many ways, "an experiment in management as well as technology," as noted by the OSC [Orbital Sciences Corporation] program manager Dr. Robert Lindberg. The program is very lean (less than 60 people) with three full-time dedicated S&MA staff. Many S&MA functions are managed through OSC corporate-matrix support and task agreements with government entities (NASA, Army, Air Force). This unique approach has the potential for increasing vulnerability. The NASA MSFC X-34 program and MSFC DMA must focus insight efforts to assure follow-through in implementation of the S&MA processes and to assure that proper staffing levels and skill mixes are maintained, especially if the program implements the optional flight test program….
>
> The review team observed that the NASA MSFC S&MA insight role is unnecessarily complicated by an inherent conflict of interest from the assignment of a single individual to simultaneously assume three oversight/insight roles: subcontractor to OSC on the Main Propulsion System development; insight-consultant to the NASA X-34 program manager (over OSC), and oversight to the MSFC FASTRAC engine program. The report recommends that this situation be remedied to assure a smoother and more effective implementation of insight responsibilities….
>
> It was also observed that the integration of the NASA-furnished FASTRAC engine with the X-34 airframe posed some management challenges for both OSC and NASA program managers.

> Concerns were raised that S&MA interfaces were not clearly understood and that increased communication and cooperation among the parties was essential to ultimate success.... The review team also noted that the current X-34 flight test approach calls for an abrupt expansion of the performance envelope from Mach 2.6 to Mach 8. This approach poses increased risk as compared with a more incremental approach.[43]

The report concluded that

> [t]he [S&MA] process-level view is positive. The NASA/Orbital Sciences X-34 Better/Faster/Cheaper program is on the right path. However, vigilance (by all parties) is necessary to assure the continued success of the program. Ongoing insight must assure that fundamentally sound [S&MA] processes are being implemented throughout the program life-cycle.[44]

September 1998: X-34 Comes Under Congressional Scrutiny

Despite the favorable Safety and Mission Assurance review and the promulgation of the initial lessons learned reviewed previously, NASA was once again debating continuation of the X-34 program, based on a number of congressional letters sent to Daniel Goldin in September 1998.

In a particularly strongly worded letter sent on September 18, Senator Charles S. Robb and Representatives Tom Davis III and Frank R. Wolf, all from Virginia (home to NASA's Langley Research Center and NASA Wallops Flight Facility, as well as Orbital Sciences Corporation), wrote that "It is our understanding that NASA is considering premature termination of this valuable and cost-effective program as part of the FY00 budget exercise. We would like to clearly state for the record our objections to such an action."[45]

Senator Robb and Representatives Davis and Wolf added that

> the X-34, along with the X-33 form the backbone of this nation's RLV program, for which NASA has ultimate responsibility as dictated by national policy and consistent legislative support. The X-34 program is a key step in developing technologies for this nation's next generation of space transportation vehicles. Results obtained through the research conducted by the planned 25 flights of the X-34 will establish the viability of new RLV technologies tested through a realistic life cycle in realistic environment. By achieving a routine flight rate of once per two weeks with an

> operations team of less than two dozen people, the X-34 program will validate a low-cost approach to operations. This achievement is critical to the decision by industry and NASA to commit to a generation of operational RLVs that will reduce today's launch costs by a factor of two or three.
>
> Industry has already proposed over 25 technology experiments to be flown on the X-34, and NASA has selected seven for flight, including two international experiments. Early termination of the X-34 program, before the industry/government team can address these critical technology questions, is unwarranted and will result in NASA not achieving any of the program's objectives.
>
> In light of current budgetary constraints, you have insisted, rightly, that industry execute NASA programs within budget; X-34 is an excellent example of effective cost management, with less than 2% real growth in program cost. Last year you sought our support for investment in a second X-34 vehicle, citing the important research that could be achieved with a robust low-cost demonstrator program; we endorsed your recommendation. In addition, you have continually encouraged industry to share in the investment to develop a next generation of RLVs. The X-33 and X-34 prime contractors have answered that challenge. If NASA now terminates its commitment, it will send a clear message to industry that NASA is not a reliable partner in such ventures.[46]

Ten days later, Rep. Dave Weldon, of Florida, Vice Chairman of the House Space Subcommittee, sent a similar later to Daniel Goldin and, like Davis, Wolf, and Robb, requested a briefing on the status of the X-34 program and future funding plans.[47]

Further indicating that NASA was already having second thoughts about the X-34 program, NASA requested its Office of Inspector General to conduct an audit of the X-34 program. In a September 3 fax that John London, NASA X-34 program manager, sent to Bob Lindberg, Orbital's X-34 program manager, and Curt Shoffner, also with Orbital, London advised that he had received

> a letter this morning from Code W that is calling for an audit of the X-34 Program, [and that] [s]pecifically, sub-objectives of the audit include, but are not limited to, determining whether:
>
> 1. Orbital Sciences Corporation is fulfilling its obligations under the contract;

> 2. Key technologies are being identified and tested in accordance with milestones;
> 3. NASA's process for transferring X-34 technology is effective.[48]
>
> London added, "I am taking this inquiry very seriously, and am operating under the assumption that this is tied to the recent questions and deliberations we have had with HQ about the program."[49]

There was something else endangering support for X-34 as well. On September 2, Spence M. "Sam" Armstrong, the highly regarded retired Air Force general (and former vice commander of Air Force Systems Command) who served as NASA's Associate Administrator for the office of Aeronautics and Space Transportation Technology (Code R), announced a reorganization that took X-34 champion Gary Payton out of space and placed him within NASA's aeronautics enterprise.

Until then, Payton had been a vigorous supporter of SSTO approaches to spaceflight, and had headed the advanced space transportation programs, including both the X-33 and X-34. "The change," NASA historian Judy Rumerman concluded, "seriously jeopardized the status of the program within the NASA hierarchy."[50] The reorganization, *Aerospace Daily* reported, "raised the hackles" of Rep. Dana Rohrabacher of California, who, as discussed previously, was a long-time space flight champion (and particularly of single-stage-to-orbit technology). Rohrabacher promptly wrote to Administrator Daniel Goldin to personally convey his own dissatisfaction with the decision.[51]

NASA Marshall's official notice of the program office realignment came on November 18, from A. G. Stephenson, director of NASA Marshall. Stephenson stated that, "[t]he Office of Aerospace Technology recently realigned the space transportation programs assigned to the Marshall Space Flight Center to provide consistency in the distinction between programs and projects and to add a new program for Future-X. As a result, the X-34 program is now considered a project under the new Future-X Pathfinder program." Stephen added that he was appointing John London, who previously served as manager of the X-34 program, as manager of the new Future-X Pathfinder Program Office. London also was to continue as acting manager of the X-34 project until a replacement was selected.[52]

February 1999: "NASA Must Lead!" The *Access to Space* Crisis Report

While the X-34 program team vigorously pressed ahead even as NASA's leadership and Congress puzzled out its position regarding X-34, the Agency's Space Transportation Subcommittee issued a sobering report on the access to space crisis facing America. The subcommittee, established in 1995, noted that, "America's future in space is at a critical decision point. Positive action is needed now on low-cost, reliable access to space. The nation urgently needs firm NASA leadership on this top priority space issue."[53]

The subcommittee urged both setting a program termination date for the Space Shuttle and formulating an alternate two-stage-to-orbit plan in case the single-stage-to-orbit program was unsuccessful and made the following recommendations:

- NASA should plan and lead the transition to low-cost, reliable manned access to space by taking three actions:
    1. Ceasing any expenditure on major performance upgrades for the Shuttle, such as liquid fly-back boosters (LFBB), reusable first stages (RFS), or five-segment reusable solid rocket boosters.
    2. Limiting future Shuttle upgrades solely to those necessary for safety.
    3. Committing now to near-term establishment of an approximate terminal date for Shuttle operations, and planning an orderly phase-down of Shuttle infrastructure.
- The history of major national programs clearly shows that it is not possible for the country simultaneously to continue upgrading an old system while developing/producing its successor. Additionally, the immense clout and perceived high priority of an open-ended, Government-funded, multibillion-dollar Shuttle program simply disables serious industry commitment to competition for a replacement. NASA must plan and lead this next-generation competition, rather than fund major Shuttle improvements while waiting for an industry-generated successor to appear.
- To provide the nation with possible alternatives to VentureStar, NASA should actively reshape the existing billion-dollar funding wedge in FY 2000–2004 into creative Government-industry programs. Most essential is a vehicle which employs robust two-stage-to-orbit (TSTO) technology in event SSTO is not viable in the near-term. In every case the operational capability date of the manned access-to-space replacement should be as early as possible in the 2000–2010 decade.[54]

In regard to this last recommendation, the subcommittee noted that the

> X-33/VentureStar is a well-conceived program; but there is considerable technical risk in VentureStar's SSTO objective, and there is considerable business risk in VentureStar's commercial funding objective. It is no longer prudent *not* to have a viable, low-cost backup. It is NASA's responsibility to stimulate immediate shaping of practical, robust, RLV alternatives using available

> technology. If progress is to be made in the vital national goal of low-cost manned access to space, NASA must lead![55, 56] [Emphasis in original.]

The subsequent collapse of the X-33 program calls into question the subcommittee's conclusion that it had been "well-conceived," although the subcommittee redeemed itself somewhat by quite rightly pointing out the "considerable technical risk" inherent to the program.

If critical of continued investment in Shuttle and cautious about the X-33, the subcommittee's conclusions were a comfort to X-34 partisans, for it was exactly the kind of "viable, low-cost backup" the subcommittee had recommended the Agency vigorously pursue.

NASA's Integrated Space Transportation Plan

During the fall of 1999, while of the Office of Inspector General's X-34 project review was underway and just preceding the final X-34 project restructuring, NASA was laying the groundwork for the follow-on project, the Space Launch Initiative (SLI). This effort, known as the Integrated Space Transportation Plan (ISTP), subsequently formed the basis for NASA's Space Launch Initiative.

The ISTP consisted of several Space Transportation Architecture Studies (STAS I, II, and III) that "identified requirements, developed candidate architectures, and identified sets of technologies to enable those architectures."[57] The ISTP studies were undertaken as a partnership between NASA and industry to identify architectures—including new designs and shuttle-derived concepts—for second-generation reusable launch vehicles that were planned to reach first operational capability in 2010. The goal set for the second-generation program was "placing payloads in low Earth orbit (LEO) at a cost of $1,000/lbm [pounds-mass], and a safety goal of $1/10{,}000$ probability of loss of crew."[58] The second-generation program, however, was not to identify or select any specific launch system. Architecture development would be the responsibility of prospective bidders planned for a 2005 competition.[59]

The next program phase was planned to be the third-generation RLV, which was scheduled to become operational by 2025. The third-generation RLV launch system would call for delivering "payloads to LEO at $100/lbm and approach airline-like reliability and safety, with a $1/10^6$ probability of loss of crew." The third-generation was to involve significant effort "to develop advanced on-orbit capabilities and conduct research into more exotic 'fourth-generation' technologies."[60]

The SLI program also sought to provide a near-term alternative to the Space Shuttle for providing payload delivery to the International Space Station (ISS). The alternative effort was to focus on "smaller payload classes than Shuttle, in the range of several hundred to a few thousand pounds, and [would be] uncrewed." The launchers for this effort would depend on "present or near-term technologies which can be readied in time to support the initial capability date [including] expendable, partially reusable, and fully reusable architectures."[61]

In March 2000—the same month that NASA's Office of Inspector General released its report on the X-34—NASA published the Research Announcement for the Second Generation RLV Risk Reduction Definition Program. *SpaceDaily* quoted Dr. John "Row" Rogacki, director of NASA Marshall's Space Transportation Directorate, in regard to the ongoing RLV efforts:

> In the last several years [obviously referring to the DC-XA, X-33, and X-34 programs] NASA has initiated several technology demonstrator programs…. We've invested in specific concepts. We've partnered heavily with industry on aggressive technology programs. We've made great progress and obtained much insight into promising emerging technologies…. However, NASA has encountered difficult lessons and delays in key technology projects…. We've learned that more development is needed. We've learned that commercial markets are not growing as previously projected…This [new] effort is part of the Administration's Space Launch Initiative intended to target these changes.[62]

March 2000: NASA's Inspector General Assesses the Future RLV Effort

From February through December 1999, NASA's Office of Inspector General reviewed the status of the X-34 Technology Demonstrator Project. The OIG noted, by way of background, that "[t]he X-34 Project is one of the three original 'stepping stones' (DC-XA, X-34, and X-34) in Marshall Space Flight Center's Program, and is the first in a series of planned Pathfinder class technology demonstrators managed by Marshall's new Future-X/Pathfinder Program Office." The OIG defined a Pathfinder program as follows: "Pathfinder class technology demonstrators are technology-focused flight vehicle projects within the Future-X/Pathfinder Program and generally cost less than $100 million each." It should be noted that the same background section also revealed that the X-34 project cost had already totaled "about $186 million" as of November 1999.[63]

Also, significantly more funding would be needed to complete the project. This funding issue for what was now a Pathfinder project, combined with the restructuring of the project and the reduction of Gary Payton's role in it, raises the question of whether or not NASA had at this time set the stage for ending the X-34 project. In further support of this possibility, it should be noted that the overall objective of the OIG review as stated in the executive summary, was "to assess the status of the X-34 Technology Demonstrator Project, through fiscal year (FY) 1999, in meeting technology requirements for the next-generation RLV."[64] To this overall objective, however, the OIG added that "[t]o evaluate NASA's planned use of X-34 technologies, it was necessary that our review also address strategic planning for Space Transportation and the role the X-34 was expected to play in meeting Agency Space Transportation technology requirements."[65] The role of the X-34 had already been determined under the X-34's previous program status.

In Appendix B to the audit report, the OIG presented the following overview regarding the need for a cheaper post-Space Shuttle launch vehicle.

> Since the 1970s, NASA has searched for a cheaper launch vehicle, which led to the decision to build the Space Shuttle. Although the original intent of the Space Shuttle Program was to significantly reduce NASA's cost of access to space, the Shuttle has not come close to the flight rates (as high as 57 flights annually) anticipated early in the program. The Shuttle fleet is currently able to sustain only about seven or eight flights per year, and the maximum flights in any one year was nine (1985). As a result, the Shuttle has proven expensive to launch (about $300–$500 million per launch depending on the number of flights lunched annually), and NASA has spent much of the last decade looking for a way to reduce launch costs. NASA's original goal of reducing the launch cost from $10,000 per pound to $1,000 per pound by 2006 may not be realized until 2010–2011 or later.
>
> NASA's *Access to Space* study in 1993 determined that an RLV offered advantages over use of an expendable launch vehicle. Specifically, while the development and production costs of an expendable launch vehicle primarily determine launch costs, the cost of launching an RLV is determined mainly by the number of times the RLV can be used. A higher flight rate for an RLV allows better amortization of the development costs, resulting in a lower overall cost per flight.
>
> The fact that the Shuttle has not been successful in significantly reducing launch costs has lead [sic] to increased concern by Congress and OMB [Office of Management and Budget]…that NASA find a solution. NASA expected to make a decision before December 31, 2000, on an RLV to replace the Shuttle. [but] According to a NASA in-house study completed in February 1999, "Not enough knowledge is available today to commit to a Shuttle

> replacement," NASA simply does not have the technology(s) at this time to support the decision. It is unlikely that NASA can make the decision prior to 2002 or 2003 at the earliest, and it may be the middle of the next decade before an informed decision can be made.[66, 67]

In starting its assessment, the OIG also noted that NASA Marshall managed the X-34 program as part its responsibilities as the Lead Center for Space Transportation, and that NASA's Headquarters Office of Aerospace Technology managed the overall Agency Transportation mission. The OIG estimated that the cost of the X-34 project totaled about $186 million as of November 1999. The estimated cost included $18.6 million for the Fastrac engine and approximately $2 million in experiments. This assessment covered the X-34 program through the end of fiscal year 1999, which preceded NASA's replanning effort that followed the OIG review.[68]

The OIG's report included the following overall findings:

- NASA was unable to adequately monitor the successes of the X-34 project;
- NASA's implementation of the National Space Transportation Policy focused on private industry requirements and failed to properly recognize the Agency's requirements to identify technology requirements; and
- there was a lack of consensus regarding the future plans for space transportation.[69]

In regard to NASA's failure to monitor the project successes, the OIG report noted that

> NASA Strategic Plans for FYs 1996, 1998, and 1999 [there was no 1997 plan], and the NASA FY 1999 Performance Plan did not adequately define the role of the X-34 in meeting Space Transportation technology requirements for the next-generation RLV. The plans, prepared by the Office of Aerospace Technology, do not state how, when, or if technologies addressed by the X-34 Project will be used to satisfy Space Transportation technology needs. The Agency's FY's 1998 and 1999 strategic plans for Space Transportation did not provide appropriate implementing strategies stating how goals and objectives would be achieved and did not include appropriate implementing strategies with performance indicators and an evaluation process to measure progress and to address resource requirements.[70]

On NASA's failure to adequately identify technology requirements, the OIG noted that

> [w]e believe NASA's implementation of the Space Transportation Policy [footnote deleted] guidance in 1994 placed too much dependence on industry to identify requirements and insufficient recognition of the Agency's needs to carry out assigned missions in science and human exploration of space. The Policy tasked NASA to "…be the lead Agency for technology development for the next generation reusable space transportation systems…." As the lead Government agency responsible for civil space transportation, NASA should, with industry input, take the lead in defining technology requirements for the next-generation RLV, recognizing both industry and NASA requirements.[71]

Finally, in reference to a lack of consensus, the OIG added that

> NASA officials told us a major stumbling block to Agency preparedness of an acceptable strategic plan for Space Transportation in recent years has been a lack of consensus within the Agency and between NASA and private industry on the future of Space Transportation and the specific solution to high launch costs. The officials stated some elements of the Agency were not receptive to anything less than a Shuttle-derived, next generation RLV. Marshall officials told us that the Space Transportation Architecture Study became bogged down in the second quarter of calendar year 1999, during our review, due to a lack of consensus within NASA regarding the future plans for Space Transportation. One difficulty was reaching agreement on the extent to which Agency launch requirements, as opposed to industry requirements should be recognized.[72]

The X-34 Inspector General Audit included 16 recommendations:

1. Improve the Agency's strategic planning documents to, at a minimum, specify goals that support mission statements—including results-oriented, measurable objectives that state how the goals and objectives will be achieved.
2. Prepare an Enterprise Strategic Plan and establish procedures to review the plan annually.

3. Implement an appropriate cost/benefit analysis process and an investment strategy to implement Space Transportation strategic plans to ensure the effective use of resources.
4. Define technology requirements for the next-generation RLV using metrics that will facilitate measuring and reporting incremental progress.
5. The Marshall Center director should issue a Lead Center implementation plan on Space Transportation that identifies requirements, objectives, and implementing strategies.
6. The Marshall Center director should establish mission-specific requirements for X-34 flight tests, determine the minimum number of flights required to satisfy X-34 project objectives, and delete those flights that are not justified.
7. The Marshall Center director should implement internal controls to appropriately document management decisions, including changes to the proposed flight test program.
8. The Marshall Center director should cancel the proposed expansion of the flight test program until justification for the existing 27-flight test program has been reassessed and the total number of flights needed to meet project objectives have been determined and revalidated.
9. The Marshall Center director should reassess the number of Fastrac engines required to support the X-34 project based on the reassessment of test flight requirements for the X-34 and on engine reliability tests.
10. The Associate Administrator, Office of Aerospace Technology, and the Marshall Center director should finalize all required program documentation for the X-34 and Future-X/Pathfinder.
11. The Associate Administrator and Marshall Center Director should revise the existing draft program commitment and draft to define appropriate technology requirements and expected results/benefits.
12. The Associate Administrator should establish internal control procedures within the Enterprise's program division to ensure that responsible Centers submit required program/project documentation during the program formulation process.
13. The Associate Administrator should discontinue the practice of approving programs and projects for which Program Commitment Agreements and program/project plans are not yet prepared or approved.
14. The Associate Administrator should require Centers to clearly identify in program documentation the approximate technology requirements, expected results/benefits, and performance metrics for

evaluating actual results and to establish internal control procedures to ensure that the documentation effectively implements Enterprise strategic plans.

15. The Marshall Center director should establish internal controls to ensure that solicitations are not issued on programs/projects for which program documentation is not complete.
16. The Marshall Center director should place added emphasis on compliance with program documentation requirements specified in Agency directives and ensure that programs and projects prepare documentation in a timely manner.[73]

NASA generally concurred with the findings and recommendations contained in the audit.

The OIG report acknowledged that their review was conducted prior to NASA's initiation in early 2000 of a "replanning effort" to improve X-34 risk mitigation Finally, the OIG recognized that

> [s]everal aspects of the X-34 have undergone change since the X-34 Project (formerly "Program") was initiated in 1995. These continual changes have had a significant effect on the X-34 Project's cost, schedule, and potential results. For example, although the X-34 first flight (current project) was to have occurred on November 21, 1998, the first flight is now planned for March 2000 or later. The proposed X-34 flight test program was still undergoing change (flight trajectories, etc.) as of November 1999. It is anticipated there will be still more changes in the Project.[74] [And indeed there were.]

2000: The X-34 Project Restructure Plan

NASA's decision to restructure the X-34 Project due to the Agency's view that the existing plan represented "unacceptable risks," occurred well after work was underway and represented significant changes that went beyond the original program/project objectives. The restructuring plan was outlined in a June 9, 2000, presentation that included the following issues: project management shortfalls, lack of a Main Propulsion Test Article, single string avionics and lack of human-in-the-loop, MC-1 (Fastrac) engine immaturity, and what was presented as "other" concerns. As a remedy, NASA implemented the following project management actions: the project office was reorganized, and organization chart defined including merging the MC-1 and X-34 projects into one integrated development program, project requirements were defined, new Orbital project management was initiated, new success criteria defined, and various other plans and activities were undertaken.[75]

Findings relating to the Propulsion Test Article included a lack of an integrated propulsion system test until late in the project, which posed a serious risk to cost, schedule, and mission success. Findings regarding the avionics noted that a "single string avionics system for powered flight poses unacceptable level of risk to vehicle mission success" and that human-in-the-loop was desirable to save the vehicle. MC-1 engine concerns included insufficient engine development through certification testing as well as specific design issues. To remedy the engine problem, NASA increased the total number of tests from 90 to 125 (40 tests had already been conducted) and design changes were implemented. A "tip to tail" vehicle review was scheduled for July 2000, and additional vehicle-level testing and hydraulic systems enhancements were directed.[76] Overall objectives of the restructured program called for safety for all phases of flight-testing, including protection of the public and public property, protection of non-mission and mission personnel (Government and contractor), and protection of high value assets (Government and nongovernment). The program was re-divided into four phases, with the fourth phase intended to "demonstrate Gen 2 [second generation] and Gen 3 RLV technologies utilizing a highly reliable and robust X-34 vehicle."[77]

Stephen Creech, who served as NASA's first X-34 resident manager and who was involved in the integration policy following the 2000 restructuring, noted that this final restructuring effort took place over a period of months, as opposed to as a series of formal directives. He added that the restructuring represented a "pendulum swing" in risk tolerance at NASA following the Mars mission failures. [78] Indeed, the OIG's recommendations and NASA's project restructuring did represent a "pendulum swing" away from the original X-34 program objectives; risk mitigation plans; industry-led concept; and faster, better, cheaper way of doing business.

On August 24, 2000, *SpaceRef* reported on the actions recommended by the Technical Interchange Meeting held in the spring of that year, noting that "[i]t is all but certain that these new activities will lead to a substantial increase in overall X-34 program cost and a significant delay in accomplishing its goal [adding that] NASA has yet to identify the scope of these costs but it is certain to be a prominent feature of the FY 2002 budget request next year." *SpaceRef* reported further that, "NASA is considering a reduction in the number of flights from the currently planned 27 to perhaps 2 to 6 flights [and that] the maximum speed would also be reduced from the planned speed of Mach 8 down to Mach 2.5." Finally, *SpaceRef* commented on the significant X-34 program change over earlier policy by pointing out that "[t]his is a reversal of NASA's previous thinking process since it revised the original X-34 program to add an additional test vehicle and increase the number of test flights to 27."[79]

Three days after the above release, *SpaceRef* issued a "Space Access Update" on August 27, which made a number of observations and recommendations regarding the SLI funding issue, including that "X-34 should also be completed and flown, but NASA should immediately fund OSC in acquiring the Russian engine they wanted as insurance against further Fastrac problems, and NASA should back off the absurd and unaffordable 'no conspicuous failure is acceptable' position.… This is an experimental vehicle project with three copies of the vehicle; a reasonable level of risk of damage to or loss of one of the vehicles is a good tradeoff for lower cost and quicker results." *SpaceRef* went on to question NASA's way of doing business under the proposed SLI follow-on program, stating that "SLI, as we've been saying all year, should be split into NASA-specific and U.S. commercial support projects, with a solid firewall between the commercial support project and the influence by the major NASA launch consumer centers, lest they once again bend all NASA efforts toward solving their Shuttle-replacement problem at expense of practical engineering support for the US launch industry."[80]

X-34 "Then and Now" Snapshot

Comparison of the previous project with the restructured project illustrates the significant changes that were directed and that changed the project to such extent that successful completion became highly unlikely. These comparisons are reflected in Table 9.1.[81]

X-34 Lessons Learned and Observations Noted by Its Program Managers

In interviews with the author, several X-34 program/project managers and senior NASA officials noted a number of "strategic" lessons learned and problems faced by the X-34 effort. Robert E. Lindberg, Orbital's first program manager of the second X-34 program, stated that fixed-price agreements were not the right arrangements for projects like the X-34 and that you need to "keep the project sold."[82]

Lindberg's criticisms appear to have merit. Orbital was asked to make a number of changes that were not covered in the initial fixed-price cost estimates, and a number of engineers involved noted the need for continued support and encouragement in keeping the program moving forward. John R. London III, who also served as a NASA program manager, added that

- the X-34 was miscast as a reusable launch vehicle, noting that it was actually a hypersonic research vehicle;
- there was not enough funding for the program; and
- changes late in the program, especially regarding redundancy, seriously impacted the X-34.[83]

Table 9.1: X-34 Before and After Restructuring

Previous Project	Restructured Project
Management Philosophy	
Lean project team	Broadened project staff
Limited insight—trust the contractor	Engineering insight team
Rapid, success-oriented development schedule	Primary focus on mission success
Limited testing	Test what we fly, fly what we test
Engine development as separate project	Engine project incorporated into X-34 program
Redundancy via vehicle ("If we crash one, we'll roll out another")	Do the right things to be successful
Implementation	
Bare-bones engine development testing	Robust engine development test matrix
Limited engine certification testing	Expanded engine certification testing
1+2 flight engines (7-use)	1+2 flight engines (2-use)
Late, success-oriented flight readiness firing	Integrated main propulsion test article
No integrated propulsion/engine testing until flight readiness firing	Early cold flow and blow-down main propulsion testing
Single-string avionics	Backup avionics suite to eliminate most critical failures
No ground intervention except flight readiness firing	Ground intervention capability via backup system
Abort options limited to "no light"	Multiple abort options during flight
Autoland validation via first flight	Extensive pre-flight vehicle-in-loop testing and simulation
Limited preflight vehicle verification testing	Surrogate aircraft certification of autoland algorithms
Flight Test Plan	
5 unpowered flights at White Sands	5 unpowered flights at White Sands
8 to 10 powered flights at Dryden	2 powered flights at Dryden
7 operations demonstration flights at KSC	Option for 4 additional flights at Dryden
5 to 7 envelope expansion/experimental up to maximum performance	—
Risk of vehicle loss during program: high	Risk of vehicle loss during program: low

Gary E. Payton, who served as Deputy Associate Administrator for Space Transportation noted that

- it should be the Government's responsibility to develop high risk/high value vehicles;
- projects should not combine too many unproven technology components in one test program; and
- consistency of leadership is needed.[84]

Regarding this last point, it should be noted that the X-34, in an approximately 5-year time period, had four NASA program managers, two Orbital managers, two resident managers, a number of component project managers, as well as several restructurings and transfers between NASA Headquarters offices, numerous internal reviews (each with recommended changes), and finally a 180-degree change in redundancy requirements.

Several of the managers likewise addressed the problem faced in developing reusable launch vehicles. Antonio Elias, Executive Vice President and Chief Technical Officer of Orbital Sciences noted several of these developmental issues. First, he stated that in regard to propulsion, aerospace engineering had already reached a 98 percent chemical energy efficiency level (using hydrogen/kerosene and LOX), and that generating energy by electrical means required too heavy of equipment for use on rockets. Next, he pointed out that the structural efficiency of rockets still basically had not exceeded that of the Atlas rocket, although the use of composite materials had greatly improved the potential capability of reusable vehicles.

Elias also addressed the current potential market and the difficulties of realizing economies of scale. He enumerated six potential market areas. The first and most important was national defense. The last and least important for the United States was national prestige, because the United States had already accomplished what other nations were now attempting to do, such as land astronauts on the Moon. This—according to Elias—left the four following primary areas for potential low-orbit launch of reusable vehicles:

- precision, navigation, and timing (GPS);
- weather forecasting;
- commercial communications; and
- science and technology.

Regarding these four areas, Elias added that Congress was under pressure to support all of the above missions and that NASA, faced with a shrinking budget, had to try to allocate funds to these various projects. Elias also added that economies of scale currently do not exist to support the anticipated usage, based upon current assumptions of how many launches per year would be needed to economically justify the costs of reusable vehicles. He indicated, however, that engineers are generally interested in challenging the highest level of technology, and that is one reason why the search for reusable vehicles continues.[85]

Risk Mitigation, the "Single String" X-34, and Possible Cancellation

As reflected earlier in the chapter, NASA had significant risk mitigation concerns about losing the X-34 vehicle during the testing, which caused the Agency to move away from the original single-string system to a fully redundant flight vehicle. NASA also significantly reduced the number of powered flights, which basically ended the experiment series that had been one of the two primary program objectives.

It is not certain—indeed there is no consensus among program participants—whether the decision to reduce the number of flights was primarily due to budget concerns or to concerns over losing another vehicle following the embarrassing and needless loss of two Mars probes, or to concerns over the lack of throttling capability of the Fastrac engine that would have been a required engine characteristic for conducting some of the experiments with the X-34 vehicles. Obviously at least some combination of these fatally wounded the program. But it is striking how concerned NASA became over the issue of robustness and redundancy.

The initial approved risk-reduction plan for the X-34 program called for the fabrication of an additional vehicle, which was completed, but was, of course, simply another single-string craft. The subsequent decision to add redundancy to the X-34 apparently played a role in the restructuring that required a significant increase in funding (and, of course, caused further schedule slippage) as noted in the NASA FY 2000 Performance Report:

> Early in the year, as a result of concerns over potential safety hazards due to the lack of redundancy in the vehicle control systems, it was determined that the X-34 program should be restructured. A replanning activity was undertaken to address these concerns. It resulted in a determination that a significant amount of additional funding would be required on the part of the Government to meet the revised flight plans. Since making these additional funds available would require the reallocation of resources planned for the Space Launch Initiative (SLI), NASA decided that additional funding for X-34 risk reduction should be completed within the SLI evaluation process.[86]

Against these concerns, program adherents offered various arguments, summarized in a presentation given at NASA Marshall on April 18, 2000, articulating the Center's reasons for continuing the X-34 project:

- NASA Marshall and NASA need a visible success;
- second- and third-generation reusable launch vehicles need a test platform for technology demonstration in relevant environments; and
- project continuation would provide a test bed to demonstrate future RLV technologies in a hypersonic, high altitude flight and operations environment.

The presenter plaintively concluded, "We believe that project cancellation is an unattractive option."[87]

In a June 22 Pathfinder Program Review of the X-34 and the X-37, John R. London noted the program's current status:

- A-1A unpowered vehicle complete and on the runway at Edwards AFB with a series of captive-carry flights and high-speed tow tests underway.
- A-2 powered vehicle complete and undergoing tests at Orbital's Dulles facility.
- A-3 airframe essentially complete at Orbital's Dulles facility.
- MC-1 (Fastrac) engine testing continuing at Rocketdyne's California facility with 45 hot-fire tests already completed at the Stennis Space Center.[88]

London added that the restructuring effort then underway could possibly lead to an increase in ground testing for the engine and vehicle, avionics modules, and new Propulsion Test Article or to refocusing the project to support the "Second Generation Program." This hint of the X-34's future came to pass, as the restructuring of the project—which made continued funding of the X-34 dependent on the follow-on Space Launch Initiative—signaled the end to the reusable launch vehicle program. That sad dénouement is reviewed in the final chapter of this book.

Endnotes

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3. Paul F. Holloway memo from the chairman of the X-34 Technical Advisory Group to NASA Marshall X-34 Program Manager, January 2, 1997, pp. 1–2, box 3, record no. 18560, NASA Headquarters History Office, Washington, DC.
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5. Ibid.
6. Ibid.
7. Ibid.
8. The A-1 vehicle was later upgraded to a flight status vehicle, although the first power flight was still scheduled to use the A-2 vehicle.
9. Anon., PowerPoint presentation, "X-34 Program: Lead Center PMC Presentation," February 17, 1998, p. 10, box 3, record no. 18560, NASA Headquarters History Office, Washington, DC.
10. Ibid., p. 21.
11. Danny Davis, "Independent Assessment Agenda," August 27–29, 1997, NASA Marshall History Office, Huntsville, AL. "Pogo" refers to a propulsion-induced oscillatory characteristic often encountered in rocket-powered vehicles. The name is a metaphor comparing the longitudinal motions to the bouncing of a child's pogo stick, and is thus not an acronym. If a rocket engine's combustion is unstable, the engine will produce thrust variations that, in turn, will generate variable acceleration forces. These forces, in turn, generate variable structural loadings, and distort flow through the propellant system, which, in turn, results in variable delivery flow and pressure levels to the engine, leading to further combustion instability and creating a self-exciting, sustained oscillation which can build to dangerous levels threatening vehicle survival.
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15. Ibid., p. 37.
16. Ibid., p. 38.

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18. Ibid.
19. Rick Bachtel, note to Jack Levine, Mike Allen, John Hudibury, Jimmy Lee, Jan Monk, and Alberto Duarte, "X-34 Alternate Engine Study," September 3, 1997, NASA Headquarters History Office, Washington, DC.
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32. Ibid., pp. 2–3.

33. Ibid., pp. 7–10.
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39. Ibid., p. 7.
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41. Ibid., pp. 9, 18–19, 25.
42. Ibid., pp. 27–28.
43. Ibid., pp. 2–3.
44. Ibid.
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The X-34 A-2 resting derelict in open storage on the east shore of Rogers Dry Lake, parked off a public road on March 17, 2010. (RPH)

CHAPTER 10

Hammer Fall: Termination of the X-34 Program

On March 1, 2001, NASA announced that Space Launch Initiative funds would not be available for either the X-33 or X-34 projects. Thus, the X-33 project would end on March 31, with the expiration of the cooperative agreement between NASA and Lockheed Martin, unless Lockheed decided to go forward with the project using the company's own funds. NASA likewise was in the process of ending its X-34 contract with Orbital Sciences Corporation. It was a very sad end to what had been a very promising project, and at Orbital, the collective mood was bleak: "The decision," one Orbital executive remarked years later, "broke my heart," adding, "it still does."[1]

Though he acknowledged that, "this has been a very tough decision," Art Stephenson, Director of NASA's Marshall Space Flight Center, wasted little time mourning both these ill-fated programs, dismissing both. He then launched into an endorsement of the Space Launch Initiative:

> [W]e think it is the right business decision…. We have gained a tremendous amount of knowledge from these X-programs, but one of the things we have learned is that our technology has not yet advanced to the point that we can successfully develop a new reusable launch vehicle that substantially improves safety, reliability and affordability. The Space Launch Initiative will take us to that point. It is a comprehensive, long-range plan to promote commercial development and civil exploration of space and provides the strategy and funding to enable at least two competing architectures for full-scale development of a 2nd generation reusable launch vehicle by mid-decade [2005–2006]. Through focused risk-reduction activities and risk-reduction technology development, we will make significant improvements in safety, reliability and affordability over the launch capability we have today. A new launch system that meets these goals could begin operating early in the next decade.[2]

At the time, no one seems to have pointed out that, little over a half-decade before, X-33 and X-34 had been touted with similar exuberant predictions. *Sic transit gloria mundi.*

Status of the X-34 Vehicles Following Termination of the Program

As of the termination date of the X-34 program, vehicle A-1A was at NASA Dryden. The vehicle had completed its initial ground handing tests and was ready to undertake a series of higher speed ground handing tests that were never made. Vehicle A-2 was at Orbital's Dulles, Virginia, site in the final stages of the integration readiness effort for vehicle-level static fire testing at Holloman Air Force Base in New Mexico. Vehicle A-3 was in the early stages of structural integration when the program was terminated.

In April 2002, planners in the Air Force Flight Test Center's 412th Test Wing drafted an agreement to facilitate the transfer of X-34 flight vehicles and associated hardware to be shipped from NASA Marshall and Orbital to Edwards. The transfer included the three vehicles (A-1A, A-2, and A-3), and all associated tooling, spare parts, and various ground support equipment. The Air Force transfer document noted that the "AFFTC foresees the potential to utilize the test assets for possible follow-on Air Force (AF) access to space (hypersonic) research and technology development and demonstration projects. The return on investment would be realized through future military test and evaluation capability advancements." The estimated cost of the transfer was $195,438.[3]

Vehicles A-1A and A-2 were stored initially in a hangar at Edwards AFB's North Base complex. The remaining hardware was housed in five Sea-Land containers placed outside of the hangar. The Air Force vacated the hangar at North Base during the summer of 2009 and transported the A-1A and A-2 vehicles to the bombing range at Edwards, where they remained until December 17, 2009, when NASA Dryden personnel temporarily moved them to the eastern edge of the lakebed.

Nearly a year later, they were taken back to NASA and stored outside of one of flight test hangars. On November 17, 2010, the two X-34s were transported to Mojave, California, in preparation for internal inspections of the vehicles.[4] *Aviation Week & Space Technology* reported that this "Mystery Move" to the Mojave Air and Space Port had occurred on November 16, and that Orbital "denied suggestions circulating at Mojave that they are to be donated to a locally based, unnamed aerospace company interested in leveraging the technology to aid in its suborbital development plans."[5]

On December 1, 2010, however, the *Aerospace Daily & Defense Report* reported that the "Sierra Nevada [Corporation] is emerging as the likely front

The X-34 A-1A is sitting on a flatbed trailer on the east lakeshore of Rogers Dry Lake on March 17, 2010. Notice that the canted vertical fin has been damaged by the gusting desert winds. (RPH)

runner to use the former NASA X-34 reusable launch vehicle demonstrator as a flying test bed for its Dream Chaser orbital space vehicle…. [and that] Sierra Nevada Executive Vice President Mark Sirangelo confirms the company is studying the X-34 for a supporting role in the Dream Chaser effort." *Aerospace* quoted Sirangelo as saying, "[w]e are interested in this project with our interest being adapting our hybrid rocket motor for our orbital space vehicle Dream Chaser program to the X- 34 as a test platform." According to *Aerospace,* Sirangelo said that, while "it remains too early to provide further details… the X-34 could likely be adapted for carriage beneath the Scaled Composites-built *WhiteKnightTwo* mothership, as well as the Orbital L-1011, which last carried the vehicle aloft for three flights in 1999." *Aerospace* added further that "[a]lthough originally conceived as a test bed for the reusable Fastrac engine designed and developed by NASA Marshall Space Flight Center, Ala., the vehicle is appropriately sized for the hybrid nitrous oxide, hydroxy-terminated polybutadiene-fueled rocket engine planned for the Dream Chaser."[6]

On December 17, 2009, representatives from Sierra Nevada had visited Orbital to discuss the development of a program to demonstrate some of Sierra Nevada's technologies using a modified X-34 airframe.[7] Subsequent discussion led Orbital and Sierra Nevada to approach John Kelly of NASA Dryden, and Dan Rasky of NASA Ames. This in turn led Kelly to host an inspection of the X-34 vehicles at Dryden on January 27, 2010, assisted by Frank Taylor of Sierra Nevada, and Bryan Sullivan of Orbital.[8] The inspection revealed that both the A-1A and A-2 had sustained some damage due to the apparent use of forklifts to load the vehicles onto flatbed trailers for transport to the bombing range. There were buckled areas of composite material that would require either replacement or extensive repair. However, there appeared to be relatively little damage to the remainder of the structure. Also, while the TPS simulator material was damaged in many areas, the underlying composite material appeared to be damage-free.

The inspection team noted that, in general, the A-1A vehicle appeared to be in good condition. The only corrosion was on a few fasteners that held the access doors on the vehicle. Likewise, the inspectors noted that the A-2 vehicle also appeared to be in relatively good condition. The nonstructural cowling on the aft end on the engine bay had been damaged and would require either repair or replacement. The lower nose panel evidenced significant depressions, but repair probably could be made due to the low loads in this region. The port, upper nose panel, had a 6-inch gash in it and would require more repair work than the lower panel.

The interior of the A-2 vehicle was surprisingly clean. Very little dust was observed, and no water intrusion was evident. All harnesses appeared to be in excellent condition. The landing gear appeared to be in reasonably good shape, although the position sensors were damaged or missing. Due to missing access doors on the wing actuator bays and the engine bay, there was standing water in these compartments. While further inspection would be required, it was hoped that the sealant paint used to minimize RP-1 and hydraulic oil contamination of the composite structure had protected the composite sandwich from the standing water. No actuators were present in the elevon and rudder because these had been removed prior to program termination to allow Allied Signal to perform rework. These components were shipped to Edwards in Sea-Land containers. The contents of these containers have since disappeared, for the most part, or were disposed of as surplus. The elevons, speed-brake, and body-flap were not present on the vehicle when inspected. Subsequent research, however, revealed that the NASA Dryden History Office had collected and stored two A-2 vehicle outboard elevons and speed brakes. The actuators apparently had been shipped to Wright Patterson Air Force Base, where they were used for research purposes. Overall, the inspection indicated that if a program were developed to fly both the A-1A and A-2, then many components would need to be remanufactured or shared between the two vehicles.[9]

The A-3 vehicle had been in the process of being assembled at Orbital when the project was terminated. The vehicle panels had been crated and shipped to NASA Dryden for storage at Edwards AFB's North Base complex.

During the inspection, the panels were located at North Base with no protection from the environment or passing vehicles. Significant damage was evident on the fuselage panels on both the top and bottom assemblies. In addition, the structural bond between the RP tank bay and forward LOX tank bottom panels was significantly compromised. However, the inspection team noted no evidence of corrosion. Even though the LOX tanks had been stored with minimal environmental protection, no damage was observed on the tanks, and the insulation was dry and appeared to be in excellent condition. The RP tank, which had been stored in the one remaining Sea-Land container, appeared to be in good condition.

The transportation mate trailer (TMT) that was needed to load the X-34 onto the L-1011 also was stored at North Base. The forward crossbeam and its castors and control panel were missing. Minimal corrosion was evident on the structure. The pneumatics system would, for the most part, need to be replaced. Four of the five Sea-Land containers were missing, and their contents believed gone. The inspection team estimated that the four containers held the pressurant tanks, reaction control system (RCS) valves, aerosurfaces, most of the structural component tooling, the structural test stand, integration tooling and many other items. The L-1011 carrier aircraft remained in flight ready status supporting Pegasus rocket launches. Following project termination, the X-34 related equipment was removed from the L-1011, but could have been reinstalled, since most of the hardware was designed for easy removal to support both the Pegasus and X-34 missions. Much of the hardware had been crated and stored near Orbital's L-1011.[10]

Following the inspection, discussions continued between the three parties until March 2010, when Sierra Nevada and Orbital parted ways, with Sierra Nevada turning its interest toward the Dream Chaser based on the NASA HL-20 lifting-body configuration, itself an outgrowth of an earlier Soviet lifting-body concept, the BOR-4. NASA, however, along with the Air Force Research Laboratory, remained interested and in August 2010 issued a task order to have Orbital assess the feasibility of returning the X-34 to flight status. But while a final report was submitted on January 20, 2011, no additional funding was forthcoming.[11]

A Contentious Cancellation

Continuation of the X-33 and X-34 projects had depended on NASA allocating funds from its new Space Launch Initiative, but NASA determined that the benefits to be gained from continuing the development of the X-33 and flight-testing the two X-34 vehicles did not warrant further Government investment.[12] NASA also claimed that in order "[t]o ensure safety and mission success of the X-34 it became necessary to increase Government technical insight, hardware testing, and integrated systems assessments. As a result, the projected cost of completing the X-34 program at an acceptable level of risk rose significantly above the planned budget. NASA decided that such additional funding for X-34 risk reduction would have to be completed within the SLI evaluation process. As with the X-33, NASA determined that the benefits to be derived from continuing the X-34 program did not justify the cost."[13]

No Reprieve from the Air Force

As a final attempt to save both the X-33 and X-34, Lockheed Martin and Orbital Sciences looked to the Air Force to continue funding the projects. On August 28, 2001, Air Force Space Command officials presented a briefing to Air Force Chief of Staff, General Michael Ryan and Air Force Secretary James Roche, on a $2 billion proposal to finish and fly the X-33 in tandem with NASA's X-37 experimental space maneuvering vehicle, but apparently no proposal concerning the X-34 was presented at the briefing.[14] By September, however, the Air Force had decided not to take on either program. Ryan retired from the Air Force in early September, replaced by General John Jumper, and it is possible the X-34 simply was caught in the inevitable change that takes place between service administrations. In any case, the terrorist attacks of September 11, 2001, which occurred on Jumper's very first day as Chief of Staff, immediately focused virtually all Air Force attention on what soon became a global war on terrorists and their sympathizers attacking and otherwise threatening the United States and causing international instability.

It is possible, however, that the X-34 was rejected due to a pre-existing plan to "grow" the X-37/X-40 into an operational orbital space asset. Roche, as "SecAF," directed the service to rapidly acquire game-changing transformational systems, establishing a secretive Headquarters USAF-level Rapid Capabilities Office (RCO), under Colonel David Hamilton, a highly regarded tester and flight research administrator, to oversee such development. Under Hamilton and RCO, the X-37 evolved into the "X-37B," a reusable spacecraft that eventually did enter military service, undertaking a series of long-duration orbital missions followed by precision entry and recovery. Though acknowledged, details of its flights, and even the purpose of the X-37B itself, are highly classified, and likely to remain so for many years to come.[15]

Orbital was not in a financial position to continue the X-34 project without Government funding. The company had reported a $105 million loss in 1999, and more than doubled this loss—to $228 million—in 2000. In response to its financial troubles, Orbital divested non-core businesses, including its interest in the Canadian communications and information company MacDonald, Dettwiler and Associates (then known as MDA—it was renamed

The first Boeing X-37B orbital test vehicle (OTV), is shown undergoing checkout at Vandenberg AFB, California, in June 2009. An outgrowth of the earlier X-37 and X-40 programs, it was America's first autonomously controlled lifting reentry system. (USAF)

Maxar Technologies, Ltd., on October 5, 2017), to free up capital for its core spacecraft and launch businesses. Orbital also took a $19 million charge relating to the termination of the X-34 project.[16]

The Cancellation as Seen Through Dryden's Aerospace Projects Reports

NASA Dryden's project reports between February 20 and August 26, 2001, reflect the Center's significant X-34 flight preparation work, including project restructuring efforts, as well as the project termination and shutdown follow-up actions.

The February 20 report noted that due to a hydraulic leak in the rudder area, the conical seals had been replaced with Teflon seals and that installation of mock TPS tiles on the leading edge of the vertical tail continued. At the same time, however, Dryden had submitted 18 Requests for Information, bringing the total requests submitted to over 300, relating to Orbital's proposal to restructure the request for proposals. The report added that the review period would end that week.[17] Just 6 days later, on February 26, the Projects Report indicated that NASA had sent a stop-work order to Orbital due to the decision not to include continuation of the X-34 project in Space Launch Initiative (SLI) funding. At the same time, the report noted continuing flight readiness work, as well as participation in NASA Marshall's Configuration Control Board activity. The report also stated that 485 comments on the Orbital restructuring proposal had been received.[18]

The March 12 Aerospace report confirmed that the X-34 project had been officially terminated on Thursday, March 8. The report stated further that

> [n]o decision has been made on what to do with the vehicles (A-1A, A-2, and A-3) and equipment. All of the hardware and spare parts are being collected and positioned in the hangar for potential shipment. The vehicle [at Dryden] has been covered with plastic to keep the open avionics compartments from getting contaminated. If the vehicle is not shipped, a considerable amount of work needs to be accomplished.[19]

The April 16, 2001, report added, "MSFC [NASA Marshall Space Flight Center] stated that the X-34 vehicles will belong to the government on April 20. Also, Orbital had offered to store vehicles A-2 and A-3 at their Dulles facility at no cost to the government."[20] The May 29 report noted that Dryden was still looking at storing the X-34 assets in the Edwards area, either at North Base or the Air Force Museum on base.[21] The June 4 report added that the Air Force Museum at Edwards AFB had offered to take the A-1A vehicle and display it in an indoor environment. The report also stated that NASA Marshall was withdrawing X-34 funds from NASA Dryden.[22] The July 2 report added that there was still no disposition decision on the now Government-owned assets.[23] Finally, the August 2 report noted that the Air Force X-34 Flight Test Support function had been closed out on July 31, and that there would be no further X-34 sections in the Aerospace Projects reports.[24]

Descent into Bickering: NASA and Orbital Trade Fire

Like a once-promising relationship gone horribly wrong, the two partners in the X-34 program first separated and then launched increasingly furious attacks on the character and intentions of the other. Following the announcement of the cancellation of the X-34 Project, disagreement over the reason for terminating the project quickly arose between NASA and Orbital, as reflected in a March 8, 2001, article in *The Huntsville Times*. J. R. Thompson, president of Orbital and a former director of NASA Marshall, was quoted as saying that NASA believed that the program was too expensive, yet NASA was the cause of the delays and increased costs. "They saddled us with redundant systems and review processes that had nothing to do with an unmanned test vehicle….

That's where the delays and costs came from." Thompson added that the Fastrac engine that was to be used in the X-34 ran into problems and that "[t]he program's dead without an engine, and there's no engine.... We have two test vehicles sitting around at Dryden (Flight Research Center in California) with no engine to power them." He added that the engine development was stymied by a lack of commitment and enough skilled engineers at NASA Marshall, and that while a prototype engine was designed, built, and tested, NASA Marshall had not produced an engine that could be placed on the X-34. *Spacetoday.net* added that in a conference call held on April 17, Thompson "blamed the cancellation of the X-34 on NASA's inability to provide the Fastrac engine that was to power the X-34 as well as a more conservative attitude towards projects in the wake of recent failures."[25]

Art Stephenson, NASA Marshall Director, acknowledged that the Fastrac engine was not perfected, but that the engine was not the reason for termination of the X-34 project. He added that, "It was canceled because it would have been too costly in the long run. The technology (for single-stage-to-orbit vehicles [which actually applied only to the X-33, as the X-34 was not an SSTO vehicle] wasn't there, and it would cost too much at this time to get it there." In regard to redundant systems, Stephenson noted that NASA's approach to experimental programs had changed in the past 2 years due to the costly failure of the Mars probes.[26]

SpaceRef, an industry newsletter, also weighed in on the issue of blame. The publication pinned the blame on X-34 project changes and an increasing unwillingness on the part of NASA to take risks. They noted the following in their August 27, 2000, press release:[27]

> In the wake of the recent spectacular Mars mission failures, NASA has gone back over its programs looking for ways to prevent more high-visibility setbacks. In general, this involves imposing an additional layer of NASA management, which costs; hence the current fuss over rising expenses and reducing the number of NASA science missions planned. In X-34's case, it also involves a specific change of approach. Till now, the program was prepared to risk losing one of the three X-34 airframes during flight test. This has now been defined as unacceptable. The changes this implies are not cheap. X-34 avionics were formerly single-string and are now being redesigned for redundancy, not generally considered cost-effective in an experimental test bed....[28]

SpaceRef added that "some of blame does go to OSC; they've been having teething troubles with various parts of X-34. The propellant tank design was a problem for a while (since solved, we're told) and the first X-34 airframe had significant electrical problems the first time it was interfaced with the carrier aircraft;[29] we understand it has since gone to NASA Dryden for rewiring and ground-tow testing." Finally, they concluded that "…NASA should back off the absurd and unaffordable 'no conspicuous failure is acceptable' position. This is an experimental vehicle project with three copies of the vehicle; a reasonable level of risk of damage to or loss on one of the vehicles is a good tradeoff for lower cost and quicker results."[30]

The General Accounting Office on the Demise of the X-33 and X-34

In June 2001, Allen Li, Director, Acquisition and Sourcing Management, U.S. General Accounting Office (later renamed Government Accountability Office), testified before the Congressional Subcommittee on Space and Aeronautics. In his prepared statement, Li noted the "Critical Areas NASA Needs to Address in Managing Its Reusable Launch Vehicle Program." At the beginning of his statement, Li testified:

> Both programs [X-33 and X-34] were recently terminated because of significant cost increases caused by problems developing the necessary technology and flight demonstration vehicle. NASA is now focusing instead on its new Space Launch Initiative. This is a broader effort to develop the next generation of reusable launch vehicles, referred to as the Second-Generation Launch Vehicle Program (2nd Generation Program). Today, I will discuss the primary factors that contributed to the difficulties experienced by the X-33 and X-34 programs and the steps needed to avoid repeating those problems within the 2nd Generation Program.[31]

In reviewing the new follow-on 2nd Generation Program, Li added:

> [t]he Space Launch Initiative is intended to be a more comprehensive, long-range plan to reduce high payload launch costs. NASA's goal is still to reduce payload launch cost to $1,000 per pound to low Earth orbit but it is not limited to single-stage-to-orbit concepts. Specifically, the 2nd Generation Program's objective is to substantially reduce the technical, programmatic, and business risks associated with developing reusable space transportation systems that are safe, reliable, and affordable.
>
> NASA has budgeted about $900 million for the SLI [Space Launch Initiative] initial effort and, in May 2001 it awarded initial contracts to 22 large and small companies for space transportation

> system design requirements, technology risk reduction, and flight demonstration….[32]

While reviewing both the X-33 and X-34 programs and also citing findings of NASA's Office of Inspector General, Li testified that, "NASA did not successfully implement and adhere to a number of critical project management tools and activities." The GAO's specific findings included the following issues.[33]

- NASA failed to develop realistic cost estimates in the early stages of the X-33 program and did not allow for major delays faced by a "high-risk" program.
- NASA failed to prepare risk-management plans for the X-33 and X-34 programs until several years after the projects were implemented, and that a "risk-management plan for the X-34 was not developed until the program was restructured in June 2000." Risk-management plans "identify, assess, and document risks associated with cost, resource, schedule, and technical aspects of a project and determine the procedures to manage those risks. [It should be noted that risk-mitigation plans did exist prior to the restructuring in 2000, but that NASA's tolerance of risk had lessened greatly since the era of the X-15, Apollo, and the early days of the Space Shuttle.]
- Contrary to the Agency's own policy, NASA failed to prepare program commitment agreements or program plans at the beginning of the X-33 and X-34 programs. A commitment agreement lays out the program's technical, schedule, and cost commitments, and overall acquisition strategy. A program plan also addresses these issues and, in addition, defines the project's management structure program resources, data management, risk management, test and verification, and planned program reviews. These plans help to define realistic time frames, identify responsibility for key tasks and deliveries, and provide a yardstick for measuring progress.
- Once again, citing OIG findings, Li's testimony noted that NASA failed to complete a configuration management plan for the X-33 until approximately 2 years after NASA awarded the cooperative agreement. Configuration management plans identify the process to be used for defining the functional and physical characteristics of a product and for systematically controlling changes in the design. As such, they enable organizations to establish and maintain the integrity of a product throughout its life cycle and prevent the production and use of inconsistent product versions.
- The GAO concluded that without the use of the management tools reviewed above, NASA encountered numerous problems on both

> the X-33 and X-34 and that these problems were compounded by a decrease in the projected commercial launch market that in turn lessened the incentives of NASA's X-33 industry partners to continue to fund the program.

Finally, the GAO testimony reviewed the budget overrun and schedule slippage as follows:

> Similarly, NASA started the X-34 Project, and the related NASA engine development project, with limited government funding, an accelerated development schedule, and insufficient reserves to reduce development risks and ensure a successful test program. Based on a NASA X-34 restructure plan in June 2000, we estimate that NASA's total funding requirements for the X-34 would have increased to about $348 million—a 307-percent ($263 million) increase from the estimated $86 million budgeted for the vehicle and engine development projects in 1996. Also, since 1996, the projected first powered flight had slipped about 4 years from September 1998 to October 2002 due to the cumulative effect of added risk mitigation tasks, vehicle and engine development problems, and testing delays.[34]

The GAO testimony reviewed above combined the X-33 and X-34 together in their Statement of Testimony and noted very specific failures regarding the X-33 vehicle and its components, including the composite fuel tank. This raises the question as to what extent the failure of the X-33 influenced the termination of the X-34 project, and whether lumping both programs together was (and is now, in historical retrospect) "fair" to the X-34.

While the two programs/projects were connected, the X-34 program had a number of standalone attributes. For example, the X-33 was to demonstrate single-stage-to-orbit technology, while the X-34 was to demonstrate reusability technology and rapid, low-cost operations. Also, neither the OIG report nor the GAO testimony apparently considered the fact that the X-34, unlike the X-33, was already built and the test article was being readied for flight-testing when the program was terminated. Furthermore, much of the estimated over budget funding that the GAO estimated would be needed was for risk reduction and vehicle modification on what, from the beginning, was intended as a single string, robotically operated, faster/better/cheaper demonstrator vehicle. This also represented a change in the risk reduction plans. The earlier risk reduction plan, which apparently was accepted by both NASA and Orbital, reduced the risk of using one single-string robotically operated test vehicle by providing for a second power flight test vehicle. The new plan required redundancy systems for the X-34.

Did the Loss of Three NASA Space Probes and One RPA Kill the X-34?

A total of 16 “faster, better, cheaper” projects were undertaken between 1992 and January 2000, with 6 of these missions resulting in failure. Between 1992 and 1998, 9 out of the 10 “faster, better, cheaper” projects undertaken were successful. A drastic change in fortunes for NASA came in 1999, however. The Wide-Field Infrared Explorer (WIRE), which was a cryogenically cooled telescope, failed in its primary mission in March due to premature separation of the vehicle’s protective cover; the Mars Climate Orbiter failed in September; and the Mars Polar Lander and the twin Deep Space 2 microprobes failed in December.[35] Also, in 1999 the composite liquid hydrogen tank of the X-33 failed. The X-33 was a “faster, better, cheaper” project and was part of the RLV program. The X-33 was still facing critical problems when the program was terminated. Falling within the same period as the failures already noted, Aurora Flight Sciences’ Perseus-B remotely piloted aircraft (RPA), was on its eighth test flight from Edwards AFB on October 1, when it experienced an electrical failure, causing a loss of control. The flight termination system was activated, but the recovery parachute failed to deploy and the vehicle flew outside of the Edwards range restricted area and crash-landed on Interstate Route 40 near Barstow, California.[36]

The failure of the Mars Climate Orbiter, the Mars Polar Lander, and Deep Space 2 microprobes are summarized in the following sections. There were three separate reviews underway at the same time, with the NASA’s Administrator-appointed Mars Program Independent Assessment Team (MPIAT) charged with coordinating the reviews, in addition to drawing up their own review and assessment.

Mars Climate Orbiter Mission Failure

The Mars Climate Orbiter was launched on December 11, 1998, atop a Delta 2 rocket. The planned mission profile is reviewed below.

> Nine and a half months after launch, in September 1999, the orbiter was to fire its main engine to achieve an elliptical orbit around Mars…. The spacecraft was to then skim through Mars’s upper atmosphere for several weeks in a technique called aerobraking to reduce velocity and move into a circular orbit. Friction against the spacecraft’s single, 5.5-meter solar array was to have slowed the spacecraft as it dipped into the atmosphere each orbit,

> reducing its orbit period from more than 14 hours to 2 hours." The orbiter was carrying instruments "to map the planet's surface, profile the structure of the atmosphere, [and] detect surface ice reservoirs." The orbiter, however, was lost on September 23, 1999, when it entered the Martian atmosphere on a lower than expected trajectory.[37]

NASA's Associate Administrator for Space Science established the NASA MCO [Mars Climate Orbiter] Mishap Investigation Board on October 15, 1999. Art Stephenson, Director of NASA Marshall, was appointed as the committee chair. The Phase I report was directed to focus on "any aspects of the MCO mishap which must be addressed in order to contribute to the Mars Polar Lander's safe landing on Mars."[38] The Phase I Report issued by the board on November 10, found that

> during the 9-month journey from Earth to Mars, propulsion maneuvers were periodically performed to remove angular momentum buildup in the on-board reaction wheels (flywheels). These Angular Momentum Desaturation (AMD) events occurred 10–14 times more often than expected by the operations navigation team. This was because the MCO solar array was asymmetrical relative to the spacecraft body as compared to Mars Global Surveyor (MGS), which had symmetrical solar arrays. This asymmetric effect significantly increased the Sun-induced (solar pressure-induced) momentum buildup on the spacecraft. This increased AMD events coupled with the fact that the angular momentum (impulse) data was in English [Lockheed Martin used English units; NASA used metric units], rather than metric, units, resulted in small errors being introduced in the trajectory estimate over the course of the 9-month journey. At the time of Mars insertion, the spacecraft trajectory was approximately 170 kilometers lower than planned. As a result, MCO either was destroyed in the atmosphere or re-entered heliocentric space after leaving Mars' atmosphere. The Board recognizes that mistakes occur on spacecraft projects. However, sufficient processes are usually in place on projects to catch these mistakes before they become critical to mission success. Unfortunately for MCO, the root cause was not caught by the processes in-place in the MCO project.[39]

The Mishap Investigation Board also identified the eight following contributing causes:

- undetected mismodeling of spacecraft velocity changes;
- navigation team unfamiliarity with the spacecraft;
- trajectory correction maneuver number 5 not performed;
- system engineering process did not adequately address transition from development to operations;
- inadequate communications between project elements;
- inadequate operations navigation team staffing;
- inadequate training; and
- verification and validation process did not adequately address ground software.

Mars Polar Lander and Deep Space 2 Mission Failures

The Mars Polar Lander and the two Deep Space 2 probes were launched on a single vehicle from the Kennedy Space Center on January 3, 1999. Upon reaching Mars, communications ended as planned as the three spacecraft entered the Martian atmosphere, but communications were never reestablished. On December 16, a special review board was appointed to investigate and assess the failure of the Mars Polar Lander and the Deep Space 2 missions. NASA's Jet Propulsion Laboratory (JPL) conducted the review, which was the lead Center for the Mars Surveyor program. The board's report was issued on March 22, 2000. The board consisted of 15 members representing JPL, industry, academia, NASA Marshall, and NASA's Independent Program Assessment Office. John Casani, from JPL, served as Chair and Charles Whetsel, also from JPL, served as Deputy Chair. The board was assisted by Frank Locatell and Parker Stafford, who served as consultants and who were involved in the Mars Polar Lander development process. The board was tasked to determine the possible root causes for the loss of the two missions, and to identify actions needed to assure future success in similar Mars landings. The review noted that

> [f]rom the beginning, the MPL [Mars Polar Lander] project was under considerable funding and schedule pressure. The project team was asked to deliver a lander to the surface of Mars for approximately one-half the cost of Mars Pathfinder, which had been done for significantly less than earlier planetary missions. In addition, the complexity and technical challenges for MPL were at least as great, if not greater. The important consequences of this technical and financial situation fell chiefly into two categories—project staffing and key technical decisions.[40]

In regard to the cause of the failure of the Mars Polar Lander mission, "[t]he Board found compelling evidence that premature shutdown of the descent engines was the cause of the loss of the MPL.... It is important to note that there are no corroborating flight data to support this finding, so other failure modes cannot be ruled out." The board listed "plausible other causes for the failure," meaning that the failure mode could not be excluded based on the design/test evaluation of available data. The plausible other causes listed were: 1) surface conditions exceeded the landing capabilities; 2) loss of control due to dynamic effects; 3) landing site was not survivable; 4) backshell/parachute contacted lander; 5) loss of control due to center-of-mass offset; or 6) heat shield failure due to micrometeoroid impact.

In regard to the failure of the Deep Space 2 missions, the board concluded that "[u]nlike the case of the MPL, there was no one failure mode that was identified as being most probable. The board, however, listed the four following plausible failure modes: 1) both probes bounced on impact due to unanticipated surface effects; 2) both probes suffered electronic or battery failure at impact; 3) the probes failed due to ionization breakdown in Mars atmosphere; or 4) the probes landed on their side, interfering with antenna performance.[41]

An "Independent Assessment"—a Third Report

NASA's Administrator established the Mars Program Independent Assessment Team (MPIAT) chartered to "review and analyze Successes and Failures of Recent Mars and Deep Space Missions," including the successful Mars Global Surveyor, Pathfinder, and Deep Space 1 missions and the failures of the Mars Climate Orbiter, Mars Polar Lander, and Deep Space 2 missions. The team was requested to examine the relationship between and among the NASA Jet Propulsion Laboratory, the California Institute of Technology, NASA Headquarters, and the industry partners. They were chartered to: 1) assess the effectiveness of the involvement of scientists; 2) identify the lessons learned from successes and failures; 3) review the Mars Surveyor Program to assure lessons learned are utilized; 4) oversee the Mars Polar Lander and Deep Space 2 failure reviews; and 5) complete their report by March 15, 2000.[42]

The report noted that

> In-depth reviews were conducted at NASA Headquarters, JPL, and Lockheed Martin Astronautics (LMA). Structured reviews, informal sessions with numerous Mars Program participants, and extensive debate and discussions within the MPIAT establish the basis for this report. The review process began on January 7, 2000, and concluded with a briefing to the NASA Administrator on March 14, 2000.[43] The MPIAT membership consisted of 18 members representing NASA (Ames, Langley, and JPL Centers and NASA Headquarters); industry (Lockheed Martin, Hughes Space

and Communications, and TRW); universities (the Massachusetts Institute of Technology and the University of Virginia); the U.S. Air Force; U.S. Geological Survey; National Reconnaissance Office; and the Naval Research Laboratory. Since Thomas Young, who was retired from Lockheed Martin, served as committee chair, the MPIAT report is commonly referred to as the "Young Report."[44]

The report identified the following lessons learned:

- Experienced project management or mentoring is essential.
- The project manager must be responsible and accountable for all aspects of mission success.
- Unique constraints of deep space missions demand adequate margins. For example, the Mars Climate Orbiter, Mars Polar Lander, and Deep Space 2 did not have adequate margins, and MCO and MPL were managed as a single Mars '98 project. Also, "[t]he selection of a launch vehicle with little margin, some growth in the science payload, and fixed planetary launch window also contributed to inadequate margins."
- Appropriate application of institutional expertise is critical for mission success. The report added that the "[u]se of JPL capabilities was significantly curtailed on Mars '98 largely because of funding limitations. Consequently, a significant opportunity was missed that may have resulted in recognition of inadequate margins and excessive risk in the Mars '98 project. JPL institutional support for DS-2 varied considerably, but was inadequate for the technical complexity of the microprobes."
- A thorough test and verification program is essential for mission success. The report added that, "FBC [faster, better, cheaper] encourages taking prudent risk in utilizing new technology and pursuing important science objectives and innovation. However, risk associated with deviating from sound principles should not be allowed." Sound principles were identified as including, for example, the following: 1) efficient, competent, independent reviews; 2) oversight, analysis, and test to "eliminate" a single human mistake from causing mission failure; 3) clear definition of responsibilities and authority; 4) prudent use of redundancy; 5) test-as-you-fly, fly-as-you-test; and 6) risk assessment and management.

- Effective risk identification and management are critical to assure successful deep space missions.
- Institutional management must be accountable for policies and procedures that assure a high level of mission success.
- Institutional management must assure project implementation consistent with required policies and procedures.
- Telemetry coverage of critical events is necessary for analysis and ability to incorporate information in follow-on projects.
- If not ready—do not launch. Not being ready for a scheduled launch opportunity is serious, but not as serious as proceeding without being ready. Senior management needs to make it unambiguously clear that "if not ready—do not launch."[45, 46]

While the jury may be out on whether these well-publicized (and, in the case of the English-metric mix-up, humiliating) failures directly influenced the demise of the X-34, undoubtedly, they added to the Agency's already risk-averse tendencies. Given its "single-string" nature, the X-34 could hardly fail to draw criticism, no matter how strenuously program advocates argued (quite rightly) that it should gain some measure of leeway given that it was a purely experimental system.

Also, the risk of failure appears to have impacted the last attempt to fly the X-34. Mark Fisher, who was NASA's last X-34 project manager, approached Daniel Goldin with a plan to launch the X-34 over the Pacific Ocean and land at an abandoned World War II B-29 air base in the Mariana Islands. Fisher claims that he informed Goldin that if the vehicle crashed into the ocean, it would represent a low-profile crash—there would be no ground damage or photos of the wreckage. Fisher added that the response he received was that Goldin could not risk another failure on his watch.[47] (The idea of a Pacific air launch, followed by a remote island recovery, is a most attractive one, and has been raised subsequently with regard to follow-on hypersonic vehicle testing, as it permits recovery and analysis of the test vehicle as opposed to letting it simply impact and sink in the Pacific).

Congressional Follow-up: The Impact of Mission Failures on the X-34

On June 29, 2001, Congressman Dana Rohrabacher sent Allen Li, NASA Director of Acquisition and Sourcing Management, follow-up questions pertaining to Li's testimony before Rohrabacher's Subcommittee. Li had testified on areas NASA needed to address in managing its Reusable Launch Vehicle Program. One of the questioned asked by Rohrabacher related to the extent that the failure of the two Mars missions "influence[d] NASA's management style regarding the restructured X-34 Program. Nearly 7 weeks later, on August 13, Li responded. In part, he replied:

> It would be difficult to quantify the extent that the Young report [Mars Program Independent Assessment Team Report] or any of NASA's internal reports influenced a particular change to the X-34 Project. We did find that NASA restructured the plan for the X-34 Project in response to both X-34 Project technical reviews and other internal assessments of NASA programs, including reports of the failed Mars missions, the Shuttle wiring problems, as well as assessment of NASA's approach to executing its "Faster, Better, Cheaper" projects. X-34 Project management reviewed these reports and assessments, identified common problems, and took corrective measures to prevent the same problems from reoccurring with the X-34 Project. For example, NASA consolidated the X-34 vehicle and engine projects under one NASA manager and relegated the contractor to a more subordinate role. The restructured plan also added several risk mitigation tasks.[48]

The media weighed in on the Mars mission failures' impact on the final restructuring of the X-34 program, including quoting NASA officials. For example, *Aerospace Daily & Defense Report* stated the following on June 13, 2000:

> NASA's X-34 technology demonstrator program is undergoing a major restructuring to incorporate lessons learned from the space agency's Mars mission failures, a move that includes a rethinking of the avionics systems used for the powered flights, says Mark Fisher, Marshall Space Flight Center's new X-34 program manager.... "The X-34 was designed under the requirement of a single-string design," explained Seunghee Lee, the project manager for X-34 at Dryden Flight Research Center at Edwards AFB, Calif. "Now, in light of [last year's] Mars [mission failures] and other lessons learned within NASA, we are looking at single-string avionics to see where we can smartly inject additional redundancy."[49]

Factors Contributing to the Failure of the X-34 Program

The official end of the RLV program came when Congress did not appropriate funding from the follow-on Space Launch Initiative program. However, there were a number of contributing factors that caused the schedule slippage, budget overruns, and the declining degree of interest in the program that, in turn, necessitated requesting additional funds that led to termination of the project. These factors can be posed as a series of questions.

Was NASA Ever Fully Committed to the Second X-34 Program?

NASA expressed disappointment in Orbital's and Rockwell's inability to continue the first X-34 program, which was planned to include a follow-on commercial vehicle that could potentially replace the Space Shuttle and reach the International Space Station. Was this what NASA really wanted, rather than simply a moderate hypersonic transatmospheric technology demonstrator? NASA's own OIG report noted that there was a lack of consensus within the Agency regarding the future plans for space transportation. NASA was basically directed to restart the program by the White House. Also, NASA appeared to be on the verge of terminating the second X-34 program in late 1998 or early 1999 until Congress exerted pressure to continue the program.

In addition, as noted in congressional correspondence reviewed in chapter 9, NASA, as early as September 1998, was considering not requesting funding for the RLV program as part of the Agency's fiscal year 2000 budget request. Likewise, during the fall of 1999, NASA was already laying the groundwork for the follow-on Space Launch Imitative through an effort known as the Integrated Space Transportation Plan (ISTP). This planning project, which also was reviewed in chapter 9, was taking place at the same time that NASA was planning for the restructuring of the X-34 project, an effort that raised the cost to a level that would have required funding through the SLI program. Finally, according to feedback received by Orbital from an engineer familiar with the SLI review team effort, NASA rejected the team's initial recommendation to fund the X-34 project as part of the SLI program.

Was the Right Engine Baselined for the X-34?

NASA merged two separate programs that each could have been successful on its own, but experienced problems when combined. NASA Marshall, by most accounts, accomplished major goals in the development of the Fastrac engine and in training a new generation of propulsion engineers. The extent of this accomplishment, as well as the interest and dedication of the engineers and technicians who worked on the Fastrac/MC-1 engine, is evident in the extensive Project Closeout Termination Report that they prepared, as well as in the engines that existed upon termination of the X-34 project. Likewise, Orbital successfully fabricated two flight-ready X-34 vehicles with a core of engineers and technicians who for the most part remained with Orbital and used the experience they gained from the X-34 program/project to build Orbital Sciences Corporation into a major aerospace company. However, many problems appear to have existed in adapting the Fastrac engine, which started as a point design engine as part of the preexisting Bantam program, for use in the X-34. These problems included satisfying changes in the vehicle and complying with NASA's decision to build redundancy into the avionics and flight termination systems of the vehicle. Orbital did successfully modify the X-34 and install a Fastrac "simulator" engine—indicating that the Fastrac engine, if flight ready, could have been integrated into the vehicle. After successful integration, the simulator engine was removed and returned to NASA Marshall.[50]

Engineers at Orbital, propulsion engineers at NASA Marshall, and aerospace/aerodynamic engineers at NASA Langley all looked at other engines for potential use in the X-34, including the Russian NK-31 and NK-39, noting their advantages such as greater thrust power, throttleability, reusability, and lower costs. Furthermore, making the necessary block changes in the Fastrac/MC-1 and the additional testing requirements led to schedule slippage and cost overruns. These factors, when combined with changes Orbital was required to make accounted for a significant amount of the time slippage and cost overruns contributing to termination of the project. Eventually, NASA apparently recognized problems regarding the two projects and, as part of the program realignment effort, combined the two projects under one manager at NASA Marshall.

Did NASA Lose Interest in the X-34 After the Agency Realized That Significant Problems Existed in the X-33 Program?

The X-34 was a reusable launch vehicle technology test bed, while the X-33, which was the vehicle that NASA officials hoped would eventually lead to a replacement vehicle for the Space Shuttle, was a first phase single-stage-to-orbit demonstrator that was hoped to lead to the follow-on full-size orbital VentureStar (and which NASA officials hoped would eventually lead to a replacement vehicle for the Space Shuttle). At the time of cancellation of the X-33 and X-34 projects, it was apparent that the X-33 was experiencing serious problems. This left the X-34 as the only one of the original three vehicles of the single-stage-to-orbit/RLV program still capable of completing its mission. The X-34, however, had many objectives that were separate from the DC-XA and X-33 and could have made significant contributions on its own if successfully flown. Even NASA's OIG report, reviewed in chapter 9, appears to have given significant weight to X-33 problems, as opposed to the benefits of the X-34, in noting the termination of the SSTO/RLV program.

What Role Did the Mars Mission Failures Play in Killing X-33 and X-34?

At the time of cancellation, media reports (and at least some NASA officials) claimed that fear of another failure caused NASA to cancel the X-33 and

X-34 projects, or at least to reinforce NASA's increased risk-adverse attitude regarding the X-34. There appears to be some merit to this viewpoint, especially as it relates to risk mitigation. While the Mars mission failures occurred after NASA's initial request to add redundancy to the X-34, all five of the failures occurred prior to the final project restructuring and most likely reinforced—and even increased—NASA's decision to require redundant systems for the X-34.

Was NASA Overly Concerned About Project Failure and Risk Mitigation?

Something did cause a change in attitude toward risk mitigation for the X-34. The original plan was to develop a single-string robotically controlled test bed vehicle. Risk mitigation was originally based on having a back-up vehicle in case of loss of the first vehicle. Daniel Goldin was reported to have even challenged NASA Marshall by saying that "[b]reaking paradigms was expected and occasional mission failures along the way would be tolerated." Later, however, he directed that the X-34 had to have redundant systems. From the outset, both NASA and Orbital realized that they were pushing the technology envelope, but by doing so were hoping to advance the technology, leading to the ultimate goal of lowering the cost of launching payloads to low Earth orbit from $10,000 to $1,000 per pound. This subsequently changed to requiring a fully redundant risk mitigation policy that led to significant cost increases and schedule slippage that ultimately lead to program termination due to lack of additional funding.

Epitaph: An Optimistic Promise Tragically Left Unfulfilled

In considering what might have been, it is interesting to note the expectations of Orbital engineer Henri Fuhrmann reflected in his October 10, 1996, outline "X-34 Will Demonstrate These RLV Technologies":

- Development costs:
  - low-cost engine, low-cost composites, low-cost fabrication, and low-risk design;
- Operations costs:
  - autonomous (minimal on-site support, minimal launch/recover support);
  - quick turnaround (real-time health monitoring, autonomous maintenance scheduling, flexible site payload integration, low part count, easy repair);

- robust launch (expanded launch window, site and weather, captive carry, and safe separation);
- flexibility (automated mission planning, payload variability);
- robust land (autoland, expanded weather capability, variable site, differential GPS); and
- robust abort (autonomous reprogram, range capability).[51]

Fuhrmann added, as a lesson learned, that it was important to fly a vehicle quickly, noting that continued program financing gives priority to a vehicle that has been flown.[52] Failure to fly the X-34 resulted in a lower rating on the Technical Rating Level (TRL) rating scale used by NASA, essentially a downgrading that, in an era of intense project competition, was unfortunate.[53]

As well, the information that would have been obtained from a successful X-34 test flight program would have provided data points to match against the Space Shuttle for future aerodynamic and reusability studies in planning for the development of the next generation of reusable launch vehicles.

While the X-34 program was still in progress, two German aeronautical engineers—Robert H. Schmucker and Christoph P. Schmucker—likewise expressed the need for additional data that was to be obtained from both the X-33 and X-34 programs in their 1998 AIAA paper. They noted that

> Numerous proposals for new and advanced systems have been published which claim to be significantly superior to existing launchers. But contrary to this, the real progress is small or even not existing!
>
> The reason for this discrepancy lies in the concentration of endless paperwork, which is mostly without any substantiation. It is well known that improvements only stem from realistic hardware activities which follow a stepwise approach. A reorientation towards building hardware represents the key activities necessary for future launchers.
>
> In the overall spectrum X-33 and X-34 are definitely the right projects to get better answers for cost and mass of reusable systems. Even if the results of these projects underline the difficulties of reusable SSTO and TSTO [two-stage-to-orbit] this way represents the only sensible means for establishing profound data.[54]

Final Offer from Burt Rutan: "Send the X-34s to Mojave, I'll Fly Them"

Few American aerospace engineers have risen to the iconic, legendary status held by Burt Rutan, whose designs have consistently achieved astonishing performance at a reasonable cost and investment of resources, time, and people.

Thus, his views of X-34 are worth considering. In a March 2001 correspondence to *Aviation Week & Space Technology*, Burt Rutan commented on NASA's decision to cancel the X-34 before it could be flown:

> The X-34s should be flown, not parked. Years behind due to problems with a Government-developed engine and a NASA risk-averse attitude toward flying a single-string flight control system, the program would still probably fail if left alone. Failure is assured by the decision late last month, with no return on the $200 million investment. What exists are two nearly complete flight articles and data that could have been generated without building hardware. Once flown, you have gathered new information that you will be able to get from analysis. This is true whether they fly fine and land smooth or make a smoking hole in the desert. *Send the X-34s to Mojave, I'll fly them.*[55]

Burt Rutan had it exactly right. There was nothing gained and much lost by failure to carry through with flight-testing of the robotically piloted X-34 Technology Demonstrator vehicles that were already built and ready for flight-testing. It should be noted that this viewpoint represents the near unanimous opinion of the NASA and Orbital engineers and officials interviewed in connection with the writing of this book. As already noted, however, funds to complete both the X-33 and X-34 were not forthcoming in the Space Launch Initiative, which was the follow-on program to the single-stage-to-orbit and reusable launch vehicle program. It is interesting to note that the NASA media release that announced the start of the Space Launch Initiative and the end of the X-33 and X-34 projects stated with the same degree of optimism as had been presented when the DC-XA, X-33, and X-34 programs were started.[56]

Six years after the retirement of the Space Shuttle, 16 years after the start of the Space Launch Initiative, and 21 years after the start of the single-stage-to-orbit reusable launch vehicle program, payloads were still launched to low-Earth orbit by expendable rockets, and American astronauts were still flown to the International Space Station in Russian spacecraft. Failure to carry through with the X-34 program truly represented a *promise denied*.

Endnotes

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APPENDIX 1

X-34 Proposed 25-Flight Envelope Expansion Program

Note to reader: This is a draft document for the planned—but never executed—X-34 envelope expansion program. The data presented here shows flight number, together with relevant mission parameters, including maximum Mach number, maximum altitude, drop (launch) altitude, drop (launch) weight, maximum crosswind allowance, and mission details including relevant technical achievements and demonstrations. As shown, planners anticipated 9 unpowered flights, followed by 12 powered flights from Mach 2.58 at 89,000 feet to Mach 7.50 at 250,000 feet. The plan also included 4 proposed contingency flights, bringing the total number of projected envelope expansion program flight tests to 25.

Flight	Mach No.	Altitude (ft.)	Drop Altitude (ft.)	Drop Weight (lbs.)	Max Allowable Crosswind (kts.)	Flight Objectives and Details
1	0.70	35,000	30,000	18,000	5	Separation and landing; unpowered flight. Minimum brake deceleration = 6 ft./sec^2
2	0.70	35,000	30,000	18,000	5	Nominal Mach separation (preset elevon variation) Speed brake effectiveness (speed brake deflection= 0, 20, 40, 60 degrees Closed-loop pitch doublets buildups (elevon variations around nominal = ±5 degrees) 70-degree turn to final heading change (40-degree bank) Minimum brake deceleration 6 ft./sec^2
3	0.70	35,000	30,000	18,000	5	Nominal Mach separation (preset elevon variation) Speed brake effectiveness (speed brake deflection = ±70, ±90 degrees) Pitch doublets (elevon variation around nominal = ±10 degrees) Aileron doublets buildups (aileron variations around nominal = ±5 degrees) Update antiskid software/hardware, validate mods
4	0.65	25,000	25,000	18,000	5	Reduced Mach separation (high α, simulated heavy L-1011) Steady heading sideslips (rudder variations = ±2 degrees) Pitch doublets (elevon variations = ±15 degrees or repeat ±10) Rudder doublets (rudder variations = ±2 degrees) Aileron doublets (aileron variations = ±5 degrees) Medium antiskid deceleration 8 ft./sec^2
5	0.65	35,000	25,000	18,000	10	Reduced separation Mach (elevon variation) Pitch doublets (elevon variations = ±20 degrees or repeat ±15) Rudder doublets (rudder variations = ±4 degrees) Aileron doublets (aileron variations = ±10 degrees) Body flap effectiveness (body flap variations = –15 degrees) 8 ft./sec^2 antiskid deceleration

Flight	Mach No.	Altitude (ft.)	Drop Altitude (ft.)	Drop Weight (lbs.)	Max Allowable Crosswind (kts.)	Flight Objectives and Details
6	0.75	35,000	35,000	18,000	10	Reduced separation Mach (lower α) Pitch doublets (elevon variations = ±25 degrees or repeat ±20) Rudder doublets (rudder variations = ±6 degrees or repeat ±4 degrees) Aileron doublets (aileron variations = ±15 degrees or repeat ±10 degrees) Update antiskid software/hardware, validate mods at 8 ft./sec^2
7	0.75	35,000	35,000	18,000	10	Increased separation Mach (elevon variation) Steady heading sideslips (rudder variations = +4 degrees) Rudder doublets (rudder variations = ±8 degrees or repeat ±6 degrees) Aileron doublets (aileron variations = ±20 degrees or repeat ±15 degrees) Body flap effectiveness (body-flap variations = +5 degrees) Validate antiskid mods at 6 ft./sec^2
8	0.70	35,000	35,000	30,000	15	Increased separation Mach med. GRWT X-34 (max. clearance) Dump system functional (RP only) Rudder doublets (rudder variations = ±6 degrees or repeat ±4 degrees) Aileron doublets (aileron variations = ±15 degrees or repeat ±10 degrees) High deceleration anti-skid 10 ft./sec^2
9	0.75	35,000				Not determined
10	2.58	89,000	35,000	47,000	5	Heavy weight separation at nominal conditions Maximum ascent dynamic pressure operation Speed brake buzz investigation Supersonic aero-coefficient determination Base and aerodynamic heating Dump system functional Low antiskid 6 ft./sec ^{2}

Flight	Mach No.	Altitude (ft.)	Drop Altitude (ft.)	Drop Weight (lbs.)	Max Allowable Crosswind (kts.)	Flight Objectives and Details
11	2.58	89,000	35,000	47,000	15	Heavy weight separation with elevon preset adjustment Repeat first powered flight profile with system modifications
12	2.58	89,000	35,000	47,000	15	Heavy weight separation with (elevon preset adjustment Mach 2.2 elevon doublet (elevon variations = ±5 degrees) Mach 2.2 aileron doublet (aileron variations = ±5 degrees) Mach 2.2 speed brake effectiveness (speed brake variations = 20 degrees) Subsonic pitch, roll, yaw doublets High antiskid deceleration 10 ft./sec^2
13	2.58	89,000	35,000	47,000	15	Heavy weight separation with δe preset adjustment Mach 2.2 elevon doublet (δe = ±10 degrees) Mach 2.2 aileron doublet (δa = ±10 degrees) Mach 2.2 speed brake effectiveness (δsb = 60 degrees) Subsonic pitch, roll, yaw doublets Low antiskid deceleration 10 ft./sec^2
14	3.0	110,000	35,000	47,000	15	Heavy weight separation with δe preset adjustment Increased Mach and altitude (longer engine burn) Reaction control system effectiveness test Subsonic: maximum slip maneuver (for crosswind evaluation) Low antiskid deceleration 6 ft./sec^2
15	4.0	130,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation Increased Mach and altitude (longer engine burn) Reaction control system effectiveness (pitch, roll, yaw) Mach 3 elevon doublets (δe = ±5 degrees) Body flap effect (δbf = 0 degrees) Subsonic maneuvers as required Low antiskid deceleration 6 ft./sec^2

Flight	Mach No.	Altitude (ft.)	Drop Altitude (ft.)	Drop Weight (lbs.)	Max Allowable Crosswind (kts.)	Flight Objectives and Details
16	4.0	130,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation with δe preset adjustment Increased Mach and altitude (longer engine burn) Reaction control system effect (pitch, roll, yaw) Mach 3 elevon doublets (δe = ±5 degrees) Body flap effect (δbf = 0 degrees) Subsonic maneuvers as required Low antiskid deceleration 6 ft./sec^2
17						Contingency flight
18	6.0	175,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation with δe preset adjustment Increased Mach and altitude (longer engine burn) Increased aero/base heating Reaction control system effectiveness Hypersonic control effectiveness Energy management Low antiskid deceleration 6 ft./sec^2
19	7.0	200,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation Increased Mach and altitude (longer engine burn) Increased aero/base heating Reaction control system effectiveness Hypersonic control effectiveness Energy management Low antiskid deceleration 6 ft./sec^2

Flight	Mach No.	Altitude (ft.)	Drop Altitude (ft.)	Drop Weight (lbs.)	Max Allowable Crosswind (kts.)	Flight Objectives and Details
20	7.5	250,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation Increased Mach and altitude (longer engine burn) Increased aero/base heating Reaction control system effectiveness Hypersonic control effectiveness Energy management Low antiskid deceleration 6 ft./sec^2
21	7.5	250,000	>35,000	47,000	20	Maximum Mach/altitude heavy weight separation Increased Mach and altitude (longer engine burn) Increased aero/base heating Reaction control system effectiveness Hypersonic control effectiveness Energy management Low antiskid deceleration 6 ft./sec^2
22						Contingency flight, if needed; details to be determined
23						Contingency flight, if needed; details to be determined
24						Contingency flight, if needed; details to be determined
25						Contingency flight, if needed; details to be determined

APPENDIX 2

The Fastrac/MC-1 Engine and X-34 Main Propulsion System

This Appendix reviews a number of components and subsystems of the Fastrac/MC-1 engine and the X-34 vehicle's main propulsion system (MPS), as well as a number of lessons learned from the project work. In commenting on the changes that had occurred in the development practices for hardware components and subsystems, Michael D. Shadoan and David L. Sparks from the Space Transportation Directorate at NASA Marshall wrote that

> Development of space hardware has traditionally been done with the philosophy that the designer must use all available technological resources to maximize performance. This philosophy placed great emphasis on high thrust to weight ratios that greatly increased the cost and complexity of space hardware. However, in recent years of budget reductions and downsizing, the Government as a whole has been tasked with reinventing itself, to adopt an FBC [faster, better, cheaper] attitude when devising and developing new program acquisitions. Applying this to the design of space hardware means we must adopt new practices that result in inexpensive and reliable components. To accomplish these goals, the designer must incorporate fabrication experience, such as material and process selection, along with innovative design approaches.[1]

Fastrac (MC-1) Engine Components and Subsystems

Overview

The NASA Fastrac/MC-1 engine primary components and subsystems were simple in design and construction and were designed to require minimal maintenance in satisfying operational requirements. "Each subsystem is segregated to avoid complexity and maximize safety and simplifies trouble shooting and maintenance of the system." System components "had to be low cost, be able to satisfy an aggressive delivery schedule, and comply with the requirements of the system." In addition, the components also had to be capable of meeting high-level life-cycle requirements due to the reusability aspects of the X-34.[2]

The primary components and subsystems of the Fastrac/MC-1 engine consisted of the *turbomachinery*, including the turbopump, and the *combustion devices*, including the main injector, thrust chamber and nozzle, combustion chamber igniter, and gas generator. In addition, there were a number of supporting subsystems.

Turbomachinery

The turbomachinery consists of the turbopump, brackets, seals, fuel and LOX inducers/impellers, turbine disk assembly, rotor shaft, bearings, various housings, turbine inlet manifold, and heater assemblies. The NASA Marshall team, including engineers from NASA's fabrication vendor, Barber-Nichols, designed the turbopump, which is the main turbomachinery component.[3] The turbopump consists of a simplified system that includes both the LOX and kerosene (RP-1) feeds on a common shaft driven by a one-piece integral turbine blade and disk ("blisk"). This innovative system eliminated the need for use of complex multiple turbopumps—one for the RP-1 fuel and one for the LOX oxidizer. In addition, the cost of the pump housings was reduced to one-third the traditional cost by the successful development of a "sand casting" technique for the superalloy Inconel 718 (an austenitic nickel-chromium superalloy). The $350,000 cost of the turbopump represented a substantial reduction from the benchmark cost of $990,000.[4]

The Fastrac/MC-1 engine "Closeout Report" noted that

> [t]his type of arrangement allowed the elimination of a turbine wheel, a turbine housing and hot gas ducting between turbines. Engine system benefits of this design include elimination of support brackets for an additional turbopump assembly, requirement for only one turbine discharge duct and reduced potential for operational runaway of either of the pumps.

These benefits, however, raised several issues that needed to be addressed:

> Most notably among these issues were the compromise in shaft speed needed to place both pumps and turbines on the same shaft, the design of the inlet for the fuel pump, and thermal conditioning of the TPA [turbopump assembly] prior to engine start.[5]

With a common shaft, the arrangement of the elements on the shaft had to be determined. [*Redacted*]

At the time of termination of the Fastrac/MC-1 engine project, 7 turbopump assemblies had been built and 5 of the units had been tested. Also, at the time of project termination, two major turbopump assembly improvement efforts were in progress. These efforts focused on improving the durability of the interpropellant seal package and the elimination of rotating cavitation in the LO2 inducer.[6]

Dynamic Seals. A series of seals and vent cavities are located between the oxidizer and the fuel pump inducer/impellers in order to maintain separation between the propellants. The labyrinth seal controls overboard leakage from the oxidizer pump during operation. The LO2 seal drain cavity collects LO2 flowing from the labyrinth seal and helium flowing from the helium buffer seal and drains via an external vent to the atmosphere. The fuel seal drain cavity collects fuel flowing from the bellows seal and helium flowing from the helium buffer seal and drains via a vent to the atmosphere. The turbine end face seal limits RP-1 leakage into the turbine from the fuel pump.[7]

Combustion Devices

The combustion devices of the Fastrac/MC-1 engine include the *main injector, nozzle, gas generator, gas generator igniter,* and *thrust chamber assembly igniter*. The thrust chamber assembly consisted of a *low-cost injector* and *single-piece chamber/nozzle*.

Injector: The Fastrac injector design consists of only three components—an injector body, a gimbal block, and a faceplate. The costs of the Fastrac injectors were approximately $40,000 each, compared to $330,000 for a similar liquid oxygen/kerosene type then in use.

Early tests of the Fastrac injectors [*Redacted*] resulted in excessive heating (streaking) of the [*Redacted*] combustion chamber material, but the problem was overcome by using a computational fluid dynamic approach. Combustion stability of the injector system also was demonstrated in stability tests where 100 percent over-pressure spike, induced by a pyrotechnic charge, damped in the appropriate time. The thrust chamber assembly, which includes the injector and chamber/nozzle also "serves as the engine skeleton since the turbopump, gas generator, and turbine exhaust duct are all mounted directly to the chamber/nozzle. As a result, a test-verified model of the thrust chamber/nozzle component is integral to performing the dynamic loads calculation for the engine system…. The chamber/nozzle (referred to as the nozzle) is composed of two main composite layers and several metallic and over-bands…and weighs approximately 528 lb."[8]

Chamber/Nozzle: The chamber/nozzle design has only three parts—the liner material that is tape wrapped, cured, and machined to shape; a stainless-steel injector attach flange that is bonded to the liner, which is a filament wound overwrap material; and brackets for turbopump and actuator attachments. Costs for the flight chamber/nozzle were $120,000 per unit with all flight brackets installed, as compared to $1.2 million for the benchmark liquid cooled thrust chamber. This new chamber/nozzle technology was enabling several emerging aerospace corporations to scale up to useful thrust levels. In August 1997, a critical series of tests were completed involving the thrust chamber assembly at high pressure nearly identical to flight conditions. The combustion of the rockets propellants (mixture of liquid oxygen and kerosene) occurs in the thrust chamber assembly, which performed as designed, thus representing another indication that the Fastrac is an engineering breakthrough.[9] A Fastrac test failure, however, occurred in November 1997, when a chamber/nozzle liner failed due primarily to a material change at the supply vendor causing the NASA team, working with industry, to undertake additional work in developing corrective solutions.

Nozzle: The nozzle, which is the "structural backbone" of the Fastrac engine, is a one-piece composite, ablative thrust chamber. An ablative system has the following advantages: 1) no regenerative cooling is required for the nozzle, thus significantly reducing the complexity of the engine system and nozzle; 2) the fabrication time for the nozzle is only 4 to 6 weeks; and 3) the composite nozzle is very low cost compared with regenerative nozzles. The interface hardware for the nozzle was fabricated out of stainless steel and bonded to the composite with mechanical locks in high temperature and stress locations. The nozzles were fabricated and assembled at NASA Marshall by Thiokol-SEHO (Science and Engineering, Huntsville Operation) and ASRI (Allied Signal Research, Inc.). The nozzle, which was not designed for multiple-use, was designed to be launched at an altitude of 30,000 feet and was optimized for the ambient pressure at that altitude.[10] The failure of the nozzle to be capable of multiple flight use impacted the planned quick turnaround flight objective of the X-34. Replacement of the nozzle and thrust chamber required the entire engine to be removed from the vehicle and then reinstalled before the next flight.

Combustion Chamber Igniter: The Combustion Chamber (CC) employs a cylindrical igniter that initially stores the hypergolic propellant used to ignite the main combustion chamber. At startup, fuel from the turbopump flows through a small line, breaking a burst disk in the igniter inlet. The fuel pushes a piston inside the igniter forcing the stored hypergolic propellant to rupture another burst disk. The hypergolic flows into the main combustion chamber where it ignites.[11] The NASA Marshall Structural Assessment Report described the LOX/RP-1 main injector as follows:

> The MC-1 engine main injector contains a manifold for each of the engine liquid propellants that force the propellants to flow through a series of concentric channels between the injector core and copper faceplate. The propellants then flow through a pattern of injection holes in the faceplate causing them to mix together in the combustion chamber. The injector lies in the primary load path of the engine. It provides part of the backbone that many of the other engine components mate to and must carry all the engine thrust load as well as much of the dynamic loads generated by the engine and flight environment.[12]

The entire injector component—excluding the gimbal assembly—consisted of the core, LOX dome cap, and faceplate. As noted by Michael Shadoan and David Sparks:

> In order to achieve the value goals established by the FBC [faster, better, cheaper] policy, a review of traditional design practices was necessary. This internal reevaluation would ultimately challenge more conventional methods of material selection, design process, and fabrication techniques. The effort was highly successful. This "new way" of thinking has resulted in an innovative injector design, one with reduced complexity and significantly lower cost. Application of lessons learned during this effort to new or existing designs can have a similar effect on costs and future program successes.

The two NASA engineers added that the initial goal was to build a LO2/RP-1 injector that exhibits good performance and wall compatibility when operated with an ablative thrust chamber and nozzle assembly at a fraction of the cost of a conventional equivalent unit. The development injector was designed, fabricated, and tested in 16 months. The design was then transformed, with minor modifications, into the main injector for the Fastrac engine.[13]

The main injector was first hot-fire tested on July 25, 1997, and subsequently underwent at least 39 tests at the component level and 40 tests at the engine level. By July 2000, it had accumulated a total of 36 starts and 1,246 operating seconds on nozzle component tests, and a total of 42 starts and 857 seconds on nozzle engine tests.[14] The component testing included performance, stability, and thermal evaluations of the thrust chamber assembly during hot fire. The engine level testing was done at both the Horizontal Test Facility and at the B2 test stand at NASA Stennis. In November 1999 the testing was moved from Stennis to Rocketdyne's Alpha 1 position at their Santa

Susana Field Laboratory in California. The testing objective at Rocketdyne was to complete the development and verification testing of the engine system. The tests were planned to include full and extended duration runs, as well as calibration verification.[15]

The main injector fabrication cost (in FY 2000 dollars) totaled a quite reasonable $42,605 ($34,975 for the injector assembly excluding faceplate, $3,000 for the faceplate, and $4,630 braze preparation and braze). It was estimated that there would be a 10 percent cost reduction for orders of 10 or more injectors.[16]

The injector design status at project termination had one unresolved issue regarding potential pooling, which represented an explosive hazard, upon lighting the engine on X-34 at altitude with the tail section elevated and with the vehicle under drag-induced deceleration. The proposed solution was opening the main fuel valve earlier. Overall, the main injector was functioning well at program termination. An important lesson learned was that the "acoustic cavity must be thoroughly dried of RP-1 before subsequent ignition. Failure to do so has been shown to result in a confined-space explosion (detonation) capable of significant damage to the TCA [thrust chamber assembly]."[17]

Gas Generator: The gas generator furnished hot gas to spin up the turbopump. Designers evolved a mixed alloy design that was at once both rugged and light.

NASA Marshall's final summary report summarized the gas generator's purpose and qualities as

> …to supply uniform temperature, hot gas flow to the turbopump with minimum carbon soot deposition." [The generator started as] "a simple three-piece design. [*Redacted*] Although a few design improvements were made throughout the development program, this basic GG [gas generator] concept was ultimately tested and developed for the flight design.[18]
>
> The design life goal was for 9 starts and 1,200 seconds of operating time; "The nominal operating conditions of the GG were to be a 575 psia chamber pressure, 1600 deg. R hot gas temperature, 7.1 lbs/sec total propellant flow-rate, at a 0.30 oxidizer-to-fuel (O/F) ratio."[19]
>
> The original gas generator design started as a 15,000 pound thrust upper stage engine for a two-stage orbiter vehicle concept for the first X-34 program. One component test 15,000-pound gas generator was actually fabricated at NASA Marshall, but was never tested due to cancellation of the first X-34 program. This 15,000-pound GG was subsequently scaled up to satisfy the

> requirements of the 60,000 pounds thrust Fastrac engine development program for the X-34. The design approach was to minimize cost and the number of parts and to use standard design practices and fabrication processes wherever possible.[20]

The MC-1 engine Closeout Report noted the major Critical Design Review issue as follows:

> At around the time of the January 2000 CDR [Critical Design Review], the MC-1 engine project also had a change in philosophy from the more Spartan "faster, better, cheaper" to that of ensuring mission success. This change imposed additional requirements on the project that increased the cost and added to its schedule. Specific to the GG, more reliability and redundancy was desired in the GG ignition system. Indeed, engine level testing conducted after the January 2000 CDR indicated that the GG pyrotechnic ignition system needed to be improved to make it more reliable. That redesign process was almost complete at the time of the MC-1 program termination…. [the gas generator design status at project termination]. [*Redacted*] The boss configuration was changed slightly from the previous design to accommodate the newly redesigned GG igniter assembly. It was planned to incorporate the new igniter boss into the new [*Redacted*] chambers [*Redacted*]. There were no changes to the GG injector design in work or planned at the time of program termination.[21] Two major gas-generator lessons learned were: [*Redacted*].
>
> A requirement should have been made and enforced for better documentation, through a formal release process from the beginning of the program.[22] There were also lessons learned regarding the design status of lines and ducts at the termination of the project. At the time of termination of the MC-1 engine project, some redesigns of other engine components were in progress. While some of these changes would necessitate modifications in the lines and ducts, none of the changes were driven by lines or ducts issues. The lines and ducts component development team "was preparing for the verification phase of engine testing [and] The Design Verification Specification…was in the final stages of draft and was within a few weeks of being ready to baseline at the Configuration Control Board." The lines and ducts teams noted the following three lessons learned:

1. Significant problems later in the design and fabrication cycle were minimized and production time lessened by locating the design engineer at the manufacturing site.
2. Significant problems later in the design cycle can be avoided if top-level requirements are defined by the project.
3. Early in the MC-1 conceptual design, simplified structural models could not be quickly run to enable successive iterations of duct size and corresponding stiffness.... Recommend simplified methodology be developed to analyze engine systems at a conceptual level.

Historically, rocket engines have been performance-driven and therefore require minimum weight components. [*Redacted*] Robust design of wall thickness prevents these problems, does not add a significant amount of weight, and does not heavily penalize engine performance. Recommend engine system designs consider trading increased duct weight for operational flexibility and life.[23] The MC-1 engine Closeout Report noted that "[e]ngine valves provided a considerable share of the problems encountered during the engine test phase of the program. As a result, there were a number of lessons learned during the valve development that may be of some value." These are listed below:

- [Some] "off the shelf" [valve manufacturers] use a rule of thumb that if the design point of the new application is more than 15% greater or less than the original design point, then significant redesign or development is required. [Therefore], [w]hen considering buying an existing design, one must know the nominal points for that design, then compare the new application's requirements to those original design points. If the 15% rule is violated, this should alert one to address those concerns early in the project.
- If any engineering development is required, a fixed price contract is not the best means for procuring a valve. In development of an engine, because requirements typically are not fully defined, or may change, valves should not be procured under a fixed price contract.
- Because the design details of a component are not known when the procurement specification is written, some very basic requirements for the component are derived requirements. For the supplier to derive the operating temperature range for the valve, actuator and pilot valve, obviously the operating ambient environment range must be specified. In addition, it was recognized that the temperature of the fluid flowing through the valve would also effect the derived requirement. [Accordingly], [w]hen writing the specification, consider the off nominal operation.... In general, the requirement should probably be

specified for a steady state condition with the fluid dropped on and/or flowing through the valve, unless the users are given a hard requirement for a shorter duration.

- The MC-1 did not address the X-34 range safety requirements until late in the program. The X-34 range safety requirements had serious impacts on the valve designs. The range specify requirements such as structural safety factors, margin on thermal environments, margin on vibration test requirements, acceleration requirements, acceptance vibration, and acceptance thermal cycling to name a few. Mission requirements should be addressed early and incorporated into the procurement specifications.
- [*Redacted*] one might want to consider special instrumentation for engine development testing to determine the magnitude of pressure differential across the valve.
- [*Redacted*] acceptance tests should be performed under the same conditions as those checkouts performed at the engine level so that a direct comparison can be made to the as received condition.
- [*Redacted*] As part of the design review one should review sub-supplier designs and materials usage as well as those of the primary supplier.
- [*Redacted*]
- [*Redacted*]
- Most of the problems encountered during engine testing would have been identified earlier if more and/or better testing had been performed at the component level. As mentioned previously, the intent was to produce existing valve designs to minimize cost. A part of this cost is development testing. Therefore, some testing was omitted. [*Redacted*] Finding the problem during the engine test phase resulted in significant schedule delays and costs impacts associated with engine testing. During the failure investigation, after the seal failures on the engine, [*Redacted*] tests were performed to attempt to duplicate the failure. Once the decision was made to perform the [*Redacted*] testing, it took approximately one week to perform. Obviously the costs and schedule impacts would have been miniscule during the component development phase.
- Again, to minimize cost, neither spare valves nor spare parts were procured. This obviously proved to be a problem especially during the engine test phase. The problems experienced during the engine test phase and the lack of spare hardware made logistics of providing valves to the engine difficult. Engines were continuously cannibalized to provide valves to the engine currently being tested. The lack of spare valves or development valves also hindered engine development

> and failure investigations. Some testing could have been performed at MSFC, but hardware was not procured to support that effort. Another thing to consider is that during the engine development phase, the specified life of components will likely be exceeded. During engine testing, the cycle life on valves exceeded the specified cycle life. One way to deal with this is to procure enough valves so that when the cycle life is exceeded, they are simply replaced. Another more feasible approach may be to identify, early in the project, life limited parts and replace those parts at appropriate intervals. [*Redacted*][24]

Drive Electronics Assembly for Use in Ground Testing of the Engine

The MC-1 engine had its own avionics system that included the drive electronics assembly, the propulsion system controller and checkout computer.

Drive Electronics Assembly (DEA). The drive electronics assembly (DEA) had the following 10 characteristics:

1. single string
2. control of the valves were slaved to the propulsion system controller
3. RS-422 communications
4. flight-qualifiable design
5. capable of actuating 28 valves up to 2 amps
6. valve drivers had no current limiting
7. capable of controlling 2 thrust vector control EMAs at 8 hp
8. required 28 volts and 220 volts for operation. [220 volts was selected to stay below the critical corona level of around 230 volts DC]
9. used industrial-grade parts that had a temperature range of –20° to 85° C
10. could be hermetically sealed[25]

In regard to the design evolution of the drive electronics assembly, NASA Marshall originally planned to use commercial off-the-shelf (COTS) hardware except where specific MC-1 requirements could not be satisfied. In actual practice, COTS hardware could not satisfy the design requirements. [*Redacted*] Accordingly, the drive electronics assembly "then became a customer designed single unit, single string, with little or no intelligence and no recovery capability. This severely limited the operating philosophies later in the program for possible failure modes."[26]

While no issues came out of the drive electronics assembly Critical Design Review, several problems that needed to be resolved surfaced during testing. First of all, the valve drivers had no current-limiting capability. This could cause a problem if a short occurred in the cables or valves that were being driven. [*Redacted*] Another problem was that the assembly only had one processor for control of the valves. [*Redacted*][27]

The Closeout Report noted that the status of the drive electronics assembly [DEA] at termination was as follows: "Since the DEA was no longer required to be a flight design, the design was not changed to fix the problems found. The fix would have been a completed new design, which would have added significant cost and schedule slips. Therefore, the design was complete and the system had been operating for the duration of the entire test program. There were no DEA failures during the course of the engine testing."[28]

Instrumentation. The MC-1 engine instrumentation included 16 pressure transducers, 1 thermocouple, and 8 resistance devices. The transducers "provide static pressure measurements of 6 turbopump pressures, 2 thrust chamber pressures, 2 gas generator pressures, and 6 purge pressures." The thermocouple measured the gas generator turbine temperature and the 8 resistance temperature devices provided surface temperature measurements of a variety of engine parameters. The pressure transducers were manufactured by Taber, Stellar, and GP:50. The thermocouples were provided by RdF and ARI and the resistance temperature devices were manufactured by RdF.[29]

The X-34 Main Propulsion System Components and Subsystems

The main propulsion system (MPS) design had to support all phases of the X-34 vehicle operation, including pre-flight, captive carry, powered flight, unpowered return, safe abort, landing, and subsequent rapid turnaround operations.

Zonal Propulsion Organization

The propulsion system components of the X-34 were arranged in five zones throughout the vehicle. The first zone in the forward area of the X-34 contained the nitrogen and helium tanks that were used to pressurize the propellant tanks, activate the pneumatic components, purge engine components, and supply the reaction control system (RCS) thrusters with propellant. These tanks could store over 40 cubic feet of nitrogen and helium gas. The hardware for the RP-1 (kerosene) vent was also contained in zone one. The second, third, and fourth zones contained the propellant tanks. The forward propellant tank contained the RP-1 and the other two tanks contained the liquid oxygen (LOX). These three zones also contained the hardware to support LOX vent and tank pressurization and RP-1 feed and dump system. The fifth zone was designed to house the engine and a majority of the feed lines.[30]

NASA Marshall supported the X-34 in three ways—program management, providing the Fastrac engine (as Government furnished equipment), and initial design of the MPS. The Marshall Center's MPS team was responsible for supplying the MPS design, analysis, and drawings to Orbital.[31] Later in the program, however, Orbital assumed the design authority for the X-34's MPS. The company then worked closely with AVICA, assisted by NASA Marshall, to adapt the MPS design to the requirements of the X-34 vehicle.[32]

The MPS consisted of the propellant (LOX and RP-1 [kerosene]) fill, drain, feed, vent, and dump systems; and the helium and nitrogen purge, pressurization, and pneumatics systems. Orbital Sciences had responsibility for the reaction control system (RCS) as well, and, as the prime contractor, for the integration, procurement, and fabrication of all subsystems. MPS requirements were driven by the vehicle requirements, namely flying 25 times a year to Mach 8 and at an altitude of 250,000 ft. The overall technologies requirements for the vehicle were thermal protective system, quick turnaround operation, reusability, autonomous flight and landing, composite airframe structure and tankage design, flush air data system, and low-cost propulsion. To achieve the above design requirements, the MPS could not exceed 5,200 lbms (pounds-mass) with a further reduced requirement of 976 lbms excluding the engine, tanks, and the RCS.[33]

The most challenging requirements were the weight allocation of 976 lbms, dumping of propellant within 300 seconds for safe landing, and two-fault tolerance to loss of L-1011 crew. In addition, requirements for reusability, automated landing, and a design reliability of .99 had broad design and fabrication ramifications for the MPS. Also, a significant effort was required to ensure that the subsystems were integrated with each other and with the rest of the vehicle.[34]

Propulsion Subsystems

The subsystems used to manage the liquid propellants included the propellant tanks; LOX and RP-1 propellant feed subsystems; fill, drain, and dump subsystems; vent subsystems; pressurization subsystem; and pneumatic, purge, and "pogo" subsystems.[35]

Propellant Tanks. The propellants used by the Fastrac engine were kerosene (RP-1) as the fuel and liquid oxygen (LOX) as the oxidizer. Since RP-1 and LOX are nontoxic, they do not require special handling procedures for ground operations. The LOX tanks, which were manufactured by Spincraft of North Billerica, Massachusetts; and New Berlin, Wisconsin; were aluminum and were foam insulated. The tanks were compartmentalized into three separate tanks—one forward and one aft LOX and one RP-1 tank. Each tank was divided further into compartments—three for the forward and four for the aft LOX tanks and three for the RP-1 tank. The RP-1 tank, manufactured by R-Cubed, was an unlined graphite composite structure. This compartmentalization design feature, which applied to both the LOX and RP-1 tanks, provided a "robust abort" capability at any point during engine burn by enabling the X-34 to land on alternate runways in the event of engine shutdown. Shutdown of the engine would cause rapid deceleration of the vehicle due to drag that forces migration of fuel forward that in turn could cause a shift in the center of gravity of the vehicle. Compartmentalization of the fuel tanks would enable the vehicle to maintain center of gravity during a robust abort scenario. The propellant tank design characteristics are summarized in Table 1.[36]

Table 1: Propellant Tank Design Characteristics

Characteristics	LOX Tanks		RP-1 Tank
	Forward	Aft	
Diameter (feet)	4.50	4.50	5.17
Length (feet)	9.16	12.81	10.25
Number of compartments	3	4	3
Volume at 70° F (cubic feet)	123.6	180.9	190.5
Storage load (cubic feet)	8,542	12,502	9,398
Maximum operating pressure (psia)	75	75	100

Also, the propellant tanks had to minimize sloshing and yet still enable propellant delivery to the engine and allow for tank pressurization. This, along with the fact that the tanks were compartmentalized, led to the use of check valves that allowed propellant to flow aft and the ullage (the space within the fuel tank above the top of the liquid propellant) gas to flow forward.[37] Two types of check valves were provided to Orbital by ValveTech, Inc., of Phelps, New York. Both types (11070-1 and 11120-1) were flapper check valves that rely on torsional springs for preload. The main parts of flappers were aluminum and were anodized to prevent corrosion. The flapper valve designs evolved from the ones used previously for the leading edge active cooling system (LEACS) and the International Space Station temperature and humidity control system. The 11070-1 valve was nearly identical to the 11070-1 used on LEACS, with the only difference being the surface finish and seats. The 11120 valve was a new design based on the same concepts as the LRACS series of valve. The surface finish and seats of the 11070 needed to be modified as the 11070-1, because initial testing showed significant leakage around the seats, where the lapping compound used to polish the seats had created small flow passages. This led to the development of new lapping techniques and the use of new compounds to generate better surface finishes and tighter seating.[38]

The tank design also impacted the manner in which the tanks were filled. Filling from the aft end through the dump line required that each tank compartment be filled to the top before propellant spills over to the next compartment. This in turn required that the LOX tanks be properly chilled prior to spill over. This procedure was performed on the LOX qualification tank using liquid nitrogen (LN2). Qualification of the LOX fuel tanks was successfully completed by Orbital (with support from Spincraft) in April 1998. It was necessary to design a system between the two LOX tanks that would not trap an ullage pocket in the forward compartment of the aft tank. This was accomplished by adding check valves and liquid transfer lines. Maximum allowable propellant residuals were limited to just 5 percent of the initial propellant mass, for the X-34 had a do-not-exceed landing weight limit of 17,500 pounds-mass. Since the vehicle had to be nearly in a horizontal orientation during the propellant dump, siphons were added in all tanks in order to ensure that the optimum amount of propellant was removed for the given vehicle trajectories. During main engine burn, however, the vehicle would transition from the horizontal to a vertical orientation, which meant that with the siphons, the usable propellant would be reduced below the required 27,500 pounds-mass. To prevent this problem from occurring, the cover plates of the RP-1 and aft LOX tanks had two outlets—one for the dump/abort case and one for the flight mode. Computational fluid dynamics modeling, using FLOW-37, was used to simulate the drop, engine start, and tank depletion (burn and dump) transients in order to determine the optimum cut angles for the siphons and location of the low-level cutoff sensors.[39]

While the liquid oxygen propellant tanks for the first two X-34 vehicles were fabricated with aluminum, NASA Marshall worked on the development of tanks that would use composite material for the main barrel section, the two domed end pieces, and the internal domes. NASA Marshall was assembling two tanks under a cooperative agreement between Marshall and Lockheed Martin Michoud Space Systems in New Orleans. One tank was to be used for ground tests and the other tank was to be used for flight-testing in the third X-34 vehicle. The experimental tank passed a Systems Requirements Review in November 1999, and its Preliminary Design Review on December 10, 1999. Manufacturing of the first barrel section began in early December 1999. Pressure and temperature testing was scheduled between May and August 2000, and ground tests for the X-34 flight tank were scheduled to begin in mid-to-late August 2000.[40] The RP-1 tank, which was made of composite material, had a fuel capacity of 190 cubic feet and the 2 LOX tanks, which were made of aluminum, had a combined volume of 304 cubic feet.[41]

On February 8, 2000, NASA announced the successful completion of the curing process of the composite oxygen fuel tank. The composite tank was one of the 10 supplemental advanced technology experiments originally planned for the powered flight-testing portion of the X-34 program. It represented the largest composite oxygen tank made and would have been the first to fly on a launch vehicle. The composite tank represented a significant step in lowering the vehicle weight and obtaining the desired cost reduction from $10,000 per pound to $1,000 per pound. Two LOX fuel tanks were being assembled and tested at NASA Marshall under a 50/50 cooperative agreement between Marshall and Lockheed Martin Michoud Space Systems. The first tank, which was in the assembly process, was planned for use in ground tests. The second follow-on tank, which also was designed by Lockheed Martin, was planned for use on the flight tests. The curing process called for heating the composite cylinder in an autoclave at 350°F for approximately 4 hours at a pressure of 92 pounds per square inch. The cylinder consisted of between 18 and 80 plies that were saturated with epoxy resin, which hardens in the autoclave.[42]

The major components of the of the LOX fuel tanks were the main barrel section, two domed end pieces, and internal domes designed to prevent oxygen from shifting in flight and altering the flight characteristics of the vehicle. The two primary obstacles that needed to be overcome were: a) composites normally become brittle and crack when exposed to liquid oxygen at minus 320°F; and b) oxygen molecules are very small making it difficult to keep them from leaking through the threads that comprise the composite layers.[43]

Propellant Feed (LOX and RP-1) Subsystems. The LOX and RP-1 feed subsystems were designed to transfer propellants from the tanks to the engine with the X-34 in either the horizontal or vertical position. The engine has a gimbal requirement of +10/–8 degrees in pitch and ±3 degrees in yaw. This motion, combined with movement of the thrust structure and the engine under thrust, along with the translation of the aft LOX tank dome due to cryogenic shrinkage, added significant design requirements to the feed system. The developed LOX feed subsystem was a 4.5-inch Inconel tube with two dual axis gimbals, a z-axis pinned gimbal, and a pressure compensating elbow. The LOX tank required a sump to minimize the flow losses by turning the flow 90 degrees to avoid the engine thrust mount. The pre-valves used in the LOX subsystem were 4-inch pneumatic ball valves designed by Ketema. The same pre-valve was used in the RP-1 system. Due to geometric considerations, the valve had two actuator configurations.[44]

Due to weight and packaging concerns, the RP-1 system used the same trunk line for the feed, fill, and dump functions. The aft portion of the trunk line divided and had one valve for feed and one for dump and fill. The gimballing section of the RP-1 feed line consisted of a 4-inch Inconel tube. The RP-1 dump system also was used to fill the RP tank and had to be able to support filling in less than 45 minutes and dumping within the 300-second

X-34 trajectory window. The RP-1 and LOX tanks were filled serially with the vent valves open.[45] "The feed systems [were] designed around the pre-existing propellant tanks and vehicle structure…[and were] packaged within a very limited spatial envelope and routed around existing vehicle structure to the engine interface. Both the LOX and RP-1 systems include several components for the control/monitoring of propellant flow."[46]

The feed lines had several unique features. First of all, the lines were able to accommodate the large gimbal angle of ±9 degrees in pitch and ±3 degrees in yaw. This gimbal angle was necessary to perform the pitch up maneuver soon after the X-34 was to be dropped from the L-1011, and to damp disturbances through powered flight. An additional unique feature was the dual outlet design on the RP-1 tank. This feature accommodated the 4-inch pneumatic valves used for propellant control that were mounted directly to the tank covers. One valve was to be used during powered flight to allow propellant to be completely emptied from the tank when the acceleration vector was directed forward. The other valve connected to a sump that opened to the bottom of the tank. This valve was designed for use during propellant dumps, when propellants settle toward the bottom of the tank. This enabled a larger portion of propellants to be dumped, which in turn lessened the weight at landing. The feed lines also implemented technology transferred from the aircraft industry to improve operability of the main propulsion system.[47]

A problem that had to be prevented related to a combination of the design of the feed subsystem and the X-34 maneuver following release from the carrier aircraft. As J. P. McDonald noted:

> Upon release from the carry vehicle, the X-34 executes a negative "g" maneuver to quickly distance itself from the carry vehicle prior to engine start. The combination of this maneuver and the feed system design must not result in the ingestion of gaseous ullage from the propellant storage tanks into the feed system. Such a gas pocket, from either the LO2 or RP-1 systems, entering a main engine turbopump will result in turbopump damage and possibly catastrophic loss of the X-34 vehicle. Computational fluid dynamic (CFD) simulations of this ullage motion provide assurance that ullage will not be ingested into either feed system at engine start. A similar ullage ingestion issue exists during the terminal drain phase for either the LO2 or RP-1 propellant tanks. Thus, CFD simulations of propellant tank terminal drain were also performed to help determine the appropriate time for engine shutdown.[48]

LOX Fill and Dump Subsystem. As described by Robert H. Champion of NASA Marshall and R.J. Darrow, Jr., of Orbital Sciences Corporation:

> The LO2 Fill and Dump subsystem provides for the transfer of propellants overboard when the vehicle is in a roughly horizontal orientation during flight and provides a means of filling the tanks during ground operations. The line must provide sufficient flow for filling the LO2 tanks in no greater than 60 minutes and dumping within the required 300 second trajectory window. This line exits the aft LO2 tank aft manhole cover, is routed down the starboard side of the vehicle, and exits through the aft bulkhead. The fill dump line is a 4" Inconel tube with a universal bellows, a flow-meter, the same 4" Ketema control valve, and has a quick disconnect GSE fitting 4" outside of the aft bulkhead. The LO2 dump line is supported by one fore-aft sliding bracket.[49]

RP-1 Feed, Fill, and Dump Subsystem. AVICA, a Meggitt Aerospace Company, was selected to manufacture the fill, feed, vent, and dump lines for the Fastrac engine. These lines were made of 625 Inconel and ranged in wall thickness from 0.049 to 0.083 inches. All of the main propulsion system fill, feed, vent, and dump lines used lightweight, low-profile AS1895 flanges, which also are used in commercial and fighter aircraft.[50]

The lines performed the functions of filling the LOX and RP-1 tanks, providing the proper inlet conditions for the main engine, venting the tanks to prevent an over pressurization, and dumping LOX and RP-1 prior to landing. The RP-1 system used the same trunk line for the feed, fill, and dump functions due to weight and packaging concerns. The aft end of the trunk branched and had one valve for feed and one valve for dump and fill. The aft portion of the RP-1 line had to accommodate the vehicle structural deflections and engine gimballing while providing propellant flow to the engine. The forward end of the subsystem had two isolation valves—one for feed and one for dump. The main trunk had a pressure compensating elbow at the forward end and four bellows along the line at the bulkheads in order to handle the motion of the RP-1 tank. The feedline was supported at the bulkheads by a combination of sliding and fixed supports. The RP-1 dump subsystem also was used to fill the tank, which must be done within a 45-minute time frame. The LOX tanks would have been filled serially with the vent valves open. The feed system contained free bellows, gimbal joints, restrained bellows, articulated bellows, pin joint, and pressure compensated elbows. These components were used to accommodate the gimbaling of the engine and the loads and deflections in the feed system.[51]

Pneumatic pre-valves were used to control the flow of propellants during fill, drain, and engine operation, and a pneumatic vent/relief valve was used to vent the LOX and RP-1 tanks. The valves (2.5-inch pneumatic vent/relief valve and 4-inch pneumatic ball valve) were supplied by Senior Flexonics Ketema Division, of El Cajon, California.[52] This 2.5-inch vent and relief valve would be open during tanking to allow for gas to escape and closed after tanking was completed. It had a heritage going back to 1958, when it was first designed and used for the Thor booster, and since that time it been used on virtually all United States cryogenic liquid-fueled launch vehicles.[53] The 4-inch Ketema ball valve, which was used as a pre-valve in the X-34 Main Propulsion System, had a heritage dating to the Delta II LOX and RP-1 fill and drain valve.[54]

Vent Subsystems. "The vent subsystems provided over-pressure relief, propellant conditioning during captive carry, and venting during filling. The tank vent subsystems for both the LOX and RP-1 used a common design 2.5-inch Ketema vent/relief valve. The vent systems had tubes, internal to the tanks, which would allow ullage pickup in both the vertical and horizontal orientation. The LOX internal vent tube had a liquid level sensor on the end to determine when the tank was full.… A bypass relief valve was required to meet the two-fault tolerance requirement, due to the self-pressurization capability of cryogens. The RP-1 tank would have been filled until it spilled into the vent line and then a ground support equipment (GSE) flow-meter would be used to adjust the level appropriately."[55]

Pressurization Subsystem. The pressurization functions were designed "to maintain the propellant pressure at the engine inlet during flight and force the propellants out of the tanks during a dump, while not exceeding the tank operating pressures of 75 psi for LOX and 100psi for RP-1." This system had 48.5 lbm (pounds-mass) of usable helium, and 76 lbm total helium stored in four Structural Composite Industries (SCI) bottles with 6.2 square feet storage for each bottle at 5,000 psi pressure regulated to 350 psi. Solenoid valves, which are controlled by the avionics that sense the tank pressure, were used to meter gas flow to the propellant tanks in order to maintain the proper pressure level. Check valves were used in the lines to prevent any mixing of the propellants and on the LOX side to keep the cryogens from damaging the solenoids.

The pressurant was introduced into the tanks through a diffuser that was designed to operate when submerged or dry. The pressurant tanks were connected by a 1-inch manifold. The RP-1 and LOX lines branched to .75-inch and 1-inch respectively downstream from the regulators. The RP-1 pressurization subsystem had two solenoid valves in parallel, two check valves in series an orifice, and was completed by the tank diffuser. The LOX system was the same as the RP-1 system, but with the addition of a third check valve that was needed to make the solenoids two fault tolerant to seeing LOX or GOX [gaseous oxygen]. The solenoids were not qualified for oxygen service. The parallel solenoids on the pressurization legs were the only functional redundant components in the main propulsion system. Failure of one of the pressurization solenoids would prevent a normal flight and also prevent the dumping of propellants; therefore, engineers deemed it prudent to provide redundancy of this component for mission assurance.[56]

Table 2 shows component type and function of the pressurization and pneumatic functions.[57]

Table 2: Pressurization and Pneumatic System Components

Component Type	Component Function
Pressurant tanks	Store pressurant gas for use in each subsystem.
Solenoid valves	Isolate pressurant from propellant tanks, pneumatic valves, engine spin start, and the engine IPS. Valves are cycled to control propellant tank pressure.
Latching valve	Isolates the pressurant tanks from downstream components.
Regulator	Reduces pressurant supply pressure to tanks, pneumatic valve, engine spin start, and the engine IPS operating pressures.
Filter	Prevents contamination of propellant and pressurization system components.

Pneumatics, Purge, and Pogo Subsystems. R. H. Champion, of NASA Marshall, and Richard J. Darrow, Jr., of Orbital, described the pneumatic and purge subsystems as follows:

> The pneumatic and purge subsystems provide[d] helium (flight) and nitrogen (ground operations) gases for actuation of the MPS [main propulsion system] and engine pneumatic valves, helium for the engine turbopump spin-start, engine start purge, engine shutdown purges, and inter-propellant seal (IPS) purge, and helium and nitrogen for post flight "safing" operations. This subsystem also provide[d] for ground purges of the feed lines to prevent contamination during engine removal.... The pneumatic purge subsystem use[d] 1 SCI bottle in the front pressurization bay and 2 Lincoln Composite bottles located in the aft end of the vehicle, under the aft LO2 tank.... The pneumatic subsystem store[d] 25.5 lbm [pounds-mass] of helium with 16 lbm of the gas usable. Most of the pneumatic purge helium [was] required

> during engine startup for the spin-start (0.5 lbm/s for 2 seconds) and startup purges (0.51 lbm/s for 2 seconds). This 1.1 lbm/s flow [was] the driving requirement for sizing many of the components and lines. A ½″ trunk line feeds the aft two bottles from the front and then a 1″ manifold is routed to the ¾″ line for the spin-start and IPS [inter-propellant seal] The pneumatic and purge subsystem contain[ed] two ¾-inch regulators, two ¼-inch latching solenoid valves, two 1-inch latching solenoid valves, three ¾-inch blanking valves, eight 3-way solenoid valves, four ¾-inch check valves, and two ¼-inch filters.… Transient analysis of the complete system was done to determine reaction times, volume requirements, regulator set pressures, and flowrates.[58]

Temperature Sensors

Three temperature sensor configurations were used on the main propulsion and reaction control systems. All three configurations were supplied by the RdF Corporation, of Hudson, New Hampshire, and employed design features that the company had previously used in other units that were approved for space service. The temperature sensors were used to measure gas and liquid temperatures either directly or indirectly. The first configuration was an immersion probe assembly that contained a 1,000-ohm platinum resistance temperature detector that was capable of operation in specified over a temperature range of –350°F to 400°F. This configuration approach had been used by the military and by other aerospace contractors over the previous 40 years. The second configuration also consisted of a 1,000-ohm platinum resistance temperature, but this sensor was a small capsule “strap-on” sensor that was welded to a stainless-steel pipe clamp for mounting on the outside of the fluid lines. The third sensor configuration was a Kapton-encapsulated 1,000-ohm platinum resistance temperature detector that had 10 feet of Teflon-insulated lead wire, which was used to detect any entrapment of air in the laminate. Lead wires of this design were welded to the sensor leads, then the sensor and lead were laminated between layers of Kapton. Qualification for all three configurations was accomplished by a combination of inspection, test, and analysis.[59]

Reaction Control System

The reaction control system for the X-34 was a cold gas system that used nitrogen gas. The system was operated in three modes—load, active, and safe. The nitrogen gas was stored in two high-pressure composite bottles, which were isolated from the rest of the system by a latching piloted solenoid valve. When activated, the system was designed for the nitrogen to flow toward a thruster manifold through a high-pressure regulator. The RCS consisted of thruster nozzles, pressurant bottles, and a feed system. The feed system consisted of a regulator, solenoid valves, and high-pressure tubing. The baseline nozzles selected were simple conical divergent sections that are typically used to provide a shock-free propellant expansion. Two high-pressure vessels designed and produced by SCI and Lincoln Composites were chosen to meet the storage requirement of 7.1 cubic feet. The feed system consisted of high-pressure tubing that directed the high-pressure nitrogen from the storage bottles located in the front end of the vehicle through a single 1-inch tube to each of the 10 thruster assemblies. The thruster assemblies consisted of two pilot-operated solenoid valves in series that were connected to nozzles customized for the X-34. The tube routing and placement of the components in the system were designed to ensure that pressure drops were nearly equal at each nozzle, thus providing a consistent level of thrust from each thruster.[60]

X-34 Avionics System

The X-34 avionics system controls were designed to monitor all vehicle systems. Orbital design team members noted that "[a]vionics distributed through the vehicle provide control and monitoring of all functions. Primary control is handled through the flight computer that sends commands to and receives critical telemetry from each utility controller. Utility controllers in the nose, wing, and engine bay communicate directly with main propulsion system (MPS) and reaction control system (RCS) components and other vehicle subsystems."[61]

Propulsion System Controller (PSC) and PSC Checkout Computer (PCOC). The propulsion system controller and checkout computer were not intended to go beyond test bed application but were designed so that the system could be upgraded to flight status hardware. The PSC controlled the operation of the engine. The PCOC was used to send commands to the PSC and to display data coming from the PSC. The PCOC was a commercial Dell PC with commercial graphic interface software. The plan was to create the Avionics subsystem as cheaply as possible in accordance with the lower cost of access to space objective. The system, which was designed to be portable, had no custom hardware. All computer boards were commercially available.

Main Propulsion System Assessment and Lessons Learned

Richard J. Darrow, Jr., of Orbital Sciences Corporation; Yogesh B. Parikh, of AVICA; Stan Summers, of Senior Flexonics Ketema Division; Taila Shnayder, of Marotta Scientific Controls, Inc.; Jeff Pulano, of ValveTech, Inc.; and Arthur W. Pearson of RdF Corporation, presented a multi-partner paper to the prestigious AIAA Joint Propulsion Conference and Exhibit in July 1998. The paper summarized the work of the engineering teams in regard to the design of the main propulsion system. They noted that "A propulsion system design has been developed for X-34," and concluded, "that meets program requirements, supports mission operations, and will demonstrate key RLV [reusable launch vehicle] technologies. The design has been completed and a successful CDR [Critical Design Review] has been held. The system is now in the manufacturing and testing phase."[62]

In another paper presented at the same conference, R. H. Champion, Jr., and Richard J. Darrow, Jr. (a co-author on the previously noted paper noted regarding program accomplishments), enumerated six lessons learned:

1. the main propulsion system Program design team should not have been brought up to full staff level until the system design freeze was completed;
2. a significant number of subsystem components were changed between the "rough order of magnitude" bids from vendors and the final negotiations and contract agreements, thus causing significant rework by the designers and analysts;
3. the initial design drawings were not vendor specific, thus causing necessary changes to be made in order to reduce cost and improve delivery time;
4. the use of a common CAD system is a requirement for a program where there are numerous interface concerns between two organizations (In the case of the X-34, the Orbital and NASA Marshall CAD models were always out of sync by a few weeks);
5. the suppliers of the design and analysis should have formal notification and acknowledgment on all changes to specifications, interface drawings, and other engineering change notices that impact the subsystems, otherwise the supplier will inevitably get out of sync with the prime contractor; and
6. in an experimental flight program, with a compressed schedule and concurrent engineering, changes are inevitable, therefore, the teams that survive are the ones that learn how to adjust to this pace and environment.[63]

Endnotes

1. Michael D. Shadoan and David Sparks, "Low-Cost Approach to the Design and Fabrication of a LO2/RP-1 Injector," paper presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 16–19, 2000, p. 1, AIAA-2000-3400.
2. Richard J. Darrow, Jr., Yogesh B. Parikh, Stan Summers, Taila Shnayder, Jeff Pulano, and Arthur W. Pearson, "X-34 Propulsion System Components," paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, pp. 1–2, AIAA-98-3520.
3. Barber-Nichols, Inc., of Arvada, Colorado, was founded in 1966 by Bob Barber and Ken Nichols. The company specializes in the design and production of turbomachinery—including pumps, generators, motors, and controllers for aerospace, cryogenic, defense, and energy applications. Barber-Nichols' work on the turbopump for NASA Marshall's Fastrac engine started in 1996 marked their entry into the space launch industry. See *http://www.barber-nichols.com/about-us*, accessed July 7, 2013.
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5. NASA Marshall Space Flight Center, "MC-1 Engine Project Termination Closeout Report," MSFC-RPT-3195, December 2001, pp. 54–55, NASA Marshall History Office Archives, Huntsville, AL. [ITAR document]
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“MC-1 Engine: Combustion Chamber Igniter (Redesign) Structural Assessment Report,” April 2001, ED22-01-66, NASA Marshall History Office Archives, Huntsville, AL.
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13. Shadoan and Sparks, “Low Cost Approach,” pp. 1–3.
14. NASA Marshall, “MC-1 Engine Project Termination Closeout Report,” p. 88. [ITAR document]
15. Ibid., pp. 4–7. [ITAR document]
16. Shadoan and Sparks, “Low-Cost Approach to the Design and Fabrication of a LO2/RP-1 Injector,” p. 4.
17. NASA Marshall, “MC-1 Engine Project Termination Closeout Report,” p. 72. [ITAR document]
18. Ibid., p. 93. [ITAR document]
19. Ibid., p. 93. [ITAR document]
20. Ibid., p. 92. [ITAR document]
21. Ibid., p. 97. [ITAR document]
22. Ibid., p. 98. [ITAR document]
23. Ibid., pp. 159–160. [ITAR document]
24. Ibid., pp. 150–154. [ITAR document]
25. Ibid., p. 162. [ITAR document]
26. Ibid., p. 163. [ITAR document]
27. Ibid., p. 164. [ITAR document]
28. Ibid. [ITAR document]
29. Ibid., pp. 161, 162. [ITAR document]
30. R. Bryan Sullivan and Brian Winters, “X-34 Program Overview,” paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, pp. 6–7, AIAA 98-3516.
31. R. H. Champion, Jr. and R. J. Darrow, Jr. “X-34 Main Propulsion System Design and Operation,” paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH July 13–15, 1998, pp. 1–2, AIAA 98-4032.
32. R. Bryan Sullivan, e-mail to the author May 6, 2014.
33. Champion, and Darrow, “X-34 Main Propulsion System Design and Operation,” passim.
34. Champion, and Darrow, “X-34 Main Propulsion System Design and Operation,” pp. 1–2.
35. As mentioned in a previous chapter, “pogo” is not a technical acronym. Rather, it is a descriptive word describing the fluctuations in acceleration

that stem from combustion instability, which induces changes in flow rates and pressures that, in turn, make the instability and acceleration variations self-sustaining. Pogo is a persistent problem in astronautics.

36. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," p. 3.
37. A check valve is a valve that normally enables fluid or gas to flow through it in only one direction. It is a two-port valve—one for fluid or gas to enter and one for fluid or gas to leave. Ullage is the space within a fuel tank above the liquid propellant.
38. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," p. 4.
39. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," pp. 1–3; Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components" pp. 1–3.
40. Marshall Space Flight Center, "NASA/Industry Completes First Component for Experimental X-34 Composite Oxygen Tank," NASA press release #00-029, February 8, 2000.
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42. Dave Drachlis, "NASA/Industry Completes First Component for Experimental X-34 Composite Oxygen Tank," NASA press release #00-029, February 8, 2000.
43. Ibid.
44. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," p. 4.
45. Ibid.
46. J. P. McDonald, R. B. Minor, K. C. Knight, R. H. Champion, Jr., and F. J. Russell, Jr., "Propellant Feed Subsystem for the X-34 Main Propulsion System," paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, OH, July 13–15, 1998, p. 3, AIAA 98-3517.
47. Sullivan and Winters, "X-34 Program Overview," pp. 6–7.
48. McDonald, Minor, Knight, Champion, and Russell, "Propellant Feed Subsystem for the X-34 Main Propulsion System," p. 2.
49. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," p. 4.
50. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," pp. 4–6.
51. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," pp. 1–3; Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," pp. 4–6.

52. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," p. 6.
53. Ibid.
54. Ibid., p. 7.
55. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," pp. 4–5, quotation on p. 4.
56. Ibid., p. 5.
57. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," p. 8; Champion and Darrow, "X-34 Main Propulsion System Design and Operation," pp. 1–3.
58. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," p. 5.
59. Ibid., p. 10.
60. Ibid., p. 6
61. Orbital Sciences Corporation, "X-34 Technology Demonstrator Summary" (Dulles, VA: Orbital Sciences Corporation, March 5, 2013), p. 5.
62. Darrow, Parikh, Summers, Shnayder, Pulano, and Pearson, "X-34 Propulsion System Components," p. 10.
63. Champion and Darrow, "X-34 Main Propulsion System Design and Operation," pp. 8–9.

Acronyms and Abbreviations

AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFMC	Air Force Materiel Command
AIAA	American Institute of Aeronautics and Astronautics
A/L	approach and landing
ALT	Approach and Landing Tests
AMD	Angular Momentum Desaturation
AOA	angle of attack (also α and alpha, as in "high α" or "high alpha")
APAS	Aerodynamic Preliminary Analysis System
APU	auxiliary power unit
ARC	Ames Research Center
ASL	American Space Lines
ASME	American Society of Mechanical Engineers
ASRI	AI Signal Research, Inc.
ASRM	Advanced Solid Rocket Motor
ASTP	Advanced Space Transportation Program
ATP	Authority to Proceed
BMDO	Ballistic Missile Defense Organization
BNI	Barber-Nichols, Inc.
BTU	British thermal unit
CAD	computer-aided design
CAM	computer-aided manufacturing
CAN	Cooperative Agreement Notice
CC	combustion chamber
CCAFS	Cape Canaveral Air Force Station
CCB	Configuration Control Board
CCD	charge-coupled device
CDR	Critical Design Review
CFD	computational fluid dynamics
cg	center of gravity
CM	command module
COTS	commercial off-the-shelf
CPU	central processing unit

DARPA	Defense Advanced Research Projects Agency
DD&T	design, development, and testing
DDT&E	design, development, test, and evaluation
DEA	drive electronics assembly
DFRC	Dryden Flight Research Center
DGPS	Differential Global Positioning System
DOD	Department of Defense
DOT	Department of Transportation
DRM	Design Reference Mission
EA	Environmental Assessment
EAFB	Edwards Air Force Base
EDV	EELV-derived vehicle
EELV	evolved expendable launch vehicle
EGSE	electronic ground control equipment
EIS	Environmental Impact Statement
ELV	expendable launch vehicle
E/W	energy over weight
FA	Flight Assurance
FAA	Federal Aviation Administration
FADS	flush air data system
FBC	faster, better, cheaper
FBV	fuel bleed valve
FCC	flight control computer
FCS	flight control system
FMECA	failure modes and effects criticality analysis
FRD	Facility Requirements Document
FRSI	flexible reusable surface insulation
FTP	flight test program
FTPG	Flight Test Planning Group
FTS	flight termination system
F/W	thrust-to-weight ratio
FY	fiscal year
g	acceleration due to gravity
GAO	General Accounting Office [renamed Government Accountability Office]
GEO	geosynchronous orbit
GFE	Government furnished equipment
GFP	Government funded program
GG	gas generator
GGFV	gas generator fuel valve
GLPV	gas generator LOX purge valve

GN&C	guidance, navigation, and control
GOX	gaseous oxygen
GPS	Global Positioning System
GRTLS	gliding return to launch site
GSE	ground support equipment
HABP	Hypersonic Arbitrary Body Program
HAFB	Holloman Air Force Base
HQ	Headquarters
HSRB	hypersonic suborbital reusable booster
HTF	horizontal test facility
HTOL	horizontal takeoff and landing
IAF	International Astronautical Federation
ICBM	intercontinental ballistic missile
IFV	igniter fuel valve
I-HEAT	Internet-based Heat Evaluation and Assessment Tool
IMU	Inertial Measuring Unit
INS	Inertial Navigation System
IRBM	intermediate-range ballistic missile
ISS	International Space Station
I_{sp}	specific impulse
ISTP	Integrated Space Transportation Plan
JP-4	jet fuel [a 50-50 blend of kerosene and gasoline]
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LASRE	Linear Aerospike Research Experiment
lbm	pounds-mass
LCBT	low cost booster technology
LCC	life-cycle cost
LCT	low cost technologies
L/D	lift-to-drag ratio
LEO	low-Earth orbit
LeRC	Lewis Research Center
LFBB	liquid fly-back booster
LH2	liquid hydrogen
LHB	low heat blankets
LMA	Lockheed Martin Astronautics
LN2	liquid nitrogen
LOX	liquid oxygen (also LO2)
LRU	line replaceable units

MALIBOO	manned air-launched intermediate booster
MCO	Mars Climate Orbiter
MGS	Mars Global Surveyor
MGSE	mechanical ground support equipment
MOA	Memorandum of Agreement
MOV	mobile operations vehicle; main oxidizer valve
MPIAT	Mars Program Independent Assessment Team
MPL	Mars Polar Lander
MPS	main propulsion system
MSFC	Marshall Space Flight Center
MTBCF	mean time between critical failures
MTBF	mean time between failures
NAC	NASA Advisory Council
NACA	National Advisory Committee for Aeronautics
NAE	National Academy of Engineering
NAL	National Aerospace Laboratory (Japan)
NAS	National Academy of Sciences
NASDA	National Space Development Agency (Japan)
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
NLS	National Launch System
nmi	nautical miles
NMP	New Millennium Program
NRA	NASA Research Announcement
NRC	National Research Council
NRE	Non-Recurring Engineering
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSTP	National Space Transportation Policy
Nz	normal acceleration
OAST	NASA Office of Aeronautics and Space Technology
OBV	oxidizer bleed valve
OIG	Office of Inspector General
OMB	Office of Management and Budget
OML	Outer Mold Line
OSC	Orbital Sciences Corporation
OSMA	Office of Safety and Mission Assurance
OSTP	Office of Science and Technology Policy
OTA	Office of Technology Assessment
OTS	off the shelf
P&W	Pratt and Whitney

PCOC	Propulsion System Controller Checkout Computer
PDR	Preliminary Design Review
PDT	Product Development Team
PIRA	Precision Impact Range
PSC	propulsion system controller
psf	pounds per square foot
psi	pounds per square inch
psia	pounds per square inch, absolute
psid	pounds per square inch, differential
PTA	Propulsion Test Article
PTM	power transfer module
R	Rankine scale
R&D	research and development
RBCC	rocket-based combined cycle
RBD	reliability block diagrams
RCS	reaction control system
RCTS	reusable cryogenic tank system
RDT&E	research, development, test, and evaluation
RFS	reusable first stage
RI	Rockwell International
RLV	reusable launch vehicle
RM&S	reliability, maintainability, and supportability
RMP	Risk Management Plan
ROM	rough order of magnitude
RP-1	rocket grade kerosene
RPA	remotely piloted aircraft
RSRM	redesigned solid rocket motor
SBTD	small booster technology demonstrator
SCI	Structural Composite Industries
SDF	system design freeze
SDIO	Strategic Defense Initiative Organization
SI	Structural Instrumentation
SIRCA	silicone-impregnated ceramic ablator tiles
SLI	Space Launch Initiative
S&MA	Safety and Mission Assurance
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
SSTO	single-stage-to-orbit
SSTO-A/R	single-stage-to-orbit air-breather/rocket
SSTO-R	single-stage-to-orbit-rocket
STAS	Space Transportation Architecture Studies

STME	Space Transportation Main Engine
STPO	Space Transportation Program Office
T&E	test and evaluation
TA	Task Agreement
TAAG	Technical Assessment Advisory Group
TAEM	terminal area energy management
TAV	transatmospheric vehicle
TCA	thrust chamber assembly
TCS	thermal control system
TEA	triethylaluminum
TEB	triethylborane
TMT	transportation mate trailer
TPS	thermal protection system
TRL	Technical Rating Level
TsAGI	Tsentralniy Aerogidrodinamicheskiy Institut (Central Aero-Hydrodynamic Institute, Russia)
TSTO	two-stage-to-orbit
TVC	thrust vector control
T/W	thrust-to-weight ratio
UAV	uninhabited aerial vehicle
ULA	United Launch Alliance
USAF	United States Air Force
UTC	United Technologies Corporation
VTO-HL	vertical takeoff and horizontal landing
VTOL	vertical takeoff and landing
W	watts
WIRE	Wide-Field-Infrared-Explorer
WSMR	White Sands Missile Range
WB	winged body

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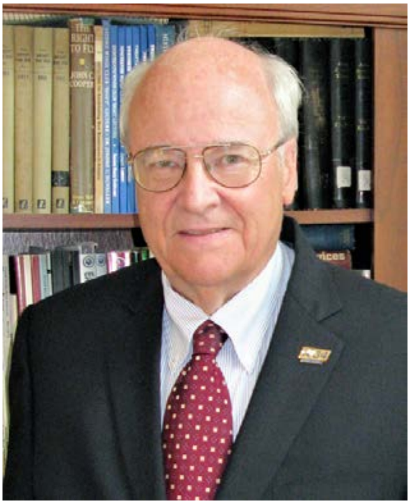

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