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Single-Stage-to-Orbit — Meeting the Challenge

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SINGLE-STAGE-TO-ORBIT — MEETING THE CHALLENGE

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ABSTRACT

There has been and continues to be significant discussion about the viability of fully reusable, single-stage-to-orbit (SSTO) concepts for delivery of payloads to orbit. Often, these discussions have focused in detail on performance and technology requirements relating to the technical feasibility of the concept, with only broad generalizations on how the SSTO will achieve its economic goals of greatly reduced vehicle ground and flight operations costs. With the current industry and NASA Reusable Launch Vehicle Technology Program efforts underway to mature and demonstrate technologies leading to a viable commercial launch system that also satisfies national needs, achieving acceptable recurring costs becomes a significant challenge.

This paper reviews the current status of the Reusable Launch Vehicle Technology Program including the DC-XA, X-33, X-34 flight systems and associated technology programs. The paper also examines lessons learned from the recently completed DC-X reusable rocket demonstrator program. It examines how these technologies and flight systems address the technical and operability challenges of SSTO whose solutions are necessary to reduce costs. The paper also discusses the management and operational approaches that address the challenge of a new cost-effective, reusable launch vehicle system.

NOMENCLATURE

ALT	Advanced Launch Technology
APS	Auxiliary Propulsion System
APU	Auxiliary Power Unit
BMDO	Ballistic Missile Defense Agency
CAN	Cooperative Agreement Notice
CFD	computational fluid dynamics
DOD	Department of Defense
DC-X	Delta Clipper Experimental
DC-XA	Delta Clipper Experimental Advanced
EELV	Evolved Expendable Launch Vehicle
Gr-Ep	graphite epoxy
LaRC	Langley Research Center
LEO	Low Earth orbit
LH2	liquid hydrogen
LO2	liquid oxygen
MSFC	Marshall Space Flight Center
NRA	NASA Research Announcement
OSTP	Office of Science and Technology Policy
RLV	Reusable Launch Vehicle
SSTO	single stage to orbit
STS	Space Transportation System
TPS	Thermal Protection System

INTRODUCTION

Cost 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 space 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.

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Providing a space transportation system with low-cost, reliable operations and a low life-cycle cost were the major requirements in the NASA Access to Space Study completed in January 1994. The study recommended the development of a fully reusable, all rocket SSTO system to replace the Space Shuttle by the year 2008.[1] To achieve this goal would require cultural changes in operations and management strategies and a technology maturation program coupling ground tests, flight experiments, and X-vehicle demonstrations. To further these goals, an Advanced Launch Technology (ALT) Program was initiated by NASA in February 1994 leading to NASA Research Announcements (NRA) with industry to pursue a number of advanced structures, thermal protection systems, and propulsion technologies including fabrication of test articles.

In August 1994, the White House Office of Science and Technology Policy (OSTP) issued a National Space Transportation Policy by which the Department of Defense (DOD) would lead the improvement and evolution of the current expendable launch vehicle fleet including appropriate technology development. The policy also designated NASA as "the lead agency for technology development and demonstration of next-generation reusable space transportation systems." The DOD program has subsequently become the Evolved Expendable Launch Vehicle (EELV) program, while the NASA program has become the Reusable Launch Vehicle (RLV) Technology program.

The RLV Technology program has as its goal the development of an all rocket, fully reusable SSTO. It has several major elements: the X-33 Advanced Technology Demonstrator (ATD), the X-34 Small Reusable Booster, the upgraded DC-XA Flight Demonstrator, and the RLV core technology programs (initiated by the Advanced Launch Technology program through the NRAs). The purpose of this paper is to review the current status of the Reusable Launch Vehicle Technology program. It examines how these elements address the technical and operability challenges of SSTO whose solutions are necessary to reduce recurring costs. The paper also examines lessons learned from the DC-X reusable rocket demonstrator program. Management and operational approaches that address the challenge of a new cost-effective, reusable launch vehicle system are also discussed.

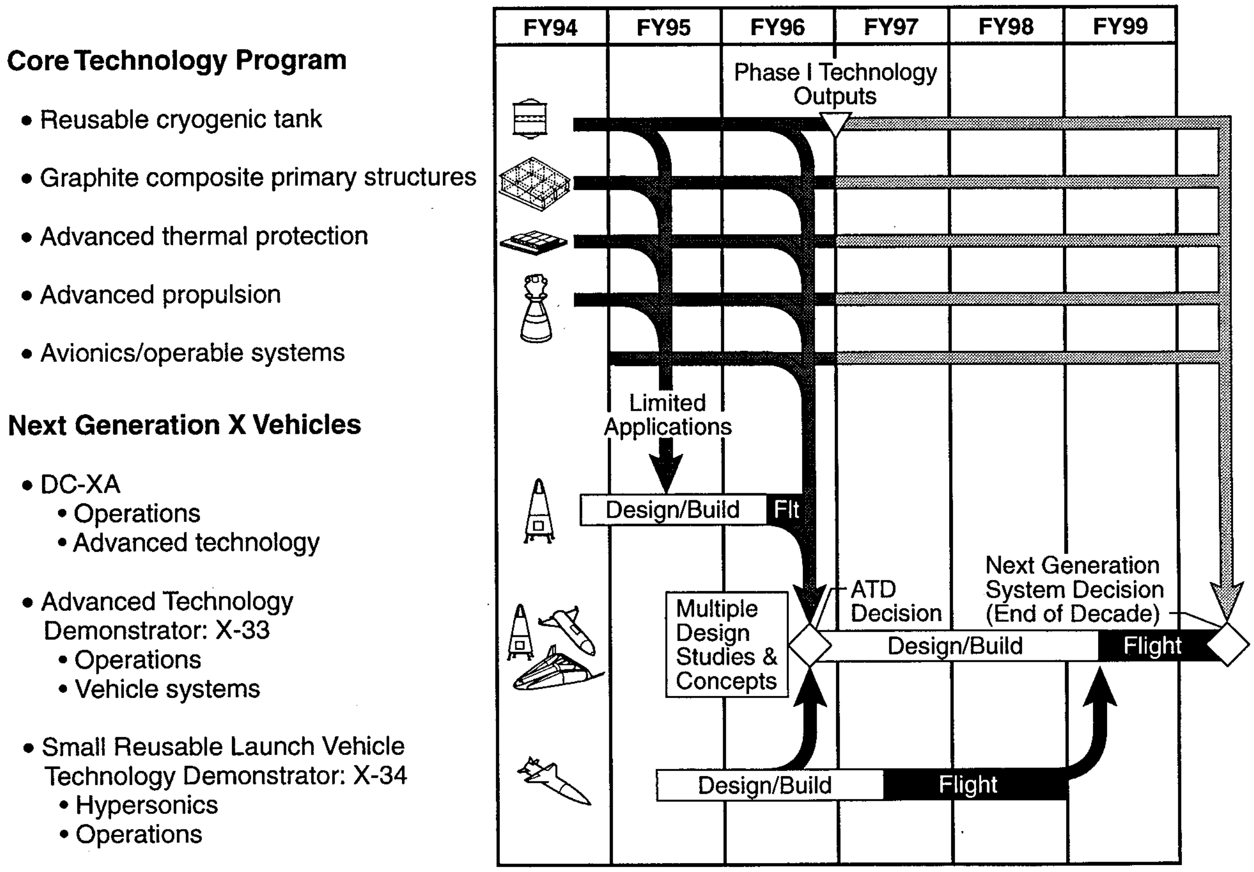

Figure 1. Reusable Launch Vehicle Technology Program Schedule.

REUSABLE LAUNCH VEHICLE TECHNOLOGY PROGRAM OVERVIEW

The goal of the RLV Technology program is the lowering of the cost of access to space to promote the creation and delivery of new space services and other activities that will improve economic competitiveness. To this end, the program supports the development of an all rocket, fully reusable SSTO. However, the private sector is free to ultimately select the operational RLV configuration to be flown in the post-2000 time frame.

The RLV Technology program has several major elements that together support its objectives. These elements are synergistic as illustrated in Figure 1 on the previous page.

The core technology program, initiated in early 1994, supports design and manufacture of key technology elements necessary for an operational RLV. Testing of initial demonstration articles will take place using the DC-XA flight test vehicle starting in the summer of 1996. The core technology program implements the National Space Transportation Policy that specifies, "Research shall be focused on technologies to support a decision no later than December 1996 to proceed with a sub-scale flight demonstration which would prove the concept of single-stage to orbit."

In January 1995, two Cooperative Agreement Notices (CAN 8-1 and 8-2)[2,3] were issued by the NASA calling for design and development of a (1) Reusable Launch Vehicle Advanced Technology Demonstrator (ATD) designated the X-33, and a (2) Reusable Launch Vehicle Small Reusable Booster designated the X-34.

NASA's intent with the X-33 solicitation is to demonstrate critical elements of a future SSTO rocket powered RLV by stimulating the joint industry/Government funded concept definition/design of a technology demonstrator, the X-33, followed by design and flight demonstrations of one or more competitive concepts. The X-33 must adequately demonstrate key design and operational aspects of a future commercially viable RLV.

The intent of the X-34 solicitation is to stimulate the joint industry/government funded development of a small reusable, or partially reusable, booster that has potential application to commercial launch vehicle capabilities and which provides significantly reduced mission costs for placing small payloads (1,000-2,000 lb) into a low Earth orbit (LEO) starting in 1998. Importantly, the CAN states that "the booster must demonstrate technologies applicable to future reusable launch vehicles."

DC-X, DC-XA

In 1990, the Ballistic Missile Defense Organization (BMDO) initiated the Single Stage Rocket Technology (SSRT) program to demonstrate the practicality, reliability, operability and cost efficiency of a fully reusable, rapid turnaround single-stage rocket. Following an initial design competition phase, BMDO awarded McDonnell Douglas a $59M contract in August 1991, with the primary emphasis on the design and manufacture of a low-speed rocket demonstrator vehicle named the DC-X (Delta Clipper Experimental), Figure 2, a subscale version of the Delta Clipper vertical takeoff, vertical landing SSTO under study by McDonnell Douglas. The goals of the DC-X program[4] were a demonstration of rapid prototyping of hardware and software, demonstration of vertical takeoff and landing, aircraft-like operations, and rapid system turnaround.

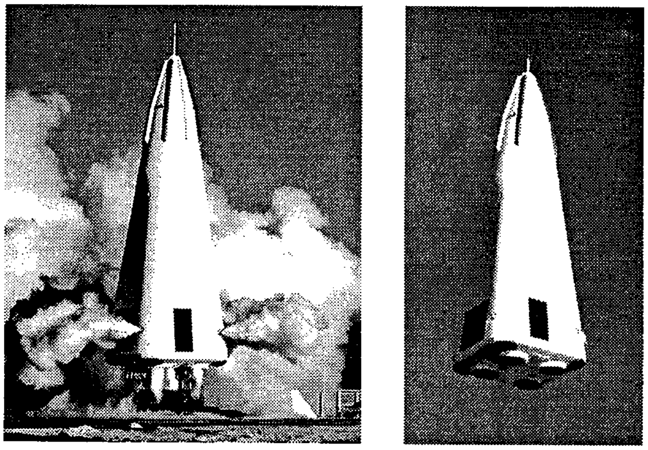

Figure 2. DC-X at takeoff and in flight.

The DC-X achieved a rapid prototyping development and flew for the first time two years after award of the contract. From August 18, 1993 through July 7, 1995, the vehicle flew eight test flights with the test envelope expanded with each succeeding flight. The last three flights in particular demonstrated engine differential throttling for flight control, the use of a gaseous oxygen/hydrogen reaction control thruster module, and engine performance under wide pitch-over excursions (see Figure 3). Ground operations data were collected and flight operations with a small number of personnel demonstrated. The test flights were not without incident. Although a ground explosion on flight #5 severely damaged the vehicle's composite aeroshell, the vehicle continued its flight,

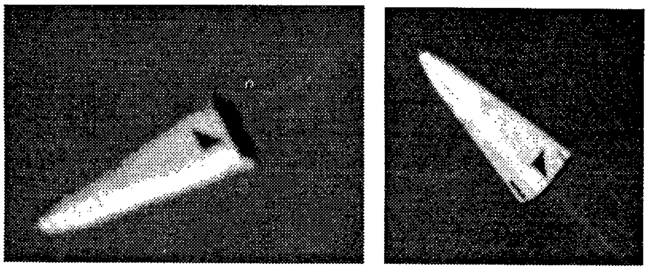

Figure 3. DC-X demonstrates pitchover manuevers on flight #8.

owing to its rugged boilerplate construction, and demonstrated its emergency autoland system as shown in Figure 4. A faster-than-nominal vertical descent to landing on the flight #8 damaged the landing gear and buckled the aeroshell. While these events demonstrate the value of X-vehicles in a development program, they also suggest the reliability challenge that exists for future demonstrators and full-scale operational vehicles.

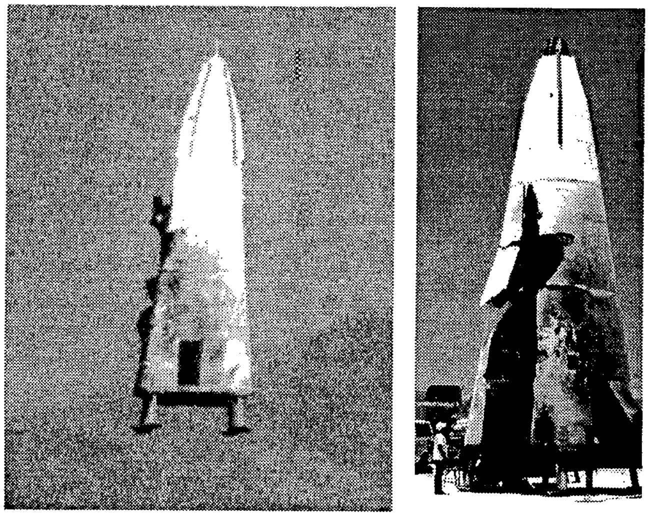

Figure 4. Damaged DC-X performs abort on flight #5.

In July 1995, the DC-X was transferred from the U.S. Air Force to NASA for use in the RLV program. Renamed DC-XA (A for Advanced), the vehicle, shown in an artist's concept in Figure 5, is being modified by McDonnell Douglas with technologies intended for use in the X-33 and X-34. Changes, depicted in Figure 6, include (1) a switch from an aluminum oxygen tank to a Russian-built aluminum-lithium alloy cryogenic oxygen tank with external insulation, (2) a switch from an aluminum cryogenic hydrogen tank to a graphite-epoxy (Gr-Ep) liquid hydrogen tank with low-density reinforced foam internal insulation, (3) a Gr-Ep composite intertank structure, (4) a Gr-Ep composite feedline/valve assembly, (5) a gaseous hydrogen/oxygen auxiliary power unit (APU) to drive the hydraulic systems, and (6) an auxiliary propulsion system (APS) for liquid-to-gaseous hydrogen conversion for use by the vehicle's reaction control system. Integration and ground tests are scheduled to be completed by January 1996 with flight tests expected to begin in mid-1996.

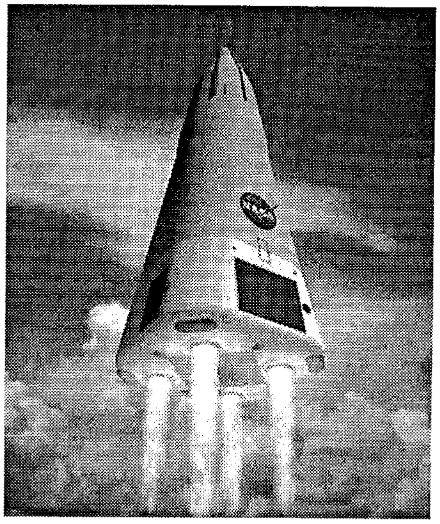

Figure 5. DC-XA rocket demonstrator.

To meet program objectives, the DC-XA flight test program will consist of two series of flights. The first series will focus on the basic functionality of the DC-XA system and its readiness to conduct regular flight operations. It is planned to (1) verify functional integrity and operational suitability of the newly installed technologies, (2) verify the hardware and software functions of the integrated DC-XA vehicle, the three-person Flight Operations Control Center, and the Ground Support System (15-person touch labor) under launch and flight conditions, and (3) determine the operational characteristics and flight readiness of the vehicle for the next series of flights. Reflight of the vehicle within 72 hours, a goal that was not attained during the DC-X flight series, is another likely objective.

The second series of flights will (1) demonstrate in-flight engine start capability during tail-first and nose-first descents, (2) demonstrate the ability to safely shut down one engine during flight and demonstrate single-engine out flight and landing capability, (3) demonstrate a landing capability at unprepared alternate sites, (4) demonstrate the redundant hydraulic load capability of the Auxiliary Propulsion System, and (5) determine the propellant tanks and intertank structure responses to flight loads.

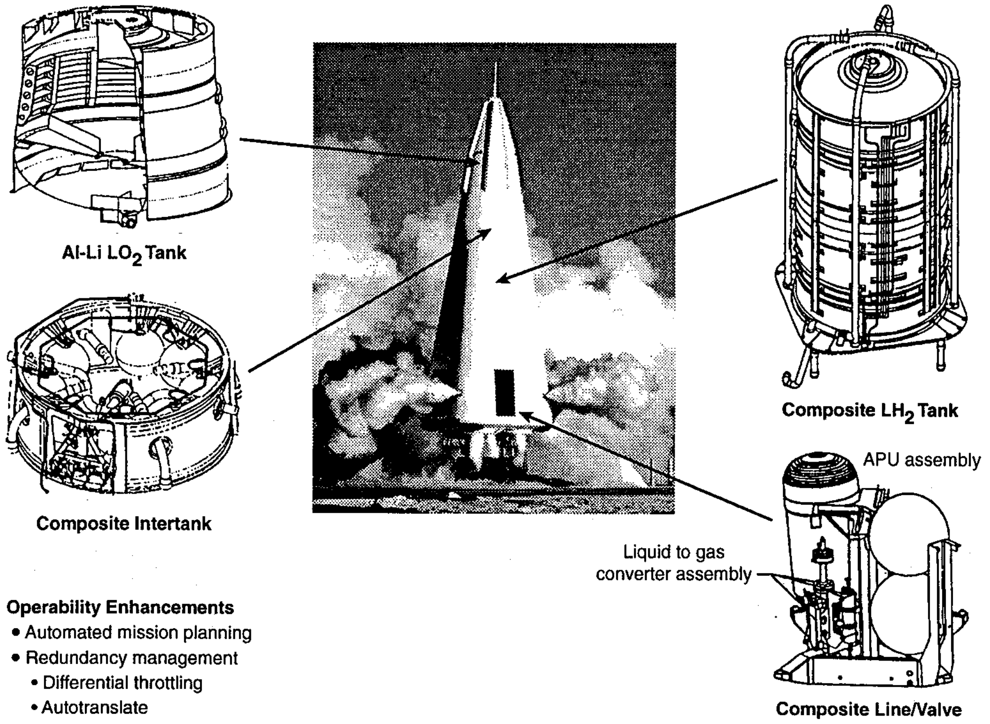

Figure 6. DC-XA Technology Components.

X-33

The objective of the X-33 NASA Cooperative Agreement Notice "is to stimulate the joint industry/Government funded concept definition/design of a technology demonstrator vehicle, the X-33, followed by the design/demonstration of competitively selected concept(s)." The three phases of the program are shown in Figure 7.

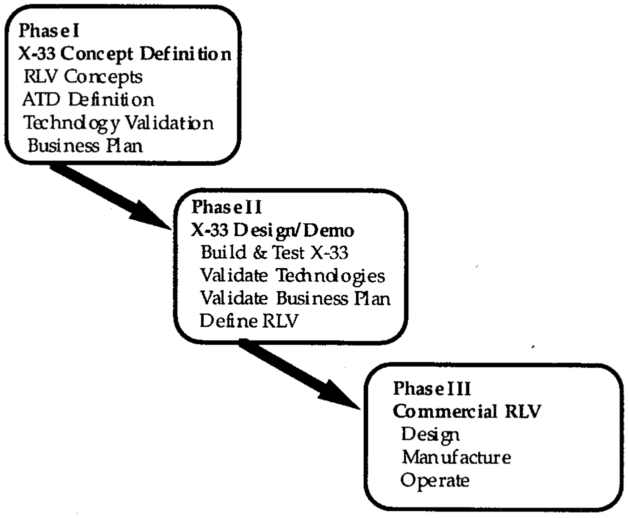

Figure 7. Reusable Launch Vehicle Technology Program.

Phase I is a Concept Definition and Design Phase, initiated in April 1995, that is slated to last 15 months. The three industry design teams selected for this phase include Lockheed/Martin, McDonnell Douglas teamed with Boeing, and Rockwell International. Government labs are teamed with and assist all the three teams during this phase. Phase II includes the design, manufacture and flight test of the X-33 concept(s) to be initiated before the end of FY 1996 and continues through the end of the decade with X-33 flight testing beginning in early 1999. Phase III will be the implementation, based on private sector and Government decisions at the end of the decade, of the development of an operational, next-generation reusable launch system.

In Phase I the teams are to look at business investment strategies and planning for X-33 and the operational RLV, provide for operations planning of the X-33 and RLV, and perform vehicle design and analysis of the X-33 designs with detail sufficient to permit a downselect to one or more concepts at the end of Phase I. The teams may also propose supporting technology demonstration efforts. Figure 8 shows the three operational RLV concepts being examined by the design teams. X-33 demonstrator vehicles are expected to be subscale versions of these concepts. Included are a vertical takeoff-horizontal landing lifting body from Lockheed-Martin, a vertical takeoff-horizontal landing winged vehicle from

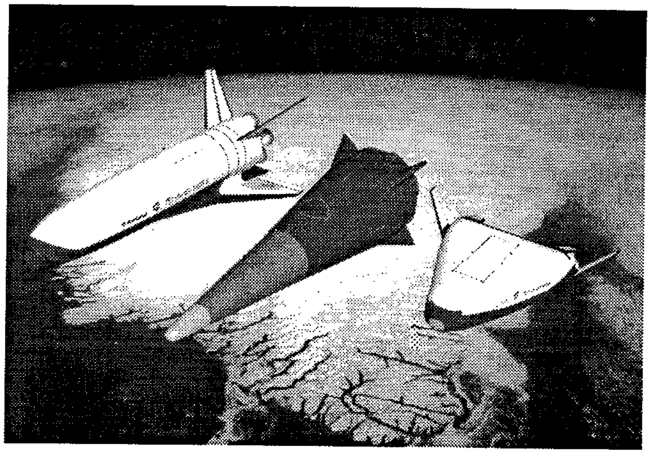

Figure 8. Industry team concepts for operational Reusable Launch Vehicles.

Rockwell, and a vertical takeoff-vertical landing system from the McDonnell Douglas-Boeing team.

The X-33 will consist of an integrated ground and flight test program that characterizes key component technologies and validates system capabilities both from a performance and operations viewpoint. There must be a traceability in terms of technologies and design similarity between the X-33 and operational RLV and a scalability in terms of design parameters that prove the critical characteristics of the operational RLV as shown figure 9. Thus, the X-33 must demonstrate RLV operations concept, flight stability and control, airframe, tanks and TPS technologies, loads, weights ascent/reentry environments, fabrication methods and testing approaches.

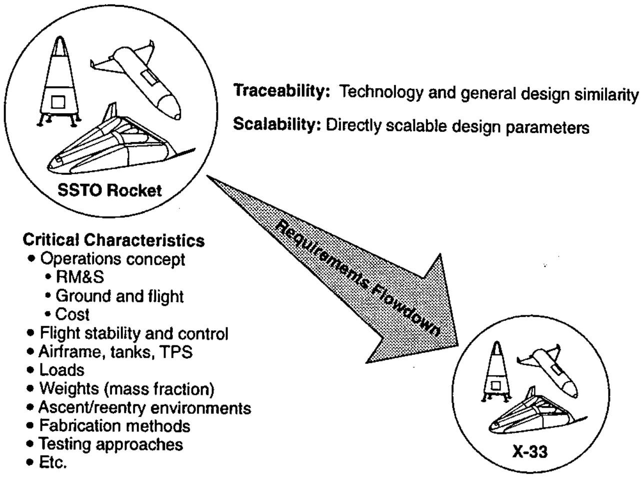

Figure 9. X-33 traceability and scalability to RLV.

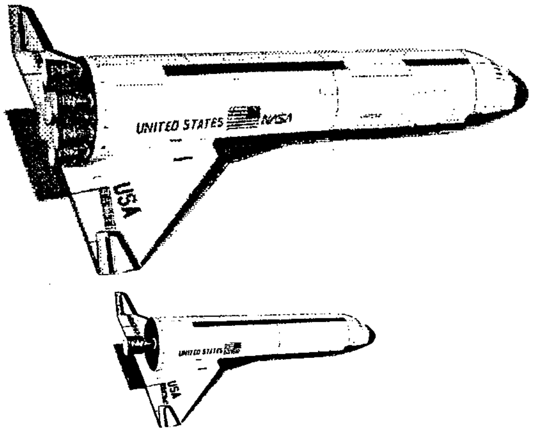

Figure 10. Scale comparison of X-33 and RLV concepts.

Although the X-33 teams are not precluded from making the X-33 an orbital test vehicle, there is no requirement that it be so. Figure 10 demonstrates the scale differences possible between an operational RLV and an X-33 designed to reach hypersonic (Mach 20) suborbital speeds.

A recent study conducted by NASA demonstrates the relation between X-33 performance capability and relative development cost. The scale of an X-33 vehicle, characterized by its gross weight, is shown as a function of its performance in Figure 11. Shown in figure 12 are the estimated relative design and development costs of each concept, including one test vehicle, but without test flight costs. The costs are estimated based on a combination of dry weights, propulsion requirements, and technologies assumed. As shown, a subscale, suborbital demonstrator with Mach 20 capability is significantly less expensive than full-scale orbital vehicles.

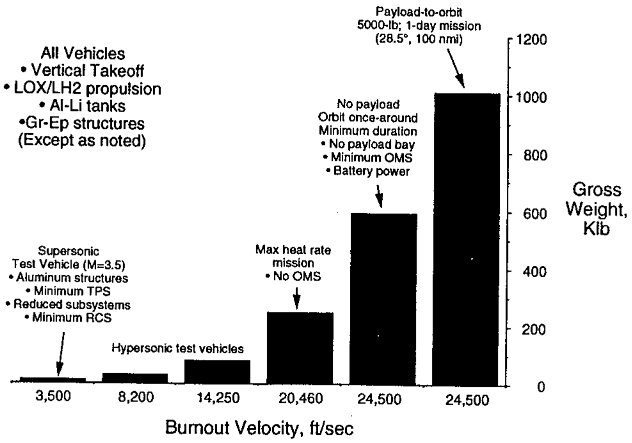

Figure 11. Relation of gross weight of ATD and performance.

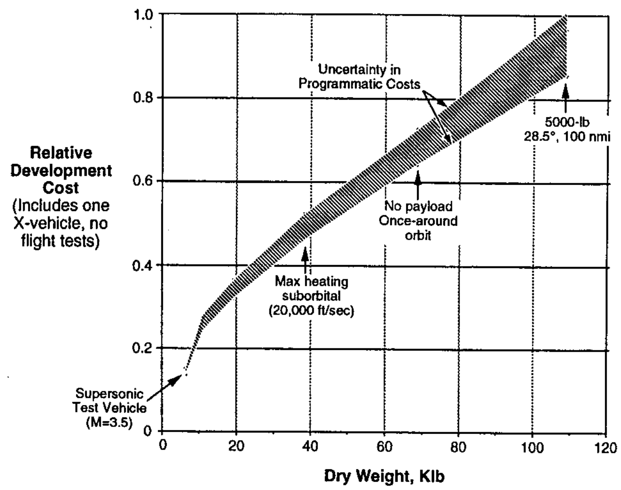

Figure 12. Relative development costs of advanced technology demonstrators.

However, the scaling of the X-33 must be large enough and the flight environments harsh enough as to provide confidence that full-scale vehicle characteristics can be traceable from X-33 testing.

X-34

The intent of the X-34 program is the joint industry/Government funded development of a small reusable, or partially reusable booster capable of placing small payloads (1 to 2 Klb class) into low Earth orbit with a factor of three reduction in launch costs. In the process, the program will demonstrate technologies applicable to future reusable launch vehicles. Some of the technologies will be demonstrated as part of the booster design. These include reusable composite or metallic propellant tanks, reusable and operable rocket engines, reusable and durable TPS materials, and operations concepts. Other technologies can be demonstrated through test bed application of the booster in test flights including advanced metal matrix composites, advanced TPS concepts, airbreathing propulsion technologies, and enhanced vehicle health monitoring systems as examples. A prime objective of the program is to demonstrate that an industry-led, joint industry/Government funded partnership can accomplish the development of a new booster within three years within a fixed Government funding profile.

The X-34 contract was awarded on March 30, 1995 to a Orbital Sciences Corporation-Rockwell team. The $70 M cooperative agreement calls for an equivalent amount of cost sharing by the industry team. Based on OSC's experience with the Pegasus air-launch small payload launcher, the OSC-Rockwell team have proposed an air-launched X-34 booster configuration depicted in Figure 13.

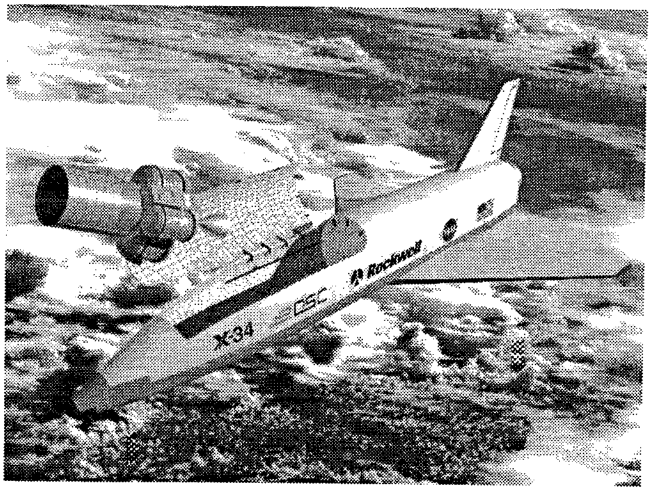

Figure 13. OSC-Rockwell X-34 concept.

Carried to altitude on the back of a Boeing 747 carrier aircraft, the X-34 booster would separate and fire its liquid rocket motors to place itself on a Pegasus-style ascent profile as depicted in Figure 14.

The X-34 booster would burn out at about less than half orbital speed at 60 nmi and, as Figure 13 shows, release the "pop up" payload and attached upper stage motor. While the X-34 reusable booster makes an entry and landing at a downrange range landing site, the upper stage would fire sending the payload into the required orbit.

Captive and approach and landing test flights are expected to begin in mid-late 1997, with suborbital and orbital demonstration flights in mid 1998, and technology demonstration flights in late 1998 and early 1999.

TECHNOLOGY PROGRAM

For an SSTO to be feasible and practical (cost effective, reliable, safe) is a major challenge. While there is considerable discussion of the merits of one configuration over another, the fact is that any SSTO must incorporate a number of newer technologies with many of them common to any configuration. Some technologies are necessary to enable the concept of SSTO (to meet the feasibility challenge), while others are required to make the system cost-effective, reliable, and safe (to meet the practicality challenge). Some technologies span the feasibility and practicality challenges in SSTO design.

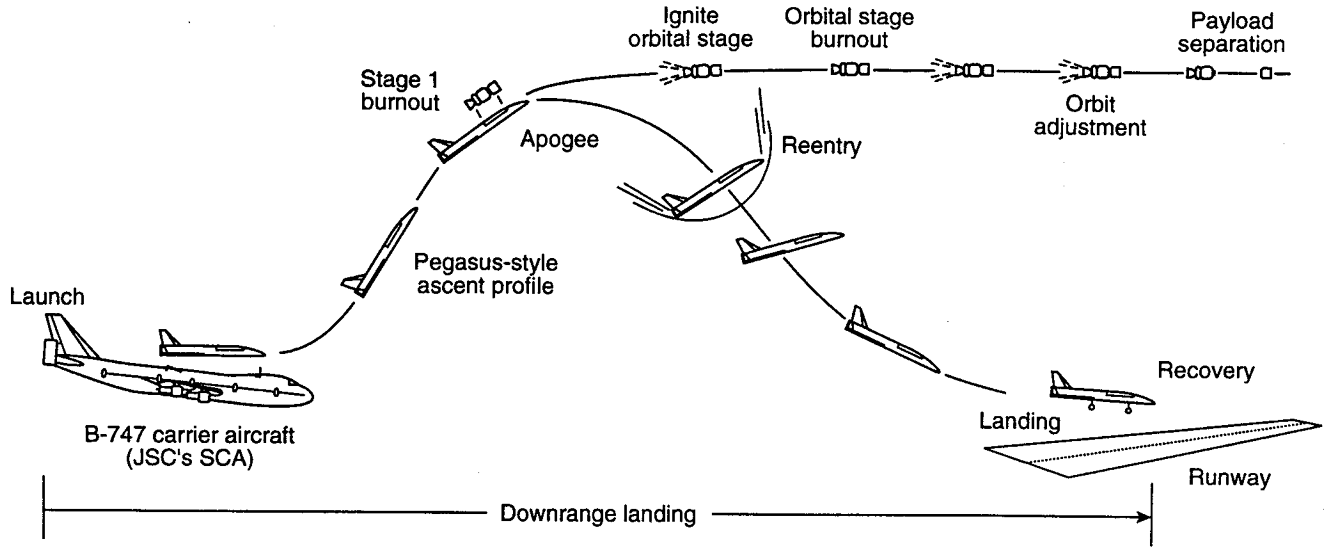

Figure 14. X-34 flight profile.

Numerous next-generation launch system studies in the past have examined the roles of technology in meeting the feasibility challenge (e.g. refs. 5, 6). A few studies have also examine how such technologies can make a next-generation system operationally practical. References 7 and 8, for example, have detailed lists of SSTO enabling and enhancing technologies. All studies have expressed the need for technology investment and development programs to ensure a readiness to proceed to a next-generation system.

Following completion of the NASA Access to Space study, the Advanced Launch Technology (ALT) program was established in January 1994 to address the technology maturation and demonstrations for the RLV program. As shown in Figure 1, the resulting core technology program will provide limited applications to the DC-XA vehicle, help in the decision-making to proceed with the X-33, and ultimately will determine the readiness to proceed with an operational RLV at the turn of the century.

The specific technologies for the DC-XA test vehicle have been described in a previous section. The core technology program, however, includes additional technology developments aimed at the X-33, X-34, and operational RLV vehicles and is enhanced by contractor technology demonstrations relative to their specific vehicle configurations.

Reusable Cryogenic Tanks

The design and manufacture of large-scale, flight-weight reusable cryogenic tanks using suitable tank and insulation materials has been considered the most challenging aspect of reusable vehicle design. Multi-use cycling and application of flight loads on the aluminum-lithium liquid oxygen and graphite composite liquid hydrogen tanks for the DC-XA are a step towards meeting this challenge. Material and structure options development will continue as the RLV program matures. Another key area of research and testing by the industry partners include material characterization, process development, integration and test of both internal and external types of cryogenic tank insulation. Reusability and inspectability are important aspects of insulation design to be evaluated. Non-destructive evaluation and health management of reusable cryogenic tanks will also be studied. Aluminum-lithium and graphite composite tanks will be constructed and integrated with the required TPS, insulation, health monitoring, and attachment subsystems for test.

A documented analysis will be performed to demonstrate that selected materials and tank subsystems are scalable to a full-scale RLV and can be adequately demonstrated by an X-33 vehicle. Correlations between analytical predictions and experimental test results must be at a high level of confidence to ensure analytical tools are valid for purposes of full-scale vehicle design.

Composite Primary Structures

Composite structures offer the potential of large weight savings for RLVs. The DC-XA composite intertank has been fabricated and is undergoing qualification tests as shown in figure 15.

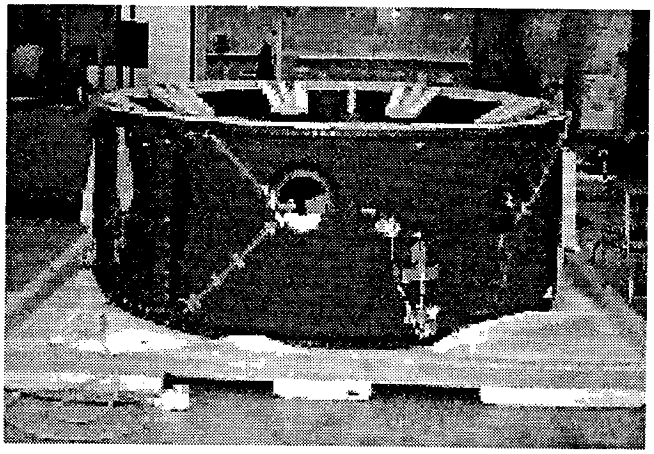

Figure 15. DC-XA composite intertank structure.

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 aerosurfaces, 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.

Thermal Protection Systems

The primary issue being addressed in this technology area is the lack of data available to estimate the durability and reuse of TPS materials in launch and entry environments. Both ceramic and metallic TPS test articles will be constructed and tested prior to use on X-33 and RLV configurations. The panels will undergo both thermal and environmental (acoustic, wind/rain, frost/ice, impact) tests. Also, fail-safe attachment options for metallic and ceramic TPS panels will be examined. New thermal seal designs based on lessons learned from the STS and NASP programs will be tested.

Test objectives are to develop thermal protection systems capable of a 100-mission minimum lifetime and an order-of-magnitude reduction in maintenance and inspection requirements as compared to existing Shuttle TPS.

Propulsion Systems

The objective of the propulsion system technology program is to develop and demonstrate main engine performance and operational characteristics. Included are investigations of thrust-to-weight, robustness, operability, inspectability, and affordability characteristics. Several engines types are being examined during the early phases of the RLV program. They include an evolved SSME, a new RS2100, a J-2-based aerospike, and a new RS2200 aerospike engine by Rocketdyne all using liquid oxygen/liquid hydrogen propellants. Also under study is an Aerojet evolved Russian RD-0120 engine as well as tripropellant technologies. Because of the schedule constraints, only the evolved SSME, evolved RD-0120, and J-2-based aerospike engine are being considered for the X-33 ATD. All engine types could be applicable to the follow-on RLV configurations.

In particular, the aerospike engine will undergo early-on flight testing to determine vehicle aerodynamic/aerospike engine interactions during flight. These relate directly to the basic understanding of overall engine performance. A 10% scale, half-span model of the Lockheed lifting body configuration and aerospike engine will be mounted on the back of an SR-71 reconnaissance jet aircraft for flight tests planned for the spring of 1996. Thirteen test flights will duplicate the trajectory of an RLV between flight Mach numbers of 0.6 through 3.2 The tests will be used to measure installed thrust, demonstrate engine operation, and validate analysis methods, including computational fluid dynamics (CFD), for use on full scale system design.

MANAGEMENT & OPERATIONAL APPROACHES

The RLV Technology program, looking to SSTO as the goal for low-cost access to space, is redefining the working relationship between Government and industry as well as commercial users and foreign involvement. Significant reductions in development and operations costs require the streamlining of management methods that oversee technology development and demonstrations, i.e. "new ways of doing business." The NASA Research Announcements (NRAs), instruments of the Advanced Launch Technology program following the Access to Space study, were set up and proceeding in just 81 days in the spring of 1994. The initial technology products from these efforts are the DC-XA upgrades discussed earlier. In like manner, the request for proposals for the Cooperative Agreement Notices for X-33 and X-34 were published in January 1995 with contract awards by late March 1995.

The use of small, efficient project offices is critical to demonstrating low-cost developments, streamlining acquisition procedures, minimizing Government oversight and providing for the "cultural changes" needed to meet cost reduction goals. The RLV program management office, for example, is staffed with no more than 20 people. The DC-XA program is being used to demonstrate that a small Government/industry project team can design, develop, and integrate advanced technology components into an experimental flight system within budget and schedule constraints. The total touch labor and flight operations personnel will remain at the level used in the DC-X program. A goal of the X-34 program is to demonstrate that an industry-led, joint industry/Government funded partnership can successfully accomplish the development of a new booster within a fixed schedule and within the fixed $70 M Government contribution to the partnership.

In concert with the fast-track management approach is the use of X-vehicle demonstrators to reduce technical risk and demonstrate technologies and operational approaches. Flight demonstrators add confidence to ground test and analytical results that address the technical feasibility and cost advantages to operational reusable launch vehicles. The DC-X and DC-XA programs represent initial steps towards these goals, but have limited capabilities in investigating the harsh flight environments, mass fraction requirements,and more complex operations of operational systems. The X-33 Advanced Technology Demonstrator and X-34 operational booster system will engage the primary issues of mass fraction, propulsion performance, flyability, structures, TPS, and operations (both ground and flight).

SUMMARY

A fully-reusable, rocket-powered single-stage-to-orbit launch vehicle is, at present, considered to be the likely means of achieving affordable access to space. The NASA Reusable Launch Vehicle Technology Program is working the challenges of SSTO by addressing both the technical and programmatic aspects of new vehicle development. Industry-led industry/Government partnerships have been established with the DC-XA, X-33, and X-34 elements of the RLV program. Technologies required for SSTO including reusable cryogenic tanks, composite primary structures, durable thermal protection, and operable main propulsion systems are under development. The DC-XA, X-33 and X-34 flight vehicles will demonstrate these technologies to a degree so as to lend confidence to the decision to proceed with full-scale RLV development.

In addition to the outcomes of the technology and flight demonstration programs, the RLV operational vehicle decision, slated for the end of the decade, will take into account the DOD progress in the Evolved Expendable Launch Vehicle program, the evolution and outlook for commercial markets, budget limitations, and national needs. Together, these factors will determine what form a feasible, practical future launch system will take. The timing of the decision will also coincide with investment decisions on maintaining Space Shuttle capabilities through 2012.

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