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REUSABLE BOOSTER SYSTEM
REVIEW AND ASSESSMENT

Committee for the Reusable Booster System: Review and Assessment

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Brian Cantwell, Stanford University,
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John D. Anderson, National Air and Space Museum of the Smithsonian Institution. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Contents

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APPENDIXES

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Summary

On June 15, 2011, the Air Force Space Command established a new vision, mission, and goals to ensure continued U.S. dominance in space and cyberspace mission areas. Subsequently, and in coordination with the Air Force Research Laboratory, the Space and Missile Systems Center, and the 14th and 24th Air Forces, the Air Force Space Command identified four long-term science and technology (S&T) challenges critical to meeting these goals. One of these challenges is to provide full-spectrum launch capability at dramatically lower cost, and a reusable booster system (RBS) has been proposed as an approach to meet this challenge.

Current Air Force medium and heavy launch capability is provided by the Evolved Expendable Launch Vehicles (EELVs), Atlas V and Delta IV, which are manufactured and operated by the United Launch Alliance for the U.S. Air Force. Projected costs for these vehicles have grown recently owing to the completion of the Space Shuttle Program of the National Aeronautics and Space Administration (NASA), which meant subcontractor support costs had to be fully absorbed by the EELV program. The Air Force would like to control this cost growth by finding a more effective method of space launch while maintaining the outstanding launch reliability achieved by EELV.

The RBS concept is an unmanned launch vehicle with an autonomous guidance and control system that consists of a reusable first stage, powered by a hydrocarbon-fueled, oxygen-rich, staged-combustion (ORSC) engine and an expendable second stage, powered by a liquid oxygen/liquid hydrogen engine. The reusable first stage operates in a return-to-launch-site (RTLS) mode, whereby the first-stage booster is recovered and readied for future launches. Several RTLS options have been explored by the Air Force. Its preferred option is to use a "rocketback" maneuver following second-stage separation. The rocketback maneuver, which is executed at high altitude (about 30 km), uses one of the first-stage engines to decelerate the downrange motion of the booster and provide sufficient velocity for it to glide back to the launch site for an unpowered landing.

The Air Force Research Laboratory has been developing many of the technologies that underpin the RBS concept, including hydrocarbon booster and vehicle technologies. Its Pathfinder project is under way to demonstrate the critical aspects of the rocketback RTLS operation, including propellant management and vehicle control using a small-scale flight-test vehicle.

The Air Force Space and Missile Systems Center has developed a baseline RBS concept and development plan, which includes a midscale reusable booster demonstrator, two RBS Y-vehicles, which are full-scale prototypes, and eight operational RBSs located at Vandenberg Air Force Base and Cape Canaveral Air Station. The Aerospace Corporation, working in conjunction with the Air Force Space and Missile Systems Center, performed an analysis

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of the projected cost for this RBS baseline concept that predicted significant life-cycle savings compared to the EELV system satisfying the same launch manifest. This cost study used industry standard models for estimating the cost of the RBS launch stages, independent cost estimates of the required propulsion systems and ground infrastructure, and model-based estimates of the operational costs.

The Air Force Space Command asked the Aeronautics and Space Engineering Board of the National Research Council to conduct an independent review and assessment of the RBS concept prior to considering a continuation of RBS-related activities within the Air Force Research Laboratory portfolio and before initiating a more extensive RBS development program. The Committee for the Reusable Booster System: Review and Assessment was formed in response to that request and charged with reviewing and assessing the criteria and assumptions used in the current RBS plans, the cost model methodologies used to frame the RBS business case, and the technical maturity and development plans of key elements critical to RBS implementation. The committee consisted of experts not connected with current RBS activities who have significant expertise in launch vehicle design and operation, research and technology development and implementation, space system operations, and cost analysis. This committee solicited and received input on the Air Force launch requirements, the baseline RBS concept, cost models and assessment, and technology readiness. The committee also received input from industry associated with the RBS concept, industry independent of the RBS concept, and propulsion system providers.

Based on the input received, its own analysis, and judgment based on committee expertise, the committee came to six major findings.

Finding 1: Cost estimate uncertainties may significantly affect estimated RBS life-cycle costs.

There are several important factors that lead to significant uncertainties associated with the RBS cost estimates developed to date. First, the vehicle development costs were estimated using NASA/Air Force Cost Model (NAFCOM), which is an industry standard model, and reasonable model inputs were used, but operability impacts on vehicle design are not captured using this model. Since NAFCOM is largely based on historical data and lacks relevant experience on reusable systems, there are large uncertainties associated with implementing the vehicle features necessary to ensure operability.

Second, the cost projections are based on the "Americanization" of Russian hydrocarbon engine technology, but cost risks associated with development of an operable engine are difficult to capture. Given the limited experience of U.S. industry in developing oxygen-rich, staged combustion (ORSC) hydrocarbon engines, the cost uncertainties associated with the engine development may be significant.

Third, the details underlying the infrastructure needs are unclear, so uncertainties exist in the costs associated with the infrastructure.

Finally, the estimated operational costs assumed modest postflight inspection requirements, which assume successful development of an effective integrated vehicle health management (IVHM) system and little added cost for the mission assurance requirement.

> **Finding 2:** The RBS business case is incomplete because it does not adequately account for new entrant commercial providers of launch capabilities, the impacts of single-source providers, Air Force need for independent launch sources for meeting their assured-access-to-space requirement, and technical risk. The cost uncertainties associated with these factors do not allow a business case for RBS to be closed at the present time.

In addition to the basic cost uncertainties associated with the RBS, three additional factors exist such that an assessment that the RBS business case is not complete and cannot be closed at the present time. First, the RBS business case does not account for new-entrant commercial providers, in that the business case is based on a comparison of the RBS concept to an extrapolation of recent EELV costs. Given the significant number of commercial entities pursuing novel approaches to achieve launch capabilities, the future of space lift may look very different from those employed today. With global competition to reduce launch costs, it is anticipated that recent EELV costs may not be the proper baseline for cost comparisons.

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Second, the RBS business case does not address the impacts of single-source providers. So, while the business case assumes that RBS captures the complete Air Force launch manifest and is developed with a single-source provider, the cost risks associated with using a single source are not adequately addressed. Put another way, the cost benefits associated with retaining competition in vehicle development were not included in the business case. Since the commercial launch market is rapidly changing and will be driven by cost considerations, not assessing the role of competition is a weakness of the current RBS business case.

Third, the RBS business case assumed full capture of the Air Force launch manifest, but the Air Force maintains a requirement for independent launch capabilities to assure its mission needs. With this need for development and maintenance of a second launch system capability, the RBS business case model is overly optimistic in assuming it will capture the entire Air Force launch manifest.

The end result of these factors is that the uncertainties associated with the RBS business case are sufficiently large that the business case cannot be considered to be closed at the present time.

Finding 3: Reusability remains an option for achieving significant new full-spectrum launch capabilities at lower cost and greater launch flexibility.

The Air Force Space Command has identified a long-term S&T objective for achieving full-spectrum launch capabilities at significantly reduced costs, and reusability remains an option for realizing this objective. A robust reusable system might have additional benefits beside reduced costs, including replenishment of satellites on demand; deployment of distributed constellations; rapid deployment; robust launch operations from multiple defendable launch sites; and operability by Air Force personnel.

Finding 4: For RBS to significantly impact Air Force launch operations, it would have to be more responsive than current expendable launch systems. However, no requirement for RBS responsiveness has been identified that would drive technology development.

The existing business case for RBS is built on satisfying the current EELV launch manifest with a launch-on-schedule assumption to operations. With this assumption and given the lack of an operability requirement for RBS, the technologies necessary to significantly enhance operability and reduce operating costs will not be given a high priority. It is in the development of design features and technologies and the resulting changes to Air Force operations that the true value of a reusable system lies.

Finding 5: Technology areas have been identified in which continued applied research and advanced development are required before proceeding to large-scale development. These areas include reusable oxygen-rich, staged-combustion hydrocarbon-fueled engines, rocketback return-to-launch-site operation, vehicle health management systems, and adaptive guidance and control capabilities.

Finding 6: Given the uncertainties in the business case and the yet-to-be mitigated technology risks, it is premature for Air Force Space Command to program significant investments associated with the development of a RBS capability.

While the committee found that the RBS business case cannot be closed at this time, and it is premature to begin large-scale RBS development activities, the committee does strongly endorse the continued research and advanced technology development needed for future launch systems. The committee makes the following six recommendations.

Recommendation 1: Launch responsiveness should be a major attribute of any reusable launch system. To address this perceived disconnect, the Air Force should establish specific responsiveness objectives independent of the Evolved Expendable Launch Vehicle launch-on-schedule requirements that can be used to drive technology development.

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The committee believes that responsiveness should be a major consideration when developing reusable launch systems and their supporting technologies. At the present time, no responsiveness requirements beyond a launch-on-schedule philosophy have been defined. Since these requirements can drive vehicle and technology needs, it is imperative that the Air Force define nominal responsiveness goals to provide a focus for research and development activities.

> **Recommendation 2:** Independent of any decision to proceed with RBS development, the Air Force should proceed with technology development in the following key areas: reusable oxygen-rich, staged-combustion hydrocarbon-fueled engines; rocketback return-to-launch-site operations; vehicle health management systems; and adaptive guidance and control systems. These technologies will have to be matured before they can support any future decision on RBS, and most of them will be also applicable to alternative launch system concepts.

Continued development is needed in these four technology areas so they can be matured to the point where significant investments can be committed to the RBS programs. Investments in the four areas should continue independent of a decision to proceed with RBS development. Since the technologies have application beyond RBS, with the exception of rocketback RTLS, their maturation will benefit the Air Force independent of RBS in advanced rocket propulsion, system reliability, and vehicle autonomy.

> **Recommendation 3:** The Air Force Research Laboratory's (AFRL's) Pathfinder project is under way to demonstrate in flight, using a small-scale vehicle, the critical aspects of the return-to-launch-site maneuver. To increase chances for Pathfinder's success, AFRL should develop and fly more than one Pathfinder test vehicle design. In addition, competition among RBS concepts should be maintained as long as possible to obtain the best system for the next generation of space launch.

The use of a rocketback maneuver for RTLS operations of an RBS has not yet been demonstrated, so this approach to reusability carries significant risk. Given these risks and the resulting parameter space for innovative solutions, the Pathfinder program should be executed in a manner wherein several vehicle designs are developed and flown. While this approach will increase costs in the near term, the long-term benefits of one day achieving a true high-performance solution to reusability will overwhelm this initial cost.

> **Recommendation 4:** The decision to proceed with the RBS development program should be based on the successful completion of the Pathfinder activities and on assurance that the technical risks associated with the reusable oxygen-rich, staged-combustion hydrocarbon-fueled engines, rocketback return-to-launch-site, vehicle health management systems, and adaptive guidance and control systems are adequately mitigated.

Given the immaturity of the principal technologies and the inherent risks of the rocketback RTLS operation, the decision to proceed with RBS development should be tied to the successful completion of the Pathfinder program and suitable mitigation of the principal technical risks. The committee understands that this approach will delay the achievement of an RBS capability. However, delaying the decision to proceed with the RBS development has an additional benefit: It enables the business environment for emerging new-entrant commercial launch providers to become clearer.

> **Recommendation 5:** Following successful completion of the Pathfinder program, the Air Force should reevaluate the RBS business case, accounting for the following factors: new-entrant commercial launch providers; potential impacts of single-source providers; and Air Force need for independent launchers to satisfy assured-access-to-space requirements.

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> **Recommendation 6:** When constructing the RBS program, the decision points for proceeding from technology development to demonstration to prototype to production for RBS should be based on quantitative assessments during the successful completion of the previous phase. These go/no-go decision points should be structured as on-ramps to subsequent phases with technical underpinnings that are sufficiently well understood to proceed. The decision points for proceeding from Pathfinder and hydrocarbon boost technology risk reduction to a mid-scale demonstrator and from the demonstrator to Y-vehicle prototypes should be considered as on-ramps.

Given the costs associated with the development of a new space launch capability and the technical uncertainties surrounding its operational approach, it is prudent to construct any future RBS program so that the decision to proceed to a next phase is strongly tied to the successful completion of the previous phase.

Today, the United States finds itself in the midst of a fundamental transition of space launch from a model wherein the government develops and controls the launch vehicles to a service-based model wherein industry develops launch vehicles and then sells services to both commercial and government organizations. Despite the uncertainties of this transition, the committee is aware of a large number of organizations that are developing capabilities using innovative designs, development, and operational approaches. The review and evaluation of the RBS concept within this transition period is inherently difficult, but the committee firmly believes that the future of U.S. space launch will be strong if the technology developments recommended in this study are coupled with innovative designs and approaches to achieve cost-effective and robust launch systems.

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Background

On June 15, 2011, the Air Force Space Command (AFSPC) established a new vision, mission, and goals to ensure continued U.S. dominance in space and cyberspace mission areas. Subsequently, and in coordination with the Air Force Research Laboratory (AFRL), the Space and Missile Systems Center (SMC), and 14th and 24th Air Forces, AFSPC identified four long-term science and technology (S&T) challenges critical to meeting these goals. One of these challenges is to provide full-spectrum launch capability at dramatically lower cost, and a reusable booster system has been proposed as an approach to realizing this lower cost.

AFSPC requested that the Aeronautics and Space Engineering Board of the National Research Council (NRC) conduct an independent review and assessment of the reusable booster system (RBS) concept before decisions are made on whether to continue RBS-related activities in the AFRL research portfolio and whether to initiate a more extensive RBS development program.

This chapter briefly describes the national security payload spacelift requirement now delivered by Evolved Expendable Launch Vehicles (EELVs), introduces the RBS program, and discusses the potential for emerging new-entrant candidates to enable the launch of EELV-class payloads. In this report, RBS is taken to mean both the reusable first stage and the expendable upper stages of the baseline reusable launcher concept. This chapter also summarizes the Air Force request for an NRC evaluation of the RBS program and the NRC's actions to support that request. More details on these items and further descriptive material are provided in Chapter 2.

1.1 SPACELIFT REQUIREMENTS AND OBJECTIVES FOR NATIONAL SECURITY PAYLOADS

Assured access to space is an overarching requirement for national security payloads, and it is Air Force policy to provide launches for them. The present manifest[1] for these payloads, which is illustrated in Table 1.1, comprises five different functional requirements, a variety of final orbits, and an average annual launch rate of eight per year. So far, EELVs have provided launches for these payloads with extremely high reliability. However, current plans call for the EELVs to be phased out in 2030 and it is now an objective[2] of the Air Force to achieve dramatically

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[1] Air Force Space and Missile Systems Center, "Reusable Booster System Costing, SMC Developmental Planning," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 15, 2012. Approved for Public Release.

[2] Air Force Space Command, "AFSPC Operational Requirements for Launch," presentation to the Committee for the Reusable Booster System: Review and Assessment, March 28, 2012. Distribution Statement: No Restrictions.

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TABLE 1.1 Satellite Launch Characteristics Showing Satellite Type and Associated Orbits, Launchers, and Effective Average Launch Rates

Satellite Type	Orbit Requirement	EELV Used	Average Annual Rate
Communications	GTO	Atlas V 531	0.64
Meteorological	GTO	Atlas V 501	0.25
	SSO	Delta IV M	0.32
Navigation	MEO	Atlas V 401	1.96
Missile warning	GTO	Atlas V 411	0.31
	SSO	Delta IV M	2.12
Intelligence	LEO (high inclination)	Delta IV M+(4,2)	0.20
	LEO (high inclination)	Delta IV H	0.29
	LEO (high inclination)	Atlas V 541	0.20
	HEO	Atlas V 551	0.29
	Polar	Delta IV H	0.29
	Polar	Atlas V 401	0.16
	GTO	Delta IV M+(5,4)	0.50
	GEO	Delta IV H	0.50
Average annual launch rate			8.00

NOTE: EELV, Evolved Expendable Launch Vehicle; GEO, geosynchronous Earth orbit; GTO, geosynchronous transfer orbit; HEO, high Earth orbit; LEO, low Earth orbit; MEO, medium Earth orbit; SSO, Sun-synchronous orbit.

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

lower launch costs, while maintaining the reliability achieved by EELVs, considering the average launch rate of only approximately eight per year distributed among the missions shown in Table 1.1.

1.2 REUSABLE BOOSTER SYSTEM APPROACH AND POTENTIAL BENEFITS

The proposed RBS must accommodate the reliable and cost-effective delivery of the manifest in Table 1.1 via appropriate vehicle designs and ground infrastructure/operations capabilities. After analyses[3] by the Air Force and the Aerospace Corporation, the RBS was proposed as an approach to meet overall launch requirements. The concept of operations (CONOPS) for the RBS is shown in Figure 1.1.

An essential feature of the RBS is that it uses reusable first stages and expendable upper stages. For reasons of operational efficiency and performance, the first stage would employ an oxygen-rich, staged-combustion (ORSC) cycle engine with liquid oxygen and kerosene-type propellants. The baseline expendable upper stage uses liquid hydrogen and oxygen propellants. A solid motor is added as a final stage to the expendable upper stage for the most energetic missions. As will be explained in Chapter 2, the staging velocity, where the first stage and second stage separate, is selected to minimize overall costs and maximize operational efficiency. This is unlike the usual selection criterion for fully expendable launch vehicles, which is to maximize delivered payload and is a critical characteristic of the RBS concept.

1.3 POTENTIAL EXPENDABLE NEW ENTRANTS

No alternatives to RBS-based launch approaches were presented to the committee; however, credible opportunities may soon be available that meet or exceed the Air Force goals for launches of EELV-class payloads. The U.S.

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[3] K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2012 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2012. This meeting was unrestricted and open to the public.

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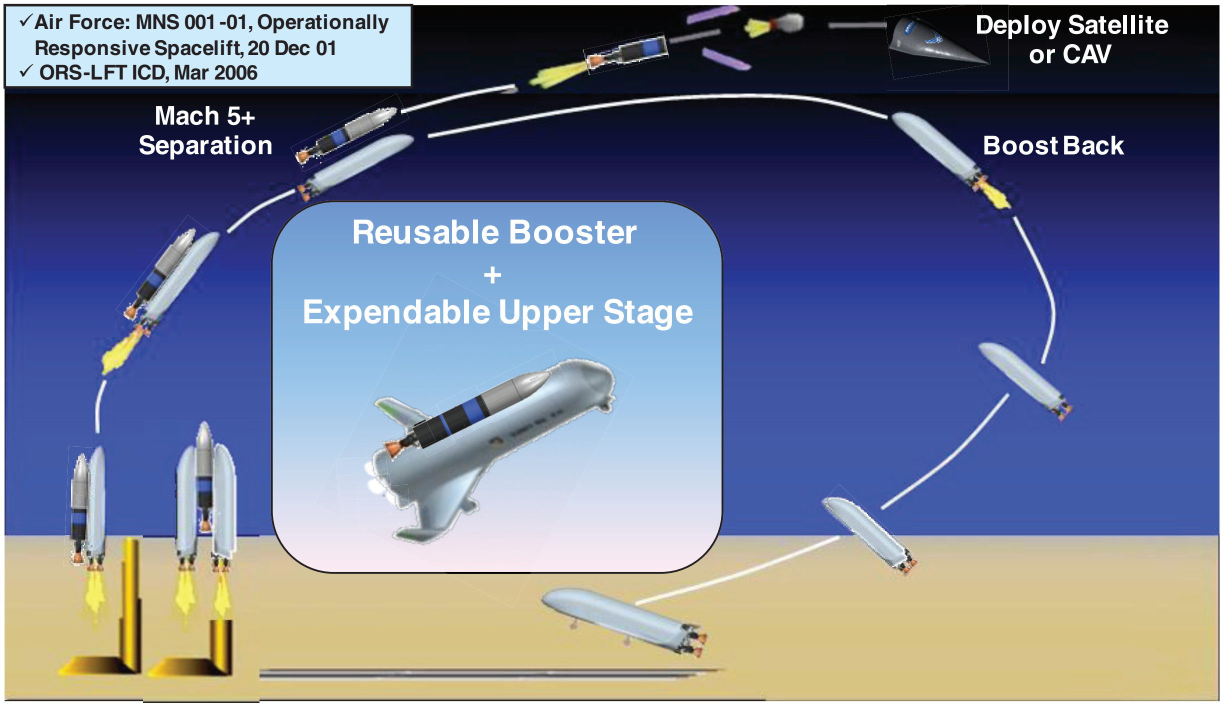

FIGURE 1.1 Diagram of flight path of reusable booster with an expendable upper stage. Following separation, the first stage is rotated approximately 180 degrees as part of the rocketback return-to-launch-site maneuver. SOURCE: Air Force Research Laboratory, "AFRL Portfolio: Responsive and Reusable Boost System (RBS)," presentation to the committee, February 17, 2012. Distribution A: Approved for Public Release.

Government Accountability Office (GAO)[4] recently released a study of the EELV situation for the U.S. Congress. The study said that "domestic commercial launch providers are emerging that may satisfy some of [the Department of Defense's] EELV-class launch vehicle needs. According to DOD officials, the newer providers have not yet demonstrated adequate reliability to provide launches for critical satellites, but may be poised in the future to compete with the current sole-source EELV provider." The GAO report also indicated that DOD and the National Reconnaissance Office plan to spend about $3 billion per year for EELV launches over the 2013 to 2017 time frame.

The Falcon 9 made by SpaceX is one of the more mature options as it has successfully flown three times, most recently delivering cargo to the International Space Station (ISS). In addition, SpaceX has entered more than 20 contracts to launch commercial satellites (COMSATs) and has a contract with the National Aeronautics and Space Administration (NASA) for more ISS cargo delivery missions. A brief review indicated that implementation of higher performance in-space propulsion or disaggregation of payloads would enable the Falcon 9 to deliver all or most of the national security payloads shown in Table 1.1. The reliability of the vehicle and its associated launch costs for Air Force payloads are not established, although it is noted that SpaceX has entered a fixed-price contract with NASA for 12 cargo missions to the ISS for $1.6 billion.[5] The 2011 price for a Falcon 9 launch of a commercial COMSAT is $54 million.[6] Perhaps more important, commercial launchers (1) could eliminate or greatly mitigate requirements for a new Air Force launcher development; (2) might be implemented much sooner than RBS; and (3) would have a large, intensively competitive customer base.

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[4] U.S. Government Accountability Office, *Evolved Expendable Launch Vehicles,* GAO-11-641, U.S. GAO, Washington, D.C., September 2011, p. 9.

[5] *The Economist,* "Keep on truckin," Science and Technology, pp. 77-78, May 15, 2012.

[6] See "Space Exploration Technologies Corporation, "Falcon 9 Overview," available at http://www.spacex.com/ falcon9.php.

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1.4 NRC EVALUATION OF THE REUSABLE BOOSTER SYSTEM

Given the potential benefits offered by the RBS and by alternative launch approaches, the Air Force asked the NRC to conduct an independent review and assessment of the RBS concept. As defined in the statement of task (provided in Appendix A), the purpose of this study was to review and assess the SMC/AFRL RBS concept for the U.S. Air Force. The items to be addressed include these:

- Criteria and assumptions used in the formulation of current RBS plans;
- Methodologies used in the current cost estimates for RBS;
- Modeling methodology used to frame the business case for an RBS capability, including
  - The data used in the analysis
  - The models' robustness if new data become available;
- The impact of unclassified government data that had not previously been available;
- The technical maturity of elements critical to RBS implementation; and
- The ability of current technology development plans to meet technical readiness milestones.

Accordingly, the NRC formed the Committee for the Reusable Booster System: Review and Assessment, which consists of experts independent of current RBS activities but with experience in the areas of launch vehicle design and operation, research and technology development and implementation, space system operations, and cost analysis. Brief biographies of the committee members are provided in Appendix B.

The committee held meetings in February, March, and May of 2012. Air Force perspectives on issues associated with the RBS concepts were provided by representatives of AFSPC, SMC, and AFRL. Costing analyses supporting the RBS concept were provided by the Aerospace Corporation. NASA perspectives on space launch were solicited, and presentations were provided by representatives of the Marshall Space Flight Center and the Kennedy Space Center. Input from industry was solicited, and presentations were received from four commercial aerospace companies involved with launch systems, two propulsion system providers, and one small business. A listing of all presenters is provided in Appendix C.

Using the materials provided, committee analyses, other available open sources of information, and its own experience and expertise, the committee developed the findings, conclusions, and recommendations contained in this report. These findings, conclusions, and recommendations represent a consensus view of the committee members regarding the RBS concept, and the bulk of this report aims to support the committee's view.

1.5 REPORT ORGANIZATION

The RBS system, the launch approach, and the basis for the RBS business case are described in Chapter 2. Chapters 3 and 4 provide evaluations of the technical and economic aspects, respectively, of the RBS as presented to the committee. The potential implementation issues surrounding the RBS program are given in Chapter 5, followed by findings and recommendations in Chapter 6. Appendix E provides details on previous U.S. reusable vehicle developments and Appendix F provides committee thoughts on operability issues associated with the design of RBS boosters.

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2

Air Force EELV-Class Launch Requirements and Approaches

This chapter provides summary descriptions of the criteria and assumptions formulating the baseline reusable booster system (RBS) program, including overall requirements, programmatic and technical approaches, summary results of the business case analysis, and a brief discussion of other, recent and relevant launch programs.

2.1 SUMMARY

Evaluation of alternative launch and upper stage options for Evolved Expendable Launch Vehicle (EELV)-class missions is the focus of this report, and nominal EELV mission frequencies and payload masses were briefly cited in Chapter 1. Assured access to space for national security payloads is the overarching requirement for EELV-class missions and has formidable programmatic and technical implications. EELV launches will be required during the development and phased introduction (estimated at approximately 5 years) of any new launch capability,[1] which has significant budgetary consequences. Air Force policy is to provide launches for the full set of missions described in Chapter 1; this calls for both equatorial and polar launches and a large range of lift capabilities. In addition, the Air Force requires that the high EELV reliability be maintained (it has resulted in more than 30 launches without a single failure) and significant reductions in costs in relation to EELV costs for the mission set of Chapter 1.

The Air Force has specified a launch-on-schedule approach for the EELV mission set, and that has mitigated vehicle, pad, and operations requirements for fast turnaround. A recently released Air Force presolicitation[2] (the Orbital/Sub-Orbital Program) calls for small and medium spacelift capabilities, of up to 20,000 lb to low Earth orbit (LEO) equivalent, which may address the critical area of "responsive" Air Force launch. In addition, the Air Force has expressed concern about the health and future of the U.S. launcher industrial base, indicated a desire for competition for future launch services, and signified its openness to either reusable or new expendable launchers to meet its global requirements.[3] Different RBS schedules are under consideration, but the nominal phaseout of EELVs is estimated to be in the 2031 time frame. No overall procurement strategy has been defined, and issues

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[1] Air Force Space and Missile Systems Center (AFSMC), "Reusable Booster System Costing, SMC Developmental Planning," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 15, 2012. Approved for Public Release.

[2] AFSMC, Presolicitation FA8818-11-R-0026, Orbital/Suborbital Small & Medium Lift Program (OSP-3), Space Development and Test Directorate, Last modification February 15, 2012.

[3] Air Force Space Command (AFSPC), "AFSPC Operational Requirements for Launch," presentation to the Committee for the Reusable Booster System: Review and Assessment, March 28, 2012. Distribution Statement: No Restrictions.

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such as the potential for competition and the relationship of RBS to the launch needs of other U.S. space sectors are open at this time.

The Space and Missile Systems Center (SMC/XR),[4] the Air Force Research Laboratory (AFRL),[5] and the Aerospace Corporation[6] extensively evaluated options to meet the Air Force, EELV-class mission requirements, and these evaluations will be augmented by newly commissioned economic analyses by industry. The RBS was judged to offer the best potential for both low-risk development and recurring cost reductions, relative to EELVs, of 50 to 67 percent.[7]

The baseline flight vehicles for the RBS concept,[8] which are shown in Figure 2.1, consist of a reusable booster demonstrator (RBD), a medium-lift launch vehicle consisting of a reusable booster and an expendable upper stage, and a heavy-lift configuration consisting of two reusable boosters and expendable upper stages. All RBS variations are envisioned to be unmanned and to operate autonomously. As discussed in Chapter 1, the RBS concept involves a reusable first stage (or two first stages in the heavy-lift variant shown in Figure 2.1), which separates from one or more expendable upper stages at velocities between Mach 3.5 to 7 and then returns to the launch base by a "rocketback" maneuver using one of the first-stage rocket engines. Importantly, the staging velocities and altitudes were selected to optimize overall costs and risks rather than to optimize staging to maximize delivered payload. The main potential benefits of the RBS are said to include cost reductions via recovery of the expensive first stage, the corresponding reduction in expendable hardware, and more efficient ground operations.[9]

The RBD vehicle is a proposed midscale demonstration vehicle that would be developed as an intermediate step between today's research program and a full-scale RBS system. The RBD would use a single NK-33 LO_2/RP oxygen-rich, staged-combustion (ORSC) rocket engine to power the reusable first stage. The RBD would initially be used to demonstrate significant aspects of the rocketback return-to-launch-site (RTLS) maneuver, including expendable stage separation. Using a Castor 30 motor and a Star 63 solid motor to power the upper stages as a small expendable stage (SES), the RBD would be capable of launching small satellites to LEO.

The medium-lift RBS configuration (middle configuration in Figure 2.1) consists of a full-scale reusable booster and a large expendable stage (LES). The baseline configuration for the reusable booster is powered by five AJ-26 rocket engines; the AJ-26 is an "Americanized" version of the Russian NK-33 rocket engine. These engines operate using liquid oxygen and hydrocarbon fuels (e.g., RP-1) using an ORSC cycle. The baseline LES is powered by one RS-25E rocket engine using liquid oxygen and liquid hydrogen propellants. This RS-25E is an expendable version of a space shuttle main engine (SSME) being developed by NASA for use in its Space Launch System.

The heavy-lift RBS configuration (right configuration in Figure 2.1) consists of two reusable booster systems, one LES, and a solid-rocket-propelled third stage. This configuration, which would only be used by the Air Force for the largest national security payloads, would result in the additional complexity of having two reusable boosters separate simultaneously and execute their RTLS maneuver in the same airspace.

In addition to the proposed vehicles shown in Figure 2.1, AFRL is actively working on technologies to support the RBS concept. These include technologies for hydrocarbon-fueled boosters, integrated vehicle health management (IVHM), and adaptive guidance and control (AG&C). AFRL is also funding development of a small-scale demonstrator vehicle called Pathfinder, which aims to investigate the rocketback RTLS maneuver, including propellant management strategies, in a series of early flight tests. While the AFRL-funded activities are not part of the baseline RBS development program, these efforts serve to provide critical information leading into the larger-scale RBS development activities.

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[4] AFSMC, "Spacelift Development Planning," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 15, 2012. Approved for Public Release.

[5] Air Force Research Laboratory (AFRL), "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 17, 2012. Distribution A–Approved for Public Release.

[6] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[7] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012; AFSMC, "Spacelift Development Planning," 2012; AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 17, 2012. Distribution A–Approved for Public Release.

[8] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[9] K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2010 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2010. This meeting was unrestricted and open to the public.

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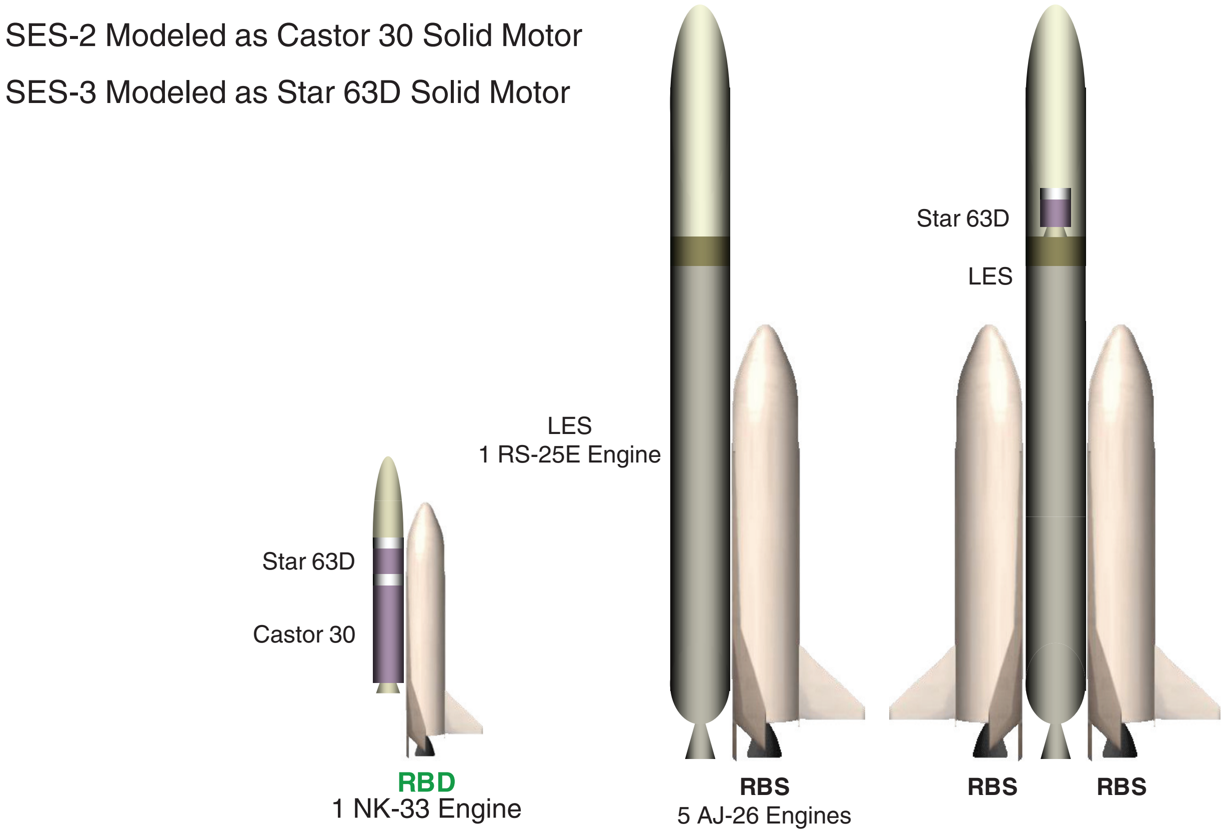

FIGURE 2.1 Reusable booster system (RBS) baseline vehicles. Note that the RBS launching of Evolved Expendable Launch Vehicle heavy payloads requires the added complexity of parallel staging of the first stage boosters. SOURCE: Air Force Space and Missile Systems Center, "Reusable Booster System Costing, SMC Developmental Planning," presentation to the committee, February 15, 2012. Approved for Public Release.

2.2 RBS SCHEDULE AND PROJECTED COSTS SUMMARIES

The costs and schedules of several RBS program scenarios were evaluated by the Air Force and the Aerospace Corporation.[10] (Detailed evaluations of the cost estimates are provided in Chapter 4.) In addition to the AFRL-funded small-scale Pathfinder, the flight vehicles included in costs for the baseline scenario were an RBD and operational vehicles with one and two booster stages. The baseline RBS architecture included two Y vehicles, which are preproduction, full-scale models with the same mass properties and dynamics of the operational RBS vehicles, and which are planned to be converted into operational RBSs after being tested.[11]

Illustrations of the estimated annual recurring costs for the EELV and baseline RBS program are shown in Figure 2.2. For the baseline architecture, RBS annual recurring costs were estimated (Figure 2.3) to be about 47 percent of those for EELVs; this was the net result of estimated reductions in operation and production costs, respectively, of ~60 and 36 percent.[12] A recommendation of the cost study was to fly Pathfinder and RBD vehicles to validate technical approaches and improve estimates of costs and operations.[13] Key technical issues and associated schedules and costs are evaluated in Chapters 3 and 4, respectively.

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[10] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[11] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[12] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[13] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

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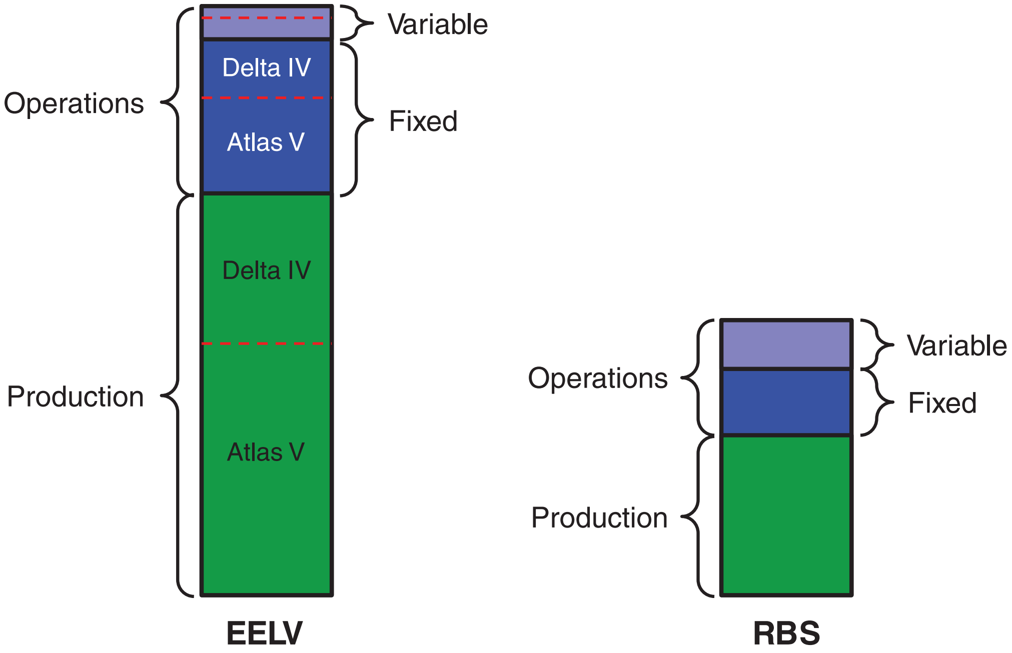

FIGURE 2.2 Evolved Expendable Launch Vehicle (EELV) and reusable booster system (RBS) relative annual recurring cost based on Air Force Space and Missile Systems Center cost estimates. Note that a RBS cost reduction is based on reducing the cost of both expendable hardware and operations. SOURCE: Air Force Space & Missile Systems Center, "Reusable Booster System Costing, SMC Developmental Planning" presentation to the committee, February 15, 2012. Approved for Public Release.

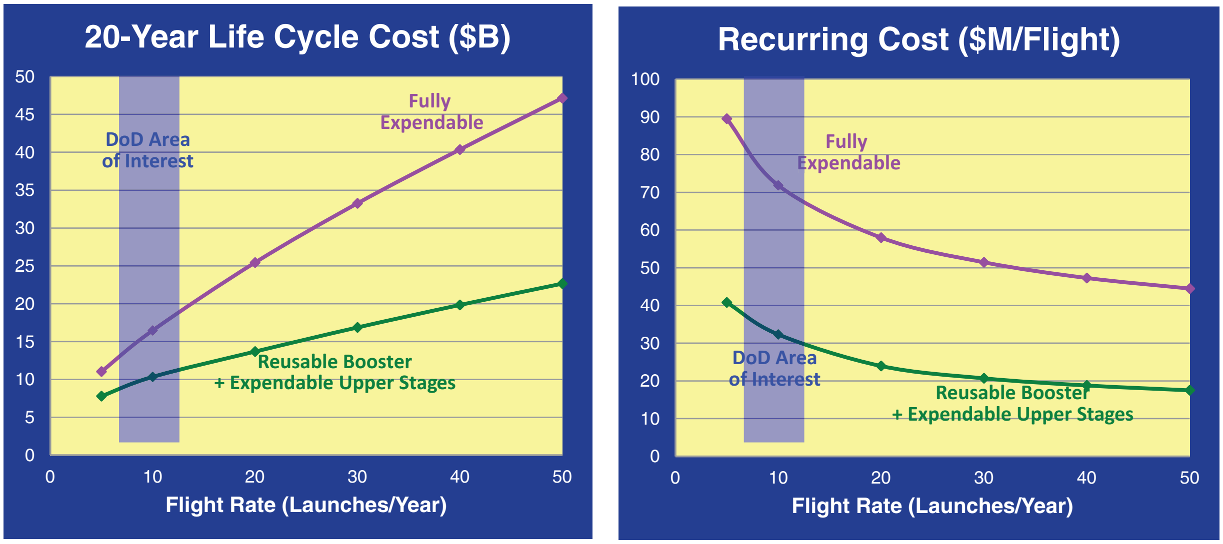

FIGURE 2.3 Comparison of the vehicle life cycle and recurring cost. For the Air Force projected launch rate of 8 to 12 per year, the reusable booster system recurring costs projected by the Air Force Space and Missile Systems Center are approximately $40 million less per launch than the costs with expendable launchers. SOURCE: Air Force Research Laboratory, SMC Development Planning Directorate, "Spacelift Development Planning," presentation to the committee, February 17, 2012.

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Several RBS program scenarios were evaluated by the Air Force and the Aerospace Corporation to assess the life-cycle cost (LCC) and development schedules of RBS options for EELV-class missions.[14] The flight vehicles included in cost models for the baseline scenario were a RBD and operational vehicles with one or two reusable boosters. (An X vehicle, which would be much closer in design to the operational vehicles and was estimated to cost about $400 million and require 6 years to build and fully test,[15] was not included in baseline cost estimates.) The baseline RBS architecture does include two Y vehicles.

Figure 2.3 shows Air Force estimates of 20-year LCC and recurring launch cost (RLC) of the (1) fully expendable, (2) fully reusable, and (3) RBS launcher options,[16] and it is seen that the RBS was projected to provide large LCC and RLC benefits for flight rates from 5 to 50 launches per year. Risks are to be minimized by (1) selection of a staging velocity that subjects the first stage to relatively benign environments, which is intended to mitigate operational requirements and costs and (2) the low sensitivity of launcher performance to first-stage dry mass, which, relative to expendables, will increase to provide for reusability. The RBS does, of course, involve risks associated with new concepts. These include risks associated with the rocketback maneuver, staging of asymmetric or parallel vehicles, first- and second-stage hardware developments, additional operations, achievement of desired operational efficiencies, and projected costs.

2.3 RBS TECHNICAL PROGRAM SUMMARIES

This section and those that follow it will provide brief descriptions of major technical elements of the baseline RBS program, including flight operational vehicles, research and development (R&D) flight vehicles, and the supporting ground R&D efforts. The descriptions below reflect inputs provided to the committee up to May 2012. RBS evaluations are ongoing, and approaches continue to evolve.

The flight vehicles planned[17] in the baseline RBS program are shown in Figure 2.1. The baseline program plan would conduct subscale flight tests with two different vehicles to validate the procedure prior to full development of operational systems. Additional details on the ongoing R&D program[18] in support of RBS development are described in Chapter 3.

2.3.1 RBS Flight Vehicles, Operations, and Infrastructure

2.3.1.1 Flight Trajectories

The Air Force analyses[19] suggest that mission costs, reliabilities, and performances are optimized by use of a RTLS concept for the first stage with expendable upper stages. Options for RTLS included glideback, rocketback, and jetback. Rocketback was selected as the preferred approach[20] for multiple reasons, including the requirement for very large upper stages with glideback and the need for an additional propulsion system with jetback.

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[14] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[15] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," February 17, 2012. Distribution A–Approved for Public Release.

[16] K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2010 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2010. This meeting was unrestricted and open to the public.

[17] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[18] U.S. Government Accountability Office, *Evolved Expendable Launch Vehicles,* GAO-11-641, U.S. GAO, Washington, D.C., September 2011.

[19] AFSMC, "Spacelift Development Planning," 2012; K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2010 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2010. Approved for Public Release.

[20] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012 Distribution A: Approved for Public Release; S.J. Edwards, D.N. Mavris, R. Douglas, and B. Hellman, Reusable Booster Sizing Sensitivities and Flight Envelope Identification Using Response Surface Methods, AIAA 2011-7127, paper presented at the AIAA Space 2011 Conference and Exposition, Long Beach, Calif., September 27-29, 2011. This meeting was unrestricted and open to the public.

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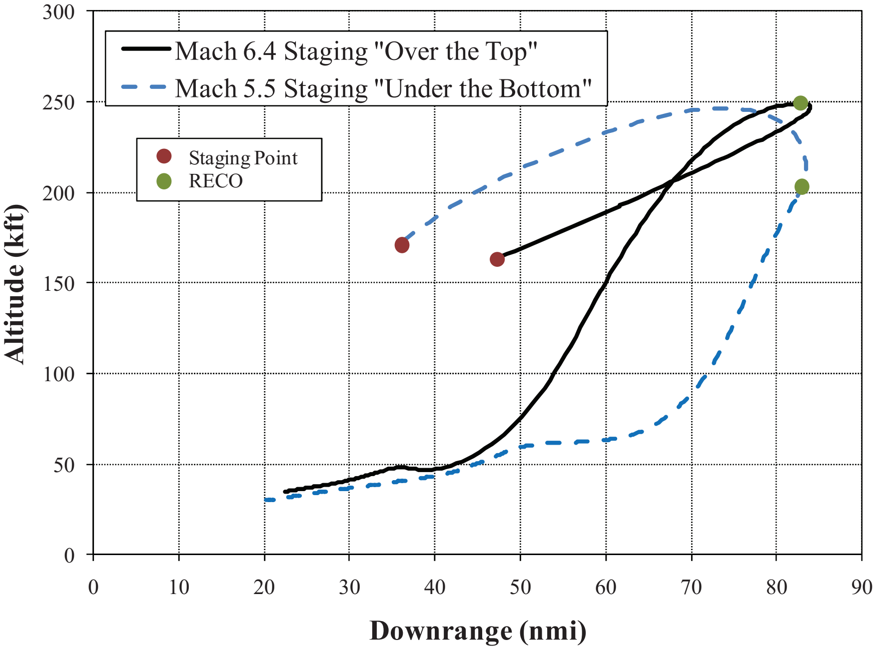

FIGURE 2.4 Typical rocketback return-to-launch-site maneuvers showing staging at Mach 5.5 and 6.4 at altitudes of approximately 160,000 ft. with rocket-engine cut-off occurring at altitudes of 200,000 and 250,000 ft. The reusable booster returns unpowered from its maximum downrange position of approximately 83 nmi. SOURCE: B.M. Hellman, A. Ngo, and J. Wallace, “Technical Challenges for an Integrated Reusable Booster System Flight Demonstrator,” AIAA-2010-8668 in *AIAA SPACE 2010 Conference and Exposition,* AIAA, Reston, Va. This meeting was unrestricted and open to the public.

Typical RBS trajectories using the rocketback RTLS maneuver are shown in Figure 2.4.[21] These sample trajectories illustrate staging at Mach 5.5 and 6.4 conditions at an altitude of approximately 160,000 ft. Two variations of an in-plane rocketback RTLS maneuver are shown. For both trajectories, one or more of the rocket engines continues to fire after staging and the vehicle maneuvers so that the engine thrust cancels the downrange velocity and provides sufficient momentum for an unpowered return segment of the trajectory profile. As seen for this example trajectory, the rocket engine cut-off (RECO) occurs 83 nmi downrange at altitudes between 200,000 and 250,000 ft.

In general, typical staging velocities are between Mach 3.5 and 7 as lower staging velocities tend to require very large upper stages, and higher staging velocities subject the first stage to atmospheric heating and structural dynamic environments that demand increased thermal protection, more stringent structural requirements, and higher operating costs.

Figure 2.5 presents a typical trade-off result[22] showing the expended dry weight as a function of the staging velocity. As will be discussed in Chapter 4, parametric cost models are heavily driven by dry mass, so total dry mass can be viewed as an early indicator of cost. Staging is complex and sensitive to a wide range of coupled trajectory and vehicle design alternatives.[23] Staging is also the second most common cause of launch failures,[24]

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[21] B.M. Hellman, A. Ngo, and J. Wallace, “Technical Challenges for an Integrated Reusable Booster System Flight Demonstrator,” AIAA-2010-8668, August 30-September 2, 2010, Anaheim, Calif., 2010. This meeting was unrestricted and open to the public.

[22] K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2010 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2010. This meeting was unrestricted and open to the public.

[23] D.G. Luchinsky et al., Physics-based modeling for stage separation recontact, *Journal of Spacecraft and Rockets* 49(2):231-242, 2012.

[24] Futron Corporation, “Design Reliability Comparison for SpaceX Falcon Vehicles,” November 2004.

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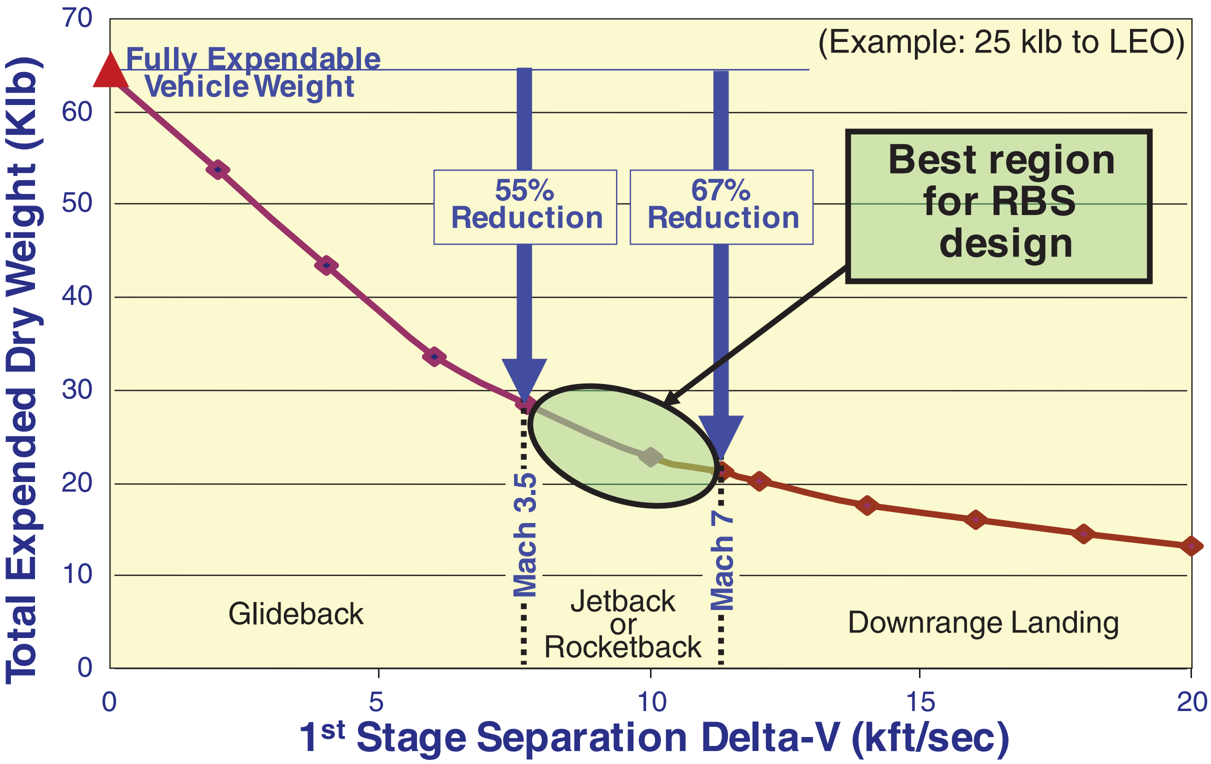

FIGURE 2.5 Expended dry weight of upper stage versus separation delta velocity. SOURCE: Air Force Research Laboratory, SMC Development Planning Directorate, "Spacelift Development Planning," presentation to the committee, February 17, 2012. Approved for Public Release.

and staging of such large, asymmetrical systems requires resolution of issues such as RBS staging implementation approaches, booster-upper stage attachment points, and subsequent loads. These results show that at lower staging velocities the expendable upper stage is very large, which drives up recurring costs. However, higher separation velocities drive requirements for thermal protection on the reusable first stage, which increases stage mass and significantly degrades ground operational efficiencies.

After staging, the expendable upper stages deliver the payloads to appropriate orbits. The first stage is subsequently maneuvered so that a single main engine can be throttled back to provide accelerations appropriate for propellant management, to eliminate the downrange velocity, and then to provide sufficient velocity for the RTLS. The maneuver requires angles of attack approaching 180 degrees, where existing computational models have not been validated and which cannot be suitably simulated in ground wind tunnel tests.[25] Shutdown of some engines and deep throttling of at least one engine is required. Additional issues such as propellant management, aerodynamic interactions, plume loads, and vehicle stability and control will have to be successfully addressed for the proposed RTLS maneuver. Finally, the main engine is shut down and the vehicle glides back for a horizontal landing at the launch site. Significant confidence in the final, glideback phase has been gained via similar experiences with vehicles such as the space shuttle and the X-37 and X-40. The rocketback maneuver has never been employed by launch vehicles and is considered one of the high-risk elements of the proposed RBS program.

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[25] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012. Distribution A–Approved for Public Release.

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2.3.1.2 First-Stage Vehicle

The RBS first and upper stages were shown in Figure 2.1. To minimize development and production costs, only one first-stage configuration is planned and one vehicle will be sufficient for all but the most energetic EELV-class missions, which instead will use two opposing first stages attached to a single upper stage. A representative first stage in the baseline concept is blunt nosed, has double delta wings, is approximately 108 ft long by17 ft in diameter, and holds nearly 900,000 lb of LO_2/HC propellants.[26] These propellants were selected over LO_2/LH_2 to reduce (1) overall operations times and costs and (2) vehicle dry masses and volumes. LO_2/LCH_4 also was evaluated as a first-stage propellant for staged combustion engines and was found to provide mission-level performance nearly identical to that with more mature LO_2/HC engines but with higher vehicle dry masses and projected costs.[27]

An ORSC engine cycle was selected over the fuel-rich, gas generator cycle for several reasons, including high performance and a large reduction in fuel coking, which introduces operational inefficiencies and reusability concerns. ORSC engines have been built and qualified in Russia and China and are under study or in development in Europe, India, and South Korea.[28] The Russian-built RD-180 ORSC engine has been successfully used on the Atlas III and V vehicles,[29] and the Russian-built NK-33 is planned for use in the near term on the first stage of the Antares launchers of Orbital Sciences Corporation.[30] Russian-produced ORSC engines are also planned for use in early RBS program efforts such as the RBD vehicle,[31] with the NK-33 used as the baseline. These NK-33 engines have been acquired by Aerojet and upgraded to include modern diagnostics and controls. The baseline operational flight vehicle concept now features the use of five AJ-26 engines,[32] which are “Americanized” versions of the NK-33 cited above. The AJ-26 engine, which would be fully produced in the United States, has a sea level thrust and specific impulse, respectively, of 338,000 lbf and 297 sec. No ORSC engine has been developed in the United States, but efforts evaluating production of U.S.-built versions of both RD-180 and NK-33-class engines have been ongoing for about a decade.[33] A reusable, U.S.-produced ORSC LO_2/HC engine is one of the main development efforts in the RBS program;[34] the technical challenges and issues are discussed in depth in Chapter 3.

Metallic structures and tanks are presently baselined for the RBS first-stage vehicle; however, the increasing pressure for performance is driving R&D[35] to examine the possible use of composites for the RBS primary structure and improved ancillary subsystems such as thermal, power, reaction control, and actuation.

2.3.1.3 Upper Stage(s)

As shown in Figure 2.1, a single LO_2/LH_2 LES design is planned for the EELV-class missions; except that for the most energetic EELV-class mission a solid Star 63D type motor is added as a third stage. The baseline LES is about 130 ft long and 15 ft in diameter; it has a dry weight of ~38,800 lb, and carries more than 340,000 lb of propellant.[36] For reference, the LES propellant load is approximately 1.4 and 0.76 times the amounts carried in,

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[26] AFSMC, “Reusable Booster System Costing, SMC Developmental Planning,” 2012. Approved for Public Release.

[27] Futron Corporation, “Design Reliability Comparison for SpaceX Falcon Vehicles,” November 2004.

[28] Pratt and Whitney Rocketdyne, “Reusable Hydrocarbon Rocket Engine Maturity for USAF RBS,” presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Approved for Public Release; Aerojet Corporation, “Reusability and Hydrocarbon Rocket Engines-Relevant US Industry Experience,” presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Approved for Public Release.

[29] Pratt and Whitney Rocketdyne, “Reusable Hydrocarbon Rocket Engine Maturity for USAF RBS,” 2012. Approved for Public Release.

[30] Aerojet Corporation, “Reusability and Hydrocarbon Rocket Engines-Relevant US Industry Experience,” 2012. Approved for Public Release.

[31] AFSMC, “Reusable Booster System Costing, SMC Developmental Planning,” 2012. Approved for Public Release.

[32] AFSMC, “Reusable Booster System Costing, SMC Developmental Planning,” 2012. Approved for Public Release.

[33] Pratt and Whitney Rocketdyne, “Reusable Hydrocarbon Rocket Engine Maturity for USAF RBS,” 2012; Aerojet Corporation, “Reusability and Hydrocarbon Rocket Engines-Relevant US Industry Experience,” 2012. Approved for Public Release.

[34] AFRL, “Hydrocarbon Boost Technology for Future Spacelift,” presentation to the Committee for the Reusable Booster System: Review and Assessment, February 15, 2012. Distribution A–Approved for Public Release.

[35] AFRL, “AFRL Portfolio: Responsiveness & Reusable Boost System (RBS),” 2012. Distribution A–Approved for Public Release.

[36] AFSMC, “Reusable Booster System Costing, SMC Developmental Planning,” 2012. Approved for Public Release.

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respectively, the Saturn SIV-B stage[37] and the Delta IV common booster core (CBC).[38] A single RS-25E engine, with a sea-level thrust of approximately 420,000 lb_f and specific impulse of approximately 350 sec is presently baselined, although options such as the RD-0120 and J-2X are under consideration. The LES is mounted to the first stage by four structural-release attachments, two forward and two aft. Staging is achieved by shutting off all but the center engine of the first stage, throttling it back and starting the RS-25E engine. When the booster and LES thrust levels are such to produce nominally equal accelerations following separation, the LES is released and, once clear of the booster, the RS-25E engine returns to full thrust. The LES fairing is jettisoned when aerodynamic and heating loads allow, and the LES then delivers its payload to the desired orbit.

Except for the size, attachment geometry, and engine, the LES design and system requirements are similar to those for upper stages of EELVs. The propellant tank must react to loads from the side mounting and separation forces, as does the CBC tank, which is similar in size. These LES loads will be different than for the Delta IV-H, but the load paths are similar and the analytic techniques used for the CBC will probably be appropriate. The propellant feed and management subsystems will likely be similar for the LES and CBC (except the LES engine thrust is considerably lower), and engines on both vehicles use single gimbaled engines. The requirements for other hardware elements of the LES, including the fairing, payload separation, thrust vector control, avionics and telemetry, and reaction control subsystems appear very similar to those of operational EELV upper stages. Unlike the EELVs, the first-stage booster will require its own avionics; but the LES software functions will be similar to those for EELV upper stages.

2.3.1.4 Operations

The RBS baseline operations requirement is efficient accommodation of an average of eight launches per year from the Cape Canaveral Air Force Station (CCAFS) and Vandenberg Air Force Base (VAFB). To meet the operations requirement, a fleet of eight RBSs is planned,[39] including the two converted Y vehicles, with four each at both CCAFS and VAFB. The baseline assumptions are 10 flights between depot maintenance and 20 flights between RBS engine refurbishments.[40] First-stage reusability goals are 20 flights for the main engine and approximately 100 flights for the overall vehicle. As previously mentioned, the EELV-class missions have been designated "launch-on-schedule,"[41] so rapid ground reprocessing is not required. During a mission the unpiloted booster will need to be capable of automatically and rapidly assessing its health, identifying degraded or failed subsystems, and taking appropriate corrective actions. These actions include (1) nominal mission completion, (2) sacrifice of the payload with recovery of the first stage, or (3) sacrifice of the booster to enable delivery of the payload. AG&C and IVHM will need to be developed to provide these capabilities.

Following a successful mission, the reusable booster would return and land horizontally at the launch base landing strip. Fluid to be handled should be nonhazardous and nontoxic to avoid operations that require self-contained atmospheric protection ensemble suits, and the booster would be designed to allow for efficient access to and energizing of critical subsystems. In addition to enabling appropriate flight control capabilities, it is desirable that the IVHM be designed to minimize the use of touch labor for ground maintenance.

The LES, payload, and fairing would be processed in parallel with the RBS. LES ground processing is likely to be similar to that being used for EELVs. The final ground operations would consist of mating the integrated LES and payload with the RBS booster, automated system checkout, transport to the launch pad, propellant loading, and launch.

Because an EELV launch-on-schedule assessment has been imposed on a fleet of eight RBS boosters, no operability requirement is generated. Lacking an operability requirement, there is no forcing function to achieve efficient booster reusability. If the Air Force desires this capability with RBS, it needs to define specific operability

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[37] See Encyclopedia Astronautica, Saturn IVB (S-IB), available at http://www.astronautix.com/stages/satvbsib.htm.

[38] See Space Launch Report, Delta IV Data Sheet, available at http://www.spacelaunchreport.com/delta4.html.

[39] K.R. Hampsten and R.A. Hickman, Next Generation Air Force Spacelift, AIAA 2010-8723, paper presented at the AIAA Space 2010 Conference and Exposition, Anaheim, Calif., August 30-September 2, 2010. This meeting was unrestricted and open to the public.

[40] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[41] AFSPC, "AFSPC Operational Requirements for Launch," 2012. Distribution statement: No restrictions.

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requirements, which will drive booster design to enable efficient ground turnaround operations. Further discussion of operability considerations based on lessons learned from the space shuttle is contained in Appendix F.

2.3.1.5 Infrastructure

The baseline RBS concept includes one modified and one new launch pad at CCAFS and one modified launch pad at VAFB.[42] The modification of Atlas V launch sites at CCAFS and VAFB was baselined for two of the three RBS launch sites. These existing launch complexes use different Atlas processing techniques as discussed in Section 3.7. Depending on the RBS processing approach(s), the infrastructure modification costs for RBS at these sites could vary considerably. Supporting infrastructure includes a mission control center, launch vehicle processing facilities, solid motor processing/storage facilities, mechanical and electrical ground support equipment (GSE), miscellaneous checkout facilities, and storage facilities. When practical, duplicate facilities based on common designs were assumed.[43] Launch complex installation items such as site preparation, utilities, access roads, and activation were also accounted for in the RBS planning. Horizontal or vertical vehicle processing are demonstrated approaches, and selection will depend on trade-offs between facility, GSE, and touch labor costs. Location of vehicle element manufacturing facilities is open but may be an important cost and schedule consideration.

2.3.2 Development Flight Vehicles

In addition to the AFRL-funded RBS Pathfinder, the baseline RBS program includes a reusable booster demonstrator vehicle, the RBD. The objectives and approaches for the Pathfinder and RBD are discussed briefly below.

2.3.2.1 RBS Pathfinder Development Vehicle

The overall objective of the RBS Pathfinder project is to provide timely and cost-effective information on RBS concept of operations, which is traceable to operational flight conditions, including the rocketback turnaround maneuver and RTLS operations. The Pathfinder project is a partnership between AFRL and SMC with an estimated cost of $57 million. Pathfinder would perform vertical takeoffs, horizontal landings, and RTLSs.[44] Flight conditions would include angles of attack over ±180 degrees, staging Mach numbers from Mach 3.5 to approximately Mach 7, dynamic pressures up to 100 psf, and rotation rates from 20 to 30 degrees/sec. System-level issues to be addressed include propellant management, especially during the rotation maneuver; main engine throttling; loads on the vehicle; and first validations of AG&C and IVHM approaches. A very wide range of relevant aerodynamic phenomena will be experienced that will provide new and difficult challenges to existing computational models to predict and lead design, development, and flight demonstration phases. Further technical details on Pathfinder dealing with the RTLS maneuver and the mitigation of the risks involved appear in Section 3.3.

Three contractors were selected[45] in December 2011 to define requirements and design concepts for the RBS Pathfinder. These contracts are the first phases of a planned four-phase program, now scheduled for completion in late 2016, to build and flight test the RBS Pathfinder.

2.3.2.2 RBD Demonstrator Flight Vehicles

The RBD is a step between the RBS Pathfinder and the operational RBS and is presently less well defined than RBS Pathfinder. Its primary purpose is to demonstrate the rocketback and RTLS maneuvers with a vehicle more closely representing the full-scale RBS booster and to demonstrate rapid ground processing operations for

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[42] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[43] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[44] AFSMC, "Spacelift Development Planning," 2012; AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012. Approved for Public Release.

[45] Guy Norris, USAF Paves Way For Reusable Booster Demonstrator, Aviation Week and Space Technology, December 12, 2011, available at http://www.aviationweek.com/Article.aspx?id=/ article-xml/AW_12_12_2011_ p32-403128.xml.

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reflight. (An additional vehicle, the RB-X, was also presented to the committee, but only the RBD was cited as part of the baseline RBS program.[46]) The RBD is a midscale version of the operational RBS, and the baseline design is a reusable booster with a single NK-33 main engine and side-mounted Castor 30 and Star 63D solid upper-stage engines. The planned flight-test program includes nine suborbital flights and one orbital mission. As mentioned previously, the baseline program would also include two Y vehicles, which serve as the highest-fidelity demonstrators in the program and would be converted to operational use after test program completion.

2.3.3 RBS Ground-based R&D

The AFRL is conducting ground-based R&D in support of key RBS technologies.[47] The R&D areas include those shown in Table 2.1.

The AFRL estimated the overall resources required for the RBS ground-based R&D from fiscal year (FY) 2012 through ORSC HC engine completion in FY2020 at about $538 million.[48] The level of actual resources presently approved for RBS ground-based R&D was unclear from presentations to the committee.

2.4 ADDITIONAL PROGRAMMATIC CONSIDERATIONS

2.4.1 External Program Considerations

The baseline RBS program indicated a requirement for significant external program support only in the maintenance by NASA of the production line for a LO_2/LH_2 upper-stage engine (i.e., the RS-25E) for the RBS. That line is associated with NASA's Space Launch System program and is provided by a U.S. entity that is undergoing downsizing and possible ownership transition. No information was provided to the committee on the consequences of either NASA's lack of support for RS-25E-class engines or changes in supplier ownership status.

Multiple opportunities do exist, especially for more fundamental aspects of the RBS program, for valuable cooperation between the Air Force RBS and other programs. Areas of potential cooperation include materials, combustion stability, and performance models for ORSC reusable engines; validated models for aerodynamic, thermal, plume, and attachment loads on the RBS; and RBS power, thermal, and other subsystems.

2.4.2 Industrial Base

Affordability and industrial base issues were identified by the Air Force as the greatest challenges facing U.S. space launch.[49] No information was provided to the committee on how the RBS program would, if successful, affect the overall U.S. industrial base for launch systems and operations. The planned RBS development program, including ground-based R&D and flight vehicle efforts and the significant overlap between the EELV and RBS programs, would warrant significant contractual efforts across a wide industrial base for a sustained period. However, the present RBS Pathfinder program would downselect to a single contractor after completion of the Phase 1 effort described above.[50] The number of suppliers for major operational RBS elements is presently unknown, but the available costing data for the baseline RBS program do not assume multiple suppliers of those systems. This suggests that at the conclusion of a successful RBS program, the industrial base for RBS EELV-class missions would resemble that supporting the present EELV program.

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[46] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[47] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012. Distribution A–Approved for Public Release.

[48] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012. Distribution A–Approved for Public Release.

[49] AFSPC, "AFSPC Operational Requirements for Launch," 2012. Distribution Statement: No restrictions.

[50] AFRL, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," 2012. Distribution A–Approved for Public Release.

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TABLE 2.1 Reusable Booster System (RBS) Ground-Based Research and Development (R&D) Areas

RBS Ground R&D Element	Comment
Oxygen-rich, staged-combustion (ORSC), hydrocarbon engine	Enable U.S.-built, ORSC engine with acceptable performance, life, reliability, and cost. Augmented by long-term industrial efforts.
Return to launch site	Development/validation of models and hardware required for successful RBS flight phases. Wind tunnel tests as appropriate.
Autonomous guidance and control	Advance controls required for RBS flight phases.
Integrated vehicle health management	Integrated with adaptive guidance and control (AG&C) for flight phases and provides benefits for ground operations.
Ground operations	Includes experiments to validate efficient designs and operations, including subsystem maintenance, propellant management, and vehicle integration.
Advanced subsystems	Efforts on structures, power, thermal, and actuation subsystems tailored to RBS requirements.

2.5 RBS AND RECENT REUSABLE VEHICLES

There have been a number of recent programs for reusable launch vehicles (RLVs). The most relevant are the space shuttle, the National AeroSpace Plane (NASP, X-30), Lockheed Martin X-33, and Kistler K-1, and it is of interest to contrast these with the proposed RBS program. In addition, reusable options for the SpaceX Falcon 9 are under consideration. (Other organizations have initiated efforts on reusable concepts but have not built or tested a full-scale concept.) Table 2.2 lists some salient features of the RBS and the RLV programs.

The requirements and approaches for RBS differ in significant respects from those of prior RLVs, and some of the key differences can be seen in Table 2.2. All these RLVs were required to accommodate crew; which imposes demanding requirements on overall vehicle design that can significantly affect mission performance and cost. The upper stages of the RLVs were designed to be recoverable, which implies they must accommodate very stressing reentry environments. Relative to the RBS vehicle approach, this adds complexity and mass to the upper stages and, in practice, increases ground operation requirements and costs. The RBS is the only concept shown in Table 2.2 that proposes an expendable upper stage and a reusable first stage. That approach enables vehicle and mission options to reduce costs relative to traditional performance-optimized approaches. Other important differences include the single-stage-to-orbit approach of NASP and the X-33; the downrange recovery of the space shuttle; and key subsystems such as first-stage propulsion. It is noted that most of the RLV programs were initiated with requirements for elements that had not been demonstrated under flight-type conditions, much as is being proposed for the RBS program. This, in general, led to unanticipated costs. Overall, the differences between the RBS and RLV programs are such that comparisons between them are unlikely to be fully relevant or prudent. Further discussion of the space shuttle, NASP (X-30), and Venturestar (X-33) is contained in Appendix E.

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TABLE 2.2 Major Reusable Booster System (RBS)/Reusable Launch Vehicle Features

Program	Customer	Crew[a]	Reused Elements	Ascent Concept	Final Orbit	Upper Stage Reuse	Key Elements at TRL<6 at Program Start
Space shuttle	NASA	Y	Orbiter and solids[b]	TSTO[c]	LEO	Y	Reusable Solids Staged Combustion Engine Reentry TPS VTHL RTLS Ground Processing Operations
National AeroSpace Plane (X-30)	Air Force/ NASA	Y	Total vehicle	SSTO	LEO	Y	Airbreathing propulsion system
Lockheed Martin X-33	NASA	Y	Total vehicle	SSTO	LEO	Y	SSTO Linear Aerospike Engine Thrust Modulated TVC EMA
Kistler K-1	Multiple	Y	1st and 2nd stages	TSTO	LEO to GEO	Y	Reusable TSTO Land Recovery
SpaceX[d] Falcon 9	Multiple	Y	1st and 2nd stages	TSTO	LEO to GEO	N	
RBS	Air Force	N	1st stage only	TSTO[e]	LEO to GEO	N	Reusable LO_2/RP-1 ORSC rocket engine Rocketback Maneuver RTLS Ground Processing Operations

[a] Booster vehicle designed for potential transport of crew.

[b] Solids recovered down range.

[c] Main propellant tank expended, solids recovered downrange.

[d] Present Falcon 9 described. A SpaceX RTLS concept in development.

[e] Critical subsystems/processes not demonstrated at flight conditions.

NOTE: EMA, electro-mechanical actuator; GEO, geosynchronous Earth orbit; LEO, low Earth orbit; ORSC, oxygen rich, staged combustion; RTLS, return to launch site; SSTO, single stage to orbit; TPS, thermal protection system; TRL, technology readiness level; TSTO, two stages to orbit; TVC, thrust vector control; VTHL, vertical takeoff, horizontal landing;

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3

Reusable Booster System Technology Assessment

The statement of task for this study (see Appendix A) specifically calls for addressing the technical maturity of the key elements critical to the reusable booster system (RBS) implementation and the ability of current technology development plans to meet technical readiness milestones. This chapter identifies these key elements, addresses their technical maturity, identifies risks, and addresses potential risk mitigation activities.

The technical approach at the system level that the Air Force presented to the committee for eventually developing a flight-ready RBS is based on a three-step process. The combined descriptions of the proposed Air Force RBS program presented by the Air Force Research Laboratory (AFRL), the Air Force Space and Missile Systems Center (SMC), and the Aerospace Corporation involve first building a small-scale Pathfinder vehicle and flight testing it in the 2015 time frame to demonstrate the technical feasibility of performing the rocketback return-to-launch-site (RTLS) maneuver with horizontal landing. If the Pathfinder is deemed successful, then the next step in the RBS development progression would be to scale up to an intermediate-size reusable booster demonstrator (RBD) (approximately 63 ft long and having a dry weight of about 25,400 lb). The RBD would demonstrate the oxygen-rich staged combustion (ORSC)-engine-based main propulsion system (MPS) (using one NK-33 or AJ-26) and the aerodynamic scalability from the much lower cost Pathfinder to the intermediate-sized RBD. Following the RBD demonstration it was advocated by AFRL that the next step in the process should be another intermediate-sized vehicle called RBX; however, the baseline plan as presented by SMC advocated going directly from RBD to the full-scale RBS design, development, test and evaluation (DDT&E) program.

3.1 ASSESSMENT OF TECHNOLOGY MATURITY OF KEY ELEMENTS

If it is accepted that significant cost savings will accrue through reuse of the first-stage, then it is necessary to determine whether the technologies needed to develop a reusable first stage for the RBS can be realized in an affordable development and certification program. To answer this question, it is necessary to first identify the new enabling technologies whose development is required, the risks associated with those developments, and the needed risk mitigation plans.

As stated in Chapter 2, the RBS will require development of technologies that would enable the successful execution of the rocketback maneuver of its first stage and inspection confirmation of the reusability of the recovered first stage before its next scheduled flight. The committee judges that meeting these requirements will involve technology development in four principal risk areas: (1) high-performance hydrocarbon-fueled booster engines;

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(2) rocketback RTLS maneuvers; (3) integrated vehicle health management (IVHM); and (4) adaptive guidance and control (AG&C). Secondary technology risk areas include (1) lightweight structures that can handle the expected loads; (2) robust power, fluid, and actuator systems; (3) advanced assembly and manufacturing techniques; and (4) upper-stage LO_2/LH_2 engines. Note that application of these technologies carries some risk because they have to be applied to a new vehicle configuration with a flight profile that has never been flown before.

The identified technology items will require various degrees of risk mitigation effort involving both analysis and testing, to achieve the technology readiness level (TRL) needed to proceed to substantial RBS development. Some of these technologies apply principally to reusable vehicles; others also have application to potential future expendable vehicles. The high-risk technologies and their application areas are summarized in Table 3.1.

In the following subsections, the four principal technology risks are discussed, secondary risks are addressed and operational and infrastructure issues, as they relate to the RBS concept, are discussed. The chapter concludes with a summary discussion of RBS risk assessment and mitigation efforts.

3.2 MAIN PROPULSION SYSTEM

There are two main propellant options for the RBS MPS, liquid oxygen/liquid hydrogen (LO_2/LH_2) or liquid oxygen/rocket propellant (LO_2/RP); each has two subchoices for the engine power cycle behind them, open or closed, for a total of four basic options. Because the committee believes that neither a pressure-fed liquid engine nor solid rocket boosters would be tractable options for the RBS, it limits discussion to these four options.

The first options for the RBS MPS are a LO_2/LH_2 propulsion system using either an open-power cycle or a more efficient but higher pressure closed cycle. The open cycle can be either combustion tap-off or gas generator;

TABLE 3.1 Highest Technology Risks

Risk Area	Risk Item	Reusable	Expendable
Hydrocarbon-fueled booster engine	Combustion instability	X	X
	Oxygen rich, staged combustion	X	X
	Power balance	X	X
	Physics-based analytical predictive models	X	X
	Injector	X	X
	Materials/coatings for O_2-rich environment	X	X
	Turbomachinery	X	X
	Long-life bearings	X	
	Transients	X	X
	Requirements for vehicle integration	X	X
Rocketback return to launch site maneuver	Sloshing/propellant management	X	
	Plume interactions	X	
	Thermal management	X	
	Deep throttling	X	
	Structural dynamics	X	
	Aerodynamics	X	
	Kinematics and mass properties management	X	
Integrated Vehicle Health Monitoring (IVHM)	Reliable/robust sensors	X	X
	Real-time critical decision making: data to action	X	X
	Identify and develop nondestructive inspection options and quantify reliability	X	X
	System integration into asymmetric vehicle configuration	X	
Adaptive guidance and controls	Integration with IVHM	X	X
	Real-time control algorithms	X	X
	Fast response actuators	X	
	Software verification and validation	X	X

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the latter is used for the Delta IV RS-68 or the Saturn V upper-stage J-2 engine. An example of the closed-cycle engine is the staged-combustion design used on the space shuttle main engine (SSME), which is in the process of being simplified to a lower cost expendable version called the RS-25E. (The RS-25E is the baseline engine selected by the Air Force for the RBS expendable upper stage.) Yet another closed-cycle LO_2/LH_2 engine could be based on an expander cycle such as is used for the RL-10 family of upper-stage engines.

While an LO_2/LH_2 MPS will result in a much higher specific impulse (I_{sp}) (approximately 390 sec at sea level) than a hydrocarbon-fueled engine, it is a nonoptimal choice for the RBS first stage, owing to the extremely low propellant density of hydrogen and its deep cryogenic properties, which must be maintained at approximately –420°F. The use of these deep cryogens results in large, heavy, and more complicated aerodynamic configurations as well as a relatively poor stage mass fraction. Since mass fraction is just as important as I_{sp} in the basic vehicle "rocket equation" design solution, a higher density, more easily storable fuel such as kerosene is a better choice than liquid hydrogen for the RBS booster. The many operational advantages of using kerosene in the first stage, as compared to cryogenic hydrogen, provide a further rationale for the selection of a hydrocarbon fuel.

The selection of a higher density fuel leads to the second set of options for the RBS MPS, which is engines that operate using liquid hydrocarbon fuels, such as rocket propellant (RP)-1, as recommended and advocated by the Air Force in their presentations to the committee. Liquid methane or even ethane or propane (such as the main constituents of liquefied natural gas) might also be a good choice for a higher density, better performing fuel, but there is only limited technology experience with these fuels and LO_2 oxidizer in rocket combustion devices and in vehicle flight experience. Thus, while the committee believes that these fuels might be a good choice for future advanced launch systems, rocket engines designed for using liquefied natural gas-type fuels are not currently at a sufficient TRL for serious consideration.

The committee therefore agrees with the Air Force baseline selection of LO_2/RP-1 for the RBS MPS. Again there are also two suboptions for this propellant combination: open cycle, either gas generator or tap-off, and closed cycle ORSC. The ORSC engine is physically the highest performance (I_{sp}) design approach for RP-1 fuels for several fundamental reasons, including these: (1) operation at high chamber pressure which provides higher net I_{sp} because of improved combustion efficiency; (2) higher sea level (liftoff conditions) area ratio; and (3) typically much higher engine thrust-to-weight ratio. Key characteristics for open-cycle gas generator or tap-off cycle engines versus ORSC closed-cycle engines are summarized in Table 3.2.

Table 3.3 summarizes the advantages of an ORSC LO_2/RP-1 engine over an open-cycle gas generator and lists the issues/concerns as well. The turbine drive gas from the fuel-rich gas generator presents a more benign condition for all the materials in the hot-gas flow path but forces the turbine to run at much higher operating temperatures in order to achieve the necessary turbine drive power.

As discussed previously, the RBS uses the booster main propulsion system to accelerate the upper stage(s) and payload to the staging velocity and to provide sufficient impulse to allow the first stage to glide back to the launch site. With these dual demands on the main propulsion system, the first-stage sizing becomes very sensitive to the specific impulse and thrust-to-weight ratio of the LO_2/RP-1 engine. For this reason, the committee agrees with the Air Force assessment that the ORSC cycle is the preferred engine cycle for the RBS system.

A typical ORSC engine is depicted schematically in the very simple diagram in Figure 3.1. Liquid oxygen and fuel are fed into a high-pressure preburner, which initially combusts at greater than stoichiometric mixture ratios (MR = 10-20), and then the initial combustion products are quenched downstream in the preburner chamber with large amounts of LO_2. The LO_2 is usually injected down below in the preburner chamber through some type of tangential slots, such that the effluent gas leaves the preburner at an MR of 60-80 or so and an exhaust

TABLE 3.2 LO_2/RP-1 Typical Range of Operating Conditions

Cycle	Nominal Chamber Pressure Range (psia)	Vacuum I_{sp} Range (s)	Thrust/Weight Ratio
Open, gas generator	500-1,000	300-315	70-80
Closed, oxygen-rich staged	>2,000-3,500[a]	325-350	100-120

[a] More typical for Russian engines such as RD-170 and NK-33.

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TABLE 3.3 Advantages of Oxidizer-Rich, Staged-Combustion (ORSC) Rocket Engines Over Open-Cycle Gas-Generator LO_2/RP Engines

Advantages	Issues/Concerns
Higher I_{sp} (up to 7-10%).	Because of its oxidizer-rich hot gas environment, engine components and plumbing (ducts) need to be made from compatible and flame-resistant materials or require the use of special nonburning, resilient protective coatings that do not erode or chip away during handling, testing, and operation (especially important for reusable engines).
Use of higher density fuel enables higher overall mass fraction and more favorable aerodynamics profile rocket stages/vehicle design.	Greater tendency for combustion instability because of the more difficult to burn hydrocarbon fuel operating at much higher chamber pressure in the preburner and main combustion chamber.
Because of higher chamber pressures, the engine design results in nozzles with higher sea-level area ratios and significantly higher engine thrust/weight ratios.	Preburner design and development is more difficult than fuel rich gas generators (GGs). Because of high operating pressures, there will be a greater tendency for combustion instabilities and the need for high-temperature oxidizer and flame-resistant materials in the turbines and any associated hot gas ducts and the oxidizer side of the main combustion chamber (MCC) manifolds and injectors.
Results in oxygen-rich shutdown, which minimizes carbon deposits and "coking" of injector orifices with hydrocarbon fuels—therefore, easier to restart multiple times.	Because of the high preburner operating pressures (6,000-9,000 psia), ORSC engines will require boost pumps and boost pump devices. Fuel-rich GGs typically run at much lower pressures—~1,000-1,500 psia—and are easier to design with fewer components.
Enables pumps to generate required power at much lower operating temperatures than with fuel-rich GG powered turbines, which results in increased life and durability (typically about 700°F versus ~1700°F for fuel-rich GG cycle).	
Eliminates open-cycle GG exhaust plume interactions and interference issues by running all of the turbine drive gas back into the MCC.	
Usually allows increased engine service life because of generally lower operating temperatures.	

NOTE: See for example: (1) Oscar Haidn, Advanced Rocket Engines, Lecture Series at the von Karman Institute, Belgium. RTO-EN-AVT-150, ISBN 978-92-837-0085-2, Published March 2007, Open to the public; (2) Robert Sackheim, Overview of United States Space Propulsion Technology and Associated Space Transportation Systems, *AIAA Journal of Propulsion and Power* 22(6), November-December 2006.

temperature of 700-800°F. The preburner exhaust gases are then run through the turbopump assembly (TPA) turbine, which typically drives both the fuel and the oxidizer pumps using a gearbox and separation seals. Note that all staged combustion engines must operate with pump discharge pressures significantly higher than the main combustion chamber (MCC) pressure because the main drive turbine operates in series with the MCC. The LO_2 is fed back to the preburner and the oxygen-rich gas from the turbine exhaust is then fed into the MCC injectors, where it is mixed with the liquid RP-1 coming from the fuel pump. Both the hot oxidizer-rich gas and the RP-1 enter the MCC through the chamber injectors. Typically, the injector has hot gas/liquid RP-1 swirling elements. The number of these swirl injector elements depends on the engine thrust level and scales somewhat with engine size and thrust level.

Boost pumps are typically used to feed the high-pressure LO_2 and RP-1 into the preburner. The engine start and shutdown sequences and methodology vary and tend to be somewhat complex, but they are usually established by the engine timing, calibration of the power balance, detailed operation of the flow control valves, and other fluidic elements. The oxidizer and the fuel pumps are usually mounted on the same common shaft, and dynamic seals and intercavity inert gas purges keep the two liquids well separated. An upstream start turbine is sometimes used to start TPA full operation.

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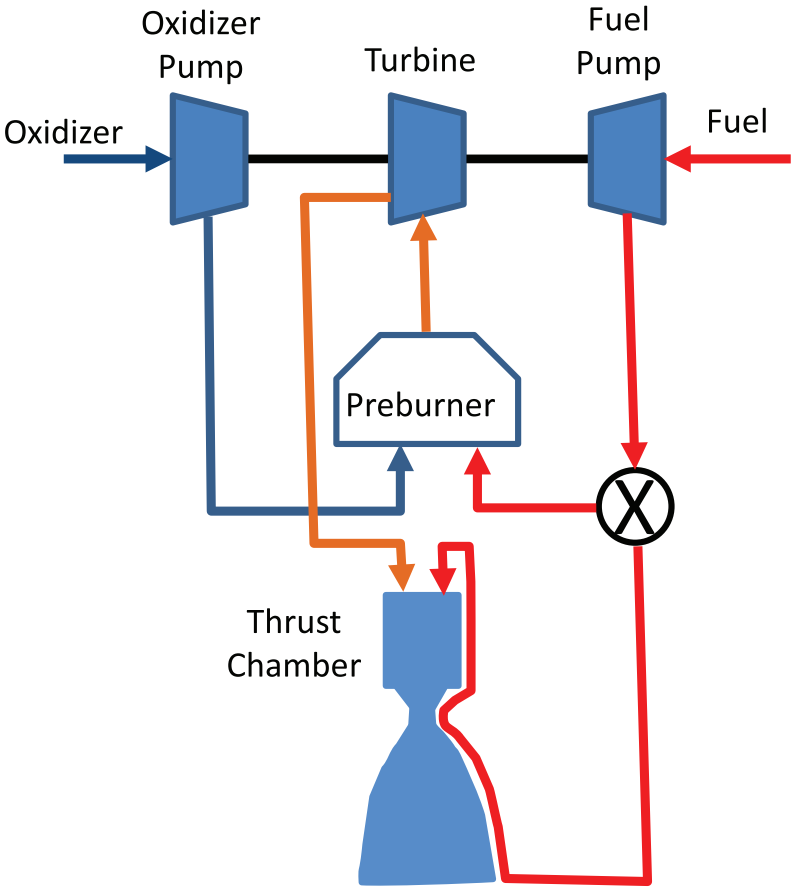

FIGURE 3.1 Highly simplified schematic of a closed-cycle, staged-combustion rocket engine. Because the preburner, turbine, and thrust chamber operate in series, the required pump pressure is higher compared to open-cycle engines. SOURCE: Air Force Research Laboratory.

There are several conventional options for vehicle thrust vector control; these would combine one or more thrust chambers with some type of non-toxic propellant reaction control subsystem, which will likely be required at a minimum to achieve roll control, but these will not be discussed here in detail.

Engine throttling, which is usually required together with control of the mixture ratio, is accomplished with a complex combination of flow bypass valves, throttle valves, and fixed bias and calibration orifices that are inserted during engine and hydraulics system build-up, calibration, and hot fire tests. All liquid RP-1 enters the thrust chamber cooling jacket prior to entering the MCC injectors and is mixed with the oxidizer-rich preburner exhaust gases to achieve the final main chamber combustion process. The liquid cooling jacket (heat exchanger), together with some film cooling of the MCC chamber wall, maintains the MCC at an acceptable operating temperature while allowing the necessary engine combustion efficiency and associated I_{sp}.

3.2.1 Hydrocarbon-Fueled Booster Engine Risk Assessment

In considering the hydrocarbon-fueled ORSC rocket engine that will serve at the MPS for the reusable booster, the committee identified 12 risk areas:

- *Combustion stability.* Combustion stability physics for high-pressure liquid-liquid preburners and the MCC gas-liquid injectors for LO_2/RP-1 ORSC engines are not well understood in the U.S. rocket industry. Combustion instability issues have plagued many rocket engine development programs during the past 60 years. Both physics-based modeling and a well-defined test program will be required to achieve and demonstrate the required stability margins for both combustion devices and thereby retire these risks. The Air Force Office of Scientific Research, in close cooperation with AFRL's rocket propulsion laboratory at Edwards Air Force Base, has been making significant investments to analyze, predict, and defeat the combustion instability problem in liquid oxygen, hydrocarbon (LO_2/HC) engines.
- *Injectors.* The new ORSC injector will most likely be based on a co-axial swirl design that will have to be tuned to MCC frequencies and set up with either acoustic cavities and/or baffles to ensure stable engine operation. Also, thrust-scaling relationships will have to be established through a combination of analysis and empirical data. While this is not presently seen as a major risk, there will have to be a dedicated experimental testing effort to tune the injector and chamber at the subscale and then the full-scale levels.
- *Operation in high-pressure, oxygen-rich environments.* High-pressure, oxygen-rich environments can be very hard on inert materials, and dangerous conditions can result following initial failures that are difficult to contain when trying to recover to a safe operating state. This type of environment is unique to the ORSC engine. As described above, in an ORSC engine all oxidizer consumed in the engine combustion process is first used to drive the TPA turbine, resulting in high-power margin and a relatively low operating temperature. The resulting oxygen-rich environment is also relatively clean, such that no soot or other residual combustion product deposits are generated during normal operation. Because of these unique conditions, the ORSC cycle generates high-pressure oxygen rich environments that present compatibility challenges for traditional turbine and ducting materials.
- *Physics-based analytical models.* Another risk for the RBS MPS is a fundamental lack of fully anchored physics-based analytical models for ORSC engines. In the anticipated fiscal environment of limited budgets and short development schedules available for RBS development, reliable and accurate analytical models and tools are critical for the successful and cost-effective completion of the planned RBS DDT&E program. Accurately anchored models enable a reduction in the number of design fabrication cycles and, most significantly, expensive test cycles that were required for past rocket engine development programs. The analytical model development needs to be multiscale, with modeling ranging from subscale components to subassembly levels such as the power head (TPA, preburner, and flow control valves) as well as at the full-scale ORSC engine level. This approach will ensure that validated analytical models are developed logically and accurately and that they are well anchored so that validated models at each step of the design process will be available for the ORSC engine when scaling to higher thrust levels. These same models will also benefit other future ORSC engine development work by accelerating and reducing the total number of expensive tests required.
- *Valves/sensors/actuators.* Some development effort will be required for the necessary reliable advanced fluid valves and control elements to enable a wide range of throttling, mixture-ratio control for proper and efficient propellant utilization, engine balance and calibration, thrust vector control (TVC), IVHM, and various other engine controls. These control elements must have modern, accurate sensors and be fully integrated with an automated digital MPS and engine control system, with the vehicle adaptive guidance and control system, and with the IVHM.
- *Thrust level.* The RBS ORSC engine thrust level requirement described in Air Force presentations to this committee is highly ambiguous. It was stated that the thrust requirement for RBS was anywhere from 350,000 to 500,000 lb_f, which is inherently a problem from the standpoint of engine size and injector scaling and of possible high-pressure instabilities. The requirement became more complicated when Air Force briefers said several times that they might be interested in using the new American ORSC engines to replace the Russian RD-180 for the EELV program, which operates at thrust levels between 800,000 and 1.1 million lb_f; this would pose a significant engine scaling problem and a much higher level of risk. The thrust level requirement should therefore be established early in the RBS development program and maintained at that level to avoid additional complications. If the Air Force wants to make the new engine compatible with the thrust requirement of NASA's Space Launch System (SLS), which is stated to be 1.1 to 1.2 million lb_f, this ambiguity would also have to be resolved to enable a single, focused ORSC engine development program without any additional complications that could lead to large program cost and schedule overruns.

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- *Systems engineering.* The Air Force presenters offered little description of the RBS needs and/or requirements for system engineering and integration of the MPS and the other major systems into the RBS vehicle. These requirements must be firmly established early in the development process to avoid serious conflicts, unnecessary complications, and, worst of all, requirements creep, before program critical design review and flight certification. If these design requirements are not firmly established and maintained early in the program, there will be a high probability of serious cost overruns and schedule slippage.
- *Power balance.* Overall engine power balance and flow calibration and control with robust margins and tolerances for wide operating variances must be established early and verified by testing. Otherwise there will certainly be problems with off-nominal operating conditions, which often occurs later in the program or, worst of all, during actual flight. There must be demonstrated anomaly and off-nominal operating capability and robust margins designed into the more complicated ORSC engine to avoid failures that would be catastrophic during flight.
- *Turbomachinery.* There are always risks with new engine turbomachinery. Because of the high-pressure preburner operation, boost pumps need to be used in the engine and as part of the overall cycle. Engine start-up transients and shutdown sequences will all have to be established and fully characterized for this more complicated ORSC, multicomponent engine to ensure safe and repeatable operation. This is not considered to be a major risk, but it is a moderate risk that will have to be addressed during the design and development process with a focused, dedicated effort that will have associated costs.
- *Long-life bearings.* High-speed, long-life reusable turbomachinery shaft bearings will have to be developed and verified for all ORSC engine rotating machinery. This is a low-to-moderate-risk concern but one that must be explicitly addressed because bad bearing choices and subsequent integration into the engine can lead to serious problems later in the DDT&E program. This happened more than once in past programs such as the SSME, when bearing issues were discovered after a number of space shuttle flights perceived to be successful.
- *Reusability:* Other than the SSME, there has been almost no requirement for multiple reuses of U.S. rocket engines. Typically, additional life margin is designed in and demonstrated on all rocket engines to allow for hot-fire testing and even retest before flight. The question of how many engine reuses will be required prior to routine maintenance and scheduled engine overhauls must be answered. This concern is not a major risk, but it is rather a moderate risk that must be mitigated because it is a new requirement for an ORSC engine that has not been previously developed by U.S. industry.
- *Materials.* The last risk, a moderate one, is the mechanical and dynamic design approach and especially the materials to be used for hot, oxidizer-rich, hot-gas ducts from the preburner, which may require flexjoints or axial joints and other complications. As mentioned above, this risk area will have to be empirically evaluated before committing to a design.

Thus, the principal technical risks associated with the development of a LO_2/RP ORSC rocket engine concern combustion stability and operation in the high-pressure oxygen-rich environment. Significant additional basic and applied research on combustion stability will be necessary before analytical tools are available that allow confident prediction of combustion instabilities. This work is under way at AFRL, but significant improvement in prediction capabilities cannot be anticipated in the near term. Fortunately, empirical techniques are available to "de-tune" the combustion system if instabilities arise, so this risk is principally one that will need additional development time and resources will be required if instabilities arise as the engine is scaled up during its development phase.

The risk associated with the oxygen-rich operation is fundamental and potentially more difficult to overcome. It is well known that Russian engine designs have overcome this material incompatibility challenge by using inert enamel coatings on traditional high-strength turbine alloys and hot-gas ducting. The alloys provide the structural load support, while the enamel coating provides the requisite hot-oxygen-compatible and/or protected surfaces. This type of solution has been used on Russian ORSC rocket engines for over 50 years and is used around the world for gas-turbine applications for jet engines and domestic power generators. There are at least three flight-certified Russian ORSC engine designs (RD-170, RD-180, and NK-33) that are well known to the U.S. rocket engine industry but not produced in the United States. Through various business arrangements with the Russian engine manufacturers, the basic design for these engines is well known and understood by the U.S. manufacturers—

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namely, Pratt and Whitney Rocketdyne (PWR)[1] and Aerojet.[2] Each company sells a version of different Russian engines (e.g., PWR sells the RD-180 and Aerojet sells the NK-33) to U.S. launch vehicle suppliers.

Another oxygen-rich compatibility approach is to develop and use a hot-oxygen inert parent material.[3] This approach is being attempted by the AFRL and large engine contractors (PWR and Aerojet) with some successful results already having been reported. PWR has developed a new hot-oxygen-compatible material called Mondaloy and has been evaluating its applicability and durability in hot oxygen-rich environments. To date, only small coupon pieces of Mondaloy have been manufactured, and the statistical basis for the thermal and mechanical properties needed for engine development is currently lacking. As such, basic issues with weldability, fatigue, and fracture remain to be investigated.

Currently, the Russian-developed enamel coatings are a far more mature and proven technology. However, application of these special coatings and/or advanced materials to U.S. ORSC engine designs has not been fully proven, so a comprehensive risk reduction program will be required. This risk mitigation effort must be focused on developing and proving a new hot-oxygen-compatible parent metal alloy or on verification of a coated material system capable of multiple reuse for the turbine and hot-gas flow-path components similar to the Russian solutions. Thus, if the known coatings, which are inert and will not react with hot oxygen, become the preferred approach, the risk mitigation effort will have to ensure that the coated engine elements are sufficiently durable for multiple reuse under all the necessary environmental exposures. In short, the program will have to verify coating durability under all relevant conditions and demonstrate traditional hot oxygen compatibility to be certified for a flight RBS-ORSC engine that launches an RBS.

The committee believes that in spite of the ORSC engine risks and concerns discussed above, there already exists an extensive database and success with this type of engine around the world. Table 3.4 lists all LO_2/HC engines using either open- or closed-cycle designs that have been flown or are flight qualified throughout the world. As can be seen from this table, ORSC engines have been or are about to be flown on launch vehicles in the United States (all Russian designed and built), Russia, Ukraine, India, China, and South Korea. This extensive successful flight history and development experience should provide confidence for the development of a LO_2/HC engine for the RBS booster. Many of these LO_2/HC-powered launch vehicles have successfully placed large payloads of all kinds into their required Earth orbits or onto space-science trajectories throughout the solar system. This long history of success also includes putting many human beings in space as well as on the moon. So, these past successful experiences on both kinds of LO_2/HC engines certainly provide assurance that a completely new ORSC engine can be developed here if adequate resources, time, and planned reserves are devoted to an affordable and reasonable program.

3.2.2 Hydrocarbon-Fueled Booster Engine Risk Mitigation

In addition to its extensive and successful EELV flight experience with hydrocarbon booster engines, the Air Force described to the committee the types of hardware technology demonstrations and risk mitigation programs that AFRL has been pursuing. These technology programs are briefly described below together with a short overview of NASA's hydrocarbon engine development activities.

The AFRL has been conducting a joint rocket technology program with industry, the Integrated High Performance Rocket Propulsion Technology (IHPRPT), to advance all forms of rocket propulsion technology, including hydrocarbon boosters, for about the last 20 years. The goals for the hydrocarbon booster portion of IHPRPT are summarized in Table 3.5.[4]

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[1] A. Weiss, Pratt and Whitney Rocketdyne, "Reusable Hydrocarbon Rocket Engine Maturity for USAF RBS," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Approved for Public Release.

[2] J. Long, Aerojet, "Reusability and Hydrocarbon Rocket Engines – Relevant US Industry Experience," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Approved for Public Release.

[3] R. Cohn, Air Force Research Laboratory, "Hydrocarbon Boost Technology for Future Spacelift," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Distribution A–Approved for Public Release.

[4] R. Cohn, Air Force Research Laboratory, "Hydrocarbon Boost Technology for Future Spacelift," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Distribution A–Approved for Public Release.

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TABLE 3.4 American Heritage or Other Available Source Hydrocarbon Rocket Engines: Previously or Currently in Use, or in Development

Rocket Engine	Manufacturer/ Supplier	Cycle	Thrust Level (lbf) / Vacuum Specific Impulse (s)	Status	Application	Comment
RS-27 MD-1 MA-7	Pratt and Whitney Rocketdyne	GG	200K S.L., 237K ALT / 303	Flown hundreds of flights (~800)	Delta II and A2L Previous Thors, Thor Delta, and Delta III	
MA-5A LR-89/ LR-105	Pratt and Whitney Rocketdyne	GG	430K (booster)+60 (sustained) / 297	Flown hundreds of times on Atlases; Project Mercury many flights (1,404)	Atlas family up to satellite launch vehicles	
H-1	Pratt and Whitney Rocketdyne	GG	200K S.L., 205K ALT / 301	Flown many flights (152)	Saturn 1B, Jupiter, and early Thor Deltas	
F-1	Pratt and Whitney Rocketdyne	GG	1,522K S.L. / 307	~65 flights	Saturn V/Apollo	5 used in first stage
RD-180	Pratt and Whitney Rocketdyne, Russian-derived NPO Energomash	ORSC	~860K S.L., 933.4K ALT / 337	~10 flights	Atlas III and V	Two TCAs, one pump
RD-170	NPO Energomash	ORSC	~1700K / 337	Flown many times	Buran, Zenit, Proton	Four TCAs
S-3D	Pratt and Whitney Rocketdyne	GG	80K / 310	46 flights	Jupiter/Juno	
AJ-87 AJ-1 AJ-3	Aerojet	GG	300K / 249	Flown many times on ICBM test flight	Titan-I first stage	
AJ-91	Aerojet	GG	80K / 310	Flow many times on ICBM test flights	Titan-I second stage	
NK-33 (AJ-26)	Aerojet	ORSC	340K S.L., 380K ALT / 330	Intended for use on Russian N-1 Moon launcher first stage	Developed for Russian N1, to be used on Taurus II (Antares)	PC = 2,109 psia
NK-39	Khrunichev/ Aerojet	ORSC		N-1 second stage	Developed for Russian N1, intended for use on K1	
RS-84	Pratt and Whitney Rocketdyne	ORSC	1,050K S.L., 1,123K ALT / 338	Finished PDR; cancelled by NASA	Intended for 100 missions, reusable launch vehicle	Incorporates advanced technology items, advanced materials, enhanced water-cooled nozzle
Merlin family	SpaceX	GG	~80K / ~302	Flown	Falcon I, 9 and 27	Privately funded development
Other miscellaneous Russian	NPO Energomash	ORSC	Various / ~330	Some flown	Various Russian and Ukrainian Rockets	RD-190

continued

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TABLE 3.4 Continued

Rocket Engine	Manufacturer/ Supplier	Cycle	Thrust Level (lbf) / Vacuum Specific Impulse (s)	Status	Application	Comment
MC-1 (Fastrak)	NASA/Marshall Space Flight Center in-house	GG	~75K / ~280	Advanced development, many tests	Looking for one, almost for X-34	
YF-100	China, Inc.	ORSC	260K S.L., 301 ALT / 336	Flown on Long March	China's Long March launch vehicle 5, 6, and 7	

NOTE: ALT, at altitude; GG, gas generator; ICBM, intercontinental ballistic missile; lbf, pounds force; ORSC, oxygen rich, staged combustion; PC, combustion chamber pressure; S.L., sea level; TCA, thrust chamber assembly, K, thousand.

TABLE 3.5 Integrated High Performance Rocket Propulsion Technology (IHPRPT) Hydrocarbon Boost Technology/Performance Advancement Goals

Goals	IHPRPT Goals Related to Reusable Booster System
Specific impulse (s) sea level/vacuum	+15%
Thrust to weight sea level/vacuum	+82%
Production cost	−50%
Failure rate	−75%
Mean time between replacement (cycles)	Defined
Mean time between overhaul (cycles)	Defined
Turnaround time (h)	Defined
Throttle range	Defined
Sustainability	Must derive from sustainable materials and processes

SOURCE: Richard Cohn, Air Force Research Laboratory, "Hydrocarbon Boost Technology for Future Spacelift," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Distribution A: Approved for Public Release.

Critical RBS technologies being studied and developed under ongoing AFRL propulsion R&D programs are summarized in Figure 3.2. The hydrocarbon boost (HCB) Phase II demonstration program aims to develop technologies to support the ORSC LO_2/RP engine capability. Conducted by both Aerojet and PWR, this program aims to mature advanced hot-oxygen-rich-compatible materials and coatings as well as engine components such as pumps, advanced hydrostatic bearings, valves, actuators, preburners, igniters, main thrust chambers and new engine controllers, IVHM systems and associated sensors. As seen in Figure 3.2, the technology development associated with the HCB Phase II demonstration program and the Advanced Liquid Rocket Engine Stability Technology (ALREST) program are scheduled to run through the year 2020, which would limit technology contributions from these programs to any near-term RBS development activities.

The ALREST combustion stability effort is focused on development of a fundamental understanding of combustion instabilities in high-pressure LO_2/RP combustion systems. These two efforts are planned for completion in 2020. Additional efforts under way include assessment of the characteristics of Mondaloy and development of IVMH diagnostic techniques applied to booster engines.

NASA has also been conducting advanced ORSC engine development programs over the last 15 years, working to solve many of the same advanced technology problems as those that the Air Force has been addressing.[5] Several years ago NASA Marshall Space Flight Center (MSFC) funded a new ORSC engine program known as the RS-84.

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[5] D. Lyles, "NASA's Reusable Stages and Liquid Oxygen/Hydrocarbon (LOX/HC) Engines," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 17, 2012. Approved for Public Release.

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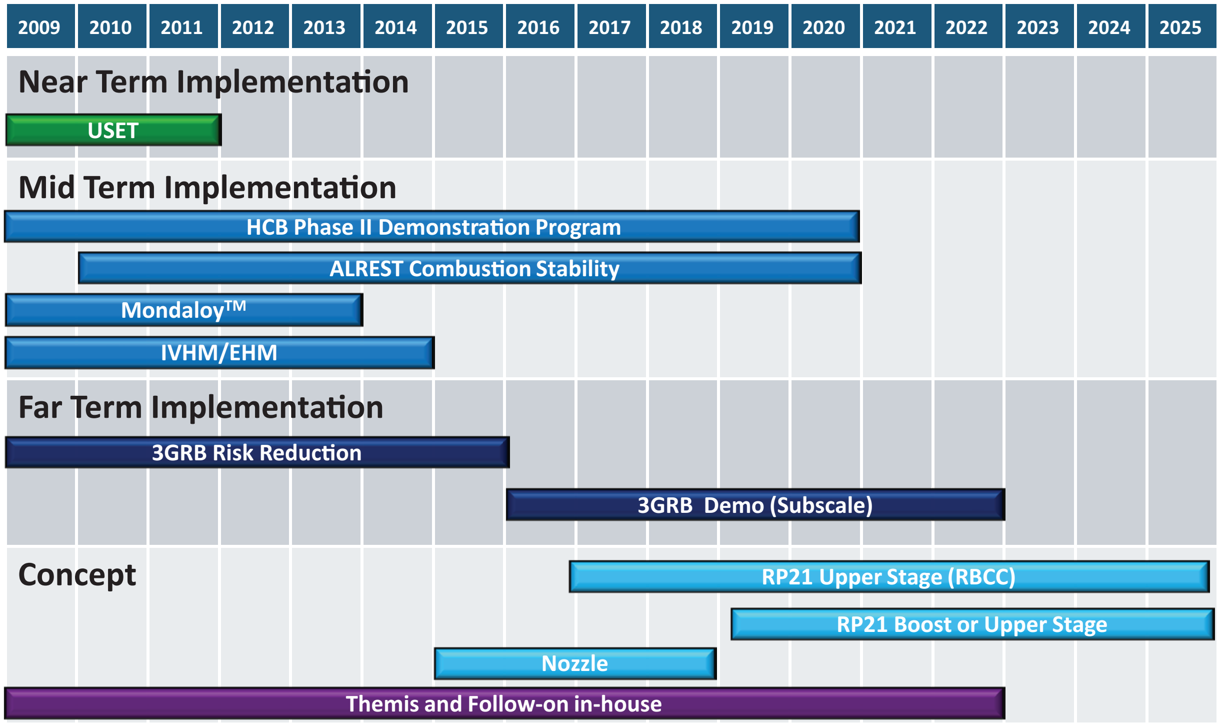

FIGURE 3.2 Air Force Research Laboratory Liquid Rocket Engine Roadmap as of fiscal year 2012. SOURCE: Richard Cohn, Air Force Research Laboratory, "Hydrocarbon Boost Technology for Future Spacelift," presentation on February 15, 2012. Distribution A–Approved for Public Release.

This engine program proceeded through the preliminary design phase and was able to conduct some advanced prototype component design, manufacture, and test before it was canceled because it had no firm mission requirement and the NASA budget did not support sufficient advanced technology funds. Nevertheless, some successful component-level results were achieved that are now directly applicable to a new Air Force ORSC engine program.

NASA also worked jointly with the Air Force on an advanced technology program known as the Integrated Powerhead Demonstration (IPD). The IPD program was initiated by the Air Force but soon evolved into an effort jointly funded by AFRL and NASA MSFC with all hot-fire testing conducted at the NASA Stennis Space Center. The power head was to be integrated into a full-flow staged-combustion engine, where all propellants (in this case LO_2 and LH_2) flow through oxidizer-rich and fuel-rich preburners that power separate fuel-pump turbine and oxidizer-pump turbine, respectively. The hot-gas exhausts from each preburner flow into the MCC through a gas-gas injection system, making 100 percent of the propellant energy available to produce thrust. The IPD was designed as a ground-based demonstrator for an engine that would produce 250,000 lb_f thrust. It was designed, built, and successfully tested, thereby demonstrating compatibility for high-performance and long-life components, materials, and technologies for reusable booster engine applications and (for the first time) a gas-gas injection MCC. After the successful tests at NASA Stennis, the program was terminated by the government, also for a lack of funding and a lack of a well-defined mission requirement. The successful IPD demonstration led to improved understanding of advanced engine components, and many of these results will be directly applicable to advanced component development associated with any type of new ORSC engine.

NASA has recently announced a requirement for a new ORSC engine in the million-pound thrust class for its new SLS Advanced Liquid Strap-on Booster (ALSB). The procurement and conceptual design activities are currently under way for a program that will demonstrate significant risk mitigation results for this new ORSC

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engine. Even though the SLS ALSB engine thrust requirement is currently higher than needed for the Air Force RBS, NASA has announced plans to develop advanced technology materials and components that are applicable to both the SLS ALSB program and the RBS ORSC program; the SLS-ALSB risk mitigation program might therefore make a significant contribution to the Air Force program.

As the risk associated with hydrocarbon booster engine development is mitigated, the performance of a new rocket engine will eventually be demonstrated through extensive testing. Previously, new engine verification testing required years of very expensive testing. These efforts were being performed before very sophisticated computer design and simulation tools had become available. As computer capability increases, the belief is that the testing once required can be significantly reduced and that "cut-and-try" will be replaced with "simulate, test, verify and improve." The cost saving associated with this new approach has not yet been fully demonstrated.

In conventional engine development, new engine design validation testing includes testing at the subscale, component, and subsystem level as well as in full flight configuration. At the component level, the required test facilities can be modest and typically include fluid flow and high-pressure testing of injectors, nozzles, pumps, and thrust chambers. The modest facilities can be used to conduct injector spray tests with cold-flow tests of the regenerative part of the combustion chamber before the full testing of ignition and ramp-up tests over a wide range of operating conditions. Engine combustion stability through all throttle levels as well as dynamic and spontaneous stability conditions is a key performance metric for both the MCC and the pressure preburner, which operates at much higher pressure. Sea-level and altitude simulated testing can be performed depending on the application. In addition to reviewing the engineering data after each subsystem test, the components are evaluated for potential failure.

Testing is generally highly instrumented to allow for verification of overall performance under a variety of performance conditions as well as to validate or provide feedback to analytical models. If sufficiently engineered into the test plan, early testing and evaluation can be used to improve system design for better performance, reliability, and safety. Detailed verification testing typically uses instrumentation, including flow meters, steady-state pressure transducers, thermocouples, high-frequency pressure measurements, strain gauges, accelerometers, and sophisticated laser and optics techniques[6] to provide detailed information on the performance of large rocket engines under widely varying conditions.

As the required testing moves toward full system-level testing, there are only a few facilities available. NASA, PWR, and Aerojet all use the NASA Stennis facility, a national test facility allowing a range of rocket propulsion testing from component- to engine- to stage-level testing. As of May 3, 2012, Aerojet had conducted eight AJ-26 hot-fire acceptance tests at the Stennis facility.[7] The RBS rocket engine testing will also be able to use this same facility. There are also limited rocket test facilities at AFRL/Edwards Air Force Base, commercial facilities at the Mojave Space Center, and contract facilities such as Wylie Labs. These facilities could be available as backup or to handle overflow and surge needs. Additionally, SpaceX has developed a facility at McGregor, Texas.

The cost realities for a rocket engine development program to support the RBS will be strongly impacted by the number and type of tests required for either an existing (AJ-26) or a new rocket engine design and the availability of testing facilities. With the goals of increasing reliability and reducing operating costs for the RBS, it will be vital to incorporate as early as possible the many sensors and control elements to be used in the IVHM system appropriate to the rocket engine. This will allow evaluation of the effectiveness of these sensors and controls and of the IVHM system so as to assess rocket engine performance and its ability to respond to off-nominal conditions.

3.3 ROCKETBACK RTLS MANEUVER

The second principal technology risk area is associated with the rocketback RTLS maneuver. As described in Chapter 2, the reusable booster reorients itself following stage separation and the MPS is used to cancel the downrange component of momentum and provide sufficient return velocity such that the booster can return unpowered

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[6] NASA, Rocket Engine Technology Test Bed Practice, NASA Preferred Reliability Practices, Practice No. PT-TE-1427, available at http://engineer.jpl.nasa.gov/practices.html, p. 4.

[7] J. Long, Aerojet, "Reusability and Hydrocarbon Rocket Engines–Relevant US Industry Experience," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 16, 2012. Approved for Public Release.

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to the launch site. While this trajectory is novel and enables the RTLS operation needed in a reusable vehicle operating from coastal launch sites, the maneuver introduces technology risks that must be considered. These risks are associated with MPS throttle requirements, aerodynamics, thermal protection, and propellant management.

The MPS engine throttle challenges are associated with the significantly different thrust levels associated with lifting the full RBS stack as compared to the thrust requirements for the rocketback maneuver where the engine is propelling the near-empty booster stage. In the baseline RBS program description, this thrust disparity is met by using five AJ-36 engines for liftoff and one throttled AJ-26 for the rocketback maneuver. This thrust disparity challenge is much more difficult if using one or two engines as the booster MPS. The issues associated with engine throttling were discussed in the preceding section.

The aerodynamic, thermal management, and propellant management issues are discussed in the following subsections.

3.3.1 Aerodynamics Risk Assessment

The proposed rocketback maneuver to be executed by the first stage involves complex aerodynamic interactions that must be investigated during risk-reduction phases of the RBS development. Prediction of the vehicle aerodynamics is complicated by three principal factors: (1) high-speed, low-Reynolds-number flows, (2) rocket plume interactions, and (3) the need for high aerodynamic efficiency to minimize drag and associated ΔV requirements during the rocketback maneuver.

As shown in Figure 2.4, the RBS staging is envisioned to occur at altitudes above approximately 50 km, which is in a flight domain where vehicle boundary layers are predominately laminar and uncertainties in vehicle aerodynamics can be dominated by boundary layer separation phenomena. Furthermore, the approximate 180-degree turn creates a broad spectrum of transient aspect angles for the winged RBS, generating complex three-dimensional transient flow structures. This situation is further complicated by a lack of existing ground test facilities able to produce the Mach number/Reynolds number simulation environment that will allow collection of required aerodynamic data.

The second factor impacting the vehicle aerodynamics concerns the plume interactions that will occur during the rocketback maneuver. With the rocket operating at highly underexpanded conditions, the exhaust plume will expand and disrupt the flow over the aft end of the RBS first stage. The degree of plume interaction will be further complicated by chemical reactions between the hot exhaust gases and the ambient airstream. Accurate prediction of the vehicle aerodynamics during the rocketback maneuver will be required to ensure that sufficient vehicle control is maintained during the maneuver.

The final factor impacting the vehicle aerodynamics concerns the need for high aerodynamic efficiency during the glide portion of the trajectory. At the completion of the rocketback thrusting, the first stage is projected to be at an altitude significantly higher than can be sustained for equilibrium glide, so the vehicle will fall through its desired altitude and use lift for recovery to the equilibrium glide trajectory. Conducting this pull-up maneuver in an efficient manner is critical to maintaining sufficient kinetic energy to enable RTLS. Once on its equilibrium glide trajectory, the vehicle must operate with high aerodynamic efficiency (i.e., high lift-to-drag ratio) to provide for sufficient glide range to return to the launch site. The achievement of this high aerodynamic efficiency is complicated by the configuration of the RBS first stage, which will likely have a center of gravity well aft of conventional atmospheric flight vehicles owing to the aft location of the large rocket boosters, with subsequent large unstable lateral aerodynamics.

These risk factors are made more challenging by the large uncertainties that exist in the atmospheric models for altitudes above 100,000 ft. These uncertainties will need to be accommodated in both the aerodynamic design of the reusable booster and in the adaptive guidance and control system.

3.3.2 Thermal Protection/Thermal Control Risk Assessment

The technical information presented by the SMC and AFRL to the committee on identification of technology risk associated with the development of the RBS did not list any risk associated with thermal protection or thermal

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control. This conclusion was substantiated in presentations by four aerospace companies in their respective responses to the question, What are the major technology risks associated with realization of a RBS for space lift? This conclusion is based on the results of a number of Air Force and NASA studies on reusable flyback booster systems, where the staging would occur between Mach 3.5 and 7, thereby avoiding the shuttle orbiter-type extensive thermal protection system, which experienced Mach 25+ reentry conditions and their associated extreme heating and thermal shock.

The rocketback maneuver is currently the favored RBS approach, but its use presents uncertainty with respect to thermal protection and thermal control.[8] RTLS recovery has been analyzed in considerable detail, specifically for the space shuttle since it was a primary ascent abort mode, but it was never tested during development nor was it necessary to exercise it during any of its 135 operational flights.

The concerns of the committee associated with the RBS thermal protection system are tied to plume-vehicle interaction, structural loading on the control and aero surfaces, and base heating depending on the engine gimbal authority required for the maneuver. In principal, these concerns present no fundamental technology risk to developing an acceptable thermal protection system for RBS; however, the loads generated by these complex interactions need to be accurately characterized.

Relative to RBS thermal control, the existing component, subsystem, and system design concepts needed for RBS are sufficiently mature that they will likely require relatively little development work to meet RBS requirements. However, operational requirements should be considered in the system design. For example, if there were a requirement for thermal conditioning that might result in long hold times during launch operations and where ground conditioning is not available, then this situation could result in a requirement for onboard thermal control, which might increase launch vehicle weight.

3.3.3 Propellant Management

Most of the first stage propellant is used in accelerating the launch vehicle to the second stage separation condition. As a result, the rocketback RTLS maneuver is executed with near-empty first stage tanks. Accurate management of both acceleration magnitude and direction during the maneuver will be needed to maintain the propellant flow throughout the maneuver. A recent Air Force white paper[9] states that a major objective of the Pathfinder program is to address the technical challenge of propellant management (slosh and propellant agitation) during the rocketback maneuver. This challenge, like that of predicting aerodynamic load, can be addressed by developing and experimentally verifying the propellant slosh and dynamics models that will be used to predict propellant conditions and to design propellant management devices for the operational RBS.

The white paper goes on to state that "as in the case of aerodynamics, scaling design factors are needed to match the operational propellant conditions. These scaling factors include the present volume of propellant and gas (ullage) in the tanks during the rocketback maneuver. Appropriate similarity parameters will be used in the design of the pathfinder vehicle and the selection of flight test parameters." The committee believes that flight experience, propellant management and slosh control technology, and existing data can be leveraged to manage propellant and control slosh during the rocketback maneuver and that these propellant concerns will be addressed as part of the Pathfinder program.

3.3.4 Rocketback RTLS Maneuver Risk Reduction

Simulating and understanding the aerothermodynamics of the unique rocketback maneuver does not lend itself to wind-tunnel investigations. Thus, computational fluid dynamic (CFD) models must be adapted to simulate and predict the maneuver, and modeling the flight regime of Mach 5 to 7 at altitudes above 50 km will require

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[8] Air Force Research Laboratory, "AFRL Portfolio: Responsiveness & Reusable Boost System (RBS)," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 17, 2012, p. 24. Distribution A–Approved for Public Release.

[9] D. Leggett, Air Force Research Laboratory, White Paper on the Pathfinder Program. Responses to Questions from the Committee for the Reusable Booster System: Review and Assessment, April 19, 2012. Available to the Public.

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empirical validation of the calculated results. Accordingly, obtaining flight-type data relevant to RBS maneuvers would help in understanding the RBS unique aerothermal environment, thereby providing calibration and validation data for the models.

Pathfinder will specifically address verification of the predicted aerodynamic and aerothermal loads during maximum dynamic pressure and the booster's rocketback maneuver. The Air Force has stated that the results of Pathfinder test flights can be scaled to the full-size RBS for the aerodynamic and aerothermal loads through the use of new improved CFD models.[10] These codes and models are constantly being advanced at many levels and will likely be available for use in predicting load levels and flight environments for the operational RBS vehicle. The Air Force has also said that the Pathfinder test and characterization approach for matching actual flight conditions is more important than vehicle scale. Therefore, the committee believes that Pathfinder test data, together with the advanced CFD models, will yield much more realistic results than would be obtained from trying to realistically assess the dynamic loads generated in the rocketback RTLS maneuver using small models in a supersonic wind tunnel and certainly at much lower costs and risks than by immediately jumping into full-scale RBS or even mid-scale RBD vehicle flight testing.

AFRL has also stated[11] that the Pathfinder flight test series represented a critical "risk reduction step" prior to attempting the rocketback turn and RTLS maneuvers with a larger-scale vehicle. It said it believes that while Pathfinder is only an intermediate step, the test data generated during its flight testing will be representative enough to anchor and validate the CFD codes that will be used to design the full-scale vehicle. Since there are no flight test data for such maneuvers, it is somewhat speculative to assume that the Pathfinder flight results will turn out as predicted. The expected results of Pathfinder test flights will certainly serve as a strong go/no-go decision gate for proceeding to design and develop a larger flight demonstrator or operational vehicle and will support that design effort.

While the planned Pathfinder project will likely provide data to support the RTLS concept, it would provide little data to validate the RBS booster thermal protection system design because its maximum Mach number capability is limited. An alternative approach might be considered to collect critical aerothermal data from low-cost sounding rockets launched from sites such as White Sands and NASA Wallops Flight Facility. With this type of fight test, an instrumented Pathfinder-like model could be boosted into relevant Mach number and altitude regimes. Once separated from the launcher, this model could be either command controlled or programmed to execute maneuvers elucidating the RBS 180-degree maneuver. Such models have many options—for example, parachute recovery and/or data stored in onboard memories, and/or telemetered data to ground stations.

3.4 IVHM ARCHITECTURE

The committee considers that the incorporation of IVHM technologies into the RBS will be necessary to meet general operability objectives and reliability goals, but few details on specific IVMH implementation needs were presented to the committee. In the absence of specific operability requirements, it is difficult to identify the parameters to be measured during RBS flight and ground operations.[12] In the absence of this information, the committee assembled a tentative list of parameters to be measured in flight that might be important to a development program:

- Multiple engine temperatures,
- Structure temperatures,
- Selective vehicle skin temperatures,
- Strain loads throughout the structure and attachments,

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[10] D. Leggett, Air Force Research Laboratory, White Paper on the Pathfinder Program. Responses to Questions from the Committee for the Reusable Booster System: Review and Assessment, April 19, 2012. Available to the Public.

[11] D. Leggett, Air Force Research Laboratory, White Paper on the Pathfinder Program. Responses to Questions from the Committee for the Reusable Booster System: Review and Assessment, April 19, 2012. Available to the Public.

[12] Background information on IVHM developed for the Kistler K-1 vehicle may be found in G.E. Mueller, D. Kohrs, R. Bailey, and G. Lai, Autonomous safety and reliability features of the K-1 avionics system, *Acta Astronautica* 54(5):363-370, 2004.

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- Accelerometers (distributed),
- Flow rates (LO_2/RP-1),
- Chamber pressure (MCC and preburner),
- Propellant levels in tanks,
- Pressure drop across injectors,
- Turbine speeds,
- Turbine dynamics,
- Pumps: inlet and discharge,
- Boost pump dynamics,
- Valve positions,
- Specific on/off valve positions, throttle valve feedback,
- Potentiometric measurements for all actuators,
- Dynamic element feedback (close loop on internal commands), and
- Valve electrical currents.

Many of the parameters listed above are relatively straightforward to measure and integrate into an IVHM system if they are introduced early in the engine or vehicle development process. One big challenge in the development of an IVHM system for the baseline RBS concept concerns the application of critical diagnostic systems to the AJ-26, an existing engine that can tolerate only limited modifications.

In addition, parameters need to be measured during ground processing to allow assessment of vehicle integrity and readiness for flight, including the need to determine leakage in ducts, seals, valves, and the like; the potential for fatigue and other structural defects; an assessment of life remaining before next maintenance; functional checks of electrical continuity and response to actuation commands; and verification of sensor operation. These measurements, together with properly detailed nondestructive evaluation, will need to incorporate state-of-the-art inspection and evaluation techniques.

3.5 ADAPTIVE GUIDANCE AND CONTROL FOR REUSABLE BOOSTER SYSTEMS

This entire section is taken directly from the AFRL paper “Adaptive Guidance and Control for Reusable Booster Systems.”[13]

> The reliability of today’s first-stage, expendable boosters is known to be approximately 97%, while the required system reliability goal for the future RBS is stated as 99.98%.Currently, expensive and time-consuming mission assurance tasks, such as hardware simulations and software verification, must be performed prior to each launch of expendable boosters to elevate the reliability to the 99% goal.
>
> Adaptive, Guidance and Control technology has been identified by the Air Force Space Command as a critical technology that can significantly increase the reliability and responsiveness of future launch vehicles, including RBS. The objective of an AG&C algorithm is to enable the RBS to track its nominal trajectory under off-nominal conditions, or compute an alternate, but flyable, trajectory under severe cases of off-nominal conditions. Off-nominal conditions might be caused by a failure (or failures) in its subsystems: control effector subsystem (e.g., stuck aileron), propulsion subsystem (e.g., loss of thrust in one engine), or thermal protection subsystem (e.g., lower allowable heating limits). Table [3.6] below shows the subsystem failures between 1980-1999 for different countries’ launch vehicles.[14]
>
> Given that the propulsion and avionics subsystems caused the failure 66% of the time, an AG&C algorithm designed to overcome those failure modes will likely improve the overall vehicle reliability. Results of an analysis conducted by Hansen illustrate how an adaptive action can potentially save the Reusable Launch Vehicle (RLV) from different subsystem failures.[15] The results are shown in Table [3.7].

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[13] A. Ngo, Air Force Research Laboratory, Control Systems Development and Applications Branch, “Adaptive Guidance and Control for Reusable Booster Systems,” submitted to the committee, May 7, 2012.

[14] I. Chang, “Space Launch Vehicle Reliability,” *Crosslink,* Winter 2001, available at http://www.aerospace.org/publications/crosslink-magazine/previous-issues/.

[15] J.M. Hansen, “New Guidance For New Launchers,” *Aerospace America,* March 2003.

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TABLE 3.6 Launch Vehicle Subsystem Failures, 1980-1999

Country	Propulsion	Avionics	Separation	Electrical	Structural	Other	Unknown	Total
U.S.	15	4	8	1	1	1		30
CIS/USSR	33	3	2			1	19	58
Europe								
China	3	1			2			6
Japan	2	1						3
India	1	1	1	1		1		5
Israel	1							1
Brazil	2							2
N. Korea							1	1
Total	64	11	11	2	3	3	20	114

SOURCE: I-Shih Chang, Space launch vehicle reliability, Crosslink, Winter 2000/2001, pp. 23-32, available at http://www.aero.org/publications/crosslink/winter2001/03.html. Table reprinted with permission of The Aerospace Corporation.

TABLE 3.7 Launch Failures and Potential Adaptive Actions to Address Similar Failures in Future Reusable Launch Vehicles (RLVs)

Date	Vehicle	Reason for Failure	Action to Save RLV with Equivalent Failure
June 27, 1994	Pegasus XL	Poor aerodynamic data	Adapt to data to maintain control
October 20, 1998	Ariane 5	Shutdown due to engine roll torque	Abort landing trajectory targeted or abort deorbit and landing
May 5, 1999	Delta III	Engine failure	Abort landing trajectory targeted
March 12, 2000	Zenit 3SL	Second stage shutdown	Abort landing trajectory targeted
July 12, 2001	Ariane 5	Combustion instability	Abort landing trajectory targeted
September 21, 2001	Taurus	Seized actuator	Abort landing trajectory targeted

SOURCE: J.M. Hanson, New guidance for new launchers, *Aerospace America,* March 11, 2003.

The fault-tolerance of the AG&C algorithm stems from its inherent ability to accommodate wide ranges of the launch vehicle's dynamics and constraints. These variations arise from the vehicle's subsystem failures during flight. The AG&C technology enhances the responsiveness of the RBS by reducing the time needed for contingency planning such as abort trajectory design and simulation during the mission planning phase of the launch preparation.

In general, an AG&C algorithm consists of three components: Trajectory Generation, Adaptive Guidance, and Reconfigurable Control. A diagram of the AG&C components and their interactions to the vehicle's Onboard Diagnostics and Operations Control Center are shown in Figure [3.3].

In the Reconfigurable Control System block, an allocation algorithm distributes stabilizing commands to the working control effector (such as TVC actuators, engine throttling, RCS thrusters, ailerons, rudders, and elevators). The stabilizing commands are computed according to the required forces and moments to maintain the stability of the vehicle. In the event of an off-nominal condition, such as a control effector frozen in place, the Onboard Diagnostics detects and provides the failure information to the Reconfigurable Control System algorithm which in turn adjusts its distribution of commands to the remaining control effectors. Vehicle constraints and/or limiters on angular rates, accelerations, loads, angle of attack, and landing are also considered by the Reconfigurable Control System algorithm.

In the Adaptive Guidance System block, the vehicle's flight path stability is maintained under both nominal and off-nominal conditions. Feedback gains are adjusted according to the inner-loop to control performance as well as the vehicle dynamics.

In the Trajectory Command Generation block, a new trajectory for the vehicle is generated when necessary so that the trajectory requires only forces and moments that can be achieved by the degraded capabilities of the vehicle while meeting critical constraints. An alternate landing site along with the aerospace constraints from the range system are provided to the Trajectory Command Generation block through the Operations Control Center. Besides interacting with the AG&C blocks, the Operations Control Center also communicates with Test Range network to receive the real-time updates of the ground and air constraints.

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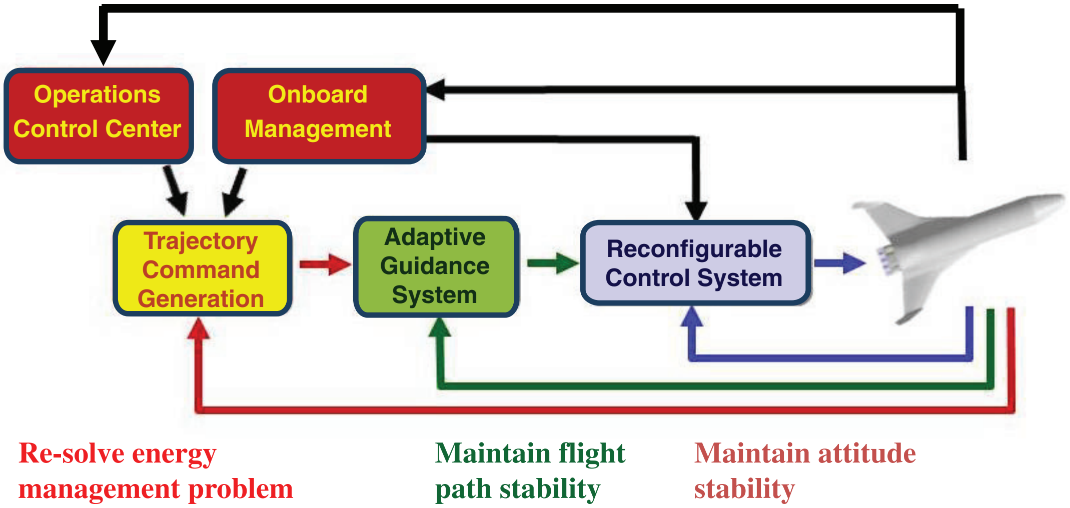

FIGURE 3.3 Major adaptive guidance and control elements. SOURCE: A. Ngo, Air Force Research Laboratory, Control Systems Development and Applications Branch, “Adaptive Guidance and Control for Reusable Booster Systems,” submitted to the committee, May 7, 2012.

The AG&C technology is targeted at an autonomous first-stage RBS that provides operationally responsive and reliable access to space. The integrated AG&C and Onboard Diagnostics facilitates these goals by allowing the autonomous RBS to detect and recover from degradation or full functional failure of control effectors, RCS thrusters, propulsion engines, and thrust vectoring gimbals without outside intervention, just as a skilled pilot can recover from failures in an airplane.

As discussed earlier, the RBS follows a novel return-to-launch-site (RTLS) trajectory. The AG&C system controls the vehicle throughout this mission, providing commands to aerodynamic control surfaces, reaction control thrusters, propulsion throttles, and thrust vectoring gimbals. Health management monitors the effectors and sends information that quantifies the capability of each effector to respond to commands. In the event of a failure, the AG&C system uses this information to reallocate control to the remaining effectors, calculate changes to the vehicle envelope, and to autonomously compute a new trajectory, if necessary.

The net effect of the AG&C technology is a significant increase in the reliability of the launch system. AG&C allows the booster to recover both from anticipated failures such as engine out and a wide range of unanticipated failures from which the robust control system can recover. Using these technologies, attaining a 99.98% reliable boost system appears feasible.

Technical challenges for the AG&C technology stem from the fact that the algorithm must perform its computations in real-time in the event of a failure(s). Two principal challenges deal with the computational requirements and convergence guarantees associated with the AG&C algorithms. Computational requirements are driven by the need for trajectory generation, which involves optimization methods that are usually quite computationally intensive and can stress real-time system capabilities. Convergence guarantees are associated with the generation of viable solutions to the trajectory optimization. Currently, this often requires involvement by the designer or engineer through trial and error, which is not practical for real-time systems operating in a dynamically changing environment. In recent years, considerable progress has been made in software development, efficiency, simulation, verification, validation, and hardware testing and these techniques can be applied to meet the above technical challenges.

AFRL has been developing the AG&C technology for over a decade for a wide range of next generation applications. Successful demonstration of AG&C algorithms during the approach-and-landing phase of flight has been performed using conventional test aircraft. For the reentry phase of flight, hardware-in-the-loop testing to examine the real time execution of the algorithm has been performed by Honeywell under contract with AFRL. Concurrent with the RBS Pathfinder flight demonstration program, AFRL is executing contracts with Honeywell to integrate, simulate and hardware-test the AG&C algorithms using high-fidelity simulations for all flight phases. This contract will use the Pathfinder and RBS flight dynamic models as they are developed to perform incremental testing: model-in-the-loop, hardware-in-the-loop, and potentially flight tests on the Pathfinder vehicle.

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3.6 SECONDARY RISK AREAS

A number of additional technology risk areas were considered by the committee and are discussed in the subsections below. These areas are considered by the committee to pose less risk than the four principal technology risk areas, but addressing each of them during an RBS development program is recommended.

3.6.1 Structures

The sizing of an RBS system is sensitive to the inert mass fraction of both the reusable booster and the expendable upper stage. Thus, the structures of both stages will need to be efficient, yet sufficiently robust to carry the applied loads. There are 12 main factors to be considered in assessing the RBS structural design:

- The specific material of construction for each element of the RBS.
- The external environments that are anticipated to be imposed on the vehicle during all phases of the flight, including ignition, liftoff, abort, maximum angle of attack and dynamic pressure, staging, the rocketback maneuver, glide aerodynamic loads, and ground handling.
- The loads imposed on the payload by vehicle at liftoff; during the complete flight profile; at and during staging and any other known events (i.e., vibration, shock, and acoustic energy impact on the integrated payload); at payload injection into its initial transfer orbit; and upon landing.
- Manufacturing and assembly techniques that impact material selection and production methods (welding, brazing, and the like).
- Nondestructive inspection and evaluation methods, especially between flights, for a rapid-turnaround, reusable vehicle.
- Structural and material fatigue assessments and structure/component life remaining before scheduled maintenance operations, repair, and replacement (initial determination prior to liftoff and state of health). This is especially critical for reusable engines, tanks, and turbomachinery.
- Mass properties—weight, center of gravity, center of pressure, moments of inertia, and management of mass property balance (static and dynamic) during the complete flight profile.
- Structural release attachment and mechanisms.
- Attachment loads associated with launch stand support before and during liftoff.
- Low-level, long-duration ground, sea, and air loads resulting from transporting/shipping the RBS vehicle to and from the launch site and the manufacturer's depot for rework, maintenance, and R&R.
- Impact loads/stresses from all aspects of the staging event and associated maneuvers and landing, both loaded and unloaded.
- Structural impacts of loads generated in flight by the RBS highly asymmetric configuration.

The baseline materials selected for RBS structures and tanks are currently all metal, probably either the best strength-to-weight aluminum and/or titanium alloys; however, the ever-increasing pressure to increase the propellant mass fraction may drive the consideration of composite materials for the RBS airframe structure and maybe even the tanks, where metal-lined composites may be attractive. Common bulkhead tanks (CBTs) are likely to be considered as development proceeds and weight savings are needed despite the inherent risks of a CBT and the associated operational difficulties of a CBT.

As discussed in Section 2.1, the Air Force described two variations of the proposed expendable upper stage for the RBS. One will be for small- to medium-size payloads and will be called the small expendable stage (SES) and the other will be for the heavier payloads and will be called the large expendable stage (LES). Both the SES and the LES will likely be mounted to the first stage by four structural hold down and redundant release attachment mechanisms. Depending on the specific upper stage employed, the separation event will initially impose loads on the booster primarily caused by shock, although likely to have some aerodynamic flutter content as well. A collision avoidance maneuver may be needed when either the SES or the LES separates from the booster.

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When the dynamic pressure and aerodynamic loads are sufficiently reduced during upper-stage ascent, the payload fairing will be released and jettisoned. The environmental loads generated by this event will have to be accommodated but they will probably pose no unusual material or structural technology risk. The only risk that might be encountered would be one from some new requirement to save launch weight by introducing new and lighter materials, which could challenge the structural design and the design of the release mechanism.

From a structural design standpoint, the RBS LES, except for the attachment and release geometry and mechanisms, will likely be very similar to the upper stages now in use with EELVs. The propellant tanks will have to accommodate loads from the nonlinear attachment and subsequent separation; however, the loads analysis and analytical models should be readily adaptable from experience with the space shuttle's unique geometry and the Delta IV Heavy side-mounted liquid boosters.

If a decision is made to use lightweight composite tanks, there will be additional technical risks having to do with the lightweight composites used to contain cryogenic propellants. There is still significant concern over the very negative experience with NASA's X-33 cryogenic composite tanks. The TRL for using these composite materials with cryogens is still low, and much more technology development would be required. There is also the very important question of how to best mount large composite tanks on the vehicle's primary structure and what type of fasteners or bonding techniques to use. The answer will depend heavily on the materials of construction and the design approaches. Then too, there is always the question of designing for distribution of flight loads. Should the loads be distributed through the tanks or around them or in some load-sharing combination? How will the design best be accomplished? Other design solutions such as engine structural mounts and thrust load accommodation are likely to be readily extractible from standard analytical techniques and past launch vehicle flight experiences.

An additional complicating factor for the reusable booster is that RTLS maneuver functions require additional hardware elements (wings, control surfaces, landing gear, and so on) that cause the RBS to suffer appreciable intrinsic mass penalties compared to conventional expendable boosters. The basic rocket equation,

$$\Delta V = I_{sp}\, g \ln[1 / (1 - \eta)]$$

where η is the mass fraction (the ratio of the fuel mass to the total mass), shows us that for a given ΔV capability, significant reductions in RBS mass require significant improvements in specific impulse or total-system mass fraction (fuel mass/total RBS mass). For ORSC LO_2/HC engines, specific impulse gains greater than approximately 10 percent are unlikely. However, the hardware elements needed for the RTLS maneuver invite both invention and the consideration of new materials. For example, Elias, in his presentation to the committee,[16] projected significant potential gains in structural material strength-to-weight ratio based on nanomaterial technologies such as large-scale nanotube structures. He stressed that the mass reductions stemming from such new materials are necessary for RBS-type systems to be cost competitive with next-generation expendable systems, especially in the emerging commercial arena. While large-scale nanotube structures are unlikely in the near future, significant reductions may be achieved by incorporating new fiber composite materials for the load-bearing structures.

While challenges exist in meeting inert mass fraction requirements for RBS, many of the structural design concerns about the best selection of construction materials should be readily resolved following flight testing of the subscale Pathfinder and the much lower cost RBD flight test vehicles. Thus, the principal technology risks for achieving the needed inert mass fraction of the RBS structure are associated with the structural materials and process selection and the accurate determination of the structural loads. Obtaining accurate flight profile aerodynamic, aerothermodynamic, and other environmental loads from subscale tests to enable validated and accurate CFD loads for design of the full-scale RBS is therefore essential.

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[16] A. Elias, Orbital Sciences Corporation, "Orbital Sciences Corporation Opinions on Launch vehicle Reusability," presentation to the Committee for the Reusable Booster System: Review and Assessment, March 28, 2012. Approved for Public Release.

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3.6.2 Power, Fluid Thermal, and Actuation R&D

While not considered a major technical risk, the RBS still must have its own power source during the full flight profile. Once the ground power umbilical disconnect separates from the booster at liftoff, the RBS will need a power source that is either accessible and replaceable or some type of rechargeable/regenerative power supply. There are four technically mature candidates to perform this function:

- *Primary thermal batteries.* These batteries are inexpensive, reliable and easy to activate, but relative to other power source listed here are heavy and will have to be replaced after every flight and mission abort.
- *Chemical energy to power an Auxiliary Power Unit (APU).* APUs have a long history of success on aircraft, Space Shuttle, etc., but their operations can be complicated and the APU expendables must be replenished after each flight.
- *Fuel cells.* Fuel cells offer higher efficiency with a compact footprint, but they are expensive, safety concerns remain, and they require recharging of expendables after each flight.
- *Rechargeable/reusable batteries.* Li-ion, NiMH, and other such batteries generally have a long life with proven high reliability and low maintenance without additional expendables, but they are expensive and require a readily available power source for recharging and regular conditioning.

The selection of the appropriate internal power source will be decided by selection of the optimum approach for meeting the concept of operations, reliability, and performance criteria. If RBS operability, including fast ground turnaround and responsiveness, are an Air Force requirement, rechargeable/reusable batteries for the short-duration booster flight are likely the best choice.

3.6.3 Assembly and Manufacturing

Modern capabilities for manufacturing and assembly of all types of vehicles throughout the world have greatly advanced in recent times. Incorporation of fully automated and robotic operations has greatly increased productivity for airplanes, automobiles, ships, mobile tool systems (e.g., tractors, lawn mowers, and the like) and even for the few expendable rockets being produced in the United States—Delta IV, Atlas V, and Falcon 9. The successful use of these advanced manufacturing methods for almost all modern vehicles has improved productivity and decreased cost and production time. The benefits of all the advanced, automated methods now in use have been widely recognized and are being employed by an increasing number of manufacturing companies the world over.

The current EELVs have adopted friction stir welding in the manufacture of their aluminum propellant tanks and adapters. This automated process generates less heat than conventional welding processes, results in a smaller heat-affected zone with its attendant poorer mechanical properties, and eliminates most defects and the need for weld repairs. If the RBS propellant tanks are made of aluminum, friction stir welding should be explored as the primary metal joining method.

The RBS baseline plan, while only planning to manufacture eight complete flight vehicles, may have real potential for cost savings using modern manufacturing technology approaches. In addition, it may be prudent to build these vehicles over a stretched-out span to permit incorporation of improvements as vehicles are built and to have an ongoing manufacturing capability if replacement boosters are needed. While a highly automated plant for booster manufacturing may initially be more expensive than the conventional option, it better accommodates personnel turnover and improves manufacturing quality. The ongoing production of upper stages and payload fairings for RBS can clearly benefit from a highly automated, modern manufacturing facility.

Accordingly, the committee believes that even with the initial requirement for only eight flight vehicles, producing the vehicles using the most modern, automated manufacturing and assembly methods would likely provide high payoffs. This approach will unquestionably improve the probability of meeting the stated RBS LCC goals, even including the high initial capital investment required to implement these advanced highly automated modern techniques.

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Over the years the major space providers have been evolving their satellite and launch vehicle capabilities, incorporating new technology into existing designs. By way of contrast, other providers, such as Iridium and SpaceX have performed clean-sheet exercises by combining the use of state-of-the-art materials and state-of-the-art manufacturing techniques in their product lines to help reduce costs and increase reliability. Clean-sheet exercises, when done effectively, allow for incorporation of a holistic vision of the end-use system into the early concept design. Additionally, simplification concepts such as standardization and modularization as well as early systems engineering to incorporate IVHM diagnostic sensor systems can be designed into the system from the beginning and validated during testing. The manufacturing process can also be designed to run in parallel with the postflight maintenance and servicing.

3.6.4 Upper-Stage Development

The RBS high-performance expendable second stage will need to be developed to be operationally compatible with the newly developed reusable first stage in a manner that would allow meeting overall mission goals as described by the Air Force. The baseline second stage uses LO_2/LH_2 propellants owing to the inherent need for very high performance upper stages for heavy payload orbit injection (as was the case, for instance, for the Saturn S-IVB, the Delta IV, and the Centaur upper stage on Atlas I, II, III, and V). The need for high performance in the second-stage engine is especially true for the RBS concept, where the staging velocity is very low compared to an optimized expendable system. With the large ΔV requirement for the RBS second-stage, the projected overall launch mass of the RBS system would need to be much larger if a high-performance LO_2/LH_2 engine was not used.

The Air Force baseline approach for this high-performance upper-stage engine is to use the existing, flight-proven RD-25E—that is, the nonreusable version of the SSME that is being developed by NASA. Backup options for a high-performance upper-stage engine (such as the Russian-produced RD-0120) are also potentially available. Given this baseline approach and the potential availability of alternatives, the committee believes that development of the RBS upper-stage engine does not pose a significant technology risk. However, for the range of payloads initially described in the Air Force RBS launch model, the upper stage will be quite large and will require large, lightweight cryogenic propellant tanks. The chosen materials (metal or composites) may introduce additional technology risks. Tank technology concerns as well as questions of propellant management and the possible benefits of CBTs for LO_2 and LH_2 to save mass are discussed elsewhere in this report.

AFRL has been developing improved analytical prediction techniques for application to upper- stage engines in its Upper Stage Engine Technology program. In addition, the Air Force is now supporting an advanced upper-stage engine technology development program, the Affordable Upper Stage Engine Program, which is developing the technology base for a new high-performance, higher-thrust-level LO_2/LH_2 engine to ultimately replace the RL-10 family, which has been around and slowly evolving since 1962. Other than the J-2 engine used on Saturn's upper stages and the SSME, the RL-10 and its various derivatives have served as the only high-performance, upper-stage engine for most U.S. launch vehicles (Delta IV, all Atlas/Centaur versions, and some Titan missions with a Centaur upper stage).

In addition to the baseline engine options of the RS-25E or RD-0120, AFRL has the option to develop a new scaled-up version (much higher thrust level) of an RL-10 class (high performance expendable) LH_2/LO_2 engine if neither the RS-25E or RD-0120 engines are available or suitable for the RBS upper stage. However, if a new upper-stage high-performance LH_2/LO_2 engine needed to be developed for any reason, this would add significant cost to the RBS development program, which was not briefed to the committee by any Air Force, Aerospace Corporation, or contractor presentations (or by any other entity).

3.7 OPERATIONS AND INFRASTRUCTURE

The baseline RBS development plan includes three launch sites: two at Cape Canaveral Air Force Station (CCAFS) in Florida and one at Vandenberg Air Force Base (VAFB) in California. The first RBS launch complex will be all new and built at CCAFS and will accommodate the RBS-Y full scale development vehicle. It will initially operate in parallel with the current CCAFS EELV launch sites. Once the Atlas component of the EELV program

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is phased out, Atlas pads can be converted to accommodate the RBS, and the initial RBS-Y pad at CCAFS could also be used for RBS. There will be many design decisions at RBS facilities to manage cost but few technology decisions. Most operability enhancements envisioned for RBS infrastructure are being used or are currently in development for existing launch vehicles or other processing/manufacturing applications. In the opinion of the committee, the RBS facilities will face a design and cost control challenge but probably not be a significant technology development challenge.

Applicability of existing EELV infrastructure to RBS will be somewhat limited because the RBS booster is so large, especially its wing and vertical tails and its LES. Table 3.8 compares the medium-lift RBS with the Atlas V-551 EELV compiled from data provided by the Air Force, the Aerospace Corporation, United Launch Alliance, and contractors, whose representatives briefed the committee. This comparison can be used to identify which current Atlas infrastructure may be applicable for RBS use. Some existing Atlas EELV horizontal processing facilities may be usable as is or with reasonable modification. Existing launch control centers can probably be used for RBS with upgraded equipment. EELV vertical processing and some launchpad facilities may require major rework if the winged RBS booster with a piggyback-mounted LES will not fit. However, it still makes economic sense to modify current launchpad facilities to avoid lengthy environmental approvals for new sites and to take advantage of existing exhaust ducts, vehicle transportation equipment, propellant storage and transfer systems, fiber-optic communications, and payload air conditioning capabilities.

Processing operations at the launch sites will most likely be based on current EELV practices, since the RBS manifest for the Air Force is “launch on schedule.” Payload and expendable upper stage operations will follow current practices with enhanced automation, while those for the reusable booster will need to be modified to accom-

TABLE 3.8 Comparison of Reusable Booster System (RBS) (medium lift) and Atlas V-551 Evolved Expendable Launch Vehicle

	RBS (approx.)	Atlas V-551
Booster		
Diameter, Length (ft)	17, 110	12.5, 106.5
Inert and Propellant Weight (klb)	105, 900	41.7, 626.3
Number of Engine(s); Thrust (klbf)	5 AJ-26; 1,655	1 RD-180 = 860
Wing, Tail Span (ft)	60, 36	
Solid Rocket Booster		
Diameter, Length (ft)		5.2, 65.5
Number of SRBs, Weight (klb)		5, 514.7
Number of SRBs, Thrust (klb)		5, 1897.8
Second Stage		
Diameter, Length (ft)	16, 130	10, 41.6
Inert, Propellant Weight (klb)	38, 340	4.9, 45.9
Number of Engines; Thrust (klbf)	1 RS-25E; 500	1 RL-10; 22.3
Interstage Adapter		
Diameter, Length (ft)		12.6, 13.6
Weight (klb)		8.8
Payload Fairing		
Diameter, Length (ft)	18, 77	17.8, 76.8
Weight (klb)	9	8.8
Spacecraft (to low Earth orbit)		
Weight (klb)	50	41.5
Total Dry Weight (klb)	200	626
Gross Lift-off Weight (klb)	1,340	1,298
Total Sea Level Thrust (klbf)	1,655	2,548
Stack Height (ft)	180	225
Booster Diameter (ft)	17	24

NOTE: The RBS data is approximate and conservative, to be used for comparative purposes only. SRB, solid rocket booster.

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modate landing, "safing" of the vehicle (making it safe for ground crews to carry out needed handling activities) and turnaround for relaunch. The following subsections are arranged to reflect a launch system nominal (historical) processing flow, with RBS influences and deviations noted.

RBS operations may require changes to existing infrastructure and launch procedures. A review of the current practices and discussion of potential RBS impacts follows.

3.7.1 Range Safety

Current practice for an established launch vehicle requires submittal of a preliminary flight data package to Range Safety at L–60 days and a final data package at L–30 days. For each upcoming unmanned vehicle launch, the Range reviews the nominal planned vehicle trajectory and establishes limit lines. If the actual flight trajectory exceeds those limits, the Range Safety Officer destroys the vehicle. RBS use of AG&C may allow these limits to be relaxed to account for RBS's ability to respond automatically to off-nominal conditions and still perform its mission. Range tracking must be performed by two independent sources.

The RBS will interact with the Range Safety and the Airspace Control systems during both launch and return. In neither regime is it likely that the booster will present new challenges, even to the Range Safety systems in place today, which are certain to evolve between now and when an RBS system would fly.

From the perspective of Range Safety, there is no significant difference between an uncrewed reusable system and an expendable booster. The same requirements for information about location, velocity, direction, and booster status, and need for a flight termination system will apply. Flight termination systems are well understood, and the RBS would present no new challenges.

The Federal Aviation Administration Office of Commercial Space Transportation (FAA/AST) is facing the challenge of handling uncrewed vehicles in the airspace today, and the committee believes that the challenges to doing so will be resolved long before the RBS is flying. FAA/AST has limited experience in supporting a crewed vehicle returning from space to a landing in the United States, but that experience will grow substantially over the next decade. The experience with autonomous entry into the airspace and landing is far more limited today (e.g., the X-37B). However, the ability to manage this kind of operation has been demonstrated and will likely not present any major barriers to RBS operations.

The various test and demonstration vehicles involved with the RBS, e.g., the Pathfinder, demonstrator and Y-vehicles, will probably be flown on traditional ranges. The Range Safety and Airspace Management requirements must be addressed during these phases of the program or alternatives found to the operational ranges.

Finally, the launch range will now have to support operations associated with the booster's return to the launch base airstrip for landing. These operations are expected to be further complicated for the RBS Heavy with two returning boosters. Their return has to be staggered to permit sequential landing/exit from the runway. The Eastern Range has dealt with the space shuttle orbiter's return for landing, and similar considerations apply for RBS. The orbiter returns with some residual Orbital Maneuvering System propellants, and the RBS booster will have remaining LO_2/RP-1 and attitude control system (ACS) propellants. These must be off-loaded and the propellant systems made safe prior to towing the booster(s) to a ground maintenance facility.

3.7.2 Launch Readiness Reviews

Current expendable launch vehicles are subjected to a number of readiness reviews starting several weeks prior to launch. This process has been institutionalized over the past 60 years and with slight differences, is practiced by all government agencies and current launch system providers. The reviews are held with the launch service provider's management, payload provider, launch customer, Range Safety, launch base management, and the engineering tiger team. To achieve responsive launch with RBS, this process will need to be significantly revised and shortened while maintaining launch system reliability. A major cultural change by all participants in the prelaunch process will be required to accomplish a more streamlined and less costly review process.

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3.7.3 Spacecraft Processing

Current facilities at CCAFS and VAFB are suitable for RBS payload processing and fairing encapsulation. At CCAFS these include the Astrotech commercial processing facility, the Air Force defense satellite communications system processing facility (4-m diameter only) and shuttle payload integration facility; and the NASA vertical processing facility, spacecraft assembly and encapsulation facility, multipayload processing facility (4-m diameter only), and payload hazardous processing facility. These facilities support spacecraft storage, preparation, propellant loading, solid rocket motor and ordnance preparations, dynamic balancing, adapter mate and encapsulation. The VAFB facilities include the Astrotech Payload processing facility and the Space Systems International integrated processing facility, which provide these same services. The facilities are all capable of processing the large 4- and 5-m diameter fairings currently used on the Atlas V and Delta IV EELVs. Transporters exist to move the encapsulated spacecraft to their launch sites. In the United States, large spacecraft processing, encapsulation, and transport has historically been performed vertically. Upon arrival at the launch complex, the encapsulated spacecraft is mated vertically to the stacked vehicle upper stage. Horizontal spacecraft processing is also feasible, and could be used in RBS processing, as demonstrated by the Russians on Soyuz, Proton, and Zenit, and by the United States on the Orbital Pegasus and SpaceX Falcon-9 vehicles.

3.7.4 Launch Vehicle Processing Options

The current EELVs are processed using three different scenarios. Understanding these scenarios and their associated infrastructure requirements will be helpful when discussing potential RBS processing and facility requirements. EELV processing and infrastructure information was obtained from United Launch Alliance, the manufacturers of Atlas and Delta IV.

- *Atlas V at CCAFS.* For relatively frequent launches, it is efficient to integrate and check out as much of the vehicle as possible away from the launch pad. This approach is used for Atlas V at CCAFS. After vertical integration on a mobile launch platform (MLP) and checkout in the vertical integration facility (VIF), the launch vehicle, minus its payload, is transported vertically on the MLP to a clean pad and placed over the exhaust duct. The vehicle is tanked and a wet dress rehearsal (WDR) is performed. The vehicle is then moved back to the VIF on its MLP for integration of the encapsulated spacecraft and then transported back to the pad for launch. Higher launch rates off the single pad could be accommodated by constructing a second VIF and MLP.
- *Atlas V at VAFB.* Because of infrequent launch requirements at VAFB, Atlas uses a conventional mobile service tower (MST), with vehicle integration occurring on the fixed launcher inside the MST. Vehicle stages are individually transported horizontally to the launch site, rotated to vertical, and stacked in their launch configuration with the MST hoist. WDR is performed and then the encapsulated spacecraft is transported to the launch site vertically and stacked onto the launch vehicle with the MST hoist. The MST is then pulled back for propellant loading, countdown, and launch.
- *Delta IV at CCAFS and VAFB.* Delta IV facilities integrate its booster(s) and upper stage in a horizontal integration facility at both CCAFS and VAFB. The horizontally integrated booster(s) and upper stage is then moved horizontally to the launch pad using a transporter/erector. Rotation onto the launch mount is accomplished with hydraulic pistons located in the concrete pad surface in front of the launch mount. A MST is used for access to the erected vehicle. The MST is rolled back to its launch position and a WDR is performed. Following WDR, the MST returns to its service position, and the encapsulated spacecraft is transported separately (vertically) and hoisted onto the stacked launch vehicle by the MST hoist. The MST is then pulled back for propellant loading, countdown, and launch.

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3.7.5 Booster and Upper Stage(s) Processing

Solid upper-stage processing is relatively insensitive to orientation for checkout, and existing infrastructure will be adequate. The current EELVs do initial checkout of their stages horizontally. For Atlas, the liquid core booster, solid rocket boosters (SRBs) and upper stage are checked out separately. In processing the Delta IV, vehicle checkout occurs after the booster(s) and upper stages are mated. Both the RBS solid and large expendable stages can be processed either vertically or horizontally, but because of the large booster and LES dimensions, the committee believes that separate horizontal processing will likely result in significantly lower facility cost. RBS booster and LES processing involves extensive electrical checkout of nonhazardous components, similar to that currently performed on EELVs. This automated computer-controlled checkout includes electrical continuity and isolation testing of all electrical harnesses and uses test squibs to validate all pyrotechnic events.

3.7.6 Booster/Upper Stage Integration and Checkout

For RBS at CCAFS, off-pad integration, either horizontally or vertically, would be very desirable for accommodating potential mission model growth and/or responsiveness requirements. At VAFB, unless there are major changes in RBS launch requirements such as increased responsiveness, either off- or on-pad integration should be acceptable. The extent to which current Atlas launch facilities at CCFS and VAFB must be modified for RBS will help determine which processing technique is most cost effective. However, it is likely that most of the existing major processing facilities for the Atlas (VIF at CCAFS and MST and SLC-3E launcher at VAFB) will require extensive modification or complete replacement. For a new launch complex, such as the initial RBD launch site at CCAFS, a trade-off of facility versus ground support equipment (GSE) requirements will be most cost effective. If maximum use of the current Atlas launch facilities is desirable, then different processing approaches may be implemented at space launch complex (SLC)-41 and SLC-3E. However, if identical off-pad processing is mandated at all three RBS launch sites, at the very least, the Atlas pad at VAFB will require major reconfiguration.

3.7.7 RBS Transport and Pad Installation

Mated booster(s) and upper stage(s) can be transported either horizontally or vertically from an integration/checkout facility to the launchpad. At SLC-41, the Atlas booster and Centaur upper stage are vertically integrated with the MLP in the VIF. The Atlas booster to MLP interface includes rise-off disconnects for all booster fluid and electrical services. The MLP has an umbilical mast for the Centaur and payload services. The MLP also includes autocouplers that mate to the GSE launch mount service connections. Since the Atlas V-551 dry weight is much greater than the RBS dry weight (see Table 3.8), the MLP that currently transports a fully assembled Atlas V-551 from the VIF to the pad can probably be used without major structural modification to transport the RBS. However, the existing MLP umbilical mast will have to be revised (removed or articulated) to accommodate the winged RBS booster, and MLP launch hold-down/release and rise-off umbilical interfaces will require modification, at the least.

EELV upper-stage services are provided via an umbilical mast, as are spacecraft services (air-conditioning, ground power, and communications). The piggyback mounting of the LES onto the RBS booster provides an opportunity to also use rise-off disconnects for LES services at the base of that stage and perhaps for some payload services routed through the upper stage. Accommodating spacecraft services adds weight to the upper stage but could eliminate the need for an umbilical mast.

3.7.8 Wet Dress Rehearsal

The wet dress rehearsal is accomplished with a complete launch vehicle but without the encapsulated payload installed. WDR includes tanking the vehicle and performing a complete vehicle countdown, stopping just short of engine start functions. Atlas RP-1 leak testing is accomplished following RP-1 loading by taking the propellant tank to liftoff pressure for 10 to 15 minutes. Cryogenic leakage checks are accomplished during WDR (and on

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launch day) by cycling the fill/drain valves and remotely monitoring the compartment temperatures and performing mass spectrometer analysis of compartment gas percentages using a hazardous materials gas detection system. All umbilicals remain connected.

WDR has been accomplished on liquid propellant launch vehicles prior to launch for the last 60 years. In the early days, a captive hot fire test was conducted in conjunction with WDRs. Except for one or two tests with new vehicles, captive hot fire testing on an operational launch pad has ceased since it is deemed high risk.

For RBS, the continuation of WDR as a regular prelaunch activity should be reevaluated. WDR is employed, especially on vehicles with cryogenic propellants, to check for component operability at low temperature and propellant leaks. The risk of finding these problems later, on launch day, is a launch delay. For Atlas at SLC-41, on-pad access does not exist (there is no MST), so depending on the problem, the MLP/launch vehicle may need to return to the VIF for corrective action. This 3- or 4-day span necessitates waiting for another range launch slot. RBS will need to be a robust design as compared to current expendable vehicles in order to meet the planned reductions in launch operation costs, so the need to perform routine WDRs may be significantly reduced. If an RBS booster is processed rapidly for its next mission, perhaps the previous launch can be considered a successful WDR for the booster. It is important to note that if WDR for RBS can be eliminated, then complete vehicle vertical integration in a VIF (booster, upper stage and encapsulated spacecraft) would be a very efficient processing technique.

Current Atlas launch site propellant storage capacity can be used for RBS but will need to be significantly expanded to accommodate the propellant requirements of the much larger RBS upper stage. Existing propellant transfer infrastructure can probably be used as is for RBS, except propellant loading time will be extended. Payload air conditioning capability is likely adequate without any modification, assuming EELV payload conditioning requirements remain unchanged for RBS.

3.7.9 Payload Integration

Following successful completion of Atlas WDR, the launch vehicle/MLP returns to the VIF for integration of the encapsulated payload. For Delta, the encapsulated payload is transported vertically to the launch pad and lifted by the MST crane to mate with the upper stage. If a complete vertically integrated launch vehicle with payload is transported to the pad, then additional on-pad checkout can be minimized. If the encapsulated spacecraft's integration occurs on-pad, then additional checkout is required there. After Atlas payload integration and checkout in the VIF, the complete vehicle stack is returned to the launch pad on the MLP.

3.7.10 Propellant Loading and Launch Countdown

This process is highly automated for the current EELVs. Automatic propellant loading is controlled by computers located at the launch pad. It is monitored by engineers in the remotely located Launch Control Center who have override capability if something goes wrong. Fully automated countdown is conducted by computers that sequence events and monitor data for out-of-tolerance conditions. Health and status data are also available via an automated system to responsible system engineers. These activities occur hands-off unless some anomaly is detected. Events can be halted at any time during the count. Fairly rapid countdown recycle is possible (depending on the problem) until the last few seconds before liftoff. Atlas currently has the tools with its automated data management system to make a sound launch decision within the 126 minutes of cryogenic tanking operations prior to the final 4 minutes to launch a safe and successful mission. The current launch control processes and facilities used for Atlas V and Delta EELVs at both CCAFS and VAFB could be adapted for RBS.

3.7.11 Exhaust Ducts and Acoustic Suppression System

Existing exhaust duct and acoustic suppression water system capacity at both SLC-41 and SLC-3E are likely to be adequate for RBS. Liftoff rocket exhaust mass flow is critical in exhaust duct and suppression system sizing. The mass flow is proportional to total engine thrust level and the propellants used. Both launch sites are designed

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to accommodate the Atlas V-551. The single booster RBS thrust level at liftoff is approximately 65 percent that for an Atlas V-551 with five ground ignited SRBs. In addition, the rocket exhaust area for an Atlas with five SRBs is two times larger than for RBS (see Table 3.8).

3.7.12 Flight Including Abort

Facility requirements are associated with telemetry and Range Safety tracking and, if necessary, command destruct. These requirements are likely to be similar to those currently available to EELVs.

3.7.13 Booster Landing and Safing

The unmanned booster returns to the launch base for landing at its air strip. Facility requirements will be similar to those used to monitor the space shuttle orbiter's return for landing, except without the concern for residual toxic and/or hypergolic reaction control system propellants. Guidance and navigation will be a fully automated onboard booster avionics function. Once the booster has safely landed, it must be towed to a protected or remote location for safing. The main LO_2 and RP-1 tanks will be drained of residuals and purged. This can be accomplished by providing horizontal tank sumps (preferred) or by rotating the booster to a vertical position. Main engines will be purged. ACS propellants must be off-loaded and tanks purged. An important operability goal is to avoid the use of hazardous or toxic RCS propellants that would require use of Self Contained Atmospheric Protection Ensemble suits. Any unused pyrotechnic devices must be safed.

3.7.14 Postflight Booster Checkout, Maintenance, and Storage

The booster is towed on its landing gear using a standard airliner tug from the airstrip to a hanger for routine ground turnaround checkout and maintenance. The booster's IVHM system will have captured any anomalies or out-of-tolerance conditions that occurred during flight and is used after landing to assess postflight vehicle health. This IVHM data will likely preclude the need for most of the technician-performed, hands-on checkout. These data identify specific maintenance requirements for returning the booster to flight readiness status. After mechanics and technicians complete required maintenance, vehicle IVHM, augmented as required by automated ground checkout equipment, will be used to validate turnaround booster maintenance. Some limited nondestructive evaluation of sensitive areas or components, such as inside the rocket engine nozzle, will also be required.

3.7.15 Booster Depot Maintenance

At the proposed depot maintenance interval of 10 flights or whenever a major anomaly occurs that cannot be handled during regular ground turnaround maintenance, the booster will be undergo depot-level maintenance. Items requiring removal and replacement, such as landing gear tires, will be determined by equipment improvement upgrades and component life qualification results. Booster postflight turnaround maintenance, depot maintenance, and storage are best accommodated in a common facility to minimize facility cost and eliminate transfer of the booster from one location to another.

3.8 SUMMARY OF RBS RISK ASSESSMENT AND MITIGATION EFFORTS

The development plan described in the presentations to the committee lacked the kind of details that would enable it to evaluate the technical merits, their creditably and risks, or even the accuracy of cost estimates. For example, other than achieving the top-level goals of demonstrating the rocketback maneuver at simulated staging

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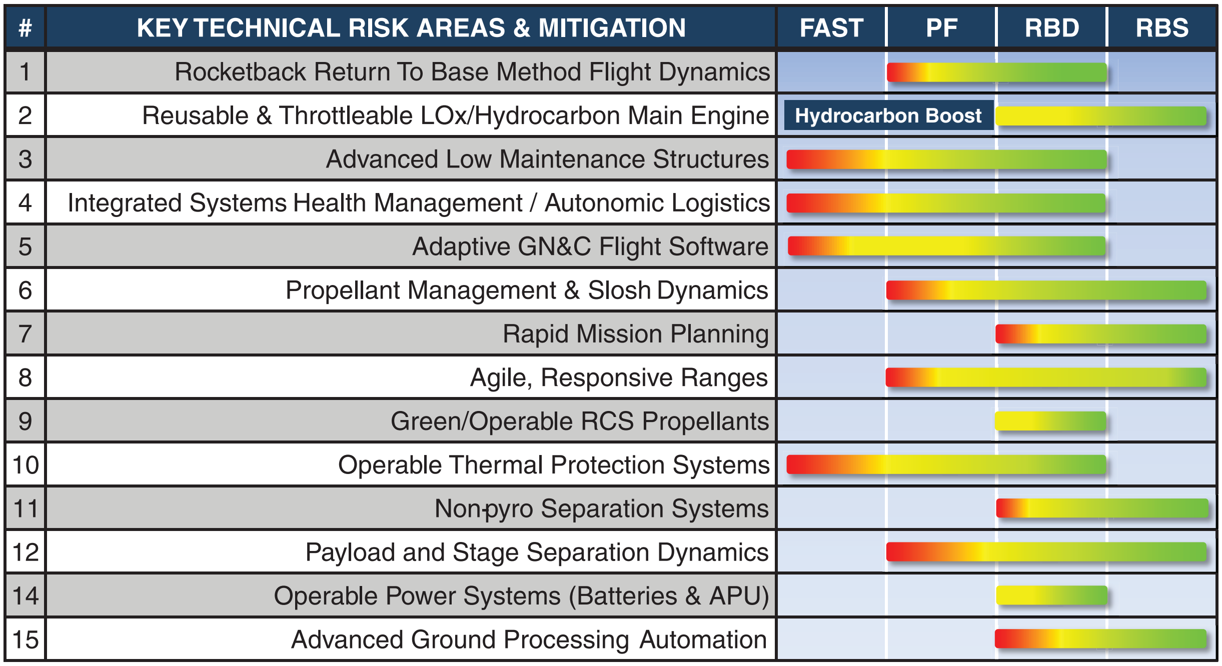

#	KEY TECHNICAL RISK AREAS & MITIGATION	FAST	PF	RBD	RBS
1	Rocketback Return To Base Method Flight Dynamics		▬	▬	
2	Reusable & Throttleable LOx/Hydrocarbon Main Engine	**Hydrocarbon Boost**		▬	▬
3	Advanced Low Maintenance Structures	▬	▬	▬	
4	Integrated Systems Health Management / Autonomic Logistics	▬	▬	▬	
5	Adaptive GN&C Flight Software	▬	▬	▬	
6	Propellant Management & Slosh Dynamics		▬	▬	▬
7	Rapid Mission Planning			▬	▬
8	Agile, Responsive Ranges		▬	▬	▬
9	Green/Operable RCS Propellants			▬	
10	Operable Thermal Protection Systems	▬	▬	▬	
11	Non-pyro Separation Systems			▬	▬
12	Payload and Stage Separation Dynamics		▬	▬	▬
14	Operable Power Systems (Batteries & APU)			▬	
15	Advanced Ground Processing Automation			▬	▬

FIGURE 3.4 Sample risk mitigation strategy. SOURCE: Slater Voorhees, Lockheed Martin Corporation, "Reusable Booster System (RBS)," presentation to the committee, March 28, 2012. Approved for Public Release.

conditions above Mach 3 and subsequent return to the launch site, it was not clear what else the Pathfinder demonstration would achieve. Also, there was no description or discussion of the Pathfinder MPS design. For example, is it intended to use one ORSC engine, such as the existing NK-33? Or, would it just use an existing, off-the-shelf, available open-cycle engine such as Fastrac[17] or a Falcon 1 Merlin? There was no discussion of which, if any, propulsion elements and associated information would be directly applicable to the RBS design.

The committee believes that developing a better definition of the goals and objectives of the Pathfinder program is important for two reasons. First, it is important to understand whether the cost is worth the investment. As stated above, there are important technical questions that can be answered in a Pathfinder program, but these questions will be answered only if the program is properly structured. Second, an understanding is needed of how the results of the Pathfinder program can be used to decide whether it is worthwhile to proceed to the next step, the RBD. So, decision gate criteria should be developed to enable a decision on what to do next after a successful Pathfinder demonstration.

The development of RBS capabilities will challenge many of the limits of state-of-the-art capabilities in such disciplines as propulsion, aerothermodynamics, controls, structures, health monitoring and sensing. The Air Force plans to develop the technologies needed to achieve the goals for the RBS program in phases. An example of a program that follows this approach is provided in Figure 3.4, taken from Lockheed Martin's presentation[18] to the committee. In the figure, the technology development is shown to occur under the following programs: the

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[17] Fastrac was a LO_2/RP-1 60,000 lbf gas-generator cycle engine that delivers a vacuum I_{sp} of approximately 280 s. It was developed by NASA Marshall Space Flight Center (MSFC) and intended for flight application on the X-34 program by Orbital Sciences, but the program was cancelled and the engine inventory was placed in storage at MSFC.

[18] S. Voorhees, Lockheed Martin, "Reusable Booster System (RBS)," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 28, 2012. Approved for Public Release.

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Future Responsive Access to Space Technologies (FAST), Pathfinder, the RBD, and RBS full-scale development. (Note that the AFRL-funded FAST program has been completed.) This phased technology development suggests that the maturation of the HCB, Advanced Low Maintenance Structures, IVHM, adaptive AG&C flight software and operable thermal protection systems, which was initiated under the FAST program and will need to continue under subsequent programs (e.g., Pathfinder, RBD, and RBS). The Pathfinder program will also initiate development of capabilities for executing the rocketback RTLS maneuver and for handling propellants management and slosh dynamics, agile responsive ranges and payload separation dynamics. The RBD program will continue the development of the above listed technologies and initiate development of capabilities for rapid mission planning, green/operable RCS propellants, operable power systems for batteries and APU, non-pyro separation, and advanced ground processing automation. The cost benefits of these technologies will be quantified during testing of the full-scale RBS Y-vehicles.

Attaining the goals of the RBS program critically depends on successful demonstration of the relatively large number of widely varying technologies and capabilities. However, it is often difficult to assess the challenges associated with overcoming certain technical barriers until these are studied and characterized over a period of time. Having said this, it seems at the outset that executing the RTLS rocketback maneuver without damaging the booster and ORSC engines will be critical to the success of this program because such a maneuver has never been demonstrated at the scale of the RBS. Executing the RTLS rocketback maneuver will be challenging because it will depend on developing capabilities for considerable hydrocarbon rocket thrust throttling, handling the sloshing and dynamics of the propellants, controlling complex aerodynamics that may involve interactions of the rocket exhaust plume with the system's aerodynamics, and providing adequate thermal protection.

Additionally, the attainment of "reusability," which is critical to achieving the expected cost savings, will require development of a reliable IVHM system. Such an IVHM system has to be capable of monitoring the health of critical components of the reusable part of the system. To be effective, the development of the IVHM would logically be undertaken in concert with the development of other system components such as the structure and the propulsion system. However, it is not clear at this point how this will be accomplished if the RBS is to employ legacy propulsion systems such as proposed with the use of the AJ-26.

Finally, development of an adaptive guidance and control system will be critical to the operation of the unmanned, autonomous reusable booster that will need to operate in a complex environment with inherent uncertainties in vehicle performance.

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4

Cost Assessment

The statement of task for this study (see Appendix A) requested that the committee address the methodologies used in the current cost estimates for a reusable booster system (RBS), including the modeling methodology used to frame the business case for an RBS. This chapter addresses the results of the committee's review and assessment of these issues.

The basic premise behind a new RBS for future space launch of Air Force space systems is that if such a reusable launch system, including all associated infrastructure and support services can be developed, flight-certified, and operated at an "affordable" cost (meaning substantially less costly than a present Evolved Expendable Launch Vehicle [EELV]), subsequent implementation of the new space launch system would bring a large reduction in space launch costs and, therefore, overall life cycle costs (LCC). As discussed in Chapter 2, the savings associated with use of an RBS for a national security payload manifest of 8 to 10 launches per year is estimated to be up to 50 percent of the current prices being paid by the Air Force for EELV services.

If an affordable RBS can be developed, these significant cost savings can be realized. This logical conclusion is supported using the cost history for fully developed EELVs—that is, recurring cost per launch. This cost history database includes the experience with the previous family of Air Force expendable launches—Delta II, Atlas II and III, Titan IV, Delta IV and Atlas V (the last two being part of the current EELV launcher family provided by United Launch Alliance). Review of the recurring cost histories of these launchers indicates that on average about 70 percent of the recurring costs arise from the expendable vehicle hardware that is "thrown away" during each launch.[1] The rest of the launch services cost consists of operations, engineering support, and management. The 70 percent hardware cost is a weighted approximation average for all expendable launch vehicles listed above. The hardware costs actually range from a low of about 55 percent (Titan IV) to a high of about 85 percent (Delta II). This strongly suggests that reuse of the first-stage flyback booster for an RBS for, say, 50 to 100 times, with a scheduled overhaul after 10 flights and engine replacement every 20 flights, could readily result in significant cost savings, maybe upwards of 50 percent as predicted by the Aerospace Corporation cost analysis.[2]

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[1] R.L. Sackheim, Overview of United States space propulsion technology and associated space transportation systems, *Journal of Propulsion and Power* 22(6):1315, 2006.

[2] Air Force Space and Missile Systems Center (AFSMC), "Reusable Booster System Costing, SMC Developmental Planning," presentation to the Committee for the Reusable Booster System: Review and Assessment, February 15, 2012. Approved for Public Release.

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The following subsections present the results of this assessment with the baseline cost modeling approach described and an assessment of the individual models, where possible. The chapter concludes with a discussion of the overall RBS business case.

4.1 BASELINE COST MODELING APPROACH AND ASSESSMENT OVERVIEW

The Air Force cost modeling approach uses a mixture of models and methodologies for estimating the various RBS elements. The configurations shown in Figure 4.1 represent the baseline flight vehicle designs examined by the committee. These include the reusable booster demonstrator (RBD) to be used to demonstrate and validate various aspects of the reusable booster design and operation as well as the RBS, which includes a heavy-lift variant to support larger payloads. The costs associated with the Air Force Research Laboratory's (AFRL's) funding of technology development efforts, including the Pathfinder small-scale demonstrator, are not included in the baseline costing, but they are relatively small.

The committee considered a number of scenarios for RBS system development. Four of them formed the basis for the analysis:

- *Scenario 1*: *Baseline.* The EELV program is assumed to end in 2031, and RBS development occurs in a time frame that would support the entire launch manifest. RBS development includes the mid-scale RBS demonstrator and

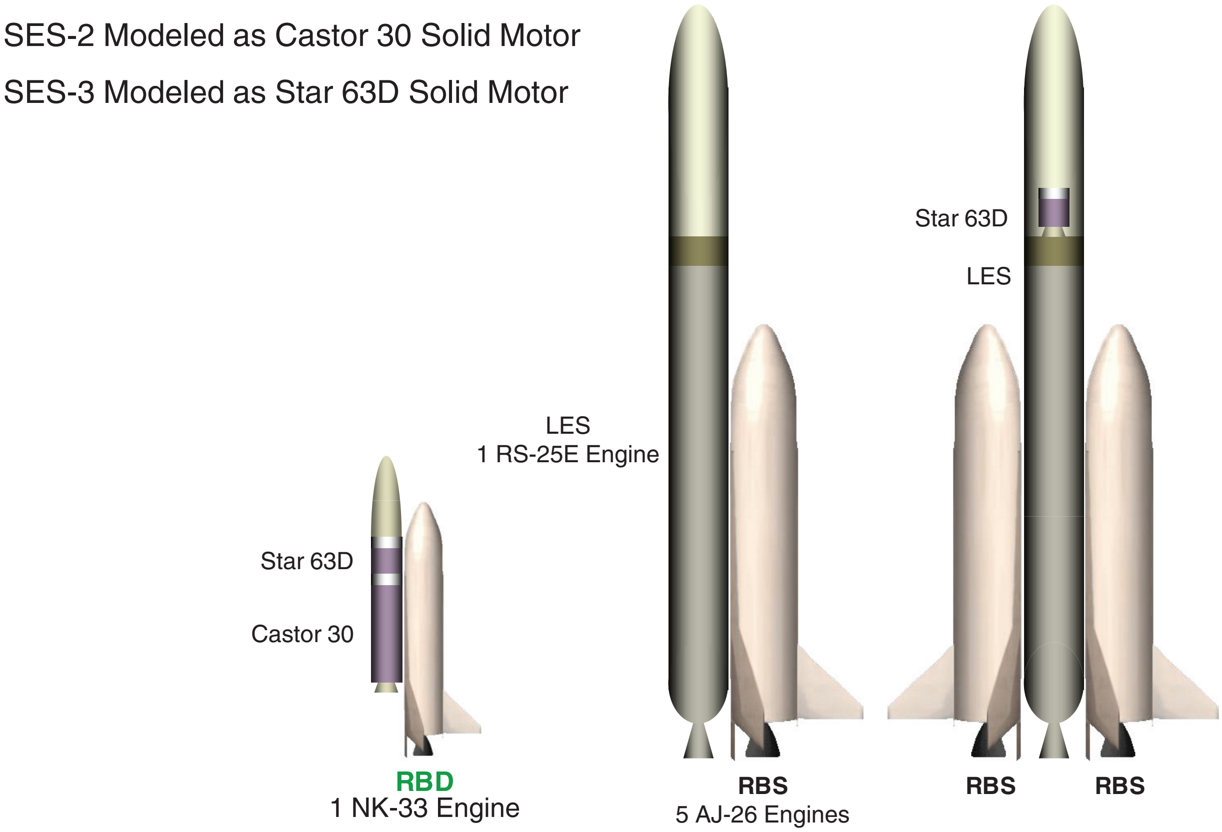

FIGURE 4.1 RBS flight hardware elements. Major elements include the RBD, the LES, the SES, and RBS. NOTE: LES, large expendable stage; RBD, reusable booster demonstrator; RBS, reusable booster system; SES, small expendable stage. SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

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assumed use of the "Americanized" version of the Russian NK-33 oxygen-rich staged combustion (ORSC) engine (i.e., a domestic AJ-26 engine). Under this baseline scenario, the time frame of the AFRL-funded hydrocarbon-fueled booster technology development does not significantly impact the booster main propulsion system.

- *Scenario 2: Extended EELV.* The EELV program is extended with operations until 2040, which allows completion of the AFRL-funded hydrocarbon-fueled booster technology development and development of an RD-180 replacement engine for the Atlas V. This engine would be of the thrust class of the RD-180 and would be built using technology currently under development in the AFRL Hydrocarbon Boost Technology program. This same replacement engine would be used in an RBS system. The mid-scale RBD is again assumed in the development program.
- *Scenario 3: Accelerated RBS.* This scenario was explored to examine implications of accelerating the end of the EELV program to 2025. This scenario uses the domestic version of the AJ-26 engine but eliminates the mid-scale RBD and proceeds directly to full-scale RBS development.
- *Scenario 4: Commercial partnership.* This scenario assumes a government-funded program to develop and conduct the RBD using the domestic AJ-26 engine, with the full-scale RBS developed by industry to support both Air Force and commercial spacelift needs.

Additional variations were explored within each of these four scenarios, including options to not include the heavy-lift vehicle in either the RBS development or its operations. These options were explored because the committee believes that the heavy-lift requirement places great challenges on a system that is already challenged by the technical risks discussed in Chapter 3. The requirement for a dual-reusable booster heavy-lift configuration adds significantly to the complexity of the launch system with respect to balancing structural loads, conducting safe separation, and simultaneously managing two autonomous reusable boosters in the same airspace. Given ongoing trends for smaller electronics and emerging desires and capabilities for disaggregation of large satellites, the committee believes that the heavy-lift requirement should not drive the basic conceptual design for the RBS, because this requirement may disappear in the future or be addressed with alternative space lift capabilities. Thus, the committee explored cost options that pose no heavy-lift requirement for the RBS.

An additional factor that requires consideration is the existing Air Force requirement for two independent launch capabilities to meet its assured-access-to-space goal. The scenarios described above are all based on the assumption that the current EELV launch systems would be fully retired and that the RBS satisfies the complete Air Force launch manifest. In this case, a problem identified in the RBS system could potentially jeopardize the entire Air Force launch capability. One possibility for avoiding this possibility would be to maintain the Delta IV production capability and use this launch system to satisfy the heavy-lift requirement.

The evaluations to follow principally focus on Scenarios 1 and 4. Scenario 2 allows for development of the hydrocarbon engine technology prior to proceeding with RBS development, so any decision regarding RBS development would be delayed for several years. This use of an RD-180 replacement engine would complicate the RBS vehicle design by requiring large engine throttling, as discussed in Chapter 3. Scenario 3 was also not addressed in detail as it was viewed by the committee as being too risky given the existing concerns about the rocketback return-to-launch-site (RTLS) maneuver. In the evaluations that follow, a subdesignation "-A" is used for a modification to the baseline scenario that does not include the RBS-heavy variant. In these scenarios, the implications of carrying the alternative heavy launch system were not factored into the cost analysis.

The costing analysis covers a 47-year life cycle (2014-2061), with EELV costs provided by the Air Force's Space and Missile Systems Center (SMC) Launch and Range Systems Directorate and RBS costs estimated by the SMC's Developmental Planning Directorate. The approaches used for the RBS cost estimates are shown in Table 4.1. The NASA/Air Force Cost Model (NAFCOM) is used for the costs of design, development, test and evaluation (DDT&E), and production and contractor proprietary approaches are used for cost estimations of the vehicle and engines. The Aerospace Corporation's operations design model and its facilities model are used for operations and facilities.

A conservative approach was taken to the flight rate assumption. Air Force analyses are based on only eight flights per year, with one heavy-lift payload every year, and commercial markets were not considered. The mission model for the assumed flight rate is provided in Table 4.2.

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TABLE 4.1 Summary of Reusable Booster System Cost Estimating Approaches

Cost Category	Cost Model/Method
DDT&E	
RBD (Except NK-33 Engine)	NAFCOM
RBS	NAFCOM
AJ-26 Engine Development	Contractor estimate + OGC
LES	NAFCOM
RS-25E Engine Development	N/A—NASA developed
Castor 30 (Mods for Side Mounting)	NAFCOM[a]
Star 63D (Mods for Side Mounting)	NAFCOM[a]
ΔDDDT&E (After Flight Test Program)	NAFCOM
Production	
RBS	NAFCOM
AJ-26 Engines	Contractor estimate + OGC
LES	NAFCOM
RS-25E Engines	Contractor estimate + OGC
Castor 30	NAFCOM
Star 63D	NAFCOM
Facilities	
SLC-2W for RBD (VAFB)	VAFB estimate + OGC
SLC-3E (VAFB)	Facilities model[b]
SLC-41 (CCAFS)	Facilities model[b]
New Facility (CCAFS)	Facilities model[b]
Operations and Sustainment	
RBD Flight Test Program	ODM[b]
RBS Flight Test Program	ODM[b]
RBS Launch Operations	ODM[b]
RBS Mission Integration	Based on EELV data
RBS Transportation	Based on EELV data
Range Costs	Based on EELV data
Sustainment	Based on EELV data

[a] Used first unit production cost as mod estimate

[b] Aerospace model

NOTE: CCAFS, Cape Canaveral Air Force Station; DDT&E, design, development, test and engineering; EELV, Evolved Expendable Launch Vehicle; NAFCOM, NASA/Air Force Cost Model; ODM, Operations Design Model; OGC, Other Government Costs; VAFB, Vandenberg Air Force Base.

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

Other key assumptions in the cost assessment include these:

- A production learning rate of 95 percent for the RBS and large expendable stage (LES) and 98 percent for the solid motors,
- A 10-flight interval between depot maintenance (with engine replacement after every 20 flights), and
- A 5-year overlap of RBS operations with EELVs.

4.2 ASSESSMENT OF BASELINE COST MODELING

To assess the approach used for cost modeling, RBS costs have been divided into four areas: vehicle, engine, facilities, and operations. The cost estimates for each are based on different approaches, as described below. While there is a strong interrelationship among these elements, the linkages are captured only to the degree that

TABLE 4.2 Basis for Reusable Booster System Flight Rate

Satellite Type	Orbit Requirement	EELV Used	Average Annual Rate
Communications	GTO	Atlas V 531	0.64
Meteorological	GTO	Atlas V 501	0.25
	SSO	Delta IV M	0.32
Navigation	MEO	Atlas V 401	1.96
Missile warning	GTO	Atlas V 411	0.31
	SSO	Delta IV M	2.12
Intelligence	LEO (high inclination)	Delta IV M+(4,2)	0.20
	LEO (high inclination)	Delta IV H	0.29
	LEO (high inclination)	Atlas V 541	0.20
	HEO	Atlas V 551	0.29
	Polar	Delta IV H	0.29
	Polar	Atlas V 401	0.16
	GTO	Delta IV M+(5,4)	0.50
	GEO	Delta IV H	0.50
Average annual launch rate			8.00

NOTE: EELV, Evolved Expendable Launch Vehicle; GEO, geosynchronous Earth orbit; GTO, geosynchronous transfer orbit; HEO, high Earth orbit; LEO, low Earth orbit; MEO, medium Earth orbit; SSO, Sun-synchronous orbit.

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

the lower-level models can identify them. All models are largely based on historical expendable vehicles and are therefore significantly handicapped by the lack of good analogous data for unmanned RBS-type reusable systems.

4.2.1 Vehicle

The vehicle estimates cover DDT&E and production costs for all flight hardware except the engines. The flight hardware includes the RBD, the RBS, and LES subsystems (less engines).

4.2.1.1 Models

The NASA/Air Force Cost Model (NAFCOM)[3] was used for all vehicle estimates. NAFCOM is a parametric cost estimating model based on a database of historical NASA and Air Force launch and space systems. The committee believes that NAFCOM is an appropriate tool for this application and the maturity level of the concept, although a bottoms-up cost estimating approach would further enhance credibility of the cost estimates.

4.2.1.2 Inputs and Assumptions

The inputs to NAFCOM include subsystem-level masses and other system characteristics. For the baseline RBS concept, the system masses are shown in Table 4.3. The other system inputs that serve as NAFCOM inputs include factors accounting for system maturity and program management approach. The cost implications of these factors are based on historical programs. Specific input factors include the following:

- *Manufacturing method.* This factor accounts for the identification and maturity of the manufacturing methods used in the production process and aims to address the level of use of advanced manufacturing techniques.

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[3] J. McAfee and G. Culver, SAIC, and M. Naderi, NASA Marshall Space Flight Center, "NAFCOM Capabilities and Results," presentation at the 2011 Joint Army Navy NASA Air Force (JANNAF) Modeling and Simulation/Liquid Propulsion /Spacecraft Propulsion Joint Meeting, Huntsville, Al., December 5, 2011, available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120002891_2012002403.pdf.

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TABLE 4.3 Reusable Booster System Mass Breakdown to Support NASA/Air Force Cost Model Estimates

Elements	RBD	RBS	LES	Castor 30	Star 63D
	Weight (lb)	Weight (lb)	Weight (lb)	Weight (lb)	Weight (lb)
Structures and Mechanisms	14,673	60,180	22,866	246	0
Vehicle Structures and Mechanisms	10,271	42,567	12,742	-	-
Tank Structures and Mechanisms	4,402	18,243	10,124	-	-
Thermal Control	0	0	949	37	9
Reaction Control Subsystem	303	1,143	118	74	44
Main Propulsion System (less engines)	1,825	9,423	3,611	-	0
Electrical Power and Distribution	1,697	3,876	999	222	91
Command, Control, and Data Handling	1,672	1,672	236	259	60
Guidance, Navigation, and Control	293	293	177	123	30
Landing System	1,884	6,002	-	-	-
Rocket Engines/Motors	3,079	22,221	8,835	1,503	370
Dry Weight	25,426[a]	105,441[a]	37,790[a]	2,464	604
Gross Lift Off Weight (GLOW)	176,955	992,857	397,890	37,343	7,771
	Dimensions (ft)	Dimensions (ft)	Dimensions (ft)	Dimensions (ft)	Dimensions (ft)
Length	63.0	108.4	130.3	29.7	12.0
Wingspan	35.0	60.1	-	-	-
Diameter	9.5	16.1	15.0	7.7	7.7
Height (landing gear up)	20.0	33.8	-	-	-
Height (landing gear down)	23.7	40.9	-	-	-

[a] Includes 25% dry weight margin.

NOTE: LES, large expendable stage; RBD, reusable booster demonstrator; RBS, reusable booster system.

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

The use varies from minimum to maximum use of manufacturing techniques such as just-in-time delivery, bar coding, robotics, commercial-off-the-shelf items, and outsourcing.

- *Engineering management.* This factor accounts for the variation in management approaches, from streamlined activities with minor expected changes to a widely distributed team with formalized procedures and managed interfaces. At one end of the spectrum is the assumption of a minimum number of design changes, with the design team making maximum use of the highly efficient Skunk Works approach with integrated product teams, rapid prototyping, design to cost, and the like. At the opposite end of the spectrum is the assumption of a distributed design team just waiting for major technology advances and hoping they will bring frequent major requirement and design changes.
- *Design level.* This factor accounts for the maturity of the vehicle design and depends on what is inherited from previous projects. A high design level value indicates that the system has little inheritance from previous projects, and vice versa. Choices for the design level range from very low values, which represent the reflight of an existing vehicle, to moderate values, which represent significant modifications to an existing design, and through high values, which represent a totally new design.
- *Funding availability.* This factor accounts for the potential of program development delays due to funding limitations, which create inefficiencies in execution. Choices for funding availability include these: funding is assured and no delays are expected; delays are possible but infrequent; or funding is constrained and delays are likely.
- *Test approach.* This factor accounts for variation in the degree of testing required during system development and reflects the amount of risk being accepted and indicated by the planned test program. Choices for test approach include minimum testing, with qualification using simulation and analysis; moderate testing, with qualification at the prototype/protoflight level; or maximum use of testing with qualification at component level.

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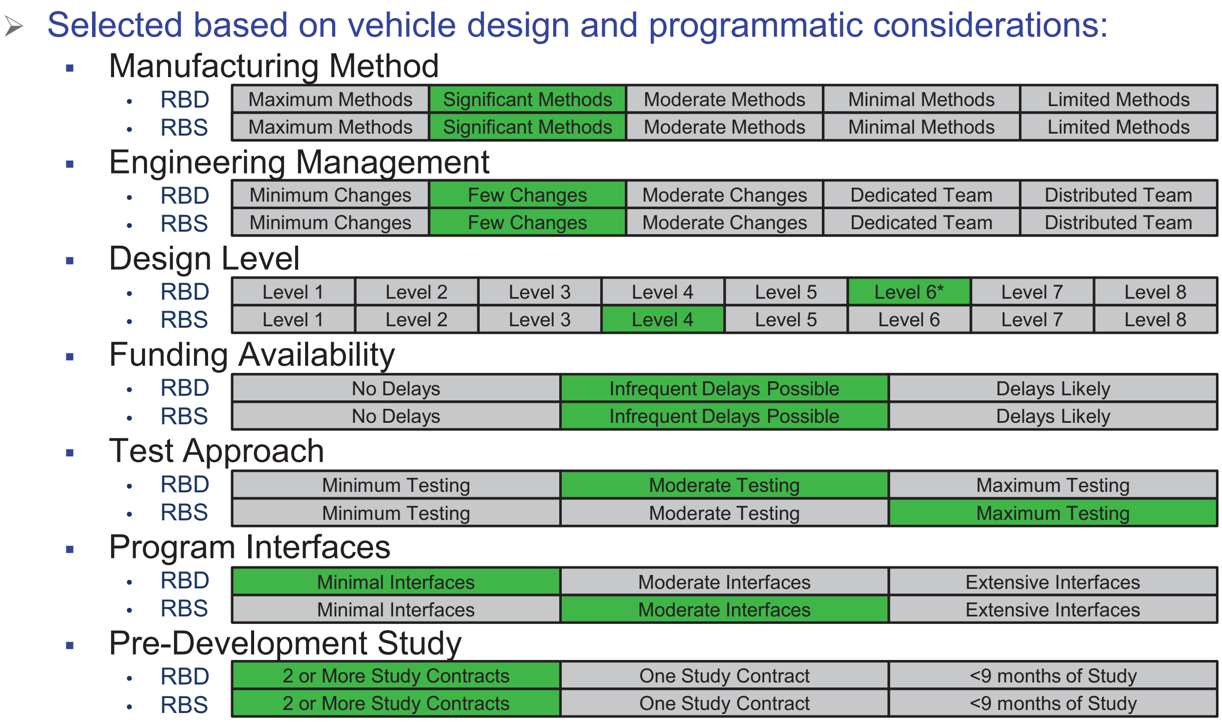
- *Program interfaces.* This factor accounts for the degree to which interfaces external to the development program impact launch system design and development and reflects the expected number of interfaces with multiple contractors and/or centers. Options include low or high number of major interfaces involving multiple contractors and/or centers.
- *Pre-development study.* This factor accounts for the depth of analysis supporting the vehicle design and reflects the level of study efforts that were conducted or are being conducted before the start of design and development. Choices for the predevelopment study level include two or more study contracts in phases A and B, with more than 9 months of study; one study contract with between 9 and 18 months of study; and less than 9 months of prephase C and D study.

Two factors not considered by the NAFCOM costing methodology are the breadth of the supplier base, particularly the implications of relying on single-source suppliers, and the degree to which the commercial market may influence future launch costs. The implications of reusable boosters for the U.S. launch industry are difficult to predict. The baseline RBS program assumes eight boosters would satisfy Air Force needs over the entire RBS life cycle. Cost models for the sustainment of these vehicles and the associated industrial support that will be required are largely absent. The potential implications for the commercial market are addressed in the next section.

The committee evaluated the NAFCOM inputs used by the Air Force in its costing analysis for the other system characteristics, which are shown in Figure 4.2. The committee agrees that these input factors are appropriate given the state of the RBS concept.



➢ Selected based on vehicle design and programmatic considerations:

▪ Manufacturing Method

RBD	Maximum Methods	🟩 Significant Methods	Moderate Methods	Minimal Methods	Limited Methods
RBS	Maximum Methods	🟩 Significant Methods	Moderate Methods	Minimal Methods	Limited Methods

▪ Engineering Management

RBD	Minimum Changes	🟩 Few Changes	Moderate Changes	Dedicated Team	Distributed Team
RBS	Minimum Changes	🟩 Few Changes	Moderate Changes	Dedicated Team	Distributed Team

▪ Design Level

RBD	Level 1	Level 2	Level 3	Level 4	Level 5	🟩 Level 6*	Level 7	Level 8
RBS	Level 1	Level 2	Level 3	🟩 Level 4	Level 5	Level 6	Level 7	Level 8

▪ Funding Availability

RBD	No Delays	🟩 Infrequent Delays Possible	Delays Likely
RBS	No Delays	🟩 Infrequent Delays Possible	Delays Likely

▪ Test Approach

RBD	Minimum Testing	🟩 Moderate Testing	Maximum Testing
RBS	Minimum Testing	Moderate Testing	🟩 Maximum Testing

▪ Program Interfaces

RBD	🟩 Minimal Interfaces	Moderate Interfaces	Extensive Interfaces
RBS	Minimal Interfaces	🟩 Moderate Interfaces	Extensive Interfaces

▪ Pre-Development Study

RBD	🟩 2 or More Study Contracts	One Study Contract	<9 months of Study
RBS	🟩 2 or More Study Contracts	One Study Contract	<9 months of Study

FIGURE 4.2 Additional NASA/Air Force Cost Model inputs for other characteristics. NOTE: RBD, reusable booster demonstrator; RBS, reusable booster system. SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

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4.2.1.3 Results, Sensitivities, and Uncertainty Ranges

Sensitivities of vehicle cost to assumed design heritage and engineering management are shown in Figure 4.3. Clearly, DDT&E costs are significantly reduced as a result of the RBD effort, which results in a higher confidence in the RBS vehicle design as the program enters full-scale development. Potential variations in the RBS assumptions used for the NAFCOM inputs covering design heritage (design levels 1-8) and engineering management (management levels 1-5) appear to show a potential for RBS DDT&E estimates to increase by 50-100 percent, although the assumptions used for the baseline cost appear reasonable.

4.2.2 Engines

The engine estimates cover DDT&E and production. For the RBD, a NK-33 engine is used with Castor 30 and Star 63D solid motors in the second stage. The RBS uses five AJ-26 engines in the reusable first stage and an RS-25E engine for the expendable second stage. The reusable AJ-26 engines are assumed to be refurbished every 10 flights and replaced every 20 flights.

4.2.2.1 Models

The models and methodologies used to generate cost estimates for the engines are contractor-proprietary. These models are generally accurate when based on similar applications, although they rely on assumptions about reusability requirements, which carry some uncertainty.

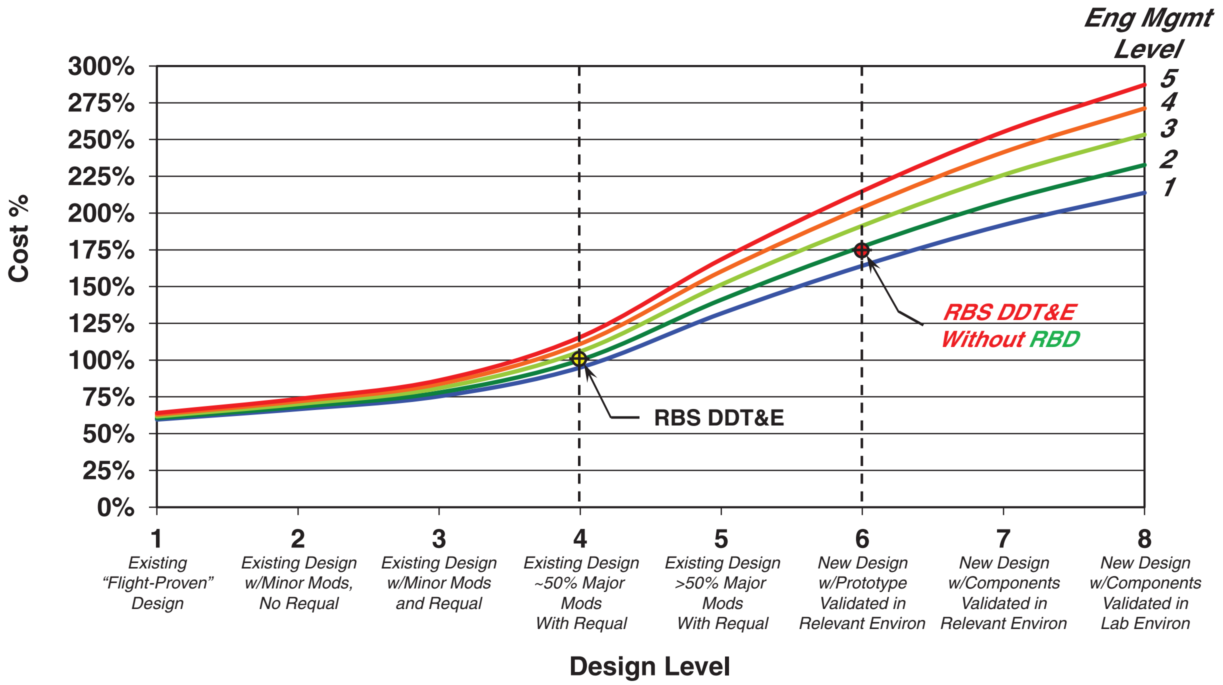

FIGURE 4.3 Sensitivities to NASA/Air Force Cost Model inputs normalized to the baseline RBS design, DDT&E program. Sensitivity of cost to the design maturity (e.g., whether or not requalification of an existing design, Requal, is needed) and Engineering Management Level needed for program execution. NOTE: DDT&E, development, test, and evaluation; RBD, reusable booster demonstrator; RBS, reusable booster system. SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

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4.2.2.2 Inputs and Assumptions

The specific inputs and assumptions for cost modeling of the engines were not provided to the committee because they are proprietary.

4.2.2.3 Results, Sensitivities, and Uncertainty Ranges

Engine cost estimates were provided to the committee and were included in its analyses. However, the data are considered sensitive and raw data are not included in this report.

4.2.3 Facilities

The facility estimates cover the costs of the initial construction/modification efforts to support all RBD and RBS operations.

- *Models.* The Aerospace Corporation's facility model[4] was used to generate all facility estimates. This model accounts for the sharing of common items at each launch site, includes site preparation/utilities/activation costs, and also accounts for site-specific cost differences.
- *Inputs and assumptions.* For the RBD, modifications to the Vandenberg Air Force Base (VAFB) SLC-2W launchpad represent the only facility investment. For the RBS, one new launchpad and modifications to the SLC-41 are planned at Cape Canaveral Air Force Station (CCAFS), as well as modifications to the SLC-3E launch pad at VAFB.
- *Results, sensitivities, and uncertainty ranges.* Facility estimates were evaluated by the committee. These estimates appear to reasonably reflect the assumptions used, but there is some uncertainty about the impact of reusability requirements, as discussed in Chapter 3.

4.2.4 Operations

Operations estimates cover all labor and support required for flight operations and vehicle turnaround tasks. Costs for expendable hardware and RBS vehicle refurbishment add to operation costs but are estimated using different methodologies.

- *Models.* The Aerospace Corporation's operability design model[5] was used to estimate operations costs. The general approach is depicted in Figure 4.4.
- *Inputs and assumptions.* Estimates are based on a buildup from 188 shuttle-like tasks needed to prepare the reusable booster for its next launch. The effort needed to support each of these tasks is based on an expected level of operability improvement attributable to a design or approach difference.
- *Results, sensitivities, and uncertainty ranges.* Table 4.4 shows the staffing results from the Air Force analysis. In the opinion of the committee, these staffing levels seem slightly below what would be expected in that they are slightly below those existing EELV operations. In the committee's view, it was not clear that the requirements associated with reusability, such as postflight checkout and refurbishment, were adequately reflected in the staffing analysis. The experience that will be gained from the RBD effort is likely to help in better refining these estimates. Table 4.5 shows cost estimate sensitivity to turnaround time. This sensitivity is not significant, unlike in past studies of reusable launch systems, largely because the relatively low assumed flight rate does not put great pressure on the launch vehicle processing schedule.

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[4] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

[5] AFSMC, "Reusable Booster System Costing, SMC Developmental Planning," 2012. Approved for Public Release.

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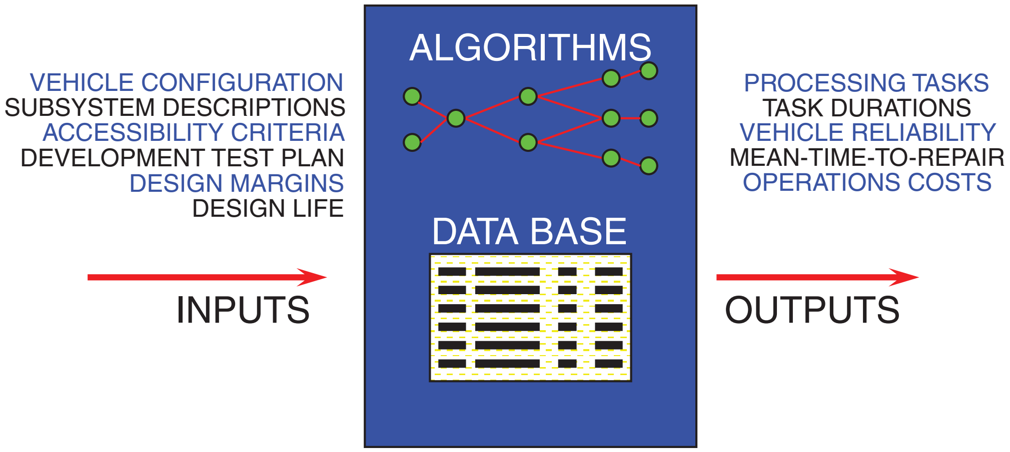

FIGURE 4.4 Aerospace Corporation's operability design model. SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

TABLE 4.4 RBS Staffing Estimates[a]

	RBS Personnel Estimates					
Category	CCAFS	VAFB	Common	Atlas I/II	Delta II	Titan IV
Vehicle processing ("Hands-On Labor")	43	43	—			
Vehicle engineering	—	—	15			
Payload Integration	8	8	4			
Flight Operations/Mission Operations	7	7	5			
Flight Software Engineering	—	—	12			
Logistics	8	8	5			
Launch Support Equipment	18	18	6			
Facilities Maintenance	14	14	8			
Landing Site Ops	22	22	—			
Administration	6	6	—			
Total	126	126	55			
		307		325[b]	175[b]	1,336[b]

[a] Assumes all contractor workforce.

[b] From C.L. Whitehair, *Cost of Space Launch Systems,* Aerospace Corporation, June 1994.

NOTE: CCAFS, Cape Canaveral Air Force Station; VAFB, Vandenberg Air Force Base.

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

TABLE 4.5 Cost Sensitivity to Launch Processing Time

Launch Processing Crew-Hours	Variable Operations Cost (at 8 per year)	Fixed Operations Cost	Average Operations Cost Per Launch (at 8 per year)	Total Cost Including Production
1X	1X	1X	1X	1X
2X	1.06X	1.05X	1.06X	1.02X
5X	1.28X	1.13X	1.22X	1.07X
10X	1.50X	1.23X	1.38X	1.12X

SOURCE: Air Force Space and Missile Systems Center, SMC Developmental Planning, "Reusable Booster System Costing," presentation to the committee, February 15, 2012. Approved for Public Release.

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4.2.5 Cost Modeling Assessment Summary

A high-level qualitative assessment of the committee's cost confidence for the various RBS elements is summarized in Figure 4.5. Without a grassroots-type cost estimate to balance the uncertainties in a NAFCOM-based approach, it is difficult to have much confidence in the estimates. Estimates for the engines may be considered comparable to a grassroots cost estimate, since the providing organizations developed the estimates but uncertainties related to the impacts of reusability requirements somewhat reduce confidence.

These estimates appear to be based on somewhat optimistic assumptions regarding the reuse of existing infrastructure and the need for new facilities to support reusability. Labor estimates for operations appear lower than would be expected for a reusable system, as they are nearly the same as those applied for EELVs, which one would expect to have lower operability requirements since the entire launch vehicle is expendable.

4.3 RBS BUSINESS CASE

4.3.1 Approach and Assumptions

For this study, the RBS business case compares the costs for the RBS system, using the Air Force cost methodology, with the projected costs for competing expendable launch vehicles, including commercial vehicles. It is noted that the very conservative launch rate (eight launches per year) can strongly impact the economic attractiveness of reusable concepts.

4.3.2 Results, Sensitivities, and Uncertainty Ranges

Figure 4.6 compares estimated cumulative costs for RBS under these scenarios to current cost projections for EELVs, with each scenario supporting eight flights per year. This comparison assumes RBS initial operating capability (IOC) in 2032, so that is where costs for the EELV also begin in this comparison. The costs used for the EELV are today's costs adjusted for inflation. Scenarios 1, 1A, and 4A were considered, the red curves illustrate the resulting variations in cumulative costs, with the 4A scenario represented by the lower curve. It can be seen that removing the heavy-lift requirement for the RBS does not have a first-order impact using the existing costing approach, but the committee believes that the heavy-lift requirement will indeed introduce significant technical risks that are not captured in the cost models.

Note that the development costs for the RBD and the full-scale RBS occur in parallel with existing EELV operations (ongoing costs associated with EELV during RBS and RBS development are not shown in Figure 4.6), so that they have a claim on funding beyond that required for planned operations. Also, note that the cost break-even point for RBS is reached relatively soon after IOC independent of the scenario evaluated. Thus, once the sustained investment has been made in developing the RBS capability, the savings relative to EELV are realized fairly quickly.

	Cost Confidence		
	Low	Nominal	High
Vehicle		X	
Engines		X	
Facilities	X	X	
Operations	X		

FIGURE 4.5 Summary of confidence in assessments of cost.

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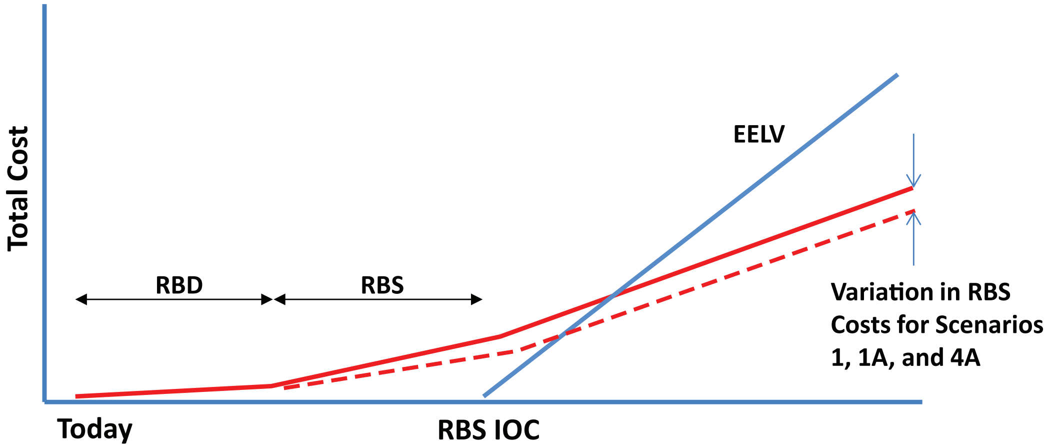

FIGURE 4.6 Comparison of reusable booster system costs to EELV costs. NOTE: EELV, Evolved Expendable Launch Vehicle; IOC, initial operational capability; RBD, reusable booster demonstrator; RBS, reusable booster system.

These results are largely in agreement with the cost modeling presented to the committee by the Air Force and The Aerospace Corporation, although it is noted that these cost trends do not account for the Air Force requirement for two independent launch systems. If some version of the EELV was maintained to satisfy that requirement, the slope of the red curves would be steeper and the break-even costs relative to those for the EELV system would push to later dates.

There are varying degrees of uncertainty regarding the estimates for each of the RBS elements, especially with respect to the technical risk areas identified in Chapter 3. These uncertainties mean the amount of funding required to reach IOC has a reasonable likelihood of growing significantly. Also, if the costs required to support each flight increase, this would further increase the slope of the cumulative funding curve, potentially pushing the potential break-even point further out. There would be improvement in the confidence of the cost picture if RBS operability improvements could be validated and especially if costs for EELVs continue to grow beyond inflation.

4.3.3 Impact of Commercial Activities

The greatest cost uncertainty affecting the RBS business case is from impacts of commercial activities. Advertised pricing for a SpaceX Falcon 9 EELV medium-class commercial launch is currently $54 million (in fiscal year 2010 dollars). Also, SpaceX has a contract with NASA for 12 launches to the International Space Station (ISS) for $1.6 billion, which works out to about $133 million per launch. While many ISS-unique requirements do not typically apply to unmanned payloads, this latter cost may be considered representative of a commercial effort with substantial government oversight. The expected expendable launch costs for Department of Defense missions, with anticipated levels of government oversight typical of those for meeting the mission assurance requirement, are expected to be still higher. *Conversely, development of a commercial launch capability that can satisfy Air Force launch requirements may lead to true competition and lower overall costs.*

Figure 4.7 compares several hypothetical cases along with the information that was shown in Figure 4.6. The green lines now represent the costs for satisfying the Air Force launch manifest with either a commercial expendable launch vehicle operating on commercial principles or the expendable launch vehicle operating with government oversight, as represented by NASA missions to the ISS. Significantly, the costs of the expendable system never cross the RBS cumulative cost curve. There are probably several reasons for this. First, the Air Force would not have paid for vehicle development in the case of the commercial vehicles, so the latter expendable vehicles would begin with a cost advantage in cases where their development costs are expected to be recapitalized across a cus-

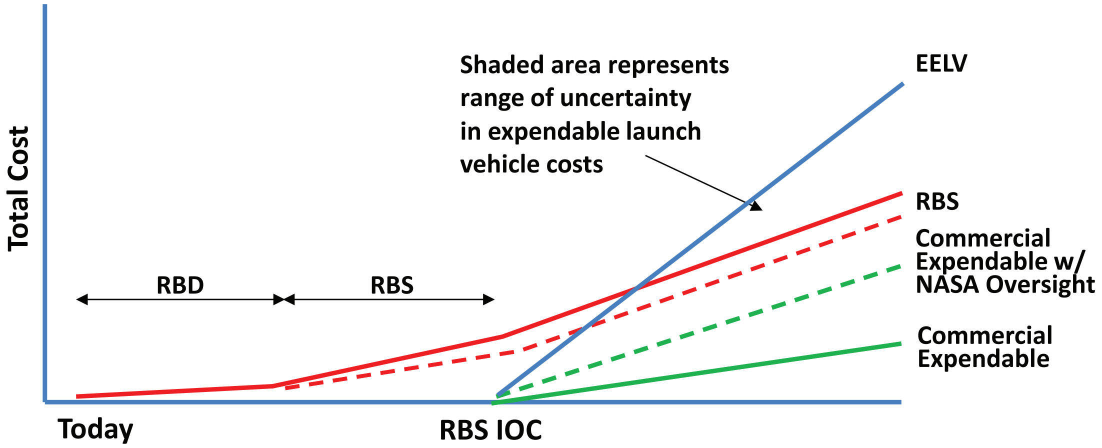

FIGURE 4.7 RBS cost compared to costs of EELVs, commercial, and other options. NOTE: EELV, Evolved Expendable Launch Vehicle; IOC, initial operational capability; RBD, reusable booster demonstrator; RBS, reusable booster system.

tomer base larger than just the Air Force. Second, this comparison is being conducted between an existing system and a conceptual RBS design, and the NAFCOM costing models provide factors to account for design immaturity. Third, NAFCOM's supporting database was developed using information from previous government-led programs, so its cost estimates may not account for entrepreneurial approaches to developing new launch capabilities. And finally, the RBS costing methodology does not account for the cost pressures associated with a launch service provider competing in the commercial market.

The commercial lines shown in Figure 4.7 represent the lower end of the potential cost spectrum associated with satisfying Air Force launch requirements. As previously stated, satisfying Air Force mission assurance requirements may result in launch costs even higher than those realized in missions executed with NASA oversight. So in this regard, the entire range of expendable launch vehicle costs can be considered to be the range of cost uncertainty.

Given the existing uncertainties in the costing associated with expendable launch vehicles, the business case for RBS development is not as clear as portrayed in Figure 4.6 when RBS costs are compared to today's EELV operations. Today, a number of commercial organizations are pursuing a wide variety of innovative launch vehicle concepts, and emerging commercial market forces may well challenge historical costing methodologies.

4.4 OTHER ISSUES AND COST CONSIDERATIONS

Other factors may also affect the viability of the RBS program both from the positive and negative standpoints. For example, there would ordinarily be clear benefits to the government for maintaining multiple options to meet launch needs, and the Air Force has a stated requirement for two independent launch systems for satisfying mission assurance criteria. Studies have shown cost benefits of from between 10 and 50 percent assuming a competitive market environment and continuous competition.[6] Relying on a single system or launch service provider takes away the benefits of this competition. The potential advantages from competition, however, need to be tempered by the very small number of launches that the Air Force model assumes. The fixed prices associated with maintaining an industrial base for such a limited number of launches would likely more than offset any cost advantages here. Thus, maintaining two independent launch systems may significantly increase the projected costs associated with

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[6] R. Nash, "The case for competition in government acquisitions," *Daily Caller,* June 18, 2012, available at http://dailycaller.com/2011/02/15/the-case-for-competition-in-government-acquisitions/#ixzz1yBhAuofP; G.G. Daly, H.P. Gates, and J.A. Schuttinga, "The Effect of Price Competition on Weapon System Acquisition Costs," Paper P-1435, Institute of Defense Analysis, September 1979.

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future scenarios using RBS. Conversely, development of a commercial launch capability that can satisfy Air Force launch requirements may lead to true competition and lower overall costs.

In addition, this analysis essentially accepts the feasibility and success of a reusable booster system in the time frames suggested by the Air Force projections. However, previous chapters have detailed a number of important technical areas (as, for example, with the rocketback maneuver) where considerable uncertainty exists about technology and timing. Additionally, persistently unstable funding may also delay technology development. Major delays in overcoming technological hurdles would significantly and negatively affect the cost trade-offs and breakeven points shown in previous charts. Technology maturity levels therefore would add another level of uncertainty to the balance of the cost equations between RBS and EELVs.

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5

Program Implementation

As described in the statement of task (see Appendix A), the committee was asked to address the criteria and assumptions in the formulation of the current reusable booster system (RBS) plans and the ability of current technology plans to meet technical readiness milestones. At the present time, very little detail is available on the structure of the reusable booster system (RBS) development plan. In the absence of these details, the committee examined programmatic issues likely to arise. This chapter provides an overview of these programmatic considerations and identifies best practices from previous launch vehicle development programs.

To begin, it is recommended that the RBS program be conducted in phases that are specifically structured to systematically reduce and retire risk. The program should have predefined go/no-go decision points structured as on-ramps for the next phase, once the technical and programmatic risks are reduced to the level specified at the completion of the preceding phase. The main RBS program risks defined by the Air Force and augmented by the committee are listed in Table 5.1.

The following subsections include a suggested program structure for risk retirement and identified on-ramps, and address other important programmatic considerations and observations.

5.1 PHASED APPROACH TO THE REDUCTION OF RISK

Although several different, high-level RBS development plans were presented to the committee, no detailed consolidated plan was provided. For this reason, the committee generated its own systematic RBS development program plan for retiring risk (Figure 5.1). The committee believes that the Pathfinder phase and the reusable booster demonstrator (RBD) conceptual design and technology efforts that support it should be completed through initial flight testing before committing funding for the remainder of RBS development. In addition, the committee believes that the demonstrator phase and the RBS-Y conceptual design and technology efforts that support it should be successfully completed through initial flight testing before the RBS-Y design is initiated. The complete RBS development program is separated into eight phases, some serial and some parallel. On-ramps are provided between phases and at the completion of some phases to assure that risk reduction goals are sufficiently accomplished to adequately support the subsequent phase.

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TABLE 5.1 RBS Development Risks in Perceived Order of Criticality

Development Risk	Section In Which Addressed
1. Rocketback maneuver	Section 3.3
2. Hydrocarbon engine using oxygen-rich, staged combustion cycle	Section 3.2
3. Upper-stage separation	Section 3.6
4. Adaptive guidance and control (AG&C)	Section 3.5
5. Integrated vehicle health management (IVHM)	Section 3.4
6. Techniques to enable rapid ground processing	Appendix F

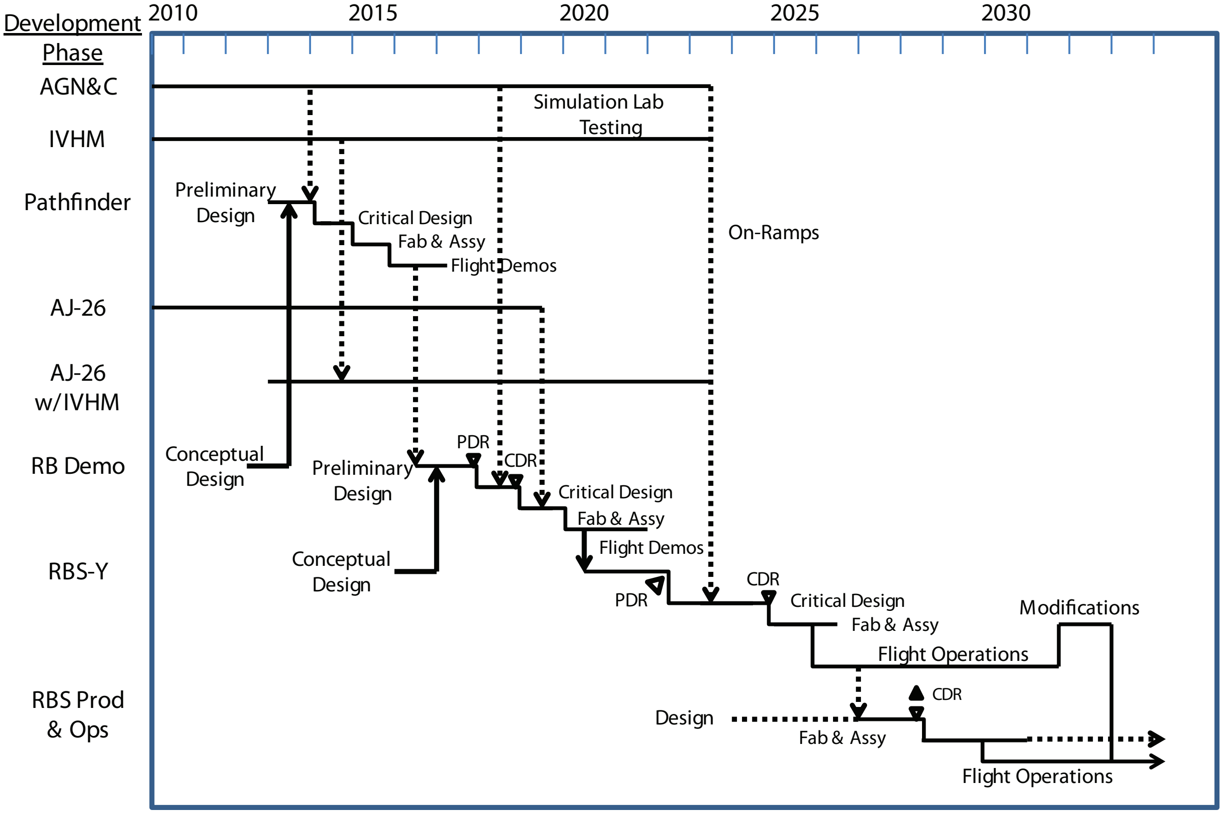

FIGURE 5.1 Committee's proposed RBS development risk reduction phases. NOTE: AGN&C, adaptive guidance navigation and control; CDR, critical design review; Fab & Assay, fabrication and assembly; IVHM, integrated vehicle health management; PDR, preliminary design review; Prod & Ops, production and operations; and RB Demo, reusable booster demonstrator.

5.1.1 AG&C Development Phase

Development of adaptive guidance and control (AG&C) capability is critical for supporting the RBS Pathfinder. This technology must be sufficiently mature for incorporation into the first Pathfinder flight to demonstrate the return-to-launch-site (RTLS) rocketback maneuver plus glideback and landing. Accomplishment of this would partially retire Risk 4 in Table 5.1. If this technology is not ready, it will delay the first Pathfinder flight and could jeopardize the RBS program. Extensive integrated testing of AG&C, combined with Integrated Vehicle Health Management (IVHM) and booster actuators in a simulation laboratory, is essential in developing booster flight

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software to accommodate potential subsystem failure modes. Critical is the availability of mature AG&C for incorporation into the RBD to assess booster rapid ground processing, fully retiring Risk 4.

5.1.2 IVHM Development Phase

A preliminary version of IVHM is required to support AG&C during the Pathfinder flight tests. Development of an evolved IVHM version will be needed for the RBD to support both flight tests and the demonstration of ground turnaround operations. Appropriate IVHM sensors will need to be integrated into the design of the new ORSC engine to meet operability requirements for reusability. This partially retires Risk 5. An IVHM version must be available for the RBS-Y booster and demonstrated through the full-scale testing to fully retire Risk 5. Extensive integrated testing of IVHM, combined with AG&C and booster actuators in a simulation laboratory, is essential for developing booster flight software.

5.1.3 RBS Pathfinder Phase

This subscale reusable booster flight test article addresses Risk 1 primarily and Risk 4 secondarily. Its main purpose is to demonstrate the feasibility of the rocketback turnaround maneuver, although at lower Mach numbers and altitude. If Pathfinder can demonstrate vehicle aerodynamic control and propellant control for engine feed during turnaround, that would partially retire Risk 1, and AG&C for flight control would partially reduce Risk 4. To reduce risk to the Pathfinder flight demonstration phase, the RBS development program should consider flying at least two competing concepts. This increases the opportunity for success and is likely to lead to more robust design(s) for the RBD booster. If neither of these Pathfinder vehicles can successfully demonstrate the rocketback turnaround and RTLS maneuver, then the RBS program development approach will need to be reassessed. This is the key on-ramp to committing funding for continued RBS Program development.

5.1.4 Booster Engine Development

Development of a reusable oxygen-rich, staged-combustion (ORSC) hydrocarbon rocket engine for RBS is likely to be conducted in two phases: a U.S. version of the Russian NK-33 (i.e., the AJ-26) to achieve some level of reusability and an upgraded and modernized version of the AJ-26 or a new ORSC engine development. A new ORSC engine improves reusability and incorporates IVHM; which provides input to the AG&C to accommodate in-flight anomalies and enhance operability for rapid booster ground turnaround.

5.1.4.1 AJ-26 Engine Development Phase

This phase is conducted in parallel with the RBS Pathfinder to support the RBS demonstrator phase. Using the NK-33 engine as a point of departure, it develops a completely U.S.-built ORSC LO_2/RP-1 rocket engine (AJ-26) that can satisfy the RBD reusability goal. If this U.S. version is not available, a back-up position would be to use several NK-33 engines to perform the RBD flight demonstrations.

5.1.4.2 New ORSC Engine Development Phase

This phase is conducted in parallel with the development of the Pathfinder and RBS demonstrator development. This engine is considered a new development by the U.S. aerospace industry and introduces a new design which requires design, development, test, and evaluation and technology development specifically in materials and processes and incorporation of IVHM sensors. Further development of the AJ-26 could conceivably satisfy this requirement. New material is required to eliminate the coating process utilized on the U.S. version of the AJ-26. The new material is required to be compatible in an oxygen-rich high-pressure environment. An ORSC engine is required to reduce coking, thereby enhancing engine reuse. It is essential that any new material selected will satisfy the LO_2 compatibility requirement and be properly characterized as well as reasonable in cost to procure and manufacture.

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To enable AG&C, IVHM sensors will have to be incorporated into this engine to provide in-flight health assessment. The cost of the new engine development and risk mitigation has been identified in the program planning. Successful completion of this phase will fully retire Risk 2 and retire the engine part of Risk 5.

5.1.5 Reusable Booster Demonstrator Phase

This phase starts once Pathfinder has successfully demonstrated rocketback turnaround, and continues in parallel with the ongoing new ORSC rocket engine development. The RBD consists of a larger, but still midscale demonstrator vehicle that is focused on demonstrating rocketback turnaround and RTLS at conditions closer to the full-scale booster (additional retirement of Risk 1), further development of AG&C (Risk 4), demonstration of vehicle-level IVHM technologies (Risk 5), and initial development of rapid ground processing operations (Risk 6) for reflight. RBD is also used to demonstrate second stage separation, using a small upper stage (reduction of Risk 3). The new ORSC engine development and RBD phases will need to be successfully completed at approximately the same time to authorize the start of full-scale RBS-Y development. This achievement would constitute the second primary programmatic on-ramp supporting design of the RBS-Y.

5.1.6 RBS Y-Vehicle Development and Demonstration Phase

The two Y-vehicle flyback boosters and the large expendable stages, payload fairings, and ground infrastructure (one launch processing facility at the Cape Canaveral Air Force Station [CCAFS]) are full-scale prototypes of the RBS. This development work constitutes a full program of System Requirements Review, Preliminary Design Review, Conceptual Design Review, and production authorization. The vehicles are developed and flight tested to validate the full program requirements and retire all of the remaining risks. Based on the experience gained during Y-vehicle flight testing and ground operations, improvements are identified for the production phase to better achieve all of the RBS goals and objectives. If this phase is not successfully accomplished, the program can be reassessed.

5.1.7 RBS Production Phase

The remainder of the Booster fleet (six vehicles as per the baseline or two vehicles as per the committee's recommendations; see Section 5.3.5.3) is produced and the two Y-vehicles are modified to incorporate the lessons learned during the previous demonstration phase. Boosters continue to be produced, but at a reduced rate, second stages and payload fairings are authorized, and the launch complex and support infrastructure at both CCAFS and Vandenberg Air Force Base (VAFB) are modified. The RBS fleet continues to operate to meet Air Force and other government mission requirements as do commercial missions if they are executed from the same facilities using the same vehicles.

5.2 PROGRAMMATICS

Incorporating important lessons learned from other recent launch vehicle programs (primarily Evolved Expendable Launch Vehicles, EELV) into the RBS development strategy will prove to be beneficial.

5.2.1 Risk Reduction Tracking Approach

A straightforward method of tracking risk reduction uses a time-phased red, yellow, green chart. Each risk is depicted as a line item, and reductions (moving from red to yellow to green) are predicated on successfully accomplishing specific events or demonstrations (the risk reduction plan).

These charts are kept up to date by the engineering department to reflect accomplishments and shown at every internal and customer program review. This approach is somewhat subjective, but provides mutual visibility for management and the project engineers on a real-time recurring basis. More complicated analytical methods tend to get lost in the process of data generation and do not provide better risk reduction visibility. An example developed by the committee and applied to the Pathfinder project is shown in Figure 5.2.

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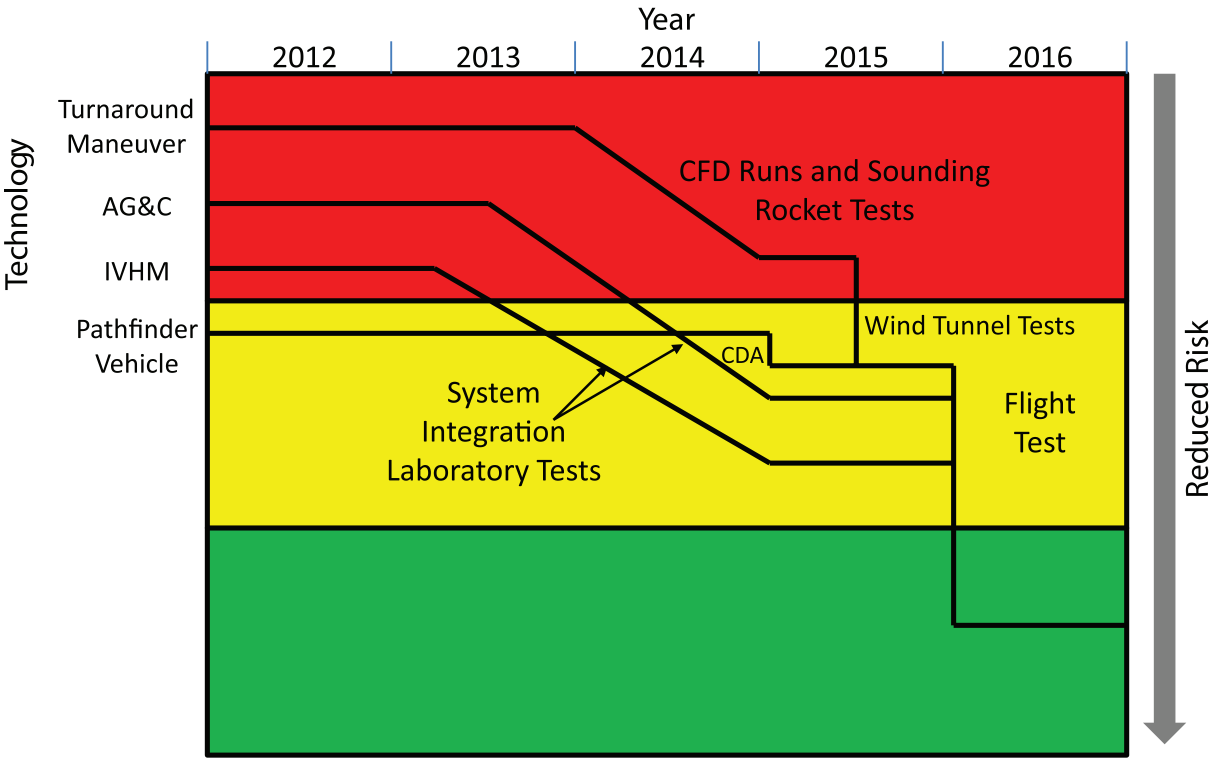

FIGURE 5.2 Example of a chart showing risk reduction of the rocketback return-to-launch-site (RTLS) maneuver. NOTE: AGN&C, adaptive guidance navigation and control; CFD, computational fluid dynamics; IVHM, integrated vehicle health management.

5.2.2 Change Philosophy

The outstanding launch reliability records of both the Atlas and Delta EELVs have been achieved, in part, by each program institutionalizing a Continuous Improvement philosophy. This happened first when both Atlas and Delta were commercial programs but has continued when they were combined under United Launch Alliance. This approach, which enjoys a program budget allocated for changes and for a supporting nonbureaucratic change process, coupled with a rigorous Systems Engineering process, allows improvements to be implemented quickly. When difficulties arise in procurement, manufacturing, or launch operations, fixes can be identified and analyzed and are presented to an Engineering Review Board (ERB). Estimated implementation costs and a phase-in schedule are included. The contractor's Program Management then makes a yes or no decision, and provides the budget needed for implementation.

Excluded from this process is the requirement to estimate the cost savings resulting from the change and preparation of an Engineering Change Proposal (ECP) for customer approval and funding. In most cases, the cost savings are difficult to capture, because the problem being addressed by the change affects the hidden factory (hard-to-build or operate hardware that causes quality problems). Continuous Improvement implementation on the Atlas program resulted in cost savings that were significantly greater than the cost of making the changes. These changes have also resulted in a more robust vehicle, more streamlined launch operations, and a workforce that is continuously engaged in fixing problems and improving the product.

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5.2.3 Configuration Identification and Management

Careful and complete identification of the subscale development article configurations (Pathfinder and RBD) is extremely important to ensure that subsequent full-scale vehicle designs understand what has been tested. As changes are made to these flight test articles, they must be well documented.

Configuration control must be rigorously maintained on the full-scale RBS elements. This is fairly straightforward for the expendable upper stage and payload fairing, which are discarded during every mission. Changes on these items must be documented as they occur, but there is no need for retrofit. For the reusable boosters, however, configuration control must be carefully managed to make sure improvement changes are incorporated across the fleet. During Y-vehicle operations, many changes will undoubtedly be identified. Some will require immediate incorporation to maintain flight status, while others will await the block change for the first production booster. Once several production boosters have achieved flight status, the two Y-vehicles will be retrofitted to incorporate all the current design changes. If a continuous improvement philosophy is adopted (see Section 5.2.2), changes to production vehicles will continue. To better manage this, a leader-follower approach to booster use may be advantageous. If one booster is used for recurring missions, while the others remain in ready status, the nonimmediate changes can be incorporated into the stored boosters without impacting flight operations.

5.2.4 Cost Management

The RBS program will be large enough that it does not escape considerable cost scrutiny throughout its development and fielding. The standard cost management techniques, including earned value management, should be incorporated from the start, with on-ramps for meeting cost objectives that are as rigorous as the technical on-ramps. Two funding philosophies should be incorporated: the program should be budgeted at 80 percent should-cost confidence, and the program should carry a 25 percent management reserve of cost-to-complete at each stage of the program until transition to a fixed-price procurement for the operational vehicles.

One of the biggest problems with the oversight process, including the Nunn-McCurdy system, is that most space systems find (or put) themselves in a position where the capabilities to be provided are “essential” to national security. Therefore, the remaining question is whether there is an alternative way to achieve the capabilities at lower cost. Once a program has spent billions buying down risk, it is highly unlikely that a lower cost option going forward can be found. The Space-Based Infrared System, the Advanced Extremely High Frequency satellite, the Mobile User Objective System, National Polar-Orbiting Observational Environmental Satellite System (NPOESS), and even EELV today are programs that experienced enormous cost growth yet were/are essential and were continued after Nunn-McCurdy breaches, including being restructured, because there was no better alternative. Eventually, decision makers above the program level decided NPOESS was simply in too much trouble and had to be terminated. SpaceX is offering the possibility of an alternative for EELV, in the future if not in the near term, subject to demonstrating the required launch reliability.

Therefore, one of the most important cost management tools is to ensure that RBS is not allowed to become essential until the risk is sufficiently low and cost confidence is quite high. To achieve this, it will be necessary that the current Air Force launch system(s) or mature alternative vehicles be maintained in production while RBS is in development.

5.3 GOVERNMENT INSIGHT/OVERSIGHT

RBS will be an Air Force-managed program, and direct involvement with development contractors, hardware manufacturers, and operations will be required. The following committee observations are based on experience with recent Air Force-managed programs.

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5.3.1 Independent Technical Review

An independent program assessment (IPA) should be conducted to provide input into a go/no go process leading into each succeeding program phase. Ideally, the IPA will have total, unrestricted access to all support data and personnel of the government and contractors, and will be responsible only to the milestone decision authority. Experience has shown that program managers rarely recognize if their program has run into sufficient trouble that it should be terminated or substantially revised. Instead, they argue for a new baseline of cost and schedule in order to proceed with a clean, "green" program. It is also noted that large independent reviews toward the end of a program or just before a launch do not tend to add value or uncover problems early enough to make a difference.

In addition to IPAs at the beginning of each major program phase, the demonstrated best practice is for technically competent government representatives to be imbedded into the contractor's development and mission support processes. These government representatives attend ERBs and other technical meetings and make their feelings known in real time. This allows the program to respond positively without causing a downstream disruption. The approach was used effectively by NASA on the Centaur program and again later with Atlas as a commercial program. Co-located Aerospace Corporation engineers have been shown to be equally effective representing the Air Force on EELV.

5.3.2 Contractor Reporting Requirements

Even with imbedded government technical personnel, Air Force management needs insight into program progress and requires periodic reviews. During development and initial Y-vehicle operations, these formal program reviews typically occur quarterly. A standardized format, showing schedule, risk reduction, and cost status, plus identification of major accomplishments and problems, is normally used. The imbedded government technical advisors should also participate in these reviews and give their opinion to both the contractor and the Air Force on progress and problems.

During ongoing stable launch operations, the use of formal status and other reviews should be significantly reduced. To meet RBS rapid ground processing goals, a cultural change will be required. This will necessarily involve reevaluation of and significant revisions to the many launch readiness and range safety reviews currently required for expendable launch operations.

5.3.3 Change Approval Approach

Different processes are suggested for approval of Requirements Changes and of Continuous Improvement Changes, as explained next.

5.3.3.1 Requirements Changes

The normal ECP approach should be used for Air Force-imposed or contractor-proposed changes to requirements. The formal ECP process serves as a brake on requirements creep and on the contractor's proclivity to spend all the available dollars on a cost-plus development. ECPs are funded by government dollars that result from requirement changes or other changes that may help the contractor's bottom line but provide little cost savings to the government.

5.3.3.2 Continuous Improvement Changes

ECPs are used on most government programs for all types of changes, which is ineffective for CI changes. In addition to identifying the technical need and cost of implementing the change, the ECP also must identify the expected benefit of making the change (reliability, performance improvement, operational improvement) and the expected cost savings. As discussed in Section 5.2.2, CI cost savings often involve quality issues associated with the "hidden factory," which are impossible to quantify. The ECP seeks additional budget from the government

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to fund the development and implementation cost associated with the change. This bureaucratic process takes an inordinate amount of time and often results in ECP rejection.

The recommended approach to facilitate CI is to provide budget within the contractor's development and recurring budget for making changes without resorting to the ECP process. Imbedded government representatives should participate in the ERBs that assess and approve improvement changes and voice objections to both the contractor's management and the Air Force, if necessary.

5.3.4 Production Monitoring Approach

With the current emphasis on cost, the potential exists for the current EELV production monitoring conducted by the Defense Contract Administration Services at United Launch Alliance's Decatur Manufacturing facility to become increasingly adversarial. Such a situation increases contractor costs, slows production, and results in demotivated production employees, which is not conducive to obtaining the highest quality launch vehicle hardware. The government is encouraged to find an imbedded oversight approach that works in cooperation with the contractor to identify and fix problems without resorting to excessive adversarial and bureaucratic reporting and resolution methods.

5.3.5 Operations Approach

A very fundamental question to be addressed by the Air Force early in the program with regard to operations that will drive many design and fielding decisions is the following: Will the operational system be operated by military personnel with contractor support or by contractors with military oversight? Since the earliest days of the intercontinental ballistic missile program, those systems have been operated by the military. Some early space launch systems were operated by the military (e.g., Thor). However, for more than 40 years the government launch systems have been operated by contractors with NASA or Air Force oversight: the space shuttle, Atlas I, II, III, and V, Delta I, II, and IV, Titan III and IV, Pegasus, and Minotaur. Since an RBS capability could lead to much improved operability, it would be surprising if the Air Force did not consider using this program to transition to "blue suit" operations for this responsive and flexible segment of their launch capability. The discussion below is based on the assumption that at some level the Air Force will conduct RBS operations.

5.3.5.1 Air Force Operations

The Air Force, with a military and civilian mix, would conduct all operations required to process the RBS for launch, mate the payload, conduct the launch, recover the reusable portions of the system, and restore them to the condition where the RBS is ready to be processed for another launch.

5.3.5.2 Contractor Role

The contractor would maintain a "depot-level" repair capability to accomplish the maintenance tasks that are determined to be beyond the cost-effective level of military personnel that may have an average duty assignment of 3 to 4 years. This may be the same capability that would accomplish the major refurbishment of flight or ground systems when that is required. The contractor would maintain on-site technical staff to assist in anomaly resolution and other issues that might arise in pre-launch or post-recovery processing.

5.3.5.3 Concepts for Operations

The approach used for reusable portions of the RBS will have significant impact on cost and the availability of the underlying industrial base. At one end of the spectrum, all the fly-back-boosters anticipated for use over the lifetime of the system might be bought in a block, with considerable savings because of the quantity. However, this would almost certainly require a total restart of the production capability if a subsequent procurement was desired

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many years later, with possible "new start" costs. A more sequential approach of delivering, perhaps, one vehicle per year would result in higher unit costs but would offer a much better opportunity for incremental improvements and continued production, as launch rates or other requirements dictate.

NASA conducted 135 space shuttle flights over 30 years, an average of 4.5 per year, with a fleet of 3 to 4 orbiters. Because of modifications and refurbishments, the "mission ready" fleet probably averaged fewer than three vehicles. While on average the orbiters flew a little more than once a year, the real use was probably more like two flights per year when the vehicle was operationally ready.

The RBS is intended to be much more reusable than the orbiters—perhaps 10 times more so. With an anticipated launch rate of about 10 per year, it seems like a vehicle fleet of four reusable flight sets, with each vehicle able to be flown from either launch base, would be sufficient to meet anticipated needs, continue operations after loss of a vehicle, and surge, if required. An open production line to replace any losses (and perhaps perform depot-level maintenance) would sustain the industrial base while providing a robust operational capability.

The committee believes that the initial RBS fleet size of eight vehicles (four at each coast) is too many. Based on the rationale presented in the preceding paragraph, an initial fleet size of four (three at CCAFS and one at VAFB) is likely sufficient, and this can be re-analyzed as the program moves toward production. This retained production capability and reduced initial fleet size is intended as an example approach that would help reduce the initial investment while maintaining program strength and flexibility.

5.3.5.4 Payload Capability

Developing a single launch vehicle to meet the full spectrum of payload delivery requirements has always been an unachievable goal. Families of vehicle elements have been fielded to meet a wide spread of requirements, but systems that are optimized for medium-class payloads are almost always far oversized for small payloads and require substantial change to meet the heaviest requirements. For example, Delta IV Heavy services a small, albeit extremely important, niche requirement. An Atlas V Heavy would need to be fielded to satisfy the same requirement with that family.

Although the Air Force may be required to meet the full spectrum of launch, the committee believes that burden should not be applied to the RBS. Specifically, the committee believes that the RBS would best be designed to meet the current EELV medium-lift requirement and not sized to accommodate the heavy-lift requirement. It is recommended that in constructing a phased development plan that the issues associated with the need for the RBS to satisfy the heavy-lift requirement be resolved prior to initiation of the development.

5.3.5.5 Commercial Use

A launch system that is as efficient as the RBS is intended to be very attractive to those wishing to provide access to space for commercial payloads. The Delta II, Atlas II, Titan III, and EELV systems did this through joint operations with the Air Force, with varying degrees of success. In most cases, government launches were conducted by contractor teams with government oversight, and commercial launches were conducted by contractor teams and contractor oversight. The potential commercial use of RBS could be addressed by the Air Force as it develops its operational concepts since, in the case of the RBS, the vehicles may be owned by the government, regardless of who does the hands-on operations.

5.4 ACQUISITION STRATEGY

The program described to the committee seems to presume a single contractor in each phase of the program: flyback demonstration (Pathfinder), engine development, RBS demonstrator, Y-vehicle prototypes, and production. The committee interprets this to mean that the contractor that does the engine development would continue into demonstration and production, and the RBD contractor would also build the Y-vehicles and the eventual production vehicles. While this is probably the lowest initial cost approach if all goes well, that benefit is achieved at the expense of both competition and alternative paths to mitigate risk. If RBS is successful, it will be the primary

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launch system for the vast majority of national security payloads for decades. The most optimistic motivation to replace or supplement the RBS would be if the launch rates got sufficiently high that it was worth the investment to build a second system. A new space launch system could be introduced to take advantage of new technologies that could not be introduced as RBS improvements or if the RBS became so expensive that an alternative would be cost effective.

The caveat "if all goes well," however, is not an insignificant consideration. Experience with aircraft programs suggests that when a fundamental change is desired (such as from fourth- to fifth-generation stealth) it has been beneficial to continue with two options well into the program, including flight test. With aircraft, there is a presumption that eventual production quantities make this continued competition cost-effective in the long run. Whether or not that has turned out to be true, there is little doubt that a better end unit was achieved than if a single contractor had been chosen based on paper designs and some component hardware. If the RBS flyback booster is the highest initial risk, the program should consider demonstrating it with two (or more) designs and take the best qualities determined from both, incorporating them into the demonstrator. This implies, as a minimum, two different Pathfinders with government ownership of all the resulting data. It would be beneficial if the same development and fly-off strategy be applied to the demonstrator vehicles for the same reasons.

In addition to a better technical outcome, a single Pathfinder that crashes, for whatever reason, early in flight test probably kills the program. A single Pathfinder that is unable to demonstrate the rocketback turnaround and RTLS maneuvers almost certainly kills the program, even if there was another approach that would have been successful but was not pursued because it did not appear better on paper.

The apparent program approach of single contractors may appear to be lower cost, especially in development, and therefore an easier "sell" for the initial investment, but it has far more technical and, in most cases, programmatic risk. It would be desirable for the RBS program to maintain competition as long as practicable to obtain and retain the "A-Team" from the contractors, foster innovation as each contractor strives to deliver the better product, sustain a larger industrial base for when reusable systems finally dominate the market, and achieve a lower life cycle cost.

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6

Findings and Recommendations

Following consideration of all materials presented in the previous chapters, the committee arrives at the following six principal findings regarding the reusable booster system (RBS) concept.

Finding 1: Cost estimate uncertainties may significantly affect estimated RBS life-cycle costs.

There are several important factors that lead to significant uncertainties associated with the RBS cost estimates developed to date. First, the vehicle development costs were estimated using NASA/Air Force Cost Model (NAFCOM), which is an industry standard model, and reasonable model inputs were used, but operability impacts on vehicle design are not captured using this model. Since NAFCOM is largely based on historical data and little relevant experience exists concerning reusable systems, there are large uncertainties associated with implementation of the vehicle features necessary to ensure needed operability.

Second, the cost projections are based on the "Americanization" of Russian hydrocarbon engine technology, but cost risks associated with development of operable engine development are difficult to capture. Given the limited experience base of U.S. industry developing oxygen-rich, staged-combustion (ORSC) hydrocarbon engines, the cost uncertainties associated with the engine development may be significant.

Third, the details underlying the required infrastructure needs are unclear, so uncertainties exist in the costs associated with the required infrastructure.

Finally, the estimated operational costs assumed modest postflight inspection requirements, which assume successful development of an effective Integrated Vehicle Health Management system and little added costs associated with mission assurance requirement.

Finding 2: The RBS business case is incomplete because it does not adequately account for new entrant commercial providers of launch capabilities, the impacts of single-source providers, Air Force need for independent launch sources for meeting their assured-access-to-space requirement, and technical risk. The cost uncertainties associated with these factors do not allow a business case for RBS to be closed at the present time.

In addition to the basic cost uncertainties associated with the RBS, three additional factors exist such that an assessment that the RBS business case is not complete and therefore cannot be closed at the present time. First,

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the RBS business case does not account for new entrant commercial providers, in that the business case is based on a comparison of the RBS concept to an extrapolation of recent Evolved Expendable Launch Vehicle (EELV) costs. Given the significant number of commercial entities pursuing novel approaches towards achieving launch capabilities, the future of space lift may look very different from that employed today. With global competition to reduce launch costs, it is anticipated that recent EELV costs may not be the proper baseline for cost comparisons.

Second, the RBS business case does not address the impacts of single source providers. So, while the business case assumes that RBS captures the complete Air Force launch manifest and is developed with a single source provider, the cost risks associated with using a single source are not adequately addressed. Said another way, the cost benefits associated with retaining competition in vehicle development were not included in the business case. Since the commercial launch market is rapidly changing and will be driven by cost considerations, neglecting an assessment of the role of competition is viewed as a weakness in the current RBS business case.

Third, the RBS business case assumed full capture of the Air Force launch manifest, but the Air Force maintains a requirement for independent launch capabilities for mission assurance needs. With this need for development and/or maintenance of a second launch system capability, the RBS business case model is overly optimistic in its assumption regarding full capture of the Air Force launch manifest.

The end result of these factors is that the uncertainties associated with the RBS business case are sufficiently large that the business case cannot be considered to be closed at the present time.

> **Finding 3:** Reusability remains an option for achieving significant new full-spectrum launch capabilities at lower cost and greater launch flexibility.

The Air Force Space Command has identified a long-term science and technology objective for achieving full-spectrum launch capabilities at significantly reduced costs, and reusability remains a potential option for realizing this objective. In concert with reduced costs, development of a robust reusable system might have additional benefits that may be realized, including replenishment of satellites on need; deployment of distributed constellations; rapid deployment of capabilities; robust launch operations from multiple, defendable launch sites; and operations by Air Force personnel.

> **Finding 4:** For RBS to significantly impact Air Force launch operations, it would have to be more responsive than current expendable launch systems. However, no requirement for RBS responsiveness has been identified that would drive technology development.

The current business case for RBS is built on satisfying the current EELV launch manifest with a launch-on-schedule assumption to operations. With this assumption and the lack of an operability requirement for RBS, the technologies necessary to significantly enhance operability and reduce operations costs will not be emphasized. It is through development of design features and technologies, and the resulting changes to Air Force operations that the true value of a reusable system lays.

> **Finding 5:** Technology areas have been identified in which continued applied research and advanced development are required before proceeding to large-scale development. These areas include reusable ORSC hydrocarbon-fueled engines, rocketback return-to-launch-site (RTLS) operation, vehicle health management systems, and adaptive guidance and control capabilities.

> **Finding 6:** Given the uncertainties in the business case and the yet-to-be mitigated technology risks, it is premature for Air Force Space Command to program significant investments associated with the development of a RBS capability.

While the committee found that the RBS business case cannot be closed at this time, and it is premature to begin large-scale RBS development activities, the committee does strongly endorse the continued research and

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advanced technology development needed for future launch systems. The committee makes the following six recommendations.

> **Recommendation 1:** Launch responsiveness should be a major attribute of any reusable launch system. To address this perceived disconnect, the Air Force should establish specific responsiveness objectives independent of the Evolved Expendable Launch Vehicle launch-on-schedule requirements that can be used to drive technology development.

The committee believes that responsiveness considerations should be a major consideration when addressing reusable launch systems and their supporting technologies. At the present time, responsiveness requirements beyond a launch-on-schedule philosophy have not been defined. Since these responsiveness requirements can drive vehicle and technology needs, it is important for the Air Force to define nominal responsiveness goals to provide focus for research and development activities.

> **Recommendation 2:** Independent of any decision to proceed with RBS development, the Air Force should proceed with technology development in the following key areas: reusable oxygen-rich staged-combustion hydrocarbon-fueled engines; rocketback return-to-launch-site operations; vehicle health management systems; and adaptive guidance and control systems. These technologies will have to be matured before they can support any future decision on RBS, and most of them will be also applicable to alternative launch system concepts.

Continued development is needed in these four principal areas to sufficiently mature these technologies to the point where significant investments can be committed to the RBS programs. The committee recommends that investments in these four areas continue independent of a decision to proceed with RBS development at this time. Since these technologies have application beyond RBS, with the exception of rocketback RTLS, this technology maturation will benefit the Air Force independent of RBS in areas of advanced rocket propulsion, system reliability, and vehicle autonomy.

> **Recommendation 3:** The Air Force Research Laboratory's (AFRL's) Pathfinder project is under way to demonstrate in flight, using a small-scale vehicle, the critical aspects of the return-to-launch-site maneuver. To increase chances for Pathfinder's success, AFRL should develop and fly more than one Pathfinder test vehicle design. In addition, competition among RBS concepts should be maintained as long as possible to obtain the best system for the next generation of space launch.

The use of a rocketback maneuver for RTLS operations of an RBS has not been previously demonstrated, so this approach to reusability carries significant risk. Given these risks and the resulting parameter space for innovative solutions, the Pathfinder program should be executed in a manner wherein several vehicle designs are developed and flown. While this approach will increase costs in the near-term, the long-term benefits to achieving a true high-performance solution will overwhelm this initial cost, if reusability is pursued in the future.

> **Recommendation 4:** The decision to proceed with the RBS development program should be based on the successful completion of the Pathfinder activities and on assurance that the technical risks associated with the reusable oxygen-rich, staged-combustion hydrocarbon-fueled engines, rocketback return-to-launch-site vehicle health management systems, and adaptive guidance and control systems are adequately mitigated.

Given the immaturity of principal technologies and the inherent risks of the rocketback RTLS operation, the committee recommends that the decision to proceed with RBS development be tied to the successful completion of the Pathfinder program and suitable mitigation of the principal technical risks. The committee understands that this approach delays potential achievement of an RBS capability. Delaying the decision to proceed with the RBS

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development has the additional benefit of enabling the business environment regarding emerging new entrant commercial launch providers to become clearer.

> **Recommendation 5:** Following successful completion of the Pathfinder program, the Air Force should reevaluate the RBS business case, accounting for the following factors: new-entrant commercial launch providers; potential impacts of single-source providers; and Air Force need for independent launchers to satisfy assured-access-to-space requirements.

Upon the successful completion of the Pathfinder program and the associated development of the four principal technologies, the Air Force should reevaluate the business case for RBS to determine if it can be closed at that point. This business case analysis should include the impacts of new-entrant commercial launch providers, single-source providers, and the Air Force need for independent launchers.

> **Recommendation 6:** When constructing the RBS program, the decision points for proceeding from technology development to demonstration to prototype to production for RBS should be based on quantitative assessments during the successful completion of the previous phase. These go/no-go decision points should be structured as on-ramps to subsequent phases with technical underpinnings that are sufficiently well understood to proceed. The decision points for proceeding from Pathfinder and hydrocarbon boost technology risk reduction to a mid-scale demonstrator and from the demonstrator to Y-vehicle prototypes should be considered as on-ramps.

Given the costs associated with the development of a new space launch capability and the technical uncertainties associated with its operational approach, it is prudent to construct any potential future RBS program in a manner wherein the decision to proceed to any next phase is strongly tied to the successful completion of the previous phase.

Today, the United States finds itself in the midst of a potentially fundamental transition of space launch from a model wherein the government develops and controls the launch vehicles to a service-based model wherein industry develops launch vehicles and then sells services to both commercial and governmental organizations. Within the uncertainties of this transition, the committee is aware of a large number of organizations that are developing capabilities using innovative designs, development, and operational approaches. The review and evaluation of the RBS concept within this transition is fundamentally difficult, but the committee firmly believes that the future of U.S. space launch will be strong, given the technology developments recommended in this study coupled with innovative designs and approaches for more cost effective and robust launch systems.

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Appendixes

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A

Statement of Task

This study will review and assess the SMC/AFRL concept for a Reusable Booster System (RBS) for the U.S. Air Force. Among the items the committee will consider in carrying out this review are:

- The criteria and assumptions used in the formulation of current RBS plans;
- The methodologies used in the current cost estimates for RBS;
- The modeling methodology used to frame the business case for an RBS capability including:
    - The data used in the analysis,
    - The models' robustness if new data become available, and
    - The impact of unclassified government data that was previously unavailable and which will be supplied by the USAF; the technical maturity of key elements critical to RBS implementation and the ability of current technology development plans to meet technical readiness milestones.

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B

Committee Member and Staff Biographies

DAVID M. VAN WIE, *Chair,* is the chief technologist of the Johns Hopkins University Applied Physics Laboratory (JHU/APL) Precision Engagement Business Area with responsibility for identifying, maturing, and developing innovative technologies in the areas of fluid dynamics; structural sciences; detection system information fusion; signal and information processing; guidance, navigation, and control; command and control instrumentation and analysis; and radio frequency technologies. Dr. Van Wie also holds a research faculty position in the Department of Mechanical Engineering at JHU and lectures in the Department of Aerospace Engineering at the University of Maryland in the areas of space propulsion, aerodynamics, and high-temperature gas dynamics. He has served as a member of the U.S. Air Force (USAF) Scientific Advisory Board, where he conducted studies on hypersonic systems, small precision weapons, virtual training technologies, future launch vehicles, and munitions for the 2025+ environment. He also served as the vice chair and chair for the 2010 and 2011 Air Force Research Laboratory Science and Technology Reviews, respectively. Dr. Van Wie serves on the Airbreathing Propulsion Subcommittee Technical Steering Group of the Joint Army, Navy, NASA, Air Force Interagency Propulsion Committee and was elected a fellow of the American Institute of Aeronautics and Astronautics (AIAA) in 2010. He attended the University of Maryland, where he received B.S., M.S., and Ph.D. degrees in aerospace engineering, and Johns Hopkins University, where he received an M.S. degree in electrical engineering. Dr. Van Wie has served on several National Research Council (NRC) committees, including the Committee on Conventional Prompt Global Strike Capability, the Steering Committee on the Decadal Survey of Civil Aeronautics, and the Committee on Future Air Force Needs for Survivability.

EDWARD H. BOCK retired from Lockheed Martin in 2000 as vice president and director of the Atlas Recurring Program. During his 5 years in this position, he was responsible for 42 launches, 40 of Atlas/Centaur and 2 of Atlas E vehicles, all of which were successful. As the Atlas program vice president, he became a champion of continuous improvement, incorporating many features into Atlas II vehicles that were flight proven and became standard in Atlas III and Atlas V. Major operational initiatives during his tenure were elimination of out-of-sequence work at the launch sites and streamlining of launch processing, which reduced vehicle on-stand time at Cape Canaveral Air Force Station by ~50 percent. From July 1991 to late 1999, Mr. Bock was program director for the conversion of launch site SLC-3E at Vandenberg Air Force Base to accommodate the Atlas IIAS. He directed this activity through the proposal phase, design completion, and early phases of construction. Before this, he was deputy director for the General Dynamics (GD) Advanced Launch System Study (ALS), which included an assessment

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of booster recovery and reuse. Results of the GD and Boeing ALS work led directly to the Atlas V and Delta IV Evolved Expendable Launch Vehicles for the USAF. During the earlier part of his 40-year career, he was director of systems engineering for GD, worked in preliminary design on advanced space concepts, designed and tested Centaur cryogenic components, and designed and implemented installation of ground support equipment for Atlas. Mr. Bock became a registered professional engineer, mechanical, in the state of California in 1965. After retirement, he was recognized by the University of Washington's Department of Aeronautics and Astronautics as their 2005 Distinguished Alumnus. He received his BSAE degree from the University of Washington and MSME degree from San Diego State College.

YVONNE C. BRILL is a consultant specializing in space propulsion systems and satellite technology. Her career as a rocket engine specialist ranges in roles from mathematician doing trajectory calculations, to research analyst deriving rocket propellant performance, and to propulsion manager building, qualifying and launching spacecraft propulsion systems. She began her career at Douglas Aircraft eventually joining RCA AstroElectronics where she had the responsibility for launch vehicles and on-board spacecraft propulsion systems. She also spent time at NASA Headquarters as Manager of the Solid Rocket Motor on Shuttle as NASA began ramping up production for increasing flight rates. She was with the International Maritime Satellite Organization (INMARSAT) in London from 1986 until her retirement in 1991. Among many honors Ms. Brill is the recipient of a 2010 National Technology and Innovation Award, a member of the National Academy of Engineering (NAE), and an honorary fellow of AIAA. She earned a B.S. degree in mathematics from the University of Manitoba, Canada, and an M.S. degree in chemistry from the University of Southern California. Since retiring from INMARSAT she has served on many NRC committees, including the Committee on Air Force and Department of Defense Aerospace Propulsion Needs and the Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions. She currently serves as a member of the NRC Space Studies Board.

ALLAN V. BURMAN is president of Jefferson Solutions (Solutions), the government consulting practice of the Jefferson Consulting Group. Under his leadership, Solutions provides analysis, evaluation, program management and acquisition assistance and assessment services to many government departments and agencies. Prior to joining the firm, Dr. Burman served in policy positions in the Office of the Secretary of Defense and in the White House's Office of Management and Budget. Dr. Burman is chairman of the Procurement Round Table, a fellow of the National Academy of Public Administration (NAPA), a fellow and member of the Executive Advisory Council of the National Contract Management Association, a member of the Partnership for Public Service, and an honorary member of the National Defense Industrial Association. He is also an adjunct professor at George Mason University and at the International Law Institute. He served on the White House Acquisition Advisory Panel established by the Services Acquisition Reform Act and co-chaired the performance-based acquisition subcommittee of the panel. In 2009 he received a Federal 100 Award in recognition of his contributions to the federal information technology community. Dr. Burman holds a Ph.D. from George Washington University, a master's degree from Harvard University, was a Fulbright Scholar at the Institute of Political Studies, University of Bordeaux, Bordeaux, France, and graduated Summa Cum Laude, Phi Beta Kappa from Wesleyan University. He has served on numerous NRC and NAPA panels addressing federal management issues such as the following NRC committees: the Committee on Cost Growth in NASA Earth and Space Science Missions, the Committee on Optimizing U.S. Air Force and Department of Defense Review of Air Force Acquisition Programs, and the Committee on Assessing the Results of External Independent Reviews for U.S. Department of Energy Projects.

DAVID C. BYERS is a consultant to U.S. government and industry entities in the areas of space propulsion and power. He reviews government and industrial R&D programs, assists NASA in program formulations and management, and performs systems analyses of space propulsion systems. Mr. Byers had more than 40 years of experience in NASA and TRW (now NGC) space programs, including initiation, conduct, and management of multiple programs that resulted in successful development and transition of advanced propulsion concepts to operational status. He has received the AIAA Wyld Propulsion Award and NASA's Outstanding Leadership Medal, and he is a fellow of the AIAA. He received a B.S. in physics from Pennsylvania State University. He has supported multiple

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NRC studies, including the Committee on Review of the NASA Institute for Advanced Concepts and the Panel to Review Air Force Office of Scientific Research (AFSOR) Proposals in Propulsion for 2003-2005.

LEONARD H. CAVENY is an aerospace consultant and former director of science and technology for the Ballistic Missile Defense Organization. His previous experience also includes service as the deputy director of innovative science and technology for the Strategic Defense Initiative Organization, staff specialist for the Office of the Deputy Undersecretary for Research and Advanced Technology for the Department of Defense, and program manager for propulsion and energetics for the Air Force Office of Scientific Research (AFOSR). From 1969 to 1980, as a senior professional staff of Princeton University's Aerospace and Mechanical Sciences Department, he guided graduate student research and served as principal investigator. Dr. Caveny's expertise and consulting include solid rocket propulsion, aerothermochemistry flight experiments, electric propulsion, space solar power, diagnostics of reacting flows, combustion, propellants, refractory materials, and aeroacoustics. He is a fellow of AIAA. He earned his B.S. and M.S. in mechanical engineering from the Georgia Institute of Technology and his Ph.D. in mechanical engineering from the University of Alabama. He served on several NRC committees, including the Committee for the Decadal Survey on Biological and Physical Sciences in Space, the Committee for the Review of NASA's Pioneering Revolutionary Technology Program, and as chair of the Panel to Review Air Force Office of Scientific Research Proposals in Propulsion.

ROBERT S. DICKMAN is the executive director of the American Institute of Aeronautics and Astronautics. He entered the Air Force in 1966; his 34-year active duty military career spanned the space business from basic research in particle physics to command of the 45th Space Wing and director of the Eastern Range at Cape Canaveral, Florida. General Dickman served as the Air Force's director of space programs, the Department of Defense Space Architect, and the senior military officer at the National Reconnaissance Office (NRO). He retired from active duty in 2000 as a major general. From 2002 to 2005, he was appointed as Under Secretary of the Air Force's Deputy for Military Space. He is a member of the U.S. Department of Transportation's Commercial Space Transportation Advisory Committee and has served on the Air Force Scientific Advisory Board and the NRO's Technical Advisory Group. He is a fellow of the AIAA. General Dickman earned a B.S. in physics, an M.S. in space physics, and an M.S. in management and is a distinguished graduate of the Air Command and Staff College and the Naval War College.

MARK K. JACOBS is a senior systems engineer with more than 25 years of experience assessing NASA science mission and instrument advanced development requirements and life cycle costs. Mr. Jacobs has participated in numerous NASA announcements of opportunity reviews supporting the Explorer, Discovery, Mars Scout, New Frontiers, and Earth Ventures programs, among others. His past experience also includes providing cost analysis support to NASA Headquarters for the Nuclear Systems Initiative, Living With a Star, Cassini, Outer Planets, Mars Exploration, and other programs. He also participates in various NASA advanced technology assessments related to instruments, spacecraft, launch vehicles, and operations. Mr. Jacobs is the author of several cost analysis book chapters and received the Distinguished Service Award for 1994-2000 contributions to the AIAA Space Systems Technical Committee. He earned his B.S. in metallurgical engineering from the University of Wisconsin.

THOMAS J. LEE is founder and president of Lee & Associates, LLC. The firm's primary emphasis has been in support of NASA space systems development programs, including Student Launch Initiative, Next Generation Launch Technology, FASTRAC Engine, Crew Launch Vehicle, space shuttle, Constellation, Space Launch System, and Commercial Operational Transportation Systems. He served as special assistant to the NASA administrator for access to space where he led NASA's efforts in defining and planning the technology and development program for the future to help the United States retain its leadership in space. Other positions held at NASA since 1980 were as deputy director and later as director of the Marshall Space Flight Center. Mr. Lee began his professional career in 1958 as an aeronautical research engineer with the U.S. Army Ballistic Missile Agency at the Redstone Arsenal. He transferred to Marshall when it was formed in 1960 as a systems engineer with the Center's Centaur Resident Manager Office. From 1963 to 1965, he was resident project manager for the Pegasus Meteoroid Detection Satellite Project, and from 1965 to 1969 he was chief of the Saturn Program Resident Office at the Kennedy

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Space Center. In 1969, he became assistant to the technical deputy director of Marshall and served in that position until 1973. He then served as deputy manager and manager of the Sortie Lab Task Team and continued as manager when that team became the Spacelab Program Office in 1974. Mr. Lee holds a B.S. in aeronautical engineering from the University of Alabama.

C. KUMAR N. PATEL is the founder, president, and CEO of Pranalytica, Inc., a Santa Monica-based company that is the leader in quantum cascade laser technology for defense and homeland security applications. He is also a professor of physics and astronomy, electrical engineering, and chemistry at the University of California, Los Angeles (UCLA). He served as vice chancellor for research at UCLA from 1993-1999. Prior to joining UCLA in 1993, he was the executive director of the Research, Materials Science, Engineering and Academic Affairs Division at AT&T Bell Laboratories. He joined Bell Laboratories in 1961 where he began his career by carrying out research in the field of gas lasers. He is the inventor of the carbon dioxide and many other molecular gas lasers that ushered in the era of high-power sources of coherent optical radiation. In 1996, Dr. Patel was awarded the National Medal of Science by the President of the United States of America. His other awards include the Ballantine Medal of the Franklin Institute, the Zworykin Award of the NAE, the Lamme Medal of the Institute of Electronic and Electrical Engineers, the Texas Instruments Foundation Founders' Prize, the Charles Hard Townes Award of the Optical Society of America, the Arthur H. Schawlow Award of the Laser Institute of America, the George E. Pake Prize of the American Physical Society, the Medal of Honor of the Institute of Electrical and Electronics Engineers, the Frederic Ives Medal of the Optical Society of America and the William T. Ennor Manufacturing Technology Award of the American Society of Mechanical Engineers (ASME). Dr. Patel holds a B.E. in telecommunications from the College of Engineering in Poona, India, and received his M.S. and Ph.D. degrees in electrical engineering from Stanford University. In 1988, he was awarded an honorary doctor of science degree from the New Jersey Institute of Technology and is a member of the National Academy of Sciences and the NAE. He has served on several NRC committees, including as chair of the Committee for an Updated Assessment of Atomic, Molecular and Optical Science and as a member of the Committee on Science, Technology, Engineering and Mathematics Workforce Needs for the U.S. Department of Defense and the U.S. Defense Industrial Base as well as the Committee on an Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives.

DIANE ROUSSEL-DUPRE is a level-5 scientist in the Intelligence and Space Research Division at Los Alamos National Laboratory (LANL). While at LANL, Dr. Roussel-Dupre has been involved with various space experiments, including acting as the principal co-investigator and mission manager for the LANL Shuttle-born Uniformly Redundant Array (URA) imaging gamma-ray experiment launched in 1991, participating in the Array of Low-Energy X-ray Imaging Sensors small satellite project launched in 1993 as the mission operations manager and later as the project leader, acting as the mission operations manager for the Fast On-Orbit Recording of Transient Events satellite launched in 1997, and, most recently, as the project leader and mission operations for the Cibola Flight Experiment Satellite Project. In addition to space instrumentation and satellite operations, Dr. Roussel-Dupre contributes to the KARNAC demonstration project for improved space situational awareness. She has served as a member of NASA Commission Mission to the Solar System: Exploration, a Current Discovery Mission and Technology Roadmap, as well as a member of the University of New Mexico's NASA Space Grant Consortium Review and Advisory Board. Dr. Roussel-Dupre also was a member of the GPS Constellation Sustainment Assessment Team as the Los Alamos representative. Dr. Roussel-Dupre has received six LANL distinguished team awards in addition to several other LANL achievement awards. She has also received a distinguished award for service to the U.S. government. She earned a B.S. in physics and astronomy from Michigan State University and was awarded a Ph.D. degree in astrogeophysics from the University of Colorado.

ROBERT L. SACKHEIM recently retired as assistant director and chief engineer for space propulsion at NASA Marshall Space Flight Center (MSFC). He is currently self-employed as a consultant to various organizations in support of rocket propulsion, launch vehicle, and space system projects. At NASA MSFC, he served on the center director's executive staff as a chief advisor for propulsion activities. Prior to joining NASA in 1989, Mr. Sackheim spent 35 years in various technical management positions at TRW Space and Electronics Group.

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His last assignment was as manager of the company's Propulsion and Combustion Center in Redondo Beach, California. In 1983, Mr. Sackheim was recognized for leading the propulsion team responsible for enabling the rescue of NASA's Tracking and Data Relay Satellite. Mr. Sackheim has received numerous awards and honors including the MSFC Director's Commendation for Outstanding Service, the Presidential Rank Award for Meritorious Executive Service, the AIAA Holger Toftoy Award for Outstanding Technical Leadership in Space Systems, and the AIAA Wild Propulsion Award. He is a fellow of the AIAA. He was elected to the NAE in 2001 and in the same year received the NASA Medal for Outstanding Leadership in Space Propulsion. Mr. Sackheim has served on numerous committees at NASA and is an adjunct faculty professor of mechanical engineering at the University of Alabama, Huntsville. He has authored more than 250 technical papers and holds nine patents for space propulsion and controls. Mr. Sackheim holds a B.S. degree in chemical engineering from the University of Virginia and a M.S. degree in chemical engineering from Columbia University. He completed his doctoral course work in chemical engineering at UCLA. Mr. Sackheim has served on several NRC committees, including the Committee on Air Force/Department of Defense Aerospace Propulsion, the Committee on Space Shuttle Upgrades, and the Committee on Advanced Space Technology.

POL SPANOS holds the L.B. Ryon Endowed Chair in Engineering at Rice University. His interests are in the area of dynamical systems with emphasis on probabilistic (risk and reliability), non-linear, and signal-processing aspects and with applications to aerospace engineering and several other engineering disciplines. His research findings have been disseminated in more than 300 papers in archival journals, technical conferences, and industrial reports. Dr. Spanos is editor-in-chief of the *International Journal of Non-Linear Mechanics* and of the *Journal of Probabilistic Engineering Mechanics*. He is a fellow of the ASME, American Academy of Mechanics, and the Alexander von Humboldt Association of America; a member of the NAE (U.S.); a corresponding member of the National Academy of Greece; a member of Academia Europaea; and a foreign member of the Indian National Academy of Engineering. He is a registered professional engineer in Texas. His work has been supported by the National Science Foundation (NSF), the Department of Energy, the Office of Naval Research, AFOSR, NASA, and by many industrial consortia. He has received several awards from NSF, the American Society of Civil Engineers, ASME, the International Association for Structural Safety and Reliability, and Rice University. He has served worldwide as a consultant to a plethora of governmental organizations and industrial entities. Dr. Spanos received an M.S. degree in structural dynamics and a Ph.D. degree in applied mechanics and with minors in applied mathematics and in business economics all from the California Institute of Technology. He has previously served as a member of the NRC Panel on Armor and Armaments.

MITCHELL L.R. WALKER is an associate professor of aerospace engineering in the School of Aerospace Engineering in the College of Engineering at the Georgia Institute of Technology. At Georgia Tech, Dr. Walker has designed and built the High-Power Electric Propulsion Laboratory, studied ion focusing in the Hall Effect Thruster (HET), built annular helicon plasmas sources for HETs, designed and built single and multichannel HETs, and developed carbon nanotube propellantless cold cathodes. His research interests include both experimental and theoretical studies of advanced plasma propulsion concepts for spacecraft and fundamental plasma physics. Dr. Walker is a recipient of an AFOSR Young Investigator Program Award, the AIAA Lawrence Sperry Award, and is an AIAA associate fellow. Dr. Walker served on the NASA Office of the Chief Technologist Advanced In-Space Propulsion Panel Review and the NASA International Space Station Electric Propulsion Testbed Study Committee. He also serves on the National Institute for Rocket Propulsion Systems Technology Solutions Committee, the AIAA Electric Propulsion Technical Committee, and the Best Paper Award Subcommittee. Dr. Walker served as the chair of the AIAA Electric Propulsion Subcommittee for Technical Achievement Award. He earned his B.S.E., M.S.E, and Ph.D. in aerospace engineering from the University of Michigan.

BEN T. ZINN is a Chaired Professor and Regents' Professor Emeritus in the School of Aerospace Engineering at the Georgia Institute of Technology. At Georgia Tech, Dr. Zinn has led the development of the largest university combustion research program in the United States. Over the years, he has made major contributions to the understanding of combustion phenomena in liquid and solid rockets, jet engines, ramjets, afterburners, and land-based

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gas turbines. Examples of his research contributions include the development of the Galerkin method that is routinely used by the propulsion community to predict the stability of propulsion systems, the development of the impedance tube technique for measuring the driving and damping of combustion instabilities, and the measurements of rocket nozzles acoustic losses that is used by industry to predict the stability of rocket motors. In recognition of his contributions, Georgia Tech's combustion laboratory was named after Dr. Zinn in 2006. Dr. Zinn is also a member of the NAE and has won all of the AIAA major combustion/propulsion awards. He earned a B.S. in mechanical engineering from New York University, an M.S. in mechanical engineering from Stanford University, and an M.A. and Ph.D. in aeronautical engineering and mechanical science from Princeton University. Dr. Zinn also served on the NRC Committee on Air Force/Department of Defense Aerospace Propulsion.

STAFF

JOHN F. WENDT, *Study Director,* joined the Aeronautics and Space Engineering Board (ASEB) as a part-time, off-site senior program officer in 2002. He has served on proposal evaluations for the AFOSR and the State of Ohio and has participated in NASA-sponsored studies associated with the Exploration Technology Development Program, NASA Innovative Advanced Concepts, and NASA's laboratory facilities. Prior to joining the ASEB, Dr. Wendt was director of the von Karman Institute (VKI) for Fluid Dynamics, a NATO-affiliated international postgraduate and research establishment near Brussels, Belgium. He joined the VKI in 1964 and was head of the Aeronautics/Aerospace Department and dean of the faculty prior to becoming director. His research interests were rarefied gas dynamics, transonics, high-angle-of-attack aerodynamics and hypersonic reentry, including major inputs to the European Hermes space shuttle program. Dr. Wendt has consulted for USAF, NATO, and the European Space Agency. He is a fellow of AIAA. Dr. Wendt holds a B.S. in chemical engineering from the University of Wisconsin and an M.S. and Ph.D. in mechanical engineering and astronautical sciences from Northwestern University.

CATHERINE A. GRUBER is an editor with the Space Studies Board (SSB) and ASEB. She joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

AMANDA R. THIBAULT, a research associate, joined the ASEB in 2011. Ms. Thibault is a graduate of Creighton University, where she earned her B.S. in atmospheric science in 2008. From there she went on to Texas Tech University where she studied lightning trends in tornadic and non-tornadic supercell thunderstorms and worked as a teaching and research assistant. She participated in the VORTEX 2 field project from 2009 to 2010 and graduated with an M.S. in atmospheric science from Texas Tech University in 2010. She is a member of the American Meteorological Society.

TERRI BAKER joined the SSB in 2009 as a senior program assistant, having worked previously at the National Academies' Center for Education. She has held numerous managerial, administrative, and coordinative positions, in which she focused on improving productivity and organization. Mrs. Baker is working on her B.A. in business management.

RODNEY HOWARD joined the SSB as a senior project assistant in 2002. Before joining SSB, most of his vocational life was spent in the health profession—as a pharmacy technologist at Doctor's Hospital in Lanham, Maryland, and as an interim center administrator at the Concentra Medical Center in Jessup, Maryland. During that time, he participated in a number of Quality Circle Initiatives which were designed to improve relations between management and staff. Mr. Howard obtained his B.A. in communications from the University of Baltimore County in 1983.

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MICHAEL H. MOLONEY is the director of the SSB and the ASEB at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the BPA, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

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C

List of Presenters to the Committee

The following organizations provided presentations to the committee:

- U.S. Air Force

  Air Force Space Command
  Air Force Research Laboratory
  Air Force Space and Missile Systems Center

- NASA Centers

  NASA Kennedy Space Center
  NASA Marshall Space Flight Center

- Federally Funded Research and Development Centers

  The Aerospace Corporation

- Commercial Aerospace Companies

  Aerojet
  Andrews Space
  Astrox Corporation
  Lockheed Martin Corporation
  Orbital Sciences Corporation
  Pratt and Whitney Rocketdyne
  The Boeing Company

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D

Acronyms and Abbreviations

ACS	attitude control system
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AG&C	adaptive guidance and control
ALREST	Advanced Liquid Rocket Engine Stability Technology
ALSB	Advanced Liquid Strap-on Booster
APU	Auxiliary Power Unit
CBC	common booster core
CBT	common bulkhead tanks
CCAFS	Cape Canaveral Air Force Station
CFD	computational fluid dynamics
CI	Continuous Improvement
COMSAT	communication satellite
CONOPS	concept of operations
DDT&E	design, development, test and evaluation
DOD	Department of Defense
ECP	Engineering Change Proposal
EELV	Evolved Expendable Launch Vehicle
EMA	electro-mechanical actuator
ERB	Engineering Review Board
FAA	Federal Aviation Administration
FAST	Future Responsive Access to Space Technologies
FY	fiscal year
GAO	Government Accountability Office

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GEO	geosynchronous Earth orbit
GG	gas generator
GSE	ground support equipment
GTO	geosynchronous transfer orbit
HC	hydrocarbon
HCB	hydrocarbon boost
HEO	high Earth orbit
IHPRPT	Integrated High Performance Rocket Propulsion Technology
IOC	initial operating capability
IOC	initial operational capability
IPA	independent program assessment
IPD	Integrated Powerhead Demonstration
I_{sp}	specific impulse
ISS	International Space Station
IVHM	integrated vehicle health management
LCH4	liquid methane
LCC	life cycle cost
LEO	low Earth orbit
LES	large expendable stage
LH_2	liquid hydrogen
LO_2	liquid oxygen
MCC	main combustion chamber
MEO	medium Earth orbit
MLP	mobile launch platform
MPS	main propulsion system
MR	mixture ratio
MSFC	Marshall Space Flight Center (NASA)
MST	mobile service tower
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NASP	National AeroSpace Plane
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRC	National Research Council
ORSC	oxygen rich, staged combustion
PWR	Pratt and Whitney Rocketdyne
R&D	research and development
RBD	reusable booster demonstrator
RBS	reusable booster system
RECO	rocket engine cut-off
RLC	recurring launch cost
RLV	reusable launch vehicle
RP	rocket propellant

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RTLS	return to launch site
S&T	science and technology
SES	small expendable stage
SLS	Space Launch System
SMC	Space and Missile Systems Center
SRB	solid rocket booster
SSME	space shuttle main engine
SSO	Sun-synchronous orbit
SSTO	single stage to orbit
TPA	turbopump assembly
TPS	thermal protection system
TRL	technology readiness level
TSTO	two stages to orbit
TVC	thrust vector control
VAFB	Vandenberg Air Force Base
VIF	vertical integration facility
VTHL	vertical takeoff, horizontal landing
WDR	wet dress rehearsal

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E

Selected Reusable Launch Vehicle Development History

The fundamental ideas underlying reusable vehicle concepts, such as the reusable booster system (RBS), are not new, and many significant activities have been conducted in both the United States and overseas that are aimed at realizing the potential gains that come with reusability. In this appendix, three large U.S. efforts are briefly reviewed and lessons learned are discussed.

SHUTTLE HISTORY

The space shuttle is the only partially reusable launch system that has successfully been used over an extended time period (USSR's Buran, which was unmanned, was only flown to orbit once). The orbiter is the principal reusable stage of the space shuttle; its solid rocket boosters were recovered and refurbished and its external tank was expended. The orbiter is a manned vehicle that goes into orbit, stays there for several weeks, then reenters and glides back for landing on a runway.

Development History

To comply with the 1969 Space Task Group recommendation that NASA focus on a reusable launch system, it was determined that the keys to space shuttle acceptance were to significantly reduce cost and obtain broad support from all involved government agencies and organizations. As a result of the phase A studies, a fully reusable two-stage concept was the best choice for lowest operational cost per flight. However, it was apparent that concurrent development of both an orbiter and a booster vehicle would be expensive, since peak-year development funding had become a concern. In 1971, the Office of Management and Budget direction constrained the space shuttle overall development cost and limited the annual funding for development to approximately half that estimated to be required for the fully reusable two-stage configuration. These budgetary constraints forced NASA to consider other alternatives, which ultimately resulted in the partially reusable configuration known today.

There were major drivers that impacted NASA's ability to achieve the objective of significantly reducing space shuttle's operational cost:

- Political decisions heavily influenced the development process;
- Budgetary constraints drove the design;

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- Abort capability with engine out (two engines provided best performance and lowest cost);
- Department of Defense (DOD) cross-range requirements drove the configuration and added complexity;
- Continuous additional requirements were introduced during the development process; and
- The complexity of the configuration and its resulting sensitivity and required interactivity provided design challenges, which affected the operational complexities and flight constraints.

Even if the original, totally reusable two-stage human-rated space shuttle system had been properly funded from the outset, it is doubtful that the initial low cost goals would have been met. This conclusion is further supported by what is now recognized as an unrealistically projected high launch rate.

Reusability Assessment

The orbiter's design was performance driven. It needed to achieve low Earth orbit, provide life support for its crew for several weeks, reenter Earth's atmosphere, and glide to a safe landing. The ability to reserve some orbiter weight during its development to make its ground turnaround operations more efficient was not possible. As a result, the anticipated flight rate was never achieved because ground turnaround operations were extensive and very costly.

Maintenance issues associated with the orbiter's reentry thermal protection system (TPS) tiles made rapid ground turnaround impossible. After every flight, each of the orbiter's more than 27,000 tiles had to be individually inspected for damage and adhesion and manually replaced, if necessary.

The orbiter's three main reusable engines (space shuttle main engines, or SSMEs) also required inspection after landing. Because of access and interference issues with other orbiter components, SSME's were removed and replaced after every space shuttle orbiter mission, beginning with operational mission STS-6. Off-orbiter engine processing during the operational phase was done for several reasons. Checkout of the SSMEs required power-up of electrical and fluid subsystems, which interfered with other orbiter processing. Also, access was often needed in the orbiter's engine compartment to other main propulsion system components, and the installed SSMEs restricted access and often resulted in serial processing work in the aft compartment. It was easier (and more efficient) to remove and replace engines than to accommodate these other needs with engines in place. Orbiter and engine processing work could be accomplished in parallel with removal of the engines, thus any unforeseen contingency processing would not impact other components.

This orbiter ground processing experience resulted in the development by NASA of operability/maintainability design considerations for next generation reusable launch vehicles.

NATIONAL AEROSPACE PLANE HISTORY

The National Aero-Space Plane (NASP) was a project jointly funded by NASA and DOD to create a single-stage-to-orbit spacecraft.[1] The NASP concept evolved from the "Copper Canyon," the Defense Advanced Research Projects Agency (DARPA) project, running from 1982 to 1985. The vehicle was planned for a crew of two and was meant to serve access-to-space missions. In 1990, McDonnell Douglas, General Dynamics, and Rockwell International formed a national team to develop a demonstrator vehicle, the X-30, to deal with the technical and budgetary issues.

There were six technologies considered critical to the success of the project; three of them were related to the propulsion system. The X-30 was intended to use an engine that could shift from a low-speed propulsion system to a scramjet system as the vehicle ascended; it would burn liquid hydrogen fuel with oxygen taken from the atmosphere. An auxiliary LO_2/LH_2 rocket engine was used to augment the scramjet engine at very high speeds and for propulsion needs in space.

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[1] B.W. Augenstein and E.D. Harris, *The National Aerospace Plane (NASP): Development Issues for the Follow-On Vehicle,* R-3878/1-AF, RAND Corporation, Santa Monica, Calif., 1993; Encyclopedia Astronautica, X-30, available at http://www.astronautix.com/lvs/x30.htm, accessed on October 9, 2012.

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The scramjet engine was a key to the NASP multi-cycle engine. In a scramjet the onrushing hypersonic air is compressed and passed into a combustion chamber in which hydrogen is injected and burned by the hot, compressed air. The exhaust is expelled through a nozzle creating thrust. The efficient functioning of the engine depends on the aerodynamics of the airframe, the underside of which serves as the air inlet and the exhaust nozzle. Design integration of the airframe and engine are thus critical to the success of the design.

Other enabling technologies include the development of materials that would maintain structural integrity at very high temperatures, sometimes in excess of 1,800°F. The enormous heat loads associated with hypersonic flight have required the development of active cooling systems and advanced heat-resistant materials.

Using atmospheric oxygen instead of tanked LO_2 for the majority of the mission, the NASP airbreathing engines were projected to have a specific impulse that is approximately 3 to 4 times that of a LO_2/LH_2 rocket engine. This enables a single-stage-to-orbit (SSTO) vehicle with propellant mass fraction of approximately 76 percent to achieve orbital speeds. So the principal technical challenge was to achieve the high performance of the airbreathing engines, while limiting the impact of the inert mass of these engines and the additional mass of the thermal protection system required to protect the vehicle during its ascent to orbit.

Despite significant progress in structural and propulsion technology, the program had substantial hurdles to overcome. DOD wanted it to carry a crew of two, plus a small payload. The demands of being a man-rated vehicle operating as a SSTO vehicle made the X-30 more expensive, larger, and heavier than is required for a demonstrator vehicle.

As a SSTO vehicle with a turnaround time of 24 hours or less, proponents initially viewed the X-30 as leading the way to faster, cheaper access to low Earth orbit. What became obvious was that the claims made for NASP as a space launch vehicle were similar to the initial claims made for the space shuttle in the early 1970s. The assertions that NASP would have airplane-like operating characteristics were assumptions, not conclusions based on detailed analysis.

NASP never achieved flight status and finally fell to budget cuts in 1993. But it also was cancelled because of its severe technological overstretch. Although the X-30 program never came near to building significant hardware, NASP development work contributed in an important way to the advancement of propulsion technology and high-temperature materials as well as materials capable of tolerating repeated exposure to extremely low temperatures (the cryogenic fuel tanks). By 1990, NASP researchers had realized significant progress in titanium aluminides, titanium aluminide metal matrix composites, and coated carbon-carbon composites. Moreover, government and contractor laboratories had fabricated and tested large titanium aluminide panels under approximate vehicle operating conditions, and NASP contractors had fabricated and tested titanium aluminide composite pieces.

When NASP was cancelled, the government admitted to making a $1.7 billion investment in the National Aerospace Plane, but parts of the research and development were classified, and the official costs may have been higher.[2]

Lessons learned from the NASP program include the following:

- SSTO vehicle technologies using airbreathing engines are beyond the existing state of the art;
- Aerothermodynamics of sustained flight at high hypersonic speed within the atmosphere creates significant challenges with regard to materials and thermal management; and
- Propulsion technology should be independently matured prior to initiation of large-scale vehicle development programs.

X-33 HISTORY

The X-33 VentureStar was intended to be a one-third-scale prototype of a Reusable Launch Vehicle (RLV), designed to significantly lower the costs of launching payloads. VentureStar was a very ambitious effort by NASA and Lockheed Martin to develop a fully reusable, vertical launch and horizontal landing, manned, (SSTO vehicle. To achieve SSTO capability, VentureStar needed to incorporate high thrust and high-specific-impulse propulsion

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[2] R. Launius, After Columbia: The Space Shuttle Program and the crisis in space access, *Astropolitics* 2:277-322, 2004.

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and have a mass fraction higher than 0.88. During development of a SSTO, any small increase in vehicle weight directly offsets payload capability, requiring either a very strict weight reduction activity (costly) or vehicle upscaling (even more costly). If the SSTO vehicle's mass fraction falls below 0.88, its weight for delivery of a given payload to orbit grows asymptotically as the vehicle becomes unable to lift even itself into orbit. Today's most efficient expendable upper stage (Centaur) has a mass fraction of 0.90. Making a stage larger helps, but adding thermal protection for reentry, aerodynamic surfaces for lift and control, landing gear, and life support for manned use makes meeting the 0.88 minimum mass fraction requirement extremely difficult. X-33 was to address and demonstrate the many technology issues associated with meeting this requirement.

Significant advances were made with the thermal protection system developed by B.F. Goodrich, which also served as the aerodynamic surface of the vehicle. The Rocketdyne XRS-2200 Linear Aerospike main engines were on target to become the next generation of liquid fueled propulsion systems. Both of the conformally shaped LH_2 and LO_2 propellant tanks were initially to be composite, but after engineering objections, the smaller LO_2 tank was successfully manufactured with aluminum-lithium (Al-Li). Management insisted, however, that for X-33 to be a useful technology enabler, the multi-lobed LH_2 tank had to be made of composites.

Development problems were encountered with the LH_2 tank, along with Rocketdyne's decision to use Narloy-Z (a heavy copper alloy), which drove changes to the flight control surfaces. These major issues (and other smaller ones) resulted in substantial cost increases and schedule delays. The composite hydrogen tank failed during testing, which resulted in program cancellation in 2001. X-33's development cost a reported $1.5 billion over 5 years; the vehicle was approximately 40 percent complete at cancellation, and its test flight facilities at Edwards Air Force Base were ready. If the LH_2 tanks had been manufactured of Al-Li instead of a composite as proposed by the X-33 engineering team, they would reportedly have been lighter than the composite tank and, therefore, successful. Unfortunately, all the successful new technology was laid to rest along with the death of the X-33, and the opportunity to gather useful flight information that would have been applicable to a reusable booster was lost.[3]

RBS DIFFERENCES

In addition to the three large programs discussed above, there have been and continue to be numerous smaller efforts in the United States and internationally aimed at development of reusable launch vehicles. Within the United States, these include the X-20 Dyna-Soar, X-34, Delta Clipper, Kistler K-1, DreamChaser, Prometheus, and Blue Origin New Sheppard. Internationally, these include the HOTOl, Skylon, Sanger, and Buran. A detailed investigation of these programs was beyond the statement of task for this committee.

A number of important differences exist between the three reusable launch vehicle programs described above as compared to the RBS concept, including the following.

- The three RLV programs described above were intended for manned operations, which imposes numerous subsystem requirements that add to the inert launch vehicle mass. The RBS concept is not intended to be human rated, so it will not be burdened by this additional inert mass requirement.
- The previous RLV programs involved reusable vehicles that were launched into space and needed to survive orbital reentry conditions. In the base of the RBS concept, the maximum Mach number of the reusable booster is between 3 and 7, so the requirements for a thermal protection system are greatly diminished.
- The space shuttle used a reaction-control system that operated with toxic propellants, which greatly complicated operations and significantly impacted turn-around time. As a new design, the RBS concept development can pursue use of non-toxic propellants for the attitude-control system, which would provide significant operability advantages.
- Most RLV programs were based on the use of hydrogen as the fuel. (An exception is the Kistler K1 project, which was based on the use of LO_2/RP propellants.) The RBS concept is based on the use of a hydrocarbon fuel for the reusable booster. This higher density fuel will likely result in a more structurally and aerodynamically efficient vehicle configuration.

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[3] R. Launius, After Columbia: The Space Shuttle Program and the crisis in space access, *Astropolitics* 2:277-322, 2004.

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Also, if the RBS development were to be pursued using the staged development approach as recommended by this committee, each of the technology risks would be matured to a much higher technology readiness level prior to committing to full-scale vehicle development and flight certification, as compared to the above RLV programs. This approach contrasts dramatically with the manner in which technology risks were addressed in the previous RLV programs. In these programs, the major technology risks (i.e., the reusable SSME and solid rocket motor for the space shuttle; the combined-cycle engine for NASP, and the ultra-lightweight structure with hydrogen fuel for the X-33) were all developed in parallel with the full-scale vehicle development.

With these considerations, there are clear differences between the RBS concept and previous RLV programs. And, while efficient reusability remains an elusive goal for launch, the committee believes that the RBS concept represents a logical compromise between fully reusable and fully expendable systems that is technically achievable in a well-structured program. So, while the committee does not believe that the business case of the RBS concept can be closed at this time, it is important to continue to mature the underlying technologies.

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RBS Booster Design for Operability

The ground and flight operations requirements for the reusable booster system (RBS) concept have not been sufficiently defined to allow assessment of the impact on the vehicle design. The Air Force baseline mission model includes eight RBS launches per year, using four RBS boosters on each coast (Cape Canaveral Air Force Station and Vandenberg Air Force Base). This mission model does not result in a rapid ground processing requirement for the reusable boosters. The committee believes that the RBS should accommodate future rapid-response space launch needs. As such, it would be desirable to design the RBS booster and its ground infrastructure for relatively rapid processing between missions. Clearly, this would result in a trade-off between the development cost and recurring operations cost, without any clear driving requirement. However, because the unpiloted reusable booster will need to include Autonomous Guidance and Control and Integrated Vehicle Health Management (IVHM) in order to reliably perform its in-flight mission, IVHM is available for use to help streamline booster ground processing.

Operability considerations will likely impose design requirements of the RBS and may lead to changes to standard launch vehicle ground operations. A brief discussion of these operability considerations follows.

- *Booster ground processing for reuse.* The reusable booster returns from a mission and lands horizontally at the launch base landing strip. It needs to be made safe, remaining fluids must be off-loaded, tanks purged, and items requiring maintenance need to be identified. It is very desirable that any fluid handling be nonhazardous so that Self Contained Atmospheric Protection Ensemble operations are avoided. IVHM are used to determine maintenance requirements without needing technician access for checkout. Once required maintenance items have been completed and checked by IVHM, the booster is mated to the integrated large expendable stage (LES) with its encapsulated payload. This can occur at the launchpad or in a separate integration facility. Rise-off disconnects attach fluid, electrical, and data interfaces to the booster and upper stage. Following final automated vehicle checkout, propellants are loaded and the vehicle is launched.
- *Operability design considerations.* Based on NASA's very challenging space shuttle orbiter reuse experience, rapid ground processing can be achieved only when system operational functions drive vehicle design. It is vitally important to apply system margins early in the design process to enhance operability. A robust reusable vehicle design should trade weight/performance to achieve increased component reliability and dependability, which are keys to low-cost operations. Hardware replacement costs should be a small percentage of the recurring cost of flight.

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- *Specific considerations for reusable systems.* Design considerations that are important to enable efficient booster reusability along with associated accessibility and maintenance goals are listed below.[1]

— Strive to isolate booster ground processing from dependence on facilities and ground support equipment by incorporating frequently used ground checkout equipment into the booster. Routine, scheduled turnaround ideally replenishes only consumables. Eliminate "flight readiness-style" booster certification for every flight. Provide aircraft-style vehicle-type certificate for repetitive flight operations.

— Booster subsystems should be independently power up-able and easily accessible when maintenance is required. This allows work to be performed in parallel with other systems and avoids processing conflicts.

— Avoid closed launch vehicle compartments, which require purges before personnel entry and complicate access and closeout requirements.

— When common propellants can be used, primary and secondary propulsion systems should be highly integrated, using common storage tanks, feed lines, etc. This reduces handling requirements for multiple propellants and reduces interfaces.

— Thermal protection systems should be robust and maintenance-free. Avoid thermal protection systems that are prone to in-flight degradation or that absorb moisture.

— Fewer rocket engines, preferably between two and four main engine, provide multiple operability benefits, such as reducing confined spaces which inherently require purges, reducing servicing and ground interfaces and reducing the number of systems for leak detection.

— IVHM can provide component and system health monitoring to identify those items requiring maintenance. It is critical that IVHM include the nonintrusive detection of fluid leakage and other techniques to reduce the large amount of unplanned maintenance that may be between flights. See Appendix E.

— Provide designs that limit the need for leak-test verification for fluids and gases in both static and dynamic applications by the use of all-welded systems whenever possible. Provide designs for electrical power and data transmission that reduce the use of cable connectors to minimize troubleshooting and repair.

— Where possible, use environmentally benign technologies. Avoid the use of hypergolics for auxiliary propulsion, main engine start, or power generation, if possible. If hypergolics must be used for the reaction control system, incorporate them as modular subsystems allowing for easy removal and replacement. Also avoid toxic freons and ammonia. Avoid the need for vehicle purges wherever possible.

— Avoid hydraulics for engine thrust vector control and to actuate aerodynamic control surfaces, landing gear, etc.; use electric actuators for these functions.

— A reusable flyback booster has a relatively short mission duration, permitting use of batteries rather than propellants for power generation.

— Implement a flight vehicle on-board system that provides its own power management, requiring only one vehicle-to-ground interface at each ground-facility station.

— Equipment should be mounted so that it is readily accessible. Avoid mounting equipment in closed compartments where access can result in collateral damage and unplanned work. Locate equipment on walls with external access or in open compartments that permit easy personnel access. Use aircraft-like access panels.

— Launchpad fluid, electrical, and communications interfaces should be implemented through rise-off disconnects located at the base of the booster and LES. If a mobile launch platform is used, its services should be connected to launchpad infrastructure with auto couplers.

— All subsystems and components should be qualified for the specified life of the reusable vehicle. Where this is not possible, and when removal and replacement over a reduced number of flights is required, these subsystems/components need to be readily accessible for ease of removal and replacement and post-installation checkout.

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[1] See also Huether, Spears, McCleskey, and Rhodes, "Space Shuttle to Reusable Launch Vehicle," presented to the Thirty-Second Space Congress, Canaveral Council of Technical Societies, 1995; NASA, *An Operational Assessment of Concepts and Technologies for Highly Reusable Space Transportation,* Highly Reusable Space Transportation Study Integration Task Force, Operations, NASA Centers, November 1998.

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RBS OPERABILITY REQUIREMENTS AND TECHNOLOGY DEVELOPMENT IMPLICATIONS

The committee believes that achieving RBS booster ground turn-around operability is more of a design-requirements issue than a technology-development issue. The problem with many of the past reusable rocket vehicle designs (either single stage to orbit or an upper stage) is that they were so performance driven that even if operability requirements had been imposed, they could not have been effectively implemented without seriously compromising vehicle flight performance. Therefore, if operability requirements were imposed, they were assigned a low priority. This is certainly what happened during the space shuttle orbiter development (see Appendix E). The RBS booster, because its design is not nearly as performance driven, offers the opportunity for operability requirements to be imposed on at least an equal footing with performance requirements.

The specific operability recommendations contained earlier in this appendix were generated by NASA as a result of their orbiter experience. In addition to imposing a top-level operability requirement (e.g., the RBS booster shall be capable of re-flight in XX hours with a YY person ground crew), the NASA-generated recommendations listed previously could be tailored for RBS and specified by the Air Force as detailed operability requirements for the RBS booster. Also, they could be imposed as being equally important as the flight performance requirements.

From a technology development standpoint, IVHM and its associated sensors is clearly the tall pole for implementing operability, which is discussed in Section 3.1.8. Most of NASA's recommendations are well understood design approaches that require little technology development. They are usually not "least weight" design options, which is why they have not been implemented in current expendables or performance-driven reusables. Many of the design approaches recommended are similar to, or fairly standard to, those used on commercial and military aircraft. Adapting these to the RBS booster will require redesign to accommodate the harsh vibration and acoustic environment imposed by rocket engines and then validation by extensive qualification testing. This redesign/qualification effort could be considered technology development, but it is not considered an especially high technical risk. However, the committee believes there is significant cost risk associated with attempting to qualify revised designs currently used on aircraft to the very harsh rocket launch environment.

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