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Report to Congressional Committees

December 2011

INTERNATIONAL SPACE STATION

Approaches for Ensuring Utilization through 2020 Are Reasonable but Should Be Revisited as NASA Gains More Knowledge of On-Orbit Performance

This report was revised on March 19, 2012, to correct the legend for Figure 4 on page 23.

GAO
Accountability * Integrity * Reliability
Highlights

Highlights of GAO-12-162, a report to congressional committees

December 2011

INTERNATIONAL SPACE STATION

Approaches for Ensuring Utilization through 2020 Are Reasonable but Should Be Revisited as NASA Gains More Knowledge of On-Orbit Performance

Why GAO Did This Study

In 2010 the National Aeronautics and Space Administration (NASA) was authorized to extend the life of the International Space Station (ISS) from 2015 through at least September 30, 2020. Gauging the feasibility of doing so is quite complex. Among the factors to be assessed are the reliability of key components, NASA's ability to deliver spares to the ISS, the projected life of structures that cannot be replaced, and the health of systems that affect safety. While some empirical data exist, the ISS is a unique facility in space and assessing its extended life requires the use of sophisticated analytical techniques and judgments. GAO provided a preliminary report on NASA's use of such techniques in April 2011. For this review, GAO assessed the extent to which NASA has ensured essential spare parts are available and ISS structures and hardware are sound for continued ISS utilization through 2020. GAO interviewed NASA officials and outside experts; assessed the methodology underlying NASA's findings; conducted a limited test of data supporting NASA's assessments; and analyzed documentation such as ongoing assessments, schedules and other relevant efforts.

What GAO Recommends

GAO recommends that NASA reassess the relative weight given to original reliability estimates of spares' life expectancies as performance data accumulates and document the rationale behind specific performance goal decisions. NASA concurred with our recommendations.

View GAO-12-162. For more information, contact Cristina Chaplain at (202) 512-4841 or chaplainc@gao.gov.

What GAO Found

NASA's approach to determining, obtaining, and delivering necessary spare parts to the ISS is reasonable to ensure continued utilization of the station through 2020. The statistical process and methodology being used to determine the expected lifetimes of replacement units is a sound and commonly accepted approach within the risk assessment community that considers both manufacturers' predictions and the systems' actual performance. To date NASA has given equal weight to manufacturers' predictions and actual performance, and currently has no plans to reassess this decision. However, as time goes on, the resulting estimates could prove to be overly conservative, given that NASA has found failure rates for replacement units to be lower than manufacturers' predictions. Therefore, continuing to weigh the manufacturers' predictions equally with actual performance could lead NASA to purchase an excess of spares. NASA also has a reasonable process for establishing performance goals for various functions necessary for utilization and determining whether available spares are sufficient to meet goals through 2020, but the rationale supporting these decisions has not been systematically documented.

International Space Station

Source: NASA.

NASA is also using reasonable analytical tools to assess structural health and determine whether ISS hardware can operate safely through 2020. On the basis of prior analysis of structural life usage through 2015 and the robust design of the ISS structures, NASA currently anticipates that—with some mitigation—the ISS will remain structurally sound for continued operations through 2020. NASA also is using reasonable methodologies, governed by agency directives and informed by NASA program experts, to assess safe operations of the ISS as a whole as well as identify replacement units and other hardware, failure of which could result in an increased risk of loss of station or loss of crew through 2020. NASA plans to develop, through 2015, methods to mitigate issues identified and expects to begin implementing corrective actions as plans are put in place.

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Abbreviations

ATV	Automated Transfer Vehicle
BSP	baseband signal processor
COTS	Commercial Orbital Transportation Services
DOD	Department of Defense
ECLSS	Environmental Control and Life Support System
FGB	Functional Cargo Block
HTV	H-II Transfer Vehicle
ISS	International Space Station
MTBF	mean time between failure
MADS	Modeling and Analysis Data Set
NASA	National Aeronautics and Space Administration
ORU	orbital replacement unit
Orbital	Orbital Sciences Corporation
PRA	Probabilistic Risk Assessment
SASA	S-Band antenna and support assembly
SpaceX	Space Exploration Technologies
TDRSS	Tracking and Data Relay Satellite System

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Accountability * Integrity * Reliability

United States Government Accountability Office
Washington, DC 20548

December 15, 2011

The Honorable John D. Rockefeller IV
Chairman
The Honorable Kay Bailey Hutchinson
Ranking Member
Committee on Commerce, Science, and Transportation
United States Senate

The Honorable Ralph Hall
Chairman
The Honorable Eddie Bernice Johnson
Ranking Member
Committee on Science, Space and Technology
House of Representatives

From 1994 through 2010, the National Aeronautics and Space Administration (NASA) estimates it directly invested over $48 billion in development and construction of the on-orbit scientific laboratory, the International Space Station (ISS). To take advantage of that investment, the NASA Authorization Act of 2010 extended the mission of the ISS by a minimum of 5 years, from 2015 through at least September 30, 2020. Traditionally, the ISS received the majority of its supplies and spare parts via the space shuttle. The space shuttle conducted its final flight in July 2011 and as a result NASA now plans to rely on a combination of foreign and commercially developed domestic launch vehicles to supply hardware spares and supplies to the ISS through 2020.

In consideration of the shuttle's retirement, section 503 of the NASA Authorization Act of 2010, directed NASA to assess its plans for ensuring essential spares were available to support the ISS through its planned operational life, and to report to Congress on that assessment.[1] The same law also directed that GAO provide an evaluation of the accuracy and level of confidence in the findings contained in NASA's assessment of the essential modules, operational systems and components, structural elements, and permanent scientific equipment required to ensure

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[1] Pub. L. No. 111-267.

complete, effective and safe functioning and full scientific utilization of the ISS through 2020.

Gauging the feasibility of extending the life of the ISS is no simple exercise. Among the many factors to be assessed are the reliability of key components, NASA's ability to deliver spares to the ISS, the projected life of structures that cannot be replaced, and in-depth analysis of those components and systems that affect safety. While some empirical data exists, because the ISS is a unique facility in space, assessing its extended life necessarily requires the use of sophisticated analytical techniques and judgments.

NASA reported to Congress on January 11, 2011, that the ISS could be effectively maintained through 2020 within the normal range of human spaceflight risk with a combination of existing and planned re-supply vehicles. Subsequently, we issued our initial evaluation on April 11, 2011.[2] We found that NASA was using analytical techniques, physical tests, and inspections to assess ISS structures and hardware as well as to determine spare parts needed to support safe functioning and full utilization of the ISS through 2020. Additionally, we noted that NASA's assessments appeared to be supported by sufficient, accurate, and relevant underlying data. We found, however, that NASA's estimates of ISS sparing needs were sensitive to assumptions about hardware reliability.

As we noted in our report, these assessments were ongoing, so not all results were available. At your request, we continued our evaluation of NASA's plans to ensure the ISS is supported through 2020. Specifically, we assessed (1) the extent to which NASA has ensured spare components essential for ISS operations will be available through 2020, and (2) the extent to which NASA has assurance that the ISS structure and hardware will be sound through 2020 and potentially beyond. To conduct this work, we examined NASA's processes for quantifying ISS maintenance needs. We interviewed knowledgeable officials and experts within and outside of NASA to evaluate and obtain an understanding of the methodologies and analytic techniques NASA and other organizations use in addressing supportability. We conducted a limited test of the

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[2] GAO, *International Space Station (ISS): Ongoing Assessments for Life Extension Appear to be Supported*, GAO-11-519R (Washington, D.C.: Apr. 11, 2011).

reliability of key data supporting NASA's assessments. We also examined the schedules for and manifests of planned re-supply missions and evaluated the status of ongoing efforts to estimate the costs of required spares. We obtained and analyzed available results of ongoing assessments of structural health and hardware systems. See appendix I for our detailed scope and methodology.

We conducted this performance audit from February 2011 to November 2011 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings based on our audit objectives.

Background

The ISS is composed of about 1 million pounds of hardware, brought to orbit over the course of a decade. It is the largest orbiting man-made object and was constructed to support three activities: scientific research, technology development, and development of industrial applications. The facilities aboard the ISS allow for ongoing research in microgravity, studies of other aspects of the space environment, tests of new technology, and long-term space operations. The facilities also enable a permanent crew of up to six astronauts to maintain their physical health standards while conducting many different types of research, including experiments in biotechnology, combustion science, fluid physics, and materials science, on behalf of ground-based researchers. Furthermore, the ISS has the capability to support research on materials and other technologies to see how they react in the space environment. In addition to these research activities, the ISS crew conducts preventive and corrective maintenance to the on-board systems.

The ISS includes (1) primary structures, i.e., the external trusses which serve as the backbone of the station and the pressurized modules that are occupied by the ISS crew, and (2) functional systems comprised of orbital replacement units (ORU), i.e., systems that provide basic functionality such as life support and electrical power which are comprised of modular components that are easily replaced by astronauts on orbit.

NASA originally planned for an ISS lifespan of 15 years—5 years to assemble the individual components of the ISS on-orbit and 10 years for operations. To ensure structural soundness for 15 years, NASA required

ISS developers to analytically demonstrate that ISS primary structures would remain structurally sound for four service lives; that is, at least 60 years. This demonstration involved showing analytically that the largest undetected crack that could exist in the structure would not grow and cause failure of the structure in four service lifetimes[3] when subjected to the mechanical, thermal, and pressure loads[4] of the on-orbit environment.

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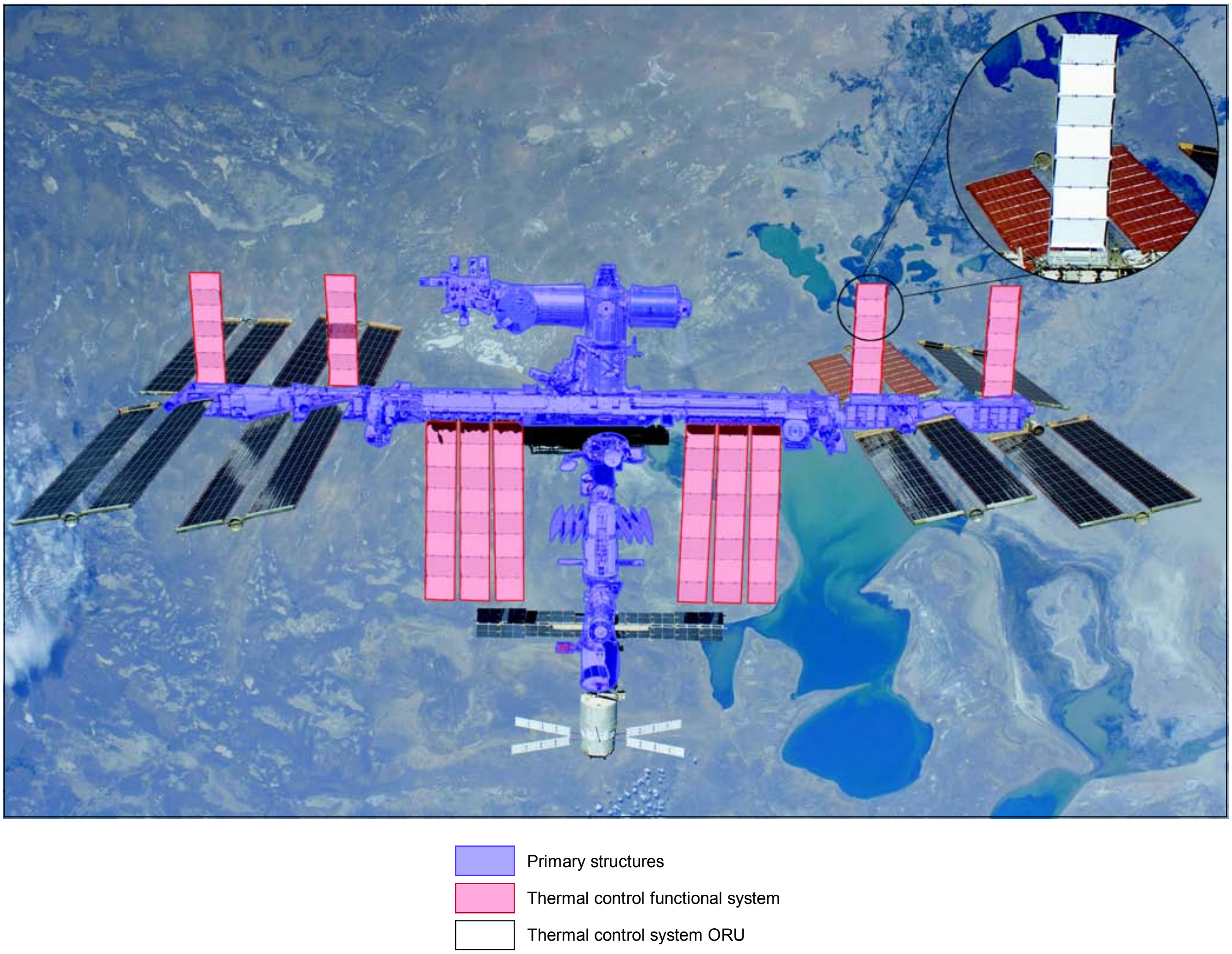
[3] Four service lives is a NASA and Department of Defense standard for spacecraft. According to agency officials, most components are designed to operate beyond four service lives.

[4] The structures of the ISS encounter thermal, pressure and mechanical loads. According to program officials, thermal loads are developed due to temperature gradients across or through a structure and/or by a mismatch in materials at a joint; pressure loads are developed due to pressure differences on the inside versus the outside of a structure, such as the atmosphere in a crew compartment versus the vacuum of space; and mechanical loads are developed when a force is applied to the structure, such as vehicle dockings and undockings.

Figure 1: ISS Primary Structures, Thermal Control Functional System, and ORU



Source: NASA.

Although the ISS originally was planned to operate until 2015, the NASA Authorization Act of 2008 directed the agency to do nothing to preclude the use of the ISS beyond 2015 and the NASA Authorization Act of 2010 directed the agency to extend operations through at least September 30, 2020.[5] NASA had originally planned for the space shuttle to serve as the means of transporting hardware and supplies to the ISS through the end of the ISS's life. However, in 2004, President George W. Bush announced his Vision for Space Exploration that included direction for NASA to pursue commercial opportunities for providing transportation and other services to support the ISS after 2010.[6] As a result of that direction, in July 2011, the space shuttle flew its last mission to the ISS.

NASA's current strategy for supporting the ISS relies on a mixed fleet of vehicles, including those developed by ISS international partners and commercial domestic launch providers, to service the ISS through 2020. International partner vehicles include the European Space Agency's Automated Transfer Vehicle (ATV), and the Japan Aerospace Exploration Agency's H-II Transfer Vehicle (HTV). NASA has agreements in place with the respective European and Japanese consortiums for the ATV and HTV to provide supplies and spares to the ISS. The domestic commercial launch vehicles, fostered under a NASA-initiated project known as Commercial Orbital Transportation Services (COTS), are being developed by private industry corporations Space Exploration Technologies (SpaceX) and Orbital Sciences Corporation (Orbital). In 2006 and 2008, NASA awarded agreements to SpaceX and Orbital for development and demonstration of cargo transport capabilities, which SpaceX and Orbital are providing through their respective Falcon 9 and Taurus II launch vehicles. In late 2008, NASA awarded both companies commercial resupply services contracts to provide supplies and spares to the ISS through 2015. NASA plans to use the SpaceX and Orbital Sciences launch vehicles to supply the ISS beginning in 2012 and continuing through 2020.

Initial ISS Supportability Strategy

NASA's strategy for supporting the ISS at the beginning of the program was based on several key factors, including:

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[5] National Aeronautics and Space Administration Authorization Act of 2008, Pub. L. No. 110-422, § 601; National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267, § 503.

[6] In 2004, President George W. Bush established a new space exploration policy-*A Renewed Spirit of Discovery*: The President's Vision for U.S. Space Exploration (Vision)-which called for the retirement of the space shuttle and development of a new family of exploration systems to facilitate a return of humans to the moon and eventual human spaceflight to Mars.

- a specified level of ORU design reliability;
- an ISS design with electrical and mechanical functions modularized into ORUs for simple on-orbit removal and replacement;
- a consistent, reliable transportation service to and from the ISS in the form of the space shuttle; and
- an approach that used the space shuttle as the vehicle for bringing failed ORUs to earth and flying repaired ORUs back to the ISS.

The ISS was designed and certified based on the idea that its 15-year design life would be achieved through returning failed or degraded ORUs to earth for repair. NASA established ISS initial estimates of spare ORUs needed using the equipment manufacturers' original reliability predictions, and a transportation plan that assumed space shuttle operations would continue until the planned end of ISS life in 2015. This strategy assumed not only that the space shuttle would provide a reliable means of delivering spares to the ISS, but also a means of returning failed or expended hardware to earth. NASA retained many of the original equipment manufacturers of ISS hardware to provide sustaining engineering and repair or refurbishment capabilities for the planned life of the ISS.

Historically, NASA's methods for determining the required number of ISS spares used a combination of the original equipment manufacturers' projections about the length of time an ORU would operate before randomly failing and the professional judgment of NASA engineers. NASA and the original equipment manufacturers express an ORU's expected frequency of random failure as the mean time between failure (MTBF), which predicts, in hours, the average amount of time an ORU will operate before a random failure occurs. NASA considers the MTBF as the primary predictive measure of an ORU's reliability and uses this information to predict when ORUs will require maintenance to prevent or correct failures. To calculate an MTBF, the ORU's original equipment manufacturer would typically use reliability models that were populated with the failure rates of the individual parts obtained from reliability handbooks, such as Military Handbook 217F and other authoritative sources.[7] These models also incorporate data on part quality and quantity as well as assumptions about the ORU's operating temperature, operating environment, and the amount of time it spends in an active

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[7] Department of Defense, *Military Handbook: Reliability Prediction of Electronic Equipment*, MIL-HDBK-217F (Washington, D.C.: Feb. 28, 1995).

state. According to agency officials, the MTBF calculated by using this process would typically be provided to NASA in a reliability report as part of the technical data package accompanying the delivery of the ORU. Officials indicated for example, as part of the technical data package accompanying the delivery of the ISS ammonia/water heat exchanger, which helps regulate heat on the ISS, Boeing prepared a reliability verification analysis report that estimated the MTBF for this ORU is 362,401 hours.

Revised ISS Supportability Strategy

NASA has revised its ISS supportability strategy for ORUs from the original “repair and return” strategy to one of “build and dispose.” Three factors played major parts in this revision:

- the decision to decommission the space shuttle;
- NASA’s observation that reliability of on-orbit ORUs has been much higher, on average, than the original equipment manufacturers’ initial predictions of MTBF; and
- NASA’s recognition that procurement of enough spares to ensure full functionality through the end of ISS life, based on manufacturers’ predictions, would be unaffordable and was not necessary to ensure safe, useful ISS operations.

Lacking a means upon retirement of the space shuttle to return failed ORUs to earth, repair them, and take them back to the ISS, NASA moved to a strategy of replacing failed ORUs with new ones. NASA pre-positioned spares on-board the ISS to ensure that the station could operate in the intervening period between shuttle retirement and expected development of new launch vehicles. Because NASA no longer has the sparing flexibility provided by the space shuttle, and astronauts can perform only minor repairs while on-orbit, NASA’s current supportability strategy relies more heavily on modeling and computational analysis to determine the quantity of spare ORUs needed to support the station.

NASA also revised its ISS supportability strategy because ORU on-orbit failure data indicated that the manufacturers’ MTBFs were, on average, too conservative. According to NASA representatives, this conservatism resulted from original equipment manufacturers’ tendency to err on the side of caution, that is, the manufacturers were primarily interested in demonstrating through analysis that ORUs they developed would meet minimum MTBF criteria established by NASA. Moreover, the component-level reliability data contained in Military Handbook 217F that served as the basis for original equipment manufacturers’ analysis has also proved to be overly conservative in many cases.

Given the actual on-orbit failure data, NASA recognized that a sparing strategy built around manufacturers' original MTBF estimates needed to be modified or it would result in the acquisition of many more spares than were truly needed to support the program. Consequently, the ISS program set up a team of experts referred to as a "tiger team" to evaluate other methods of determining more accurate MTBF estimates for ORUs. In 2005, this team settled on a new NASA process that used a Bayesian estimation process to update the ORUs' original MTBFs. The Bayesian estimation process combines the manufacturer's original MTBF with actual on-orbit data—including the accumulated hours of operation and random failure history of an ORU population—and results in an updated MTBF reflecting NASA's experience with ORU performance.[8] In January 2006, the ISS Reliability and Maintainability Panel approved the use of the Bayesian estimation process to update MTBF estimates.[9] Since that time, NASA has implemented an annual Bayesian MTBF update process that continues to refine reliability and failure projections for ISS ORUs.

While an improved method for updating the MTBF of each ORU was needed to inform NASA's sparing decisions, it was not sufficient by itself to predict the required quantity of spares needed, since the reliability of individual ORU is only one piece of the puzzle. Groups of ORUs are arranged into an ORU architecture to support a specific function. Many functional architectures include redundancy within their design so that the failure of a single ORU does not disable the function. For example, the S-band communications and tracking function—which supports all command and control from the ground—consists of six ORUs arranged into two independent strings.[10] Each string consists of three ORUs: (1) the S-Band antenna and support assembly (SASA); (2) the Tracking and Data Relay Satellite System (TDRSS) Transponder; and (3) the baseband signal processor (BSP). Each string has the capacity of being designated prime or backup using a software switch which automatically turns on the backup if the prime fails. Figure 2 illustrates the ORU

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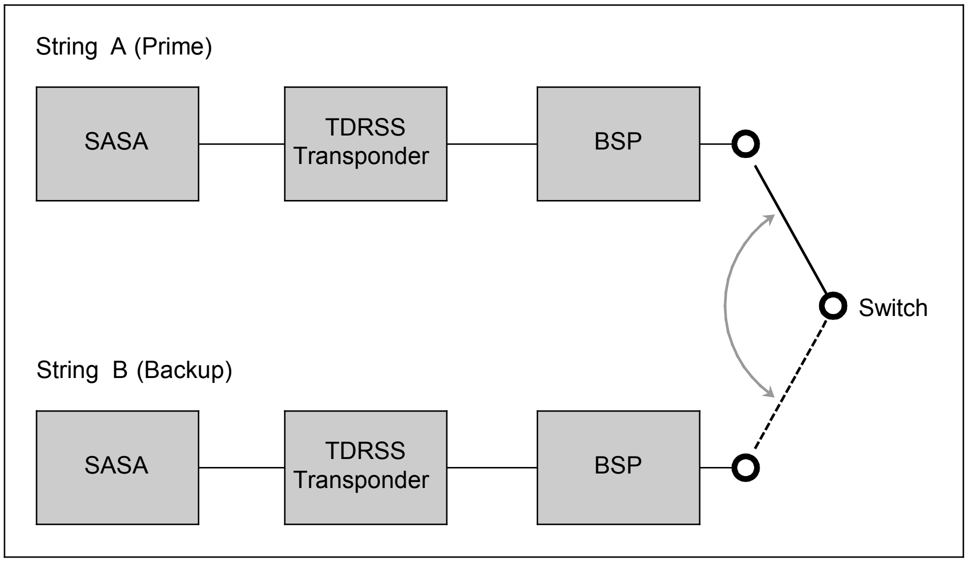
[8] Bayesian analysis is a method of statistical inference (named for English mathematician Thomas Bayes) that allows one to combine prior information about a population parameter with evidence from information contained in a sample to guide the statistical inference process.

[9] The ISS Reliability and Maintainability Panel at Johnson Space Center in Houston, Texas, provides support to all ISS hardware teams at all NASA centers.

[10] S-band is a radio band used by NASA to communicate with the ISS.

functional architecture for the S-band communications and tracking function.

Figure 2: S-Band Functional Architecture



Source: GAO analysis of NASA data.

A failure of a single ORU will disable its string, but will not disable the function since the function can be switched over to the second string.

To enable the ISS program to predict how many spare ORUs it required, NASA needed not only the best available estimate of each ORU's MTBF, but also a means of quantifying what level of redundancy was required for each function, and with what level of confidence each function must be maintained. When it considered the challenges of supporting ISS without the space shuttle's ability to guarantee the repair and refurbishment of failed ORUs, the ISS program recognized that the ISS would need to "gracefully degrade" without compromising safety as it approached its end of life. Graceful degradation was defined by the ISS program for 27 functions through the establishment of a functionality target at the end of the ISS's life, and a confidence goal for meeting that functionality target. The ISS program also recognized that it would need an appropriate analytic method for predicting whether it would meet its functionality targets and confidence goals. The functionality target and confidence goal for each function drives the quantity of spare ORUs required through the end of the ISS's life. For example, the ISS program established a functionality target for its S-band communications and track function of having at least one of the two ORU strings operating at end of life, and a 98 percent confidence goal for meeting this functionality target. The ISS program has conducted an annual functional availability risk assessment of 27 functions every year since 2006 to assess whether or not the ISS is meeting its functionality targets and confidence goals through 2015. In 2010 NASA conducted the first assessment addressing ISS functionality through 2020. This assessment employs a Monte Carlo model to calculate, for each ISS function, the probability of meeting its functionality targets as a function of time through end-of-life under different sparing quantity assumptions.[11] The assessment uses the results from the Bayesian MTBF process as an input.

NASA's Sparing Approach to Ensure Continued ISS Operations and Utilization through 2020 Employs Appropriate and Reasonable Methodologies

NASA has chosen appropriate and reasonable methodologies to predict the quantity of spares it requires to maintain ISS operations and full scientific utilization through 2020. NASA uses a Bayesian estimation process to improve estimates of ORU MTBF and functional availability risk assessments to determine with what confidence ISS functionality targets can be maintained. The Bayesian estimation process is an appropriate and reasonable technique for updating the original predicted MTBF of ISS ORUs. Similar techniques have been used on other NASA programs and are used throughout government and industry to update reliability estimates for nuclear power plant components, pressure vessels at oil and gas facilities, and medical devices. Moreover, the ISS program's specific implementation of this process is reasonable, given its current level of knowledge of the on-orbit performance of ORUs. However, the results of the Bayesian estimation process are sensitive to key assumptions, particularly with regard to the weight given to the manufacturer's original estimated MTBF relative to the actual on-orbit performance and failure data. The ISS program's functional availability risk assessment process is also an appropriate and reasonable technique for predicting whether available spares are sufficient to allow the ISS to meet its functionality targets and confidence goals, set by the program manager with input from experts. Moreover, the ISS program conducts sensitivity analysis to determine how the number of required spares would change if the functionality targets and confidence goals were

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[11] Monte Carlo modeling is used to approximate the probability outcomes of multiple trials by generating random numbers. Monte Carlo models are widely used throughout government and industry to calculate approximate probabilities for complex events when the calculation of exact probabilities would be difficult or impossible.

relaxed. The ISS program manager's rationale for selecting these targets and goals, however, has not been systematically documented.

Bayesian Estimation Process Is an Appropriate and Reasonable Technique for Updating Estimates

The ISS program's Bayesian estimation process employs a common statistical technique for updating the original reliability estimates of ISS ORUs. The process combines the probability distribution of the original equipment manufacturer's estimated MTBF with actual on-orbit data, which includes the accumulated hours of operation and random-failure history of the ORU population.[12] The result is a probability distribution of a new "operational MTBF" reflecting NASA's experience with the ORU. The basic idea underlying Bayesian estimation is that an original estimate for a statistical parameter—the MTBF, for example—can be improved upon by combining it with actual experience. As more experience is gained and applied in the updating process, the accuracy of the new distribution that defines the MTBF will improve. If the original distribution has a relatively large variance—for example, substantial uncertainty in the value of the MTBF—then the new evidence (accumulated hours of operation and the number of on-orbit random failures) will tend to have a larger effect on the new distribution. On the other hand, if the original distribution has a relatively small variance—that is, a high degree of certainty that the value of the MTBF falls between a relatively narrow range—then the new evidence will have less influence on the new distribution. Figure 3 illustrates a typical example of the relationship between the original and updated probability distributions.

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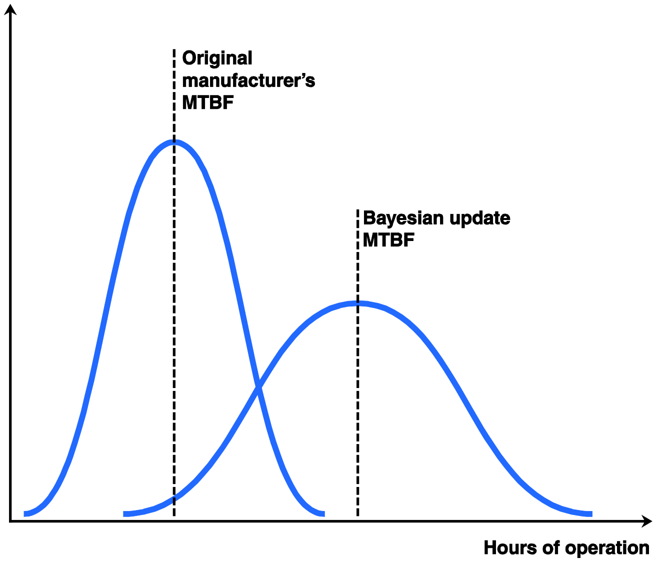
[12] A general description of a probability distribution is a function that describes the probability of a random variable taking certain values.

Figure 3: Hypothetical Example of the Relationship between Original and Updated Probability Distributions



Source: GAO analysis of NASA data.

According to NASA representatives, the Bayesian estimation process was found to be the most appropriate for ISS given:

- the Bayesian process is an accepted method to update data within the probabilistic risk assessment discipline;
- the process incorporates original reliability data with observed performance data; and
- the Bayesian process can be performed even with no observed random failures, which is important because many types of ORU have experienced no failures over the life of the ISS.[13]

Statistics textbooks and other authoritative sources of guidance describe the use of the Bayesian estimation process to update statistical variables,

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[13] A probabilistic risk assessment is a comprehensive, structured, and logical analysis method aimed at identifying and assessing risks in complex technological systems for the purpose of cost-effectively improving their safety and performance in the face of uncertainties. Probabilistic risk assessments assess risk metrics and associated uncertainties relating to likelihood and severity of events adverse to safety or mission. (NASA Procedural Requirements 8715.3C, *NASA General Safety Program Requirements*).

including MTBF. Moreover, the Bayesian estimation process is a key element of NASA's recommended approach for conducting probabilistic risk assessments, a basic requirement for all major NASA programs and projects.[14] NASA's probabilistic risk assessment guidance describes the importance of the Bayesian estimation process, and provides broad implementing guidance for NASA program managers on incorporating Bayesian estimation into these assessments. According to representatives from NASA's Office of Safety and Mission Assurance—the organization within NASA that developed NASA's probabilistic risk assessment guidance—the use of Bayesian estimation is critical to ensuring that a program's probabilistic risk assessment is supported by the best available evidence of system reliability and performance. NASA officials indicated that Bayesian estimation has proven to be more accurate than original manufacturers' reliability estimates in predicting overall failure rates for ORUs on the ISS. Bayesian estimation has been used to update MTBFs for components on numerous NASA programs, including the space shuttle, the Hubble Space Telescope, and the TDRSS family of satellites.

Similar methodologies are also used within government and industry to update values for statistical parameters:

- The Nuclear Regulatory Commission employs the Bayesian estimation process to update the failure rates of components in nuclear power plants.

- The oil and gas industry employs the Bayesian estimation process to update the failure rates of pressure vessels and other types of equipment at industrial oil and gas facilities.

- The Food and Drug Administration has developed guidance for the assessment of medical device effectiveness based on the Bayesian estimation process.

While NASA's Office of Safety and Mission Assurance provides NASA programs with broad implementing guidance on employing the Bayesian estimation process, it leaves the details of implementing this process to the discretion of the individual programs. The ISS program's application

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[14] NASA Procedural Requirements 8705.5A, *Technical Probabilistic Risk Assessment (PRA) Procedures for Safety and Mission Success for NASA Programs and Projects*.

of the Bayesian estimation process requires four key sources of input data: (1) an ORU's original manufacturer-estimated MTBF; (2) a parameter that governs the variance of the original MTBF's probability distribution—a measure of the dispersion of values about the MTBF's most likely value; (3) the total aggregated hours of operation for the ORU population under consideration;[15] and (4) the actual number of random failures experienced by the population of ORUs.

For three of the four sources of input data, the ISS program generally has complete data readily available for each set of ORUs. For example, each ORU's original estimated MTBF was obtained from the reliability analysis performed by the original equipment manufacturer and incorporated into an authoritative ISS database.[16] In addition, detailed data on each ORU's total hours of operation and the number of random failures is maintained by the ISS program's logistics and maintenance team, and is therefore readily available as a source of reliable input data.

For the fourth source of input data—the parameter that governs the variance of the original MTBF's probability distribution—there is no readily available source. In most cases, originally predicted MTBF estimates were provided to the ISS program from original equipment manufacturers as a single value, without any estimate of variance. Therefore, an assumption about the variance of MTBF must be made. However, selection of a parameter that defines the variance of the original MTBF's probability distribution is the most challenging aspect of applying the Bayesian estimation process. The ISS tiger team consulted at least two sources of information including a 1990 study of external maintenance activities for Space Station Freedom—the precursor to ISS—which had

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[15] Because the failure rate is constant, the Bayesian estimation process does not care whether the on-orbit run time is a single ORU operating for 100,000 hours, or 4 identical ORUs operating for 25,000 hours.

[16] The ISS program maintains an "original MTBF" data field in its Modeling and Analysis Data Set (MADS)—the database it maintains on key orbital replacement unit parameters—and uses the information from this data field in its Bayesian estimation calculations. We discussed with ISS program representatives the steps they had taken to ensure that the MTBF data captured in MADS reflect the data from the reliability analysis performed by the original equipment manufacturers. We also confirmed for a small number of orbital replacement units, that the MTBF data contained in MADS matched the MTBF data from the original equipment manufacturers' reliability analysis. However, because many of these reliability reports were performed well over a decade ago, and many exist only in hard copy at a long-term storage facility, we did not conduct detailed tests of these underlying data.

recommended using a parameter that produced a relatively large variance for the original estimated MTBF, and a 2005 independent technical consulting report by NASA's Engineering and Safety Center (NESC), which recommended using a parameter that would produce a relatively small variance.[17] After deliberating, the tiger team recommended adopting a variance parameter for the original MTBF that would grant approximately "equal weight" to an ORU's original estimated MTBF and its on-orbit experience. The ISS program applies the Bayesian process to all ORUs that have experienced random failures. For an ORU that has not experienced any random failures, the ISS program allows each set of ORUs to operate for at least one-half of the number of hours that is equal to the original predicted MTBF for that set of units before updating the MTBF by applying the Bayesian estimation process.

The ISS program believes that its choice of variance parameter is appropriate and consistent with on-orbit experience to date. Using a parameter that produces a larger variance would place more weight on on-orbit experience. Because many ORUs have experienced no failures, however, this could lead to overly optimistic updates of MTBF. On the other hand, using a parameter that produces a smaller variance would place more weight on the original estimated MTBF and lead to continued unwarranted conservatism, according to the ISS program. Given the current state of knowledge about ORUs, NASA's choice of an MTBF variance parameter appears to be reasonable and based on sound professional judgment. Thus far, NASA has not revisited the relative weight given manufacturers' original reliability estimates versus on-orbit experience, and currently has indicated no plans to do so. However, as time goes on, the variance parameter selected could prove to be overly conservative given that NASA has been seeing failure rates for ORUs that are far more in line with Bayesian updates than manufacturers' predictions. Continuing to weigh manufacturers' original estimates equally with on-orbit experience through the ISS end of life for those ORUs that have experienced a random failure could lead to the purchase of an excess of spares because NASA could continue to predict more failures than actually occur.

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[17] NASA, *Space Station Freedom: External Maintenance Task Team Final Report*. (July 1990). (This study is more commonly referred to as the Fisher-Price report, after its two principal authors.)

ISS program representatives have noted that the MTBFs based on implementation of their Bayesian estimation process—with their choice of MTBF variance parameter—are much closer to actual overall ORU failure rates. For example, in 2005, a comparison of actual and predicted failures of the external ISS ORU population showed the hardware experiencing only about one-third the predicted number of failures based on original MTBF estimates. However, given its selection of a parameter for MTBF variance, the operational MTBF calculated using ISS's Bayesian estimation process is sensitive to single failures—that is, a single failure of an ORU can dramatically change the operational MTBF calculated by using this process. In one sense, this Bayesian update process does exactly what one would expect—modify the original MTBF based on observed failure data. Because many ISS ORUs have operated for well beyond their original predicted MTBF without experiencing a random failure, and consequently have updated operational MTBFs that are several times greater than their original predicted MTBFs, a single random failure will quickly reverse this growth. For example, successive annual updates of the operational MTBF (in hours) for the ISS pump module assembly increased each year through 2009. A single failure of the pump module assembly in July 2010,[18] however, resulted in a significant decrease in MTBF—from an October 2009 estimate of 104,683 hours to an August 2010 estimate of 58,119 hours. This decrease of 44 percent could result in the need to procure additional spares. Table 1 shows how the estimated MTBF of the pump module assembly has changed over time.

Table 1: Successive Annual Updates of MTBF (in Hours) for the ISS Pump Module Assembly

Pump module assembly	Original MTBF in October 2006 data	Updated MTBF October 2007	Updated MTBF October 2008	Current MTBF October 2009	Estimated runtime hours at failure per ISS risk team to August 3, 2010	New MTBF Bayesian updated with one failure August 2010
Hours	39,800	52,450	86,560	104,683	63,600	58,119

Source: NASA.

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[18] According to ISS program office representatives, the July 2010 failure of the pump module assembly has been categorized as a random failure. However, if further analysis and testing reveal that the unit failed for some other reason—for example, a workmanship problem—then the failure would be re-categorized, and the Bayesian estimation calculation would be repeated without the failure.

Similarly, the ISS television camera interface converter has not yet experienced any random failures. Consequently, its predicted MTBF has grown by more than 170 percent—from an original value of 100,675 hours to 272,908 hours (as of October 2010). A single random failure of this device today, however, would cut the value of the operational MTBF by more than half its current value—to about 134,000 hours. These large changes in MTBF may have consequences for the results of the ISS functional availability risk assessment, and could result in the need to procure additional spares as discussed below. Given the fact that the majority of ORUs on the ISS have yet to experience a random failure, this issue is one that could affect sparing decisions and place the program at risk of procuring too few spares. NASA officials indicated that the agency mitigates this risk by updating its sparing estimates annually.

Process for Establishing Functionality Targets and Confidence Goals Is Reasonable but Rationale for Decisions Is Not Well Documented

NASA has reasonable processes in place for establishing functionality targets and confidence goals for each ISS function being modeled in its functional availability risk assessment.[19] The ISS program manager considers the recommendations of system experts who validate each functionality target to ensure that it meets all science utilization and crew habitability requirements. The ISS program manager's rationale for establishing functionality targets and confidence goals is also driven by an assessment of the operational needs of ISS as a whole, and by whether the needs satisfied by a given function might be accomplished in some other way. NASA officials indicated, for example, that the program manager's decision to set the functionality target for S-band communications and tracking as "at least one of two strings operational" instead of "both strings operational" was influenced by the planned upgrades to ISS Ku-band capability, which will be able to perform some functions that could previously be performed only by using S-band, thereby mitigating the loss of S-band redundancy. Finally, ISS functionality targets and confidence goals are revisited based upon the results of each annual functional risk assessment. Table 2 below shows several examples of the 27 ISS functions NASA includes in its functional availability risk assessment.

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[19] The functional availability risk assessment employs a Monte Carlo simulation model to calculate the number of spares required to meet the functionality targets and confidence goals for each function. Monte Carlo modeling is widely accepted by industry and government as appropriate for these types of simulations.

Table 2: Examples of ISS Functions Included in a Functional Availability Risk Assessment

Function	Purpose
Command & Data Handling	Provides command and control capability of ISS via a network of computers, data buses, and software.
Electrical Power System	Generates, stores, and distributes electrical power.
Structures & Mechanisms	Provides the primary and secondary structures of the ISS, such as trusses and payload racks, as well as ISS mechanisms, such as the joints and gimbals for positioning solar arrays.
Thermal Control System	Maintains temperature control of the ISS.

Source: NASA.

Once initial functionality targets and confidence goals have been established for each of the 27 functions, the ISS program employs a Monte Carlo simulation to predict how many spare ORUs would be required to meet these targets and confidence goals through the ISS end of life. The ISS program also conducts a sensitivity analysis to determine how the number of required spares would change if the functionality targets and confidence goals were relaxed. For example, the sensitivity analysis may reveal that a 98 percent confidence goal for a given functionality target can be met with a given quantity of spares, while a 99 percent confidence goal would require two to three times as many spares. Similarly, analysis may reveal that while one functionality target (e.g., three of four strings operational) may be achievable with a certain number of spares, achieving a more demanding functionality target (e.g., four out of four strings operational) might require several times as many spares. This result would not necessarily support the less demanding functionality target and confidence goal in all cases—despite the significant increase in the number of spares required—since the 99 percent confidence goal may be justified based on safety-of-life concerns. This assessment, however, allows the ISS program to see the costs, in terms of the required number of spares, of setting functionality targets and confidence goals at particular levels.

On the basis of this analysis, a technical community of system experts supporting each modeled function validates each functionality target and confidence goal and recommends them to the ISS program manager. The ISS program manager is free to reject these recommendations based on his or her broader knowledge of all ISS functions and other factors affecting sparing decisions. For example, during the 2010 functional availability risk assessment,[20] the technical community for the S-band communications and tracking function recommended a functionality target of at least one of two strings operational, and a confidence goal of 99.5 percent for maintaining this target. The program manager agreed with the functionality target, but decided to set the confidence goal at 98 percent. By setting a lower confidence goal, the number of additional spares required dropped from a total of six for all three types of ORUs to just two.

According to the ISS program manager and the system experts who make the functionality target recommendations, they go through a deliberative process wherein options for functionality targets and confidence goals are developed and presented to the ISS program manager at the Space Station Program Control Board meeting. These presentations contain the technical community's recommendation on the most appropriate functionality target and confidence level for a given function. As illustrated above, the program manager has the discretion and authority to select functionality targets and confidence levels other than the ones recommended by the technical community. Agency officials indicated that while the program manager's rationale for not accepting the recommendation of the technical community is discussed at these meetings, the meeting minutes do not typically capture the rationale for the program manager's decision to deviate from the recommendation of the system experts. Our *Standards for Internal Control in the Federal Government*[21] require, however, that important events and transactions are clearly documented and readily available for examination. This type of documentation provides evidence for the benefit of future decision-makers to continue to ensure that the rationale remains valid.

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[20] The 2010 functional availability assessment had focused on the number of spares required to meet the functionality target and confidence goals through 2020. The 2011 functional availability risk assessment addressed meeting functionality targets and confidence goals beyond 2020. However, we did not receive information on the 2011 assessment until late in our review and, therefore, did not have time to assess the results.

[21] GAO, *Standards for Internal Control in the Federal Government*, GAO/AIMD-00-21.3.1 (Washington, D.C.: November 1999).

NASA's ISS Sparing Plan Relies on International and Domestic Vehicles and Currently Includes Some Cargo Shortfalls

NASA plans to use both international and domestic commercial launch vehicles to ensure ISS spares are available through 2020 because these are NASA's only near-term options for resupplying the ISS. Planned launches, however, may not provide enough cargo capability to cover anticipated growth in scientific utilization or margin for unforeseen ISS maintenance needs, especially from 2015 through 2020. Additionally, delays in domestic commercial launch vehicle development could affect sparing deliveries planned for 2012 and beyond.

NASA plans to rely on ISS international partner and new commercial launch vehicles to meet crew needs as well as support maintenance and scientific experiments through 2020. The agency has agreements in place with the European and Japanese space agencies for their respective vehicles, the ATV and HTV, to conduct sparing missions beginning in 2012. The ATV and HTV are unmanned vehicles, which have flown to the ISS, and carry such items as hardware and water.[22] NASA expects to employ a total of 13 international partner launches—7 from 2012 to 2015 and 6 from 2016 through 2020.

As we have reported, the international partner vehicles alone cannot meet ISS sparing needs.[23] Consequently, NASA plans to use two types of domestic commercial launch vehicles to maintain ISS from 2012 through 2020. Development of these vehicles—the Falcon 9 and Taurus II—was fostered under a NASA-initiated effort known as Commercial Orbital Transportation Services (COTS). These vehicles are being developed by private industry corporations SpaceX (Falcon 9) and Orbital Sciences (Taurus II). In late 2008, NASA awarded contracts to both companies to provide cargo transport services to the ISS. Only SpaceX's Falcon 9 vehicle is designed to safely return significant amounts of cargo to earth, such as scientific experiments. NASA anticipates that SpaceX will begin providing that capability in 2012.

Commercial vehicles are essential to sustaining and utilizing the ISS. As Table 3 below indicates, SpaceX and Orbital are scheduled to fly 19 (73

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[22] In 2008 and 2009, the ATV and HTV vehicles respectively flew to the ISS and docked at the station to demonstrate their capabilities. In 2011, both vehicles again launched. These flights were the second for both systems.

[23] GAO, *NASA: Commercial Partners Are Making Progress, but Face Aggressive Schedules to Demonstrate Critical Space Station Cargo Transport Capabilitie*s, GAO-09-618 (Washington, D.C.: June 16, 2009).

percent) of the 26 launches NASA plans through 2015 and follow-on SpaceX and Orbital commercial vehicles are expected to fly 24 (80 percent) of the 30 launches from 2016 through 2020.[24] Additional international partner flights from 2014 to 2020 beyond those already scheduled are an unlikely option, according to NASA officials, because the European and Japanese space consortium's manufacturing facilities are not equipped to manufacture vehicles at a rate faster than their current commitments.

Table 3: NASA's Planned Vehicle Launches for 2012 to 2020 to Resupply the ISS

Vehicles	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
ATV	1	1	1		1			1		5
HTV	1	1	1	1	1	1	1		1	8
SpaceX	3	3	3	2						11
Orbital	2	2	2	2						8
SpaceX Follow On Vehicle A					3	3	2	3	3	14
Orbital Follow On Vehicle B					1	2	3	2	2	10
Total	**7**	**7**	**7**	**5**	**6**	**6**	**6**	**6**	**6**	**56**

Source: GAO analysis based on NASA documents.

Note: This table does not include flights by the Russian Soyuz or Progress vehicles.

Although NASA expects domestic commercial launch vehicles to deliver the bulk of cargo required by the ISS through 2020, NASA strategic planning manifests indicate that NASA may not have sufficient capability to carry all the cargo that could be needed on the ISS. The manifests show that, when anticipated growth in national laboratory demands and margin for unforeseen maintenance needs are accounted for, the current number of flights NASA is planning for may not cover all of NASA's anticipated needs beginning in 2014.[25] These shortfalls amount to a total of 2.3 metric tons—approximately the cargo that one SpaceX commercial vehicle can transport to the ISS. NASA has indicated, however, that these shortfalls could increase or decrease because transportation demand,

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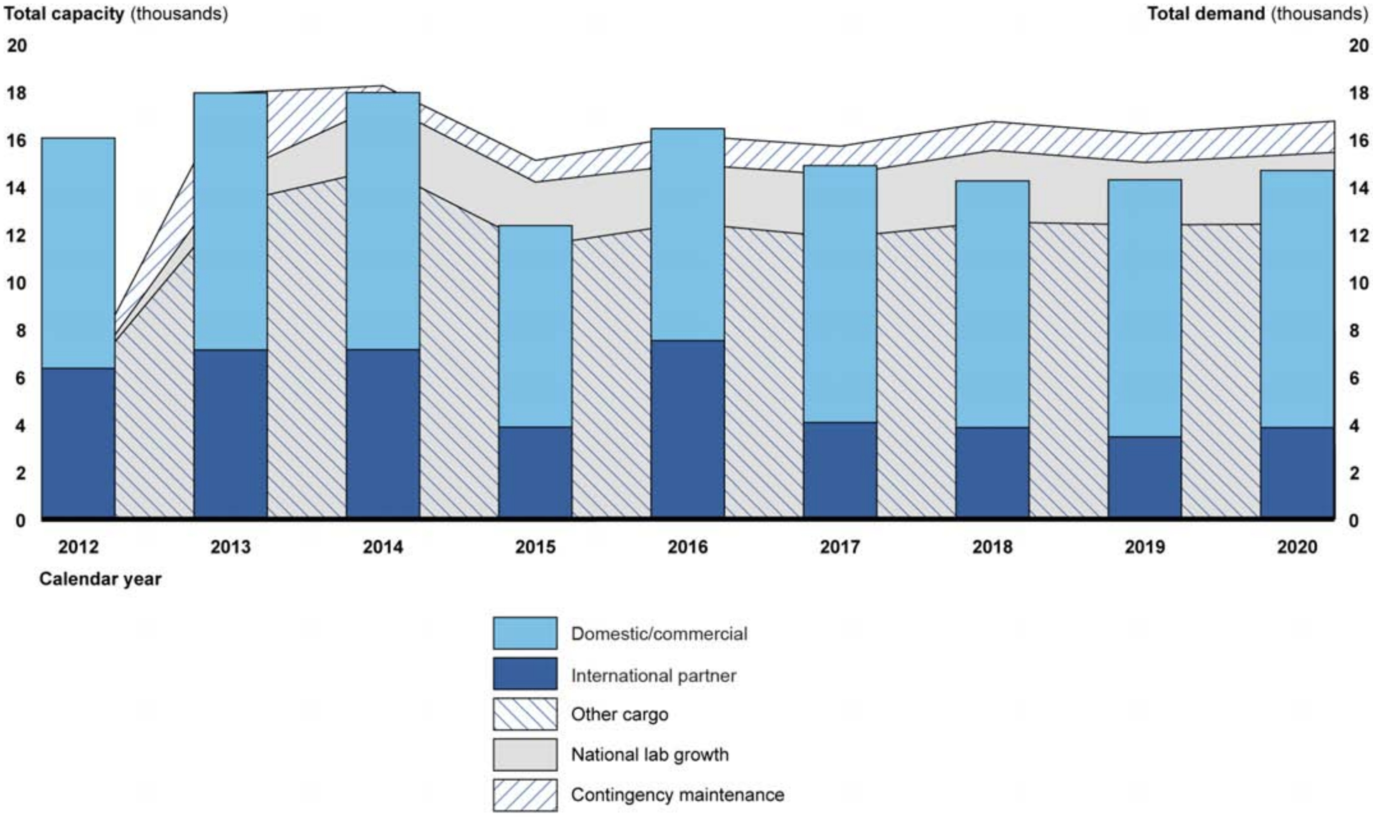
[24] NASA has awarded contacts to SpaceX and Orbital for cargo resupply services to the ISS through 2015. Planned follow-on vehicles are the vehicles NASA will use for flights beyond those currently on contract.

[25] NASA selected a nonprofit organization to facilitate increased use of the ISS on-orbit research capabilities by entities outside of NASA.

vehicle flight rate, and vehicle capability projections beyond 2015 are estimates only. Additionally, ISS agreements with commercial vehicle providers are not in place beyond 2015 and agreements for use of international partner vehicles beyond 2015 are in negotiations.

Figure 4: Cargo Capability of U.S. Commercial and International Partner Vehicles Versus NASA's ISS Sparing Needs from 2012 to 2020



Source: GAO analysis of NASA data.

As we have previously reported, both SpaceX and Orbital are working under aggressive schedules and have experienced delays in completing demonstrations.[26] SpaceX may gain some ground in its schedule by

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[26] GAO, *NASA: Commercial Partners Are Making Progress, but Face Aggressive Schedules to Demonstrate Critical Space Station Cargo Transport Capabilities*, GAO-09-618 (Washington, D.C.: June 16, 2009).

combining demonstration missions planned for 2011, but this likely would not provide much overall schedule gain because previous delays had already placed the program about 18 months behind schedule. Additionally, in the summer of 2011 Orbital experienced an engine failure during testing, which could affect its planned launch vehicle availability. NASA has made efforts to accommodate delayed commercial vehicle development, including use of the final shuttle flight in July 2011 to pre-position additional ISS spares. However, if the commercial vehicle launches do not occur as planned in 2012, the ISS could lose some ability to function and sustain research efforts due to a lack of alternative launch vehicles to support the ISS. The need for these vehicles to launch in late 2012 could become even more important as a result of the failure of the Russian Progress re-supply mission in August 2011,[27] one of the last Progress flights that NASA had contracted with Russia to transport cargo to the ISS. As noted by NASA officials, the Russian vehicle was to provide supplies that would help sustain crew and scientific experiments aboard the ISS. At this time, NASA officials indicated that the agency does not believe the loss of the Progress flight increased the need for the commercial launches in 2012 because the agency anticipates that a Progress flight in 2013 will carry the supplies to the ISS and provide margin against delays in the commercial vehicle launches. However, if that Progress flight is not conducted, NASA could become more reliant on the commercial vehicles.

NASA Has Budgeted for Estimated Hardware Spares through 2020

To ensure that spares essential to ISS operations will be available, NASA has budgeted approximately $900 million to supply ISS hardware spares needed to meet functional targets through 2020. NASA officials indicated that, of that amount, the agency plans to spend about $515 million procuring ISS spares to be used from 2010 through 2015 and about $384 million for spares to be used from 2016 through 2020. According to NASA officials, the difference in budgets between the 2010 through 2015 and 2016 through 2020 time frames reflects the need to procure fewer spares from 2016 through 2020 because NASA already purchased and pre-positioned spares aboard the ISS. The officials indicated that this strategy allowed for schedule margin against delayed development of commercial launch vehicles; that is, spares would already be pre-positioned on the ISS in case commercial launch vehicles were not available as planned in

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[27] The Progress vehicle’s mission failed when the third stage engine failed during launch.

2012. Additionally, the officials stated that the strategy of graceful degradation reduces the amount of spares required as the ISS nears its planned end of life in 2020.

As shown in Table 4 below, of the $515 million planned for spares to be used through 2015, NASA officials anticipate that the agency will spend about $288 million to procure spares for the Environmental Control and Life Support System.[28] The agency officials expect NASA to use the remaining funds, about $227 million, to procure spares for the electrical power system; the thermal control system; communications and tracking systems; command and data handling; and structures and mechanisms, such as hatches and payload racks.

Table 4: Cost Estimates for ISS Hardware Spares to be Used through 2015

System type	Total cost (dollars in millions)	Last delivery date
Electrical Power System	$31.6	2012
Structures and Mechanisms	$92.8	2012
Command and Data Handling	$1.3	2009
Communications and Tracking	$76.5	2013
Thermal Control System	$24.5	2012
Regenerative ECLSS	$233.0	2013
ECLSS	$55.2	2012
Total all systems	**$514.9**	

Source: GAO analysis based on cost data provided by NASA officials.

Of the $384 million NASA plans to use to procure spares for use in 2016 through 2020, agency officials estimate NASA will need about $196 million to replace ISS batteries and lighting and about $115 million for spares for electrical power, environmental control and life support, and other systems. The remaining budget estimate of about $73 million, as noted by NASA officials, is expected to be used for repair of spares

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[28] The Environmental Control and Life Support System (ECLSS) makes the ISS habitable for crew by providing or controlling oxygen supply, fire detection and suppression, waste management and water supply. The total of $288 million includes $233 million NASA has budgeted to procure spares for the Regenerative ECLSS, which recycles liquid waste into potable water and oxygen. In terms of estimating the needed spares, the Regenerative ECLSS is the most high-risk functional system, as several of its ORUs are failing faster than originally anticipated.

returned to earth via SpaceX commercial launch vehicles. The officials emphasized that budget estimates and hardware quantities for 2016 through 2020 are not firm, and they continually refine both estimates and quantities of spares needed as the agency gains increased knowledge of how long hardware spares will last. For example, officials indicated that they are already adjusting budget projections based on the results of the 2011 functional availability assessment, which indicated that some functions may need more spares than anticipated while other functions may require fewer spares.

NASA Is Using Reasonable Methods to Assess Structures and Hardware

NASA is using reasonable analytical methods to assess structural health as well as station hardware and ORUs that could affect the safety of the station. NASA's software tools, in use since the program's inception, indicate the ISS is structurally sound to support continued operations through 2020 and potentially beyond with some mitigation. Other federal agencies recognize analytical assessments as valid methods for evaluating structural health, and the software NASA uses is widely used by industry. Currently, however, NASA has assessed only 40 percent, by weight, of the assembled ISS because most of the ISS structures have not been on orbit long enough to accumulate the data needed for analysis.[29] NASA expects to complete ISS structural assessments in early 2016. NASA plans to use improved software tools for evaluating life extension of ISS's structures and expects these tools to provide greater insight into the structural health of the ISS. By 2012, NASA expects to complete analytical safety and mission assurance reviews designed to assess operations of the ISS as a whole as well as identify ORUs and other hardware failure of which could result in an increased risk of loss of station or loss of crew. Through 2015, NASA plans to develop methods to mitigate issues identified. When these mitigation actions are developed and implemented, NASA expects to have increased assurance that the ISS can safely operate through 2020 and potentially beyond.

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[29] The timing of initial structural assessments of ISS components was originally driven by programmatic judgment calls as to when predicted and actual loads had diverged enough to provide a meaningful assessment. The timing and order of current assessments are now driven by the assembly sequence of the ISS and NASA's desire to complete the initial assessment of each component before its 15-year structural certification expires.

Analysis Ongoing but NASA Expects the ISS to Remain Structurally Sound with Mitigation

Based on prior analysis of structural life usage through 2015 and the robust design of the ISS primary structures, NASA anticipates that—with some mitigation—the ISS will remain structurally sound to support operations through 2020, though its analysis through 2020 is still ongoing. NASA standards for manned spaceflight systems require the ISS program to monitor the structural health of the ISS.[30] Other federal agencies—including the Federal Highway Administration, Federal Aviation Administration, and National Institute of Standards and Technology—recognize visual, physical, radiographic (x-ray), and sonographic inspections as well as analytical assessments as valid methods for evaluating the structural health of bridges or airplanes. Visual inspections of the ISS are limited to using television cameras to assess the station's exterior, but the cameras do not provide sufficient detail for structural inspection. Additionally, the position of payload racks within the ISS severely hampers visual inspection of the station's interior weld seams. Physical assessments are limited to one ISS structure—the US-funded, Russian-built Functional Cargo Block.[31] These ground-based assessments, conducted on a full-scale model of the cargo block, have shown that it should remain structurally sound through 2028.[32] According to agency officials, NASA has not attempted to develop techniques or equipment to conduct x-ray or sonographic inspection of the ISS. The officials stated that doing so would be extremely expensive, impractical, or both.

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[30] NASA Technical Standard-5007, *General Fracture Control Requirements for Manned Spaceflight Systems* (March 13, 2001); and NASA Technical Standard-5003, *Fracture Control Requirements for Payloads Using the Space Shuttle* (October 7, 1996) establish the requirements for protection against fracture within spaceflight system structures. Fractures, simply put, are cracks that form in structures as a result of the loads they encounter. Fracture criticality deals with the likelihood that a structural element will fail under the loads it experiences. For a component to be considered fracture critical, its potential failure must cause loss of life, loss of mission, or loss of a manned spaceflight system. Fracture control ensures a paper trail of fracture analysis and non-destructive testing/evaluation.

[31] The Functional Cargo Block (FGB) was the first portion of the ISS put into orbit.

[32] The Russian Space Agency used repetitive physical tests of a full-scale model of the FGB to initially certify the FGB for 15 years of life on-orbit. The original certification performed by the Russian Space Agency was set to expire in 2013. To assess the viability of using the FGB an additional 15 years to 2028, NASA relied on the Russian Space Agency to conduct further testing on the full-scale model originally used to certify the FGB. In July 2011, NASA and the Russian Space Agency recertified the FGB for 15 additional years of service—until 2028.

Because NASA cannot feasibly use traditional methods to assess the majority of the ISS on orbit, the agency relies on analytical assessments to determine ISS structural health. Since program inception, NASA has used various versions of a software tool known as NASGRO® [33] as its key analytical tool for monitoring the structural health of the U.S. portions of the ISS.[34] NASGRO assumes that non-discernable cracks are present in any given structure and predicts the growth rate and likely size of a crack or "crack growth" based on: (1) the shape of the structure, (2) the material composition of the structure, and (3) the physical loads placed on the structure. NASGRO is widely used by government and industry including the Department of Defense (DOD), Federal Aviation Administration, The Boeing Company, Lockheed Martin, Honda, Airbus, and Spirit Aerosystems. NASGRO is also used by the International Partners, i.e., the Japanese and European space agencies to monitor the structural health of their elements. NASA, in conjunction with other users, continually provides input for the update and release of new versions of NASGRO with increased analysis capabilities and materials knowledge. One NASGRO industry user we talked to said that his company chose to rely on NASGRO as its tool for predicting structural health because it is conservative in its projections, has an extensive materials properties database, and is a Federal Aviation Administration-accepted analysis method for fatigue and damage assessment of structures.

NASA's approach to assessing structural health compares initial NASGRO predictions of crack growth with updated NASGRO predictions of crack growth. NASA used NASGRO to calculate initial predictions of crack growth during the ISS design phase based on the mechanical, thermal and pressure loads NASA expected the ISS to experience throughout its operational life ending in 2015. NASA annually updates crack growth predictions based on the actual loads the ISS has experienced since being placed in orbit.[35] NASA prepares the updated predictions of crack growth with the same version of NASGRO used to

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[33] NASGRO is a suite of programs used to: analyze fatigue crack growth and fracture, perform assessments of structural life, process and store fatigue crack growth properties, and analyze fatigue crack formation.

[34] When conducting structural assessments of the ISS, NASA assesses each structural component with the same version of NASGRO.

[35] Actual loads are calculated by analytical modeling of the ISS structure. The models are validated by data obtained from sensors on-board the ISS.

prepare the initial prediction. NASA prepared the initial predictions of crack growth for each structural component with the version of NASGRO that was current at that time. As the ISS was developed over several years, NASA uses several versions of NASGRO to assess structural health.

For these comparisons to be useful, the structural elements of the ISS under examination must have been in orbit long enough to accrue meaningful differences between predicted and actual loads. Thus far, NASA has found that the actual loads experienced by ISS structures have been generally less stressful than those originally predicted. The last completed assessment, in fiscal year 2010, examined the ISS structures placed in orbit as of November 2002, which represents approximately 40 percent of the ISS measured by weight.

The structural health assessment uses a risk-based screening approach and examines in detail only those components originally estimated to have less than 6 service lives or safety margins of less than 10 percent.[36] According to program officials, because ISS developers were conservative in their design approaches and in most cases built hardware that exceeded requirements, most structural locations do not need to be examined in detail. As of the last analysis, completed in November 2010, of the 10,000+ structural locations within the on-orbit segments of the ISS, 829 locations were examined in detail because they met screening criteria. Of the 829 locations examined in detail, 196 are using structural life faster than originally predicted, but only 19 no longer meet the original requirement of 60 years of service life. Fifteen of the 19 are located on the P6 truss.

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[36] NASA engineers believe there is a reasonable expectation that components that have analytically demonstrated more than 6 service lives, or 90 years, are not likely to fail within the original service life timeframe.

Figure 5: P6 Truss in Interim and Permanent Locations

Source: NASA.

Interim location of P6 truss.

Source: NASA.

Permanent location of P6 truss.

The P6 truss—an end portion of the truss that serves as the structural backbone of the ISS, as shown in figure 5 above—holds 4 of the ISS's 16 solar panels. The P-6 truss provides an example of the impact of actual loads data on the determination of structural health of ISS structures. The truss was left in what was planned as an interim location for an extended period of time following the Space Shuttle Columbia accident. This location left it exposed to greater extremes of hot and cold temperatures than anticipated. According to program officials, the P6 truss may require mitigation to remain sound through 2020 and potentially beyond. NASA is evaluating mitigation processes, such as adding thermal insulation blankets and changing how and where vehicles dock to the ISS, to slow down the rate at which the locations on the P6 truss, as well as the other locations, are expending structural life.

As part of its life extension effort, NASA is using a single version of NASGRO—NASGRO 6.0—to develop new crack growth baselines for assessing structural health through 2020 and potentially beyond. The agency is deriving the new baselines from the actual on-orbit loads the ISS has experienced since being placed in orbit and predicted loads for using the ISS through 2028.[37] The agency expects to incorporate these new baselines into biennial ISS structural health assessments beginning in 2012. Methodologically, these assessments will be virtually identical to the earlier assessments, but they will use the new baselines and improved NASGRO software with increased capabilities. NASA plans to establish these new baselines in 3 phases, with the last one established in 2015.

- Phase 1, beginning in 2009 and ongoing through 2012, examines structures with original certifications expiring on or before 2013.
- Phase 2, beginning in 2012 and ongoing through 2014, examines structures with original certifications expiring on or before 2017.
- Phase 3, beginning in 2012 and ongoing through 2016, examines structures with original certifications extending beyond 2020.

On the basis of the results of these analyses, NASA will determine what mitigation actions need to be put in place to ensure the ISS remains structurally sound through 2020.

On the basis of familiarity with NASGRO software, NASA officials expect the updated software to provide greater insight into the structural health of the ISS. For example, NASA expects the new version of NASGRO to better capture the impact of high cycle, low impact loads, such as those caused by astronauts running on the treadmill on the structural health of the ISS. Further, NASA expects the new software to support more in-depth analysis of how thermal, pressure and mechanical loads affect ISS structures. NASA also anticipates that improved knowledge of materials properties data within the software will support more informed

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[37] NASA is conducting life extension structural and hardware analyses through 2028 for two reasons: (1) the physical tests of the FGB assessed its structural soundness through 2028 and, (2) the program does not want to have to replicate the analysis if the ISS's life is extended beyond 2020.

analysis of how the structures of the ISS respond to different loads and environments.

When NASA begins using the updated software tools, part of the agency's input, the detailed design of the structures, will be based on existing models of the ISS. Officials indicated, however, that in some instances, these models are not detailed enough to take advantage of all the expanded features of the updated NASGRO software. According to the officials, these models were designed to be used with less sophisticated software than NASGRO 6.0. In areas not expected to meet service-life requirements, one of the mitigation strategies available is refined modeling with increased details. For example, more detailed models could allow NASA to more precisely pinpoint structural issues and focus mitigations accordingly.

NASA Is Employing Reasonable Methodologies to Ensure Safety of ISS Hardware through 2020

NASA is employing reasonable analytical methodologies to assess the extent to which ISS hardware, including ORUs and associated components such as flex hoses and tubing, can be safely operated through 2020 and potentially beyond. These methodologies employ established safety and mission assurance practices, governed by agency and program directives,[38] to perform a safety and mission assurance assessment as well as rely on program experts to assess the safety of hardware whose failure could result in the loss of ISS crew or the ISS as a whole.

NASA is performing two types of safety assessments. The first, a safety and mission assurance assessment, is an analytical review of hazards to the ISS as a whole providing a "top-down" look at how extending the life of the ISS through 2020 and potentially beyond affects ISS safety. Additionally, for the second assessment, NASA is using program experts

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[38] These directives include NM 7120-97, NASA Procedural Requirement 7120.5D, SRB Handbook*, NASA Space Flight Program and Project Management Requirements*, which is the interim directive to NPR 7120.5D; NASA Policy Directive 8700.1E, *NASA Policy for Safety and Mission Success*, (October 28, 2008); NASA Policy Directive 8700.3B, *Safety and Mission Assurance Policy for NASA Spacecraft, Instruments, and Launch Services*, (October 28, 2008); Space Station Program 30599 Revision A, *Safety Review Process* (January 11, 1995); Space Station Program 30309 Revision E, *Safety Analysis and Risk Assessment Requirements Document*, (October 28, 1994).

to assess the ORUs[39] and other hardware, whose failure could result in loss of ISS crew or the entire ISS. This assessment is a “bottom-up” analytical review to determine whether this hardware can be safely operated through 2020 and potentially beyond. According to NASA officials, addressing safety from two different perspectives—top down and bottom up—offers increased assurance that safety issues are fully addressed.

NASA’s safety and mission assurance practices call for identification of safety hazards and mitigation planning to address hazards. Safety hazards on the ISS are varied and consist of hazards to both the crew and the station. Examples of hazards include loss of crewmembers due to inability to reenter the ISS after conducting a spacewalk or loss of ISS attitude control. As indicated by NASA officials, the agency originally documented these hazards in 92 hazard reports applicable to ISS operations through 2015. NASA is now in the process of conducting a “top-down” review of these reports to determine if existing hazards require additional mitigation as a result of extending ISS life through 2020 and potentially beyond. An official working on the assessment stated that preliminary results of this assessment indicate that 58 hazard reports are affected by extending ISS life beyond 2015 and require further study. Mitigation actions could take a variety of forms, for example, procuring additional ORUs, updating hazard reports and operational procedures, and performing hardware modifications and redesigns.

In conjunction with the “top-down” safety and mission assurance assessment, NASA is using existing hardware teams who are responsible for and knowledgeable of their respective systems to assess the impact of extending station life on ORUs and other hardware. These teams are conducting in-depth, “bottom-up” reviews of ORUs and associated hardware, such as hose assemblies and tubing, to identify hardware that must be replaced before failure because the hardware’s failure could lead to loss of crew or station. According to NASA officials, the analysis is currently in progress, but preliminary results indicate that some hardware will not be affected by ISS life extension, while other hardware may require replacement or other mitigation to ensure it does not fail and

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[39] NASA’s safety assessment covers only those ORUs whose failure could result in loss of life or loss of station. These ORUs are a subset of those covered by NASA’s approach to determining spares required to ensure utilization of the ISS through 2020 discussed earlier in the report.

result in a catastrophic loss of life or station. For example, NASA's early findings show that 52 hardware items, including tubes and hose assemblies in the Internal Thermal Control System, the system that moderates temperature throughout the ISS, can be used until they fail because their failure would result only in degradation of system functions and not endanger the ISS or crew.

NASA expects to complete both the "top-down" safety and mission assurance and "bottom-up" hardware assessments by 2012. Agency officials stated that they will begin mitigation planning immediately after the completion of both assessments and continue that planning through 2015. They noted that the ISS program will implement corrective actions as mitigation plans are developed and put in place, so that some mitigation efforts will occur as early as 2012 and some after 2015. When mitigation actions are developed and in place, NASA expects to have increased assurance that the ISS can safely operate through 2020 and potentially beyond.

Conclusion

Extending the operational life of the ISS to 2020 will allow NASA and the United States to capitalize on the nearly two decades and billions of dollars invested in its construction and operation. During the time required to finish ISS construction, however, many changes occurred in the assumptions and conditions underlying NASA's initial ISS supportability strategy—the planned operational life of the ISS has extended, the space shuttle program has ended, and ORUs on the ISS are lasting longer than originally expected. In response to the changing conditions, NASA has appropriately evolved its strategy for supporting the ISS through 2020. Assessing ISS extended life necessarily requires the use of sophisticated analytical techniques and judgments. To that end, the agency has adopted reasonable approaches and methodologies for estimating the spares needed for continued operation and ensuring that the ISS structure and hardware are safe for operation through 2020 and potentially beyond. For example, NASA actively incorporates new knowledge to update estimates of MTBF for its ORUs, which provides greater efficiency in the use of resources necessary for purchasing spare parts. While this approach is sound, it is important that this process continue to evolve as the agency gains knowledge to ensure the most effective and efficient use of resources for ISS utilization through 2020. NASA has not indicated, however, that it plans to incorporate this new knowledge by revisiting the variance parameter that governs the relative weight given to on-orbit experience versus manufacturers' original reliability estimates in conducting Bayesian updates. Doing so when the appropriate amount of knowledge is obtained could allow NASA to achieve even greater efficiency in the purchase of spares. In considering these assumptions, however, NASA must balance efficiency with risk. If NASA weights on-orbit experience too heavily, it risks overstating the MTBF and potentially underestimating the number of spares needed, especially for ORUs that have not experienced a random failure. Conversely, weighing manufacturers' original estimates too heavily could result in NASA expending resources on unneeded spares. Moving forward, NASA needs to carefully balance these competing information sources based on future on-orbit experience to ensure an appropriate risk posture in the procurement of spares. The basis underlying NASA's functionality targets and goals, which are revisited annually, could also be affected by factors such as increased knowledge of performance and functionality and additional capabilities provided as new launch vehicles become available. Understanding the rationale behind NASA's functionality targets and goals is important so that as new information is gained it can be assessed to ensure that it remains valid. For example, if a particular goal was set at 98 percent due to the assumed availability of spares and those spares become unavailable, that goal may no longer be achievable and mitigations or an alternative approach would need to be devised to meet that goal. Without documentation of the rationale behind the original decision, ISS officials have limited means to assess whether the rationale remains valid and the goal is achievable.

Recommendations for Executive Action

As the ISS program accumulates additional knowledge about the on-orbit performance of ORUs, we recommend that the NASA Administrator direct the ISS program manager to revisit, as appropriate, the relative weight given to manufacturers' original reliability estimates and to the actual reliability of ORUs based on on-orbit experience by reexamining the program's choice of a value for the parameter that governs the variance of the original MTBF's probability distribution.

To ensure decision makers have a full understanding of the rationale behind ISS functionality targets and confidence levels to better inform future decisions, we recommend that the NASA administrator direct the ISS program manager to ensure these rationales are documented, at a minimum, in the minutes from meetings of the Space Station Program Control Board.

Agency Comments and Our Evaluation

In written and oral comments on a draft of this report (see app. II), NASA concurred with our recommendations. NASA acknowledged the benefit of revisiting the relative weight given to manufacturers' original reliability estimates and to the actual reliability of orbital replacement units and indicated that the ISS program office intends to reexamine these weighting values as appropriate. NASA also acknowledged that the ISS program office should document the rationale underlying the Program Manager's decisions concerning ISS functionality targets and confidence levels and indicated that the ISS Program Manager is already in the process of implementing this recommendation. Separately, NASA provided technical comments, which have been addressed in the report, as appropriate.

We are sending copies of this report to the appropriate congressional committees. We are also sending copies to NASA. This report will also be available at no charge on the GAO website at http://www.gao.gov.

Should you or your staff have any questions concerning this report, please contact me at (202) 512-4841 or chaplainc@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

Cristina T. Chaplain
Director
Acquisition and Sourcing Management

Appendix I: Scope and Methodology

We interviewed and obtained briefings and relevant documents from knowledgeable National Aeronautics and Space Administration (NASA) and contractor officials on the content and decision-making approach NASA used to prepare its assessment in response to section 503 of the NASA Authorization Act of 2010.[1] directing the agency to assess its plans for ensuring essential spares were available to support the International Space Station (ISS) through the station's planned operational life. We also reviewed the scope and methodology NASA used in the ISS assessment. We conducted our work at NASA headquarters in Washington, D.C., and NASA's Johnson Space Flight Center, in Houston, Texas.

For purposes of assessing NASA's findings and approach to estimating spares essential for ISS operation through 2020, we focused our efforts on the statistical techniques NASA used to calculate operational mean time between failure (MTBF) rates and the modeling techniques NASA uses to assess functional availability as well as NASA's process for establishing functionality targets and confidence levels for ISS functional systems. For a limited number of orbital replacement units (ORU), we recalculated the values NASA obtained for the operational MTBF based on its statistical methodology. We also conducted limited tests of the data NASA used to support the functional availability model. We discussed the ISS program's approach with NASA experts outside the ISS program at NASA headquarters. We discussed NASA's approach for ensuring data reliability and configuration control of ISS models and analytical systems with cognizant and responsible officials. We also obtained and reviewed a briefing on the results of an internal review of ISS program models and analytical systems. We limited the scope of our assessment to the scope of NASA's report, i.e., the sparing necessary to support critical functions as modeled in the ISS functional availability assessment. We did not examine the sparing or launch vehicle needs of the international partners or the sparing needs of functions not included in the ISS functional availability assessment.

For purposes of assessing NASA 's findings and approach to monitoring and assessing the structural health of the ISS, we interviewed and obtained briefings and relevant documents from knowledgeable NASA and contractor officials at the Johnson Space Center. We obtained and

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[1] Pub. L. No. 111-267.

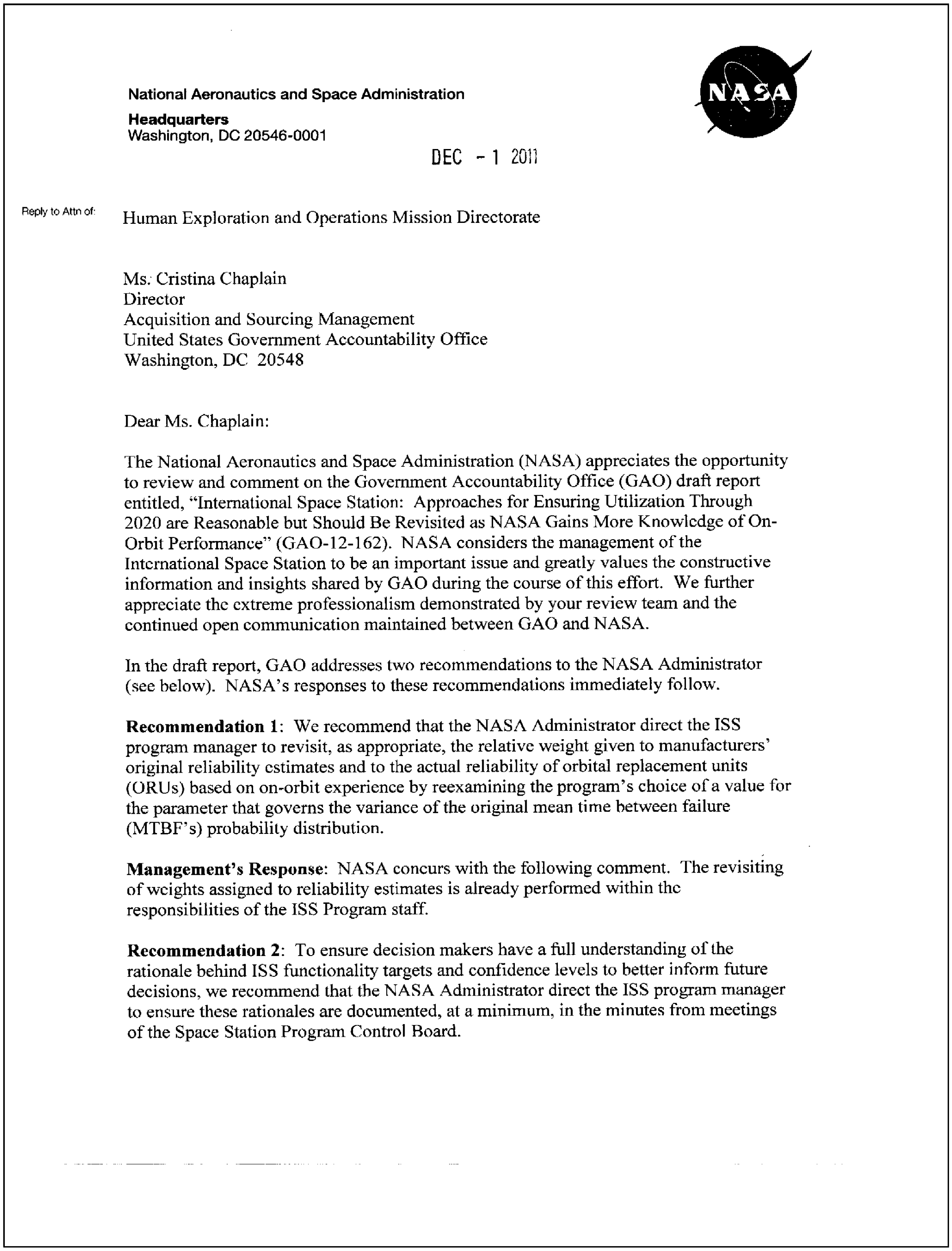
reviewed the results of NASA's past assessments of ISS primary structures to identify issues that could affect ISS operations through 2020. We obtained and reviewed Department of Defense and NASA guidance documents and determined NASA's basis for establishing four service lives as its baseline requirement for structural life. We discussed NASA's basis for establishing six service lives as the cutoff point for conducting ongoing structural health assessments with knowledgeable agency and contractor officials. Through discussions with NASA's NASGRO experts at Johnson Space Center; with NASGRO experts responsible for managing the commercial side of the NASGRO structural analysis software at Southwest Research Institute; and commercial users of NASGRO, we obtained an understanding of NASA's structural heath assessment software tools and models, how NASA uses them to support its assessments of structural health, and NASA's plan for incorporating improved software tools into future assessments. We reviewed Federal Aviation Administration and Federal Highway Administration policies guiding the inspection of aircraft and bridges and compared them to NASA's approach to measuring structural health. We identified NASA's plans to use improved software with increased knowledge of material properties and enhanced software tools to gain improved measurements of structural health. We discussed with knowledgeable NASA officials the mitigation strategies NASA is considering to address structural problems discovered by structural health assessments.

To determine the viability of NASA's findings and plans regarding transportability for and supportability of the ISS, we examined NASA's plans for transporting cargo to support the ISS through 2020 and examined ISS launch vehicle schedules from 2012 through 2020. We discussed those schedules, including launch vehicle availability, with NASA officials. We also reviewed NASA launch manifests for 2012 through 2020. We compared the launch schedules to the planned cargo manifests and determined whether planned launch vehicles would be capable of meeting ISS supportability needs. Additionally, we reviewed prior GAO reports and testimonies addressing commercial domestic launch vehicle development and NASA's management and program challenges. To evaluate the status of NASA's efforts to estimate the costs of ISS spares through 2020, we obtained documents providing information about NASA's past and predicted ISS sparing costs. We discussed these estimates with knowledgeable NASA officials to gain insight into how the cost estimates were developed and how changes in cargo needs and vehicle availability might affect the estimates.

To assess NASA's findings and plans for ensuring ISS safe operations through 2020, we interviewed and obtained briefings from NASA officials on their methodologies for assessing the safety of the ISS as a whole as well as the hardware that could affect safety of the crew or station through 2020. Specifically, we reviewed the methodology NASA is using to perform top-down safety and mission assurance assessments. We also reviewed the methodology NASA is using to perform bottom-up assessments of ISS hardware to determine if there are ISS hardware safety issues associated with extending ISS mission life. Additionally, we assessed NASA's approach to reviewing ISS safety in terms of the agency's and Johnson Space Center's internal regulations and guidance. We also discussed NASA's approach with ISS program and contractor officials. We interviewed and obtained briefings from NASA officials on the results-to-date of ISS safety and mission assurance and hardware assessments and discussed issues that could affect the safety of ISS operations through 2020 as well as NASA's plans for mitigating any such issues.

We conducted this performance audit from February 2011 to November 2011 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings based on our audit objectives.

Appendix II: Comments from the National Aeronautics and Space Administration



National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

DEC - 1 2011

Reply to Attn of: Human Exploration and Operations Mission Directorate

Ms. Cristina Chaplain
Director
Acquisition and Sourcing Management
United States Government Accountability Office
Washington, DC 20548

Dear Ms. Chaplain:

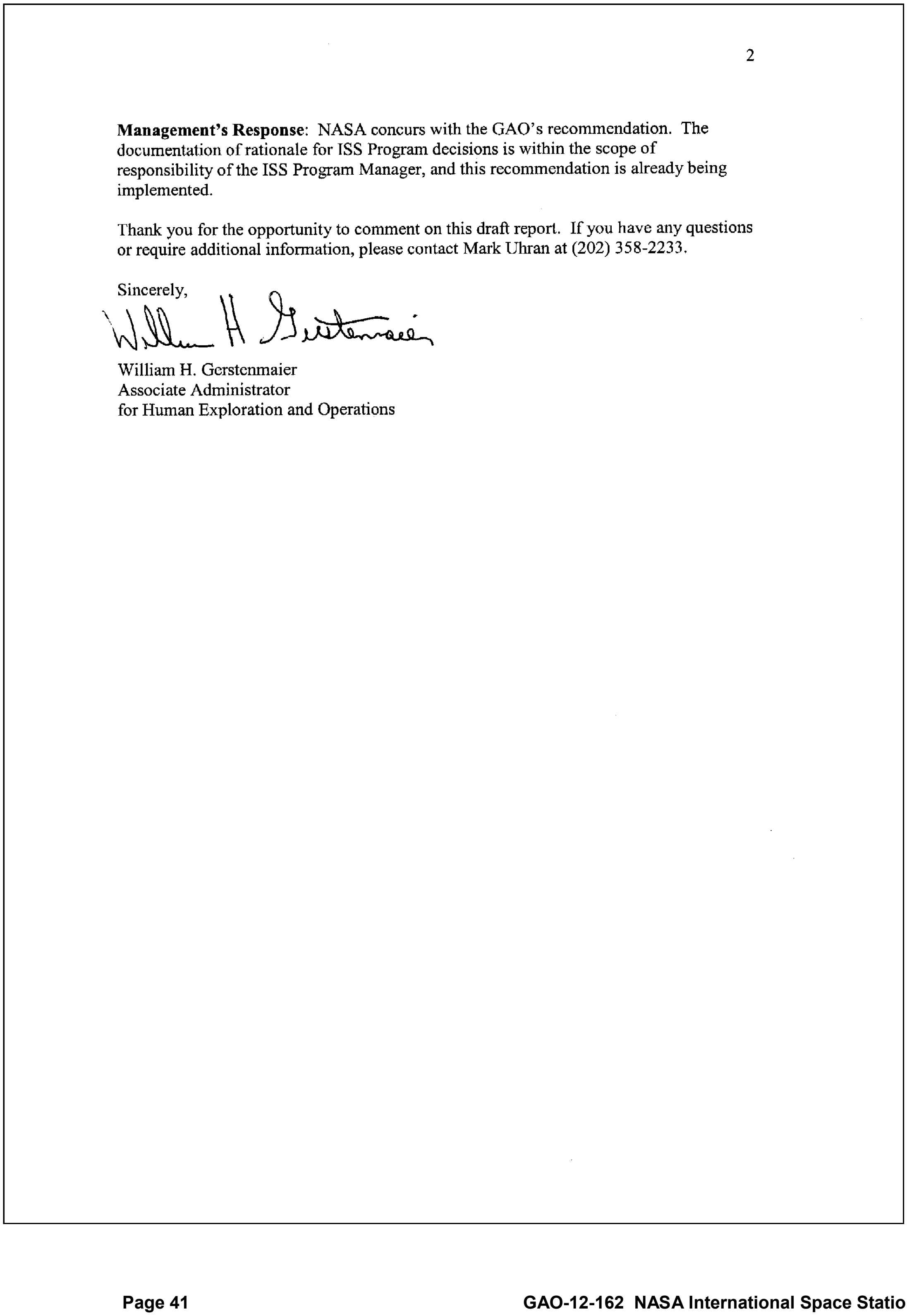
The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Government Accountability Office (GAO) draft report entitled, "International Space Station: Approaches for Ensuring Utilization Through 2020 are Reasonable but Should Be Revisited as NASA Gains More Knowledge of On-Orbit Performance" (GAO-12-162). NASA considers the management of the International Space Station to be an important issue and greatly values the constructive information and insights shared by GAO during the course of this effort. We further appreciate the extreme professionalism demonstrated by your review team and the continued open communication maintained between GAO and NASA.

In the draft report, GAO addresses two recommendations to the NASA Administrator (see below). NASA's responses to these recommendations immediately follow.

Recommendation 1: We recommend that the NASA Administrator direct the ISS program manager to revisit, as appropriate, the relative weight given to manufacturers' original reliability estimates and to the actual reliability of orbital replacement units (ORUs) based on on-orbit experience by reexamining the program's choice of a value for the parameter that governs the variance of the original mean time between failure (MTBF's) probability distribution.

Management's Response: NASA concurs with the following comment. The revisiting of weights assigned to reliability estimates is already performed within the responsibilities of the ISS Program staff.

Recommendation 2: To ensure decision makers have a full understanding of the rationale behind ISS functionality targets and confidence levels to better inform future decisions, we recommend that the NASA Administrator direct the ISS program manager to ensure these rationales are documented, at a minimum, in the minutes from meetings of the Space Station Program Control Board.



Management's Response: NASA concurs with the GAO's recommendation. The documentation of rationale for ISS Program decisions is within the scope of responsibility of the ISS Program Manager, and this recommendation is already being implemented.

Thank you for the opportunity to comment on this draft report. If you have any questions or require additional information, please contact Mark Uhran at (202) 358-2233.

Sincerely,

William H Gerstenmaier

William H. Gerstenmaier
Associate Administrator
for Human Exploration and Operations

Appendix III: GAO Contact and Staff Acknowledgments

GAO Contact

Cristina T. Chaplain, (202)512-4841 or chaplainc@gao.gov

Acknowledgments

In addition to the contact named above, Shelby S. Oakley, Assistant Director; John Warren, Analyst-in-Charge; Ana Ivelisse Aviles; Andrea Bivens; Tana Davis; Jay Tallon; Sonya Vartivarian; Laura Greifner; Roxanna Sun; and Sylvia Schatz made key contributions to this report.

(120993)

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