Impacts of Shuttle Extension

pursuant to
Section 611(e) of the NASA Authorization Act of 2008 (P.L. 110-422)

April 2009

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

This Space Shuttle extension study was conducted pursuant to direction in Section 611(e) of the NASA Authorization Act of 2008 (P.L. 110-422). The study was carried out through late 2008. As directed in Section 611(e) of P.L. 110-422, this study assesses two bounding cases for extending the Space Shuttle Program (SSP). For the purposes of this study, NASA assumed that the Constellation Program baseline schedule and Ares I/Orion initial operating capacity (IOC) were held constant.

It is important to note that Shuttle extension would require several billion dollars in additional funding above what is currently in the FY 2009 budget runout to avoid delaying IOC of the Ares I/Orion vehicle. Otherwise, the gap between the two capabilities would simply be shifted out, not shortened, delaying the development of a unique domestic capability for both ISS crew transport and rescue and exploration missions beyond low-Earth orbit.

NASA's independent Aerospace Safety Advisory Panel (ASAP) recently recommended: "From a safety standpoint, the ASAP strongly endorses the NASA position on not extending Shuttle operations beyond successful execution of the December 2008 manifest, completing the ISS. Continuing to fly the Shuttle not only would increase the risk to crews, but also could jeopardize the future U.S. Exploration program by squeezing available resources (and, in the worst case, support) for the Constellation program."

> **Bounding Case 1** would add three flights and extend the Space Shuttle through 2012. Case 1 would use the existing inventory of External Tank components but would require additional Solid Rocket Booster material and other procurements. Unless billions of dollars are added to NASA's budget, Case 1 would extend the transition time between Space Shuttle retirement and Constellation’s initial operations because the funding for the extension would need to come from Constellation and the funding reductions would greatly slow Constellation development. This case would require that the Shuttle production workforce work for two years longer than is currently planned In addition, Case 1 would require that approximately $4.7 billion be added to the NASA budget or redirected to the Shuttle from other NASA programs through FY 2012. This estimate includes all costs associated with adding three flights and flying through 2012, and assumes no significant schedule slips within the Shuttle manifest and no changes to the existing (2015 IOC) Constellation baseline. The cost estimate includes all costs associated with maintaining production, sustaining engineering, and critical workforce skills needed to safely fly out this scenario. Again, these additional costs are not included in the NASA budget.
>
> **Bounding Case 2** would maintain a capability to fly three missions per year through 2015, or a total of 13 beyond 2010. This capability, along with international partner transportation capabilities, would be available to support the ISS, either through the baseline planned Orion IOC in 2015 or earlier if a crew transport capability supplied by a private U.S. commercial enterprise were viable before 2015. Case 2 could only potentially eliminate the interval between Space Shuttle and Constellation operations if about $14 billion were added to NASA's budget through FY 2015. Extending Space Shuttle operations to 2015 would introduce serious challenges to the existing schedule for the Constellation Program’s Ares V lunar capability and might not allow for any “retooling” period between the last flight of Shuttle and the first flight of Ares I/Orion. However, Case 2 would preserve the facilities, workforce, and infrastructure for a heavy lift capability. NASA does not believe Space Shuttle operations can be extended this long without severe budget and operational impacts that would effectively postpone Constellation development indefinitely. The $14 billion cost estimate for Case 2 includes all costs associated with flying through 2015, and assumes no changes to the existing (2015 IOC) Constellation Program baseline. The cost estimate includes all costs associated with maintaining production, sustaining

engineering, and critical workforce skills needed to safely fly out this scenario. These additional costs are not included in the NASA budget.

Table 1: Summary of Costs, Space Shuttle Baseline and Extensions Cases ($ billion)

NOTE: real year dollars; excludes civil servant salaries, travel, defense contract management services, other contract administration, transition and retirement, and severance and retention; totals may not add due to rounding.

	ACTUALS									FY09 – FY15	
	FY06	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**TOTALS**	**DELTAS** compared to baseline
Baseline	3.3	3.2	3.1	2.9	2.2	0.1	-	-	-	-	**5.1**	-
Case 1	3.3	3.2	3.1	2.9	2.9	2.1	1.9	0.1	-	-	**9.9**	**4.7**
Case 2	3.3	3.2	3.1	2.9	3.2	2.6	2.7	2.7	2.6	2.3	**19.1**	**14.0**

Table 2: Summary of Flight Rates, Space Shuttle Baseline and Extension Cases

	FY09	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**TOTALS FY09 – FY15**
Baseline	5	5	-	-	-	-	-	**10**
Case 1	5	4	3	1	-	-	-	**13**
Case 2	5	3	3	3	3	3	3	**23**

NASA assessed the impacts of both extension cases on the ISS and Constellation baseline programs. If $4.7 billion in additional funds were provided, Case 1 had only minor negative impacts on planned Constellation baseline milestones, which NASA believes could be mitigated. If $4.7 billion is not added to the budget and instead had to come out of Constellation, Case 1 would have major negative impacts on the program. Case 1 benefited ISS by providing three additional missions to the ISS and additional crew rotation, although it did not reduce the need for the purchase of Russian Soyuz vehicles for crew rescue purposes. Case 2 had more significant impacts on planned Constellation milestones independent of additional funding from other parts of NASA. In particular, flying the Space Shuttle beyond 2012 would delay handover of some facilities critical to the Ares V program including areas of the Michoud Assembly Facility (MAF) where the Space Shuttle's External Tanks are constructed; Pad A at the Kennedy Space Center (KSC) launch complex, which Constellation plans to reconfigure for Ares V; and the A2 test stand at the Stennis Space Center, which Constellation plans to use for J-2X engine development.

The Space Shuttle provides unique capabilities in support of the ISS program. From an ISS perspective, extending Space Shuttle operations would provide some additional (but currently unfunded) opportunities for increased utilization, while at the same time mitigating some of ISS' operational risks. The Space Shuttle's large carrying capacity (with a cargo bay measuring 15 x 60 feet and capable of carrying approximately 35,000 pounds to the ISS) means that it can deliver payloads that no currently available vehicle in either the U.S. or international partner inventory can deliver. Extending the Space Shuttle beyond the current manifest would create more opportunities for flying experiments within the large pressurized Multi-Purpose Logistics Modules (MPLM), or carrying oversized research payloads or additional pressurized and unpressurized elements. It is important to note, however, that none of this research is currently funded.

The Shuttle is also currently unique in being able to return large, failed orbital replacement units (ORU) to Earth for detailed failure analysis. Overall, ISS hardware continues to perform well on orbit, and NASA is pre-positioning hardware and supplies on the ISS with Space Shuttle before 2010. If Station operations continue past 2015 and no new capability to return ORUs emerges, additional Shuttle flights beyond 2010 could be used to fly these ORUs and therefore reduce overall operational risk to the ISS program. Extending Shuttle operations, however, is no substitute for commercial providers of primary cargo and (eventually) crew transportation capabilities to the ISS once these capabilities are available.

Given the fact that Space Shuttle and Constellation draw upon a largely common pool of workforce skills, production capabilities, operational facilities, and budget resources, efforts to extend either Space Shuttle or accelerate Constellation would likely impact, to some extent, capabilities that are critical to the success of the other (though some of these impacts can be mitigated through additional coordination). Additional analysis would be required to fully identify the mutual dependencies, key decision points, shared resource strategies, and cost impacts of a strategy that incorporated elements of both extension and acceleration. Ultimately, however, available budget resources essentially compel a cessation in operations between the Space Shuttle and Constellation, as reflected in current national space exploration policy.

II. BACKGROUND

Section 611(e) of the NASA Authorization Act of 2008 (P.L. 110-422) directs that NASA submit to the Congress a report on the potential costs and impacts of extending Space Shuttle operations beyond the end of FY 2010. Section 611(e) reads as follows:

> *(e) REPORT ON IMPACTS OF SPACE SHUTTLE EXTENSION.—Within 120 days after the date of enactment of this Act, the Administrator shall provide a report to the Congress outlining options, impacts, and associated costs of ensuring the safe and effective operation of the Space Shuttle at the minimum rate necessary to support International Space Station operations and resupply, including for both a near-term, 1-to-2 year extension of Space Shuttle operations and for a longer term, 3-to-6 year extension. The report shall include an assessment of—*
>
> *(1) annual fixed and marginal costs, including identification and cost impacts of options for cost-sharing with the Constellation program and including the impact of those cost-sharing options on the Constellation program;*
>
> *(2) the safety of continuing the use of the Space Shuttle beyond 2010, including a probability risk assessment of a catastrophic accident before completion of the extended Space Shuttle flight program, the underlying assumptions used in calculating that probability, and comparing the associated safety risks with those of other existing and planned human-rated launch systems, including the Soyuz and Constellation vehicles;*
>
> *(3) a description of the activities and an estimate of the associated costs that would be needed to maintain or improve Space Shuttle safety throughout the periods described in the first sentence of this subsection were the President inaugurated on January 20, 2009, to extend Space Shuttle operations beyond 2010, the correctly anticipated date of Space Shuttle retirement;*
>
> *(4) the impacts on facilities, workforce, and resources for the Constellation program and on the cost and schedule of that program;*
>
> *(5) assumptions regarding workforce, skill mix, launch and processing infrastructure, training, ground support, orbiter maintenance and vehicle utilization, and other relevant factors, as appropriate, used in deriving the cost and schedule estimates for the options studied;*

(6) the extent to which program management, processes, and workforce and contractor assignments can be integrated and streamlined for maximum efficiency to support continued shuttle flights while transitioning to the Constellation program, including identification of associated cost impacts on both the Space Shuttle and the Constellation program;
(7) the impact of a Space Shuttle flight program extension on the United States' dependence on Russia for International Space Station crew rescue services; and
(8) the potential for enhancements of International Space Station research, logistics, and maintenance capabilities resulting from extended Shuttle flight operations and the costs associated with implementing any such enhancements.

III. EXTENSION BOUNDING CASES

Overview

Both Case 1 and Case 2 would fly the current manifest, as scheduled, through STS-128 (17A), currently scheduled to launch August 2009. Maintaining the near-term manifest through these flights would stabilize ISS crew rotations on Space Shuttle. ISS missions 19A and ULF 4 would fly in the same general time period as shown on the current manifest to support ISS logistics for a six-person crew. Pursuing Case 1 would foreclose the possibility of additional flights beyond 2012 without significant additional cost and technical risk due to the closure of flight hardware production contracts no longer needed to complete hardware already in production. Case 2 would preserve the capability to fly beyond 2012 to no later than 2015, if required. In either case, several billion dollars would need to be added to the NASA budget or redirected from other areas within the NASA budget. This section addresses the manifest for each case and the major and minor challenges associated with each case, in terms of technical issues, procurement issues, and impacts to the Constellation Program. It also provides a summary cost profile for the two bounding cases.

A. Bounding Case 1: Extension through 2012

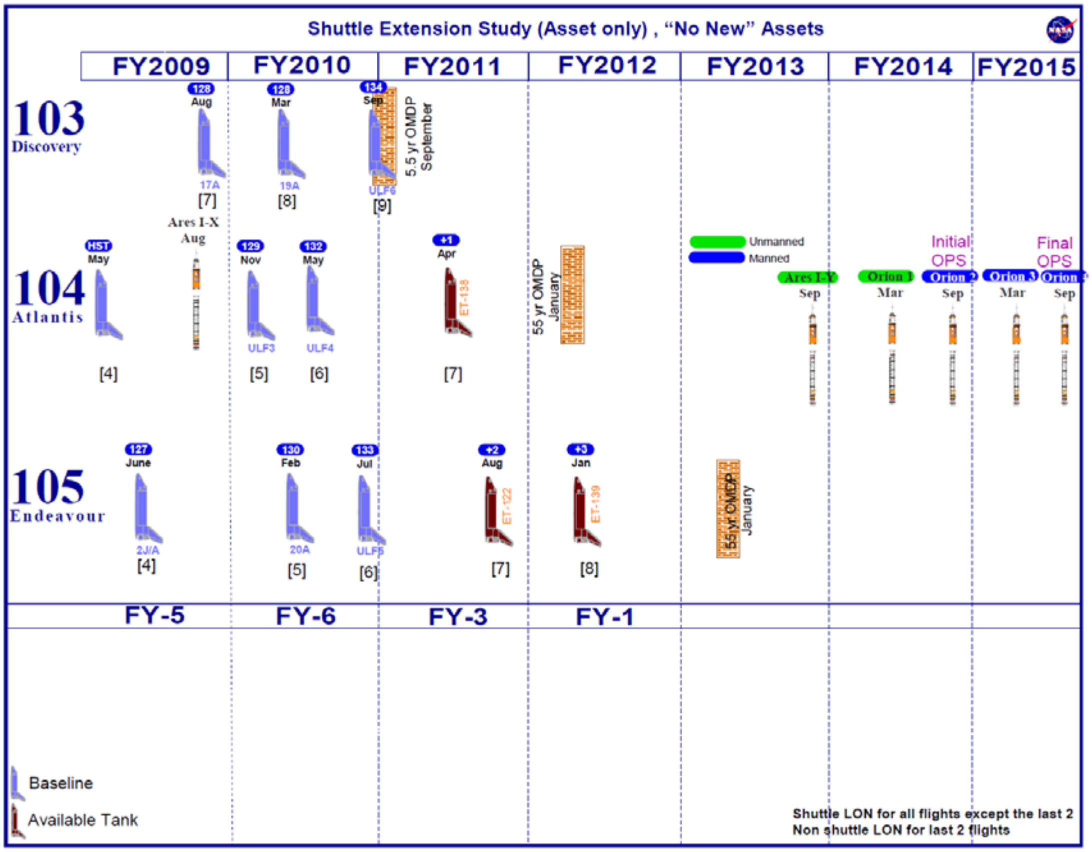
Flying all remaining production assets to execute Case 1 and extending through 2012 would require approximately $4.7 billion of NASA's budget through 2013.

1. Manifest

Case 1 would require no new External Tank production through 2012. It would require an extension to the Orbiter Maintenance Down Period (OMDP) 5.5 year interval requirement for *Atlantis*/OV-104; *Discovery*/OV-103 and *Endeavour*/OV-105 have sufficient margin to fly out the manifest through 2012. The Case 1 manifest rephases some flights from the current manifest as shown below.

Figure 1: Shuttle Extension Case

NOTE: planning manifest as of April 2009



2. *SSP Costs*

Table 3: Summary of Costs, Space Shuttle Baseline and Case 1 ($ billions)

NOTE: real year dollars; excludes civil servant salaries, travel, defense contract administration services, other contract administration, transition and retirement, and severance and retention; totals may not add due to rounding.

	ACTUALS										
	FY06	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**TOTALS FY09 – FY15**
Baseline	3.3	3.2	3.1	2.9	2.2	0.1	-	-	-	-	**5.2**
Case 1	3.3	3.2	3.1	2.9	2.9	2.1	1.9	0.1	-	-	**9.9**
DELTAS	-	-	-	-	**+ 0.7**	**+ 2.0**	**+ 1.9**	**+ 0.1**	-	-	**4.7**

These estimates are based on a NASA determination that it could reduce the SSP annual budget requirement compared to annual current baseline costs. SSP's estimated out-year costs beyond 2010 were reduced from the current annual baseline because it assumed several sources of cost savings beyond 2010, including increased synergy between the Shuttle, ISS and Constellation programs; funding only marginal costs on institutional capabilities (since costs for sustaining institutional capabilities are already assumed in the Constellation Program baseline); a reduction in the planned flight rate; and increases in production efficiency. These estimates of cost savings are preliminary.

In addition, this estimate does not include costs associated with supporting any expanded research opportunities that might be created by additional Shuttle flights, nor does it necessarily capture either all potential cost synergies or cost impacts to Constellation associated with Space Shuttle extension. The cost estimate also does not include the costs for Shuttle retirement, which are assumed to move to the two years following completion of the SSP; the Program assumed that retirement and transition costs would be deferred commensurate with the extension at approximately the same cost as estimated for retirement in 2010, plus an escalation of 3.5 percent per year. The band of uncertainty for this estimate is approximately 10 percent, based on actual historic costs, known risks, and opportunities.

3. Challenges

There will need to be cessation in operations between the Space Shuttle and Constellation. This operational reconfiguration period is necessary to allow time to prepare for the next phase of space exploration. Facilities that are needed for both Space Shuttle and Constellation operations need to be modified, key workforce needs to be retrained on Constellation systems (ideally while their Space Shuttle operations experience is fresh), and Constellation production and operations processes need to be exercised. For these reasons, NASA estimates that a minimum of approximately 18–24 months of reconfiguration time is needed to enable an orderly transition from Space Shuttle to Constellation operations while minimizing disruptions to the workforce with critical skills.

NASA identified issues that presented major and minor obstacles to achieving the proposed Space Shuttle manifest cases, ISS key milestones, and Constellation key milestones. *Major issues* are those that need considerable program attention or funding to resolve that is outside the span of control for the program. If not adequately resolved, these issues could prevent NASA from executing its programs as proposed. *Minor issues* are those for which mitigation currently exists or that can be resolved with a minimum of additional work or funding.

a. Major Issues

The following major issues were identified for Case 1:

Space Shuttle Program (SSP)

The additional funding required within the NASA budget for implementation of Case 1 would likely adversely affect Constellation or other NASA programs.

b. Minor Issues

The following minor issues were identified for Case 1:

Orbiter Project. In its 2003 report, the *Columbia* Accident Investigation Board (CAIB) recommended that, if NASA chose to fly Shuttle Orbiters beyond 2010, the Agency should develop and conduct a vehicle certification at the material, component, subsystem, and system levels to determine if Orbiter hardware was being processed and operated within qualification and certification limitations. The Space Shuttle program performed a review of the vehicle certification and the certification verification assessments during return to flight (RTF) to assure the vehicles could fly through 2010. At the time of this initial review, NASA Shuttle managers decided that a complete vehicle recertification would not be necessary to fly past 2010; however, under the Case 1 scenario, NASA would need to reassess the certification packages and material review of the critical components on the Orbiter to ensure there were no time and cycle or material age-related issues or other potential safety considerations. NASA would also ensure that the vehicle continues to operate within the constraints and requirements defined by its current certification. Required inspections and testing during vehicle processing would provide opportunities to constantly monitor the health of Orbiter systems and to mitigate any performance degradation before it could become a safety of flight concern. Finally, the Orbiter Project would need to retain certain critical skills at the White Sands Test Facility (WSTF) (thruster and Orbital Maneuvering System pod testing), Palmdale (coldplate), and Lockheed Martin (wing leading-edge reinforced carbon-carbon panels). The Orbiter Project would also need to retain the WSTF, Palmdale, and NASA Shuttle Logistics Depot (NSLD) facilities.

Orion Docking Hardware. If the Shuttle Program were extended beyond 2010, Orbiter-ISS docking hardware, the Androgynous Peripheral Assembly System (APAS), would not be available for handover to the Orion Project in January 2010. This would delay the development of the Orion ISS docking system. To address this delay, the Orion Project would likely re-evaluate a previously studied alternate to develop the docking system using a common berthing mechanism instead of the Shuttle APAS interface. Potential delivery of this docking adapter to ISS by the Shuttle might also be evaluated.

Civil Servant Workforce. The Constellation Program is anticipating that, as Shuttle retires, SSP civil servant workforce will transfer to Constellation to support exploration. Extending the Shuttle would alter the profile of this workforce transfer. NASA engineering and operations teams currently support both programs, so NASA anticipates that there would continue to be significant synergies between the two programs that would mitigate this risk.

4. Potential Benefits

Extending SSP could provide ancillary benefits for the ISS and Constellation programs, assuming that the $4.7 billion needed to extend SSP aren't taken from those programs. The Space Shuttle provides upmass capability to the ISS and the only significant downmass capability from the Station. This downmass capability could enable the U.S. to expand science and basic research aboard the Station and to support future exploration. Until replacement crew and heavy-lift capabilities are available, the Space Shuttle is also the only vehicle that can, if necessary, carry out some ISS repairs and large component replacements in the event they are necessary, although NASA is pre-positioning spares on the Space Station prior to 2010 retirement to mitigate this need. Because the Space Shuttle can provide ISS crew rotation, extension might also provide the U.S. with greater flexibility in negotiating with Russia for Soyuz purchases; however, the U.S. would still require the Russian Soyuz to provide emergency crew return from ISS. The additional Space Shuttle missions could potentially benefit the Constellation Program by providing a limited opportunity to use the Shuttle as a platform for testing the Constellation Program hardware, software, and new operational principles in the combined environments of space.

5. Risk

The latest Space Shuttle probabilistic risk assessment (PRA) indicates that the single mission risk for loss of crew and vehicle (LOCV) is 1 in 77; stated another way, there is a 98.7 percent probability of safely executing each flight. NASA has conducted a number of PRAs for the Space Shuttle since 1987, and the average risk of LOCV has remained fairly consistent over that time. This risk is predicted to remain consistent over the remaining life of the program. The primary drivers for LOCV are, in order of the magnitude of their contribution to the overall risk: micro-meteoroid/orbital debris (MMOD), ascent debris, and Space Shuttle Main Engine (SSME) malfunctions.

In addition, NASA will continue to evolve its PRA tools to address anomalies encountered during flight operations. By monitoring anomaly trends across different categories (for example, by whether an anomaly is due to design issues, age, operations or procedurally-induced effects, or unknown or random phenomena), NASA gains both near-term insights into Space Shuttle performance opportunities for potential safety improvements during ongoing operations as well as longer-term benefit in applying experience-based risk models to future programs like Constellation.

For Case 1, flying 12 missions would result in a higher cumulative risk of catastrophic failure due to more flights, when compared to the current nine mission baseline. The Shuttle PRA calculates the probability of LOCV during a nominal mission to be between 1 in 45 and 1 in 130 per mission with 90 percent confidence. This number contains many assumptions, however; for more information on Space Shuttle risk assessment, please see the Appendix starting on page 21.

The option of flying 12 total missions over 4-year period (an average flight rate of 3.25 per year) would likely pose a low schedule risk since most of the hardware is already in production. For this case, NASA would continue to pursue improvements to the Space Shuttle system to eliminate risk and improve the single mission risk as much as possible, although this would require additional funding.

It is important to note that PRAs are most effective when used: 1) to gauge relative risk between systems, rather that create an absolute risk number for a particular system; and 2) to generate a range of risk, rather than a single-point, "mean" number that can promote an overly simplistic (and thus, incomplete) understanding of the risk of using a system. In addition, in the case of extending Shuttle operations, PRAs would have to be adjusted to account for incremental safety improvements to the vehicle, as well as the effects of age on the Shuttle's various subsystems.

For more information, please see the Risk Assessment Overview in the Appendix beginning on page 21.

6. Safety Enhancements

NASA's safety and mission assurance strategy emphasizes the need for rigorous program and independent safety reviews, as well as continual safety improvements throughout a program's life cycle. Improvements to both processes and hardware are made for each Space Shuttle flight, and NASA will continue to invest in prudent safety enhancements through the last mission. Recently, these have included analyses of composite overwrap pressure vessels, thermal protection systems, and structural components from Space Shuttle *Columbia*. These analyses provide NASA engineers with insight into the performance of Space Shuttle systems under extreme conditions and performance data on flight systems which are normally inaccessible during regular and major maintenance processing flows. In addition, instrumentation that was recently added to the Space Shuttle Solid Rocket Motors and crew cabin as part of the Constellation Program's development activity has provided useful data to help refine existing Space Shuttle engineering models.

A number of other safety investment opportunities were identified by the *Columbia* Crew Survival Investigation Report, which evaluated what, if any, additional safety measures could be implemented to enhance survivability in the event of a mishap. SSP has already implemented several safety and survivability recommendations, including installing improved inertial reels on the crew restraint straps and providing an upgraded crew survival radio with GPS tracking. NASA is evaluating several other enhancements that could be implemented before 2010, including a GPS personal locator beacon; improved seatbelts and retention straps; increased head and neck protection; and improved supplemental oxygen. If Shuttle were extended beyond 2010, several other safety improvements would be assessed for implementation. These include conformal crew helmets; battery powered intercoms; automatic parachute deployment; and automatic helmet visor closure during depressurization. NASA's cost estimates for Space Shuttle extension include approximately $20M per year, starting in FY 2010, to continually evaluate and implement these and other potential Shuttle safety enhancements. SSP would also work closely with the Orion Project to identify opportunities to use the Space Shuttle as a testbed to evaluate safety enhancements to Orion seats and crew equipment.

B. Bounding Case 2: Extension through 2015

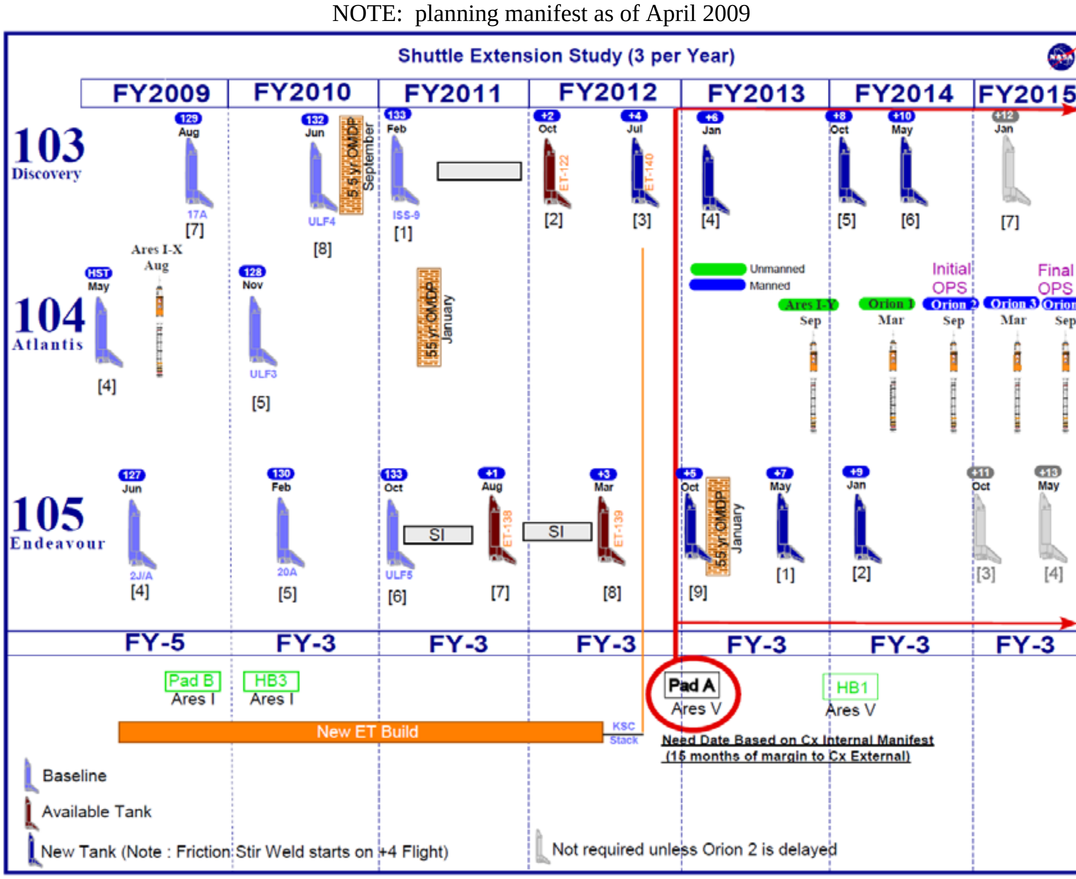
Case 2 would preserve the capability to extend the Space Shuttle manifest through 2015 or until the availability of either a U.S. commercial capability or an operational Constellation Program vehicle. Flying the Shuttle to execute Case 2 would require approximately $14 billion though FY 2015 that is not in NASA's budget.

1. Manifest

The Case 2 manifest would be based on 5 flights in FY 2009 and then 3 flights per year beginning in 2010, with the ability to extend through 2015. In this extension case, NASA would retire *Atlantis*/OV-104 in 2011 and fly the remainder of the manifest with two orbiters. There is one major conflict in this manifest (circled in red in the figure below): handover of Pad A to the Constellation Program for Ares V modifications in support of Lunar Exploration missions is currently scheduled to occur in 2012, but would be delayed until after the Shuttle stops flying. The need dates shown for lunar development, including Pad A, are based on the Constellation Program's internal manifest and reflect 15 months of schedule margin.

Figure 2: Shuttle Extension Case 2

NOTE: planning manifest as of April 2009



2. SSP Costs

Table 4: Summary of Costs, Space Shuttle Baseline and Case 2 ($ billions)

NOTE: real year dollars; excludes civil servant salaries, travel, defense contract administration services, other contract administration, transition and retirement, and severance and retention; totals may not add due to rounding.

	ACTUALS										
	FY06	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**TOTALS FY09 – FY15**
Baseline	3.3	3.2	3.1	2.9	2.2	0.1	-	-	-	-	**5.2**
Case 2	3.3	3.2	3.1	2.9	3.2	2.6	2.7	2.7	2.6	2.3	**19.1**
DELTAS	**-**	**-**	**-**	**-**	**+ 1.0**	**+ 2.5**	**+ 2.7**	**+ 2.7**	**+2.6**	**+2.3**	**14.0**

In constant year dollars, the Space Shuttle operations baseline budget would go from $2.9 billion for 5 flights per year in FY 2009 to $2.3 billion in Case 2 for 3 flights in FY 2015, while maintaining core capabilities in flight support and vehicle processing. These estimates are based on a NASA determination that it could reduce the SSP annual budget requirement compared to annual current baseline costs. SSP's estimated out-year costs beyond 2010 were reduced from the current annual baseline because NASA assumed several sources of cost savings beyond 2010 including increased synergy among the NASA human spaceflight programs; funding only marginal costs on institutional capabilities; a reduction in the planned flight rate; and increases in production efficiency. These estimates of cost savings are preliminary.

In addition, this estimate does not include costs associated with supporting any expanded research opportunities that might be created by additional Shuttle flights, nor does it necessarily capture either all potential cost synergies or cost impacts to Constellation associated with Space Shuttle extension. The cost estimate also does not include the costs for Shuttle retirement, which are assumed to move to the two years following completion of the SSP; the Program assumed that retirement and transition costs would be deferred commensurate with the extension at approximately the same cost as estimated for retirement in 2010, plus an escalation of 3.5 percent per year. The band of uncertainty for this estimate is approximately 10 percent, based on actual historic costs, known risks, and opportunities.

3. Challenges

There will need to be cessation in operations between the Space Shuttle and Constellation. This operational reconfiguration period is necessary to allow time to prepare for the next phase of space exploration. Facilities that are needed for both Space Shuttle and Constellation operations need to be modified, key workforce needs to be retrained on Constellation systems (ideally while their Space Shuttle operations experience is fresh), and Constellation production and operations processes need to be exercised. For these reasons, NASA estimates that approximately 18–36 months of reconfiguration time would allow for an orderly transition from Space Shuttle to Constellation operations while minimizing disruptions to the workforce with critical skills.

NASA identified issues that presented major and minor obstacles to achieving this proposed manifest or to the ISS or Constellation Program key milestones. *Major issues* are those that need considerable program attention or funding to resolve that is outside the span of control for the program. If not adequately resolved, these issues could prevent NASA from executing its programs as planned. *Minor issues* are those for which mitigation currently exists or that can be resolved with a minimum of additional work or funding.

a. Major Issues

Major Impacts to Other Programs. Significant budget resources from other NASA programs, including Constellation, would be required for implementation of Case 2.

Ares V Project. Flying the Space Shuttle to 2015 would significantly delay handover of facilities critical to the current schedule for the Ares V program. These delays would include:

- 18-25 months for transfer of areas of MAF where the Space Shuttle's External Tanks and Ares V segments would be constructed;
- 24-36 months in the turnover of Pad A at the Kennedy Space Center launch complex, which Constellation plans to reconfigure for Ares V; and,
- 15-16 months in handover of the A2 test stand at the Stennis Space Center, which Constellation plans to use for J-2X engine development. NASA could pursue mitigation strategies for all of these schedule conflicts, some of which are discussed in greater detail below.

External Tank (ET) Project. There would be significant conflicts between ET extension and Ares I Upper Stage floor space requirements. Continued ET manufacturing would cause the Upper Stage Project to reevaluate their manufacturing plans and potentially move some or all of their manufacturing to an alternate location at MAF, which would impact Ares costs. Mitigation plans are in work among ET project, MAF Integration and Operations, and the Ares I Upper Stage Project. Finally, ET production would cause impacts to MAF facility reconfiguration and development of Ares V by as much as 18-25 months. As the Ares V vehicle definition matures, there would be opportunities to explore means for reducing the impact to Ares V work.

KSC Ground Operations Project. Without mitigation, Ground Operations could not maintain a 2017 Operational Readiness Date for Ares V. Extending SSP to 2015 would cause a 2-3 year impact to the Constellation Program need date of 2012 for Ares V launch pad A modifications unless the program could share Pad B between Ares I and Shuttle. A mitigation study for joint Shuttle and Ares/Orion use of Pad B is underway.

Vehicle Assembly Building (VAB) High Bay 3 Handover. Under certain acceleration scenarios, the Constellation Program might require VAB High Bay 3 as early as July 2009. This would add significant risk to completing both the Space Shuttle's current manifest and any potential extension, but NASA believes these conflicts could be resolved with some additional work.

Space Shuttle Main Engine (SSME) Project. Extending flights beyond 2010 could slip the J-2X development schedule 15-16 months by delaying handover of the A2 test stand. Some Constellation acceleration scenarios currently need the test stand as early as July 2009. SSME has identified some alternate approaches that could mitigate this schedule impact, including building an adaptor for the A1 test stand, reevaluating the Deviation Approval Request for each turbopump relative to its life limits, and substantially modifying other test facilities for use by either J-2X or SSMEs.

b. Minor Issues

Manifest supportability. Historically, the Space Shuttle program has encountered unexpected technical issues that require the program to assess and address. Based on the Space Shuttle's flight history, NASA believes that the planned three-flight per year manifest is sufficiently spaced to allow most issues to be addressed without significant impacts to the manifest—the Shuttle program flew at double this rate for many years. Additionally, individual orbiters sometimes require repairs that take them out of flight status for extended periods. After *Atlantis*/OV-104 retires in 2010, SSP will have less flexibility to shift missions among Orbiters to maintain the planned manifest. However, this risk is somewhat mitigated by the ability to use the retired *Atlantis*/ OV-104 to provide spares for the other Orbiters.

KSC Ground Operations. There are conflicts between the SSP and Constellation requirements for the following KSC facilities, equipment, and materials: Recovery Hangar; recovery ships; Rotational Processing and Storage Facility (RPSF) build up stands and surge facilities; Launch Control Center (LCC) use for tests and launches; Assembly Refurbishment Facility and Parachute Refurbishment Facility space; shared handling equipment; warehouse space; commodities including gaseous helium and gaseous nitrogen; crawler way use and modification; and range safety requirements. These conflicts would require further coordination.

External Tank (ET) project. ET would require additional funding in FY 2010 to preserve the ability to support Case 2. This would include costs for skill retention, procurement of parts to support ET manufacturing need dates, and development and certification of Self-Reacting Friction Stir Welding (SRFSW) to allow ET relocation in MAF building 103. No funds are in NASA's budget to support this work.

Orbiter project. Orbiter would require a series of early decisions to maintain the option to extend flights through 2015. At the time of this initial review, NASA Shuttle managers decided that a complete vehicle recertification would not be necessary to fly past 2010; however, under the Case 2 scenario, NASA would need to reassess the certification packages and material review of the critical components on the Orbiter to ensure there were no time and cycle or material age-related issues or other potential safety considerations. NASA would also ensure that the vehicle continues to operate within the constraints and requirements defined by its current certification. Required inspections and testing during vehicle processing would provide opportunities to constantly monitor the health of Orbiter systems and to mitigate any performance degradation before it could become a safety of flight concern. Specifically, Orbiter would need to restart or recertify vendors providing payload bay floodlights, Felt Reusable Surface Insulation (FRSI) and Strain Isolation Pad material, and Fuel Cell Plating. Orbiter would need to make additional purchases for windows, tires, emittance primer coating, RTV 560 and RTV 566, Emergency Egress Slide, Fasteners, Flash Evaporator System Controllers, STA-54 for TPS repair kits, SSME Interface Seals, Waste Collection system Parts, Thruster Piece Parts, Transducers, Water Spray Boiler Controllers, Lithium Hydroxide Bags, and many low value spares. There are currently no issues identified with these restarts or recertifications. Finally, the Orbiter Project would need to retain certain critical skills at the White Sands Test Facility (WSTF) (thruster and OMS pod testing), Palmdale (coldplate), and Lockheed Martin (wing leading-edge reinforced carbon-carbon panels). The Orbiter Project would also need to retain the WSTF, Palmdale, and NASA Shuttle Logistics Depot (NSLD) facilities No funds are in NASA's budget to support this work

RSRB-Booster. RSRB-Booster would anticipate minor issues with attrition of inventories of Safe & Arm devices and Fuel Isolation Valves. No funds are in NASA's budget to resolve these issues.

RSRB-Motor. RSRB-Motor would need to adjust motor production planning to accommodate Case 2. Long lead material procurements would be required for some currently stockpiled items. Ninety percent of the materials procured for RSRB could be transferred to Ares if the motors were not produced. The production of Chrysotile/Asbestos insulation is scheduled to end in December 2010; continued production would require new indemnification agreements between NASA and the vendor or the qualification of a replacement material. Finally, RSRB-Motor would need to spend $23 million that is not in the budget in FY 2009 for skills retention to support Case 2.

Civil Servant Workforce. Constellation is anticipating that as Shuttle retires, key elements of the SSP workforce will transfer to Constellation to support exploration. Extending Shuttle would alter the profile of this workforce transfer. NASA engineering and operations teams currently support both programs, so NASA anticipates that there would continue to be significant synergies between the two programs that will mitigate this risk.

Orion Project Impacts due to Shuttle Extension. The Constellation Program currently plans to use some Space Shuttle hardware assets as the Shuttle operations draw down. This includes items such as Thermal Protection Systems (TPS) materials, Orbital Maneuvering Systems engines, docking adapters, and various test facility avionics equipment boxes. Extension would delay the transfer of these assets to support Orion systems development. Removal of a vehicle from flight status to use for spares might help mitigate some of these concerns. To address a delay in the delivery of docking adaptors, the Orion Project would likely re-evaluate a previously studied alternate to develop the docking system using a common berthing mechanism instead of the Shuttle APAS interface. Potential delivery of this docking adapter to ISS by the Space Shuttle would need to be evaluated further.

4. Potential Benefits

Case 2 is provided as a bounding case, but carries significant resource risks to the Constellation Program. For the ISS program, extending Space Shuttle could allow the U.S. to expand science and basic research aboard the station and to support future exploration although funds for expanded ISS research are not currently in NASA's budget. Because the Space Shuttle can provide ISS crew rotation, extension might also provide the U.S. with greater flexibility in negotiating with Russia for Soyuz purchases for crew rescue, which will still be necessary. The Space Shuttle would also provide heavy lift capability to accomplish ISS repairs and large component replacements in the event they are necessary, although NASA is pre-positioning spares on the Space Station prior to 2010 retirement to mitigate this need. Finally, ISS might realize cost savings based on sharing facilities, and would also be able to meet the manifest with only two Multi-Purpose Logistics Modules (MPLM) and avoid having to refurbish the third. Case 2 would preserve the facilities, key workforce, and infrastructure for this heavy lift capability should it be needed, but this would come at the cost of other NASA programs that would likely need to be cut to find the $14 billion needed to extend the Shuttle. Finally, although there are significant schedule and budget challenges, there would be the potential for significant costs savings that could be realized through concurrent Space Shuttle and Constellation operations. These savings could include consolidation of some contracts, more favorable rates for contractors that work with more than one program, and the opportunity to share civil service labor among the three programs. These estimates of cost savings are preliminary, and would need to be further refined through continued coordination between SSP and the Constellation Program if approval to proceed is authorized.

5. Risk

As was true of Case 1, in Case 2, Space Shuttle missions might be extended beyond 2010 without an increase in the single mission risk of flight. The latest Space Shuttle PRA indicates that the single mission risk for LOCV is 1 in 77; stated another way, there is a 98.7 percent probability of safely executing each flight. NASA has conducted a number of PRAs for the Space Shuttle since 1987 and the average risk of LOCV has remained fairly consistent over that time. This risk is predicted to remain consistent over the remaining life of the program. The primary drivers for LOCV are, in order of the magnitude of their contribution to the overall risk: micro-meteoroid/orbital debris (MMOD), ascent debris, and SSME malfunctions.

In addition, NASA will continue to evolve our PRA tools to address anomalies that we encounter during flight operations. By monitoring anomaly trends across different categories (for example, by whether an anomaly is due to a design issues, age, operations or procedurally-induced effects, or unknown or random phenomena), NASA gains both near-term insights into Space Shuttle performance opportunities for potential safety improvements during ongoing operations as well as longer-term benefit in applying experience-based risk models to future programs like Constellation.

For Case 2, flying 23 missions would result in a higher cumulative risk due to more flights, when compared to either Case 1 or the current nine mission baseline. The Shuttle PRA calculates the probability of LOCV during a nominal mission to be between 1 in 45 and 1 in 130 per mission with 90 percent confidence. This number contains many assumptions, however; for more information on Space Shuttle risk assessment, please see the Appendix starting on page 21.

However, NASA would continue to pursue improvements to the Space Shuttle system to eliminate risk and improve the single mission risk as much as possible. Retiring *Atlantis*/OV-104 after FY 2010 would allow NASA to perform destructive testing on some Orbiter components that are ordinarily inaccessible. This might improve NASA's insight into the Orbiter systems and reduce risk. This reduction, however, is not quantifiable today.

It is important to note that PRAs are most effective when used: 1) to gauge relative risk between systems, rather that create an absolute risk number for a particular system; and 2) to generate a range of risk, rather than a single-point, "mean" number that can promote an overly simplistic (and thus, incomplete) understanding of the risk of using a system. In addition, in the case of extending Shuttle operations, PRAs would have to be adjusted to account for incremental safety improvements to the vehicle, as well as the effects of age on the Shuttle's various subsystems.

For more information, please see the Risk Assessment Overview in the appendix beginning on page 21.

6. Safety Enhancements

As with Case 1, for Case 2, NASA's safety and mission assurance strategy would emphasize the need for rigorous program and independent safety reviews, as well as continual safety improvements throughout a program's life cycle. Improvements to both processes and hardware would be made for each Space Shuttle flight, and NASA would continue to invest in safety enhancements through the last mission. Recently, these have included analyses of composite overwrap pressure vessels, thermal protection systems, and structural components from Space Shuttle *Columbia*. These analyses provide NASA engineers with insight into the performance of Space Shuttle systems under extreme conditions and performance data on flight systems which are normally inaccessible during regular and major maintenance processing flows. In addition, instrumentation that was recently added to the Space Shuttle Solid Rocket Motors and crew cabin as part of Constellation Program's development activity has provided useful data to help refine existing Space Shuttle engineering models.

A number of other safety investment opportunities were identified by the *Columbia* Crew Survival Investigation Report, which evaluated what, if any additional safety measures could be implemented to enhance survivability in the event of a mishap. NASA has already implemented several safety and survivability recommendations including installing improved inertial reels on the crew restraint straps and providing an upgraded crew survival radio with GPS tracking. NASA is evaluating several other enhancements that could be implemented before 2010, including a GPS personal locator beacon; improved seatbelts and retention straps; increased head and neck protection; and improved supplemental oxygen. If SSP is extended beyond 2010, several other safety improvements would be assessed for implementation. These include conformal crew helmets; battery powered intercoms; automatic parachute deployment; and automatic helmet visor closure during depressurization. NASA's cost estimates for Space Shuttle extension include approximately $20 million per year, starting in FY 2010, to continually evaluate and implement these and other potential Shuttle safety enhancements. SSP would also work closely with the Orion Project to identify opportunities to use the Space Shuttle as a test-bed to evaluate safety enhancements to Orion seats and crew equipment.

IV. PROCUREMENT ANALYSIS

The procurement offices at Johnson Space Center and Marshall Space Flight Center reviewed six of the Space Shuttle prime contracts to determine the impact of extending the SSP. All of the contracts reviewed would require a procurement action to extend performance to 2012 and beyond. To extend the contracts, NASA would have to complete a master buy submission, a Procurement Strategy Meeting (PSM), a complete Request For Proposal and subsequent negotiation, and a contract instrument. Three of the 6 — the Space Program Operations Contract (SPOC) and the SSME and ET contracts — would not require additional justification for other than full and open competition (JOFOC), while the other 3 would require new JOFOC authority.

Extension of the contracts would require a length of contract Federal Acquisition Regulation (FAR) deviation which needs approval by the HQ Office of Procurement. Two of the contracts, Reusable Solid Rocket Motor (RSRM) and ET, would have a potential for an Undefinitized Contract Action (UCA) to assure availability of long-lead materials. In addition, there are other, small activities which would be accomplished with procurement activity to extend performance.

Most of the contracts currently include special provisions for human capital retention which would have to be renegotiated since the current provisions were timed for a program end in 2010. The exception to this is the imaging contract with Neptec because this contract does not contain a retention provision.

V. LOOKING AHEAD

From a strategic perspective, U.S. leadership in human space flight space will be demonstrated by both ensuring robust ISS operations after the retirement of the Shuttle and developing a space transportation system capable of supporting exploration activities on the Moon and beyond.

Pursuant to U.S. Space Exploration policy and direction in the NASA Authorization Acts of 2005 and 2008 (P.L. 109-155 and P.L. 110-422, respectively), the Agency plans to retire the Space Shuttle after completing the assembly of the International Space Station (ISS) in 2010. Funds, personnel, and facilities freed from the Shuttle's retirement will enable the Agency to support development of systems to deliver people to the International Space Station and the Moon and other destinations beyond low Earth orbit. This strategy allows the U.S. to remain a leader in human space flight by developing the next generation of systems that will enable travel beyond low Earth orbit, as well as development of new transportation systems by the commercial sector.

After the Shuttle retires in 2010, and until a credible commercial crew transport provider or the Ares I/Orion system becomes operational, the United States will continue to rely on Russian Soyuz spacecraft to transport crew, and serve as a rescue vehicle for ISS. NASA will purchase comprehensive Soyuz support, including all necessary training and preparation for the launch, crew rescue, and landing, consistent with U.S. obligations to Canada, Europe and Japan. This ensures access to the Station and, unlike periodic visits by the Shuttle, enables the international partnership to maintain a crew complement of six to conduct research onboard.

Temporary reliance on Russia allows NASA to allocate needed resources to the development of new U.S. human space flight capabilities, such as the Ares I Crew Launch Vehicle and the Orion Crew Exploration

Vehicle. The Ares I/Orion system will enable the capability to carry out human missions beyond low-Earth orbit and will also be capable of providing crew transportation and rescue services to the ISS. The Initial Operational Capability (IOC) for Ares I, defined as the first crewed flight of Orion to the ISS, is targeted for March 2015. The Full Operational Capability (FOC) for Orion, defined as the date when the spacecraft is able to transport crew to the ISS; remain for up to 180 days; serve as a crew rescue vehicle; and safely return crew from the station to Earth is scheduled for 2016.

In parallel, to meet the logistics needs of the ISS and to develop domestic commercial capabilities, NASA has established the Commercial Orbital Transportation Services (COTS) project to stimulate the emerging private sector launch providers who plan to offer cargo and potentially crew services to the ISS. Activities pursued under the COTS project thus far have focused on demonstrating the capability to deliver cargo to the ISS.

The purchase of cargo services to ISS is being conducted through the separate ISS Commercial Resupply Services (CRS) procurement effort. Contracts were awarded to two service providers in December 2008. Timely commercial cargo capability is critical for effective ISS operations. Without commercial cargo capability, the crew size and research operations planned for ISS would need to be reduced.

It is NASA's intention to purchase commercial crew transportation and rescue services domestically once a viable U.S. commercial capability becomes available. Technically all of the basic systems needed for crew transportation are a part of cargo transportation, thus allowing commercial companies to gain experience with cargo vehicle development and operations, which should facilitate the development of crew transportation capabilities in the event such an effort is established.

With use of Soyuz in the near-term and domestic commercial transportation capabilities, coupled with Orion and possibly future international partner transportation systems in the longer-term, astronauts from the United States and our international partners will continue to work productively aboard ISS. The Station will host its first 6-person crew as early as mid-2009 and they will conduct research and operational activities in the American *Destiny*, European *Columbus*, and Japanese *Kibo* laboratories. NASA research on the Station will be focused on experiments to increase our understanding of the effects of the microgravity environment on the human body and to enable the development of countermeasures to address the challenges of long-duration space flight. Many of these investigations have natural parallels to understanding and controlling conditions seen in our terrestrial aging population. The United States and our partners will also use the Station as an engineering test bed to evaluate hardware, technologies, and systems needed for future human space missions, and to allow crew members and ground personnel to gain experience in robotic operations using the Canadian Special Purpose Dexterous Manipulator, or *Dextre*. The ISS will also serve as a node to test delay-tolerant Internet protocols that are critical for the development of space communication systems that will be needed for distant robotic probes in the future.

As a National Laboratory, the Station will support research sponsored by other Federal agencies and by private enterprise. The National Institutes of Health and the U.S. Department of Agriculture have signed Memoranda of Understanding with NASA to conduct innovative research onboard ISS. The Ad Astra Rocket Company has signed a Space Act Agreement with NASA to investigate and test ion engines on the Station.

Human space flight is important to America's political, economic, technological and scientific leadership. The plan outlined above ensures U.S. leadership in human space flight.

VI. APPENDIX: RISK ASSESSMENT OVERVIEW

Introduction

The fact that space travel is inherently risky is well documented. History has shown that the reliability of launch vehicles rarely exceeds 0.95 (I-Shih Chang, "Space Launch Vehicle Reliability," Aerospace Corporation, *Crosslink*, Winter 2001). The Space Shuttle has experienced 2 mission losses in 114 missions to date. This corresponds to a reliability of ~0.98. If we consider the ascent phase reliability alone (a more direct comparison to other launch systems), the Shuttle has experienced one loss, which indicates a ~0.99 reliability. However, given the national significance of the Shuttle and the fact that it is a crewed vehicle improving the system's reliability is of paramount importance.

To understand the risks associated with space flight, NASA has performed highly detailed and comprehensive qualitative risk assessments using Failure Modes and Effects Analysis (FMEA) and Hazard Analysis (HA). This approach was initially applied in the Space Shuttle program. These assessments were useful in identifying the many risks inherent in the design and operating environment of the spacecraft for the purpose of improving design and operational risk controls. However, the qualitative nature of these assessments can lead to inconsistency and imprecision in risk characterization that make risk prioritization difficult and risk aggregation impossible. For these reasons, it was not historically feasible to derive a robust Shuttle reliability estimate or to accurately prioritize top risk contributors. Such insight is crucial to improving the reliability of the Space Shuttle system.

With this in mind, the Space Shuttle Program (SSP) initiated the development of a Shuttle Probabilistic Risk Assessment (SPRA) in March 2001. The purpose of the SPRA is to provide a useful risk management tool for the SSP to identify strengths and possible weaknesses in the Shuttle design and operation. In general, PRA is a process that seeks answers to three basic questions:

- What kinds of events or scenarios can occur?
- What consequences could result from these events or scenarios?
- What are the likelihoods and associated uncertainties of these events or scenarios?

SPRA Iteration 1 results were presented to the Shuttle Program Requirements Control Board in May 2003. This document provides SPRA Iteration 2.2 results. Iteration 2.2 results were presented to the NASA Administrator in October 2006 as part of the Hubble manifest decision package. Iteration 2.2 includes updated Thermal Protection System (TPS) and micro-meteoroid/orbital debris (MMOD) assessments, including inspection, repair, and crew rescue. Additional iterations will be performed as more is learned about the Shuttle or changes occur to its design or operations, such as the reduced ascent debris risk.

The Constellation Program is developing the Ares I launch vehicle and the Orion crew capsule to provide the capability to conduct crew rotation missions to the ISS and as part of the transportation architecture to conduct human missions to destinations beyond low Earth orbit, such as the lunar surface. NASA selected these vehicles based in large part on an estimated reliability that was inherently better than that of the Space Shuttle. The primary improvements to the risk come from adding a launch abort system, from reducing the number of components (hydraulics, aero surface actuators, and turbomachinery), and from shielding the thermal protection system from ascent debris. NASA continues to refine the estimated reliabilities as the design for these vehicles continues to mature; however, it is difficult to compare these estimates to the SPRA. NASA has a far higher level of knowledge about the Shuttle system and the PRA methodologies for operational systems are different from the risk estimation methodologies for systems in development.

The Russian Soyuz TM has the best reliability and safety record of any manned vehicle in history, so our Russian partners have a long track record of success. Based on this track record, the ISS Program will use the Soyuz TM for ISS crew exchanges, subject to Congressional constraints (i.e., the Iran, North Korea and Syria Non-Proliferation Act and amendments), because it is the only vehicle available in the world today that can meet the mission requirements with a proven reliability record once the Space Shuttle is retired.

Scope

The SPRA includes hazards that may result in an in-flight LOCV. In-flight is defined as the time from T-0 to wheel stop. Although rendezvous and docking, and extravehicular activity occur within this time, they are excluded from the scope, because these activities were considered mission-specific when the SPRA was initiated (prior to STS-107). The current version of the SPRA assumes the vehicle configuration is equivalent to that of a generic Orbiter prior to the Columbia accident. Post-Columbia improvements will be added in the next iteration. The SPRA generally assesses hazards that consist of:

- Equipment functional failures
- Flammable/explosive fluid leaks
- Environment (or external) events, such as MMOD
- Structural failures
- Human errors

Since Shuttle missions vary in payloads, durations, etc., these hazards are assessed in terms of a nominal or “generic” mission. The SPRA documentation provides specific information regarding the scope of the overall “generic” mission, but information on various element and system analyses is contained in the corresponding system analysis notebooks.

The SPRA generally follows PRA best practices as outlined in the *NASA PRA Procedures Guide*. However, these practices have been augmented based on the uniqueness of the Space Shuttle systems and operations and on recommendations made by SPRA independent peer reviewers. While technical management of the SPRA resided with SSP Safety & Mission Assurance (S&MA), the assessment included representatives from a variety of organizations. Almost 200 engineers, astronauts, instructors, analysts, and managers have contributed to the SPRA to date. The SPRA methodology used was independently peer reviewed by PRA experts from outside NASA. The Shuttle failure history and failure logic were reviewed by each of the project offices within the Shuttle Program.

Results

The results of the SPRA are consistent with Shuttle flight history. The SPRA calculates the probability of LOCV during a nominal mission to be between 1 in 45 and 1 in 130 per mission with 90 percent confidence. The mean calculated risk is 1.3E-2 per mission or 1 in 77 missions, which is consistent with the loss of two vehicles over the first 114 Shuttle missions or a 1 in 57 probability. This overall result can be broken down in different ways.

Since the mission is dynamic and a failure in one phase may not result in LOCV until a later phase, it is useful to establish when failures occur and when they affect the mission. Table 1 shows the overall results of when LOCV is initiated and when it is realized. Approximately 84 percent of the estimated risk is initiated on ascent or orbit; however, over 60 percent of the risk is actually realized on entry. For those risks that do not immediately result in LOCV, evaluations may be performed to determine if any additional recovery actions can be taken or improved upon (e.g., improved tile repair or improved imaging).

The current SPRA does not model risk associated with intact ascent aborts. However, it does estimate the frequency of a single, benign SSME shutdown during ascent as 3.6E-03 per mission or 1 in 278 missions. Work is in progress to extend this assessment to successful landing.

Table 1: Estimated Phase Contributions to When LOCV is Initiated and When it Occurs

	Estimated Phase Contributions to When LOCV is Initiated		**Estimated Phase Contributions to When LOCV Occurs**	
Phase	**Per Mission LOCV Probability**	Percent	**Per Mission LOCV Probability**	Percent*
ASCENT	1 in 161	47%	1 in 270	28%
ORBIT	1 in 208	37%	1 in 1000	8%
ENTRY	1 in 476	16%	1 in 122	64%

Another way to summarize these results is a breakdown by element or risk contributor. Figure 1 shows each of the major element contributions and some of the higher risk contributors. Ascent debris, MMOD, and human error are specifically broken out due to their relatively large contributions. Note that while each basic event is assigned to one or more elements or contributors, some of the risk contributors are broader integration issues. For example, the risk of ascent debris is assigned to the Orbiter Thermal Protection System (TPS), but the debris may originate from many sources.

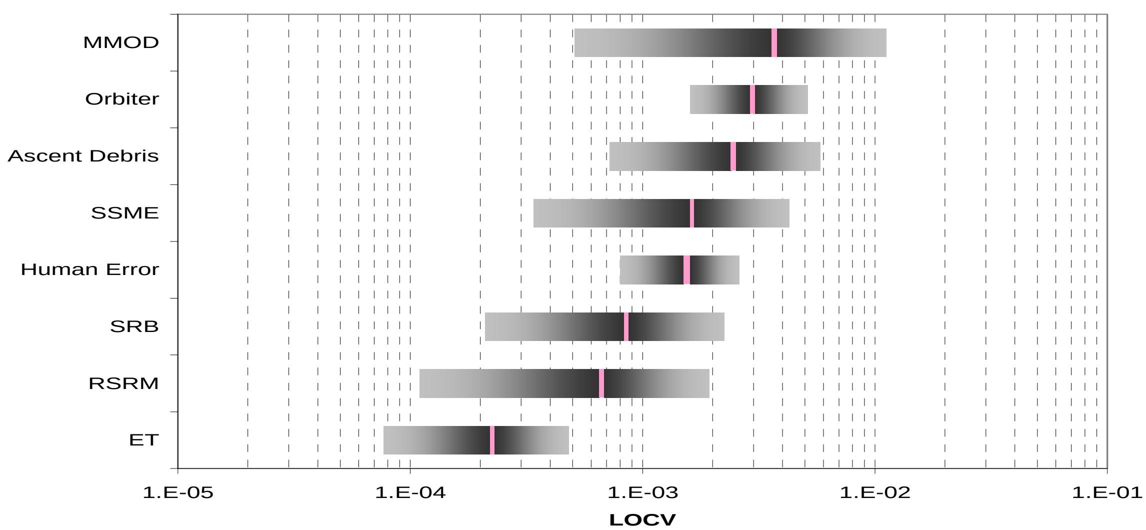


Figure 1: Shuttle Risk Contributors

Table 2, on the last page of this document, provides a list of the top scenarios contributing to Shuttle risk during a mission. The top 10 scenarios alone represent about 80 percent of the total mission risk.

The table also lists actions being taken by the Space Shuttle Program (SSP) for each scenario. Depending on the specific scenario, one of the following basic actions is being taken by the SSP:

- Program risks have been formally defined and a risk mitigation plan has been put into action aimed at reducing the likelihood and/or consequence of the risk.
- Program personnel are performing additional study to better understand the risk.
- No practical mitigation plan is available to significantly reduce the risk of LOCV; therefore, the scenario is an accepted risk.

Insights

The SPRA is intended to be used as a risk management tool. The SPRA provides insights into the significant risks of Space Shuttle flight. Although the results are still being reviewed, several general insights may be made:

- The overall mean estimate for LOCV from the SPRA model highly agrees with flight history. As described earlier, the historical LOCV probability is 1 in 57, which corresponds well with the SPRA risk estimate of 1 in 77.
- An estimated 92 percent of Shuttle LOCV risk is realized during ascent and entry. This estimation represents a small fraction of overall mission duration and may be the result of the current ground rule to not include mission-specific on-orbit activities. Much of this risk is related to the inherent design and operating environment of the Shuttle, and therefore would be difficult to improve without significant design changes. However, the role of ascent debris and MMOD are very significant; therefore, additional focus on managing these risks is warranted.
- Approximately 48 percent of the risk is associated with scenarios that are potentially recoverable during orbit, if the risk condition is isolated and controlled prior to entry. Therefore, efforts to provide greater operational capability for risk recovery should be further developed.
- Human errors of commission during the latter stages of entry (e.g., landing exceeds maximum sink rate) contribute to about 8 percent of the overall risk.

Limitations

As with any PRA of a large, complex, and engineered system, the SPRA is developed for a defined scope, and reasonable engineering judgment is used to make assumptions where necessary. Therefore, limitations exist as to its use. However, the SPRA is only one part of the risk-informed decision making process. Operational constraints, qualitative risk assessments, budgetary considerations, etc., are also integral parts of program decision making. The following are primary limitations and observations regarding the current SPRA scope. A more detailed discussion of these items is provided in the SPRA documentation.

- Does not include mission-specific on-orbit operations (e.g., rendezvous, docking, extravehicular activity).
- Does not include ascent abort risk (only identifies performance abort initiating event frequencies).
- Does not include all flight rules, and therefore all pre-planned operational procedures.
- Does not encompass ground operations (e.g., tanking, scrub turnaround, ground tracking, crew egress, etc.). Note that in some cases, ground-induced failures are incorporated in defined failure rate functions. However, ground processing is not explicitly modeled.

Summary

The SPRA is currently the most comprehensive and peer-reviewed NASA PRA. Additional work remains to expand the scope of the SPRA to include more on-orbit activities (e.g., docking, rendezvous, extravehicular activity), reduce both modeling and data uncertainties (e.g., MMOD, leak scenarios, human actions), and include ascent abort scenarios (e.g., return to launch site). Until then, the Shuttle Program must be careful to ensure the use of this assessment is correctly applied to the question being addressed.

The Shuttle is a very reliable vehicle in comparison with most other launch systems. However, continuous improvement is a program objective. Much of the risk posed by Shuttle operations is related to fundamental aspects of the spacecraft design and the environments in which it operates. It is unlikely that significant design improvements can be implemented to address these risks in a time-effective manner. However, it seems clear that significant improvements are possible in the areas of MMOD, ascent debris, ground and flight crew training, and operational risk response flexibility.

Table 2: Dominant Loss of Crew and Vehicle (LOCV) Scenarios

Ranking	% Total	Cumulative %	Total Estim. Scenario Probab.	Scenario Description	Phase Event Initiated	Phase LOCV Occurs	Program Action
1	**27.3 %**	**27.3%**	**3.6E-03**	**MMOD Strikes Orbiter on Orbit Leading to LOCV on Orbit or Entry**	**Orbit**	**Orbit, Entry**	**(SIRMA 2430, numerous child risks) Optimizing vehicle mission flight attitude profile to reduce risk. Inspection, repair, and crew rescue capabilities are applicable through late inspection.** ***0.25" discernment on late inspection reduces to 1:419*****.**
2	**18.3 %**	**45.6%**	**2.4E-03**	**Ascent Debris Strikes Orbiter TPS Leading to LOCV on Entry**	**Ascent**	**Entry**	**(SIRMA Ascent Debris Risks 2689, 2691, 2692) Additional design and processing plans under evaluation for further improvement. Inspection, repair, and crew rescue capabilities provide significant benefits.** ***With significant debris mitigation and improved repair, the probability reduces to 1:822. PRA work is on-going to incorporate flight data***

Ranking	% Total	Cumulative %	Total Estim. Scenario Probab.	Scenario Description	Phase Event Initiated	Phase LOCV Occurs	Program Action
							and integrate results with physics models.
3	**11.3 %**	**57.0%**	**1.5E-03**	**SSME-induced Catastrophic Failure**	**Ascent**	**Ascent**	**(No Program Risk Assigned)** **Advanced Health Management System (AHMS) Phase 1 upgrade will provide some risk reduction. AHMS Phase 2 cancelled.** ***Additional PRA development planned to characterize benefit of (AHMS I)*****.**
4	**8.2%**	**65.2%**	**1.1E-03**	**Crew Error during Entry**	**Entry**	**Entry**	**(SIRMA 3068)** **Action to discuss potential additional mitigation through training with FCOD and MOD. Will be proposed during SSP PRA out-brief.**
5	**5.0%**	**70.2%**	**6.5E-04**	**RSRM-induced Catastrophic Failure**	**Ascent**	**Ascent**	**(No Program Risk Assigned)** **No significant upgrade activities planned.** ***No significant additional PRA development planned.***
6	**3.4%**	**73.6%**	**4.4E-04**	**APU External Leak on Entry**	**Entry**	**Entry**	**(SRIMA 2819)** **Electrical APU upgrade intended to reduce APU-related risks was cancelled due to lack of funds.** ***No significant additional PRA development planned.***
7	**2.4%**	**76.1%**	**3.2E-04**	**SRB APU Shaft Seal Fracture**	**Ascent**	**Ascent**	**(No Program Risk Assigned)** **This failure mode addressed on Orbiter APU through design changes. Due to reduced mission exposure, no action**

Ranking	% Total	Cumulative %	Total Estim. Scenario Probab.	Scenario Description	Phase Event Initiated	Phase LOCV Occurs	Program Action
							taken on SRB. *No significant additional PRA development planned.*
8	**1.6%**	**77.6%**	**2.0E-04**	**Four SRB Hold-down Bolts Hang Up**	**Ascent**	**Ascent**	**(No Program Risk Assigned)** **C*hanges in ranking expected.*** **Probability assumes four hang-ups are catastrophic. Additional structural analysis of Orbiter and payloads may show that structural margin is available, thus decreasing the probability of this event.**
9	**1.5%**	**79.2%**	**2.0E-04**	**Water Coolant Loop Rupture due to ATCS Overcool**	**Orbit**	**Orbit**	**(No Program Risk Assigned)** ***Changes in ranking expected. Efforts underway to improve the fidelity of the PRA model.***
10	**1.4%**	**80.5%**	**1.8E-04**	**Common Cause Failure of the Electrical Power System**	**Orbit**	**Orbit**	**(No Program Risk Assigned)** **No significant upgrade activities planned. *No significant additional PRA development planned.***