Upgrading the Space Shuttle

Committee on Space Shuttle Upgrades, National Research Council

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Upgrading the Space Shuttle

Committee on Space Shuttle Upgrades
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

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Preface

The space shuttle is a unique national resource. One of only two operating vehicles that carries humans into space, the space shuttle functions as a scientific laboratory and as a base for construction, repair, and salvage missions in low Earth orbit. It is also a heavy-lift launch vehicle (able to deliver more than 18,000 kg of payload to low Earth orbit) and the only current means of returning large payloads to Earth. Designed in the 1970s, the shuttle has frequently been upgraded to improve safety, cut operational costs, and add capability. Additional upgrades have been proposed—and some are under way—to combat obsolescence, further reduce operational costs, improve safety, and increase the ability of the National Aeronautics and Space Administration (NASA) to support the space station and other missions.

In May 1998, NASA asked the National Research Council (NRC) to examine the agency's plans for further upgrades to the space shuttle system. The NRC was asked to assess NASA's method for evaluating and selecting upgrades and to conduct a top-level technical assessment of proposed upgrades. The complete statement of task is reprinted in Appendix A.

In June 1998, the NRC, under the auspices of the Aeronautics and Space Engineering Board, formed the Committee on Space Shuttle Upgrades to carry out this task. (Short biographies of the committee members appear in Appendix B.) In July, the committee met with shuttle program managers and received briefings on current and proposed upgrades to the space shuttle and the process for selecting upgrades for implementation. Additional teleconferences and site visits were held in August and September to gather more detailed information about individual upgrades, the prioritization process, and the upgrades program as a whole. The committee would like to thank the many enthusiastic and responsive individuals who briefed or otherwise interacted with the committee during this process. We would also like to thank Hugo Delgado, of NASA's Office of Space Flight, for acting as liaison between NASA and the committee.

This report is the committee's response to the Statement of Task. The report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review was to provide candid and critical comments to assist the authors and the NRC in making the 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 participation in the review of this report:

Mel Eisman, RAND Corporation
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John M. Logsdon III, Space Policy Institute
Simon Ostrach, Case Western Reserve University

While the individuals listed above provided constructive comments and suggestions, responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee was not asked to—and does not—discuss the larger issue of whether the shuttle should be upgraded. This report is limited to a review of NASA's approach to selecting and prioritizing upgrades and a top-level technical assessment of several representative proposed upgrades. The decision to implement many of the major proposed shuttle upgrades must await a high-level national policy decision on when the shuttle should be phased out in favor of some other launch vehicle (or vehicles). Although it may be tempting to delay making this decision until it becomes perfectly clear when a shuttle replacement will be available, a timely decision is crucial for NASA to act efficiently either by phasing out its shuttle upgrade program or by making the major investments necessary for the shuttle to carry out its long-term mission reliably and efficiently.

Bryan O'Connor, *chair*
Committee on Space Shuttle Upgrades

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The National Academy of Sciences is a private, nonprofit, selfperpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vicechairman, respectively, of the National Research Council.

Executive Summary

The space shuttle system has been modified many times since the first launch of space shuttle Columbia in 1981. During the 1980s, major upgrade programs were established to respond to problems and anomalies experienced during the initial flights and the Challenger accident. Additional upgrades were approved in the early 1990s to enable the shuttle to visit the Mir space station and support the International Space Station. In 1996, however, the shuttle program effectively ceased approving new changes to the space shuttle design to concentrate scarce resources on developing potential replacements for the shuttle. The same year, the responsibility for some operational elements of the Space Shuttle Program were transferred to the United Space Alliance (USA) corporation.

During fiscal year 1997, the National Aeronautics and Space Administration (NASA) lifted the "design freeze" and authorized the Space Shuttle Program to dedicate about $100 million of its reserves each year to a new upgrade program. This program funds relatively minor modifications intended to reduce obsolescence, support missions, improve safety, and reduce costs, as well as studies of potential major upgrades. Implementation of any major upgrades, however, will necessarily be held off until a high-level national decision scheduled for the end of the decade is made on whether to phase out the shuttle by the year 2012 or to continue operating it indefinitely.

Information on potential upgrades to the shuttle is collected, organized, and prioritized by the Space Shuttle Program Development Office, which reports to the manager of the Space Shuttle Program. Each candidate upgrade is designated as Phase I, Phase II, Phase III, or Phase IV, depending on when it was approved and its anticipated cost and effect on the space shuttle design (see Table ES-1).

TABLE ES-1 Upgrade Phases

Phase	Main Focus	Typical Cost	Status
I	Improving safety, supporting the International Space Station	> $100 million	Either completed or will be by 2000
II	Combating obsolescence	$10 to $50 million	Some under way; some in study phase
III	Enhancing shuttle capability (does not change the fundamental shuttle configuration)	$10s to $100s of millions	Studies only
IV	Enhancing shuttle capability (changes the fundamental shuttle configuration)	> $1 billion	Studies only

In addition to the phased upgrades, the USA corporation has limited incentives to initiate and implement cost-saving upgrades.

CHOOSING UPGRADES

NASA uses its limited budget for shuttle upgrades to fund minor upgrades with identifiable short-term benefits and to conduct preparatory studies for major upgrades that may be warranted if the shuttle program is called upon to operate after 2012. In spite of budget uncertainties, technical risks with the development of a reusable launch vehicle (shuttle replacement strategy), and existing national policy restrictions on shuttle use, the committee believes that NASA's approach to upgrade planning is appropriate. Candidate upgrades are proposed to a central office, which prioritizes them with the assistance of tools that are under development. The committee commends NASA for its efforts to develop a formal process for evaluating and prioritizing upgrades.

Prioritizing and Selecting Upgrades

Decision makers in the shuttle program are facing an uncertain future. They do not know how long the nation will want shuttle flights to continue, the number of flights per year that will be required, or the missions (if any) beyond supporting the International Space Station (ISS) the shuttle will be expected to perform. For these reasons, developing an appropriate process for selecting upgrades for implementation has been difficult. Other organizations, such as the U.S. Air Force, have faced similar situations, however, and NASA should evaluate their investment decision processes for upgrades and identify appropriate processes and investment strategies to emulate.

The committee strongly supports NASA's use of program goals to help prioritize upgrades. However, the Space Shuttle Program Development Office should restate the goals of the upgrade program to ensure that they reflect the upgrade program's actual priorities, are feasible, and are clearly understandable by everyone working in the program. NASA should also provide better incentives for the USA corporation (and any future prime contractors for shuttle operations) to propose, fund, and implement upgrades to achieve the shuttle program's goals. Whether or not a shuttle-unique upgrade supports an increased flight rate should not be considered in the prioritization process unless NASA can prepare a viable business plan showing that (1) the shuttle could attract enough additional business to justify the increased flight rate, (2) the Space Shuttle Program would not unfairly compete with commercial launch vehicles, and (3) the shuttle, a national asset, would not be subjected to unnecessary risks.

NASA is taking steps to improve its process for selection of upgrade candidates for implementation. These steps are designed to provide a more visible quantitative comparison approach that should help balance some of the traditional internal and external political and other subjective pressures on the program.

One of the tools that NASA is using to help prioritize candidate upgrades is the quantitative risk assessment system (QRAS), a software tool being developed specifically for assessing risks to the shuttle. The committee believes that this tool has the potential to be very helpful in assessing and comparing the impact of shuttle upgrades on shuttle safety. NASA should continue to increase the scope and capability of the QRAS system so that it provides better models of failures caused by human error, combinations of risks, abort modes, on-orbit hazards, reentry and landing hazards, and software problems. Until these improvements are made, the Space Shuttle Program Development Office should be very cautious in using QRAS to aid in prioritizing upgrades.

NASA is also funding development of the Decision Support System to assist in prioritizing upgrades. The committee believes that when this system is more mature, it will be a valuable tool. However, the current Decision Support System will require significant modifications before it can be a reliable input to the prioritization process. NASA should consider modifications that would place less emphasis on quantitative results and more on a clear, defensible decision process that takes into account all of the available evidence.

Upgrade cost estimates provided by NASA to the committee contained inconsistencies in their scope, assumptions, and basis. For these estimates to be helpful, the agency must ensure that they are as accurate as possible and are calculated consistently. All calculations, comparisons of costs and cost savings, and cost-benefit assessments should be based on fixed-year dollars and should include all of the costs associated with the upgrade, including hidden costs, such as integration costs and the cost of operating and maintaining the upgrade.

Improving Candidate Upgrades

To ensure that NASA can select the best upgrades for the shuttle program, there must be a pool of high quality potential improvements. The shuttle program can take steps to improve the pool of proposed upgrades such as external proposals, early compatibility studies, limits to software changes, and trade-off studies. The Space Shuttle Program Development Office should not consider proposed upgrades as stand-alone proposals, but where appropriate, should look for ways to combine upgrades (or features of upgrades) to efficiently meet future requirements.

ASSESSMENTS OF PROPOSED UPGRADES

From the information presented to the committee, it is clear that a great deal of creative and useful work has been done to design and develop ongoing and proposed upgrades to the space shuttle system. The committee was able to assess the potential of some key upgrades to meet Space Shuttle Program goals, point out areas of technical or programmatic risk, and suggest alternatives. Figure ES-1 shows the locations of selected representative upgrades in the shuttle system.

Phase II Upgrades

Checkout Launch and Control System

The checkout launch and control system (CLCS) is an upgrade to the launch processing system used to check out, control, and process shuttle flight systems, ground support equipment, and facilities at Kennedy Space Center. The current system is growing obsolete, and the CLCS upgrade will replace it with modern commercial hardware and software. Based on historical precedent, the committee believes that the large and complex CLCS upgrade is likely to experience schedule delays and budget overruns. NASA should audit the requirements, specifications, plans, schedules, development budgets, status, and life cycle costs of the CLCS project. The objective of this audit should not be to cancel the upgrade but to make more accurate estimates of the time and cost required to complete it and to identify potential problems early enough in the project to rectify them.

Protection from Micrometeoroids and Orbital Debris

As part of the Phase II upgrade program, the shuttle orbiters will be modified during 1999 and 2000 to protect the radiators and the leading edge of the wings from meteoroids and orbital debris. Considering the predicted high level of risk from this hazard even after these modifications are made, the space

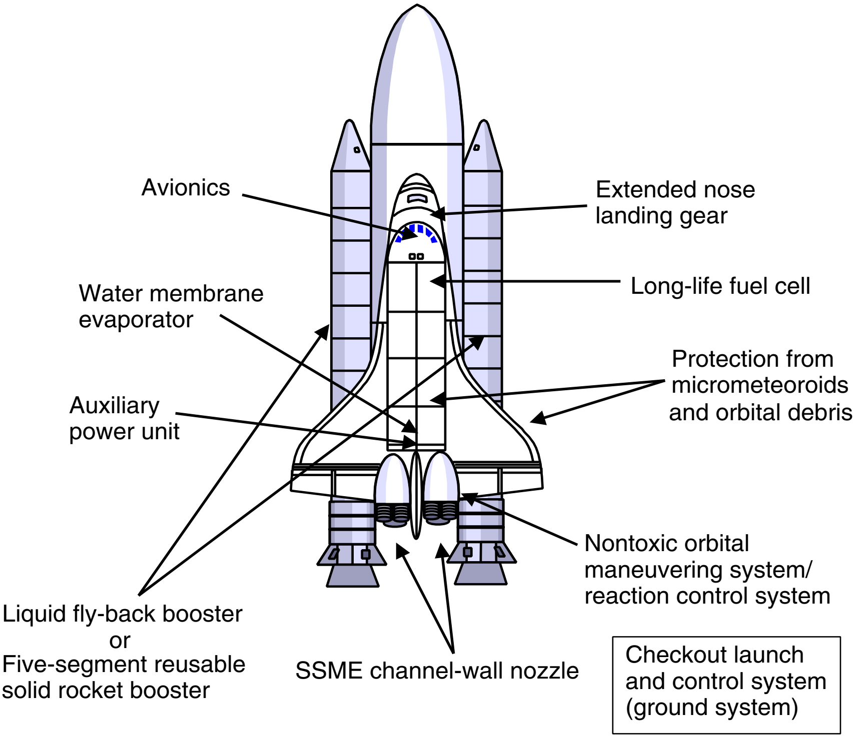

FIGURE ES-1 Location of assessed upgrades.

shuttle upgrades program should solicit additional upgrade proposals for protecting the shuttle from meteoroids and orbital debris.

Phase III Upgrades

Auxiliary Power Unit

Every shuttle orbiter has three auxiliary power units (APUs) to pressurize the vehicle's hydraulic systems during ascent and reentry. NASA is studying a number of options for replacing the current APUs—which use toxic hydrazine propellant—with an electric system that would be safer and easier to maintain. NASA should continue studying potential modifications to the APUs to determine the costs, benefits, and appropriate scope of each upgrade. The development of electric power systems worldwide should be monitored for technologies and techniques that could improve an APU upgrade.

Avionics

The orbiter's current avionics system was conceived in the early 1970s but contains hardware that was added during the 1980s and 1990s. The objective of NASA's proposed avionics upgrade is to avoid the growing costs associated with obsolescent components by judiciously replacing hardware and, at the same time, positioning upgrades as components of a modern, functionally partitioned avionics architecture. NASA should continue this strategy and should develop and publish scaleable, long-term requirements and interface definitions for the future architecture.

Channel-Wall Nozzle

The channel-wall nozzle is a proposed replacement for the current space shuttle main engine nozzle. The channel-wall nozzle is a relatively simple design based on a manufacturing process developed in Russia. NASA plans to build the nozzle in Russia (through Rocketdyne's subcontractor Aerojet) to reduce development costs. If NASA decides to implement this upgrade, it should take steps to ensure that channel-wall nozzles are available in the United States, either by stockpiling additional nozzles or developing a channel-wall nozzle manufacturing capability in the United States.

Extended Nose Landing Gear

The proposed extended nose landing gear is a modification intended to reduce loads on the orbiter's landing gear. Based on work performed to date, the proposed upgrade appears to be a good design for reducing shuttle landing loads. However, the existing nose landing gear meets current requirements, so NASA should pursue the upgrade only if future plans require that the shuttle land with heavier payloads than are currently allowable.

Long-Life Fuel Cell

The orbiter's fuel cells provide electric power for the orbiter and water for the crew. Two distinct upgrades—longer-life alkaline fuel cells and proton exchange membrane (PEM) fuel cells—are being considered to replace the current cells. Modified alkaline cells would be similar to the current cells but would require less maintenance. The PEM cells would last longer, produce more power, and be less toxic than either the current or the improved alkaline cells. However, the PEM cell upgrade would involve an expensive and potentially open-ended technology research program. NASA should explore the costs and benefits of the PEM cell further before deciding on a new fuel cell. Planners of future space missions that could benefit from PEM fuel cells should be closely involved in these studies. These planners could help determine the value of PEM cells for future missions, influence the design of the shuttle's PEM cells so that they will be applicable to future missions, and, perhaps, provide funding.

Nontoxic Orbital Maneuvering System/Reaction Control System

This upgrade would modify the shuttle orbiter's orbital maneuvering and reaction control systems to use nontoxic liquid oxygen and ethanol propellants and would connect both systems to common propellant tanks. NASA believes that the proposed upgrade would reduce hazards on the ground and in orbit, improve ground operations and turnaround times, save money, and increase shuttle performance. Before making any decision on implementation, however, NASA should very carefully study all of the risks inherent in changing to a liquid oxygen/ethanol system and conduct trade-off studies to determine whether modifications to the existing system may be a more cost-effective means of meeting program goals. Commonality with the propulsion (and possibly the life-support) systems of the ISS and other future NASA programs should be considered in the final design.

Water Membrane Evaporator

The water membrane evaporator (WME) is being considered as a replacement for the orbiter's flash evaporator system (FES), which cools the orbiter during ascent and entry and provides supplemental cooling in orbit. The WME appears to be a simple passive device that can accomplish the FES's cooling function without the corrosion that creates a risk of freon leaks in the FES. However, other options to reduce freon leakage (such as using more corrosion-resistant materials in the FES) could potentially be lower-cost and lower-risk solutions to the problem. NASA should carefully weigh the costs and benefits of all options for dealing with the FES corrosion problem before choosing a solution.

Phase IV Upgrades

NASA is currently evaluating the merits of two new first stage booster concepts: the five-segment reusable solid rocket booster (RSRB), and the liquid fly-back booster (LFBB). To varying degrees, each concept promises improvements in safety, performance, and life cycle cost. Each concept also requires significant system integration, as well as a thorough ground and flight test program. Each will also require large initial investment.

An important consideration in NASA's ongoing space transportation studies is that the existing four-segment RSRB has demonstrated high reliability since its first flight in 1988. It also satisfies NASA's known performance requirements for the Space Station era. These facts, combined with the risks involved in changing to a relatively unproven booster on a manned vehicle with only minimal crew escape capability means that NASA is not likely to, and the committee agrees it should not, enter into any major new booster program without substantial national need for the performance enhancements and long-term safety and cost benefits.

Five-Segment Reusable Solid Rocket Booster

A recent proposal by Thiokol Propulsion, this upgrade would add a fifth segment to the shuttle's RSRB, alter the grain of the solid fuel to provide a safer thrust profile, and modify the RSRB's nozzle and insulation. On its surface, the five-segment RSRB appears to be a relatively straightforward approach to improving the performance of the booster, but it will require substantial integration engineering and testing. Early estimates suggest at least $1 billion development cost. A thorough evaluation of the potential for separate implementation of subsets of the proposal should be included in NASA's ongoing assessment.

Liquid Fly-Back Booster

This NASA generated concept would replace the shuttle's solid rocket boosters with liquid-fueled boosters designed to fly back automatically to the launch site after they have separated from the orbiter. NASA believes that the LFBB would cost $4 to $5 billion to develop but would improve safety, reduce long-term operational costs, enable a higher flight rate, and increase the shuttle's payload capacity. Before proceeding with the LFBB, NASA should initiate a detailed independent assessment of configuration trade-offs, costs, and programmatic and technical risks to determine the best fundamental configurations for a new liquid shuttle booster. Should NASA proceed with this program, they should closely coordinate their efforts with other government and industry transportation initiatives.

1

Background

In 1972, President Nixon approved the development of the space shuttle. The shuttle—the world's first reusable space launch vehicle—was intended to provide routine, economical access to space. It would be capable of delivering a variety of government and commercial satellites to low Earth orbit and would serve as a platform for numerous human-related space activities. Plans called for a multiple-orbiter fleet that could fly many times a year, thus bringing down the cost of launching payloads into space. A massive development program culminated in the first launch of space shuttle Columbia in 1981.

In the early years of shuttle operations, every successful mission showed that the shuttle was indeed a very versatile spacecraft. However, some systems had to be modified in response to problems and anomalies experienced during the initial flights. Initial upgrades included improvements to the external tank insulation, the replacement of several thousand insulation tiles with insulation blankets, and modifications to the wheel brakes and auxiliary power units (APUs). Despite these and many other improvements, it became clear that the shuttle's extensive requirements for refurbishment and maintenance would make it difficult for the program to achieve high flight rates and low launch costs.

After 24 successful shuttle flights, the 1986 Challenger accident stunned the nation and caused the National Aeronautics and Space Administration (NASA) to reevaluate many fundamental design features of the shuttle vehicle, as well as its entire operations support system, in order to reduce risk. During the nearly two-and-one-half year recovery period following the accident, more than 200 changes were made to the shuttle system, including a major redesign of the solid rocket motor joints and the addition of a limited crew escape capability.

Maintenance and flight procedures were also significantly modified, and substantial structural improvements were made to the launch pad, the external tank, and the solid rocket booster.

More than a billion dollars was spent on these changes before the shuttle returned to flight, and funding in subsequent budgets was allocated for several major follow-up improvements. Upgrades planned for incorporation after the shuttle's return to flight included the advanced solid rocket motor (ASRM), a 14-inch diameter disconnect valve for the main engine propellant line, high-performance carbon wheel brakes, redundant high-speed nose wheel steering, and modifications to the shuttle's software to increase the chances that aborts during ascent will be successful. Virtually all changes were approved based on their capability to improve system reliability or operational safety. Some, including the ASRM, the 14–inch propellant disconnect valve, and a high-performance escape system, were later canceled because of unanticipated technical problems and/or high costs.

At the same time, the role of the shuttle in the nation's space endeavors was being reassessed at the national policy level. A December 1986 National Security Decision Directive stated that "NASA shall no longer provide launch services for commercial and foreign payloads unless those spacecraft have unique, specific reasons to be launched aboard the Shuttle." In 1991, a new National Space Launch Strategy restated the shuttle restriction and added "as the nation is moving toward development of a new space launch system, the production of additional space shuttle orbiters is not planned." It also stated:

> By continuing to operate the Shuttle conservatively, by taking steps to increase the reliability and lifetime of existing orbiters, and by developing a new launch system, the operational life of the existing orbiter fleet will be extended (White House, 1991).

In compliance with these policy statements, NASA phased out shuttle launches of most commercial and defense payloads and initiated steps to improve the reliability of the shuttle and cut its operating costs to help fund new launch technologies with NASA's shrinking budget.

In 1992, NASA undertook a new initiative to assess and improve the safety and reliability of the shuttle. Based on the results of a limited 1988 quantitative risk assessment of the shuttle launch phase for the Galileo mission (General Electric, 1988) and building on the space shuttle main engine (SSME) project's attempts to improve the engine's safety margins, the program prioritized potential upgrades according to their ability to address the perceived predominant risk contributors. High on the list of proposed upgrades were new high-pressure fuel and oxidizer turbopumps, a two-duct powerhead (main injector), and a redesigned main combustion chamber. A new, more reliable, main engine heat exchanger, an upgraded APU, a health monitoring system for the main engines, and an upgrade to the orbiter cockpit displays were also given high priorities. Total funding for these upgrades—most of which have been or are being implemented—was approximately $1.5 billion. (The health monitoring system for the main engine is still in the early research and development (R&D) stage.)

While these safety and reliability improvements were under development, the shuttle program was undergoing substantial cuts in contractors and civil service personnel and was implementing many changes to reduce the program's operational budget. In a five-year period, the shuttle budget was cut from $3.5 billion per year to $2.9 billion per year (in real-year dollars), while the flight rate of six to eight shuttle launches per year was maintained.

Three events in 1993 resulted in additional upgrades to the space shuttle system. A new program in which the shuttle would rendezvous and dock with the Mir space station required several modifications to the orbiter, including the development of a new payload bay airlock/docking system. The ASRM program was canceled, depriving the shuttle of approximately 5,000 kg of additional payload capacity. Finally, the planned orbit for the newly restructured International Space Station (ISS) was moved to a 51.6 degree inclination. The new orbit was compatible with Russian launch facilities but reduced the amount of payload the shuttle could deliver to the ISS by more than 5,000 kg.

In order to address these decrements, the shuttle program embarked on a campaign to improve the shuttle's payload capability significantly so that it could meet the ISS program requirements. The largest upgrade was a super lightweight tank, a $200 million program that increased the payload the shuttle could deliver to the ISS by 3,500 kg. Additional upgrades, including lightweight crew seats, adjustments to trajectory and propellant reserves, and many minor weight reductions throughout the orbiter, increased payload capacity by approximately another 4,000 kg.

The national policy debate about the possible replacement of the shuttle took another step forward with the National Space Transportation Policy of August 5, 1994 (White House, 1994). This policy charged NASA to "provide for the improvement of the space shuttle system, focusing on reliability, safety, and cost-effectiveness" and also to "be the lead agency for technology development and demonstration for next-generation reusable space transportation systems, such as the single-stage-to-orbit concept." Following the release of this policy statement, NASA initiated the X-33 and X-34 prototype demonstration programs to test technologies for low-cost, highly reliable access to space. To free its scarce resources for the new programs, NASA decided to further reduce the cost of the shuttle program where possible, consistent with flight safety.

In February 1995, the Space Shuttle Management Independent Review Team issued a report (known as the Kraft report) recommending a freeze of the space shuttle configuration to cut costs (NASA, 1995). According to the report, "freezing the current vehicle configuration, hardware, and software will stabilize the program and allow reductions in cost." The Kraft report also recommended that "future changes should be minimized and [should] concentrate on making the vehicle more reusable and operational." Following the release of this report, the shuttle program effectively stopped approving new changes to the space shuttle's design, unless the changes were required for approved missions or necessary for safety reasons, to avoid obsolescence, or to meet new environmental regulations.

In keeping with a new national space policy (White House, 1996), NASA planned for the shuttle design freeze to continue until the end of the decade, at which time a decision would be made as to whether developments in the X-series vehicles were likely to result in a replacement for the shuttle. If at the end of the decade a shuttle replacement appeared to be imminent, the shuttle design would essentially remain frozen until the shuttle was replaced by an operational reusable launch vehicle. If, however, no replacement vehicle were on the horizon, a program for major renovations and upgrades would be initiated to extend the shuttle's viability to 2020 and beyond. In the latter case, upgrades would be aimed at reducing life cycle costs, alleviating obsolescence, and supporting activities beyond the ISS.

To further reduce operational costs, NASA also began to transfer responsibility for some elements of the Space Shuttle Program to the private sector. In September 1996, NASA signed a contract making United Space Alliance (USA) the prime contractor for space shuttle operations. USA corporation—a joint venture between Boeing and Lockheed Martin—is now primarily responsible for operations, including launching, landing, refurbishing, logistics, and sustaining engineering. NASA retains control over the development of upgrades and plans to continue its overall management of the shuttle program for the foreseeable future, even as day-to-day operations for individual elements of the program come under USA corporation's authority.

During fiscal year 1997, NASA, still not sure if a timely shuttle replacement would become available, lifted the configuration "freeze" and authorized the shuttle program to dedicate the majority of its reserves each year to a new upgrade program. At approximately $100 million per year, this program funds minor modifications to reduce obsolescence, support missions, improve safety, and reduce costs, as well as advanced studies of potential major upgrades in preparation for a decision to continue operating the shuttle beyond 2012. Chapter 2 of this report describes this program. Chapter 3 assesses the process by which NASA prioritizes and selects proposed upgrades, and Chapter 4 presents a top-level technical assessment of key proposed upgrades.

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2

Shuttle Upgrades Program

ORGANIZATION

The Space Shuttle Program is part of NASA's Human Exploration and Development of Space (HEDS) enterprise, under the authority of the Office of Space Flight. The program manager reports to the director of the lead center for the Space Shuttle Program, the Johnson Space Center (JSC), who reports to the associate administrator for the Office of Space Flight at NASA headquarters, who in turn reports to the NASA administrator.

Potential upgrades to the shuttle are coordinated by the Space Shuttle Program Development Office, which was created in 1997 and reports to the Space Shuttle Program manager. This office is responsible to the program manager for collecting, organizing, and prioritizing all upgrade concepts proposed by NASA organizations and shuttle contractors. The manager of the Space Shuttle Program Development Office chairs the Space Shuttle Upgrades Program Requirements Control Board (SSUPRCB), which has the authority to fund upgrades for which development and production will cost less than $5 million and to review and forward proposals for more expensive candidate upgrades to shuttle program management for disposition. Figure 2-1 shows how the upgrades program fits into the NASA organization.

BUDGET

The budget for the Space Shuttle Program, which is part of the "Human Space Flight" line item in the NASA budget, provides funds for shuttle flights

FIGURE 2-1 Space Shuttle Upgrades Program's location in the NASA hierarchy.

and ground operations (excluding civil service salaries). The two major components of the shuttle program budget are "Shuttle Operations," and "Safety and Performance Upgrades" (S&PU). Historically, most space shuttle upgrades have been funded through the S&PU line. In fiscal year (FY) 1998, about $650 million was spent on S&PU, out of a total shuttle budget of $2.9 billion. The vast majority of S&PU funding is dedicated to modifications and improvements to the flight and ground elements of the program, including the expansion of safety and operating margins and the enhancement of space shuttle capabilities, as well as the replacement of obsolescent systems (and systems that are noncompliant with anticipated changes to environmental regulations). Figure 2-2 shows how the S&PU budget compared to the total shuttle budget during four different years since 1985, including the projected budget for FY99.

The funding for upgrades managed by the Space Shuttle Program Development Office comes from Space Shuttle Program reserves, although the funding is considered to be in the S&PU budget for bookkeeping purposes. The program manager has the authority to spend these reserves—approximately $190 million per year in FY98 and FY99—on any problem areas and, since FY97, has dedicated about $100 million per year to the development of new shuttle upgrades.

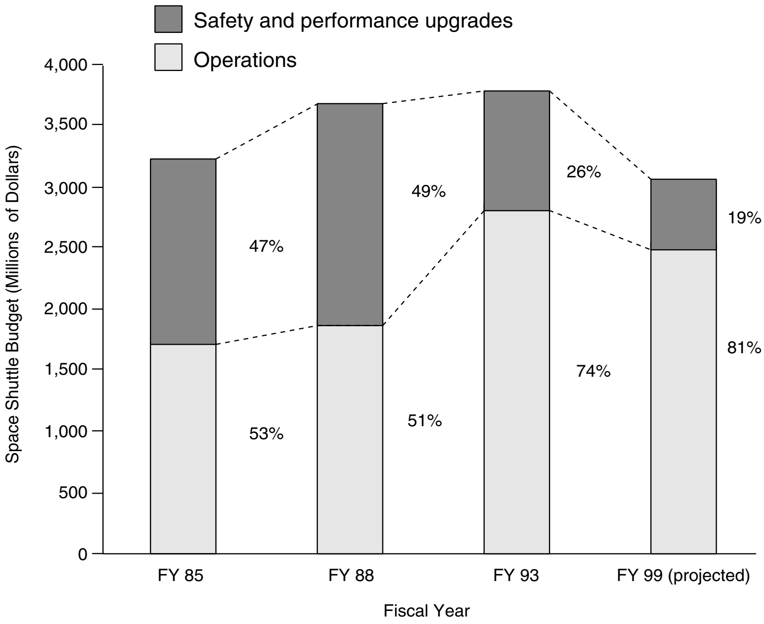

FIGURE 2-2 Changes in the shuttle budgets over time.

(This is the only part of the S&PU budget focused on *new* upgrades; the remainder is allocated primarily to previously approved upgrades and other ongoing activities.) The Space Shuttle Program Development Office uses these funds to study, develop, and implement minor upgrades and to study potential major upgrades. The implementation of larger upgrades would require additional funding and higher level approval within the Administration and Congress.

GOALS

According to NASA's 1998 strategic plan,

> The Space Shuttle program is committed to flying safely, meeting the manifest, improving system supportability and reliability, and reducing cost—in that order of priority. HEDS (Human Exploration and Development of Space Enterprise) is implementing the shuttle upgrade program to improve reliability, performance, and longevity of Space Shuttle operations to meet ISS needs and human exploration goals beyond 2012 (NASA, 1997).

These goals have been further defined by the management of the shuttle program. "Fly safely" includes eliminating failure modes, reducing the number of in-flight anomalies, and decreasing the probability of catastrophic failure. "Meeting the manifest" involves improving the shuttle program's ability to launch on time and recover rapidly from slips in the launch schedule. "Improving mission supportability" includes replacing obsolete hardware, complying with new environmental regulations, increasing the flight rate capability, and reducing cycle times for refurbishment. "Reducing cost" includes any and all measures adopted by the program to improve efficiency or otherwise reduce life-cycle costs. This goal has been rephrased within the shuttle program to "improving the system" to capture the idea that efficiencies can be motivated in ways other than traditional top-down budget cuts. The fifth and final goal is to "support other human space flight programs" (Holloway, 1998).

UPGRADE PHASES

According to NASA's FY99 budget request, space shuttle upgrades will be developed and implemented in "a phased manner supporting one or more of the program goals." The phasing strategy "will be coordinated with the reusable launch vehicle (RLV) project and other development projects to capture common technology developments" (NASA, 1998a). Proposed upgrades are categorized as either Phase I, Phase II, Phase III, or Phase IV, depending on when they were approved, their anticipated costs, and their effects on the space shuttle design. In addition to the phased upgrades, the Space Flight Operations Contract (SFOC) between NASA and the USA corporation contains limited incentives for USA corporation to initiate and implement (with NASA's approval) cost-savings upgrades.

Phase I upgrades include ongoing modifications initiated in the early 1990s to improve shuttle safety (e.g., modifications to the main engine), as well as upgrades (such as the super lightweight tank) to increase the shuttle's ability to support the ISS. Funding for Phase I upgrades accounts for most of the S&PU budget in FY98 and FY99. Since these upgrades have already been approved, developed, and in many cases completed, they are outside the scope of this report.

Phase II upgrades are defined as high value, low impact, incremental improvements, primarily to combat obsolescence. Phase II upgrades typically cost \$10 to \$50 million each, including development and production. Proposed Phase II upgrades are coordinated by the Space Shuttle Program Development Office and prioritized by their projected cost and potential to meet program goals. The office funds the study and implementation of Phase II upgrades out of its annual budget of approximately \$100 million. At the time of this review, more than 20 Phase II upgrades had been approved for implementation, with nearly as many in the study/definition stage.

Phase III and IV upgrades are proposed major modifications (\$100 million to billions of dollars) to the shuttle system designed to increase the shuttle's capabilities. The distinction between Phase III and Phase IV upgrades is that Phase III upgrades would not change the fundamental configuration of the shuttle (the "mold line"), while Phase IV upgrades would. Preliminary studies on Phase III and IV upgrades are also funded out of the Space Shuttle Program Development Office's $100 million budget. Implementing these upgrades, however, would require additional funding.

LIFE CYCLE OF AN UPGRADE

Shuttle upgrade concepts generally originate in the various project elements of the shuttle organization and percolate up through the management chain. Some of the ideas are long-standing concepts, while others are relatively new. Many of the safety-related upgrades, for example, arise from contractor sustaining engineering based on ongoing evaluations of flight and test data, anomalies, failures, and mishaps. Others result from R&D in government laboratories or engineering work conducted by government and support contractors at NASA centers. Many obsolescence and supportability upgrades originate from USA corporation logistics activities.

The Space Shuttle Program Development Office coordinates the flow of all new upgrade concepts through the study, analysis, and approval system. The office in charge of each project element—the orbiter, SSME, external tank, solid rocket booster, solid rocket motor, launch and landing operations, and mission and flight crew operations—as well as USA corporation, send lists of top candidate upgrades to the Space Shuttle Program Development Office, which then prioritizes them. Prioritization is necessary because there are many more upgrade candidates than dollars to fund them.

Many factors influence the prioritization process. One is the anticipated impact of the upgrade on program goals (fly safely, meet the manifest, improve supportability, reduce cost/improve the system, and support other human spaceflight programs). Another is the projected cost of developing and implementing the upgrade, including cost savings that would result from the change. Advice from within the agency, including the HEDS enterprise, the Safety and Mission Assurance Office, and the NASA Advisory Council, as well as from outside sources, such as Congress, the Aerospace Safety Advisory Panel, and the National Research Council, may also be considered.

Several tools are being developed to support the upgrade prioritization process. The program development office uses the quantitative risk assessment system (QRAS), a probabilistic tool being developed to compute the probability and consequences of failure of many elements of the space shuttle system, as an aid in the prioritization of safety-related changes. The agency is also beginning to use quantitative approaches more often to help prioritize nonsafety-related upgrades. However, these quantitative tools are only one component of the decision process, which includes many other technical and programmatic considerations.

An upgrade must be approved by the SSUPRCB (Space Shuttle Upgrades Program Requirements Control Board) before it can be implemented. The SSUPRCB is chaired by the manager of the Space Shuttle Program Development Office, and the members represent all shuttle project elements, USA corporation, and systems integration, flight crew operations, logistics operations, safety and mission assurance, and other support organizations. Box 2-1 is a list of the organizations represented on the SSUPRCB.

The SSUPRCB has the authority to approve upgrades for which development and production are projected to cost $5 million or less. Upgrades that are

BOX 2-1
Members of the Space Shuttle Upgrades Program Requirements Control Board

Chair

Manager, Space Shuttle Program Development (or designee)

Secretary

Representative of Space Shuttle Management Integration

Members

Representative of Space Shuttle Systems Integration, Johnson Space Center (JSC)
Representative of Space Shuttle Customer and Flight Integration, JSC
Representative of Space Shuttle Vehicle Engineering, JSC
Representative of Space Shuttle Integration, Kennedy Space Center (KSC)
Representative of Space Shuttle Business Management, JSC
Representative of Space Operations Management Organization, JSC
Representative of Engineering, JSC
Representative of Flight Crew Operations, JSC
Representative of Mission Operations, JSC
Representative of Safety, Reliability, and Quality Assurance, JSC
Representative of Space and Life Sciences, JSC
Representative of Shuttle Processing, KSC
Representative of Payload Processing, KSC
Representative of Logistics Operations, KSC
Representative of Advanced Development and Shuttle Upgrades, KSC
Representative of External Tank Project, Marshall Space Flight Center (MSFC)
Representative of Space Shuttle Main Engine Project, MSFC
Representative of Solid Rocket Booster Project, MSFC
Representative of Reusable Solid Rocket Motor Project, MSFC
Representative of Space Flight Operations, USA corporation

SOURCE: NASA, 1988b.

expected to cost more than $5 million, affect the shuttle schedule, increase risk, or cause problems for the ISS are reviewed by the SSUPRCB and forwarded to the Space Shuttle Program Requirements Control Board, which has the authority to resolve conflicts involving shuttle schedule or risk and to approve upgrades of up to $50 million. The more expensive upgrades (Phase III and IV, generally) will require approval at higher levels of the agency, the Administration, and Congress.

Once a Phase II upgrade is approved, the SSUPRCB assumes program oversight of the performance of the implementing organization. When the design and production phases have been completed, most upgrades are implemented by support or prime contractors during the periodic down periods for orbiter maintenance (when each orbiter is taken out of service for detailed structural inspections and thorough testing before being returned to operational status.) NASA civil servants participate in engineering, system safety, and project management activities.

Decisions on implementing Phase III or Phase IV upgrades will probably have to await the anticipated policy decision on shuttle replacement. NASA is currently gathering data in support of this decision through an industry-led study process, the Space Transportation Architecture Study, which was initiated in June 1998 to

> determine: (i) if the Space Shuttle system should be replaced, (ii) if so, when the replacement should take place and how the transition should be implemented and (iii) if not, what is the upgrade strategy to continue safe and affordable flight of the space shuttle beyond 2010 (NASA, 1998c).

The study will be the basis for NASA's FY01 budget and, presumably, for deciding the space shuttle's role in NASA's future space transportation plans. (Final decisions on NASA's space transportation plans, of course, will be made by the Administration and Congress.)

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3

Choosing Upgrades

OPERATING IN AN UNCERTAIN POLICY ENVIRONMENT

Because the long-term future of the shuttle is uncertain, and policies related to the Space Shuttle Program are subject to change, shuttle program decision makers do not know how long the space shuttle must continue to operate, the number of flights per year that will ultimately be required, or the missions (if any) beyond supporting the ISS that the shuttle will be expected to perform. Uncertainties about the shuttle's operational lifetime have made it difficult for NASA to decide whether to implement upgrades to combat obsolescence and reduce operating costs. Uncertainties about the shuttle's future roles and flight rates have also made it difficult for NASA to decide whether upgrades to support non-ISS missions should be implemented. The shuttle program's limited budget for upgrades has constrained the program's responses to this environment, which has made it difficult for program managers to prepare adequately for the range of possible future scenarios.

NASA is not the only organization that must decide whether to upgrade an aging fleet and infrastructure in the face of component obsolescence, increasingly stringent environmental regulations, limited budgets, and an uncertain future. The Air Force, for example, has been faced with similar issues about the future of its B-52 long-range bombers, which have been operating for more than 40 years. Other examples can be found in the aerospace, transportation, telecommunications, energy, and defense industries. NASA could learn from the methods that have been used successfully by other large organizations to develop upgrade selection processes and strategies.

Recommendation 1. NASA should benchmark other large organizations' investment processes for technological upgrades and attempt to identify and emulate appropriate processes and investment strategies.

Uncertain Operational Lifetime

Decisions about implementing the more forward-looking and expensive proposed shuttle upgrades—particularly Phase III and IV upgrades—will probably have to be delayed until the time of a national decision on the space shuttle's future. A timely decision would enable NASA to act efficiently by either (1) only implementing the upgrades necessary to keep the program operating until it is phased out or (2) making major investments to reduce long-term program costs and improve long-term reliability. Although the policy decision was originally planned to be made in 2000, there is no guarantee that it will be made that year. The decision could be postponed for a number of reasons, including inconclusive results from other launch vehicle programs, or the unwillingness of the President or Congress to make an election year decision.

The committee supports NASA's approach of using its limited shuttle upgrade budget to fund minor upgrades that have identifiable short-term benefits and to conduct preparatory studies for major upgrades that may be warranted if the shuttle program is called upon to operate after 2012. This approach should help shuttle operations remain relatively safe and efficient for the next few years and enable the program to implement major upgrades if a decision is made to extend the shuttle's lifetime or to close out the upgrade program with minimal waste if the decision is made to phase out the shuttle.

If a national policy decision does not appear to be imminent as the year 2000 approaches, NASA may find it necessary to begin to implement some Phase III or Phase IV upgrades to the shuttle. If so, NASA must balance long-term risks, benefits, and costs, and primarily pursue candidate upgrades that would be valuable even if the shuttle program is later terminated (such as upgrades that provide safety benefits or could be used in other government or commercial programs).

Uncertain Flight Rate

Part of the shuttle program's goal to "improve mission supportability" is to increase the flight rate capability of the shuttle to 10 flights per year by 2002, 12 flights per year by 2004, and 15 flights per year by 2012 (Holloway, 1998). The ability to support increased shuttle flight rates is currently one of the metrics used to prioritize upgrades. However, NASA has not identified a need for more than the seven or eight missions per year planned to support the ISS and conduct research. Unless NASA's own needs for shuttle flights increase drastically, additional customers—most likely from the U.S. Department of Defense (DoD) or the commercial sector—will have to materialize to support NASA projections. Two barriers would have to be overcome before this could occur.

First, current national space policy states that "the Space Shuttle will be used only for those important missions that require manned presence or other unique Shuttle capabilities, or for which use of the Shuttle is determined to be important for national security, foreign policy, or other compelling purposes" (White House, 1991). This policy has two purposes. It protects the shuttle, which is a unique national resource, from being put at risk in noncritical or nonunique applications, and it protects commercial launch firms from U.S. government-subsidized competition. This policy would have to be revised for the shuttle to be used by virtually any commercial customer for purposes that could be served by other launch vehicles.

Second, the shuttle would have to become a financially attractive launch vehicle for commercial customers. Prior to the Challenger accident, the shuttle was a viable commercial launch vehicle only because launches were heavily subsidized by the government and because competition for commercial payloads was limited. In the current political climate, however, that type of government-subsidized competition against commercial launch vehicles seems unlikely. If the shuttle is to become a viable competitor without government subsidies, a necessary step will be to greatly reduce its cost per pound to deliver payloads to orbit.

The committee believes NASA would be unwise to use an upgrade's ability to support a significantly increased flight rate as a factor (implicit or explicit) in choosing upgrades unless the agency can show through a viable business plan that has been reviewed and approved by financial and technical experts inside and outside the agency, as well as national policy makers that the shuttle could attract sufficient commercial and DoD business to justify the increase in flight rates. The business plan would also be useful for determining which upgrades would be most important for achieving higher flight rates. For example, if the shuttle program intended to launch commercial geostationary communications satellites, an upper stage rocket would be required. However, the shuttle does not currently have an operational upper stage. The inertial upper stage (IUS) is out of production and unavailable for new missions, and the infrastructure for another proven upper stage, the payload assist module (PAM), is virtually nonexistent after years of nonuse. One estimate is that it would take at least $10 million to resurrect the first PAM for shuttle use (Nichols, 1998).

Recommendation 2. The ability of a shuttle-unique upgrade to support an increased flight rate should not be a factor in the prioritization process, unless NASA can show through a viable business plan that has been reviewed and approved by financial and technical experts inside and outside the agency, as well as national policy makers (1) that the shuttle could attract enough business to justify the increased flight rate, and (2) that the shuttle program would not unfairly compete with commercial launch vehicles or pose unnecessary risks to a national asset.

Uncertain Funding

The $100 million budgeted for new upgrades is not secure because the money comes from shuttle program reserves. Cuts in the overall shuttle budget or problems in a shuttle system that require the use of reserve funds could reduce the amount available for the upgrades program. However, this approach gives the program manager flexibility to shift funds to match immediate priorities and problem areas. If the national decision is eventually made to substantially enlarge the upgrade program, it will be necessary to specifically fund Phase III and Phase IV projects in the NASA budget. Otherwise, the current approach and budget (assuming it is adjusted for inflation and there are no new major technical problems to solve) will probably be adequate for the remainder of the shuttle's operational life.

REFINING PROGRAM GOALS

According to NASA's 1998 strategic plan, the primary goals of the Space Shuttle Program are, in order of priority: (1) fly safely; (2) meet the flight manifest; (3) improve supportability; and (4) reduce costs (NASA, 1997). The shuttle upgrade program considers an upgrade's contributions to meeting these goals in its prioritization process. (Support for other activities in the HEDS enterprise are also considered.) The committee strongly supports NASA's use of program goals to prioritize upgrades. However, the committee also believes that more focused goals would provide better guidance to groups proposing new upgrades and would make the process for prioritizing and selecting upgrades more transparent.

Because goals provide important guidance for teams developing new upgrades, the goals of the upgrade program should accurately reflect the criteria used by program management to select new upgrades. For example, nearly half of the $100 million for new upgrades each year is being spent on obsolescence-related changes. If upgrades that combat obsolescence continue to be given a high priority, this should be reflected in the upgrade program's stated goals.

The goals of the $100 million per year upgrade program do not necessarily have to be identical to the goals of the overall Space Shuttle Program. Because a substantial amount of the S&PU budget is already being spent on ongoing safety-related improvements, for example, new upgrades could focus on achieving other elements of the program goals. Table 3-1 provides an example of how goals used to prioritize new upgrades might differ from, but still complement, the goals of the overall program.

Another key to creating clear goals is ensuring that they are feasible. The 1998 NASA strategic plan challenges the shuttle program to pursue "a systems

TABLE 3-1 Sample Goals for the Upgrade Program

Shuttle Program Goals (in order of priority)	**Goals for New Upgrades (in order of priority)**
• Fly safely • Meet the manifest • Improve supportability • Cut costs • Help other programs	• Fix known safety problems • Meet requirements of the ISS, the research community, and other known customers • Minimize cost increases and subsystem life problems caused by obsolescence (ensure program viability through ISS era) • Reduce predicted flight and ground safety risks • Improve efficiencies (reduce the cost of delivering payload to orbit) • Help other programs

upgrade program that will reduce payload-to-orbit costs by a factor of two by 2002" (NASA, 1997). The current upgrades program cannot meet that goal, not because the goal is technically impossible, but because the upgrades program does not have sufficient funding to meet the goal. A 50 percent cost-per-pound to orbit reduction in this time frame would require that NASA: (1) spend billions of dollars to implement most or all of the known cost-saving upgrades by the year 2002, and/or (2) achieve a flight rate of at least 15 missions per year in addition to implementing significant new cost-cutting (i.e., people reduction) initiatives. The $100 million per year (increased for inflation over time) of program reserves managed by the Space Shuttle Program Development Office is probably sufficient to maintain a reasonable level of obsolescence control through the ISS era, but it is grossly insufficient to meet the cost target stated in the strategic plan.

Recommendation 3. The Space Shuttle Program should reassess the goals used to prioritize candidate upgrades to ensure that they reflect the upgrade program's priorities, are feasible, and are clearly understandable to everyone working in the program.

Recommendation 4. The Human Exploration and Development of Space Enterprise should bring the cost goals for the space shuttle in its strategic plan into line with budget and policy realities.

PRIORITIZING AND SELECTING UPGRADES

In the past, the Space Shuttle Program Office has used a variety of ad hoc approaches to prioritize the multitude of proposed modifications to the shuttle and its support systems. In the end, approval for funding has depended on a combination of objective and subjective factors, including the following:

- program requirements
- technical merit
- resource requirements
- life cycle cost
- schedule
- external political pressures
- agency institutional needs
- relative visibility and vigor of internal advocacy groups (government and contractor)

In the past two years, the program has begun to develop a more formal, less qualitative process to help the program manager make more informed decisions. This improved process will not, and is not meant to make the inevitable political and other subjective decision parameters go away. However, it will, according to the program manager, allow him more visible, apples-to-apples comparison capability for the traditionally objective programmatic and technical decision parameters.

The committee commends NASA for working to develop a more formal process to evaluate and prioritize upgrades. The groups involved in the development of new upgrades appear to appreciate that upgrades are being handled in a relatively proactive and organized manner (compared to past years when upgrades were usually reactive solutions to problems or mishaps). The Decision Support System (DSS) and the QRAS risk assessment system, both of which are still under development, have the potential to improve the selection process, although significant additional modifications (discussed below) will be required before their results can be fully trusted inputs to the process. Additional benefits could be gained by improving cost assessment procedures and modifying the shuttle operations contract to provide stronger incentives for USA corporation or any future prime contractor to develop and implement upgrades.

Quantitative Risk Assessment System

The NASA administrator initiated the development of QRAS in 1996. QRAS is a risk assessment software tool developed primarily by the University of Maryland and managed by NASA's Office of Safety and Mission Assurance. The system, which builds upon earlier risk analyses of the SSME, the reusable solid rocket booster (RSRB), the APU, and other shuttle components, has primarily focused on risks during the shuttle's launch phase. NASA has spent \$1.5 to \$2 million on the system to date and is continuing to improve and expand QRAS.

The current version of QRAS has many significant deficiencies that make it difficult to determine how much faith NASA should place in the validity and utility of its assessments. The primary weakness of QRAS as presently implemented is that it can only consider the impact of one risk at a time. In reality, however, catastrophes often occur when minor problems, which by themselves would not cause a failure, occur in combination with other problems. Other deficiencies of QRAS are listed below:

- It does not consider abort modes.
- It does not consider external dangers, such as meteoroids or orbital debris.
- It does not directly consider human error and crew response.
- It does not consider the effects of software-induced problems.

These are major omissions. Software-induced problems, for example, have caused many recent launch vehicle failures (e.g., Ariane 501 and the initial flight of the Pegasus XL), and human error is the most common cause of aircraft accidents.

To calculate the safety impacts of proposed upgrades, QRAS will also have to be able to incorporate increased risks from implementing each upgrade. New design modifications always involve a risk, however small, of causing new problems from unanticipated interactions with existing subsystems. To get a better picture of the true safety impact of an upgrade, QRAS risk assessments would have to include quantitative assessments of the potential of new hardware or software to increase the risk (including uncertainties) to the shuttle system.

Unless all of these sources of risk are included in the analysis, QRAS will give a skewed picture of the overall risks to the shuttle. Taken out of context, these skewed assessments could lead to inefficient spending to improve shuttle safety. For example, until the risk to the shuttle from meteoroids and orbital debris began to become clear in the mid-1990s, none of the billions of dollars spent on improving shuttle safety had been used to protect the shuttle from these significant external hazards.

The committee believes that this probabilistic modeling tool has the potential to be very helpful in assessing and comparing the impact of shuttle upgrades on shuttle safety. However, it is critical that NASA be aware of the system's limitations. As the scope and capabilities of the QRAS system are increased, the program will be able to rely more on its assessments of safety risks to the shuttle and the ability of various upgrades to reduce that risk.

Recommendation 5. NASA should continue to increase the scope and capabilities of the quantitative risk assessment system by improving its models of failures attributable to combinations of risks, human error, abort modes, on-orbit hazards, reentry and landing, and software. Until these improvements are made, the Space Shuttle Program Development Office should be very cautious in using the quantitative risk assessment system to aid in prioritizing upgrades.

Space Shuttle Upgrades Decision Support System

The DSS (Decision Support System), which is still under development by the Futron Corporation, receives information from every group that proposes an upgrade about the upgrade's cost, technological readiness, contribution to meeting program goals, risks, and ability to satisfy other NASA or federal government requirements. This information is provided to the program manager as qualitative independent assessments of the merits and costs of each candidate. The information is also translated into dollar figures and mathematically manipulated to create quantitative prioritized rankings of upgrades. These rankings (along with many other inputs, including the raw survey data used by the DSS) are used by the Space Shuttle Program Development Office in prioritizing upgrades for implementation.

The committee believes that when this type of support system is more mature it will be a valuable tool in the evaluation and prioritization of candidate upgrades. However, the committee distrusts the accuracy and applicability of the techniques employed by the DSS enough to caution that it not be used as the sole or most influential criterion of the program manager's decision making.

First, some of the means by which the DSS mathematically manipulates data could be improved. For example, the current system assigns dollar values to costs and benefits. It then models the benefit-minus-cost as a Gaussian random variable, whose mean and standard deviation are estimated from survey inputs and historical evidence, and constructs an "S-curve" of the cumulative probability of the upgrade's benefit-minus-cost value. The system then reads the 20th percentile value off the S-curve and uses this to discriminate between upgrades. However, because a Gaussian probability distribution is being used to model the benefit-minus-cost value, the S-curves are superfluous. The 20th percentile value is also unnecessary because, with very little additional work, explicit calculations could be used to compute the full probability that the benefit-minus-cost value of a particular upgrade exceeds the value of a different upgrade.

However, a bigger challenge with the DSS, as currently implemented, is that important information is often lost when survey inputs are transformed into single, numerical "expected upgrade values." A survey to obtain inputs on upgrades is a valid way to draw on the technical expertise of the NASA and contractor engineering staffs. However, when these essentially nonmathematical inputs are mathematically manipulated, critical information can be lost and results can be perceived as having more credibility than they deserve. For example, in calculating the safety benefit of an upgrade, the DSS divides the cost of the shuttle by the number of items that an upgrade will remove from the shuttle's "critical item list." The reality that some critical items are orders of magnitude more likely to cause failures than others is lost in the process. A more accurate way to compare the safety merits of two candidate upgrades would be to employ failure probabilities and their associated uncertainty bands.

To address the inherent difficulties associated with quantification of certain characteristics, the case for each upgrade could also be presented in a form that uses more of the available information and, at the same time, results in a much more transparent decision-making process. (A transparent process is critical to convincing upgrade proposers as well as program stakeholders that upgrades are being treated fairly.) One approach that could be used is "expert elicitation" (see Box 3-1). This technique—which is used by the U.S. Department of Energy and the Nuclear Regulatory Commission—can be an extremely effective (and transparent, with proper structuring and documentation) approach for prioritizing a relatively small number of alternatives. Although NASA often consults experts informally, formal expert elicitation would add a structured process that, if performed in accordance with strict rules, would provide what is missing in the existing DSS—a clear rationale for the results.

Recommendation 6. NASA should take care that the Decision Support System's quantitative tools are used as a supplement to, not as a substitute for, formal qualitative evaluations. Expert Elicitation should be considered as an additional formal qualitative tool. Also, NASA should consider modifying the quantification algorithm that the Decision Support System employs for cost-benefit comparisons so that it uses full probability values rather than 20th percentile S-curve values.

BOX 3-1
Eliciting Expert Opinions

Expert elicitation is a process to obtain knowledge from experts on a specific question, issue, or problem (Meyer, 1991). Formal expert elicitation is a process of documenting knowledge (judgments, opinions, parameter distributions, data, etc.) about the outcome of events, physical processes, etc., for which comprehensive observed or actuarial experience is lacking. The systems where expert elicitation has been most actively applied are nuclear power plants (USNRC, 1996) and geological nuclear waste repositories (Kotra et al., 1996).

A number of basic steps appear to be common to all well conceived applications of expert elicitation. These are: (1) properly framing the question or questions to be answered, including the desired form of the results, (2) providing consistent background source material, (3) recruiting and training the experts, and (4) aggregating and documenting the supporting evidence and results. These basic ingredients, together with appropriate leadership (facilitators, process experts, and subject experts), are key to a defensible result.

Cost Assessment

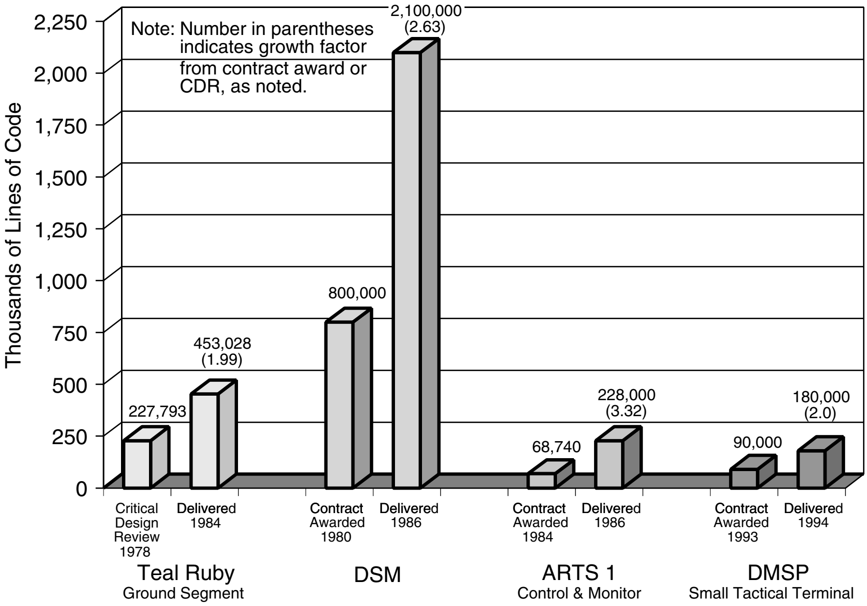
A key input to prioritizing upgrades is the estimated cost of developing, implementing, and operating each upgrade. For this input to be helpful, cost estimates must be accurate and calculated consistently. The first step in achieving this goal is to ensure that the costs of proposed upgrades are compared using the same definition of a dollar. Calculating the present value of anticipated expenditures is essential for comparing upgrades fairly and making cost-benefit calculations. However, the shuttle upgrades program does not consistently use fixed-year dollars in its assessments of candidate upgrades. The committee found inconsistencies in both the scope and accuracy of upgrade cost data. Although the varying degrees of maturity of the upgrades explains much of this, NASA must strive for consistent cost data in any cost/benefit analysis.

Second, cost estimates must include all costs (including hidden costs) associated with integrating a proposed upgrade into the shuttle system. These should include the following costs:

- integration costs, such as the expense of modifying structure, power, and other shuttle subsystems to comply with the needs of the upgraded components
- potential costs for mitigating the risk of replacing fully developed, tried, and tested hardware and software with newly developed hardware and software
- the cost of ground systems
- the cost of operating and maintaining the upgrade
- the cost of civil service labor
- the costs of transitioning flight and ground systems and personnel to the new upgrade (including the costs of maintenance and operations training, testing, and any costs of operating both old and new systems while the upgrade is being phased in)
- the cost of money

Third, cost estimates for upgrades must be accurate. Inaccurate cost estimates are a particular problem for projects involving a large amount of new software. Government cost estimates for software have been notoriously inaccurate, often underestimating costs by as much as an order of magnitude. This cost increase is typically attributable to an increase in lines of code by a factor of 2 to 3 (see Figure 3-1) and a decrease in the productivity of individual programmers by a factor of 3 to 4 (see Figure 4-1 and associated text).

Recommendation 7. All calculations, comparisons of costs and cost savings, and cost-benefit assessments done by NASA, as well as its DSS independent contractor, should be performed using fixed-year dollars and should include all costs (including hidden costs) associated with the upgrade.



Teal Ruby = an advanced development, ground-based, strategic missile defense laser
CDR = critical design review
DSM = data systems modernization (of the Air Force Satellite Control Facility at Onizuka Air Force Station, Sunnyvale, California)
ARTS = automated remote tracking station
DMSP = defense meteorological satellite program

FIGURE 3-1 Risk in estimating lines of code. SOURCE: The Aerospace Corporation, 1998.

United Space Alliance Selection Process

The SFOC (Space Flight Operations Contract) between NASA and USA corporation covers two fundamental types of work, as shown in Table 3-2. USA corporation is currently performing approximately $75 million in upgrade work (much of it related to obsolescence-driven design changes) under the "operations" part of the contract. USA corporation has also provided technical inputs to many of the upgrades under way under the "program provisioning" part of the contract.

The operations part of the contract gives USA corporation 35 percent of any underrun during the six-year, $7.4 billion contract. USA corporation has invested some of the 35 percent award fee they have earned to date in improvements to processes and training. However, the incentive has not been strong enough to convince USA corporation to invest in major shuttle upgrades because most

TABLE 3-2 Space Flight Operations Contract

Operations **(85 percent of contract)**	**Program Provisioning** **(15 percent of contract)**
• contractor managed • primarily covers repetitive operations • performance based • cost plus award fee plus incentive fee — award fee (fixed percentage of total contract value) — incentive fee (35 percent of underrun)	• NASA managed • primarily covers nonrepetitive engineering and development work • completion form (level of effort) • cost plus award fee

development takes years to complete and is not likely to show significant savings before the current contract ends in 2002. (Current procurement rules prohibit the government from compensating the contractor for savings achieved after the end of the contract.)

NASA can, and has, negotiated adjustments to minimize the effects of the weak incentives created by this contractual structure. NASA also has $15 million of discretionary money for award fees that can be given to the contractors for efforts or performance above and beyond the literal requirements of the SFOC. To date, USA corporation has not been awarded any of this discretionary money.

In addition to these "carrots," NASA also has a "stick" to encourage the contractor to develop shuttle upgrades. The SFOC has provisions for penalties for contractor-caused mishaps and schedule slips, and the contractor must receive a relatively high score in "safety" in order to receive any underrun award fee. This "safety gate" could be considered an indirect incentive for USA corporation to propose safety upgrades.

None of the contractual arrangements covers contractor-financed developments per se. If USA corporation (with NASA's approval) decides to put company resources into a reliability enhancement upgrade that NASA has chosen not to fund, USA corporation could improve its safety grade or otherwise look better to the official determining the award fee. But USA corporation's only direct contractual compensation would be the 35 percent share of operations underruns that result from a cost-saving upgrade. In most cases, these initiatives make no business sense and, not surprisingly, no USA corporation-financed upgrades are in progress.

Although USA corporation appears to be an involved partner in defining and developing shuttle upgrades, the SFOC could be improved to provide stronger incentives for (1) prioritizing shuttle upgrade initiatives more consistently with the program's stated priorities (e.g., safety risk reduction before cost reduction) and (2) developing long-term improvements (both government- and contractor-financed) to the shuttle system. NASA is currently defining a process that will provide the USA corporation with incentives to undertake upgrades that will result in savings beyond the term of the contract. If permissible under future procurement policies, one approach worth pursuing would be to provide "royalties" or other long-term (post-contract) compensation. Another approach which has been used on other programs is to pay out incentives up-front based on predicted future savings. All modifications to the contract are opportunities to add incentives for USA corporation (and future prime contractors) to initiate upgrades to meet other shuttle program goals.

Recommendation 8. NASA should provide stronger incentives for the shuttle prime contractor to propose, finance, and implement upgrades to meet the shuttle program's goals.

IMPROVING CANDIDATE UPGRADES

To ensure that NASA can select the best upgrades for the shuttle program, a pool of high quality potential improvements must be developed. The shuttle program can take five steps to improve the pool of proposed upgrades:

- Broaden the range of proposed upgrades by actively soliciting and supporting proposals from outside of NASA.
- Improve the quality of proposed upgrades by conducting early assessments of their effects on the entire shuttle system.
- Minimize the risk that upgrades will experience problems with software during development or operations.
- Examine alternatives to proposed upgrades and conduct trade-off studies to determine the most cost-effective solutions.
- Modify groupings of upgrades to create sets of upgrades that will contribute most toward meeting particular goals.

Input from Outside NASA

To conserve funds and retain its engineering expertise, NASA is developing many of the shuttle upgrades in house, with minimal contractor participation. Although NASA's efforts appear to be technically excellent, the program runs two risks by taking this approach. First, the transition of an upgrade to industry for production could be difficult if the contractor base is not familiar with the upgrade or the technology involved. Bringing the contractor up to speed could require additional hiring or a slower development process, either of which would increase development costs. Second, NASA could miss out on superior upgrade concepts originated by industry or universities. By requesting upgrade concepts from the outside and, just as important, by taking steps to assure outsiders that their upgrade candidates will be considered on an equivalent basis with proposals from within the agency, NASA could greatly improve its pool of potential upgrades.

Recommendation 9. Upgrade project managers should involve industry more in the definition and early development of candidate upgrades.

Early Systems Integration

NASA's FY99 budget request states that "the space shuttle upgrade activity will be planned and implemented from a system-wide perspective. Individual upgrades will be integrated and prioritized across all flight and ground systems, ensuring that the upgrade is compatible with the entire program and other improvements" (NASA, 1998). The committee strongly supports this concept but believes that a number of steps can be taken to strengthen the upgrade program.

A concerted effort early on to ensure that upgrades are compatible with other shuttle systems is essential for avoiding more expensive problems later in the development process. The effort might include the following steps:

- Early in the process of defining an upgrade, assess the structural, certification, weight and balance, aerothermal dynamic, and other effects of the upgrade on the entire shuttle system.
- Make detailed cost estimates as early as possible so the program manager can weigh the benefits against total program costs and cancel work on less promising upgrades.
- Analyze upgrades not only to determine potential safety risks to the shuttle design under standard operating conditions but also to determine how the upgrade might perform in a degraded state or under abnormal operating conditions.

In addition to determining the impact of potential upgrades on the rest of the shuttle system, the program could benefit from an early assessment of the effects of the upgrade on achieving program goals. If there is no way to show the connection analytically, the team working on the upgrade could document how the goals were being addressed and how the goals had affected the final design of the upgrade. This would provide an additional incentive for proposers to develop upgrades directed towards achieving program goals.

Obviously, the amount of analysis required early in the process should not overwhelm the actual development of the upgrade concept. The depth of analysis should depend on its relevance to the particular upgrade and the magnitude of the development effort. (For example, a proposed new shuttle wing and a proposed upgrade to the shuttle tires should both be evaluated to identify potential integration issues, but the depth of analysis should be much greater for the wing upgrade.)

Recommendation 10. The Space Shuttle Program should institute a process early in the development of a candidate upgrade to ensure that the upgrade is compatible with other shuttle systems and relevant to meeting program goals.

Software

Many shuttle modifications are accompanied by software changes. The committee has two major concerns about software changes associated with potential shuttle upgrades. The first is the potential that software changes can dramatically increase an upgrade's development costs and delay its implementation. The second is the potential risk to shuttle operations from the use of commercial off-the-shelf (COTS) software.

As already noted, government estimates of software costs and schedules have been notoriously inaccurate, and problems in producing software can result in large and unexpected cost overruns and delays. Historically, the cost and implementation schedules of shuttle upgrades have often been driven by the software verification process. For example, the modest (60,000 lines of code) software change accompanying the multifunction electronic display systems upgrade to the shuttle cockpit took five years from go-ahead to final qualification. If the changes to software associated with an upgrade could be minimized, NASA could, in many cases, lower the cost, development time, and risk of the upgrade. NASA appears to be taking a wise course with the proposed avionics upgrade, which focuses initially on replacing hardware components, rather than on changing the shuttle software.

The use of COTS software in the shuttle environment is another area of concern. COTS software and the COTS software industry itself often do not meet the requirements for safety, data integrity, robustness, testability, validatability, performance, longevity, and supportability for prolonged use in the shuttle program. NASA currently makes decisions about whether to use particular COTS software on a case-by-case basis, and it also develops rules and guidelines on a case-by-case basis. A strategy for the procurement, verification and validation, maintenance, and other requirements for that particular application is then spelled out in the upgrade's software development plan. No general guidelines for COTS software selection or use are available, partly because of the wide range of applications in which the software is deployed.

Comprehensive guidelines for using COTS software could put an end to the proliferation of potentially unsafe or inefficient ad hoc policies and procedures. The committee recognizes that COTS software will be used in a wide variety of applications and that the guidelines would have to be broad enough to cover all of them. However, the committee believes that the improvements in efficiency and safety would be worth the effort.

Recommendation 11. NASA should limit the software changes associated with new shuttle upgrades. The agency should consider standardizing its guidelines for using commercial off-the-shelf software in shuttle upgrades.

Alternatives and Trade-off Studies

The committee is concerned that NASA often does not conduct concrete, indepth trade-off studies to determine whether a proposed upgrade is the best approach to solving a particular problem or achieving a particular goal. Upgrade concepts typically originate in the various project elements of the shuttle organization. This allows the people who know the shuttle best to suggest new upgrades but often produces high-technology, expensive upgrade proposals, instead of less radical, more incremental upgrades that could achieve much the same benefit at a much lower cost. The upgrade program manager's role should be to determine whether proposed solutions are cost effective and, if they are not, to implement a more effective alternative.

Recommendation 12. Before embarking on the larger, more costly upgrades, NASA should examine alternative solutions and conduct trade-off studies to determine if the proposed upgrade is the best way to achieve the desired result.

Grouping Upgrades

With the exception of avionics, the upgrades were presented to the committee as stand-alone modifications. The most effective way to meet a particular program requirement will often not be through any of the individual upgrades proposed to the Space Shuttle Program Development Office but through a combination of candidate upgrades (or elements of candidate upgrades). For example, the most cost-effective approach to increasing payload capacity at today's flight rate might involve the development of a five-segment solid rocket booster and the extended nose landing gear. A package of upgrades that would enable the shuttle to fly 15 times per year might include a liquid fly-back booster—possibly one less capable than the one currently proposed—electric APUs, and a new high-energy upper stage for the payload bay. The search for efficient groupings could reveal synergies among candidate upgrades, and the results could be useful in optimizing modification schedules and resources and explaining to stakeholders outside of the program the upgrades required to meet specific program goals.

Recommendation 13. The Space Shuttle Program Development Office should not consider proposed upgrades as stand-alone modifications but should look for opportunities to combine upgrades (or features of upgrades) to efficiently meet future requirements.

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4

Assessments of Proposed Upgrades

Based on information NASA presented to the committee on numerous ongoing and proposed upgrades to the space shuttle (see list of upgrade topics: Appendix C), it is clear that a great deal of creative and useful design and development work has been performed. The committee conducted a top-level technical assessment of the upgrades and developed findings and recommendations about some of the ones that had not yet been developed and/or implemented. (see Table 4-1). The committee points out areas of technical or programmatic risk, suggests alternate approaches, and addresses the potential of proposed upgrades to meet the goals of the Space Shuttle Program. With rare exceptions, however, the committee does not recommend particular upgrade candidates for implementation. Those decisions must be based on careful and thorough assessments of requirements, costs, and benefits using analytic tools as well as engineering judgment (see Chapter 3).

PHASE II UPGRADES

Checkout Launch and Control System

The checkout launch and control system (CLCS) is an upgrade to the launch processing system used to check out, control, and process shuttle flight systems, ground support equipment, and facilities at Kennedy Space Center. The current system is growing obsolete; approximately one-fourth of its components are no

TABLE 4-1 Upgrades Discussed in Chapter 4

Upgrade	Phase	Status
Checkout launch and control system	II	Ongoing
Micrometeoroid and orbital debris protection	II	Ongoing
Auxiliary power unit replacement	III	Under study
Avionics	II	Component replacement ongoing
	III	Major upgrade under study
Channel-wall nozzle	III	Under study
Extended nose landing gear	III	Under study
Long-life fuel cell	III	Under study
Nontoxic orbital maneuvering system/ reaction control system	III	Under study
Water membrane evaporator	III	Under study
Five-segment reusable solid rocket booster	IV	Under study
Liquid fly-back booster	IV	Under study

longer supported by vendors, it uses a unique software language, it is unable to support new tasks, and its operations and maintenance costs are estimated to be $50 million per year and rising.

The CLCS upgrade will replace this system with modern commercial hardware and software. The upgrade, which was approved and funded in December 1996, is intended to reduce operations and maintenance costs by at least 50 percent without impacting flight hardware or software. As of September 1998, approximately $60 million had been spent and about 50 percent of the system software and 10 percent of the applications software had been developed. The system, which is designed not to impact the shuttle schedule as it is phased in, is expected to cost a total of $183 million by its completion in FY02.

The committee believes that an upgrade to the launch control system is necessary and worth pursuing. A modern system that incorporates advances in both hardware and software could not only reduce costs related to obsolescence and personnel but could also facilitate future computer-intensive shuttle upgrades, such as an integrated vehicle health management system. However, the committee has some serious concerns about the CLCS project as currently planned.

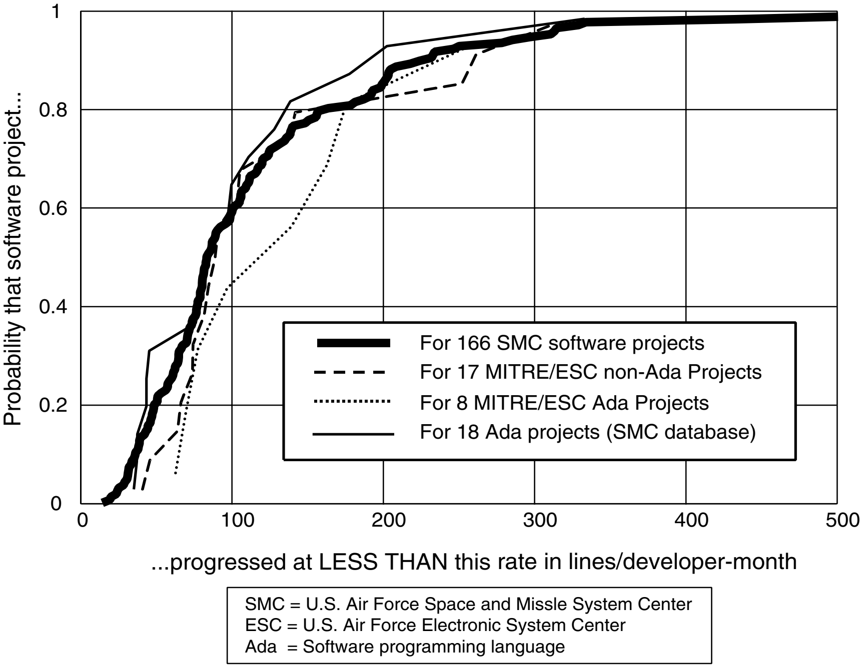

FIGURE 4-1 Historical software coding rates. Source: The Aerospace Corporation, 1998.

The CLCS is a large, distributed, heterogeneous computer project involving the development of more than 3 million lines of new software, much of it automatically generated. The program schedule has already slipped once, and most of the projected software has yet to be developed. Programmer productivity is projected to be 300 lines per programmer per month, which is substantially higher than industry norms. (The historical average for software tasks of this type is closer to 85 lines per month, as illustrated in Figure 4-1).

The CLCS project management appears to be confident that the project is on track and will be completed on time, although it will consume some of the management reserve budget. Management is satisfied that the problem that caused the delay has been corrected and should not cause further delays. Based on their experience with similar NASA projects (notably the Johnson Space Center's Mission Control Center), management believes the predicted level of software productivity can be achieved with the aid of software generation tools. Based on other historical precedents, however, the committee believes that a system as large, complex, heterogeneous, and tightly scheduled as the CLCS has a high potential for running behind schedule and over budget.

Recommendation 14. NASA should conduct an audit of the requirements, specifications, plans, schedules, development budgets, status, and life cycle costs of the checkout launch and control system project. The objective of this audit should not be to cancel the upgrade but to estimate more accurately the time and cost required to complete it and to identify potential problems early enough to rectify them.

Protection from Micrometeoroids and Orbital Debris

The space shuttle was not originally designed to withstand the impacts of orbital debris. As the threat (and the understanding of the threat) has increased, the shuttle program has taken steps to protect the orbiter. As part of the Phase II upgrade program, the shuttle orbiters will be modified during 1999 and 2000 to protect the radiators and the leading edges of the wings from meteoroids and debris. Once these upgrades have been completed, the predicted risk of a penetration that could cause the loss of the orbiter or its crew in a worst case scenario will typically be in the range of 1 in 800 per mission compared to 1 in 400 before the modifications (Johnson, Loftus, 1998).

A 1997 National Research Council report, *Protecting the Space Shuttle from Meteoroids and Orbital Debris*, noted that the proposed modifications to the radiator and the leading edges of the wings appeared to be positive steps towards protecting the shuttle from meteoroids and debris and recommended that NASA investigate additional modifications to the orbiter to improve its survivability (NRC, 1997). The committee chose not to revisit the orbital debris issue, deferring to the 1997 report. However, considering the relatively high predicted level of risk to the orbiter and crew even after the initial modifications are made, and considering the high priority of safety as a goal of the upgrade program, the committee concurs with this recommendation.

Recommendation 15. The Space Shuttle Program Development Office should solicit additional proposals for upgrades to protect the shuttle from meteoroids and orbital debris.

PHASE III UPGRADES

Replacement of the Auxiliary Power Unit

Each shuttle orbiter has three APUs, which are used to power the vehicle's hydraulics during ascent and reentry. The APUs use hydrazine propellant to drive a high-speed turbine that produces mechanical power. The APUs pose a hazard because they use toxic fuel, and they have experienced problems during testing and flight, including a fire involving the hydrazine fuel after the landing of the STS-9 mission.

Existing APUs could support the shuttle program through 2014 at current flight rates. After that (or earlier if flight rates increase) the APUs will start to reach their 75 hour operational life limit, resulting in shortages and requiring cannibalization of APU systems. In an exercise to determine the long-term operational costs of the current APUs, contractors estimated that the cost of keeping the current system operational until 2030 would be approximately $550 million.

NASA is studying a number of options for replacing the APUs with an electric system to support a decision in 2000 on proceeding with the upgrade. NASA is now exploring different battery chemistries and ultracapacitors to provide energy storage and peak power production. Most of the electric systems under consideration would weigh slightly more than the current APUs but would be less toxic. NASA has spent about $650,000 so far, and total development and implementation costs are estimated at $100 to $150 million. Total costs of developing the system and operating it until 2030 are estimated to be about $350 million.

Few systems are more important to the safe operation of the shuttle than the APUs. These flight-critical systems are essential for the important launch and reentry phases; they involve high concentrations of mechanical energy and a very toxic, corrosive, and combustible fuel; and in spite of redundancy against single failures, they are spatially vulnerable to common cause failures, such as fire, explosion, and leaks. Not all of these vulnerabilities would be eliminated with the proposed upgrade, but the very important vulnerability from chemical energetics would be eliminated. In addition, the replacement of the existing APUs by longer-life, less toxic, more efficient power units would reduce turnaround time during ground processing of the orbiter system.

In its search for a replacement for the APU, NASA can take advantage of worldwide efforts to develop advanced electric power systems, including aerospace applications (e.g., the Joint Strike Fighter, the F-22, the Comanche helicopter, the X-33, and the X-34), as well as the development of electric cars (by many companies, including Ford, General Motors, Honda, Toyota, and Nissan). By learning from and applying the technologies developed elsewhere, NASA could greatly leverage its funding for development of a replacement for the APU.

However, considerably more study will be necessary to determine the benefits and costs of the upgrade. Probabilistic risk analysis can be used to estimate the safety impact of improving APUs and compare it with other safety improvements. Further analysis can be performed to determine more accurately the viability of other approaches to upgrading the APUs (including purchasing additional spare parts for the current APUs). Additional analysis is also warranted to determine whether the hydrazine-driven units that power the solid rocket booster's thrust vector control system (and which have similar problems and concerns as the current APUs) should also be replaced as part of the APU upgrade.

Recommendation 16. NASA should continue studying potential modifications to the APUs to better determine the costs, benefits, and appropriate scope of an upgrade. Developments in electric power systems worldwide should be monitored to identify technologies and techniques that could be useful for an APU upgrade.

Avionics

The orbiter's current avionics system was conceived in the early 1970s but contains hardware added during the 1980s and 1990s (including the current computers, which were installed in the late 1980s). The system consists of more than 270 components and approximately 500,000 lines of code. Its primary functions include flight control, guidance and navigation, communication, and orbiter landing support. A secondary, but important, task is to provide operational services for nonavionics systems, such as data handling for the payloads and caution and warning alerts to the crew.

The objective of NASA's proposed avionics upgrade strategy is to avoid the growing costs associated with obsolescence by judiciously replacing obsolescent hardware while, at the same time, positioning the upgrades as components of a modern, functionally partitioned avionics architecture. (Replacement of obsolete avionics hardware is considered to be a Phase II upgrade; the development of a complete modern avionics architecture is considered to be a Phase III upgrade.) To date, $3.5 to $4 million has been spent on studies and on replacing some hardware elements. Total costs will depend on the eventual scope of the avionics upgrade.

Obsolescence probably affects avionics more than any other system, particularly when the avionics include interfacing computers and software. Obsolescence is primarily a cost issue because obsolete components can usually be repaired or replaced if sufficient funding is available. NASA appears to be doing a good job of identifying components that are becoming obsolete, prioritizing potential upgrades in terms of their payback and the urgency of the situation, and applying its limited budget to addressing the most pressing near-term needs.

The proposed partitioned avionics architecture would reduce the cost of development and testing as well as improve safety by lessening the impact of subsystem changes on the remainder of the avionics as well as the current software. Progressing efficiently from the current system to the long-term architecture, however, will require that NASA create scaleable, long-term requirements and interface definitions for the future architecture. If NASA does approve a large-scale avionics upgrade (presumably as a part of a year 2000 decision not to replace the shuttle in the near-term), the availability of long-term requirements would be critical to smooth systems integration.

Recommendation 17. NASA should continue its strategy of judiciously replacing obsolete avionics components while developing a plan for a future improved architecture. Consistent with the year 2000 decision process, NASA should develop scaleable, long-term requirements and interface definitions for the future architecture.

Channel-Wall Nozzle

The channel-wall nozzle is a proposed replacement for the current SSME nozzle. Employing a process developed in Russia and used for the Russian RD-0120 rocket engine, flat stock is roll formed into a conical shape, which serves as the nozzle liner. The liner is slotted to form channels for the nozzle's liquid hydrogen coolant to flow through. A jacket is then installed over the liner and welded at the ends. The entire assembly is then furnace brazed. The channels in the liner take the place of the 1,080 tubes that regeneratively cool the current SSME nozzle.

The channel-wall nozzle is a relatively simple design that has fewer parts and welds than the current complex SSME nozzle. (The current SSME nozzle takes two-and-one-half years to build, costs $7 million, and is currently flown no more than 12 to 15 times because of safety concerns related to hydrogen leaks.) NASA expects the channel-wall nozzle to be more reusable than the current nozzle and to have less risk of critical failure. The new nozzle is also expected to improve engine performance slightly (although any gain in payload capacity may be canceled by the increased nozzle weight), to cost less and take less time to produce, and to cost less to operate. NASA and Rocketdyne (through Aerojet) have spent $0.8 and $1.2 million respectively to study this upgrade, and development could start at the beginning of 1999. The proposed upgrade would cost an estimated $63 million over four years for development and testing, plus an additional $71 million to build 18 certification and production nozzles.

The committee believes that this upgrade could improve the safety of the shuttle because eliminating the tubular construction should eliminate the major source of nozzle leaks. After a recent SSME failure during test firing was attributed to the current nozzle, replacement with the channel-wall nozzle was endorsed by NASA's Mishap Investigation Board. Although adding a new part to the shuttle might increase risk, it seems unlikely in this case because the channel-wall design is based on an established technology that appears to be quite robust (although the technology has not previously been applied to reusable nozzles or any U.S. programs).

The channel-wall nozzle upgrade may also have additional benefits. It appears to be simpler to fabricate than the current SSME nozzle, for example. In addition, the technology may be broadly applicable to other engines and launch vehicle programs, which might benefit from the lessons learned applying the technology to the shuttle. It is not clear whether the upgrade will result in cost savings; that will depend on the durability of the nozzles, as well as on the shuttle's longevity and flight rate.

The committee is concerned, however, about possible problems arising from NASA plans to build the nozzle in Russia (through Rocketdyne) to reduce development costs. NASA will have to be extremely careful in drafting the agreements related to Russian production and technology transfer to ensure that potential problems in Russia do not compromise the shuttle schedule. Although it would probably increase the cost of the upgrade, NASA could ensure that the nozzles could be fabricated in the United States by licensing the technology and know-how to build the nozzles to a U.S. firm. By procuring sufficient numbers of Russian-fabricated nozzles before the U.S. production begins, NASA could also ensure that unanticipated delays in this project would not jeopardize the shuttle's ability to meet its manifest.

Recommendation 18. If NASA decides to implement the channel-wall nozzle upgrade, it should take steps to ensure that channel-wall nozzles are available in the United States, either by stockpiling additional nozzles or developing a channel-wall nozzle manufacturing capability in the United States.

Extended Nose Landing Gear

The proposed extended nose landing gear is a modification intended to reduce the loads on the orbiter's landing gear. The proposed extension would include a new middle segment for the landing gear, a redesigned upper strut housing, and a gas supply cylinder for pneumatic actuation. The upgrade would add approximately 70 to 90 kg to the landing gear system but would either increase the safety margins during shuttle landing or, at existing safety margins, allow the shuttle to land with a higher maximum weight.

About $200,000 has been spent to date on this upgrade, culminating in the development and testing of a prototype unit. The proposed upgrade appears to be a good design for reducing landing loads for the shuttle. However, extensive improvements have already been made to the landing and deceleration systems since the return-to-flight after Challenger, existing hardware meets current requirements, and there are no other apparent benefits to implementing this upgrade. The expected total cost for design and production is $15 million dollars over 28 months.

Recommendation 19. NASA should pursue the extended nose landing gear only if future plans require that the shuttle land with heavier payloads than are currently allowable.

Long-Life Fuel Cell

The orbiter's fuel cells provide electric power for the orbiter and water for the crew. Ninety-six fuel cells in three stacks convert hydrogen and oxygen into electrical power, water, and heat via an alkaline electrolyte. The fuel cells require approximately four overhauls (at about $3.5 million per overhaul) and four repairs (at approximately $100,000 per repair) each year. With continuing overhauls and repairs, the current inventory of fuel cells could support current shuttle flight rates beyond 2012. If the flight rate increases to 12 per year or more, additional fuel cells will be needed. Two distinct upgrades—longer-life alkaline fuel cells and proton exchange membrane (PEM) fuel cells—are being considered to replace the current cells.

Longer-Life Alkaline Fuel Cells

This upgrade, proposed by International Fuel Cells and Boeing, would entail replacing the current fuel cells with modified alkaline cells. The modified fuel cells would operate at reduced reactant temperatures and would be designed to inhibit corrosion and improve reliability. Their electronic controls would also be upgraded to enable new monitoring capabilities and to preclude obsolescence. The lifetime of the upgraded fuel cells is estimated at 5,000 hours. The present fuel cells are certified to 2,600 hours before overhaul. In reality NASA is experiencing an average overhaul time for the current fuel cells of 2,100 hours. It should also be noted that the current fuel cells are operating in the vehicle for an average of only 1,200 hours before they must be removed to repair system component failures.

The contractors estimate that certification of the units to fly on the shuttle would cost about $14 to $17 million, with a production cost of approximately $3 to $4 million for each of the four power plants, assuming that many of the current fuel cell components are reused. The development of advanced alkaline fuel cells could begin in 1999. The contractors estimate that the certification program would take three years, with the first production unit delivered a year later. Because the longer-life alkaline fuel cells appear to be straightforward engineering modifications of the existing orbiter fuel cell power plants and the changes are relatively minor, these estimates of cost and schedule should be reasonably accurate.

If this upgrade were implemented, the primary benefit would be to reduce operations and maintenance costs and time. NASA estimates yearly savings from reducing the number of overhauls and annual repairs would be $22 million. The current fuel cells have flown successfully with an excellent reliability record, so the new cells would have no major functional or safety advantages. The advanced alkaline cell could, however, support longer missions and an increased flight rate, and the associated electronics upgrade could enable improved health monitoring of the fuel cells.

The decision to upgrade to an advanced alkaline fuel cell is primarily a business decision, because the major benefit is cost savings. By calculating the return on investment and comparing this upgrade with other cost-saving upgrades with a high probability of success, NASA can ascertain whether this is a good business proposition.

Proton Exchange Membrane Fuel Cells

This proposed upgrade would replace the current alkaline fuel cells with PEM cells, which operate at a comparatively low temperature (70°C to 100°C) and use a moist polymer membrane as the electrolyte. Although PEM cells were flown in space before alkaline fuel cells, alkaline systems were chosen for the Apollo program and then the shuttle program. The proposed PEM fuel cells would have a lifetime of 10,000 hours (as opposed to an average lifetime of 2,100 hours for the existing fuel cells) and would produce more power than the equivalent mass and volume of alkaline cells.

Like the advanced alkaline cell, the PEM cell upgrade would reduce operations and maintenance costs, support longer missions, and allow improved monitoring capabilities. Because the PEM cells do not involve hazardous materials, however, safety on the ground and in space would also be improved. NASA hopes that advanced PEM fuel cells will also be applicable to future extravehicular activity suits, human space exploration activities, and launch vehicles.

To date, funding for the project has totaled about $1.5 million. NASA is now evaluating prototype PEM fuel cells from four different vendors. The development of PEM fuel cells for the shuttle would cost an estimated $25 to $34 million plus $2.5 to $4.5 million per fuel cell stack (approximately 15 stacks are required). NASA estimates that if the upgrade were approved, the development of fuel cells for the shuttle could begin in 2000 or 2001, with production commencing in late 2004.

The committee believes that the development of PEM fuel cells for the shuttle would be difficult but is feasible. The development of a PEM fuel cell could, however, be substantially facilitated by work going on outside the agency. After a long hiatus, renewed interest in fuel cells for automotive, person-portable, and direct methanol applications has stimulated a major resurgence in PEM development. Thus, NASA has an opportunity to leverage long-life fuel cell development with U.S. Department of Energy and DoD money being spent on other applications. (Advancements to PEM technology developed for the shuttle may contribute in turn to the fuel cell development funded by other agencies.)

One concern about PEM cell development is water management, a critical issue in providing a long-life PEM cell. The cell membrane must be maintained at 100 percent relative humidity. If any part of the membrane is allowed to operate at a lower humidity, reactant gas crossover increases, causing hot spots and accelerating membrane decomposition. This may be a bigger problem in a microgravity environment than in other applications. NASA is aware that cell lifetime data from one contractor is not necessarily applicable to another contractor's design and is wisely evaluating fuel cell life with the appropriate water management scheme in full-size stack hardware.

A decision to develop PEM fuel cells for the shuttle would require more complex analysis than the decision to develop advanced alkaline fuel cells. The benefits of the PEM cells could include large savings in operations costs, improvements in safety through the use of nontoxic electrolytes, and an increase in power for the shuttle. However, the PEM cell upgrade would require an expensive and potentially open-ended technology research program, with delivery not expected until 2004. In addition, like any other completely new component, PEM cells might pose a slightly increased risk of failure to the shuttle until significant flight hours have been logged by the new power plant. (This concern could be mitigated by flying one PEM power plant with two alkaline power plants for a few missions.)

Eventually, the decision to proceed with the PEM upgrade may depend on NASA's desire to pursue this technology for future space missions for which the 2,100-hour stack life of current alkaline fuel cells is unacceptable in terms of maintenance requirements or operational constraints. Planners of future space vehicles and missions could help determine the value of PEM cells for future missions, could influence the design of the shuttle's PEM cells so that it will be applicable to future missions, and, perhaps, provide funding.

Recommendation 20. NASA should continue to explore the costs and benefits of PEM cells before making a decision on a future shuttle fuel cell. Planners of future space vehicles and/or missions that could benefit from PEM fuel cells should be closely involved in these studies.

Nontoxic Orbital Maneuvering System / Reaction Control System

The nontoxic orbital maneuvering system (OMS)/reaction control system (RCS) upgrade would modify the shuttle orbiter's OMS and RCS to use liquid oxygen and ethanol propellants instead of the current engines' toxic N_2O_4 and mono-methyl hydrazine propellants. The proposed upgrade would involve replacing the current engines with pressure-fed liquid oxygen/ethanol engines. In addition, the forward reaction control system would be connected to new common propellant storage tanks that would also be used by the OMS. (Currently, the forward RCS has its own propellant tanks in the nose of the orbiter).

NASA believes that the elimination of toxic and corrosive propellants would reduce hazards on the ground and in orbit, improve ground operations and turnaround times, and decrease corrosion. NASA estimates that this upgrade would result in $24 million in savings at Kennedy Space Center each year. The switch to liquid oxygen and ethanol could also improve the shuttle engines' performance in orbit, enabling it to better support the ISS program, and would provide increased redundancy during an engine malfunction. Technologies implemented in this upgrade might also be useful for other ISS support vehicles (e.g., the crew rescue vehicle), as well as for future space exploration missions. One potential advantage of a nontoxic OMS/RCS upgrade could be use of the system's liquid oxygen as an element of a contingency redundant life support system for the shuttle or the ISS.

Approximately $4 million has been spent to study the OMS/RCS upgrade. The total cost of the upgrade is estimated at $90 to $100 million for development, plus $400 million to build the eight OMS pods necessary for a four-orbiter fleet. NASA is currently assessing the replacement RCS and OMS engines, including existing engines (such as the Ariane V upper stage engine), and designing the overall OMS/RCS system. NASA expects to be ready for a decision on whether to proceed with the upgrade by mid-2000.

Although NASA has years of experience handling toxic, corrosive propellants, the removal of such materials from the shuttle could enable more rapid turnaround (and thus result in a cost savings) because fewer precautions would have to be taken to protect the ground crew. However, the shuttle often carries payloads that use toxic hypergolic fuels, so this upgrade alone may not allow the shuttle program to completely scale back its safeguards against toxic propellants unless payloads carrying hypergolic propulsion systems could be loaded away from the shuttle and treated as sealed prepackaged systems. (This approach is used by the military in numerous programs, including the Minuteman and Peacekeeper missiles.)

The OMS/RCS upgrade has some disadvantages. Although the modified OMS pod would have fewer parts than the current system, it would be more complex because the liquid oxygen propellant would require additional tanks, insulation, and thermal controls. Structures and other subsystems in the vicinity of the liquid oxygen may also require thermal protection. Because the nontoxic propellants are not hypergolic, an ignition system would also be required, which might reduce reliability and could require additional maintenance. Because the engines being considered for the upgrade are not as well understood or tested as existing OMS and RCS engines, the risk to the shuttle may actually be increased during the early transition timeframe. Redundancy may be compromised by the proposed reduction in the number of separate propellant tanks and supply systems. Finally, the designers will have to ensure that the length of the feed system from the aft to the forward compartment does not compromise the rapid response characteristics of the RCS. The cost of ground system modifications will be significant and will require the existing ground systems to remain in place until all orbiters are modified.

Recommendation 21. Before NASA makes any decision on implementation, it should very carefully study the risks inherent in changing to a nontoxic OMS/RCS system and conduct trade-off studies to determine whether modifications to the existing system may be a more cost-effective means of meeting program goals. Commonality with the propulsion (and potentially life-support) systems of the ISS and other future NASA programs should be considered in any final design.

Water Membrane Evaporator

The water membrane evaporator (WME) is being considered as a replacement for the orbiter's flash evaporator system (FES), which cools the orbiter during ascent and reentry and provides supplemental cooling (in concert with the payload bay door radiators) in orbit. A replacement is being considered because the FES is experiencing corrosion, which creates a risk of freon leaks. Three FES units have been removed and replaced to date, and two more units have slow freon leaks which will eventually require repairs. NASA has already taken some steps to combat the problem, including cutting the iodine content of the water in the FES and replacing the FES's original aluminum material with aluminum that has a thicker anodized layer.

The WME appears to be a simple passive device that can perform the FES's cooling function. The WME takes advantage of the hydrophobicity of microporous Teflon to evaporate water while maintaining excess liquid water in a hydrophilic layer behind the hydrophobic layer. Thus, the WME should be immune to corrosion and able to function longer than the FES. The team developing the WME also believes that the WME's simpler design and fewer moving parts will make it more reliable than the FES. NASA has spent approximately $200,000 on this project to date and estimates the total cost to place operational WMEs on the orbiters to be $15 to $20 million. The project team expects to be ready for a decision on whether to implement the upgrade by early 1999.

The committee has some concerns about the WME. First, as the WME designers are aware, any trace of a surface-active impurity in the water will cause the WME's Teflon to become wet and fill with water, which could cause the loss of liquid feed water. Such surface-active impurities can be very difficult to prevent. (NASA might consider adding a sensor to ensure a high water surface tension.) Second, because this type of system is not used in any other application and thus will probably require an exacting development and qualification test program, the cost and schedule estimates may not be accurate. Finally, the committee believes that other options to reduce freon leakage (such as employing materials in the FES that are less susceptible to corrosion) might be lower-cost and lower-risk solutions to the problem.

Recommendation 22. NASA should reassess the costs (including those associated with surface tension issues and development testing) and benefits of all options for dealing with the corrosion problems in the flash evaporator system before choosing a solution.

PHASE IV UPGRADES

The only Phase IV upgrades briefed to the committee were two new first stage booster concepts: the five-segment RSRB (reusable solid rocket booster), and the liquid fly back booster (LFBB). Each concept represents a major programmatic and technical undertaking. By the time either system would be ready to fly, the current reusable solid rocket booster will have demonstrated more than 100 flights (200 operational firings). As was the case with the cancelled advanced solid rocket motor program, any new booster design, no matter how many safety and reliability enhancements it contains, will necessarily pose additional risk to the first few crews who fly it. Part of the risk will be in the form of any failure uncertainties carried forward from the ground and/or unmanned flight tests, and part will be due to the continued lack of adequate crew escape capability in the shuttle. Because of all this, NASA is not likely to, and the committee agrees it should not, enter into any major new booster program without substantial national need for the promised performance enhancements and cost savings.

Five-Segment Reusable Solid Rocket Booster

This upgrade, informally proposed by Thiokol Propulsion, consists of modifications to the shuttle's four-segment RSRB intended to improve safety and performance and reduce overall systems costs. In addition to adding a fifth segment to the RSRB, the proposed upgrade would modify the RSRB's nozzle and insulation and alter the grain of the solid fuel to provide a more risk-tolerant thrust profile. Thiokol, USBI, and Boeing have funded preliminary designs, estimated benefits, and examined systems integration issues. Estimated total costs for the upgrade are in the range of $1 billion with an estimated four year schedule from authority to proceed until the first flight.

On the surface, the five-segment RSRB appears to be a relatively straightforward approach to increasing the performance of the shuttle's boosters. The extra performance from this upgrade could either allow the shuttle to carry heavier payloads, eliminate the need to throttle the main engines during ascent (thus improving safety), or minimize or eliminate a high-risk launch abort mode. A full understanding of costs and risks will require more analyses of the cost and weight impacts associated with the RSRB's modified vehicle attachments, aerodynamic and structural loads, control dynamics, separation rockets, and other integration issues

The potential improvements in performance and safety warrant a close formal examination by NASA of the five-segment RSRB. A recent initiative by the Office of Space Flight directing the Independent Program Assessment Office to perform an assessment of the five-segment RSRB and the LFBB is a good step in that direction. A complete assessment should also consider the possibility that some of the smaller improvements of the five-segment RSRB (e.g., grain shape optimization) might be more effective if they are considered as smaller stand-alone Phase II or III upgrades.

Recommendation 23. NASA should formally evaluate the merits of the five-segment reusable solid rocket booster as it prepares for the decision on the future of the shuttle program. A thorough evaluation of the potential for the separate implementation of subsets of the proposal should be included in this assessment.

Liquid Fly-Back Booster

This proposed upgrade would replace the shuttle's two solid rocket boosters with winged liquid-fueled boosters that would automatically fly back to the launch site (using conventional gas turbine engines) after they have used up their rocket fuel and separated from the orbiter. Figure 4-2 illustrates some design concepts for the LFBB. The proposers of the upgrade believe that the LFBBs would improve safety by reducing or eliminating the need for some high-risk

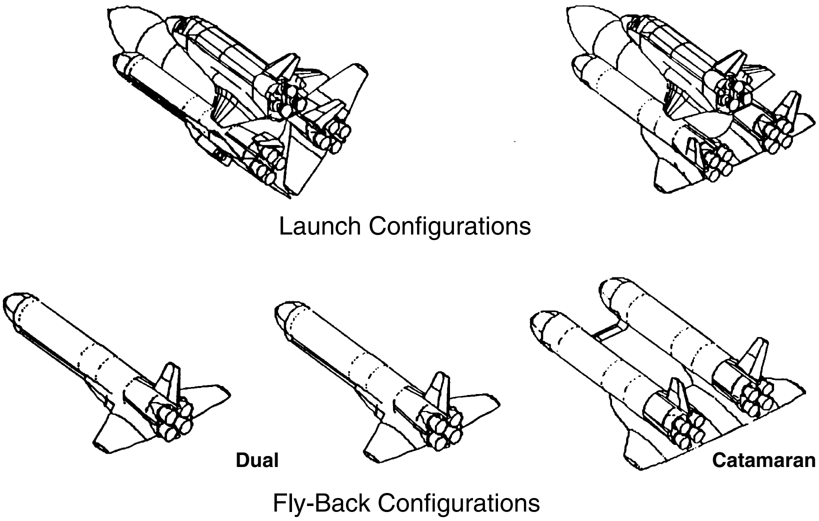

FIGURE 4-2 Representative LFBB concepts.

abort modes, save $400 million per year in operations costs (with seven shuttle flights per year), and increase the shuttle's payload capacity. The proposers also predict that the LFBB would enable a three-week turnaround time between missions, and (with three sets of LFBBs) could allow the shuttle to fly 15 times per year.

Approximately $12 million has been spent by NASA to study the LFBB. Lockheed Martin and Boeing have also funded studies and produced some initial competing design concepts. NASA plans to continue studying the LFBB in preparation for a decision on whether to proceed at the end of year 2000. (Like the five-segment RSRB, the LFBB will be assessed by NASA's Independent Program Assessments Office.) If NASA decides to proceed, the upgrade proposers estimate that hardware fabrication and testing will take four years and will cost about $4 to $5 billion.

The committee has a number of concerns about the LFBB. The most serious is that the fundamental configuration of a new shuttle booster seems to have been predefined without adequate trade-off studies to determine whether it is the most appropriate way to meet the needs of the shuttle and other programs. Low cost, but high-performance/highly reliable throwaway liquid boosters, an improved solid rocket motor, or relatively low-cost ocean-recovered reusable liquid boosters, for example, might be better choices. Bringing in experts from inside and outside the agency to conduct and review trade-off studies to determine the most appropriate fundamental configurations for a new shuttle booster would help NASA ensure that it is spending its upgrade money wisely. Understanding the uncertain future of the program, these tradeoffs will most probably include various flight rate and mission scenarios.

A second important concern about the LFBB program is the accuracy of estimates of the total costs of the program from development through production and operation. Almost every aspect of the LFBB suggests that the development costs will be high. The LFBB:

- must be extremely reliable ("human rated")
- will be a highly complex vehicle that uses both rocket and gas turbine propulsion
- will have all the systems and subsystems required to fly and land, including wings, a tail, and landing gear
- will modify the mold line of the shuttle (thus requiring major testing and analysis of the new configuration)

More accurate estimates of the costs of developing the LFBB would require assessing these issues, as well as the feasibility and cost of achieving a three-week turnaround time, the cost of maintaining human-rated vehicles, and the cost of design and development testing to ensure that overall system risk is acceptable on the first few manned flights.

The operations costs of the LFBB may also be higher than predicted. For example, current cost estimates do not include the potential need to replace LFBBs. NASA assumes that six LFBBs will be sufficient to support up to 15 flights per year. Table 4-2 shows the relationship between LFBB reliability and hardware requirements over time. Clearly, if the reliability of the LFBB is less than perfect, it may be necessary to purchase additional LFBBs. (NASA currently estimates that the LFBB will experience a catastrophic failure every 1,520 launches—an unprecedented level of reliability for a new, highly complex booster.)

The committee's third concern is the programmatic status of the LFBB. If the LFBB were designed only for the shuttle (like the RSRB and the canceled ASRM), funding for development could be problematical, considering recent budgetary decisions and Congress's desire to finance new transportation initiatives through industry. If the LFBB is funded only from the shuttle program, it is also likely that it would be optimized to support the shuttle (thus making it less attractive for other uses). By finding other compelling uses for the LFBB (e.g., as a booster for a new heavy-lift vehicle) and by involving other potential users (e.g., the DoD) in the funding and design of the LFBB, NASA could both improve the overall value of the program and increase the likelihood that it would be funded.

Recommendation 24. NASA should initiate a detailed independent assessment of configuration trade-offs, costs, and programmatic and technical risks for a new shuttle booster.

TABLE 4-2 Required Inventory of LFBBs

Number of LFBBs	**Probability that at least 6 LFBBs[a] remain in inventory after 30 shuttle launches,[b] assuming successful recovery of each booster**			
	0.90	**0.95**	**0.98**	**0.99**
6	0.002	0.046	0.30	0.55
7	0.014	0.19	0.66	0.88
8	0.053	0.42	0.88	0.98
9	0.14	0.65	0.97	1.0
10	0.27	0.82	0.99	1.0
11	0.44	0.92	1.0	1.0
12	0.61	0.97	1.0	1.0
13	0.75	0.99	1.0	1.0

[a] Assumes dual booster configuration

[b] 2 years at 15 flights per year, 3 years at 10 flights per year, or 4 years at 7 or 8 flights per year

Recommendation 25. NASA should coordinate closely with other government and industry transportation initiatives in determining the need and the resources for any new shuttle booster.

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Appendixes

APPENDIX A

Statement of Task

The committee will examine NASA's plans to upgrade the space shuttle system. The assessment will be conducted with reference to the National Space Transportation Policy and NASA's 1988 strategic plan, which calls for the shuttle upgrade program to improve the reliability, performance, and longevity of space shuttle operations to meet International Space Station needs and human exploration goals beyond 2012.

NASA will present a set of proposed shuttle upgrades, approved as well as under study, and the rationale and criteria used to select the upgrades. The committee will assess NASA's approach to upgrading the space shuttle in a single final report. In that report, the committee will:

- Assess NASA's method for evaluating and selecting upgrades. Modifications to NASA's approach for evaluating and selecting upgrades to the space shuttle may be recommended.

- Conduct a top-level technical assessment of proposed shuttle upgrades that have not yet been implemented. Where appropriate, the report will include findings and recommendations about individual upgrades and address the potential of those upgrades to enhance operational safety, system effectiveness, and other program goals.

APPENDIX B

Biographical Sketches of Committee Members

Bryan O'Connor, chair, is a consultant on aerospace safety. Previously, he served as the deputy associate administrator of the Office of Space Flight at National Aeronautics and Space Administration (NASA) Headquarters, the chief of staff of the Naval Air Test Center, and a NASA astronaut. At NASA, he led the redesign of the space station program, founded and led NASA's Spaceflight Safety Panel, and introduced probabilistic risk assessment to the space shuttle and space station programs. He has been awarded NASA's Distinguished Service Medal, Exceptional Service Medal, and Outstanding Leadership Medal, as well as the Defense Superior Service Medal, and the Distinguished Flying Cross, the American Institute of Aeronautics and Astronautics (AIAA) System Effectiveness and Safety Award, and the Aviation Week Laurel. Mr. O'Connor holds degrees in engineering and aeronautical systems from the U.S. Naval Academy and the University of West Florida.

Stephen A. Book is a distinguished engineer at The Aerospace Corporation, serving as the corporation's principal technical authority on costs of space and space-related systems. At Aerospace, several innovative approaches to cost-risk analysis and other statistical aspects of cost and economics have been developed under his direction. Dr. Book served on the NASA Advisory Council's Cost Assessment and Validation Task Force for the International Space Station (the "Chabrow Committee"). He earned his Ph.D. in mathematics from the University of Oregon, Eugene, his A.B. degree in mathematics from Georgetown University, and his M.A. degree in mathematics from Cornell University.

Benjamin Cosgrove is a retired senior vice president of the Boeing Commercial Airplane Group. Mr. Cosgrove has been associated with almost all Boeing jet aircraft programs during his 44 years with the company. He was honored by the Society of Aviation and Space Technology for his role in converting the Boeing 767 transport design from a three-man to a two-man cockpit configuration and received the Ed Wells Technical Management Award for addressing aging aircraft issues. Mr. Cosgrove was honored with the 1991 Wright Brothers Memorial Trophy for his lifetime contributions to commercial aviation safety and for technical achievement. He is a member of the National Academy of Engineering and a fellow of both the AIAA and England's Royal Aeronautical Society. He holds a B.S. degree in aeronautical engineering and an honorary D. Eng. degree from the University of Notre Dame.

Donald H. Emero is a retired former vice president of Rockwell's Space Systems Division. Mr. Emero was the chief engineer for the space shuttle orbiter from 1989 to 1993. In this position, he headed numerous teams assigned to resolve complex problems with the shuttle. Mr. Emero has been awarded the NASA Distinguished Public Service Medal and the National Management Association Gold Knight of Management and is an associate fellow of the AIAA. He received an M.S. degree from the University of Massachusetts.

B. John Garrick was a founder of PLG, Inc., and retired as president and chief executive officer in 1997. Currently, he has an active consulting practice in the development and application of the risk sciences to nuclear power, space, chemical, and marine systems. His accomplishments include his Ph.D. thesis on unified systems safety analysis that first advocated what is now known as probabilistic risk analysis (PRA) and the establishment of the first consulting team to perform initial comprehensive and quantitative risk assessments for the commercial nuclear power industry. Dr. Garrick is a member of the National Academy of Engineering and has been a major contributor to the analytical methods and thought processes employed in PRA. He holds a Ph.D. in engineering and applied sciences from the University of California at Los Angeles (UCLA).

Richard Harper joined the staff of IBM Research on August 7, 1998. Previously, Dr. Harper was a senior technical consultant at Stratus Computer, Inc., where he served as senior technologist, consultant, cross-function problem solver, and technical advisor to senior engineering management. Dr. Harper has also worked as a principal member of the technical staff at the Charles Stark Draper Laboratory, Inc., where he was the system architect and main investigator for numerous fault-tolerant processing system development programs. Dr. Harper received his Ph.D. in computer systems architecture from the Massachusetts Institute of Technology (MIT) and his M.S. in aerospace engineering from Mississippi State University.

Nancy Leveson is professor of aeronautics and astronautics at MIT. Dr. Leveson is a fellow of the Association for Computing Machinery and was awarded the 1995 AIAA Information Systems Award for contributions in space and aeronautics computer technology and science for "developing the field of software safety and for promoting responsible software and system engineering practices where life and property are at stake." She has served as the editor-in-chief of the Institute of Electrical and Electronics Engineers Transactions on Software Engineering and chaired the 1993 National Research Council study on Space Shuttle Software. Dr. Leveson received all of her degrees, in mathematics, management, and computer science, from UCLA.

Donald Maricle is a private consultant working on small electrochemical devices and fuel cells. For 23 years until 1996, he was manager for materials engineering at International Fuel Cells, where he worked on a variety of fuel cells and batteries. Previously, he was director of research at the Zito Company, where he was responsible for developing a zinc-bromine battery. Before that, he was a group leader at American Cyanamid, where he invented and developed the $LiSO_2$ battery and discovered electrochemiluminescence. Dr. Maricle has a Ph.D. from MIT and a B.A. from Wesleyan University.

Robert Sackheim is manager of the Propulsion and Combustion Center at TRW, where he is responsible for liquid, solid, and gel propellant rocket propulsion as well as other areas related to rocket propulsion. He has served as manager of TRW's Propulsion and Power Laboratory and has worked on diverse in-space propulsion efforts, including the lunar module descent engine, the Mariner Mars flight propulsion system, and the TDRS-A recovery effort. He has also worked for the U. S. Air Force and COMSAT corporation and has 35 years of experience in the field of rocket propulsion and energy conversion research, technology, development, and flight applications. Mr. Sackheim is a fellow of the AIAA. He earned B.S. and M.S. degrees in chemical engineering from the University of Virginia and Columbia University, respectively.

George Sutton is a principal engineer at ANSER. Dr. Sutton is an expert in thermal protection systems, ablation heat protection and materials, thermophysics, hypersonics, lasers, aero-optics, homing interceptors, and missile defense. He has served as scientific advisor to Air Force Headquarters, vice president of Jaycor, and chief scientist of Aero Thermo Technology, Inc. He is the author of more than 90 publications and holds 10 patents. Dr. Sutton is a member of the National Academy of Engineering and a fellow of the American Association for the Advancement of Science (AAAS) and the AIAA. He received his B.S. from Cornell University and his M.S. and Ph.D. from the California Institute of Technology.

Richard R. Weiss is a consultant in aerospace science and engineering involving launch vehicles and space systems. Previously, he was deputy director for space launch systems and technology in the Office of the Undersecretary of Defense, Missiles and Space Systems. He served in the Air Force laboratory system as the chief scientist of the Rocket Propulsion Laboratory, director of the Astronautics Laboratory, and director of the Propulsion Directorate, Phillips Laboratory. Dr. Weiss has been involved in the development and transition of advanced technology for most of the space and missile systems (both strategic and tactical) in the U.S. inventory today. Dr. Weiss has received several awards including the Air Force Outstanding Civilian Achievement Award and AIAA's 1994 Wyld Propulsion Award for leadership in developing propulsion technology. Dr. Weiss holds a Ph.D. in mechanical engineering from Purdue University, an M.S. in mechanical engineering from the University of Southern California, and a B.S. in aeronautical engineering from the University of Michigan.

APPENDIX C

Shuttle Upgrades Presented to the Committee

Phase II

- Orbiter Projects
  - Global positioning systems
  - Multifunction electronic display systems
  - Advanced master electronics controllers
  - Thermal protection system improvements
  - Shuttle integrated global positioning system and inertial navigation system
  - Micrometeoroid and orbital debris protection
  - Advanced air data transducer assembly
  - Reinforced carbon-carbon upgrade
  - Solid state recorder/mass memory storage unit
  - Solid state lights
  - Precision approach
  - Wireless video
  - Checkout and launch control system
  - Integrated vehicle health management
  - Fiber-optic flight experiment
  - Standard single payload carrier study
  - Less toxic thermal protection system waterproofing
- Reusable Solid Rocket Booster Projects
  - Hydraulic power unit fuel isolation valve/shaft seal
  - Aft skirt factor of safety bracket
  - Composite solid rocket booster nose cap

- External Tank
  - External tank ground umbilical carrier assembly upgrades
  - Friction stir welding
  - Extravehicular activity projects

Phase III

- Channel-wall nozzle
- Reusable solid rocket motor J-joint insulation upgrade
- Avionics upgrade
- Auxiliary power unit replacement,
- Nontoxic orbital maneuvering system/reaction control system
- Regenerative carbon dioxide removable system
- Water membrane evaporator
- Extended nose landing gear
- Main propulsion system electromechanical actuator

Phase IV

- Solid rocket motor fifth segment
- Liquid fly-back booster

APPENDIX D

List of Recommendations

Recommendation 1. NASA should benchmark other large organizations' investment processes for technological upgrades and attempt to identify and emulate appropriate processes and investment strategies.

Recommendation 2. The ability of a shuttle-unique upgrade to support an increased flight rate should not be a factor in the prioritization process, unless NASA can show through a viable business plan that has been reviewed and approved by financial and technical experts inside and outside the agency, as well as national policy makers (1) that the shuttle could attract enough business to justify the increased flight rate, and (2) that the shuttle program would not unfairly compete with commercial launch vehicles or pose unnecessary risks to a national asset.

Recommendation 3. The Space Shuttle Program should reassess the goals used to prioritize candidate upgrades to ensure that they reflect the upgrade program's priorities, are feasible, and are clearly understandable to everyone working in the program.

Recommendation 4. The Human Exploration and Development of Space Enterprise should bring the cost goals for the space shuttle in its strategic plan into line with budget and policy realities.

Recommendation 5. NASA should continue to increase the scope and capabilities of the quantitative risk assessment system by improving its models of failures attributable to combinations of risks, human error, abort modes, on-orbit hazards, reentry and landing, and software. Until these improvements are made, the Space Shuttle Program Development Office should be very cautious in using the quantitative risk assessment system to aid in prioritizing upgrades.

Recommendation 6. NASA should take care that the Decision Support System's quantitative tools are used as a supplement to, not as a substitute for, formal qualitative evaluations. Expert Elicitation should be considered as an additional formal qualitative tool. Also, NASA should consider modifying the quantification algorithm that the Decision Support System employs for cost-benefit comparisons so that it uses full probability values rather than 20th percentile S-curve values.

Recommendation 7. All calculations, comparisons of costs and cost savings, and cost-benefit assessments done by NASA, as well as its Decision Support System independent contractor, should be performed using fixed-year dollars and should include all costs (including hidden costs) associated with the upgrade.

Recommendation 8. NASA should provide stronger incentives for the shuttle prime contractor to propose, finance, and implement upgrades to meet the shuttle program's goals.

Recommendation 9. Upgrade project managers should involve industry more in the definition and early development of candidate upgrades.

Recommendation 10. The Space Shuttle Program should institute a process early in the development of a candidate upgrade to ensure that the upgrade is compatible with other shuttle systems and relevant to meeting program goals.

Recommendation 11. NASA should limit the software changes associated with new shuttle upgrades. The agency should consider standardizing its guidelines for using commercial off-the-shelf software in shuttle upgrades.

Recommendation 12. Before embarking on the larger, more costly upgrades, NASA should examine alternative solutions and conduct trade-off studies to determine if the proposed upgrade is the best way to achieve the desired result.

Recommendation 13. The Space Shuttle Program Development Office should not consider proposed upgrades as stand-alone modifications but should look for opportunities to combine upgrades (or features of upgrades) to efficiently meet future requirements.

Recommendation 14. NASA should conduct an audit of the requirements, specifications, plans, schedules, development budgets, status, and life cycle costs of the checkout launch and control system project. The objective of this audit should not be to cancel the upgrade but to estimate more accurately the time and cost required to complete it and to identify potential problems early enough to rectify them.

Recommendation 15. The Space Shuttle Program Development Office should solicit additional proposals for upgrades to protect the shuttle from meteoroids and orbital debris.

Recommendation 16. NASA should continue studying potential modifications to the APUs to better determine the costs, benefits, and appropriate scope of an upgrade. Developments in electric power systems worldwide should be monitored to identify technologies and techniques that could be useful for an APU upgrade.

Recommendation 17. NASA should continue its strategy of judiciously replacing obsolete avionics components while developing a plan for a future improved architecture. Consistent with the year 2000 decision process, NASA should develop scaleable, long-term requirements and interface definitions for the future architecture.

Recommendation 18. If NASA decides to implement the channel-wall nozzle upgrade, it should take steps to ensure that channel-wall nozzles are available in the United States, either by stockpiling additional nozzles or developing a channel-wall nozzle manufacturing capability in the United States.

Recommendation 19. NASA should pursue the extended nose landing gear only if future plans require that the shuttle land with heavier payloads than are currently allowable.

Recommendation 20. NASA should continue to explore the costs and benefits of PEM cells before making a decision on a future shuttle fuel cell. Planners of future space vehicles and/or missions that could benefit from PEM fuel cells should be closely involved in these studies.

Recommendation 21. Before NASA makes any decision on implementation, it should very carefully study the risks inherent in changing to a nontoxic OMS/RCS system and conduct trade-off studies to determine whether modifications to the existing system may be a more cost-effective means of meeting program goals. Commonality with the propulsion (and potentially life-support) systems of the ISS and other future NASA programs should be considered in any final design.

Recommendation 22. NASA should reassess the costs (including those associated with surface tension issues and development testing) and benefits of all options for dealing with the corrosion problems in the flash evaporator system before choosing a solution.

Recommendation 23. NASA should formally evaluate the merits of the five-segment reusable solid rocket booster as it prepares for the decision on the future of the shuttle program. A thorough evaluation of the potential for the separate implementation of subsets of the proposal should be included in this assessment.

Recommendation 24. NASA should initiate a detailed independent assessment of configuration trade-offs, costs, and programmatic and technical risks for a new shuttle booster.

Recommendation 25. NASA should coordinate closely with other government and industry transportation initiatives in determining the need and, if appropriate, the resources for any new shuttle booster.

Acronyms

APU	auxiliary power unit
ASRM	advanced solid rocket motor
CLCS	checkout launch and control system
COTS	commercial off-the-shelf
DSS	Decision Support System
DoD	U.S. Department of Defense
FES	flash evaporator system
FY	fiscal year
HEDS	Human Exploration and Development of Space
IUS	inertial upper stage
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LFBB	liquid fly-back booster

MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NPD	NASA Policy Directive
NRC	National Research Council
NSPD	National Space Policy Directive
OMS	orbital maneuvering system
PAM	payload assist module
PEM	proton exchange membrane
QRAS	quantitative risk assessment system
R&D	research and development
RCS	reaction control system
RLV	reusable launch vehicle
RSRB	reusable solid rocket booster
S&PU	safety and performance upgrades
SFOC	space flight operations contract
SSME	space shuttle main engine
SSUPRCB	Space Shuttle Upgrades Program Requirements Control Board
USA	United Space Alliance corporation
USNRC	U.S. Nuclear Regulatory Commission
WME	water membrane evaporator