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REUSABLE LAUNCH VEHICLE

Technology Development and Test Program

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NATIONAL RESEARCH COUNCIL

REUSABLE LAUNCH VEHICLE

Technology Development and Test Program

Committee on Reusable Launch Vehicle
Technology and Test Program

Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

National Research Council

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Preface

The National Aeronautics and Space Administration (NASA) requested that the National Research Council (NRC) assess the Reusable Launch Vehicle (RLV) technology development and test programs in the most critical component technologies. At a time when discretionary government spending is under close scrutiny, the RLV program is designed to reduce the cost of access to space through a combination of robust vehicles and a streamlined infrastructure. Routine access to space has obvious benefits for space science, national security, commercial technologies, and the further exploration of space.

Because of technological challenges, knowledgeable people disagree about the feasibility of a single-stage-to-orbit (SSTO) vehicle. The purpose of the RLV program proposed by NASA and industry contractors is to investigate the status of existing technology and to identify and advance key technology areas required for development and validation of an SSTO vehicle. This report does not address the feasibility of an SSTO vehicle, nor does it revisit the roles and responsibilities assigned to NASA by the National Transportation Policy. Instead, the report sets forth the NRC 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).

Because of the divergent approaches to and unique requirements for each of the key technology areas, the committee quickly discovered the equivalent of four reports would be needed to do justice to the program. Therefore, this report emphasizes each of the four key component areas and addresses issues pertaining to the performance, producibility, and reusability of each. Advances in all of these areas are critical to reducing the cost of access to space.

The committee would like to express its appreciation to the many NASA and industry teams that invested long days describing their programs and answering questions. The committee also appreciates their willingness to provide additional clarification. A list of the participants in meetings with the committee appears as Appendix A.

In addition, the chairman would like to express his appreciation to the committee members for their extensive contributions to this study with extra thanks to the leaders of the technical areas for taking on that additional responsibility. Finally, the invaluable contributions of the NRC staff are gratefully acknowledged: JoAnn Clayton for her

advice to the chairman and assistance in preparing background material and editing sections of the report; Dr. Ali Eskandarian for his tireless efforts in arranging all the briefings, for collating, editing, and commenting on the committee's additions to the final report, and for providing counsel to the chairman; and Bill Campbell for his many contributions throughout the study, including preparation of numerous drafts of the report.

Richard A. Hartunian, Chairman
Committee on Reusable Launch Vehicle
Technology Development and Test Program

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Executive Summary

The objective of the National Aeronautics and Space Administration (NASA) Reusable Launch Vehicle (RLV) Program is to develop technology and demonstrations for providing reliable, low-cost access to space. Phase I of the RLV program consists of concept definition and technology development leading to a Phase II subscale flight demonstration vehicle, the X-33. Shortly after the NASA Office of Space Access and Technology requested that the National Research Council (NRC) examine the RLV Phase I technology development and test program, decision criteria for this phase were developed by NASA, the Office of Management and Budget (OMB), and the Office of Science and Technology Policy (OSTP); these criteria are cited in the body of the report. The NRC committee took these criteria into consideration when making judgments about whether the Phase I program would provide adequate information to "support a decision no later than December 1996 [whether] to proceed with a subscale launch vehicle flight demonstration which would prove the concept of single-stage-to-orbit (SSTO)." However, it needs to be emphasized that the committee assessed the extent to which the technology development programs represent rational paths (and alternatives) toward RLV goals. The NRC task was limited to the Phase I propulsion and materials technology programs; the NRC was asked not to assess the feasibility of SSTO. However, the technologies required for an SSTO vehicle were considered throughout the study because the Phase I development and test programs are structured to focus on three crucial areas in the development of a cost-effective SSTO vehicle: lightweight materials for the tanks and primary structure, efficient propulsion systems, and multimission reusability and operability.

Materials considerably lighter than those currently used for the tanks and primary structure are required because reaching orbit with an SSTO vehicle (using current technologies) requires that about 90 percent of the vehicle's total mass at launch be propellant. In the propulsion area, a significant improvement in the thrust-to-weight (F/W) ratio (sea level) of the engines is necessary—compared to the F/W ratio of the two existing large-thrust liquid oxygen/liquid hydrogen engines, the Russian RD-0120 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 SSTO and maximum reusability, all of the components for the vehicle primary 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 have a lifetime of at least 100 missions.

The committee reviewed the RLV program and found the three-phase approach to the program to be sound. Phase I of the program includes demonstrations of critical technologies. These demonstrations will be required before proceeding with the more costly, largely subscale flight demonstrations of Phase II. The committee found that the Phase I development, test, and analysis programs are appropriate to support a decision about proceeding with Phase II, subject to implementation of the committee's recommendations.

Three prime contractors have proposed three distinct RLV designs and are pursuing different paths in critical technology areas (in some instances a given contractor is pursuing several paths at this stage). NASA centers are providing supporting and complementary research and development in many instances; thus, if there is a failure along one path, alternative paths may be pursued. Phase II must successfully demonstrate that the technical challenges have been met before industry teams can proceed with costly, full-scale RLV development in Phase III. Using this phased approach, NASA can avoid the high development costs and technical risks of previous programs that depended on significant technological advances being concurrent with vehicle development.

The committee studied the four major technology areas in Phase I of the RLV program: composite primary structures, aluminum-lithium (Al-Li) and composite cryogenic tanks, TPS, and propulsion systems. However, the committee did not address issues of design integration of component technologies into flight vehicle configurations. In any event, because of the current stage of vehicle design by industry partners and NASA, it was not feasible for the committee to make definitive assessments. The committee's recommendations reflect those aspects of the technology programs believed to require special emphasis. Other important aspects of the programs, even those involving significant challenges, were not addressed in the report if the committee believed that the participating industrial teams and NASA were not only well aware of the challenges but were also paying sufficient attention to meeting them in the program plans. The major findings and recommendations in each of the four technological areas crucial to Phase I are discussed below.

COMPOSITE PRIMARY STRUCTURES

The technology development program is robust, well organized, and addresses all of the major issues. There are three basic structural approaches: basic composite materials, an isogrid design for the intertank, and a sandwich structure design being developed by a NASA center. Major contractor test articles include an 8-ft-diameter by 38-inch-long DC-XA intertank; an 8-ft-diameter by 10-ft-long ground test intertank; an

8-ft-diameter filament-wound isogrid, a one-fourth segment of a full-sized intertank (designed to address scaleability concerns); a segment of a full-scale thrust structure; and a full-scale wing-box section for one of the RLV configurations. NASA centers are providing considerable analyses, material characterization, and subscale component tests, as well as an intertank/cryotank interface with a joint that is 8 ft in diameter and 6.5 ft long. Under cooperative agreements with industry, NASA also will provide structural test articles for system-level tests. Many of these test articles will be subjected to combined-load testing for life cycle; and some will undergo acoustic and damage-tolerance testing. Integrated health-monitoring systems will be attached to many of the full-scale segments during testing.

Efforts to validate analysis techniques and to address scaleability to single stage RLVs is progressing satisfactorily. Testing ranges from extensive coupon and other subscale tests, to panel tests, to reasonably large test articles and includes continuous validation of the necessary predictive tools at every stage.

Although the approach is sound, the committee is concerned about the 15 percent maximum weight-growth margin specified by the program managers; 20 to 25 percent weight growth is typical during the early stage of design development. The need to control weight growth tightly this early in the program places a premium on accurate calculation of structural performance and weight and on early verification that the structure can be built at or below the predicted weight.

The committee was unable to cover fully issues such as aging, ease of assembly, and maintenance of structures because of the time constraints. However, the committee considers these issues to be very important over the long term.

"Scaleability" refers to scaling to larger or smaller sizes the physical attributes of a given test article according to scaling laws. If the laws are not known, an iterative process must be used; that is, the predictions based on scaling models must be checked against actual test results at each scaling step. The discrepancies between the model predictions and actual data are used to improve the model for the next step. In most realistic situations, the scaling laws are not known exactly; therefore, extensive testing is required to provide sufficient data to build confidence in the model. It is also important to note that various physical (and chemical) phenomena that directly affect the RLV design and performance, scale in significantly different ways with changes in geometric size (e.g., structural strength and stability under load and thermal stress versus aerodynamic heating rates versus heat conduction through solids—all interacting in the design of launch vehicle structures). Also, with changes in size or other parameters affecting loading, dynamics, or configuration, failure phenomena may be encountered that have not occurred in previous situations.

MAJOR RECOMMENDATIONS REGARDING PRIMARY STRUCTURES

- Test articles of each size must be designed, built, and tested to RLV-scaled conditions using design codes that are being validated. Furthermore, all of the joints and fittings for the larger test articles should be properly scaled to the RLV flight configuration. This may require full-scale testing of some joints.
- The planned combined-loads tests, which simulate the appropriate thermal and acoustic environments integrated with flight vehicle interfaces (e.g., TPS on the cryogenic tank or the intertank), should be conducted with as many cycles as possible.
- Many health monitoring systems and nondestructive evaluation (NDE) techniques were mentioned in the briefings, but there does not seem to be a well-ordered program to identify which measurements will be made and where or how NDE will be used to penetrate multiple layers of material. The committee is aware of the extreme difficulty of this task and strongly recommends the development of a clear plan for certifying readiness for launch of flight-critical hardware.
- Weight requirements (not only the 4lb/sq ft given in the decision criteria) must be defined for each vehicle concept.

REUSABLE CRYOGENIC TANKS

Another key component of the RLV program is the development of reusable cryogenic tanks. Both Al-Li and organic-matrix composite tanks are under development by NASA and industry partners. The development programs are generally robust in that most critical areas are addressed by more than one approach. Both the Al-Li cryogenic tanks and the organic-matrix composite tanks are discussed below.

Al-Li Cryogenic Tanks

Two alloys with different properties are being investigated for use in the cryogenic tanks. In addition, three fabrication techniques—net shape extrusion, net shape spin forming, and net roll forging—are being considered, and two welding techniques—variable polarity plasma arc and friction-stir welding—are being developed and tested. To address scaleability issues, the RLV program will fabricate and test both 8-ft and 14-ft diameter tanks; data from the space shuttle super lightweight tank, with a 28-ft-diameter tank, are being added to the RLV Al-Li database. Several groups are conducting material properties characterization tests, including tests to assess reusability (e.g., fatigue and crack-growth rate) and liquid-oxygen (LOX) compatibility for each alloy.

Several areas of concern affect producibility, operability, and reusability of the tanks. These include assuring proper microstructure and texture for all product forms and addressing the issues of weldability and weld repair, lot-to-lot variations, and anisotrophy in Al-Li alloys. NASA and the industry partners are aware of most of these concerns; they are identified here because they are crucial to the success of the program.

Major Recommendations Regarding Al-Li Cryogenic Tanks

The committee's recommendations for Al-Li cryogenic tanks are as follows:

- Recent microstructure and texture analyses have shown that current processing methods produce excellent products. However, each casting and product form must be characterized extensively to assure that the required microstructure properties are obtained. Other product forms for which such characterization is required include all welded, weld-repaired, and extruded near-net-shape formed products.
- Weldability and weld repairs are major issues of concern. Although the 2195 alloy can be welded, repair or second-pass welding is a major problem. Marshall Space Flight Center (MSFC) has been experimenting with an aluminum-silicon (Al-Si) filler material. The committee recommends caution in the application of this material because it forms an AlLiSi phase that attracts and absorbs moisture, which introduces the possibility of stress-corrosion cracking. Tests for stress corrosion in the 2195 weld zones should be rigorous.
- Because of the limited database on Al-Li alloy 1460 and the possible lot variations in Al-Li alloys, extensive testing is needed on small samples of all product forms. The fatigue, crack-growth, and stress-corrosion behavior of welds and weld repairs should be determined.
- Because Al-Li alloys have been shown to be more anisotropic than conventional aluminum alloys, texture, strengths, and elastic moduli should be characterized at various orientations.
- Weight predictions (other than 0.7 lb/ft^3 for an oxidizer tank or 0.5 lb/ft^3 for a hydrogen tank, as given in the decision criteria) must be clarified for each vehicle concept. Achievement of these predictions must be verified using properly designed and scaled articles.

Organic-Matrix Composite Cryogenic Tanks

There are three approaches to development of organic-matrix composite cryogenic tanks. Carbon cloth layups impregnated with epoxy formed to shape and subsequently cured in an autoclave (an oven capable of raising the pressure to desired levels) have traditionally been used for the heat shield on reentry vehicles and similar applications.

A second approach is to use winding machines to apply graphite filaments coated with epoxy to a mandrel in the desired shape; this is followed by curing in an autoclave. The third approach is to use a sandwich construction of honeycomb or foam core between sheets of graphite epoxy. At least two sizable tanks will be fabricated using each method: one 8-ft-diameter by 16-ft-long tank; and one 8-ft-diameter by 9-ft-long tank. Fabrication of a third, slightly larger tank is under review. Several organizations will conduct material properties characterization and subscale tank/bottle and panel tests to address the issues of basic weight, strength, and reusability.

The committee has two concerns about these tests. Although the sizes selected for the test tanks are reasonable, producing full-scale tanks five times larger than the test article while maintaining the required material properties may be difficult. Second, if autoclaving is necessary, it is unclear that there will be an autoclave large enough to accommodate the full-scale tanks or primary structures; and the cost and time for building one must be evaluated. There are multiple approaches to evaluating the critical issue of joining the tank to the intertank structure, both in design and tests. These evaluations may reduce the risks in this important area.

Major Recommendations Regarding Organic-Matrix Composite Cryogenic Tanks

The committee's recommendations on organic-matrix composite cryogenic tanks are as follows:

- A detailed plan addressing producibility of full-scale organic-matrix composite tanks should be developed, and the advisability of demonstrating fabrication techniques should be evaluated.
- The necessity for autoclaving must be evaluated and the availability of large-capacity autoclaves should be resolved as soon as possible.
- Thermal/load-cycle testing should be conducted on all tanks 8 ft in diameter (or larger) that have cryogenic insulation interfaces with neighboring components and TPS affixed to demonstrate that the integrated system will satisfy reusability requirements. These tests will provide a database for the RLV comparable to the database for the tank to be tested and flown on the DC-XA.
- Weight predictions (aside from the ones specified in the decision criteria) must be clarified for each vehicle concept, and satisfaction of predicted weight requirements must be verified using properly designed and scaled test articles.

THERMAL PROTECTION SYSTEMS

The current well-balanced program for developing advanced thermal protection materials addresses the key issues of significantly improved operability and reusability, without exceeding the weight requirements allotted to that system. Two NASA centers have proceeded along two distinct but complementary development tracks. One approach takes advantage of the long heritage of the Shuttle TPS with significant improvements in the robustness of reusable blankets and ceramic tiles; the second pursues the use of metallic panels to improve robustness. A third concept, the use of ceramic-matrix composites, is being developed for application to the highest-temperature areas of the vehicle during reentry (i.e., the nose and leading edges of the wings and control surfaces). Each of these approaches raises some concerns, and the program appears to be addressing them.

Producibility does not appear to be a major issue for new TPSs. But there are important concerns about the resistance of the tiles (refractory or metallic) to particle impact at liftoff and landing and, especially, in orbit at Space Station altitude, where it is predicted that penetration of a tank may occur at least once in a 100-mission cycle. It is clear that both the Shuttle-improved and metallic TPS are more resistant than the earlier Shuttle TPS, but the performance of both systems has yet to be fully quantified for various operational conditions. Tests for this type of resistance to damage are in progress.

A major workshop was conducted at Ames Research Center (ARC) to define experimental programs for evaluating environmental and vibroacoustic effects on the TPS. Environmental effects being evaluated include rain/particle erosion, lightning, and pad ice/frost. A valuable, comprehensive "robustness test matrix" was devised by the community of experts.

Other questions, such as the levels of rain that can be absorbed safely and issues related to waterproofing, still need to be resolved. The time and effort required after each Shuttle flight to return the vehicle to service are unacceptable in terms of turnaround time for an RLV. Neither NASA nor the industry partners has successfully developed either agents or coatings that provide permanent waterproofing or rapid techniques of applying waterproofing to the TPS materials. It remains to be seen if existing technology and ongoing research can solve the problem of waterproofing.

Significant development in methods of attaching the TPS to the tanks, insulation, and structure is needed for both of the generic TPS systems. This is an important problem area. Concepts that satisfy the requirements for structural integrity in flight and, at the same time are easily replaceable, will require innovative development and testing. The Shuttle-improved TPS system includes adhesive bonding, which is safe for flight but difficult to replace. The metallic panels depend on mechanical attachments that are still under development.

A permissible heat-leakage rate into the propellants has been specified for the space shuttle external tank. However, a corresponding rate has not been determined for an X-33 or RLV. Neither the sensitivity of propulsion efficiency to propellant temperature nor the resulting permissible heat-leakage rate is known for subcooled propellants that have not been previously used in operational vehicles.

Major Recommendations Regarding TPS

The committee's recommendations on TPS are as follows:

- NASA should evaluate the probability that particles in space will penetrate not only the TPS but also the propellant tanks during a 100-mission life cycle. NASA also should assess the impact of penetration on the reentry survivability of the RLV.
- The "robustness test matrix" evaluations should be carried out as soon as possible, with early emphasis on determining hypervelocity impacts and the resistance of new TPS candidate materials to environments known to cause the most problems for the Shuttle orbiter.
- Activities related to metallic panel attachments should be enhanced, and more-operable attachment mechanisms for the Shuttle-improved TPS should be investigated to assure easy replacement. Metallic and ceramic-matrix composite standoff panels should be tested in arc jets to demonstrate that there is no overheating at the attachment points.
- Methods of waterproofing need to be pursued vigorously if reasonable ground-processing times are to be achieved.
- Permissible heat-leakage rates into liquid hydrogen (LH_2) and LOX propellants should be established for normal and subcooled propellants.

PROPULSION SYSTEMS

The prime contractors have indicated a requirement for an engine sea-level F/W ratio greater than 75 for the RLV. The SSME Block II and RD-0120 ratios are 51 and 43, respectively, with a projection that SSME Block II+ (with a short nozzle) may achieve an F/W ratio of 58. Shortening the nozzles of the SSME or RD-0120 engines will increase sea-level F/W performance. Therefore, an increase of 30 percent or more will be required, which presents developers with an extremely difficult challenge. Methods of achieving this increase have been identified by the contractors, and, although in the opinion of the committee achieving a F/W ratio greater than 75 will be very difficult, it is by no means impossible.

In addition to developing the X-33 engine in Phase II, an engine development and ground test program is planned that will lead directly to the engine technology for an RLV. However, these plans are not well defined. Because the characteristics of the X-33 engine are only partially scaleable to the RLV, it is through engine development and testing on the ground that the scaleability to the RLV will be demonstrated.

Efforts to significantly reduce engine turnaround time after each flight have not yet achieved the objective of a rocket engine that can be handled much the way an operational jet engine is handled.

Major Recommendations Regarding Propulsion Systems

The committee's major recommendations on propulsion systems are as follows:

- RLV engine sea-level F/W requirements to achieve SSTO should be re-validated by the prime contractors and independently using NASA's vehicle design/performance groups. Current goals of greater than 75 F/W will be difficult to achieve in the SSME or RD-0120 derived engines, as well as in new engines, without raising concerns about the structural margins required to satisfy reusability goals. If the requirement of high sea-level F/W is re-validated, the committee recommends that development of the selected RLV engine be initiated at the beginning of Phase II and vigorously pursued. Because the X-33 vehicle engine will make only reasonably small contributions to the F/W goal, the development program will be the major source of data for a decision about proceeding with Phase III. Concurrent trade studies should be conducted to assess whether larger, but viable, vehicles will alleviate the F/W requirement.
- The decision criteria for proceeding from Phase II to Phase III for the propulsion system should reflect the required RLV engine performance targets (such as a sea-level F/W of greater than 75 and vacuum Isp of 440 or higher).
- NASA should evaluate the contractor's detailed analyses of projected methods and component improvements for achieving a sea-level F/W greater than 75. The practicality of each required component design should be documented by the engine contractors and evaluated by an independent group of propulsion experts.
- The ground RLV engine program for Phase II should be thoroughly defined and executed to provide a high level of confidence that RLV engine requirements will be met.
- If the prime contractors considering SSME or RD-0120 engines for the X-33 demonstrator determine that higher sea-level F/W performance is needed, development of a short (truncated) nozzle should begin soon.
- The X-33 and RLV Aerospike engine configuration details of combustor body, throat shape, nozzle shape, expansion ratio, and vehicle integration should be completed before the Phase II decision date. The throttling and thrust vector methods proposed, including interaction effects between adjacent engines, should be evaluated.
- More robust and reliable health monitoring instrumentation than is currently used should be developed and thoroughly tested. The overall approach to health monitoring and assuring flight readiness of the propulsion system within turnaround goals should be defined.
- NASA should evaluate the program and engine changes required to meet the rapid turnaround goals. In general, operability and engine reliability

requirements should be developed for X-33 and RLV. The fact that the RLV engine will not be subjected to major inspection or maintenance between each flight unless problems are indicated by on-board health monitoring or visual inspection should be considered in the design.

GENERAL OBSERVATIONS

Although NASA and its industry partners have adopted reasonable approaches to advance the state of the art in both space materials and propulsion during Phase I, formidable challenges remain. The committee did not address issues related to time or money constraints. In addition, because of time constraints on the study, the committee could not review several important areas:

- important aspects of the propulsion system such as: plumbing; leak sensors; lines, valves, and joints upstream of the engine; purge systems; pressurization systems; and the small reaction control system and orbital maneuvering system
- the integrated health monitoring system for all components and NDE technologies
- ground support equipment for the propulsion system, such as propellant quick disconnect, automation, automated fluid and electrical connections, and safe, operationally efficient ground and flight/vent purge systems
- operations issues that were explicitly excluded from the committee's charge to make the committee's task feasible within the allotted time

1

Introduction

BACKGROUND

More affordable access to space is needed to bring down the cost of using space for communications, reconnaissance, and civil remote sensing; opening space for experimentation and processing; and learning about living in space in preparation for human space exploration. A number of important reports in recent years have identified lowering the cost of access to space as one of the highest national aerospace priorities.[1-6]

In the past, the National Aeronautics and Space Administration (NASA), the Department of Defense (DoD), and the U. S. launch industry have attempted to grapple with the problem of lowering the costs of space transportation by undertaking various research and development programs. In 1993 NASA issued a report entitled "Access to Space" recommending directions for future space transportation efforts.[7] Specifically, the NASA study focused on improving reliability, crew safety, and reducing operations costs. The study concluded that a single-stage-to-orbit (SSTO) vehicle is a feasible system for achieving reliable, low-cost access to space. DoD considered launch-vehicle modernization in a parallel study issued in early 1994.[8] Building on these studies, the White House issued the National Space Transportation Policy in August 1994. The policy was developed by the Office of Science and Technology Policy (OSTP) and intended to address the issue of space transportation by assigning NASA the lead-agency responsibility for "technology development and demonstration for next-generation reusable space transportation systems."[9] The policy further stated that "NASA's research shall be focused on technologies to support a decision no later than December 1996 to proceed with a subscale flight demonstration which would prove the concept of SSTO." NASA established the Reusable Launch Vehicle (RLV) program (see Figure 1-1) in the "Implementation Plan for the National Space Transportation Policy"[10] in response to the OSTP mandate. NASA's Office of Space Access and Technology instituted the RLV program, focusing on maturation of the key technologies for development of an SSTO: advanced propulsion systems, reusable cryogenic tanks, composite primary structures, advanced thermal protection system, avionics, and more operable systems.

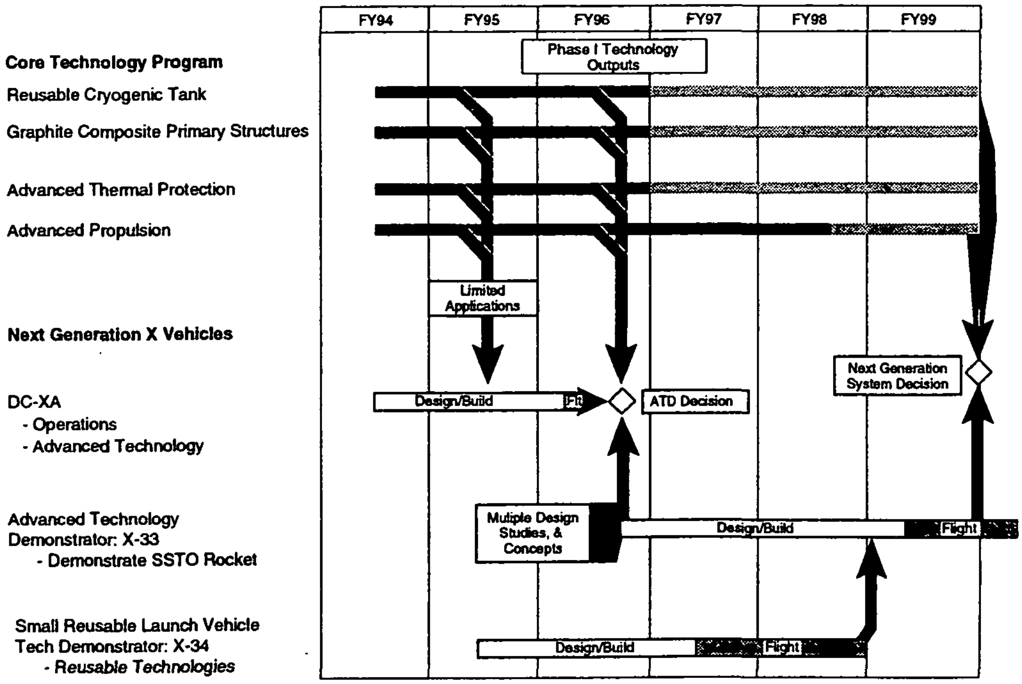

FIGURE 1-1 RLV Technology Demonstration Program. Source: NASA.

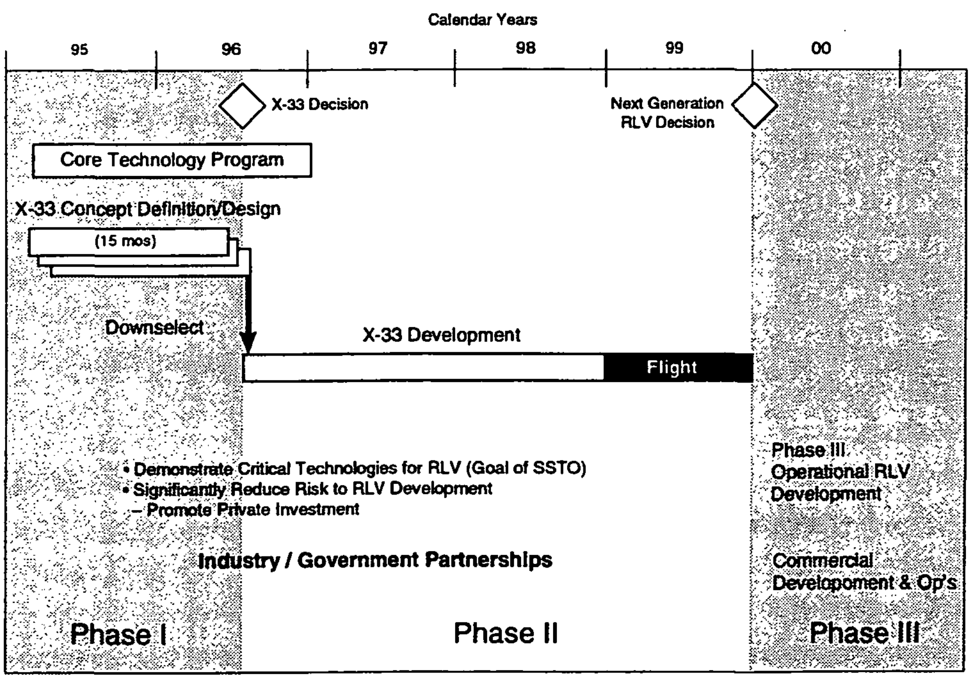

FIGURE 1-2 RLV Program Phase Descriptions. Source: NASA.

There has been much debate concerning the direction of the National Transportation Policy. This debate has focused mainly on whether NASA should attempt to develop an SSTO vehicle or should focus its limited resources on a less challenging goal, such as a reusable two-stage-to-orbit vehicle. Because this issue is being scrutinized in other forums, NASA asked that the National Research Council (NRC) not revisit the roles and responsibilities assigned to NASA by the National Transportation Policy or attempt to determine the feasibility of developing an SSTO vehicle.

NASA will use three experimental vehicles for testing and technology development, the DC-XA, the X-34, and the X-33. The DC-XA vehicle will be the successor to the Delta Clipper-Experimental (DC-X) vehicle, which was initially developed and demonstrated by the Ballistic Missile Defense Organization. The DC-X vehicle, which was transferred to NASA in August 1995, will be reconfigured into the DC-XA. Numerous SSTO technologies will be added to the DC-X, and the reconfigured DC-XA will be flight tested in mid-1996. Both the X-34 and X-33 programs are likely to benefit from the technological advances and operational experiences of the DC-XA.

The X-34 small booster technology demonstrator is intended to stimulate the joint industry/government-funded development of a small reusable (or partially reusable) booster that will be used to investigate advanced technologies for a future RLV. The demonstrator model is expected to provide an early testbed for some of the advanced technologies that could be used on a RLV and demonstrate significantly reduced mission costs for placing small payloads in low Earth orbits. NASA anticipates that the X-34 program will begin test flights in late 1997 and will achieve orbital launch by mid-1998, with two more test flights by the end of 1998.

The advanced technology demonstrator program, the X-33, which will last longer than the X-34 program, is divided into the three phases shown in Figure 1-2. According to NASA's implementation plan, "the X-33 system must prove the concept of a reusable next-generation system by demonstrating key technology, operations, and reliability requirements in an integrated flight vehicle."[11] The three phases of the X-33 program are as follows:

- Phase I—Concept Definition/Design. This phase began in March 1995 and is scheduled to continue for 15 months during which the maturity levels of a wide range of candidate technologies should be demonstrated.
- Phase II—X-33 Advanced Technology Demonstration. If approved, this phase will begin by the end of 1996 and will continue through the end of the decade. The X-33 vehicle will be built and flown during Phase II.
- Phase III—Commercial Development of a Next-Generation Space Launch System. This phase is expected to begin at the end of the decade, pending the success of Phase II, and could lead to the development of an operational RLV by 2005.

To reduce the technical risks of the RLV program, NASA has contracted with three industry teams to develop and improve the desired technology. NASA maintains only a small RLV program office with a staff of about 20 people. The three industry teams are operating as prime contractors and, accordingly, have selected subcontractors. In several instances, NASA centers that have the appropriate expertise or facilities have been chosen as subcontractors to the industry teams.[a] Prior to December 1996, NASA and the contractors will make a recommendation to the President about whether to proceed with Phase II of the program (i.e., development of the X-33). If one or more U.S. aerospace companies opt to proceed with the Phase III development of a full-scale RLV, that company will be free to adapt new propulsion systems, materials, and other technologies to whatever type of reusable, or partially reusable, vehicle design it believes will be most economical.

In Phase I, each industry team is developing a different concept for the X-33 and RLV flight vehicles. The teams and concepts are described below:

- Lockheed Martin—Lockheed Martin's concept for both the RLV and X-33 demonstrator vehicles is a lifting body aeroshell with vertical liftoff and horizontal landing capability and horizontal processing and aircraft-like operation and support. The propulsion system of choice is an altitude-compensating linear Aerospike engine.
- McDonnell Douglas and Boeing—The McDonnell Douglas/Boeing team's current baseline X-33 demonstration and RLV configuration is a vertical takeoff/vertical lander; however, trade studies on other vehicle options, including horizonal landers, are also underway. The team's current propulsion choices are the near-term modified space shuttle main engine (SSME) for the X-33 and a SSME-derived engine (with high sea-level F/W) or RD-O120 Russian engine for the RLV.
- Rockwell International—The Rockwell concept for the RLV and X-33 vehicles is based on a wing-body approach with vertical liftoff and horizontal landing capabilities. Rockwell sees the wing-body approach as a low-risk configuration based on information from the Shuttle database. Rockwell's current propulsion choices are a near-term modified SSME for the X-33 and a SSME-derived engine (with high sea-level F/W) or the new RS-2100 engine for the RLV.

DECISION CRITERIA

On May 1, 1995, OMB issued a set of decision criteria that had been developed jointly by NASA, OMB, and OSTP for assessing technology maturation in preparation for an X-33 vehicle. These criteria, established in accordance with the 11-point

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[a] Examples of NASA centers serving as subcontractors to industry include the Langley Research Center, where work is being done on a metallic TPS for McDonnell Douglas/Boeing and Lockheed Martin, and super lightweight tank development for Lockheed Martin; the Ames Research Center, where work is being done on a ceramic TPS for Rockwell International and McDonnell Douglas/Boeing; and the Marshall Space Flight Center, working on friction-stir welding for Rockwell International.

agreement between NASA and OMB that was signed by NASA Administrator Daniel S. Goldin on November 25, 1994, provide the basis for decisions to be made in 1996 and at the end of the decade about whether to proceed with Phase II (X-33 Advanced Technology Demonstration) and Phase III (Commercial Development of a Next-Generation Space Launch System). The decision criteria are consistent with the National Transportation Policy, and the relevant sections are cited in appropriate chapters of this report.

STUDY TASK

In the spring of 1995, the NASA Office of Space Access and Technology requested that the NRC undertake a study to examine whether the technology development and test programs planned by the prime contractors and engine companies would, indeed, provide adequate, meaningful data upon which to base a decision in December 1996. The Statement of Task is as follows:

> The NRC/ASEB [Aeronautics and Space Engineering Board] committee, drawing on available data and analyses, extensive briefings by NASA and its industry partners, and on information gathered in site visits to development and test facilities, will assess whether the development and test program for the propulsion and vehicle materials technologies is sufficient and appropriately structured to support a decision at the end of 1996 on whether to proceed with the X-33. In accomplishing this task, the committee will: (1) Receive briefings and data from NASA which relate the goals of the X-33 and their relationship to the requirements for a SSTO reusable launch vehicle; (2) Review the technology capabilities currently available to meet the X-33 objectives for propulsive and structural efficiency; (3) Review the analytical and development and test programs for propulsion and vehicle structures and structural materials; and:
>
> - Assess whether the technology development, test and analysis programs are properly constituted to provide the information required to support a December 1996 decision to build the X-33.
> - Suggest, as appropriate, necessary changes in these programs to ensure that they will support vehicle feasibility goals.
>
> Vehicle technologies may include cryogenic propellant tanks, cryogenic insulation, thermal protection systems, and load-carrying airframe structures, focusing on their producibility, operability, weight, and multi-flight reliability. Propulsion technologies may include bipropellant and tripropellant rocket systems, focusing on multi-mission robustness, operability, and performance. The committee will not revisit the findings

operability, and performance. The committee will not revisit the findings and recommendations of the Access to Space Study nor the roles and responsibilities assigned to NASA by the National Space Transportation Policy.

In order to ensure maximum impact, emphasis will be placed on providing final findings and recommendations in a timely fashion. The report will be subject to National Research Council report review procedures prior to release.

APPROACH

In response to NASA's request, the NRC formed the committee on the Reusable Launch Vehicle Technology and Test Program, which met on June 20–22, July 7, July 14, July 31–August 4, August 23–25, and August 30–September 1, 1995. The committee heard extensive briefings by officials and researchers at the appropriate NASA centers and by NASA's industry partners in the RLV program and their major engine subcontractors. The committee also conducted site visits of facilities and viewed the available hardware. The first committee meeting was at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama, where NASA briefed the committee on the general features of the RLV program in all areas of interest, with an emphasis on MSFC's role in providing testing facilities and expertise for propulsion systems, cryogenic tanks, and advanced technology development (e.g., friction-stir welding). To accomplish its task more efficiently, committee members were divided according to their expertise into four subgroups: propulsion systems, cryogenic tanks, primary vehicle structure (PVS), and TPS. Because of the broad charter and the short time frame, the committee composed a list of specific questions to be submitted to the presenters and briefers during subsequent meetings and site visits. The committee also decided to augment its own expertise with an independent advisor on TPS.

The committee next met at the Langley Research Center in Hampton, Virginia. At this meeting, the committee learned about the computational and simulation capabilities Langley used to help define and optimize concepts for the X-33 and X-34 demonstrators and for the composite primary structures, reusable cryogenic tank systems, aluminum-lithium (Al-Li) technology, and metallic/refractory composite TPS. The committee also visited Langley's materials and structures facility and the pressure box test facility. Some committee members then visited NASA's Ames Research Center in Moffett Field, California, for a briefing on the development and test programs for advanced ceramic TPS material and the information technology for integrated health management. This group also reviewed the Ames analysis program, which incorporates various TPS tradeoffs in the vehicle design and inspected the available advanced TPS hardware.

At the third full meeting, the committee met with NASA's industry partners in the RLV program (Lockheed Martin, McDonnell Douglas/Boeing, and Rockwell International) and their major engine subcontractors (Aerojet, Pratt&Whitney, and

Rocketdyne). In this week-long meeting in the Los Angeles, California, area, the committee was briefed on the details of each contractor's current vision of the RLV program and its precursor demonstrator, the X-33. As the committee had requested, the emphasis of the briefing was on technology development and test programs related to the X-33 decision and indicating the traceability to the eventual SSTO RLV. The prime contractors described their alternative vehicle concepts for the X-33 and RLV as well as the associated propulsion systems and TPSs, structural materials, and cryogenic tanks. The committee gathered data about the contractors' fall-back positions and examined facilities and hardware. The major engine subcontractors provided the committee with technical details about the propulsion systems available for immediate use in the X-33 demonstrator, as well as those that could be used with minor modifications, and described development and test programs for more advanced RLV propulsion systems. This meeting marked the conclusion of the information gathering phase of this study.

Subsequently, the propulsion and TPS subgroups met at the National Academy of Sciences Beckman Center in Irvine, California, to discuss their findings and recommendations. The primary structure and cryogenic tank subgroups met in Washington, D.C. one week later to finalize their findings and recommendations. The findings and recommendations were coordinated between the two groups by teleconference.

ORGANIZATION OF THE REPORT

This report is organized to reflect the findings and recommendations of the full committee and the subgroups. This introductory chapter is followed by chapters on primary vehicle structures (chapter 2), cryogenic tanks (chapter 3), TPS (chapter 4), and propulsion systems (chapter 5). Each chapter begins with an introduction detailing issues and objectives specific to the technology under consideration. This is followed by the decision criteria for implementing Phase II of the RLV program, a discussion of the NASA/industry programs for meeting Phase II criteria, and the committee's technology-specific findings and recommendations.

NOTES

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5. Vice President's Space Policy Advisory Board. 1992. The Future of the U.S. Space Launch Capability: A Task Group Report. Washington, D.C.: U.S. Government Printing Office.

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8. Moorman, Jr., Lt. Gen. Thomas. 1994. A briefing by the chairman of the Defense Space Launch Modernization Plan presented to the Committee on Space Facilities at the National Academy of Sciences in Washington, D.C., March 9, 1994.

9. The White House Office of Science and Technology Policy. 1994. Statement on National Space Transportation Policy. Washington, D.C.: U.S. Government Printing Office.

10. NASA. 1994. Implementation Plan for the National Space Transportation Policy. Washington, D.C.: U.S. Government Printing Office.

11. Ibid.

2

Primary Vehicle Structure

INTRODUCTION

Primary vehicle structure (PVS) is defined as the structure that carries loads from or to another structure or structures. Some examples of PVS in the RLV are the intertank, the payload bay, the engine-thrust mount, and wing/control surface-box structures. Cryogenic fuel tanks will also play a structural role in all planned RLVs. The development plans for composite cryogenic tanks include many features common to all primary structures. The common features, as well as features specific to nontank structures are discussed in this chapter; features specific to the plans for composite tanks are discussed in chapter 3.

Systems studies indicate that compared with current launch vehicles, major improvements in the weight and robustness of PVS will be required to achieve SSTO performance. Primary structure materials have the greatest impact on weight. Phase I technology development will demonstrate the applicability of state-of-the-art composite materials to PVS subsystems for both the X-33 and potential RLV configurations. Final material selection for the X-33 design will be based on systems analyses that incorporate the results of the technology program.

The primary issue relevant to the development of a PVS is the lack of data for estimating material properties, life cycle, manufacture, inspectability, and repairability of composite materials potentially applicable to primary structures in launch-vehicle environments. Therefore, the objective of PVS technology development is to determine whether structures can be produced that meet weight, reuse, cost, and operations requirements for X-33 and RLV configurations. Information obtained during technology development, as described in the decision criteria below, will be used to determine if a reusable PVS can be built and integrated into an X-33 flight test vehicle as a demonstrator model for an eventual SSTO vehicle to be developed by the end of the decade.

DECISION CRITERIA

The PVS decision criteria developed to determine whether to proceed to Phase II of the RLV program are given below:

a. At least one composite intertank test article will be constructed and integrated with the required TPS, health monitoring, and attachment subsystems, and will be under test. Appropriate coupon and other subscale testing (e.g., pull-test, panel specimen) required to achieve this goal will be completed and documented.
b. At least one composite thrust structure test article will be constructed and integrated with the required TPS, health monitoring, and attachment subsystems, and will be under test. Appropriate coupon and other subscale testing (e.g., pull-test, panel specimen) to achieve this goal will be completed and documented.
c. At least one composite wing or aero-surface test article will be constructed and integrated with the required TPS, health monitoring, and attachment subsystems, and will be under test. Appropriate coupon and other subscale testing (e.g., pull-test, panel specimen) to achieve this goal will be completed and documented.
d. The material selection for intertank, thrust structure, and wing or aero-surface will be completed and documented. The selection must consider performance (e.g., weight, strength) producibility, inspectability, and operability characteristics.
e. A documented analysis will have been completed which demonstrates that the selected materials and primary structure subsystems are scaleable to a full scale RLV and will adequately be demonstrated by an X-33 vehicle. This analysis will contain the correlations between analytical predictions and experimental test results. These correlations will be at a level of confidence sufficient to ensure that analytical tools are valid for purposes of full-scale vehicle design. Estimated requirements for the RLV, which will be supported by this analysis, include a weight target of 4.0 lb/ft^2 of surface area or less for the airframe structure (TPS, vehicle health monitoring system not included).

NASA/INDUSTRY PROGRAMS

The design practices used by the industry teams, as well as structural component designs and the development and test programs, are discussed in the following sections.

The development of alternate and advanced technologies by industry and at the NASA centers will also be discussed briefly.

Design Practices

The strong sensitivity of gross liftoff weight to vehicle dry-weight mass ratio is illustrated in Figure 2-1. Economically viable gross liftoff weights and technically feasible specific impulse (Isp) restrict the dry-mass fraction to a narrow range of 10–11 percent, of which the structural mass fraction is about 5 percent, which emphasizes the importance of rigorous weight control of all vehicle components.

Components that meet the derived system requirements were designed by contractors using standard analytical techniques; however, design details varied from one contractor to another. The contractors applied factors of safety to various components differently and assumed differing factors of safety and weight penalties for joints and other nonstandard areas of structure, materials, and the level of composite layup. The strategies for assuring robustness and reusability also varied among contractors. Producibility, cost, health monitoring, NDE inspection, and repair considerations are included to some extent in all designs and are primarily correlated to the maturity level of the design. One of the most important design factors was the assumed weight growth margin for the RLV configuration. All contractors used very low values, varying from almost zero to 15 percent. The resulting requirements for primary structure weight per unit area vary from slightly less than the NASA/OMB requirement of 4 lb/ft^2 up to a high of 5.3 lb/ft^2.

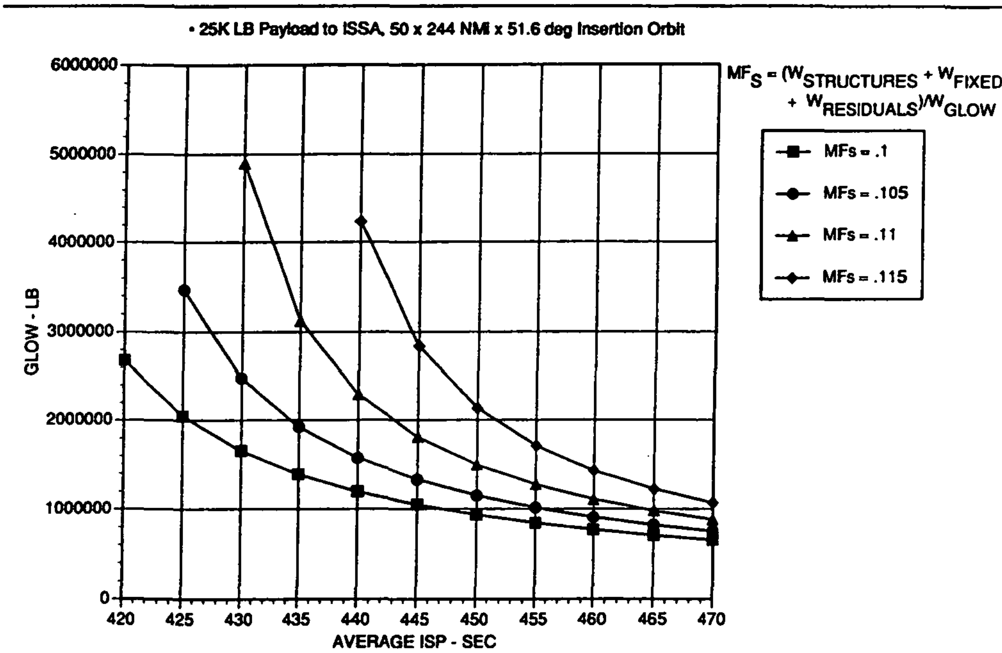

FIGURE 2-1 What Does It Take to Achieve SSTO? Source: Lockheed Martin.

Components of Major Structures

The contractors selected three vehicle design concepts to demonstrate RLV primary vehicle structure technology in the X-33 program: wing body, lifting body, and vertical lander. In all three, the fuel tanks are incorporated as major structural elements. The designs also incorporate the following major dry components:

- intertank structure(s)
- thrust structures
- control surfaces and/or wings
- an external aeroshell (in one case only)

The intertank is the structure between the liquid oxygen (LOX) and liquid hydrogen (LH_2) tanks. This structure is designed to carry loads and transition them to adjacent fuel tanks. In addition, some launch vehicle guidance, navigation, and control systems are located in and supported by the intertanks. In most RLV designs the payload bay is also located between the intertanks. Inasmuch as the intertank accommodates a network of support structures, many attachments and cutouts for feedthrough holes are necessary. The structural concepts being considered for the intertank design include truss structures, frame-supported sandwich panels, and skin-stringer, semi-monocoque structures.

The primary function of the thrust structure is to transfer and distribute engine thrust loads through the launch vehicle. The thrust structure is a highly loaded system and must perform in a severe thermal and vibroacoustic environment. Configurations under study include trusses, conical shells, and longeron-reinforced, frame-stabilized shells. The thrust structure, which carries large loads, consists of multiple components requiring joining and/or complex integral manufacturing. The engines are attached to the thrust structure with mechanical fasteners.

The aeroshell and control surfaces, including the wings, are based on specific designs, each with different performance criteria. The wing and control-surface designs being considered consist of box beams built up either from skin-stringer panels or from honeycomb-core panels. Aeroshells are lightly loaded stiffened panels connected to the cryotank or other structures through a space-frame network of composite trusses.

Materials under primary consideration for dry structure include graphite/epoxy composites and higher-temperature graphite/bismaleimides (BMI) composites, with the latter being favored in most designs. Graphite/thermoplastic, graphite/polyamide, and graphite/cyanate ester composites are also under consideration either as backup or eventual improvements.

Development and Test Programs

The contractors followed a reasonable preliminary design approach to developing the primary vehicle structures—a "building block" approach typical of composite structure design. Tests have been specified at the material, laminate, full-sized substructure, and subscale structure levels. Tests were designed to confirm the assumed material properties, structural behavior, and performance of the system designs and to identify properties to further design revisions. Extensive material-level testing has been or will be performed, as well as hundreds of material and laminate coupon tests. The test results will be added to the contractors' large database of composite properties. Material testing under the current program is concentrated on newer, less well characterized materials, on less familiar properties (such as cryofuel compatibility and permeability), and on performance at low and high temperatures. Materials being considered in this program include composites of high-strength graphite fibers (IM7, T650, and T1000) with toughened epoxy (977, 8552) BMI (5250, and others), cyanate ester (EX1509), and thermoplastic (X3009, K3B) matrices. Basic (ply) material properties to be tested under the program include longitudinal and transverse tension and compression, in-plane shear, and interlaminar strength. These tests are usually performed at a variety of temperatures and absorbed-moisture levels (although the latter are not as numerous as in aircraft programs) and also after thermal cycling. Most testing is intended to complete or supplement existing databases.

Testing laminate properties is the next step in the building-block approach. The laminates being considered vary by contractor, and a wide variety of layups and thicknesses are being considered. Preliminary designs include pseudo-isotropic layups, 0/90/+−45 families, and optimized 0/15/30/45/60/90 designs. Longitudinal and transverse tension and compression and in-plane shear were also tested. The results of these tests are used primarily to check and verify laminate stiffness calculations and to determine the design strengths of undisturbed laminates. Most laminate failures are associated with design details; therefore, a wide variety of more complex tests is planned (the following list is not all inclusive):

- open hole strength (tension and compression)
- filled hole under compression
- bearing (pin and bolt loaded holes)
- compressive strength after impact
- LOX compatibility
- through-thickness H_2 permeability
- microcracking and strength after thermomechanical cycling
- compatibility with health monitoring inclusions, such as optical fibers

These properties have little meaning at the ply level and are used only as design data for the selected laminates.

The next level of structural complexity is dominated by joining considerations. Joints are recognized as critical by all contractors. The same building-block approach has been applied to developing joints. Fundamental tests that yield information critical to joint designs include lap shear tests, bearing, interlaminar tension, and pin or bolt tension tests. The results of these tests, particularly for lap shear, are susceptible to many factors. Therefore, the program includes extensive testing of lap joints, adhesives, temperatures, surface preparations, layups, and material architectures (cloth and tape). Joint details, such as tapering and ply dropouts, are also being tested. Joints between panels and structural details, such as stiffeners and tension clips, are tested extensively, and specific tests are performed to test clip and stiffener pull-off and load transfer at stiffener terminations and panel closeouts.

The next element in the building-block approach is large-scale built-up components. These components include flat, stiffened panels; curved, stiffened panels; and complex joints. These components will be partial structures of full-scale RLV tank and intertank sections and thrust structure sections. Testing for damage resistance (usually by after-impact testing) and repair techniques will also be performed. Integration of components with TPS and cryoinsulation systems will be included in some of these tests. A variety of thermal and mechanical loading conditions will be considered, including cyclic and combined loads.

Large-scale joint tests in all programs are concentrated on the joint between the cryotanks and the intertank structures, referred to as the Y-joint because of its shape when viewed in cross section. Numerous tests of Y-joint sections and subscale versions of complete joints are planned. Other design details, such as joints between panels and metal fittings, tank fittings, and double-lap joints for tanks, will also be performed.

Finally, complete structures, such as thrust-structure components, wing boxes, and structural tanks, will be built and tested. Some components will be full-scale flight components (to be flown on subscale vehicles), such as tanks and intertanks that will be used on the DC-XA flight. Other components will be subscale models of complete structures, such as quarter-scale intertank structures or subscale structural tanks. Full-scale, but simplified structures, such as a complete wing box, also will be built and tested. Generally, these tests are scheduled to be underway by June 1996.

Material and laminate tests will be performed under a wide variety of conditions, including a wide range of temperatures, and pre-conditionings including exposure to moisture, thermal cyclings, and impacts. Joints and subscale components will be tested under fewer conditions; and built-up test structures and substructure specimens under fewer still. Generally, although fewer specimens (and therefore fewer load conditions) will be used in the more complex tests, the conditions tested will be more complex. For example, for a new fixture under development at NASA Langley, intertank section panels will be subjected simultaneously to multiaxial enplane loading, pressure loads from one side, and a complex thermal environment. In another case, composite tanks will undergo both thermal cycling and extensive, repeated mechanical loading after which they will be tested functionally (e.g., for hydrogen leaks).

Alternate and Supplemental Technologies

The advanced and alternate technology development programs relevant to the work on cryotank and composite structures will provide alternatives to primary technologies and materials if the primary technologies fail to meet requirements. Alternative technologies and materials are being studied both at NASA centers and by the contractors. NASA work relevant to cryotank and primary structure development includes alternate integrated TPS/structure, sandwich structures, debris damage-assessment techniques, structural joint techniques based on ongoing work in the advanced composite technology and high speed research programs, and full-scale pressure testing methodology and test facility development.

Contractor work on alternate and advanced technologies includes alternate material (cyanate ester and K3B thermoplastic) database development, alternate construction techniques (i.e., Russian isogrid composite structure), and health monitoring and assessments of damage-detection technology.

FINDINGS AND RECOMMENDATIONS

Findings

The committee, with some reservations, believes that the design methodology for PVS is sound. The analysis techniques are appropriate for the designs, and key technology issues have been identified for the preliminary designs. Technology is being advanced through a building-block approach, similar to the approach to earlier composite structures. Robustness issues are being addressed by the use of damage tolerant approaches. The range of technologies under development by the contractors makes the program itself a resilient one.

The committee is concerned about the low, 15 percent maximum weight-growth margin being applied this early in the development phase of a new design using materials of moderate maturity. However, the committee agrees that simply increasing the weight-growth margin will lead to a first estimate for a larger vehicle. There is a real need for strict limits on weight growth, which means emphasizing the accurate calculation of structural performance and weight early in the program and necessitates early verification that a given structure can be built at or below the predicted weight.

Efforts to validate the analysis techniques and scaleability to SSTO RLVs are progressing in a reasonable direction. Extensive subscale tests, moving from coupon size through panel size to reasonably large test articles, are to be accompanied by continuous validation of the predictive tools. However, ways to validate as-built structural mass fractions and their required growth margin have not been fully determined at this time.

The variety of concepts being considered by contractors is an asset to the program. Exploring the viability of a range of concepts will enhance the range of potential tradeoffs available for the eventual SSTO RLV. Using composite materials also will increase the number of potential tradeoffs because, in theory, a wide range of materials and layups is available. This range is somewhat restricted by the building-block approach, which relies on empirical data on specific laminates; however, at this stage in the program a reasonable range of materials and laminates is under consideration. Toughened-matrix graphite/epoxy for tank structures and graphite/BMI for dry structures are currently the prime candidates for the RLV. Selection of these materials is based on existing material databases and previous design and manufacturing experience.

The committee believes that important design details, such as joints, built-up structures, and damage tolerance, are being considered in reasonable ways. Essential joints are being designed in detail and tested extensively. A variety of approaches is being employed to assure a sound structure. Most work focuses on damage tolerant designs. Health monitoring and NDE have also been discussed as ways to relax structural robustness requirements, but these technologies appear to be immature at this time.

Alternate and advanced technologies have not been explicitly defined in the decision criteria. They can, however, play a valuable part in the program by providing alternate paths to success through either higher performance or lower risk than baseline designs.

The decision criteria identify a specific target for primary structure weight—4 lb/ft^2 of vehicle surface. This requirement is not explained, but it is typical of published SSTO designs.[1] Because the weight limit may not apply equally to all vehicle designs it should be reconsidered for each design concept.

It is important to note that time constraints did not allow the committee to explore fully issues such as aging, ease of assembly, and maintenance of structures. However, the committee considers these issues to be very important over the long term.

Recommendations

- The most rigorous requirement for the primary structure is to achieve robust functionality at a very low mass fraction. Quantitative targets for material, laminate, subcomponent, and component tests should be reached during Phase I. Critical elements include assuring that the conditions under which testing is done (particularly the complex conditions for the component tests) are accurate; in cases of uncertainty, determining worst case scenarios; and designing tests so the information can be used to demonstrate that mass fraction goals have been achieved.
- Test articles of each size must be designed, built, and tested to RLV-scaled conditions using the design codes that are being validated. For larger test articles, all of the joints and fittings should be properly scaled to the RLV flight configuration. This may require full-scale testing of some joints.
- The planned combined-loads tests that simulate the appropriate thermal and acoustic environments integrated with flight vehicle interfaces (e.g., TPS on the cryogenic tank or the intertank) should be conducted with as many cycles as possible.
- Many health monitoring systems and NDE techniques were mentioned in the briefings, but there does not seem to be a well ordered program to identify which measurements will be made and where or how to use NDE in the difficult situation of penetrating multiple layers of material. The committee is aware of the extreme difficulty of this task and strongly

recommends that a clear path toward certifying readiness for launch of flight-critical hardware be developed.

- Weight requirements (not only the 4 lb/ft^2 given in the decision criteria) must be defined for each vehicle concept.

NOTES

1. Aldrich, Arnold D. 1993. Access to Space Study: Report to the Administrator. Washington, D.C.: National Aeronautics and Space Administration.

3

Reusable Cryogenic Tank System

INTRODUCTION

A key component in the success of the reusable launch vehicle program is the development of a reusable cryogenic tank system (RCTS) that can withstand the environments of launch and reentry and can meet the weight and reusability goals of the RLV. In the past, fuel tanks, such as the space shuttle external tank, have been jettisoned before the vehicle entered orbit. The semi-conformal and integral reusable tanks proposed for the RLV, however, not only store propellants but are also part of the primary structure of the vehicle. Because the tanks are used to store propellants, which comprise most of the vehicle volume, they contribute significantly to the mass of the primary vehicle structure. To date no reusable cryogenic tanks of this scale have been used in flight, but two subscale models have been built and tested at LH_2 temperature under the auspices of the National Aerospace Plane (NASP) technology program. The NASA/industry program is building on the experience of the NASP program.[1]

Technology development during Phase I is designed to demonstrate the relative merits of both composite and metallic materials for the RCTS in the X-33 and in potential RLV configurations. The RCTS program includes development of metallic Al-Li alloys (primarily for LOX) and composite tanks (primarily for LH_2). At this point, however, data are incomplete for evaluating the material properties, life cycle, manufacture, inspectability, and repairability of some tank materials being considered for reusable cryogenic tanks. Therefore, the objective of RCTS technology development is to determine whether these tanks can be functionally produced and whether weight, reuse, cost, and operations requirements for X-33 and RLV configurations can be met.

DECISION CRITERIA

During Phase I a series of developmental tests are planned to provide data to determine whether reusable cryogenic tanks can be integrated into an X-33 flight test vehicle to support a demonstration of the SSTO by the end of the decade. The following tasks must be accomplished for the metallic and/or composite tanks to meet the Phase II go-ahead criteria:

a. At least one metallic (Al-Li) tank will be constructed and integrated with the required TPS, health monitoring, and attachment subsystems and will be under test. Current plans call for two such tanks to be manufactured and integrated for test. Appropriate coupon and other element testing (e.g. LOX compatibility, reusability) required to achieve this goal will be completed and documented. All applicable sub-scale testing will have been conducted to scaled (to full scale RLV) pressures and loads.

b. At least one graphite composite tank will be constructed and integrated with the required TPS, health monitoring, and attachment subsystems and will be under test. Current plans call for two such tanks to be manufactured and integrated for test. Appropriate coupon and other subscale testing (e.g., LOX compatibility) to achieve this goal will be completed and documented.

c. The material selection for both fuel and oxidizer tank subsystems will be completed and documented. The selection must consider performance (e.g., weight, strength) producibility, inspectability, and operability characteristics.

d. A documented analysis will have been completed demonstrating that the selected materials and tank subsystems are scaleable to a full scale RLV and will adequately be demonstrated by an X-33 vehicle. This analysis will contain the correlations between analytical predictions and experimental test results. These correlations will be at a level of confidence sufficient to ensure that analytical tools are valid for purposes of full-scale vehicle design. Estimated requirements for the RLV, which will be supported by this analysis are a minimum of 100 lifetime missions including depot maintenance not more than every 20 missions, volumetric weight targets (which will be updated for selected X-33 configuration) of 0.7 lb/ft^3 or less for an oxidizer tank and 0.5 lb/ft^3 or less for a liquid hydrogen tank, with leakage rates within the limits set for the space shuttle.

The NASA/industry programs and the findings and recommendations for Al-Li alloys and composites are discussed separately in the following sections.

NASA/INDUSTRY PROGRAMS—Al-Li CRYOGENIC TANKS

The objective of the NASA/industry cryogenic tank technology program is to test structurally a "flight like" Al-Li cryogenic tank to validate the analysis and manufacturing methods used in its design. Advanced technologies, such as near-net-shape extrusion, near-net forging, and spin forming of Al-Li, are expected to be demonstrated at the NASA technology readiness level (TRL) of 6. (On the TRL scale, TRL 6 refers to demonstration of a system/subsystem model or prototype in a relevant ground or space environment.)

The cryogenic tank technology program tank will be 14-ft in diameter and will include near-net-shape extruded, integrally blade-stiffened panels; net-shape, spin-formed bulkheads; and near-net-shape, roll-forged stub adapters. The tank, which is being built now, is an all Al-Li alloy 2195 tank. External cryogenic insulation will be installed later. On one tank, the TPS panels will be installed, and a life-cycle test will be conducted on the ground.

One industry partner has contracted with the Russians to build a LOX tank system from the Russian Al-Li alloy 1460. Russia is also building an Al-Li LOX tank for the DC-XA from alloy 1460, with some components fabricated from the Russian equivalent of alloy 2219. This tank is designed to SSTO loads and environment; however, the Al-Li alloy 1460 currently being used for this tank is not optimized. The industry partners will also be focusing on developing a LOX tank constructed from Reynolds alloy 2195 and building, friction-stir-welded tank 3 ft in diameter.

The Super Lightweight Tank (SLWT) for the space shuttle at the NASA Michoud Assembly Facility in New Orleans, Louisiana, is being constructed using alloy 2195 thick plate stock with Al alloy 2219 ring frames. There are a number of key SLWT milestones that are important to the technology for the X-33 LOX program. Fabrication of the advanced launch test article began in February 1995, and the advanced launch test article proof test was scheduled for October 1995. The welding techniques and procedures developed in this program apply directly to the X-33 program, and the results of tests on the welded article should be particularly informative. The advanced launch test article tests are scheduled to be completed by May 1996 and will be available for use in the X-33 program. The size of the LOX and LH_2 tanks for the RLV will be similar to those of the space shuttle SLWT; therefore, demonstrating producibility of a large tank like the SLWT will be reassuring.

In addition to alloys 2195 and 1460, an isotropic Al-Li alloy is being developed under Air Force Contract F33615-92-C-5914 with the University of Dayton and its subcontractor ALCOA. The alloy, designated AF(UDRI), contains more than 2-percent-weight lithium, which is the minimum for achieving approximately 10 percent savings in weight (compared with conventional aluminum alloys of equivalent mechanical properties) if only density and modulus are considered. The mechanical properties of alloy AF(UDRI) are far more isotropic than the mechanical properties ever observed for a similar density Al-Li alloy and are extremely encouraging. For instance, in-plane anisotropy has been reduced to less than 4 percent for 2 percent cold-worked recrystallized plate and to less than 8 percent for 6 percent cold-work unrecrystallized plate; fracture toughness was nearly doubled in the short, transverse direction and was improved significantly in plane; and fatigue-crack growth improved significantly compared with 7050-T7451, a leading non-lithium bearing plate alloy. A comparison of alloy AF(UDRI) with alloy 2195-T8, based on similar thickness and degree of recrystallization, is shown below:

	AF(UDRI)	2195-T8
Ultimate strength in the L direction	79.5 ksi	80 ksi
Yield strength in the L direction	71.5 ksi	75 ksi
Fracture toughness parameter	40 ksi-in$^{1/2}$	34 ksi-in$^{1/2}$

Because of the higher lithium content, alloy AF(UDRI) has a 3 percent lower density and a 6 percent higher modulus than alloy 2195. Although AF(UDRI) is not as mature as alloys 2195 or 1460, it may offer some advantages, and its development should be monitored for possible future use.

MSFC will conduct mechanical tests on the Russian Al-Li alloy 1460 and Reynolds alloy 2195 and will specifically evaluate reusability. Reusability testing is defined as testing time-dependent properties, such as fatigue-crack-growth rate and susceptibility to stress-corrosion cracking. Alloy 1460 will be tested for baseline tensile, LOX compatibility, fracture, fatigue, weld development, and stress corrosion. Tests will be conducted at both cryogenic and high temperatures.

A critical step in the manufacture of the LOX cryogenic tank is welding the chosen Al-Li alloy. Although alloy 2195 can be welded, weld repair and/or second-pass welding is a major problem. MSFC experiments with an Al-Si alloy filler have resulted in some improvement in weld repair. In cooperation with MSFC, the Edison Welding Institute, Boeing, and Reynolds Aluminum, one industry partner will be examining a new method of "friction-stir welding." The friction-stir-welding process shows promise and could, if successful, solve the welding problems associated with Al-Li alloys. Data for alloy 2195 on the space shuttle SLWT will also be incorporated into the database.

Al-Li alloys are primarily used for the LOX cryotanks. One industry partner is considering the use of a titanium (Ti) honeycomb tank as backup for the composite LH_2 tank. The Ti alloy (Ti-6Al-4V ELI) is being considered for use in the face sheet.

FINDINGS AND RECOMMENDATIONS—Al-Li CRYOGENIC TANKS

Findings

In general, the criteria for Phase II goals appear to be well conceived and reasonable, with the exception of the requirement of 0.7 lb/ft^3 or less for the oxidizer tank, which may not be appropriate as a universal, absolute target. Appropriate weight targets for all major components should be based on the system design-engineering process. Target weights depend on specific design concepts and parametric trade studies to optimize the overall design rather than on individual components of the design.

The development program for the Al-Li tank primarily for LOX application is robust because more than one approach is being developed in almost all of the critical categories. Among NASA and the industry partners, two alloys of Al-Li with somewhat different properties are being used (Reynolds alloy 2195 and the Russian alloy 1460). Three fabrication techniques (machining to net-shape extrusion, net-shape spin forming, and net-roll forging) and two welding techniques (standard and friction-stir welding, which is under development) will be used. Finally, with respect to the scale of tanks to be fabricated and tested, there are one 14-ft-diameter, one 3-ft-diameter, and two 8-ft-diameter tanks being developed in the RLV program; a 28.5-ft-diameter by 154-ft-long tank made of Al-Li alloy 2195 with Al alloy 2219 rings is being developed as a replacement for the space shuttle's external tank. The Al-Li tank for the SLWT will clarify the issue of scaling the smaller test tank data to the full-scale RLV tank, which is approximately 40 ft in diameter. As is required by the decision criteria for Phase II approval, more than one organization is conducting tests to characterize material properties, including reusability (e.g., fatigue-crack-growth rate) and LOX compatibility for both the 2195 and 1460 alloys.

Despite the robustness of the Phase I development program, there are several technical areas of concern affecting producibility, operability, and reusability that are detailed in the following sections.

Selection of Materials

Using Al-Li alloys for the LOX cryogenic tank is an excellent choice. Current tests are focused on Reynolds alloy 2195, which has been selected for the SLWT, and the Russian alloy 1460.

Alloy 1460 is similar, although slightly lower in alloy content, to ALCOA alloy 2090, except a small amount of scandium (Sc) has been added. The Russians claim Sc improves weldability of the alloy by refining the grain size in the pool of molten metal formed during welding.[2] Alloy 1460 was developed specifically for use with LH_2 and LOX. With properties similar to alloy 2090, alloy 1460 has a higher modulus and a lower density than alloy 2195. Alloy 1460 may not be as strong as alloy 2195; however, their specific properties are similar.

Except for data in the proceedings of recent conferences on Al-Li and aluminum alloys, little has been published about alloy 1460.[2,3] Recent preliminary data provided to one industry partner indicate that the properties of alloy 1460 are at least 25 percent above specifications. Because alloy 1460 is relatively new (the effect of Sc on the properties of alloy 2090 is not well documented), there will have to be extensive tests to characterize all product forms (including welded products) to establish a reliable database. Tests should include wide panel testing, not just coupon testing, of the weld zone because cutting out coupons may relieve the residual stresses associated with the welding process that can affect fracture toughness and fatigue properties. Fracture toughness and fatigue-crack-growth studies should be conducted over the total temperature range, including cryogenic temperatures.

Alloy 2195 exhibits better cryogenic ductility and significantly greater strength than the conventional alloy for cryogenic tanks, alloy 2219. Alloy 2195 also exhibits a positive fracture-toughness ratio when subjected to a range of temperature (from room temperature to cryogenic temperatures), which is an important consideration for cryotanks. Greater strength, coupled with higher modulus and lower density, can lead to significant weight savings. The alloy also has good corrosion resistance, excellent fatigue properties,[4] can be near-net-shape formed, and, with proper precautions, can be adequately welded.[5] However, there has been some concern about consistent producibility. Specifically, some thick plate has failed to meet minimum properties at T/8, where T is the thickness of the plate. Consequently, there may be problems associated with through-thickness anisotropy. Recent microstructural and texture analyses have shown that an excellent product from the microstructural point of view can be produced with current methods.[6] However, each casting and product form should be extensively characterized to ensure that it meets the required microstructure/properties criteria.

Welding

Weldability and weld repair are major areas of investigation. MSFC has been experimenting with an Al-Si alloy filler, which has resulted in some improvements in weld repair. But the committee believes MSFC should exercise caution in using an Al-Si filler material because silicon combines with Al-Li to form an AlLiSi phase that attracts and absorbs moisture, which increases susceptibility to stress-corrosion cracking. Alloy 8090 was found to be very susceptible to stress corrosion when the alloy contained an excess of only 0.08 percent weight silicon.[7] NASA should include stress-corrosion tests of weld zones of alloy 2190 to ensure that the filler material does not produce a weld zone susceptible to stress-corrosion cracking. This test is not included in the current program. If the weld repair problem is not resolved, an alternative would be to cut out the defective area and replace it with virgin metal because no problems have been identified if the first weld is sound.

The Russians claim that alloy 1460 is weldable and have reported weld-zone strengths of more than 40 ksi. Russian alloy 1217, which is used for weld wire, contains an Sc addition and appears to be superior to conventional weld wire for Al-Li applications. Boeing has obtained weld-zone strengths approaching 40 ksi for alloy 2090. Weld-zone strengths should be verified and stress-corrosion tests should be conducted on the weld zone of alloy 1460.

Friction-stir welding seems to be a promising solution to the problem of welding Al-Li alloys. However, the process is in an early stage of development, and extensive tests are needed to determine the feasibility of using this technology on the thin sheet (less than 1/8-inch-thick) that will be used for the LOX tank. Results obtained from welding 1/4-inch-thick alloy 2195 for the proposed demonstrator LOX tank may not be scaleable to the proposed X-33 tank.

Near-Net-Shape Forming

Near-net-shape forming is another technology that is critical for the LOX cryogenic tank and will require extensive microstructural and property characterization of the finished products. Properties obtained on the machined isogrid panels for the SLWT may be different from the properties of the near-net-shaped formed panels that are planned for the X-33.

LOX Tank

Russia is building an Al-Li LOX tank from alloy 1460 for the DC-XA using some components fabricated from Al alloy 2219. The Russians have extensive experience in building welded aircraft structures from Al-Li alloys 1420 and 1421, which should be helpful in constructing the LOX tank. The tank is designed to SSTO loads, and the environment and fabrication methods should be scaleable to the requirements for SSTO. Because of the limited database on alloy 1460 as well as possible lot-to-lot variations in Al-Li alloys, extensive coupon testing for durability—fatigue, fracture, stress-corrosion cracking (time-dependent properties), thermal stability, and similar tests will be needed as well as full-scale tests of the tank. The fatigue-crack growth and stress-corrosion behavior of welded and weld-repaired alloy 1460 should also be determined. Al-Li alloys have been shown to be more anisotropic than conventional aluminum alloys; therefore, the texture of these alloys should be characterized and properties in the L, T, and 45° orientations should be measured. If thin structure is to be produced by chemical milling of a product thicker than 10 mm, properties of the milled product should be determined. In addition, all properties should be determined for the entire range of temperatures relevant to the X-33. Some of these tests are planned as part of the McDonnell Douglas Aerospace/Langley Research Center (LaRC) plan, which is funded separately. If the funding is withdrawn, other funding will be necessary to ensure that the database for the X-33 program is adequate.

The Al-Li LOX tanks constructed during Phase I must be scaleable to the tank size required for Phase II. Problems with the through-thickness properties of thick plate, the weldability of thin sheet, and other properties of the candidate Al-Li alloys must be identified and resolved prior to tank construction in Phase II. Tests of the time-dependent properties of alloy 2195, similar to the tests suggested for alloy 1460, should also be conducted to establish the durability of this alloy system. If near-net-shape manufacturing methods will be used for the X-33, the properties of these product forms must be established. By the end of Phase I, structural models should be in place to validate the concepts being considered for construction of the Phase II tank.

LH_2 Tank

Composite materials are the prime candidates for construction of the LH_2 tank for the X-33. However, a metallic Al-Li option should be considered as a backup. A titanium (Ti) honeycomb tank is being considered as a backup for the composite LH_2 tank, and the Ti alloy (Ti-6Al-4V ELI) is being considered for the face sheet. Alpha and alpha/beta titanium (e.g., Ti-6Al-4V) are susceptible to embrittlement in the presence of very small levels (less than 250 ppm) of gaseous hydrogen.[8] Nelson and Williams at NASA-Ames have published a series of papers describing the susceptibility of alpha/beta alloys to gaseous hydrogen alloys; including Ti-6Al-4V.[9-11] Nelson and Williams have shown that the apparent susceptibility of these alloys depends, in a complex way, on microstructure, test temperature, crack tip strain rate, and hydrogen pressure. However, Nelson has shown that all microstructures of Ti-6Al-4V are susceptible to hydrogen embrittlement.[12] Alloy Ti-6Al-4V ELI has a very low interstitial content, and it is known that interstitials increase the susceptibility of alpha and alpha/beta titanium to hydrogen embrittlement. Therefore, in spite of its very low interstitial content, Ti-6Al-4V ELI requires extensive characterization studies (similar to the studies conducted by Nelson on conventional alloy Ti-6Al-4V) before it can be used in a reusable LH_2 tank.

Recommendations

The following recommendations are intended to ensure that special attention is paid to several areas of concern. The committee realizes that NASA and the industry partners are aware of most of these concerns and are attempting to resolve them.

- Recent microstructural and texture analyses of alloy 2195 have shown that the current processing methods produce an excellent product. However, each casting and product form should be characterized extensively to ensure that the required microstructure/properties are obtained. Other product forms requiring characterization include all welded and weld-repaired products, as well as extruded near-net-shape formed products.
- Because of the limited database for alloy 1460 and possible lot-to-lot variations in Al-Li alloys, extensive coupon testing of all alloy 1460 product forms should be conducted.
- Because Al-Li alloys have been shown to be more anisotropic than conventional aluminum alloys, their texture, strengths, and elastic moduli should be characterized, and properties in the L, T, and 45° orientations should be measured. If a thin structure is produced by chemical milling of a product thicker than 10 mm, properties of the chem-milled product should be determined for the entire range of temperatures relevant to the X-33.
- Weldability and weld-repair strength are major issues. Although alloy 2195 can be welded, weld-repair or second-pass welding is a major

problem. MSFC has been experimenting with an Al-Si filler material. The committee recommends caution when using an Al-Si filler because it forms an AlLiSi phase that attracts and absorbs moisture, which increases the potential for stress-corrosion cracking. Alloy 2195 weld zones should also be tested for stress corrosion.

- Friction-stir welding should be vigorously pursued and demonstrated using the thin sheet Al-Li (less than 1/8-inch) that will be used for the LOX tank.
- The scaleability criterion must be rigorously satisfied because of issues related to the through-thickness properties of thick plate, the weldability of thin sheet, and other factors. Validated structural models must be in place for designing the tanks in succeeding phases.
- In addition to the 2195 and 1460 alloys, the progress of an isotropic Al-Li alloy (alloy AF[UDRI]) being developed by the University of Dayton and its subcontractor, ALCOA, should be followed. This alloy shows very good material properties when compared with other conventional aluminum alloys, and it may be a candidate for future use.
- Al-Li should be considered as a backup composite material for the LH_2 tank if system studies show that the performance penalty acceptable. Caution is recommended regarding use of Ti honeycomb, which is being studied by one industry partner, because the Ti alloy Ti-6Al-4V is susceptible to hydrogen embrittlement and not enough hydrogen embrittlement studies have been conducted on the ELI variant of this alloy.
- Thermal/load cycle testing on the alloy 2195 tank is strongly recommended to ensure that the integrated system will satisfy reusability requirements and to provide a database comparable to the database designed for the alloy 1460 tank-flight and ground test articles in the DC-XA program.
- Weight predictions (not only the 0.7 lb/ft^3 for an oxidizer tank or 0.5 lb/ft^3 for a hydrogen tank given in the decision criteria) must be defined for each vehicle concept; achievement of these (scaled) weights must be verified with properly designed test articles.

NASA/INDUSTRY PROGRAMS—ORGANIC-MATRIX COMPOSITE TANKS

Several issues are critical to the use of organic matrix composites for cryotanks: weight, producibility, permeability, and cycle life. All the contractors and NASA centers are aware of these concerns and are working to address them. The activities range from testing small-scale coupons to testing tanks of substantial, but subscale, dimensions. Three approaches to fabrication of a cryotank are being investigated. Any or all of them may produce a satisfactory product; however, given the somewhat speculative state of this technology, the probability of success is greatly enhanced by the pursuit of diverse construction concepts.

One approach to the fabrication of the organic-matrix composite tank is to use carbon cloth layups impregnated with epoxy formed to shape. The layups are then cured in an autoclave. Historically, the layup approach has been used, for example for fabricating the heat shield on reentry vehicles. The second approach uses filament-placement machines to apply graphite filaments coated with epoxy to a mandrel in the desired shape, followed by curing in an autoclave. In the third approach, a honeycomb or foam core is sandwiched between sheets of graphite epoxy, which are used to fabricate the tank. At least two sizeable tanks will be fabricated using each method, one 8 ft in diameter and 16 ft long, the other, 8 ft in diameter and 9 ft long. Fabrication of a third, slightly larger, tank is in the initial planning stage. Several contractors will test material properties, subscale tank/bottles, and panels to determine the basic strength (therefore weight) and reusability of the tanks.

Permeability testing has a long history. Contractors in the NASP program tested numerous 2-inch samples that were 0.030 inches thick (much thinner than the proposed RLV or X-33 tanks) in LH_2 at pressures on the order of 50 psi. When toughened epoxy was used in these tests, there was no evidence of significant microcracking or permeability. The samples were cycled extensively under load prior to being cut into coupons for the permeability tests. Also a 10-inch diameter composite tank was subjected to hundreds of cycles in LH_2 at pressures up to 300 psi without leaking.

Two of the NASP contractors built and tested subscale tanks. One of the tanks was tested at 7 psi. This tank was subjected to 10 full LH_2 temperature cycles. During each cycle, the tank was pressure-cycled 10 times for a total of 100 pressure cycles. The tank was then filled with liquid nitrogen, taken to full pressure, and loaded simultaneously with the maximum predicted positive and negative structural loads. Four hydrogen detectors were placed in various locations on the tank for each test, and air samples were taken at various locations near the tank skin during the low-temperature tests. No significant amount of hydrogen was detected. The tank was thoroughly tested for leaks at ambient temperature using helium both before and after testing. The only leakage was at the flange joints. It should be noted that this tank was mounted in a titanium, metal-matrix fuselage section to simulate a flight-like environment. A second tank leaked severely on the first test but not through the composite. A bonded invar ring joining the bulkhead to the cylinder leaked at the invar ring joint. This tank was later tested successfully.[13]

Indications to date are that if strain caused by combined thermally induced and mechanical loads is kept below certain levels, microcracking is minimized and permeability is not a serious problem. Refining this limit will satisfy a major design criterion.

Various tests are underway on cryostats in support of the X-33 and RLV. One industry partner has developed a composite hydrogen line and ball valve for the DC-XA auxiliary power unit. A 50+ cycle temperature and pressure test in LH_2 was recently completed on this valve at MSFC. The valve is also being tested in LH_2 to account for the characteristics of composites, and the results to date are encouraging. MSFC is also producing a number of 32-inch-diameter, half-scale tanks being used to evaluate structural and integration-related issues, such as stiffener attachment, Y-joint design, and others.

In addition to planned tests on subscale tanks, all of the contractors will constantly monitor the tanks for leaks of all types, including permeability, particularly as the number of pressure and temperature cycles increases and microcracking may become more significant. One method of dealing with permeability problems is to line the tank. This would create another set of problems, however, and probably increase production costs. Thus, this option is to be avoided, if possible. All evidence to date indicates that when proper design and material are used permeability is not a major concern. Because it will not be easy to develop leak-free tanks, one of the industry partners is investigating using an aluminized mylar liner. This liner has been tested for a limited number of cycles, but the test results are promising. The developer is less concerned with the graphite-epoxy membrane than with joints and penetrations (based on the NASP experience).

In an attempt to resolve the permeability question, an industry partner plans to test a large number of 6-inch-diameter, organic-matrix composite tanks to evaluate various materials and construction techniques, as well as liners. These small tanks are relatively inexpensive and should be useful for evaluating the factors discussed above through a number of cycles. Unfortunately, because of their small size, the scaling issues are significant. Four 3-ft-diameter tanks, one of them of sandwich construction, will also be built. These tanks will be subjected to several thermal and stress cycles (e.g., five). One tank will be used only for evaluating vehicle health-management instrumentation. Funding recently has been added to this program to allow testing one of the tanks for 100 cycles. The tank construction to be chosen for the 100 cycle tests and whether the tank will have a liner depend upon results of the 6-inch-tank tests. Performing 100-cycle tests on the 3-ft tank may verify life expectancy.

Integration of TPS and insulation with the cryogenic tank is an area being investigated by all of the contractors. This problem is being addressed by 4-ft by 5-ft panel tests and tests on scaled tanks. One industry partner has recently recognized that larger scale testing is desirable and has approved production of a 10-ft-diameter tank. The current plan is to build a two-lobed tank with a mechanical interlobe joint.

FINDING AND RECOMMENDATIONS—ORGANIC-MATRIX COMPOSITE TANKS

Findings

In general, the criteria for Phase II goals appear to be well conceived and reasonable, with one exception. It is not clear that the requirement of 0.5 lb/ft^3 or less for the hydrogen tank is appropriate as a universal, absolute target. Appropriate weight targets for all major components should come from the design-engineering process.

Target weights depend on the specific design concepts and on the parametric trade studies to optimize the overall design rather than on individual components of the design.

Development of the organic-matrix composite propellant tank appears to be well focused toward achieving the ultimate goals of the project. The development program in this area is robust because the participants are pursuing a multiplicity of technical approaches. There are, however, several areas of concern, which are discussed in the following sections.

Cycle Life

Cycle life of the tanks is a far more significant problem than it was with expendable launch vehicles. Previous tanks were certified for as few as five temperature and pressure cycles; however, a reusability target of 100 missions could easily require certifying the tanks to as many as 200 or more cycles. There is no precedent for this level of reusability, particularly for composite tanks. In addition to the temperature and pressure cycling, requirements for reusability and multiple orbital flights mean the tanks must withstand particle impact damage and be repairable. The results of the 10-inch-tank tests are most encouraging, but more data are needed for larger tanks and correct load levels. The large-tank test programs now being planned will not test nearly enough cycles to give real comfort. Also, it is difficult to accumulate the required number of cycles when testing large tanks because of the length of time required for the chill down, test, and warm-up cycles. Small sample tests will continue and will certainly add some degree of comfort, but they cannot fully address the problem.

Producibility

Fabrication of the tanks is also a major area of concern. Although the three proposed techniques are conventional and well understood, application of the techniques to tanks of the required size and weight per enclosed volume is not. The tanks needed for the RLV will range from 25 ft to 40 ft in diameter and will vary in length. As noted previously, autoclaves of the correct dimensions may not be available. Thus, the tanks may require out-of-autoclave assembly of segments that have been autoclaved; or the tanks may have to be cured by other methods. Tooling for the fabrication process may also be expensive. The hand layup process eliminates some of the tooling and equipment costs, but this process may not be practical for a tank of the required size. A broad goods-dispensing technique has been used experimentally as an alternative to the hand layup method. This technique seems to retain the advantages of using cloth.

The committee believes the sizes selected for the test tanks are reasonable; nonetheless, the committee is concerned about producing full-scale tanks that maintain the required material properties some five times larger than the test tanks.

The issue of whether autoclaving is required is very important. At this time, it is not clear that there will be an autoclave large enough to accommodate the full-scale tanks or primary structures (discussed in a separate chapter). The cost and schedule impact of building an autoclave of this size should be evaluated. Tests have been scheduled to resolve the issue of autoclaving versus non-autoclaving.

The critical issue of joining the tank to the intertank structure is receiving the same multiplicity of evaluations both in design and tests, which reduces the risk in this important area.

LOX Tank

The primary focus of development of the composite tank is on the LH_2 tank; however, there is a possibility that composites will be used for the LOX tank as well. Compatibility is, of course, the key. Results of early testing at ambient pressures by one of the industry partners are encouraging. Tests at required pressures representative of the vehicle application should be expedited to determine if using composites for the LOX tank is a viable option. Sometimes there is an immediate emotional reaction about the risks of using composites with oxygen. This line of thought ignores the fact that, once ignited with oxygen, both aluminum and stainless steel, which are commonly used tank materials, burn furiously. It must be clearly demonstrated that the risk of ignition for organic matrix composites is not significantly greater than for conventional materials. The possibility of using oxygen-compatible liners is also being explored.

Recommendations

The following recommendations are presented to ensure that special attention is paid to areas of concern. The committee recognizes that the program participants are aware of most of these concerns and are in the process of addressing them.

- A detailed plan addressing the producibility of full-scale composite tanks should be developed, and the advisability of some convincing fabrication demonstration should be evaluated.
- The autoclave issue should be resolved as soon as possible.
- Evaluation of the use of composite tanks for LOX should be continued to resolution.
- Thermal/load cycle testing should be conducted on all the 8-ft-diameter or larger tanks with cryoinsulation, interfaces with neighboring components and TPSs affixed to ensure that the integrated system satisfies reusability requirements. This testing will provide a database comparable to the database for the tank that will be tested and flown on DC-XA.
- Weight predictions (not only the 0.7 lb/ft^3 for an oxidizer tank or 0.5 lb/ft^3 for a hydrogen tank as given in the decision criteria) must be defined for each vehicle concept, and (scaled) achievement of these weights, with properly designed test articles, should be verified.

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4

Thermal Protection System

INTRODUCTION

The thermal protection system (TPS) for the RLV must protect the structure and cryogenic fuel tanks from extremely high temperatures during launch and reentry. To meet the requirements of an RLV, the TPS must be readily producible, lightweight, operable, and reusable with a minimum lifetime of 100 missions. The TPS for the RLV must have an adverse weather capability with 95 percent availability. The TPS must also exhibit an order of magnitude reduction in maintenance and inspection requirements as compared with the existing shuttle TPS to permit rapid turnaround. Unfortunately, during the course of this study, the committee could not obtain the breakdown of the total shuttle maintenance and inspection figures, including the TPS, both in terms of cost and manhours.

The space shuttle orbiter TPS, the only demonstrated reusable TPS, provides valuable lessons for development of the RLV TPS. The aluminum orbiter structure has successfully remained within temperature limits, and the primary bonded attachment method has prevented heat leaks directly into the structure. However, as shown in a detailed assessment of TPS damage, (Table 4-1), the TPS systems covering various parts of the orbiter were exposed to temperatures beyond their true reuse limits, causing embrittlement, the slumping of edges, and overheating, cracking and flaking of the coating. Damage to ancillary TPS systems (e.g., gap fillers, thermal barrier coatings, filler bars) was especially high. The designated orbiter TPS reuse temperatures (Table 4-2) are obviously too high because irreversible changes in exposed materials occurred at those temperatures. Additional damage was caused by liftoff and landing debris (chips, gouges) and by airflow and pressure gradients (erosion, fabric frays and tears, lost gap fillers). This lack of TPS robustness and resiliency would result in repair/replacement times and manhours that do not meet RLV goals.

Another factor that contributes to the long TPS turnaround time and high cost after each flight is extensive re-waterproofing, which is necessary for many of the tiles and blankets on the orbiter to prevent them from absorbing moisture; additional moisture would increase vehicle weight and, therefore, reduce payload to orbit. Re-waterproofing is required after each flight because parts of the vehicle TPS reach temperatures that

TABLE 4-1 Space Shuttle TPS Damage[1]

TPS	Discrepancy	Notes
Tile	Chips, gouges, coating cracks, edge and corner slumping (melting and deformation), erosion (tile material after loss of protective glass coating)	Most common TPS damage
Advanced Flexible Reusable Surface Insulation (AFRSI)	Coating loss, embrittlement, fabric frays, tears, broken threads, blanket debonds	Can be repaired
Felt Reusable Surface Insulation	Coating overheating, coating tears, joint seal damage, edge member damage	Least frequent
Reinforced Carbon-Carbon	Chips or cracks in SiC coating, flaking or loss of sealant, pin holes, exposure of underlying carbon substrate	Refurbished by vendor, less frequent than tile or AFRSI
Gap fillers and thermal barrier coatings	Lost coatings, frays, fabric breaking, tears, charring, protruding or lost gap fillers	Two of the major items that require reworking
Filler Bars	Overheating caused by out-of-tolerance steps, gaps, or heating environments	

TABLE 4-2 100 Mission Maximum Operating Temperature for Space Shuttle Orbiter[1]

Material System	100 Mission Max. Operating Temp.(° F)	Failure Mode
Reinforced Carbon-Carbon	2960°	Carbon oxidation and mass loss
High Temperature Reusable Surface Insulation	2300°	Surface cracking and shrinkage
AFRSI	1500°	Fabric and thread embrittlement; susceptible to erosion
Low Temperature Reusable Surface Insulation	1200°	Surface cracking and shrinkage
Felt Reusable Surface Insulation	700°	Surface cracking and shrinkage

degrade the waterproofing agent. In summary, to achieve the RLV goal of low cost per launch, the TPS subsystem must be substantially more robust than the shuttle TPS, and the waterproofing issue must be resolved.

Both the X-33 and RLV are more complex than the shuttle orbiter. Large surface areas require that the TPS protect against overheating during reentry, and cryogenic insulation protect surfaces covering the reusable LOX and LH_2 tanks. Cryogenic insulation on the orbiter is limited to areas adjacent to feedlines because the cryopropellants are carried in the disposable external tank. The RLV TPS mounted on the cryogenic insulation which is attached directly to the cryotanks, either internally or externally, form the surface of the vehicle. These components must prevent moisture in the air from forming ice on the cryogenic tanks prior to liftoff and during early ascent. Icing adds unwanted weight to the vehicle and, if chunks of ice break off during ascent, they could damage parts of the vehicle. Cryogenic insulation also prevents atmospheric heat from reaching the cryogenic propellants, which would result in vaporizing the propellant prior to liftoff or during ascent.[2]

Figure 4-1 shows the layered configurations for the two locations of the cryoinsulation relative to the tank wall. This figure shows that for internal insulation the TPS may be attached to the tank wall; for external insulation, the TPS would be attached to the lightweight cryoinsulation. The issue of attaching the TPS is raised here because it is one of the critical technologies that must still be developed. This is not so much a question of feasibility because the TPS can be bonded adhesively as it is today. The goal is to develop a technique that permits easy, rapid removal and replacement when necessary.

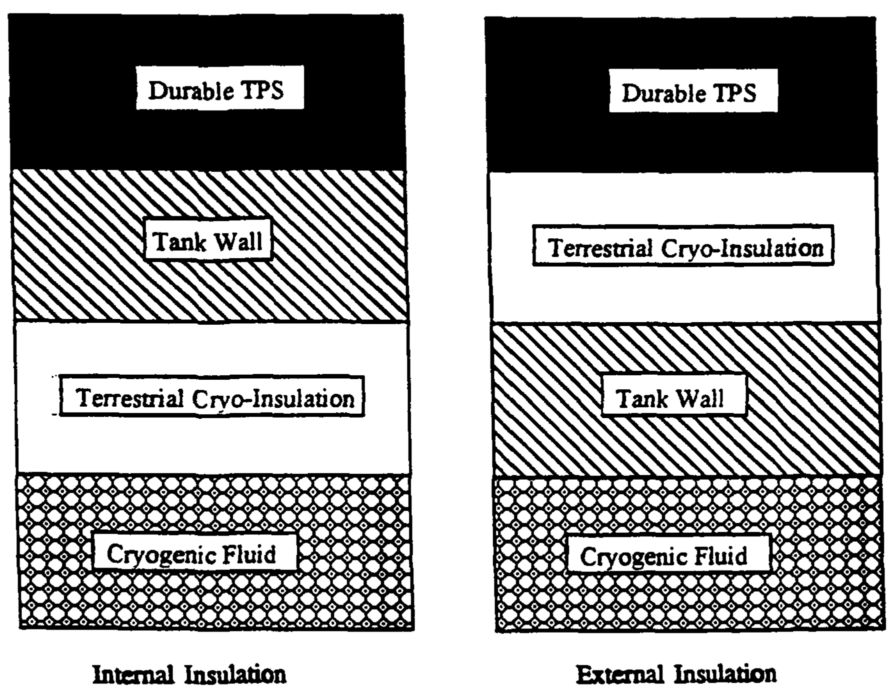

FIGURE 4-1 Examples of Cryogenic Tank Configurations

The primary issue of concern for the TPS is the lack of data for estimating the durability and operability of newly developed TPS materials in launch-vehicle environments. The TPS must be resistant to: rain erosion; low and high speed particle impacts; and aerothermal, acoustic and thermal-mechanical loading. TPS operability issues that must be resolved include: type of waterproofing; robustness or coatings (no coatings preferred); ease of inspection, maintenance, and repair; and attachment techniques that permit rapid replacement. The objective is to determine whether these materials can be produced and integrated to meet weight, reuse, cost, and operations requirements for X-33 and RLV configurations.

Data obtained from the technology development program as specified in the following decision criteria will be used to determine whether reusable, operationally efficient components can be built for the TPS and integrated into an X-33 flight test vehicle to support the demonstration of SSTO by the end of the decade. Various materials and attachment options will be investigated. Integrating TPS options with structural test articles is discussed in chapters 2 and 3 of this report.

DECISION CRITERIA

a. At least one ceramic TPS test article will be constructed and under test. All appropriate element testing required to achieve this goal will be completed and documented. All appropriate attachment mechanisms will have been analyzed and preferred technologies included in the test article.

b. At least one metallic TPS test article will be constructed and will be under test. All appropriate element testing required to achieve this goal will be completed and documented. All appropriate attachment mechanisms will have been analyzed and preferred technologies included in the test article.

c. Material selection for TPS applications in primary structure and reusable cryogenic tank sections will be completed and documented. The selection must consider performance (e.g., weight, durability), producibility, inspectability, and operability and cost characteristics.

d. A documented analysis will have been completed which demonstrates that the selected materials and TPS subsystems are scaleable to an operational RLV and will adequately be demonstrated by a X-33 vehicle. This analysis will contain the correlation between analytical predictions and experimental test results. These correlations will be at a level of confidence sufficient to ensure that analytical tools are valid for purposes of full-scale vehicle design. Estimated requirements for the RLV which will be supported by this analysis, include a 100 mission minimum lifetime and an order of magnitude reduction in maintenance and inspection requirements as compared to existing Shuttle TPS (a baseline for Shuttle will be developed for inclusion in this criteria).

NASA/INDUSTRY PROGRAMS

Two NASA centers are participating actively in the development and testing of the advanced TPS by providing direct support to industry and by working on complementary tasks related to high risk issues. NASA Langley Research Center (LaRC), which has a long history of working with metallic and refractory TPSs, including applications in the NASP program, has two programs in progress: one to develop and mature a metallic TPS; and one to develop a composite refractory TPS (C/SiC). A common attribute of these materials is their inherent resistance to rain or particle-impact erosion and to environmental exposure, such as moisture, lightning, and frost. LaRC's goal for the metallic panels is to reduce the mass of the currently used ceramic tiles by 15 to 25 percent at or near 1,800°F by using lighter weight insulation and improved designs and materials. The RLV TPS design will be based on LaRC's sophisticated thermal-structural analysis and sizing codes to satisfy RLV flight conditions. The TPS based on these designs will be fabricated to RLV requirements and tested against weather exposure and thermal vacuum conditions, rain erosion, low speed and hypervelocity particle impacts, aerothermal effects in wind tunnel and arc jets, thermal acoustic environments, and, finally, an oxidation environment.

Tests are planned both at the individual TPS tile or panel level and at the large, integrated cryotank wall/cryoinsulation/TPS/attachments scale. The larger size tests will be done using realistic aerothermal, thermal/acoustic, trajectory heating and pressure simulation for oxidation studies and combined thermal and mechanical loading. LaRC has developed, fabricated, and tested a superalloy honeycomb concept and is now working on reducing the weight of the superalloy honeycomb. In addition to the design and fabrication of metallic TPS, LaRC is working on attachment concepts and repair of refractory TPS, with operability as a major goal. Viable concepts will be integrated with substructure and cryoinsulation and tested. LaRC supports the industry partners by applying their designs, as well as aerothermal environment codes, to contractor-specific configurations, developing new codes on request for special purposes, and providing TPS concepts to industry. LaRC also conducts tests at all levels.

NASA Ames Research Center (ARC) has been a recognized center of excellence for TPS since the 1950s. The refractory TPS was developed at ARC during the shuttle era. Since then, ARC has continued to develop considerably more robust TPSs, including several innovative candidates for RLV. One TPS developed by ARC is the insulation blanket, which is primarily used on the upper (leeward) surface of the vehicle but can also be used in areas that reach 2,000 to 2,200°F. All of the materials in the blanket insulation can withstand higher temperatures than the blankets currently in use. Several advanced TPS blanket types and characteristics are described below.

- Nextel AFRSI—Advanced fibrous refractory surface insulation is made from Nextel 440 fabric and alumina batting and can withstand temperatures of about 2,000°F.
- TABI—Tailorable advanced blanket insulation, an integrally woven, fluted blanket made of Nextel, silicon-carbide fabrics, or alumina batting, forms a smooth, toughened surface good to 170 dB acoustic environment.
- CFBI—Composite flexible blanket insulation is made of AFRSI with added multilayer insulation and provides improved insulation properties.
- DurAFRSI—AFRSI is modified by adding metallic foil brazed to the wire mesh top surface to create DurAFRSI, which makes the material more robust.

Several techniques for attaching blankets to the RLV are being evaluated including adhesive bonding with silicone adhesive. Adhesive bonding has both advantages and disadvantages. The advantages include a uniform bond line, no thermal shorts, relatively high bond line strength (3-4 psi), water resistance, and proven reliability. The disadvantages include complexity of installation and removal, difficulty of inspecting the structure visually, limited temperature resistance (650°F), and degradation of the adhesive if alternate waterproofing compounds are used.

A number of mechanical fastening techniques for attaching TPS blankets have also been evaluated, including hook and loop (Velcro), floating nut plates (used as specified in metal foil blankets), snaps and grommets, and capstans (with lacing wire to install blankets). Advantages of using mechanical fasteners include ease of installation, inspection, and replacement; resistance to waterproofing agents; and high-temperature resistance. The disadvantages include potential heat shorts; increased weight; water intrusion; poor vibroacoustic performance; and unproven technology for use with flexible blankets.

A second type of TPS being developed at ARC is insulation tile used on the underside (windward side) of the vehicle, which is exposed to higher temperatures than the upper surface. The materials are:

- AETB—Alumina enhanced thermal barrier is a high-temperature tile incorporating alumina fibers; can withstand temperatures up to 2,600°F.
- TUFI—Toughened uni-piece fibrous insulation is a toughened tile-coating preparation that provides order of magnitude improvement in damage resistance.
- SIRCA—Silicone impregnated reusable ceramic ablator is a silica tile impregnated with an ablative silicone that has potential for multiuse capabilities at RLV leading edge and nosecap conditions.

Coated ceramic tiles are used in the high-temperature, high-aerodynamic-force areas of the space shuttle. These tiles are reusable but not very robust; and they are not impact resistant. TUFI is basically the same type of ceramic insulation with an impact-resistant coating. Flight performance data have already been generated for the space shuttle, and the TUFI coating has shown significant improvement in damage resistance.

The third type of TPS uses the following ceramic-matrix composites:

- C/SiC—Carbon-fiber-reinforced silicon-carbide matrix composites
- SiC/SiC—Silicon-carbide/silicon-carbide composite
- ACC—Advanced carbon/carbon composite

Ceramic matrix composites are designed to protect leading edges of the vehicle during reentry and must withstand temperatures in the 3,000°F range. High-temperature TPSs may replace heavy leading-edge components like the ones used on the space shuttle. The TPSs described above are available to the RLV industry partners and are considered either as primary or backup candidates by each of the contractors.

In addition to developing the candidate TPSs, ARC provides direct support to the prime contractors, as requested, including performing aerothermal environment studies for specific configurations and TPS materials. These include studies on the use of ARC's advanced computational fluid dynamics codes, TPS requirements, design and trade support, blanket coating evaluations, advanced waterproofing techniques, and integrated health monitoring systems (including the development of sensors). ARC also conducts tests for the prime contractors in the center's arc jets, hypervelocity particle facilities, and wind tunnels. These complementary tasks are intended to provide a quantitative methodology for assessing life-cycle performance, including operations. ARC's inputs to this analysis include the weight, robustness, durability, and reuse of TPS concepts in all the environments to which they will be exposed. Robustness of the TPS will be established by a robustness test matrix, which was developed in an ARC-conducted workshop with the direct participation of the industry partners. Development and validation of the matrix tool will help satisfy the last two decision criteria. A "large-panel rigid TPS" task is intended to demonstrate attachment and sealing between large rigid tiles, and more generally, to demonstrate reduction in maintenance and repair requirements. ARC is also developing a quantitative tool, THERMPRO, to identify the appropriate health monitoring/NDE systems to ensure TPS flight readiness.

The prime contractors are doing most of the work for the development program, relegating special tasks to NASA centers that have the expertise and test facilities/capabilities best suited to the task. Accordingly, the prime contractors select the TPS candidates appropriate for their vehicle, assume responsibility for the producibility of the TPS, and define the attachment methods to be used. Further, the prime contractors define the test program, prepare test procedures, fabricate/provide test articles, and analyze test results. In some cases, a prime contractor may perform all mechanical testing, including dynamic mechanical testing. The prime contractors have also taken the lead in integrated health monitoring management, identifying failure mechanisms, defining appropriate sensors, preparing and executing a plan to evaluate TPS using integrated health monitoring/NDE, and integrating health monitoring with other TPS tests. In the final analysis, they assume responsibility for satisfying the Phase II decision criteria. Examples of special tasks for which NASA is given the lead are the development of advanced TPS candidates and durable waterproofing techniques. Again, the vast majority of activity in the industry/government program is led by industry.

To summarize, NASA and the industry partners are investigating many TPS materials and design approaches. Some are improved versions of the orbiter TPS (advanced carbon/carbon; TABI; AETB/TUFI); others were investigated under the NASP program (C/SiC; SiC/SiC); and the metallic panels have been evaluated and refined over the past 25 years, since the inception of the space shuttle program.

Table 4-3 shows the principal TPS concepts for different locations on the RLV as proposed by the prime contractors and supporting NASA organizations. Both attributes and concerns are shown in the table. In a number of instances, the concerns indicate that more test data will be needed after the TPS attributes have been confirmed. Although all of the concerns are being addressed in the program, they must be carefully monitored.

There are a number of promising candidates for use in various parts of the RLV, all of which are improvements over current operational TPS systems in terms of higher temperature capability; robustness against impact damage; and, in several cases, resistance to water absorption and lower weight. All of these characteristics (and others) suggest considerable improvement in reusability, which is one of the main objectives to be met in the TPS area. However, although there is little doubt that the new materials will perform better, detailed quantification of whether RLV goals will be achieved cannot be provided until the results of the extensive test programs are received. The committee is concerned about the small number of critical test facilities available to evaluate all these candidates before the target date for the end of Phase I; therefore, it is important that the industry/NASA partners prioritize the TPSs that are most likely to achieve all of the RLV program goals and test them first.

TABLE 4-3 TPS Concepts for Reusable Launch Vehicle (RLV)

Concept	Attributes	Concerns/More Data Required
Nose Cone and Leading Edges		
Advanced Carbon/Carbon	Higher strength than reinforced carbon-carbon; used on orbiter.	Oxidation-effects data required. High thermal conductivity may require complex, heavy attachment mechanism. Rain-erosion resistance data required.
Carbon/SiC or SiC/SiC	Good potential. No coatings required (oxidation resistant).	High thermal conductivity. Rain-erosion resistance data required. Development tests required.
SIRCA	Easy to produce in appropriate size. Low thermal conductivity. Allows backface attachment.	Reusability and rain-erosion resistance data required.
AETB tiles with TUFI coating	Easy to produce in appropriate size. Low thermal conductivity. Allows backface attachment. Low fabrication cost.	Data required on temperature resistance. Requires waterproofing. Lack of appropriate thermal cycling data. Data required on rain-erosion resistance of coating.

TABLE 4-3 TPS Concepts for Resuable Launch Vehicle (Continued)

Concept	Attributes	Concerns/More Data Required
AETB/TUFI	Best reusable surface insulation tile material/coating system. Attachment by bonding. Fabrication analogous to shuttle tile.	Requires waterproofing. Requires gap fillers.
C/SiC or SiC/SiC standoff panels	Potential low weight. Thermally stable.	High cost. Standoff design for thermal expansion. Development tests required.
Metallic (superalloy)	Robust and damage tolerant. Protected insulation. Panel-to-panel overlap minimizes gap seal problems. Design refined over many years.	Attachment must allow for thermal expansion. Heat transfer through attachment.
TABI	Best blanket insulation. Attachment by bonding, no heat shorts. Potential 2,000°F reuse. Larger size than tile insulation.	Requires waterproofing. Protective coating performance data required.
Upper (Leeward) Surfaces		
NEXTEL/AFRSI	Lower cost than TABI. Better insulator than TABI. Flight experience on orbiter.	Requires waterproofing. Coating performance data required. Stitching needs more development.
Titanium Honeycomb	Robust and damage tolerant. Lightweight. Large panel sizes. Panel-to-panel overlap minimizes gap seal problems.	1,000°F limit.
Polybenzimidazole (polymer) Felt	High temperature polymer (800°F). Low density. Low thermal conductivity. Attached by bonding.	Higher cost than Nomex. Lack of test data. No data on waterproofing.
Thermal Insulation		
Internal Multiscreen Insulation	Good potential.	High cost. Unproven concept. Development testing required.
Ceramic Fiber Bat	Low-cost, commercial item. Can be encapsulated to protect from elements. Material change with reduced temperature for maximum efficiency.	Settling under vibratory loading and thermal cycling.
Reflective-coated Fiber Bat	Good potential.	Higher cost than fiber bat. Test data required.
Multilayer Insulation	Mature concept.	Most efficient in vacuum; less efficient in air.

TABLE 4-3 TPS Concepts for Resuable Launch Vehicle (Continued)

Concept	Attributes	Concerns/More Data Required
Cryogenic Insulation		
External Foam-Filled Honeycomb	Failsafe design for foam. TPS attachment by bonding to honeycomb. Minimizes foam cracking.	High TPS to cryogenic insulation interface temperature due to lack of heat sink.
Note: Standoff panels could be attached directly to the tank walls through holes in the cryogenic insulation. Subsequently, holes could be closed out with pour foam.		
Internal Fiber-Reinforced Foam Panels with Fiberglass Liner	Provides heat sink capability of tank wall for entry heating. Uses water (CO_2)-blown foam which causes no stratospheric ozone depletion.	Ice formation on exterior of LH_2 tank wall because of hydrogen permeability. Inspection/repair requires access to tank interior, which can be source of contamination. Not suitable for LOX tank because not LOX compatible.

FINDINGS AND RECOMMENDATIONS

Findings

The current program appears to be well balanced in the development of advanced thermal protection materials that can meet the goals of significantly improving operability and reusability while maintaining the weight target allotted to that system. Development, primarily at two NASA centers, has proceeded along two distinct, but complementary lines. One approach takes advantage of the long heritage of the shuttle TPS while significantly improving the robustness of reusable blankets and ceramic tiles against damage known to require excessive manpower for vehicle turnaround. The second approach continues to pursue the development of metallic panels to increase robustness. In addition, a third concept, ceramic-matrix composites, is under development for use in the highest temperature regions during reentry (i.e., the nose and leading edges of the wings control surfaces). Each approach raises some concerns that are being addressed in the program.

Although production of most of the new TPSs does not appear to be a major issue, there are questions about the resistance of tiles (refractory or metallic) to particle impact at liftoff and landing and especially while in orbit at space station altitude (where some predictions are that penetration of a tank may occur at least once in a 100-mission cycle). The level of rain that can be safely penetrated must also be determined. It is clear that both the shuttle-improved and metallic TPSs have significantly higher resistance, but neither has been totally quantified across the operational map. Tests for this type of robustness are in progress.

A major workshop was conducted by ARC to define experimental programs for evaluating environmental and vibroacoustic effects on TPS, including rain/particle erosion, lightning, and pad ice/frost. The workshop resulted in the development of a comprehensive "robustness test matrix" by the community of experts.

The TPS waterproofing issue must be resolved. The time and manpower required to apply waterproofing after each shuttle flight do not meet the requirements for the turnaround times required for an RLV. The developers are attempting to find agents/coatings that provide permanent waterproofing; however, to date, they have not been successful. Techniques for applying waterproofing to the TPS materials more rapidly are also being considered. Whether the waterproofing problem can be resolved with existing technology and ongoing research is still uncertain.

Methods for attaching each of the two generic TPSs (ceramic and metallic) to the tanks, cryogenic insulation, and primary vehicle structure still require significant development. This is an extremely important problem area that requires innovation to develop concepts that demonstrate satisfactory structural integrity in flight, while permitting easy replacement when necessary. The shuttle-improved TPSs are compatible with adhesive bonding, which has been proven safe for flight, but replacing tiles or blankets is time consuming. Use of metallic panels will require mechanical attachments that are still under refinement.

Cryogenic foam insulation has been used on expendable vehicles (including the shuttle's external tank), but reuse has been limited to one or more tanking-detanking cycles. The contractors recognize the problem of fraying of the foam systems and are using honeycomb or fiber reinforcement configurations to keep the foam from cracking or crumbling. Subscale tank tests will be used to evaluate this approach.

A permissible rate of heat leakage into the propellants has been specified for the space shuttle external tank; however, the corresponding rate for X-33 or RLV has not been determined. The sensitivity of propulsion efficiency to propellant temperature and the resulting permissible rate of heat leakage are not known for subcooled propellants that have never been used in operational vehicles.

Recommendations

- NASA should evaluate the probability that particles in space will penetrate not only the TPS but also the propellant tanks during a 100-mission life cycle. NASA should also assess the impact that penetration might have on the ensuing survivability of the RLV. A recent NRC study concerned with hazards to spacecraft by meteoroids and orbital debris should be useful in this regard.[3]
- The "robustness test matrix" evaluations should be carried out as soon as possible with early emphasis on determining hypervelocity impacts and the resistance of new TPS candidates to the environments known to cause the most problems for the shuttle orbiter.

- Development of metallic panel attachments should be enhanced, and more-operable attachment mechanisms for the shuttle-improved TPS should be investigated to ensure easy replacement. The metallic and ceramic matrix composite standoff panels should be tested in arc jets to demonstrate that there is no overheating at the attachment points.
- Methods for waterproofing need to be pursued vigorously if reasonable ground-processing times are to be achieved.
- Permissible rates of heat leakage into LH_2 and LOX propellants should be established for normal and subcooled propellants.

NOTES

1. Rockwell International Corporation. 1995. Space Shuttle Orbiter Thermal Protection System Processing Assessment: Final Report. Space Systems Division, Report SSD95D0250. Downey, California: Rockwell International Corporation.

2. Strauss, Eric L. 1989. Definition of TPS Concepts for the Advanced Launch System. Report ALS-424. Denver, Colorado: Martin Marietta Astronautics.

3. National Research Council. 1995. Orbital Debris: A Technical Assessment. Committee on Space Debris, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

5

Propulsion

INTRODUCTION

Propulsion will play a significant role in determining whether the goals of SSTO will be achieved in the RLV program. Performance of the only high thrust reusable engine in the nation, the SSME, has been excellent, but the SSME does not have the sea-level F/W ratio needed to place an adequately sized SSTO vehicle into the required orbits. Operability of current engines, in terms of the maintenance, parts replacement, and inspections required after each flight, are too costly in time and manpower to meet the low cost-per-flight goals of the RLV. Basic contributing factors to these costs are the lack of significant demonstrated reusability of critical components and adequate, reliable health monitoring instrumentation with automated rapid engine health diagnosis. Production costs of the current engines are also high because of their complexity, including the large number of parts needed and the manufacturing technology that was available when the SSME was developed. Overcoming these shortcomings are the basic objectives of the NASA/industry program in propulsion. The role of propulsion in four specific areas—program performance, producibility, reusability, and maintainability/operability—are as follows:

- Performance. Rocket engine performance coupled with the vehicle size, weight, and payload characteristics are the key challenges to developing an RLV with SSTO capabilities. Based on presentations from the contractors and engine companies, an engine sea level F/W of 75 to 80 with a vacuum trajectory average specific impulse (Isp) of at least 440 seconds is needed. The SSME has a F/W of 51 and a vacuum Isp of 453 seconds.
- Producibility. In order to produce an RLV engine with high-quality equipment at lower cost, simplifications in design and careful verification of manufacturing methods will be required. Simplified but thorough inspection methods, coupled with experienced state-of-the-art engine production facilities, are also needed. During Phase I of this program, key rocket engine components are being evaluated with the primary objectives of reducing the costs of production and operation.

- Reusability. A thorough evaluation of all the factors that make current engines and engine-vehicle interfaces less than efficient for reuse is critically needed. Phases I and II technology and test programs are intended to minimize operational delays and hardware failures for the RLV program. Long life and repeatable performance with minimal inspection will be essential.
- Maintainability/Operability. Engine health monitoring, simplified turnaround procedures, and improved and expedited before- and after-flight procedures are important goals. Several technology programs in Phase I are directed at engine health monitoring and simplifying operational systems.

The committee reviewed the engine technology projects established by the prime vehicle contractors and the engine contractors with the intent of determining whether the approach was adequate to support a decision about whether to proceed with an X-33. The engines that will be used to meet the design criteria for an X-33 may differ substantially from the engines contemplated for an eventual RLV. Because of the lengthy development period required for major modifications of existing or new engines, the contractors and engine companies are developing engines to fulfill the X-33 requirements in the short-term while pursuing the development of the more-capable products that will be needed for an RLV. Therefore, the committee considered the initiation of programs to meet key long-range RLV engine requirements as well as X-33 engine requirements.

DECISION CRITERIA

a. The propulsion technology area will be adjusted by August of 1995 to reflect the needs of the X-33 industry partners. Propulsion systems not required by the proposed X-33 or RLV will not be funded by this program.

b. A propulsion concept for the RLV configuration will be selected prior to the Phase II decision which will be required by the preferred RLV configuration.

c. A documented analysis will have been completed prior to the Phase II decision which demonstrates that the selected propulsion subsystems are scaleable to a full scale RLV and that reuse/operations requirements will be adequately demonstrated by a X-33 vehicle. Estimated requirements for the RLV, which will be supported by this analysis, include a 100 mission life with 20 flights between depot maintenance and a 50 percent reduction in engine inspection time between flights as compared to the shuttle.

d. Results from component work will be documented and provided with the above analysis. Only propulsion technology supporting the X-33 contractors will be pursued within this program.

NASA/INDUSTRY PROGRAMS

Phase I propulsion technology programs are supported by the three prime vehicle contractors and are being conducted by the engine contractors (i.e., Rocketdyne, Aerojet, and Pratt & Whitney), several material contractors (e.g., Allied Signal, FMI), and Pennsylvania State University, as well as by the NASA MSFC and Lewis Research Center. MSFC provides direct support to the contractors, performs complementary tasks, and funds technology development tasks related to propulsion.

The technology development, test, and analysis programs planned for Phase I include: analysis of existing rocket engines that may be considered for X-33; evaluation of modifications to existing engines for upgrades to X-33; analyses of new engine systems both for the X-33 and for advanced RLVs; technology programs to improve performance, producibility, reusability, and maintainability/operability for application to the X-33 and RLV; and advanced concept studies to evaluate candidates to improve future RLVs.

Table 5-1 is an assessment of technology programs in terms of performance, producibility, reusability, and maintainability/operability.

Engines

The propulsion systems for the three vehicle configurations under consideration for Phase II have different requirements. Each contractor is proposing a different propulsion package using the common oxidizer/fuel combination of LOX/LH_2. Prior to the first meeting of the committee, the proposed use of the tri-propellant LOX/LH_2/kerosene was abandoned, apparently because the complexities of requiring a third propellant in both the vehicles and the engines would offset the marginal improvement in performance.

The engine systems being considered by the airframe contractors are grouped below by existing engines, modified and upgraded engines, and new engines, along with the programs to be carried out in both Phase I and Phase II to evaluate alternate ideas and features of these engine types. Various components for each of these engines will be analyzed and, assuming favorable results, will be included in the hardware and tested in cold flow, hot flow, and structural test facilities.

Existing Engines

Four engines that have undergone extensive ground and flight testing are proposed for application to the X-33, the SSME, RD-0120, RL-10, and VULCAIN.

SSME. This is the basic LOX/LH_2 engine that has powered the space shuttle for 70 flights. The SSME develops a nominal 470,000 lb vacuum thrust at an Isp of 453 seconds and is capable of throttling from 104 to 65 percent. The SSME has an excellent

TABLE 5-1 NASA Industry Cooperative Propulsion Technology Programs

Program	Performance	Producibility	Maintainability/ Operability	Reusability	Remarks
<u>Engine-specific programs to achieve Phase II</u>					
SSME Derivatives (RKD)					
Block II+					Block II+ and Block III engine programs require NASA's implementation of Block II engine improvements independent of X-33 under the shuttle contract.
Nozzle area ratio 57:1	✓		✓	✓	Nozzle modifications will enhance engine F/W.
Block III					All programs are pertinent.
Light weight nozzle	✓	✓			
Universal main chamber	✓	✓	✓	✓	Schedule details require clarification.
Jet boost pumps	✓	✓	✓	✓	
Enhanced health monitoring	✓		✓	✓	
Electro-mechanical actuator valves	✓	✓	✓	✓	
Block III controller	✓	✓	✓	✓	
RD-0120 (Aerojet)					
Familiarization		✓			All programs are highly pertinent to establishing performance of Russian engine to U.S. standards.
Lightweight nozzle - analysis & design	✓	✓			Component changes will increase F/W ratio.
Nozzle area ratio: 37.5:1	✓		✓	✓	
Altitude compensating nozzle analysis	✓				
Component hardware test	✓	✓	✓	✓	
Electronic controller breadboard	✓	✓	✓	✓	

TABLE 5-1 NASA Industry Cooperative Propulsion Technology Programs (Continued)

Program	Performance	Producibility	Maintainability/ Operability	Reusability	Remarks
Life test CADB and NASA/MSFC	✓	✓	✓	✓	
J-2S Aerospike (RKD)					All programs are pertinent to support Lockheed design.
Modular thrust cells cold flow and combustion	✓				
Aerospike nozzle flows	✓				Schedule for first two programs may need to be accelerated.
SR-71 flight flow evaluation	✓				
<u>Programs supporting technology for specific RLV engines</u>					
RL-400 (P&W)					This is a new engine. Some turbopump work is supported by contract. NASA coop programs are not detailed.
Advanced nozzles: two position; dual contour	✓				
Milled channel nozzle	✓	✓	✓	✓	
Nonmetallic skirts	✓	✓			
Turbopump; hydrostatic bearings, integral rotor	✓	✓	✓	✓	
Full flow preburner	✓		✓	✓	Intense materials evaluation is needed for oxygen-rich combustors.
Gas-Gas injector	✓		✓	✓	Intense materials evaluation is needed for oxygen-rich combustors.
RS-2100 (RKD)					
Engine definition	✓				This is a new engine.

TABLE 5-1 NASA Industry Cooperative Propulsion Technology Programs (Continued)

Program	Performance	Producibility	Maintainability/ Operability	Reusability	Remarks
Supercooled propellants	✓				Effect on engine restart needs to be evaluated.
Deep throttling	✓				Preliminary tests on SSME.
Oxygen-rich turbine drive	✓		✓	✓	Required materials evaluation for oxygen-rich combustors initiated.
Gas-Gas 40K injector	✓				
Restart	✓				Emphasis is required.
Dual bell nozzle	✓				
Jet pump	✓	✓	✓	✓	All pump work is pertinent. Schedule details need firming.
Revolutionary reusable technology turbopump (RRTT)	✓	✓	✓	✓	
RS-2200 (RKD) (RLV Aerospike)					Schedule detail lacking, but acceleration appears to be required to validate engine concept for X-33/RLV.
Injector concepts	✓				
Single-thrust cell (round/rectangular)	✓				
Multicell technology	✓				
Alternate nozzle shapes	✓				Altitude compensating.
RRTT or IPD pump	✓	✓	✓	✓	
Restart	✓				
Additional support programs DC-XA Project. (McDonnell)	✓		✓	✓	A test vehicle to demonstrate vertical takeoff and landing.

THROTTLING

Throttling is the ability of an engine to operate at various thrust levels different from, and usually lower than, the designated nominal value. Throttling is required both for ascent and landing to control acceleration or deceleration of the vehicle to the appropriate level. Some throttling is necessary regardless of the vehicle design or configuration; however, particular configurations or designs may require less severe throttling. For instance, if the vehicle is designed so that aerodynamic lift can be used in landing, then the throttling requirements are less severe in landing than for a comparable vehicle that relies solely on the engine to decelerate it to the appropriate level. Throttling levels often are quantified as percentages of the optimum nominal thrust of the engine. For example, if the output thrust of a nominally 100,000 lb engine can be controlled to provide a thrust of 10,000 lb, then throttling to 10 percent has been achieved. The capability of an engine to produce a small fraction of its nominal thrust during flight (as given in the previous example) is sometimes referred to as deep throttling.

Several methods of throttling have been used in engine systems. These methods all reduce the flow of propellants to the main thrust producing chamber, which results in (1) a reduction in combustion pressure, and (2) a reduction in thrust.

performance record and outstanding flight reliability on the space shuttle. However, because of its weight and inadequate F/W, as well as extensive turnaround time and requirements for checking out and refurbishing components, the basic SSME does not meet the long-term requirements for a less costly, easily maintained RLV with rapid turnaround capabilities. Proposed use of the SSME in the X-33 vehicle is marginal. Technology programs are in place to improve the basic engine. The current technology programs will result in the modified SSME Block II, which is described in the section on upgraded engines.

RD-0120. This Russian LOX/LH_2 engine, designed and tested by the Chemical Automatics Design Bureau, was first used in 1976 and has completed 793 ground tests and two successful flight tests (four engines each) on the Energia vehicles. The engine develops a 441,000 lb vacuum thrust and, with the existing design, has a vacuum Isp of 455 seconds. The RD-0120 reportedly has a throttling capability of 114 percent down to 25 percent. Without major modifications the RD-0120 cannot meet RLV sea-level F/W requirements. Improvements in F/W similar to those for the SSME are required for X-33. Plans are underway by one contractor to upgrade this engine for increased operability and modest increases in sea-level F/W.

RL-10s (RL-10A-3-3A and RL-10A-4). These engines have extensive ground and flight experience and develop a 20,000 to 25,000 lb thrust and an Isp of 390 seconds. It is proposed that these engines be used in clusters for various X-33 roll control and descent modes.

VULCAIN. A French/SEP (Société Europeenne de Propulsion) engine that develops a 200,000 lb thrust. VULCAIN is currently used in the Ariane vehicle program. It is proposed for cluster installation in specific X-33 applications.

Table 5–2 shows the characteristics of the existing flight-proven 400,000 lb thrust LOX/LH_2 engines under consideration for primary propulsion.

Upgraded Engines

Optional upgrades are available for all of the existing engines to improve specific qualities. Improvements will be evaluated in the proposed technology programs. Application of the advanced features is intended for the X-33, with later development for the RLV.

SSME Block II. Modifications of the present SSME engine that will be used in the space shuttle program include improved LOX and LH_2 turbopumps, a single-tube heat exchanger, a two-duct powerhead, a simplified low-pressure oxidizer turbopump, a large throat main chamber, and an improved engine controller. This engine will be certified for use in the space shuttle by 1997 and will be available for the X-33. Unlike the current SSME, which requires that engines be pulled between flights to replace turbopumps, the Block II engine should withstand at least 10 launches before engines must be pulled.

TABLE 5–2 Characteristics of Flight-Proven 400,000 lb Thrust LOX/LH_2 Engines

Parameter	U.S. Space Shuttle	Russia: Energia Engines
Engine designation	SSME, Block II (in production)	RD-0120 (in production)[a]
Thrust (1,000 lb)	395 (SL)	330 (SL)
Isp (s)	453 (vac)	341 (SL) 455 (vac)
Chamber pressure (psia)	3,200	3,170
Feed system	Staged combustion	Staged combustion
Mixture ratio	6.0	6.0
Throttling capability	65–104%	25–114%
Expansion ratio	77.5:1	85.7:1
Restart capability	Yes[b]	Yes
Dry weight (lbs)	7,675[c]	7,606
F_N/W_E	51	43

[a] Data source: Aerojet briefing presented to the committee on August 4, 1995.
[b] Pending proper propellant conditioning.
[c] Rocketdyne briefing presented to the committee on August 2, 1995.

Technology programs are also planned to improve the SSME engine. Two improved versions, Block II+ and Block III, are planned. Block II+ incorporates a 57:1 shortened nozzle; the Block III engine features a lightweight nozzle, jet boost pumps, electrical valves, a new combustion chamber, and a new controller. The Block II+ engine could support the X-33, but Block III would be available only for the RLV. The goal for Block II+ is a sea-level F/W of 58; the target for Block III is a F/W value near 70.

RD-0120 AD-1. This modification of the basic RD-0120 design features a reduced nozzle expansion ratio of 37.5:1 and an electronic controller. Planned development includes certification of rapid reuse operations and 10 turnarounds without refurbishment. This modification will allow the RD-0120 to support the X-33 program.

RL-10A-5-1. This improvement will increase thrust to 25,000 lb and increase the nozzle expansion ratio (59.5:1) for increased altitude performance.

VULCAIN Mk II-1. The improved VULCAIN will have an increased MR (from 5.3 to 6.2), a larger nozzle expansion ratio (62:1), and deeper throttling.

New Engines

There are three new engines projected for use in RLV planning. One of these, the Aerospike, is being funded and developed by an industry contractor for an X-33 demonstration. The other two, RL-400 and RS-2100, are not applicable to the X-33 because they require funding as well as new long-term development programs.

Aerospike. This concept, which evolved from considerable development work in the 1960s, begins with development of an engine for the X-33 and is followed by development of a larger, gas-generator cycle engine (RS-2200) for use in a future RLV. The X-33 Aerospike is a 200,000-lb thrust unit that uses 2 banks of 12 thrust cells each in a linear array that will be installed in the boattail of a lifting-body X-33 using Saturn V J-2S turbomachinery. The technology programs for the evaluation of this concept are integrated through Phase I and Phase II. Single-thrust cell testing will be completed in the third quarter of FY96, and multi-cell preliminary testing will be completed in the fourth quarter of 1996. Engine design, fabrication, hot firing, and flight tests are scheduled for Phase II. A scaled Aerospike system will be flown (piggy backed) atop an SR71 aircraft and hot fired during the altitude portion of the flight to determine rocket exhaust effects. These test results, combined with wind tunnel tests and computational fluid dynamics, will be used as design criteria for one contractor's X-33 flight design. If selected, the advanced Aerospike systems are projected for RLV implementation.

RL-400. This is a projected full-flow, bi-propellant, preburner engine that uses oxygen-rich gases to drive the oxygen turbopump and increase engine efficiency. The development of this engine is proposed to support an RLV vehicle after the year 2000. Technology programs during Phase I and Phase II are aimed at analysis and evaluation of engine components.

RS-2100. This is a projected full-flow, staged-combustion engine that uses a fuel rich preburner on the fuel side and an oxidizer-rich preburner on the oxidizer side operating at reduced turbopump temperatures for greater pump operating margins. Many other improvements will be implemented. This engine is also projected to be developed for flight after the year 2000.

The two proposed engines now being analyzed and evaluated are the RL-400 and RS-2100. Both use a full-flow, staged-combustion cycle, which is the preferred cycle for conventional nozzle engines. This cycle uses the engine propellant flow, LOX-rich propellant to drive the LOX pump turbine and fuel-rich propellant to drive the fuel pump turbine and mixes the two in the thrust chamber. This method provides substantial power to the turbopumps while maintaining relatively cool turbine inlet temperatures. By passing the entire flow through the turbines, this cycle keeps low turbine operating temperatures, which results in longer life and fewer inspections. Seal leakage concerns are also reduced because the turbine gas is compatible with the pumped fluids on both the fuel and oxidizer sides of the engine.

Full-flow, staged-combustion engines may have distinct advantages over other engine types, and several NASA/industry programs have been initiated to investigate this potential. For example, materials evaluation programs for oxygen-rich combustion, new element designs for gas-gas injection, and full-flow preburner development are included in several Phase I and Phase II technology programs. The complementary U.S. Air Force (USAF) Integrated Powerhead Program is directed toward building components for these engines, albeit on a smaller scale than those required for the RLV (250,000 lb thrust). This USAF program and other technology programs being conducted at Air Force facilities (Phillips Labs, and others) are structured to allow transfer of all the results and findings to the contractors on the X-33 and RLV programs. The data will be shared to benefit the entire propulsion community. An engine based upon this cycle will not be available for the X-33.

There appear to be no significant "show-stoppers" in the development of full-flow combustion engines although development of the hardware may be complex. One challenge is that preburners must be built of materials and coatings that are resistant to hot oxidizer-rich gases. Russia has demonstrated this technology, but it has not been used in U.S. rocket engine development. Developing new, simplified pumps with fewer parts that are enabled by hydrostatic bearings will also be a challenge. Depending on the rate of progress and available funding, this type of engine may or may not be available in time for use in the RLV. The committee sensed that all of the contractors, especially the engine builders, may be waiting for the government to initiate development of a new engine. Compared with the costs of improving an existing engine, developing a new engine is expensive and may raise questions regarding cost effectiveness.

Engine Applicability to X-33 and RLV

Both existing LOX/LH_2 engines (SSME & RD-0120) can be modified for an X-33 flight vehicle. Technology programs are underway to modify them by reducing weight and permitting longer intervals between servicing. Tests are underway on the SSME testbed at MSFC to demonstrate a 25 percent extension of throttling capability for the current SSME. This improved capability may be adequate for X-33 requirements. However, in view of the approach being taken, this demonstration is of questionable value for two reasons. First, it does not reproduce the throttling dynamics associated with going from full thrust down to 25 percent; and second, the SSME uses Rocketdyne pumps instead of the Pratt & Whitney ATD pumps planned for the RLV.

The current SSME must demonstrate deep throttling to satisfy one prime contractor's RLV requirement; another requires only current throttling capability of 65 percent. The RD-0120 reportedly has throttling capabilities to 25 percent and, even with the weight-reduction potential, will require an increase in F/W before it can be used as a cluster engine in an RLV. When upgraded by the technology programs described here, both the SSME and RD-0120 engines are viable options. Both could be ready in time, and both are directly applicable to the RLV. Work on reducing the cost of these engines was not apparent at the time of this study.

The Aerospike engine is viable for the lifting body X-33, as has been demonstrated in the Aerospike technology programs. But engine characteristics of the required shape, size, performance parameters, and interaction must still be demonstrated (as scheduled). To meet both X-33 and RLV requirements, the research and development of Aerospike should include new manufacturing and chamber configuration modifications. To meet RLV specifications, an even greater effort will be necessary. The risks involved in timely development and modification of this engine system for the X-33 are higher than the risks for more conventional, proven engines.

The smaller engines (RL-10 and VULCAIN) are being considered as auxiliary control systems and orbital maneuvering systems. Technology programs for these applications are notably absent from the Phase I and II programs.

Performance

With some improvements in performance, current engines can be used for X-33 demonstrators; however, RLVs will require very high rocket engine performance (thrust/weight and specific impulse). A series of technology programs are planned to improve these performance characteristics.

Sea-Level F/W Improvement

Rocket engines for the X-33 and RLV must show a considerable increase in sea-level F/W over current levels. The SSME Block I, which flew on the shuttle in 1995, and RD-0120 have F/W values of 51 and 43, respectively, whereas the requirement for the RLV is between 75 and 80, depending upon vehicle configuration, vehicle weight, and engine specific impulse. An increase of this magnitude will require some increase in sea-level thrust and major weight reduction in many engine components. At the same time, high reliability and low cost must be maintained, and reusability must be improved. This is not a simple task.

For the X-33, modifications for both the SSME and the RD-0120 have been defined. These modifications could achieve a F/W approaching 60. The SSME Block II+ configuration with a truncated rocket nozzle (higher thrust and lower weight) is expected to come close to the desired performance. The RD-0120 with the same nozzle truncation and additional changes to other hardware would achieve somewhat lower performance levels.

Historically, changes in sea-level F/W values have required long periods of development. Both the SSME and RD-0120 will require extensive modifications to achieve sea-level F/W values of 75 to 80. SSME modifications have been developed in detail, and the contributions of each modification to improved sea-level F/W performance have been quantified. The RD-0120 team also has identified required modifications, which would require long development times. (Details of these modifications are not included in this report to protect proprietary information.) The development of a new engine, RS-2100, for example, would not be constrained by existing envelopes and components. But a new engine would not benefit from the accumulated knowledge and experience of the existing engines. In either case, the task will be difficult to complete successfully.

Throttling

Whichever vehicle concept is selected, significant throttling capability will be needed. The Aerospike will throttle by keeping pumps at full rpm for pitch changes and diverting the flow from one thruster bank to another through a differential throttling valve; for yaw conditions, pump speed changes will be needed. Work on the differential throttling valve is included in the Phase I development and test program. Conventional bell engines will throttle by changing pump speed. The first approach (Aerospike) requires development of a sensitive valve and flexibility in the injection system to accommodate variable flows. Conventional bell engines rely primarily on the preburner(s) and pump. Programs are in place to demonstrate both conventional engine and Aerospike configuration throttling, but these programs may need to be expedited to meet RLV goals. Concerns about deep throttling during pump speed changes include controlling pump speed with turbine inlet temperatures that do not drop rapidly and are low enough to freeze moisture in the pumps; controlling the preburner injector dynamics, and ensuring sufficient flow to cool the combustion chambers and nozzle; overall system dynamics; and sustained preburner combustion at the mixture ratios required for deep throttling. Any of these engines that can successfully and reliably deep throttle would be viable for X-33.

Turbopumps and Pumps

Reducing the weight of the turbomachinery is a crucial factor in improving engine F/W. All three engine companies are establishing benchmarks for new turbomachinery with precision casting, hydrodynamic bearings, single crystal turbine blades, stout rotors, improved casings and shrouds, and other alternate designs. The proposed new pump designs are applicable only to RLV and will not be ready in time for X-33. The schedules presented to the committee are tight.

Combustion and Mixture Ratio

Several programs are planned to improve combustion performance and overall engine balance. In support of a potential RS-2100 engine concept, a full-flow mixed preburner cycle featuring a LOX-rich preburner, which reduces engine power requirements, will be tested. Testing will include an analysis of material sensitivity to oxygen-rich products. Techniques for running preburner oxygen-rich gaseous combustion products into a main injector along with heated gaseous hydrogen fuel to achieve complete high-efficiency (gas–gas) combustion are also being evaluated. This approach does not apply to the Aerospike engine, which uses a conventional gas generator cycle. A main combustion mixture ratio of 7:1 is also being tested to evaluate performance loss versus vehicle mass fraction gain.

Gas generators

Oxygen-rich combustion, single versus dual units, and full-flow preburner development and test programs are scheduled. However, the programs do not yet appear to be detailed enough to verify the expected performance results.

Injectors

Gas–gas injection (for RLV), new element designs, and full-flow, high-pressure injection technology programs are proposed for improving engine performance; however, the advantages of these technologies must be evaluated in more detail to determine the feasibility of using them for the X-33.

Combustion Chambers

Programs to develop a large throat chamber, alternate materials, milled slot design modifications, and shape reduction were discussed with the committee. All of these concepts are viable and should result in performance gains.

Nozzles

On an SSTO vehicle, optimizing nozzle performance on Isp, from sea-level takeoff to the vacuum space environment, will be critical. Several nozzle technology programs are planned for reducing the expansion ratio operation at low altitudes and expanding to high ratios as altitude increases. Development of a two-position, moveable bell nozzle, a dual-inner-contour nozzle to induce flow separation, and an Aerospike altitude compensating nozzle are directed toward this objective. A series of wind tunnel flow tests are planned to evaluate various nozzle shapes upon expansion, with and without a double contour. New lightweight nozzles, alternate fabrications of nozzle shapes, variable nozzle expansion area ratios by means of inserts, dual-step nozzles for sea level/altitude performance, and milled slot nozzles are also being investigated. These investigations are aimed at: (1) improving sea level performance of a high nozzle expansion ratio; and (2) reducing the weight of the units. The programs have high merit, and there is much to be learned from them.

Producibility, Reusability, Maintainability and Operability

Manufacturing Operations

In general, the engine companies did not highlight overall engine manufacturing procedures and materials in their presentations to the committee. No product improvement programs were presented that addressed the question of manufacturing hardware exactly to print, although this is a common problem in existing hardware programs and decreases producibility. Because there is only one major U.S. development program for reusable engines, attention should be paid to the issues of producibility.

One of the existing flight-proven engines that may be applicable to the X-33 (i.e., the RD-0120) was designed, developed, and qualified in Russia, where the Voronezh plant manufactures as many as 20 engines a year. Manufacturing time for each engine is reported to be one year. The time required to manufacture one SSME is four to five years, leading to the conclusion that it would be prudent to examine carefully the manufacturing processes and controls used by Russia's Chemical Automatics Design Bureau (CADB). Under a strategic business partnership between Aerojet and the CADB, Aerojet plans to test the RD-0120 in the United States and, pending contract award, will create U.S. production facilities for the RD-0120. A NASA/industry program will facilitate this technology transfer and provide benchmark life testing of the RD-0120 both in Russia and at MSFC. The life tests will provide answers to questions about the maturity of the X-33 and questions on long life engine design. Life tests will be duplicated at NASA MSFC.

Turbomachinery (turbines, pumps, assemblies)

Programs are in progress to enhance the producibility and maintainability/operability of the high-speed turbomachinery required for reusable high-performance engines. For example, the producibility of the alternate high-pressure LOX and hydrogen turbopumps of the SSME Block II engine has been improved substantially through development of nonmetallic bearing balls, integral turbine tip seals, precision castings, and single crystal turbine blades. Precision castings have eliminated the sheet metal housings, which required many welds, in the SSME Phase II engine turbopump designs, thus reducing the need for tedious crack inspections and crack weld repairs during fabrication. The LOX pump is already in use and should be easily available for X-33. The fuel pump is still being tested, but it should also be ready in ample time for X-33. The increased weight of these pumps can be a great drawback, however.

Improved turbomachinery is vital to the RLV. In this context, improved means reducing weight substantially while maintaining or exceeding the reusability demonstrated by the Block II SSME turbopumps. If Block II pumps live up to expectations, they will approach the minimum reusability requirements for the RLV. Engine F/W is critical to the SSTO, and engine weight is particularly important because of the aft location. Applicability of the best available jet engine technology and experience must be emphasized. This may be expensive, but payoffs will be high.

Revolutionary Reusable Technology Turbopump (RRTT) and Other Advanced Turbopumps

All of the engine manufacturers, in cooperation with NASA, are evaluating advanced turbopumps for future engines. The current programs are applicable to new engine concepts in the 400,000-lb-thrust class, such as the Aerospike, the RL-400, and RS2100. Although the approaches differ in detail, all advanced concepts involve reducing the number of parts, using hydrostatic bearings, investigating advanced manufacturing approaches, and utilizing new materials. The record of the SSME pumps clearly indicates that this is a fruitful area for improvement. Development of advanced concepts is essential to achieving the ultimate goal of a highly operable vehicle. Advanced turbopumps incorporating new materials and substantially fewer parts, as exemplified by the RRTT concept, will greatly reduce required maintenance and enhance operability by reducing failure modes and eliminating currently required inspections.

Hydrostatic (Hydrodynamic) Bearings

This technology is fairly mature but has not been used in rocket engine turbopumps, although some tests were conducted in connection with the alternate SSME pumps. Hydrostatic bearings are being considered for use in the RRTT and other advanced turbopump designs. These bearings may eliminate many of the failure modes that are a major source of problems in current engines and make designing long-lived pumps easier because they would not have critical speed problems. Although highly reliable pumps can be designed without this technology, hydrostatic bearings show great promise and could be available for use in an RLV engine with further development.

High Performance Low Maintenance Powerheads

This unit features a higher performing injector and a new, single-tube heat exchanger. Manufacturing heat exchangers for converting liquid oxygen to gaseous oxygen (to pressurize the oxygen tanks) has been complicated because the exchanger consists of a primary tube, a bifurcation joint, and two secondary tubes that are assembled by welding. Advanced technology to produce the very long jointless tube of the appropriate material has recently been developed, and single-tube heat exchangers can now be fabricated. The new heat exchanger eliminates a potential Category I failure (i.e., a failure involving loss of life or mission) that might have occurred as a result of leakage in one of the many welds in the original heat exchanger. Eliminating the welds also enhances producibility. The single-tube heat exchanger also improves maintainability and operability, and eliminating welds reduces concern about leakage and failure of tubes. This, in turn, reduces the need for inspections and checking for leaks.

Combustors and Nozzles

The programs for improving the producibility of the main combustion chamber (MCC) are based on eliminating welds and developing new fabrication processes. The potential pay-off of this approach is illustrated in the case of the SSME, for example. Rocketdyne reported that the SSME Phase II engine MCC requires 40 months to manufacture. MCC manufacture of the SSME Block II engine will be reduced to 24 months by using precision castings of the combustion manifolds rather than welding and by improvements in the plating and assembly process. Changing to a proposed milled channel combustor allowed the manufacturer to demonstrate production of a universal MCC in 12 months. This universal MCC will need to be certified prior to use in the SSME, but these changes in fabrication and material processes have yielded dramatic improvements in producibility. The goal is to extend the life of the SSME thrust chamber to at least 100 flights. Although the universal MCC would greatly enhance engine producibility, it may not be available in time for the X-33.

Programs for simplifying the fabrication of nozzles have also been proposed. One of these combines Russian technology and advanced manufacturing technologies to produce a lightweight, milled, channel nozzle.

SSME Block III Controller/New RD-0120 Controller

All of the engine manufacturers propose programs to use electromechanical actuated valves and simplified electronic controllers. Although the current SSME controller has not caused major problems, a newer controller with modern electronics will weigh less and be more reliable; it will also enhance operability and maintainability. The additional capacity of the controller for health monitoring should be even more beneficial. A new U.S. technology controller for the RD-0120 will offer similar improvements. The new SSME and RD-0120 controllers should have applicability to the X-33.

Valve Actuation

If electrical actuators are used to open and close valves, pneumatic and hydraulic systems, along with their numerous parts and potential for leaks, could be eliminated. The higher cost of electrical actuators derives from the need for intermittent high electric power. In general, electric valve actuation is a mature, available technology that can improve reusability. And the overall simplification of this method will reduce failure modes. The primary concern seems to be whether a sufficient variety of valve/actuator combinations is available to fit all needs. It was not clear to the committee how thoroughly this question is being addressed.

Health Monitoring

Onboard or built-in health monitoring for rocket engines involves installing instrumentation to measure critical temperature, pressure, vibration, and rotation speed. By monitoring these parameters during operation, and particularly by noting trends, engine health may be assessed, which can eliminate many aspects of ground inspection (e.g., torque checks on pumps) and expedite maintenance by allowing the scheduled replacement of components. The software to monitor and analyze the data is as critical as the instrumentation. An overarching architecture to determine which measurements are necessary is essential for vehicle health monitoring. This architecture will define the software instrumentation to be developed and the ways subsystems will interact with the vehicle controller.

Although built-in health monitoring will not directly enhance near-term reusability, this capability will greatly increase confidence by increasing knowledge of the condition of hardware. Onboard health monitoring can pinpoint failures before they happen, so the affected components can be replaced in a timely manner. By establishing trends and identifying weak points, onboard health monitoring will encourage product improvements that will substantially enhance reusability.

There is general agreement about the importance of engine health monitoring; however, there is less agreement about exactly what to measure and how to measure it.

The latter is particularly important because spurious data or the failure of sensors could cause major problems. The development of software to analyze data must go hand in hand with the development of sensors. This is a complex problem with a high payoff and should be pursued vigorously because test and evaluation on the X-33 are essential. The committee received relatively little information about health monitoring of the rocket engine from NASA/industry partners.

For the proposed RLV and, for reasons of traceability, the X-33, enhanced engine health monitoring is essential. Relevant work is underway to develop and test new nonintrusive sensors, and/or more rugged sensors; analysis software is also being developed. It is not clear if the program will reach the needed level of maturity in a timely fashion.

High Reliability Sensors

Erratic readings and the mechanical failure of sensors have long been a problem in rocket engine work. Development of more rugged, nonintrusive sensors to measure temperature and pressure is being pursued with an eye toward improving reliability and reducing failures that might cause engine damage. Such failures have caused premature shutdown of shuttle engines in flight and have raised concerns that mechanical failures could cause catastrophic damage. Given the importance of health monitoring and the continuing concern about engine damage from sensor failure, newer more robust and reliable sensors are vital. The development of sensors should receive special emphasis in the RLV program.

New Fabrication Techniques

New fabrication methods, such as friction-stir welding and near-net-shape forming show promise for reducing fabrication-induced stress and cracking that lead to potential failures. Friction-stir welding is a developmental process that will require significant maturation, whereas near-net-shape forming is a fairly well-developed technology. The potential reduction of failure modes should greatly enhance reusability. A new welding process, for example, could reduce many of the concerns about Al-Li welding. However, it was not clear how rapidly the new processes are being pursued or whether they will be available in time for the RLV.

New Materials

Composite materials show promise for reducing weight and increasing the robustness of some engine parts, such as lines and valves. Experimental work is in progress on composite cryogenic valves and lines. Ground tests are also in progress, and these components may be flight tested in 1996. If successful, these components could be ready for the RLV engine. This will probably require some acceleration of the effort to ensure that the engine companies are comfortable with the new components. Such technology improvements, at relatively low cost, address the critical question of engine weight and will contribute substantially to reducing the turnaround time by reducing the need for inspections and maintenance between flights.

FINDINGS AND RECOMMENDATIONS

Findings

The most significant finding is that the prime contractors believe an engine sea-level F/W ratio of greater than 75 is required for the RLV. The SSME Block II and the RD-0120 engines provide sea-level F/Ws of 51 and 43 respectively, and the SSME Block II+ (with a short nozzle) may achieve F/W of 58. An increase of approximately 30 percent in sea-level F/W presents developers with a difficult challenge. Developments to achieve this increase have been identified by the contractors; however, the committee believes that achieving greater than 75 F/W will be very difficult, even with a totally new engine. Upgrading an existing engine to meet this challenge, although less costly than developing a new engine, will be even more difficult.

The shortened nozzle modifications can facilitate an increase in the sea level F/W performance of the SSME or RD-0120 engine. Two of the three prime contractors appear to have selected the SSME or RD-0120 for the X-33 technology testbed. At least one, and possibly both engines, will require throttling to a level deeper than has been currently demonstrated by SSME. Tests are underway on the SSME testbed engine to demonstrate throttling to 25 percent. However, it is not clear to the committee that there is a fall back position if this demonstration is unsuccessful.

In addition to development of the engine for the X-33 in Phase II, there are plans for an engine development and ground test program leading directly to engine technology for an RLV. However, these plans are not well defined at this point. The X-33 engine will only partially demonstrate scaleability to the RLV, so engine development and testing on the ground will have to be relied upon to demonstrate scaleability to the RLV. The schedule for development and qualification of the Aerospike engine for flight on the X-33 may be difficult to meet because development of a new engine typically takes as long as a decade.

Some of the concepts being evaluated may require restart of the main engines, including both engine/propellant conditioning and ignition mode. Although this has been done in the past with a variety of engines, restarting the main engines during flight can be difficult. In addition, engine/propellant conditioning may constitute a significant mass penalty in a mass-critical vehicle.

Development efforts to reduce engine turnaround time significantly after each flight do not adequately reflect the desire for a rocket engine that can be handled the way an operational jet engine is handled. The proposed turnaround procedures for the SSTO were arrived at by reducing the number of similar procedures currently used for the space shuttle rather than by initiating procedures tailored to the RLV.

Recommendations

- RLV engine sea-level F/W requirements to achieve SSTO should be revalidated independently by the prime contractors and by NASA's vehicle design and performance groups. Current F/W goals of greater than 75 will be very difficult to achieve with existing engines and even new ones, without compromising the structural margins required to satisfy reusability goals. If the requirement of high (sea-level) F/W is revalidated, the committee recommends that development of the selected RLV engine be initiated at the beginning of Phase II and pursued vigorously. Because of the different requirements for the X-33 vehicle engine, it will not advance the F/W goal by much. Therefore, the decision to proceed with Phase II will have to be based largely on data from the development program. There should be ongoing trade studies to assess whether larger, but still viable, vehicles will satisfy the F/W requirement.
- The decision criteria for progressing from Phase II to Phase III for the propulsion system should reflect the required RLV engine performance targets (such as F/W of greater than 75 and vacuum Isp of 440 seconds or higher).
- NASA should evaluate the contractors' detailed analyses of projected methods and component improvements for achieving a sea-level F/W greater than 75. The practicality of each required component design should be documented by the engine contractors and evaluated by NASA and, perhaps, by an independent group of propulsion experts.
- The RLV engine ground program for Phase II should be thoroughly defined and executed to provide a high level of confidence that RLV engine requirements will be met.
- If the prime contractors considering SSME or RD-0120 engines for the X-33 demonstrator determine that higher sea-level F/W performance is needed, development of the short (truncated) nozzle should begin soon.
- Dual contour nozzles specifically designed for optimum expansion conditions through the flight trajectory must be verified by hot firing tests in a flight-like environment to assure smooth flow transition without excessive side loads or abrupt skewed shock conditions.
- A plan for developing and qualifying the required throttling must be proposed. Specific details and experimental verification of deep throttling must be demonstrated on the engines proposed for the X-33 and RLV vehicles requiring this capability.
- Requirements for restarting the main engine should be evaluated. A plan showing how this requirement will be met should be developed.

- The detailed configuration of combustor body and throat shape, nozzle shape and expansion ratio, and vehicle integration for the X-33 and RLV Aerospike engine should be completed before the Phase II decision date. Throttling and thrust vector methods, including interaction effects between adjacent engines should also be evaluated.
- Overall engine health monitoring requirements should be better defined. More robust and reliable health monitoring methods and instrumentation than are currently used should be developed and thoroughly tested.
- NASA should evaluate the program and engine changes required to meet the goals of rapid turnaround times. In general, operability and engine reliability requirements should be developed for the X-33 and RLV. Producing an RLV engine that does not have to be touched between flights unless problems are indicated by on-board health monitoring or visual inspection should be a design goal.
- NASA and industry should consider funding high risk/high payoff technology efforts after the X-33 is selected.

6

Conclusions and Observations

In terms of organization and content, the Phase I technology and test program is generally sound. With the participation of three industry partners and three NASA centers, the program for developing and testing materials-related areas (cryogenic tanks, primary structures, and thermal protection systems) as well as the propulsion system are robust in that more than one approach is being pursued in almost all critical areas.

The program is rationally directed toward eliminating as many unknowns as possible early in the technology development and test program—before they are on the critical path in a vehicle development program. In several areas of materials and propulsion, the program is pushing the envelope beyond proven technology, and some failures are to be expected before the required knowledge is obtained. However, the committee found that the Phase I development, test, and analysis programs are appropriate to support a decision regarding whether to proceed with Phase II, subject to implementation of the recommendations herein.

It should be noted that, owing to time constraints on the study, the committee could not review several important areas, which are listed below:

- important aspects of the propulsion system, such as plumbing, leak sensors, lines, valves, and joints upstream of the engine, purge systems, pressurization systems, and the small reaction control system and orbital maneuvering system
- the integrated health monitoring system for all components and NDE technologies
- ground support equipment for the propulsion system, such as propellant quick disconnect, automation, automated fluid and electrical connections, and safe, operationally efficient ground and flight/vent purge systems
- operations issues that were explicitly excluded from the committee's charge to make the committee's task feasible within the allotted time

MATERIALS

The committee anticipates that when the Phase II exit criteria for the development and testing of materials-related areas have been met, the following results may be achieved:

- A first estimate of the mass fraction achievable for these components will be available, especially from the larger scale test articles (e.g., 8-ft to 14-ft-diameter cryotanks and larger primary structures). However, for the estimate to be reasonable, each of the various sized test articles must be designed, built, and tested to RLV-scaled conditions using the design codes that are being validated. All of the joints and fittings for the larger test articles should be properly scaled to the RLV flight configuration.
- Reusability will be partially demonstrated by subscale components and cryostat/pressure box integrated structures, insulation, and TPS panel tests. In all probability, thermostructural cycle testing of the larger test articles will not be adequate to answer the question of whether these components will achieve their cost per flight goals. This will be demonstrated only with adequate cycle testing of the totally integrated large test articles in flight configuration (structure, insulation, and TPS) and in appropriate flight-equivalent environments. Flight tests on the X-33 technology demonstration vehicle, with the individual components integrated in vehicle configuration and with health monitoring systems in place (which have been tested pre-flight with applicable NDE techniques) will verify these essential qualities.

For the materials-related technologies, the question of scaleability of test results from subscale test articles, including the X-33 vehicle, to the RLV will be based on systematic validation of the analytical codes, such as NASTRAN and Mechanica, that were used to design the RLV. For this validation to be effective, all test articles, from small bottles of composite material for the LH_2 tank (as an example) through intermediate-sized test articles, and to the 8-ft-diameter tanks, must be designed by the codes being validated, properly scaled to RLV conditions, and tested with scaled forces and in appropriate thermal environments. The validated code should then be used to design the X-33 vehicle tanks (scaled to RLV conditions) and the flight results compared to pre-flight predictions of the design codes. The other requirement for proper scaleability is that the test articles must be fabricated by the exact same process to be used for the RLV article. If the program is carried out in this manner, as anticipated, it should validate design codes for the RLV. However, compelling reasons for resolving the scaleability issue for the propellant tanks and primary structures include:

- The super lightweight external Al-Li tank using 2195 alloy is being developed for the shuttle program. Because this tank is 28 ft in diameter, the design codes will be validated to that size, so much less information will have to be extrapolated to the 40-ft-diameter tank of the RLV than from the 14-ft-diameter test article in the X-33 program. Another important factor will be the scaleability of the analysis of the welding of the Al-Li tank. If using dissimilar materials becomes necessary, welding will induce stresses because of coefficient of thermal expansion mismatches, and scaling will have to be correlated with subcomponent (full-size) testing.

- For the LH_2 composite tank, the committee believes that the program should "demonstrate fabricability and structural capability of a full-scale cryotank during Phase II." This statement reflects a concern about fabricating such a large graphite-epoxy tank with the desired properties (and the lack of a large autoclave, if needed), and the scaling accuracy of the design codes over such a large extrapolation range (from 8-ft-diameter test tanks to the 40-ft-diameter RLV tank). Correlation of analysis codes to full-scale sizing will be difficult because (based on contractors' tests of 32-inch bottles to 8-ft tank design) areas that can not be stressed to critical levels because of scaling issues will not correlate correctly into the mathematical models; thus the test results may not indicate critical stresses in the full-scale RLV design in complex geometric areas, such as Y-joints, skirt, and conic and internal tank structures. Full-scale test articles for these more difficult areas will probably be required.
- For the composite primary structures, one of the contractors will fabricate test articles that are segments of full-scale RLV components to address the scaleability issue. These will be segments of the intertank, thrust structure, and composite wing structure. Other contractors will use 8-ft-diameter intertanks. Scaleability of load peaking, that is, edge effects at geometric discontinuities, will be important for correlating from testing of scaled designs. These data will be useful for designing structural interfaces for the RLV. The global effect of TPS on the RLV primary structure must be understood. Increased loads and thermal environments caused directly or indirectly from the TPS must also be correlated into mathematical models for structural influences.
- Many of the test articles of the TPSs will be full-scale. In cases where subscale test articles are used, or where the thermal or aerothermal environment is not simulated, appropriate analytical codes developed and validated over the years, including the large shuttle database, will be used to properly scale the test results to full scale RLV conditions.

PROPULSION

By the end of Phase I, the propulsion program will have identified X-33 and RLV versions of existing engines (SSME and RD-0120) for two RLV contractors, and the Aerospike engine for the X-33 vehicle will be defined. Critical component technologies will be identified and/or under development for all candidate engines. Hot fire tests are planned for three different engines:

- a three-cell X-33 Aerospike configuration
- current SSME demonstration of rapid turnaround time, high mixture ratio, and throttling
- extended-life RD-0120 engine benchmark tests in Russia to demonstrate reusability, followed by life tests in the United States with operability enhanced electronics added to the benchmark engine.

OBSERVATIONS

The following suggestions may fall outside the charter of this committee, but were deemed important.

- The committee would like to emphasize that satisfying the Phase II decision criteria does not guarantee that the two major objectives of SSTO, performance and low cost per launch, will be achieved. Some of the reasons have been discussed in the preceding section. Other concerns have to do with the considerable extrapolation in size of test articles to full-scale and issues still to be resolved with propulsion development. But satisfying the Phase II criteria will be a good benchmark indicating that risks have been lowered enough to allow proceeding to the next phase. The committee believes this is the same rationale NASA, OMB, and OSTP used to formulate the decision criteria.
- It is important to realize that the RLV requires engine technology beyond the technology demonstrated in the X-33 engine.
- The X-33 should test as many critical components for the SSTO and TPS as possible. The cryotanks and composite primary structures should be designed to RLV-scaled conditions. The X-33 is a test program and, as such, should be prepared to take prudent risks.
- It would be advisable to demonstrate fabrication and structural capability of a full-scale composite cryotank during Phase II to avoid undue risks during Phase III when heavy expenditures will be necessary.
- For a suborbital X-33, the committee's queries about launch sites and, much more important, landing sites, revealed that this issue requires considerably more attention because of technical constraints imposed by various potential orbits.
- As described in the introduction to this report, the study focused on specific technologies that must be advanced to achieve an SSTO RLV. The ASEB study committee and NASA identified the four categories of technology to be studied: PVS, RCTS, TPS, and propulsion. These categories are discussed individually in the preceding chapters, but little

attention has been paid to the interaction and interdependence of these technologies for SSTO/RLV. Each of the three design concepts has unique interdependencies that must be dealt with by the contractors in the iterative design integration and optimization process. It is important to recognize that creative and innovative integration of designs and vehicle shaping can provide benefits and create risks as significant as the benefits and risks of developing individual technologies. One design concept may involve higher risks but potentially greater payoffs in terms of size, cost, and ultimate commercial value. Another may be heavier or more costly to operate but create lower technical and commercial risks. The committee simply points out that these factors must be evaluated before the crucial decisions planned for late 1996 can be made.

APPENDIX A

List of Participants

1. First meeting/site visit, Marshall Space Flight Center, Huntsville, Alabama, June 20–22, 1995

Rick Bachtel	Carmelo Bianca
Dallas Bienhoff	Wayne Bordelon
Archie Burds	James Cannon
Steve Cook	Richard Cooper
Dan Dumbacher	Shawn Fears
Cynthia Frost	Donald Fulton
Fred Garcia	Robert Garcia
Terry Greenwood	David Hartung
Tracy Lamm	Brian Lariviere
Jack MacPherson	Dick McMillion
Steve Mercer	Jan Monk
Kevin O'Hara	Roger Romans
Henry Stinson	Lamar Thompson

2. Second meeting/site visit, Langley Research Center, Hampton, Virginia, July 7, 1995

Damodar Ambur	Tom Bales
Lee Beach	Max Blosser
Charlie Camarda	Del Freeman
Paul Holloway	Charles Miller
Chris Naftel	Dick Powell
Wayne Sawyer	David Throckmorton

3. Third meeting/site visit, Ames Research Center, Moffett Field, California, July 14, 1995

John Balboni	Jeff Bowles
Domenick Cagliostro	Chuck Cornelison
Palmer Dyal	Michael Green

Ann Patterson-Hine	Demetrius Kourtides
Deepak Kulkarni	Daniel Leiser
Dave Olynick	Daniel Rasky
Marc Rezin	Imelda Terrazas-Salinas
Dave Stewart	Keith Swanson

4. Fourth meeting/contractor site visits, Los Angeles, California area, July 31-August 4, 1995

Lockheed Martin, Palmdale, California, July 31, 1995

Robert Baumgartner	Dick Harris
Tom Hartmann	Paul Landry
Barry Strauss	John Vinson

Rockwell International, Downey, California, August 1, 1995

Ross Blanchard	Tom Gormley
Stan Greenberg	Tom Healy
Pete Hogenson	Mike Scheiern
Dan Suh	Don Weeks

Rocketdyne, Canoga Park, California, August 2, 1995

Bob Brengle	Jim Davis
Frank Edwards	Mike Hampson
Fred Jue	Pete McCourt
Rethia Williams	

McDonnell Douglas, Huntington Beach, California, August 3, 1995

Dana Andrews	Jim Berry
Ed Cady	Andy Gerrick
Paul Klevatt	Bruce Leonard
Dave Schweikle	Laura Thompson

Pratt & Whitney, Briefing at Beckman Center, Irvine, California, August 4, 1995

Randy Parsley	Chris Sanders

Aerojet Corporation, Briefing at Beckman Center, Irvine, California, August 4, 1995

Tom Fanciullo	Frank Sciorelli

APPENDIX B

Biographical Sketches of Committee Members

Dr. Richard A. Hartunian (*chair*) is a consultant with the Aerospace Corporation where he held a series of positions before retirement, including vice president of space launch operations. In that capacity he certified readiness of more than 100 space launch vehicles and was responsible for development of the Inertial Upper Stage, Shuttle Launch Facility at Vandenberg AFB, and other DOD space activities. Earlier in his career at Aerospace, as a principal director of the Aerodynamics and Propulsion Research Laboratory, he directed reentry aerophysics, advanced propulsion, and mechanics research activities. As general manager of the Reentry Systems Division of Aerospace Corporation, he directed the Advanced Ballistic Reentry Systems Program and developed new reentry vehicle concepts and enabling technology in advanced materials, structures, and guidance systems; supervised flight test of full scale prototypes of the new concepts at full ICBM range; and conducted more than 100 launches of test vehicles on Atlas, Titan II, and Minuteman I missiles. Dr. Hartunian holds Ph.D. and M.S. degrees in aeronautical engineering (Cornell University), and a B.S. (RPI) degree in physics. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), has chaired several AIAA sessions, and is a past general chairman. Dr. Hartunian organized and chaired an Advanced Missile Systems Workshop for the Ballistic Missile Organization, and a Submarine Technology Workshop for the Defense Advanced Research Projects Agency (DARPA). In addition, he was a member of the board of the Air Force Materials Laboratory's Mantech Program and served on DARPA's Submarine Technology Program.

Dr. Richard J. Arsenault, professor of materials science and engineering at the University of Maryland, has lectured widely on the subject of materials throughout the world. Professor Arsenault's earlier research was focused on properties of metals and metal alloys; however, during the past 12 years he has been involved in research of composite properties. Professor Arsenault's several honorary memberships include election to the Chinese Academy of Science and appointment as senior scientist fellow of the Science Research Council, England. He holds a Ph.D. degree (Northwestern University) in materials science, and a B.S. (Michigan Technological University) in metallurgical engineering. Professor Arsenault was the only materials scientist on the

Scientific Advisory Board of the Air Force, and during his four-year involvement, he participated in several studies, including one on Hypersonic Air Breathing Vehicle Technologies (NASP).

Ms. Yvonne C. Brill, a member of the National Academy of Engineering, is a consultant specializing in satellite technology and space propulsion systems. Since retiring from INMARSAT in 1991, Ms. Brill participated in a comprehensive tour of 16 Russian space facilities and Baikonur as a member of an AIAA Technical Delegation; served as an independent reviewer on the Ballistic Missile Defense Organization's NEPSTP, Skipper, and RHETT programs; and served as a member on two NRC committees, *Earth to Orbit Transportation Options* and *Advanced Solid Rocket Motor Quality Control and Test Program*. At INMARSAT, Ms. Brill managed the Space Segment Engineering activities on the Combined Propulsion System. Prior to INMARSAT, she held several positions including manager of NOVA propulsion at RCA AstroElectronics where she managed the fabrication and qualification of a Teflon solid propellant pulsed plasma propulsion system whose successful utilization brought electric propulsion to an operational status in the United States. Ms. Brill holds a B.S. degree (University of Manitoba, Canada) in mathematics, and an M.S. degree (University of Southern California) in chemistry. In addition to NAE, she is a member of the International Academy of Astronautics and a fellow of AIAA and the Society of Women Engineers. In 1993, Ms. Brill was the recipient of the Society of Women Engineers' Resnik Challenger Medal for "expanding space horizons" through several innovations in rocket propulsion systems.

Mr. Paul D. Castenholz is an independent consultant for many major programs and operations involving launch vehicles and space vehicles for both U.S. and European agencies and contractors. Mr. Castenholz first worked on rocket engines while at Rockwell International and was responsible for engine development of NATIV, Redstone, Jupiter, Thor, Atlas, Saturn/Apollo, and later, as a vice president, led the team that captured the Space Shuttle engine contract. Mr. Castenholz continued his career as president, BSP Division, Envirotech Corporation, and group president, Process Equipment Worldwide, Joy Technologies, until his retirement in 1989. Mr. Castenholz holds B.S. and M.S. degrees (University of California at Los Angeles) in mechanical engineering, and an A.M.P. degree (Harvard University, School of Business) in business. He has received NASA's Exceptional Public Service—Apollo Program Award, and AIAA's Robert H. Goddard Award.

Mr. James R. French is currently a consultant for the NASA Marshall Space Flight Center, USAF Phillips Laboratory, Jet Propulsion Laboratory, and Ball Aerospace. At JRF Engineering Services he has been a consultant for the Ballistic Missile Defense Organization, Space Vector Corporation, Martin Marietta Space Studies Institute, and others. Prior to that, as vice president of engineering and chief engineer at American Rocket Company, he was responsible for all technical aspects of development of low-cost commercial launch vehicles. At JPL, Mr. French was system test engineer and designer of advanced space missions, and at TRW Systems, he was responsible engineer for the high energy propulsion test stand and high altitude test stand. Mr. French is an associate fellow of AIAA, and former chairman of Space Systems Technical Committee, as well as a fellow of the British Interplanetary Society. He co-authored the textbook, *Space Vehicle Design*.

Mr. Clark W. Johnson is a scientist with Hughes Space and Communications Company. At Hughes, Mr. Johnson is in charge of advanced material development. Previously, at Rockwell, he was closely involved with the Apollo and the space shuttle programs. Later, at Martin Marietta, he worked on launch vehicles and space systems. Mr. Johnson's experience encompasses a wide range of government and commercial spacecraft, including the Titan, Space Shuttle External Tank and Expendable Launch Vehicle Programs. His areas of expertise are in bonded and mechanically fastened structures, thermal insulations, fibrous composites, thermal management, and electronic materials and components. He has developed several proprietary silicone-based ablative insulations for use in launch vehicle and aerospace industry. Mr. Johnson holds an M.S. degree (University of Denver) and a B.S. degree (Grambling University) in chemistry. He also holds an M.B.A. from Pepperdine University.

Dr. Marshall Kaplan, currently chairman of Launchspace Incorporated, Falls Church, Virginia, previously was professor of aerospace engineering at Pennsylvania State University, University Park, Pennsylvania. Dr. Kaplan is a noted expert in launch vehicle systems and technologies. Most recently he has developed and presented professional development seminars on launch vehicle systems design and engineering for both expendable and reusable launch vehicles. He has served as chief engineer for the early development of a fully-reusable two-stage launch vehicle concept, and from March 1992 until July 1993 he was on assignment as chief engineer for the Conestoga Launch Vehicles at the EER Space Company in Seabrook, Maryland. Dr. Kaplan was in charge of all systems engineering, analyses, and integration planning for a new family of all-solid-rocket-motor launch vehicles. In his academic career, he has been associate vice president for research and executive director of the Space Research Institute. Dr. Kaplan is the author of numerous publications in the areas of aerospace technology and systems engineering including an internationally used textbook for engineers studying astronautics, *Modern Spacecraft Dynamics and Control*. He holds a Ph.D. (Stanford) and an M.S. degree (MIT) in aeronautics and astronautics and a B.S. degree (Wayne State University) in aeronautical engineering.

Dr. Hugh L. McManus is assistant professor of aeronautics and astronautics at MIT. Dr. McManus' principal research interests are in integrated multidisciplinary programs to understand the behavior of advanced materials and structures in realistic aerospace environments, and the utilization of this understanding to design both advanced aerospace structures and improved material systems. His interests include predicting how materials will respond in extreme thermal environments, how advanced composites will respond in the space environment, the aging and durability of composite structures, and the development of advanced materials. Prior to his appointment at MIT, he held positions with Kaman Avidyne as a research engineer and Lockheed Missiles and Space as a structural engineer. Dr. McManus holds a Ph.D. degree from Stanford and M.S. and B.S. degrees from MIT. He received NSF's Young Investigator Award in 1992.

Dr. Edgar A. Starke is University Professor and Oglesby Professor of Materials Science and Engineering and director, Light Metals Center, School of Engineering and Applied Science, at the University of Virginia. Previously, he was dean of the School of Engineering and Applied Science at the University of Virginia. Dr. Starke's research interests are in the mechanical behavior of materials and alloy development with emphasis on the relationships between primary processing, microstructural development, and mechanical properties. Dr. Starke's most current research is concerned with monolithic aluminum alloys and aluminum matrix composites. He is a member of NRC's National Materials Advisory Board and currently chairs the NRC Committee on Evaluation of Long-Term Aging of Materials and Structures Using Accelerated Test Methods.

Dr. Richard R. Weiss is currently a consultant in aerospace science and engineering involving launch vehicles and space systems. Dr. Weiss is a noted expert on rocket propulsion and technology development. Previously, he was deputy director for space launch systems and technology in the Office of the Undersecretary of Defense, Missiles and Space Systems. Prior to that, he served in increasingly responsible positions within the Air Force laboratory system, including chief scientist of the Rocket Propulsion Laboratory, director of the Aeronautics Laboratory, and, after consolidation, Director of the Propulsion Directorate, Phillips Laboratory. Dr. Weiss has been involved in development and transition of advanced technology for the majority of space and missile (both strategic and tactical) systems in the U.S. inventory today, including the space shuttle main engine. He has served on many national and international committees, including the JANNAF Committee on Chemical Propulsion, AIAA Propulsion and Power Committee, AGARD Propulsion and Energetics Panel, NRC committees and boards including the ASEB Panel on Small Spacecraft Technology and the Committee on Advanced Space Technology, and the NASA Research and Advanced Technology Propulsion Panel. He directed the Technical Panel for the congressionally directed Space Launch Modernization Panel, chaired by Gen. J. Moorman. Dr. Weiss has received several awards including the Air Force Outstanding Civilian Achievement Award and AIAA's 1994 Wyld Propulsion Award for leadership in developing propulsion technology. Dr. Weiss holds a Ph.D. (Purdue University) and M.S. degree (University of Southern California) in mechanical engineering, and a B.S. degree (University of Michigan) in aeronautical engineering.

Mr. Peter G. Wilhelm is director of the Naval Center for Space Technology. Under Mr. Wilhelm's direction, the NRL has developed and flown two upper stage vehicles for expendable space missiles. These vehicles incorporated technologies of solid fuel, bi-propellant, mono-propellant, and cold gas rockets. He also has directed efforts to develop advanced technology to lower space transportation cost. These technologies include advanced propulsion (hybrid, bi-modal, and electric), as well as structures, guidance, and mission operations (including reusability). Mr. Wilhelm's involvement in the development of low-cost launch technology began with the initiation of the Sea Launch and Recovery (SEALAR) Program. The SEALAR rocket was to be a flotation launched, two-stage pressure fed, liquid rocket with simplified operations. Both the first and second stages were to be recovered for reuse. Mr. Wilhelm also led an extensive study called HARVE (Hybrid Augmented Recoverable Vehicle), which was a partially reusable launch vehicle design that used non-recoverable hybrid boosters and a reusable LOX-LH_2 upper stage. He has also had extensive experience in the design, operation, and economic tradeoffs associated with orbital transfer vehicles. Along with other awards, Mr. Wilhelm has received the E.O. Hulburt Science and Engineering Award (NRL's highest award) and the Captain Robert Dexter Conrad Award (the Navy's highest award for outstanding technical and scientific achievement). Mr. Wilhelm is a fellow of the AIAA.

APPENDIX C

List of Acronyms/Abbreviations

AETB	Alumina-Enhanced Thermal Barrier
AFRSI	Advanced Flexible Reusable Surface Insulation
Al-Li	Aluminum-Lithium
ARC	Ames Research Center, NASA
CADB	Chemical Automatics Design Bureau (Russian)
DurAFRSI	Durable Advanced Flexible Reusable Surface Insulation
F/W	Thrust-to-weight ratio
LaRC	Langley Research Center
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
MCC	Main Combustion Chamber
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NDE	Non-Destructive Evaluation
Nextel	Aluminoborosilicate Fiber (Registered Trademark, 3M Corp.)
OMB	Office of Management and Budget
OMS	Orbital Maneuvering System
OSTP	Office of Science and Technology Policy
PVS	Primary Vehicle Structure
RCTS	Reusable Cryogenic Tank System
RLV	Reusable Launch Vehicle
RRTT	Revolutionary Reusable Technology Turbopump
SiC	Silicon Carbide
SIRCA	Silicone Impregnated Reusable Ceramic Ablator
SLWT	Super Lightweight Tank
SSME	Space Shuttle Main Engine
SSTO	Single-Stage-to-Orbit
TABI	Tailorable Advanced Blanket Insulation
TPS	Thermal Protection System
TUFI	Toughened Uni-piece Fibrous Insulation

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