United States General Accounting Office

GAO

Report to Congressional Requesters

January 2004

SPACE SHUTTLE

Further Improvements Needed in NASA's Modernization Efforts

GAO-04-203

GAO

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Highlights

Highlights of GAO-04-203, a report to congressional requesters

January 2004

SPACE SHUTTLE

Further Improvements Needed in NASA's Modernization Efforts

Why GAO Did This Study

The Columbia tragedy has accentuated the need to modernize the 20-year-old space shuttle, the only U.S. launch system that carries people to and from space. The shuttle will now be needed for another two decades. As it ages, the spacecraft's components will also age, and it may become increasingly unreliable.

GAO examined the National Aeronautics and Space Administration's (NASA) plans to upgrade the shuttle through 2020, how it will identify and select what upgrades are needed, how much the upgrades may cost, and what factors will influence that cost over the system's lifetime.

What GAO Recommends

NASA needs to fully define shuttle upgrade requirements so decisions on upgrade projects can be integrated with its transportation plan. The agency must improve how it selects upgrades by developing an indicator that shows how upgrading will increase shuttle life or safety as well as other analytic tools to help its staff make judgments. It must develop a thorough estimate of the total life-cycle cost of upgrades through 2020, to determine the funding that will be needed for shuttle upgrades.

NASA fully concurred with most GAO recommendations, and agreed with the intent of the recommendation to develop a cost estimate for all shuttle upgrades through 2020.

www.gao.gov/cgi-bin/getrpt?GAO-04-203.

To view the full product, including the scope and methodology, click on the link above. For more information, contact Allen Li at (202) 512-3600 or lia@gao.gov.

What GAO Found

NASA cannot fully define shuttle upgrade requirements until it resolves questions over the shuttle's operational life and determines requirements for elements of its Integrated Space Transportation Plan such as the International Space Station. Prior efforts to upgrade the shuttle have been stymied because NASA could not develop a strategic investment plan or systematically define the spacecraft's requirements because of changes in its life expectancy and mission.

NASA is trying to improve how it identifies, selects, and prioritizes shuttle upgrades. In March 2003, it institutionalized a Space Shuttle Service Life Extension Program to ensure safe and effective operations, along with a management plan documenting roles and responsibilities and an annual process for selecting upgraded projects and studies. In addition, NASA will try to improve shuttle safety by implementing the recommendations of the Columbia Accident Investigation Board (CAIB).

NASA's estimate of the total cost to upgrade the shuttle—$300 million-$500 million a year, or a total of $5 billion-$8 billion through 2020—is reasonably based but could be significantly higher, as it does not include potential projects such as a crew escape system. It will be difficult for NASA to make an accurate estimate until it firmly establishes the basic requirements (such as life expectancy) for the shuttle and the process for selecting shuttle upgrades. A number of potential changes could significantly increase the cost of shuttle upgrades, including responses to the recommendations of the CAIB.

Space Shuttle Atlantis Lift-Off

Source: NASA.

Contents

Abbreviations

AHMS	Advanced Health Management System
ATP	Authority to Proceed
C/W	Caution and Warning
CAIB	Columbia Accident Investigation Board
CAU	Cockpit Avionics Upgrade
CG	Center of Gravity
ET	External Tank
ISS	International Space Station
ISTP	Integrated Space Transportation Plan
MLG	Main Landing Gear
NASA	National Aeronautics and Space Administration
OMM	Orbiter Major Modification
OSP	Orbital Space Plane
PLB	Payload Bay
PRA	Probabilistic Risk Assessment
PRSD	Power Reactant Storage and Distribution (fuel cells)
ROM	Rough Order of Magnitude
RSRM	Reusable Solid Rocket Motor
SLEP	Service Life Extension Program
SSME	Space Shuttle Main Engine
STE	Special Test Equipment

G A O

Accountability * Integrity * Reliability

United States General Accounting Office
Washington, DC 20548

January 15, 2004

The Honorable John Breaux
Ranking Minority Member
Subcommittee on Science, Technology, and Space
Committee on Commerce, Science, and Transportation
United States Senate

The Honorable Bill Nelson
United States Senate

The space shuttle is the only U.S. launch system capable of carrying people to and from space. It has operated for over 20 years and is planned for use well into the second decade of this century and possibly beyond. As the shuttle ages, the National Aeronautics and Space Administration (NASA) is faced with an increased need to modernize the shuttle due to component obsolescence and/or to enhance safety. The Shuttle Columbia tragedy has accentuated this need. At your request, we reviewed the shuttle modernization efforts to determine (1) NASA's past requirements and plans to upgrade the shuttle through 2020, (2) how NASA will identify what upgrades are required in the future and how those upgrades will be selected and prioritized, and (3) NASA's estimated life-cycle cost for shuttle upgrades through 2020 and identify the potential program uncertainties that may affect cost.

Results in Brief

Even before the Columbia tragedy, NASA faced critical decisions on how best to modernize the shuttle to keep it flying safely throughout its operational life. With NASA's need to improve shuttle safety as the shuttle fleet returns to service, NASA has not yet clearly defined shuttle upgrade requirements, improved the process for selecting and prioritizing upgrades, and developed an estimate of the total life-cycle cost of upgrades through 2020.

NASA cannot fully define shuttle upgrade requirements until it resolves its uncertainty over the shuttle's operational life and determines the basic requirements for elements of its Integrated Space Transportation Plan[1]

[1] NASA's Integrated Space Transportation Plan provides a road map for continued shuttle operations and for key investment decisions.

(ISTP), which includes the International Space Station (ISS). NASA has known that it needs to establish an upgrade program to modernize various components of the space shuttle to keep it flying safely throughout its life. However, efforts to upgrade the shuttle have been stymied by the agency's inability to develop a long-term strategic investment plan to fly the shuttle safely and a systematic approach for defining the spacecraft's requirements because its life expectancy and mission have continued to change from an original design of a 10-year life to the year 2020 and possibly beyond.

NASA is making an effort to improve the process that identifies, selects, and prioritizes shuttle upgrades. In March 2003, it institutionalized a Space Shuttle Service Life Extension Program (SLEP) as the primary framework for ensuring safe and effective operations, along with a management plan documenting roles and responsibilities and an annual process for selecting and prioritizing upgraded projects and studies. Prior to the SLEP, NASA had no documented systematic selection process, and managers made decisions on upgrades using their professional insight and judgment and a limited number of quantitative or analytic tools rather than relying on extensive use of hard data or rigorous analysis. In addition, NASA is planning to make upgrades and other improvements to enhance shuttle safety as a result of implementing the recommendations of the Columbia Accident Investigation Board (CAIB).

NASA has not yet attempted to prepare a total detailed life-cycle cost estimate for all upgrades through 2020. NASA did prepare a rough order of magnitude estimate of the total cost to upgrade the shuttle—$300 million-$500 million a year, or a total of $5 billion-$8 billion through 2020—based on current project estimates. Although the estimate appears to be reasonably based, the total cost could be significantly higher, as the estimate does not include the costs of major potential projects such as a crew escape system. NASA will continue to have difficulty making an accurate and reliable estimate of the total cost until it finalizes the basic requirements (such as life expectancy) for the shuttle and further improves the process for identifying and selecting shuttle upgrades. Accurate and reliable cost estimates to upgrade the shuttle and enable it to continue operations are needed by decision makers. In addition, a number of potential program changes could significantly increase the estimated cost of shuttle upgrades, including major changes in shuttle requirements such as redesigned rocket boosters to provide additional lift capability. Other costly potential program changes include schedule slippages caused by delays in software and hardware integration and modifications responding to the recommendations of the CAIB.

We are making recommendations aimed at strengthening NASA's efforts to modernize the space shuttle by fully defining basic requirements for the shuttle; improving its analytic tools to assess shuttle upgrades; and, once basic requirements are defined, developing a comprehensive estimate of the total cost for the shuttle through 2020.

In written comments on a draft of this report, NASA's Deputy Administrator stated that the agency concurred with the first three recommendations and concurred with the intent of the fourth recommendation concerning development of a cost estimate for all shuttle upgrades through 2020. NASA's detailed comments are included as appendix I.

Background

The space shuttle is the world's first reusable space transportation system. It consists of a reusable orbiter with three main engines, two partially reusable solid rocket boosters, and an expendable external fuel tank. The space shuttle is an essential element of NASA's transportation plan that includes a framework for maintaining shuttle fleet capability to fly safely through 2020. The space shuttle is NASA's largest individual program accounting for about 25 percent of the agency's fiscal year 2004 budget request. Since it is the nation's only launch system capable of transporting people, the shuttle's viability is critical to the space station.

We have reported in the past that extensive delays in the development and assembly of the ISS and difficulties defining requirements and maturing technologies for the next generation space transportation systems have hindered the development and funding of a long-term space transportation program.[2] We have also testified that NASA faced a number of programmatic and technical challenges in making shuttle upgrades, including revitalizing its workforce and defining shuttle technical requirements. In another report, we reported that NASA continued to rely on qualitative risk assessments to supplement engineering judgments and had made only limited progress in the use of quantitative assessment

[2] See U.S. General Accounting Office, *Space Transportation: Status of the X-33 Reusable Launch Vehicle Program*, GAO/NSIAD-99-176 (Washington, D.C.: Aug. 11, 1999), *Space Transportation: Challenges Facing NASA's Space Launch Initiative*, GAO-02-1020 (Washington, D.C.: Sept. 17, 2002), and *Space Station: Impact of the Grounding of the Shuttle Fleet*, GAO-03-1107 (Washington, D.C.: Sept. 12, 2003).

methods.[3] Recognizing such needs, NASA has taken steps to bring a more formal approach to identifying, prioritizing, and funding improvements.

In February 1997, NASA established the Space Shuttle Program Development Office at NASA's Johnson Space Center to sustain, improve, and add capability to the space shuttle through an upgrade program. In December 2002, a new selection and prioritization process for upgrades was implemented through the Service Life Extension Program. The SLEP provided a formal process to select, prioritize, and fund upgrades needed to keep the shuttle flying safely and efficiently and allow upgrades to be evaluated and approved on a priority basis. Shuttle upgrades are items that contribute toward the Space Shuttle Program goals to (1) fly safely, (2) meet the manifest, (3) improve mission supportability, and (4) improve the system in order to meet NASA's commitments and goals for human operations in space. According to NASA, upgrades achieve major reductions in the operational risks inherent in the current systems by making changes that eliminate, reduce, or mitigate significant hazards and critical failure modes and that increase the overall reliability of the current system with respect to the likelihood of catastrophic failure. Examples of upgrade projects currently funded to improve safety include Cockpit Avionics, Vehicle Main Landing Gear Tire and Wheel, External Tank Friction Stir Weld, and Shuttle Main Engine Advanced Health Management System.

Shuttle Requirements Process Lacks Systematic Approach

To keep the shuttle flying safely, NASA needs to fully implement an upgrade program to modernize various shuttle components. However, efforts to do so have been stymied by the agency's inability to develop a long-term strategic investment plan and a systematic approach for defining shuttle requirements, because the spacecraft's life expectancy and mission have continued to change. Key decisions about the ultimate life and mission of the basic elements of the integrated transportation plan—the ISS and the Orbital Space Plane (OSP)—were not made prior to fully defining shuttle requirements.

Originally, the shuttle was designed for a 10-year/100-flight service—transporting satellites and other cargo for the Department of Defense and

[3] See U.S. General Accounting Office, *Space Shuttle Safety: Update on NASA's Progress in Revitalizing the Shuttle Workforce and Making Safety Upgrades*, GAO-01-1122T (Washington, D.C.: Sept. 6, 2001) and *Space Shuttle: Need to Sustain Launch Risk Assessment Process Improvements*, GAO/NSIAD-96-73 (Washington, D.C.: Mar. 26, 1996).

others and placing in orbit and maintaining the Hubble Space Telescope—after which its life was to end. During this time, NASA was reluctant to make long-term investments due to the shuttle's perceived short life expectancy. With the advent of the ISS, the agency's transportation plan indicated that the shuttle would be used to operate and support the ISS until 2012, when a new space launch vehicle was to take over that mission. Recently, use of the new launch vehicle was de-emphasized by a new ISTP, which in its place proposed development of an OSP (to transfer the crew to the ISS) and continued use of the shuttle (to transfer cargo). The new plan proposes upgrading the shuttle's software and hardware to extend its operational life to 2020.

NASA recognizes the need for a systematic approach for defining requirements to upgrade the shuttle, and it recently institutionalized a new process to select and prioritize shuttle upgrades. However, NASA has not yet fully defined the basic elements of the ISTP—which include the ISS, the OSP, and the Next Generation Launch Technology.[4] NASA has not precisely determined when the ISS will be completed; its ultimate mission, its useful life, and even how many astronauts will be on board, for example. Specifically, NASA has not made explicit decisions on shuttle requirements--such as its future mission, lift capability, and life expectancy. According to NASA officials, these decisions will significantly affect shuttle upgrades. Similarly, the CAIB found that the shifting date for shuttle replacement has severely complicated decisions on how to invest in shuttle upgrades.

NASA's Process for Selecting and Prioritizing Upgrades Could Be Further Improved

NASA is making an effort to improve how it identifies, selects, and prioritizes shuttle upgrades. In December 2002, NASA initiated a SLEP as the primary framework for ensuring safe and effective operations. By March 2003, NASA had prepared a formal management plan documenting roles and responsibilities and defining an annual process for selecting and prioritizing upgraded projects and studies. Prior to the SLEP, NASA had no documented systematic selection process, and managers made decisions on upgrades using their professional insight and judgment and a limited number of quantitative or analytic tools rather than extensive use of hard data or rigorous analysis. As a result, projects that were identified, funded, and implemented flowed from an informal "bottom-up" approach that

[4] Next Generation Launch Technology will develop key technologies, such as propulsion and structures, for a future launch vehicle.

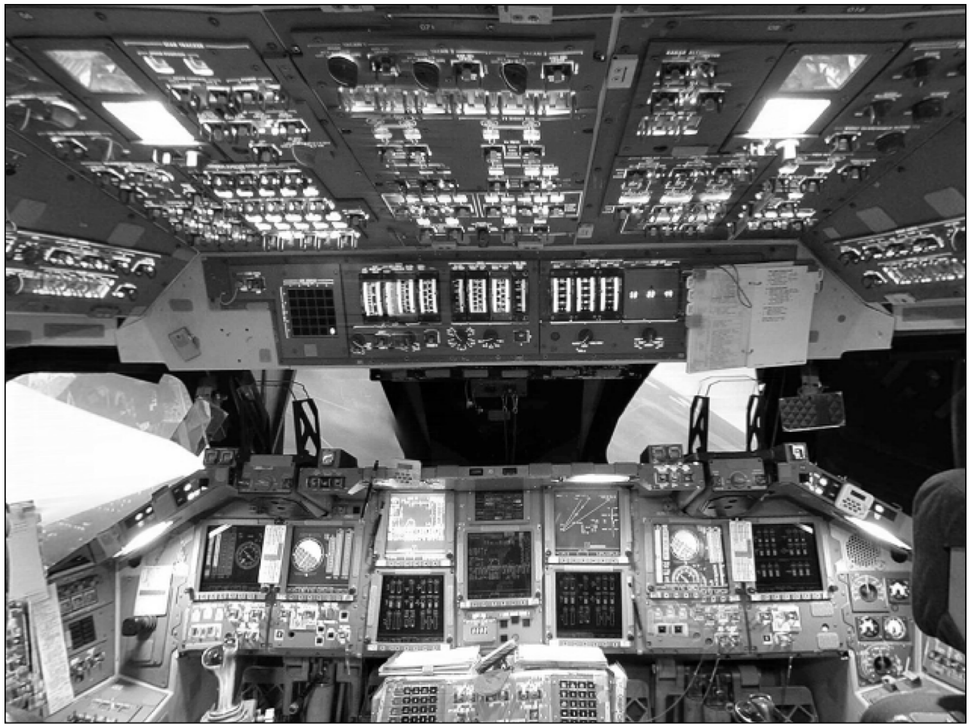
relied largely on insight and judgment of selected managers and limited use of quantitative tools.

Earlier Process to Identify and Prioritize Upgrades

According to NASA officials, prior to the new SLEP process, the identification, selection, and prioritization of shuttle upgrade projects largely involved an informal bottom-up approach. The upgrades were first proposed in an open and a continuous call for projects concepts and were drawn from shuttle element project organization, industry, or other shuttle program stakeholders. Upgrade projects would then go to the Space Shuttle Program Manager, the Shuttle Program Development Manager, and the directors of the affected NASA field centers, who would provide proposed projects to the Associate Administrator for Space Flight, who would select and prioritize the projects. This early process was much more strongly driven by collective management insight or “judgment” rather than by hard data or rigorous analysis. During this process, there was little guidance from top management as to how the decisions on shuttle upgrades integrated with all the other elements of the ISTP.

The identification, selection, and prioritization of the Cockpit Avionics Upgrade (CAU) is one example of a lack of a documented, structured, and systematic selection process prior to the SLEP. The CAU is estimated to cost $442 million and is NASA’s most costly of the currently approved upgrade projects. The CAU will update the cockpit’s dials and gauges with a modern instrument panel. By automating complex procedures in the shuttle cockpit, the upgrade is intended to improve the situational awareness of the crew and to better equip them to handle potential flight problems by reducing crew workload. (See fig. 1.)

Figure 1: Cockpit Avionics Upgrade



Source: NASA.

Managers gave the CAU project the highest priority based on their professional insight and judgment and a limited number of quantitative or analytic tools rather than extensive use of hard data or rigorous analysis. The upgrade was ranked as the highest priority based on the perceived importance of crew situational awareness. NASA did not have a metric to show the relationship of the cost of the upgrade to an increase in shuttle life and/or safety. The ranking was essentially a collaborative voting process based on their professional knowledge that crew error accounts for 50 percent of all incidents. As crew awareness depends on a number of human factors, a quantitative metric, such as NASA's Quantitative Risk Assessment System, could not be used since it did not contain key human attributes needed to evaluate the percentage of safety improvement of the upgrade project.

The SLEP Process Currently in Place

In December 2002, NASA initiated a SLEP as the primary framework for ensuring safe and effective operations, along with a management plan a few months later, documenting roles and responsibilities and an annual process for selecting and prioritizing upgraded projects and studies. The new process, which was first used in March 2003 at the first SLEP Summit, uses panels of experts from NASA, which are mostly chaired by the Deputy Center Directors, who meet periodically to develop and assess project recommendations. The SLEP is structured around eight panels of senior managers that make greater use of quantitative tools in areas such as safety and sustainability, including an outside panel of industry experts and an Integration Panel. The Integration Panel refines the prioritized recommendations of each panel into final recommendations to a group of top-level managers known as the Space Flight Leadership Council (the Council). As a result of the last Summit in March 2003, the Council approved all project recommendations of the Integration Panel with a total estimated cost of about $1.7 billion from fiscal years 2004-08. (See app. II.) In making its recommendations, the Council was not restricted by fiscal constraints. The Council endorsed 60 SLEP upgrade projects for fiscal year 2004 costing $416 million. By contrast, NASA's fiscal year 2004 budget request, submitted in February 2003, asked for $379 million. The difference is being deliberated within NASA's internal budget process.

One product resulting from the SLEP 2003 Summit was NASA's selection and identification of upgrade projects related to safety improvement, sustainability, and requirements for new capabilities as defined by "customers" such as the ISS. NASA then placed the projects into one of the following four categories: (1) "Should Start"—projects strongly recommended for start in fiscal year 2004 and which would create near term risk if they did not start, (2) "Existing Commitments"—projects previously authorized, (3) "Foundational Activities"—projects that add insight into the current condition of assets, and (4) "Projects and Studies"—system specific activities at various levels of maturity. (See table 1.)

Table 1: Service Life Extension Program Projects by Category—Fiscal Year 2004-2008

Categories	Sustainability	Safety improvement	Customer driven capabilities
Should Start	RSRM Case Vendor		
	PRSD Tank Vendor		
	SSME STE Equipment		
Existing Commitments	RSRM Obsolescence	Cockpit Avionics	
	Infrastructure	AHMS Phase I	
		MLG Tire/Wheel	
		Industrial Safety	
Foundational Activities	Aging Vehicle Studies	PRA Development	Performance Trade Studies
	RSRM Ground Test		
	Sustainability Health Metrics		
Projects and Studies	Vehicle Health Monitoring	New Start: AHMS II	
	STE Obsolescence	Study: Hydrazine Replacement	
	Material Obsolescence	Study: SSME Nozzle	
	Component Obsolescence	Study: Orbiter Hardening	
	Supply Chain Viability	Study: Enhanced C/W	
	Spares Augmentation	Study: Crew Survivability	
	ET 3rd Generation Foam		

Source: NASA.

Legend:

AHMS Advanced Health Management System
C/W Caution and Warning
ET External Tank
MLG Main Landing Gear
PRA Probabilistic Risk Assessment
PRSD Power Reactant Storage and Distribution (fuel cells)
RSRM Reusable Solid Rocket Motor
SSME Space Shuttle Main Engine
STE Special Test Equipment

NASA also considers development of the infrastructure to sustain shuttle operations through 2020 equally as important as upgrades to keep the shuttle flying safely. One example of a sustainability project for fiscal year 2004 is the replacement of the roof of the 39-year-old Vehicle Assembly Building at Kennedy Space Center, which is in poor condition, as shown by the bubbles that have developed in its surface. (See fig. 2.) The roof replacement is estimated to cost $16 million and is part of NASA's total spending on infrastructure of $54 million in fiscal year 2004.

Figure 2: Roof Deterioration on the Vehicle Assembly Building at Kennedy Space Center (the tape shows a 5-foot section for perspective)

Source: NASA.

Further Improvements in the SLEP Possible

NASA needs to improve its analytic tools to help it improve the basis for identifying and selecting shuttle upgrades. NASA uses Probabilistic Risk Assessment (PRA) methodologies, specifically the Quantitative Risk Assessment System, to improve safety by assessing the relative risk reduction of potential upgrade projects to overall shuttle risk. However, program managers are aware that the PRA is incomplete and does not contain certain key attributes that would make it more accurate, reliable, and useful. Early next year, they plan to begin using a revised PRA more oriented toward the shuttle. In addition, the Manager of the Shuttle Program Development Office believes it is important to develop a new Sustainability Health Metric System in order to mitigate the risk that an asset required to fly may not be available. The metric would score a proposed sustainability project after an evaluation of a set of common sustainability factors for all elements of shuttle flight and ground systems and subsystems. Similarly, the CAIB could not find adequate application of a metric that took an integrated systematic view of the entire space shuttle system. NASA is considering development of a sustainability metric, and the Manager of the Shuttle Program Development Office believes that if approved, it could be ready for use during the SLEP Summit in February 2004. NASA expects that the nomination of projects at that meeting will come from a more comprehensive evaluation through extensive use of hard data and rigorous analysis.

Although creation of the SLEP may improve the identification and selection process, further improvements are possible. According to SLEP program officials responsible for identifying, selecting, and prioritizing shuttle upgrades, they need clear guidance from top management as to how those decisions integrate with the other elements of the ISTP, such as the ISS and the OSP. In addition, SLEP program officials said the identification and selection of upgrades for the shuttle program lack a clear measurable metric showing the relationship of an upgrade investment to an increase in shuttle operational life. They believe such a metric would be useful to decision makers in identifying, selecting, and prioritizing shuttle upgrades. Finally, according to NASA Headquarters officials, recommendations of the CAIB are under study and will likely change the selection and prioritization of shuttle upgrades for both the near term and the long term.

Shuttle Upgrades Could Potentially Cost Billions More Than Currently Estimated

Until NASA finalizes the basic requirements for the shuttle and further improves its process for identifying and selecting upgrades, it will be difficult to accurately and reliably estimate the total cost of upgrades through 2020. NASA's current estimate for the cost of upgrading the shuttle is itself highly uncertain. Accurate and reliable cost estimates to upgrade the shuttle to continue operations are needed by decision makers. We found that the agency has not yet attempted to prepare a detailed life-cycle cost[5] estimate for all upgrades through 2020. NASA did prepare a rough order of magnitude estimate based on an analysis of current project estimates through 2020. The total cost of shuttle upgrades, however, could potentially be significantly greater as the estimate did not include potential projects such as a crew escape system. In addition, a number of potential changes could significantly increase the estimated cost, such as changes in program requirements, schedule slippages caused by delays in software and hardware integration, and implementation of recommendations of the CAIB.

Current Estimate Is Rough Order of Magnitude

A NASA official stated that it is difficult to develop accurate and reliable long-term estimates of shuttle upgrades through 2020, particularly in light of uncertainty of the shuttle's basic requirements such as its life expectancy. However, developing life-cycle cost estimates for agency programs is not a new issue in the federal government. The Office of Management and Budget maintains guidelines for preparing a cost-effectiveness analysis, including life-cycle cost estimates applicable to all federal agencies within the executive branch.[6] Cost estimates should include all costs consistent with agency policy guidance. NASA performs a cost and systems analysis to produce feasible concepts and explore a wide range of implementation options to meet its program objectives. To do this, NASA must develop the life cycle of the program to include the direct, indirect, recurring, nonrecurring, and other related costs for the design, development, production, operation, maintenance, support, and retirement of the program.[7] Comprehensive life-cycle cost estimates include both the

[5] Life-cycle cost is the sum total of direct, indirect, recurring, and nonrecurring costs of a system over its entire life through disposal. A detailed life-cycle cost estimate would include a full range of all potential upgrades, as well as their full range of potential costs.

[6] Office of Management and Budget Circular No. A-94.

[7] NASA Procedures and Guidelines (NPG) 7120.5 B.

project cost estimate and the operations cost through the end of shuttle operations.[8]

NASA has not prepared a detailed total life-cycle cost estimate for upgrades through 2020 due to the uncertainty of the shuttle's basic requirements, as well as the difficulty of preparing estimates of out-year funding to 2020. However, in June 2003, the agency estimated the shuttle upgrade cost through that year by using a rough order of magnitude estimate of $300 million-$500 million a year, or a total of $5 billion-$8 billion. The $300 million-$500 million per year estimate projected for out-year funding was modeled using a simulation tool[9] and developed by an independent consulting firm. According to a NASA official, they will rerun this estimate by the next SLEP Summit in February 2004, using as a basis whatever the recommended upgrade projects are at the time.

We performed an analysis of the rough order of magnitude estimate completed by NASA for all upgrades through 2020. Based on the data, we found that the $300 million-$500 million range of estimated costs per year, and the methodology used to estimate the costs, appears to be reasonable. According to a NASA official, NASA's cost estimates are focused on the annual budget process, rather than long term through 2020, because any individual project takes a while to mature and near-year estimates, such as those from the current year and through 2008, would be more accurate than those from 2009 and beyond, which are more likely to change. NASA's estimate is based on known projects for fiscal years 2004 and 2005 whose costs taper off in later years and the assessment of an additional 20 projects through 2020, where cost estimates and implementation plans are not certain.

Although the rough order of magnitude estimate, as well as the methodology used to derive it, appears to be reasonable, the total cost could be billions more since potential upgrade projects such as a crew escape system are not included. Initially, Boeing released a list of safety and supportability options that included crew/cockpit escape concepts for

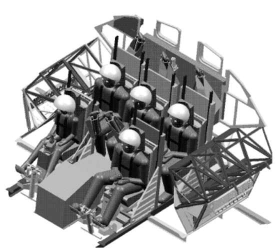
[8] Space Shuttle Program Upgrades Management Plan (NSTS 37400, volume I, revision A).

[9] Performed through the use of a "Monte Carlo" spreadsheet simulation, which randomly generates values for uncertain variables over and over to simulate a model. Without the aid of simulation, a spreadsheet model will only reveal a single outcome, generally the most likely or average scenario, but after hundreds or thousands of trials, one can view the statistics of the results and the certainty of any outcome.

the shuttle. Figure 3 illustrates the primary types of crew escape presently under consideration. The approximate costs involved for the eight present concepts range between $1 billion and $3.9 billion, depending on the one selected.[10] There are three other ejection concepts under development, none of which have received a full assessment. These other concepts will be assessed in a more in-depth manner, as well as previous metrics and costs, at the next SLEP Summit in February 2004. (Appendix III contains information on all 11 concepts.)

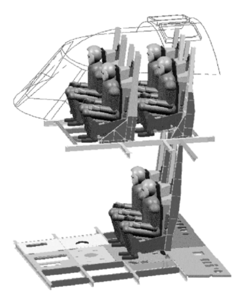
Figure 3: Space Shuttle Crew Escape Design Concepts

Extraction System



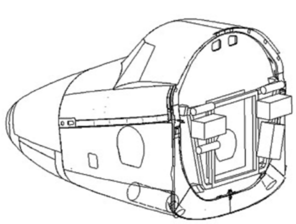
- 1960's/70's military applications
- Crew pulled from seat by rocket and tether system attached to crew restraint harness

Ejection Seats



- Primary system for military aircraft escape
- Crew and seat combination pushed out by staged underseat catapult and rocket system

Forebody Separation



- Military applications include F-111 and B-1A bombers
- Primary system for Mercury & Apollo
- Provides added protection for high altitude and Mach, and catastrophic environments
- Forward body separates aft of crew module and staged return to earth (land or water)

Forebody Separation Hybrids

- Combines forebody separation with extraction or ejection to provide lower weight and extended escape envelope
- Forebody separates and provides stable descent to safe extraction/ejection condition

-OR-

- Extraction/ejection performed directly under less severe or low altitude conditions
- No operational applications

Source: NASA.

[10] The estimated cost for each of the eight present concepts is proprietary information.

Potential Program Changes Could Increase Total Upgrade Cost

A number of potential program changes could significantly increase the estimated cost of shuttle upgrades through 2020. For example, rough order of magnitude estimates do not account for possible slippages in the shuttle schedule. According to a NASA official, if NASA and/or Congress deem a crew escape option a major priority, more highly developed costs and schedules would be created. Also, slippage due to delays in hardware or software integration can affect projects where the final vehicle modifications are planned for the major maintenance periods.

NASA has not yet made explicit decisions about the end state of the International Space Station.[11] For example, if the useful life of the ISS were extended and/or an OSP were put into service to support the station as an alternative to the shuttle, the life-cycle costs of the shuttle may be affected. Until all requirements about the ISS have been fully defined, it will be difficult to determine a detailed cost of shuttle upgrades through 2020.

Other potential program changes that would increase costs include a requirements change, such as additional lift capability that would require a new rocket booster. Any redesign option, if selected, would add billions to the total upgrade cost. For example, redesign and development of new liquid-fueled rocket boosters is estimated at a rough order of magnitude cost of $5 billion. Redesign and development of a five-segment solid booster would be a cheaper but less flexible option, at an estimated rough order of magnitude of $2 billion.

Another major driver of increased costs would be implementing the recommendations of the CAIB. Its numerous recommendations, such as major changes to the shuttle's thermal protection system, could potentially increase costs. NASA officials have said the agency intends to implement all the recommendations the CAIB issued in its report, but precise costs have yet to be determined.

Conclusions

NASA is at a critical juncture in the life of the space shuttle. NASA had planned to upgrade the shuttle in the future. Now, after the Columbia tragedy, NASA has an increased emphasis to fly the shuttle safely through 2020. NASA officials acknowledge that the loss of the Columbia will be a

[11] See U.S. General Accounting Office, *Space Station: Actions Under Way to Manage Cost, but Significant Challenges Remain*, GAO-02-735 (Washington, D.C.: July 17, 2002).

key influence on the selection and prioritization of shuttle upgrades as NASA officials assess both the short-and long-term implications of the CAIB recommendations. Although creation of the Space Shuttle Service Life Extension Program institutionalizes the process for identifying, selecting, and prioritizing upgrades, additional changes are needed to further strengthen that process such as increased use of analytic tools and metrics to complement professional judgment. NASA management has also not yet made explicit decisions about the basic requirements for key elements in its Integrated Space Transportation Plan—the ISS, the OSP, and the space shuttle. The agency's lack of a long-term plan, caused by frequent changes in the life of the shuttle, has made it hard to fully define, select, and prioritize shuttle upgrade requirements, which form a basis for identifying needed upgrades. Such a long-term plan needs to be developed now in conjunction with activities to return the shuttle to fly safely. In addition, accurate and reliable life-cycle cost estimates are important for determining resources needed for the selection and priority of upgrades and to determine annual budget requests. Even though an estimate of the total life-cycle cost has not been made, it is evident that the cost of upgrades through 2020 could be billions more than NASA's current rough order of magnitude estimate if potential projects, such as a crew escape system and new projects resulting from the CAIB recommendations, are included. Unless improvements are made in NASA's shuttle modernization efforts, NASA will not be able to ensure upgrades are being made to address the most necessary needs or to articulate the extent of safety that has been enhanced, and determine the total cost of the program.

Recommendations for Executive Action

To strengthen the agency's efforts to modernize the space shuttle, we recommend that the NASA Administrator take the following four actions:

- Fully define the requirements for all elements of the ISTP so that those responsible for identifying, selecting, and prioritizing shuttle upgrades will have the guidance and a sound basis to ensure their decisions on upgrade projects are completely integrated with all other elements of the transportation plan. In particular, the Administrator should determine, in conjunction with its international partners, the ultimate life and mission of the ISS in order to provide a sound basis for fully defining shuttle requirements.
- Develop and consistently apply a clear measurable metric to show the relationship of upgrade investments to an increase in shuttle operational life and/or safety for the entire space shuttle system. NASA's Quantitative Risk Assessment System could be a basis for such a metric since it is intended to measure the safety improvement of a single upgrade project.

- Continue to pursue development of analytic tools and metrics to help assure that SLEP program officials have accurate, reliable, and timely quantifiable information to complement their professional judgment.
- Develop a total cost estimate for all upgrades through 2020 by updating the current rough order of magnitude estimate to include new projects resulting from the CAIB recommendations, estimates of project life-cycle costs, and estimates of major potential projects, such as a crew escape system, so that the resources needed to fund shuttle upgrades can be ascertained.

Agency Comments

In written comments on a draft of this report, NASA's Deputy Administrator stated that the agency concurred with the first three recommendations. Furthermore, NASA concurred with the intent of the fourth recommendation concerning development of a cost estimate for all shuttle upgrades through 2020. However, the Deputy Administrator commented that there were major uncertainties that severely limit the agency's ability to foresee budget requirements beyond 3 to 5 years, such as unanticipated technical problems and the required time to accurately assess upgrade projects. Consequently, NASA believes that it is better to size the long-term (5 to 15 years) anticipated budget run-out based on broad estimates rather than on specific lists of projects.

We recognize that there can be many uncertainties in developing long-term budget estimates. However, NASA's proposal of an anticipated budget run-out based on broad estimates is not a substitute for identifying the financial implications of identified needs. Specifically, in order for NASA to develop a credible Integrated Space Transportation Plan, the agency needs a more accurate and reliable long-term total cost estimate. As we stated in our recommendation, establishing such an estimate could be facilitated by (1) using life-cycle cost estimating techniques on its list of potential projects that NASA used to develop its cost estimate through 2020, (2) updating its list of potential upgrade projects to include recommended projects of the CAIB, and (3) including major potential upgrade projects currently under consideration, such as a crew escape system. The comprehensive nature of this cost estimate will enable (1) NASA to formulate a more definitive picture of how it will ensure that the shuttle fleet flies safely in the future and (2) decision makers to understand associated costs. Therefore, our recommendation remains unchanged.

Scope and Methodology

To assess NASA's requirements and plans to upgrade the shuttle for continuous service through 2020, we obtained and reviewed internal documents and independent studies and discussed the requirements and plans with responsible NASA officials.

To assess how NASA determined what upgrades were needed and how they were identified, selected, and prioritized, we obtained and analyzed schedules and documents from program officials and obtained an understanding of the process for identifying, selecting, and prioritizing shuttle upgrades. We also reviewed documents regarding analytic tools used to select and prioritize shuttle upgrades.

To assess the estimated life-cycle cost of shuttle upgrades, we reviewed and discussed NASA's guidance regarding preparation of life-cycle cost estimates with program officials. To assess the rough order of magnitude estimate for out-year funding completed by NASA for all upgrades through 2020, we obtained data and analyzed the estimate using a Monte Carlo simulation tool called @Risk—an Excel-based spreadsheet. Monte Carlo simulation helps to assess the risks and uncertainties associated with Microsoft Excel spreadsheet models by randomly generating values for uncertain variables over and over to simulate a model. We assessed this technique to determine the level of confidence around the estimates and verified our assessment with responsible program officials.

To accomplish our work, we interviewed officials and analyzed documents at NASA Headquarters, Washington, D.C.; Johnson Space Center, Houston, Texas; and Kennedy Space Center, Florida.

We also reviewed reports and interviewed representatives of NASA's Office of the Inspector General, Washington, D.C., and NASA's Independent Program Assessment Office, Langley Research Center, Hampton, Virginia.

We conducted our work from April to October 2003 in accordance with generally accepted government auditing standards.

Unless you publicly announce the contents of this report earlier, we plan no further distribution of it until 30 days from the date of this letter. We will then send copies to others who are interested and make copies available to others who request them. In addition, the report will be available on the GAO Web site at http://www.gao.gov.

Please contact me at (202) 512-4841 if you or your staffs have any questions about this report. Major contributors to this report are listed in appendix IV.

Allen Li
Director
Acquisition and Sourcing Management

Appendix I: Comments from the National Aeronautics and Space Administration

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

December 19, 2003

Mr. Allen Li
Director
Acquisition and Sourcing Management
United States General Accounting Office
Washington, DC 20548

Dear Mr. Li:

Thank you for the completed comprehensive evaluation of the Space Shuttle Upgrades/Service Life Extension Program (SLEP). I am pleased to express my gratitude for the professionalism your team exhibited while conducting this essential audit. NASA appreciates the insight of the General Accounting Office. We welcome your findings. Below, please find our comments to the recommendations provided in your report.

Recommendation 1:
"Fully define the requirements for all elements of the Integrated Space Transportation Plan (ISTP)..."
We concur with your recommendation. The investments we make in the Space Shuttle Program can change significantly depending on the suppositions that are made on the strategic direction of human space flight. As was noted in the report, investments in the Space Shuttle Program cannot be completely addressed until these requirements are fully defined. The Agency's ISTP defines these high-level requirements. The strategic direction for the long-term Space Shuttle Program investments will be realized as the ISTP is refined, including plans for the lifetime of the International Space Station. As such, the Space Shuttle Program staff is working closely with the NASA Space Architect to update investment activities, as updates to the ISTP are finalized.

Recommendation 2:
"Develop and consistently apply a clear measurable metric..."
We concur with your recommendation. We fully realize the critical importance of accurately selecting the needed investments to safely maintain and operate the Space Shuttle system into the future. In fact, as you mentioned in your report, this effort is already underway and is being addressed within the Space Shuttle SLEP Summit process. We are pleased that your lead auditor attended the Inaugural Summit held in March of this year. We are anticipating his attendance at future Summit events. As the Summit process evolves, the consistency and measurability of those investments selected to upgrade the Space Shuttle fleet will be further refined.

Recommendation 3:
"Continue to pursue the development of analytic tools and metrics…"
We concur with your recommendation. The organization of the Space Shuttle SLEP is designed to build upon previous investment management initiatives and to advance the effectiveness of allocating resources to ensure that our mission to safely fly the Space Shuttle fleet into the future is realized. The SLEP process has given impetus to the improvement of the Probabilistic Risk Assessment tool and the development of a new all encompassing metric that will address Space Shuttle sustainability and infrastructure concerns. We will continue to seek out additional investment metric tools to accurately capture reliable and timely quantifiable information.

Recommendation 4:
"Develop a total cost estimate for all upgrades through 2020 by updating the current rough order of magnitude estimate…"
We concur with the intent of your recommendation. As we discussed in the exit briefing, there are major uncertainties that severely limit our ability to foresee definitive budget requirements beyond 3-5 years, such as:

a) emergence of unanticipated technical problems and,
b) the time required to accurately assess upgrades, projects for cost, schedule, and technical merit (up to 2 years for major upgrades).

Therefore, we believe it is better to size the long term (5-15 year) anticipated budget runout based on broad estimates than on specific lists of projects and to size the near-term (3-5 year) budget on a finalized list of approved projects.

Again, thank you for the critical insight the report provided. We assure you that we are well on our way toward implementing your recommendations.

Cordially,

Frederick D. Gregory
Deputy Administrator

Appendix II: Recommended Upgrade Projects Resulting from the Service Life Extension Program Summit

Real Year Dollars in Millions—Not in Full Cost						
Subcategory	**FY 04**	**FY 05**	**FY 06**	**FY 07**	**FY 08**	**Total**
Should Start in FY04[a] (Sustainability Related)						
RSRM–Case Hardware Availability	5	5	5	5	5	**25**
Orbiter–Certify PRSD Tank Supplier and Procure Spares	4	8	8	4	8	**31**
SSME–Sustaining Test Equipment Tasks	6	3	1	0	0	**10**
Existing Commitments[b] (Safety Related)[c]						
Vehicle CAU	91	77	14	0	0	**182**
Vehicle Main Landing Gear Tire and Wheel	3	0	0	0	0	**3**
SSME AHMS (Phase 1)	4	3	2	1	0	**10**
Industrial Engineering for Safety	15	15	15	15	15	**75**
Others[d] **(Sustainability Related)[e]**	51	43	27	21	10	**152**
RSRM Obsolescence	18	19	20	20	21	**98**
Infrastructure	92	77	78	79	80	**406**
Foundational Activities[f] (Sustainability Related)						
Aging Vehicle Studies[g]	10	14	0	0	0	**24**
RSRM Ground Test Program	4	10	20	9	21	**64**
Improved Tools/Metrics[h]	7	5	3	3	3	**21**
(Customer Driven Capabilities Related)[i]						
Performance Trade Studies (Lift, Power, Stay Time)	2	2	0	0	0	**4**
Projects and Studies (Sustainability Related)[j]						
New Start: Vehicle Health Monitoring Study	4	4	0	0	0	**8**
New Start: ET 3rd Generation Foam Study	3	7	8	0	0	**18**
STE Obsolescence (14)[k]	16	18	11	7	7	**59**
Material Obsolescence (3)	2	0	0	0	0	**2**
Component Obsolescence (14)	6	23	27	16	13	**85**
Supply Chain Viability (8)	4	0	1	1	0	**5**
Spares Augmentation for SLE (5)	5	10	26	23	18	**82**
(Safety Related Improvements)						
New Start: SSME AHMS (Phase 2b)	35	45	45	23	12	**160**
Study: Hydrazine Replacement	3	3	1	0	0	**7**
Study: Orbiter Hardening	2	2	0	0	0	**4**
Study: SSME Channel Wall Nozzle	4	12	16	0	0	**32**
Study: Crew Survivability Trades	1	0	0	0	0	**1**

Real Year Dollars in Millions—Not in Full Cost						
Subcategory	**FY 04**	**FY 05**	**FY 06**	**FY 07**	**FY 08**	**Total**
Reserves	20	20	20	20	20	**100**
Total[l]	**416**	**426**	**347**	**246**	**233**	**1,668**

Source: NASA.

Note: Final funding profile is dependent on the outcome of the FY 2005 President's Budget Submission.

[a]"Should Start" – High scoring sustainability projects that are strongly recommended by NASA for starts in FY04 and which would create near-term risk for the program if they did not start.

[b]"Existing Commitments"–Projects previously authorized.

[c]"Safety Improvement"–Projects and studies designed to improve loss of vehicle/loss of crew probabilities.

[d]"Others"–A major item in this category is the program installation costs for the Cockpit Avionics Upgrade, which is tracked separately, as well as the costs of other smaller projects.

[e]"Sustainability"–Assuring the assets required to fly are in place.

[f]"Foundational Activities"–Tasks that add to NASA's general insight into the current condition of their assets. Non-system specific.

[g]Aging Vehicle Studies include: Mid-Life Certification Assessment & Issue Mitigation, Fleet Leader Program, Corrosion Control, STE Survey/Evaluation, Non-Destructive Evaluation Upgrades.

[h]Probabilistic Risk Assessment (safety related), Sustainability Health Metrics (sustainability related), Analytical Hierarchy Tool System (sustainability related).

[i]"Customer Driven Capabilities"—Requirements for new capabilities as defined by current or potential customers. Customers in this context are the entities that require the space shuttle for access to space. Currently, that is mainly the space station, the research community, and the space telescope community.

[j]"Projects and Studies"—System-specific activities at various levels of maturity within the system.

[k]This number represents the number of projects in each subcategory.

[l]Totals do not add due to rounding.

Legend:

AHMS	Advanced Health Management System
CAU	Cockpit Avionics Upgrade
ET	External Tank
PRSD	Power Reactant Storage and Distribution (fuel cells)
RSRM	Reusable Solid Rocket Motor
SLE	Service Life Extension
SSME	Space Shuttle Main Engine
STE	Special Test Equipment

Appendix III: Comparison of Crew Escape Concepts Under Consideration

Concept[a]	Crew size	Mass properties	1st kit delivery and OMM	Ascent coverage no fireball[b]	Ascent coverage fireball potential	NASA PRA % risk
1. Extraction-50	5 crew 5 flight deck	122 lb added No ballast required	4.5 y after ATP 18 m OMM	0 to 9k ft	None	31%
2. Ejection-42A	6 crew 4 flight / 2 mid deck	1,788 lb added 1,900 ballast	4.5 y after ATP 18 m OMM	0 to 70k ft	10k to 70k ft	52%
3. Ejection-43A	7 crew 4 flight/ 3 mid deck	3,012 lb added 2,700 ballast	4.5 y after ATP 18 m OMM	0 to 70k ft	10k to 70k ft	52%
4. Forebody-1-2N	7 crew 4 flight / 3 mid deck	8,315 lb added 2,700 ballast[c]	5.5 y after ATP 18 m OMM	3k to 210k ft	10k to 210k ft	80%
5. Hybrid-1-H-42A	6 crew 4 flight / 2 mid deck	6,448 lb added 2,700 ballast[d]	5.5 y after ATP 18 m OMM	0 to 210k ft	10k to 210k ft	87%
6. Hybrid-1-H-50	5 crew flight deck	4,825 lb added 2,700 ballast[d]	5.5 y after ATP 18 m OMM	0 to 210k ft	10k to 210k ft	87%
7. PLB Capsule & Seats	7 crew 2 flight / 5 capsule	7,256 lb added 2,700 ballast[d]	5 y after ATP 16 m OMM	Capsule 2k – 210k Seat 0 – 70k	Capsule 10k – 210k Seat 10k – 70k	52%
8. Payload Bay Compartment and Seats[e]	7 crew 2 flight / 5 PLB	6,024 lb added 2,700 ballast[d]	4 y after ATP 12 m OMM	No Pad[f] 75k/80k ft Max	10k to 70k ft	52%
9. Ejection[g]	2 crew 2 flight deck	xxxx lb added xxxx ballast	x.x y after ATP xx m OMM	0 to 70k ft	10k to 70k ft	52%
10. Ejection[g]	3 crew 3 flight deck	xxxx lb added xxxx ballast	x.x y after ATP xxx m OMM	0 to 70k ft	10k to 70k ft	52%
11. Ejection[g]	4 crew 4 flight deck	xxxx lb added xxxx ballast	x.x y after ATP xx m OMM	0 to 70k ft	10k to 70k ft	52%

Source: NASA.

[a]Under the “Concept” column: The first number usually represents the number of crew on the flight deck and the second number usually represents the amount of crew on the mid-deck. The letter following these numbers represents the option. For example, for #2, “42A” represents 4 on Flight Deck, 2 on Mid-deck, option “A”. However, for #4, “1-2N” strictly represents the option and for #5 & #6, “1-H” stands for “Hybrid” option.

[b]The “fireball” is the environment following a shuttle explosion during ascent. The fireball size, temperature, and pressure are a function of the amount of ascent propellant remaining and the altitude of the vehicle. The more the propellant and the lower the altitude, the larger the fireball and the more difficulty for the crew to survive. The options do not adjust for a fireball ascent.

[c]Center of Gravity cannot be corrected with max ballast of 2,700 lb.

[d/e]PRA and Ascent coverage based on 42A ejection seat assessment.

[f]“NO PAD” means that it does not have pad-abort capability (crew could not use option to escape while Shuttle is on pad).

[g]Assessment due by February 2004 for Service Life Extension Program Summit.

Legend:

ATP	Authority to Proceed
CG	Center of Gravity
OMM	Orbiter Major Modification
PLB	Payload Bay
PRA	Probabilistic Risk Assessment
ROM	Rough Order of Magnitude
SLEP	Service Life Extension Program

Appendix IV: Staff Acknowledgments

Acknowledgments

Individuals making key contributions to this report included Jerry Herley, Thomas Hopp, T. J. Thomson, and Karen Richey.

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