Hubble Space Telescope Crew Rescue Analysis

Teri L. Hamlin[a*], Michael A. Canga[a], and Grant R. Cates[b]
[a]National Aeronautics and Space Administration (NASA), Houston, USA
[b]Science Applications International Corporation (SAIC), McLean, USA

Abstract: In the aftermath of the 2003 Columbia accident, NASA removed the Hubble Space Telescope (HST) Servicing Mission 4 (SM4) from the Space Shuttle manifest. Reasons cited included concerns that the risk of flying the mission would be too high. The HST SM4 was subsequently reinstated and flown as Space Transportation System (STS)-125 because of improvements in the ascent debris environment, the development of techniques for astronauts to perform on orbit repairs to damaged thermal protection, and the development of a strategy to provide a viable crew rescue capability. However, leading up to the launch of STS-125, the viability of the HST crew rescue capability was a recurring topic. For STS-125, there was a limited amount of time available to perform a crew rescue due to limited consumables (power, oxygen, etc.) available on the Orbiter. The success of crew rescue depended upon several factors, including when a problem was identified; when and what actions, such as powering down, were begun to conserve consumables; and where the Launch on Need (LON) vehicle was in its ground processing cycle. Crew rescue success also needed to be weighed against preserving the Orbiter's ability to have a landing option in case there was a problem with the LON vehicle. This paper focuses on quantifying the HST mission loss of crew rescue capability using Shuttle historical data and various power down strategies. Results from this effort supported NASA's decision to proceed with STS-125, which was successfully completed on May 24th 2009.

Keywords: PRA, Shuttle, HST, Crew Rescue

1. INTRODUCTION

Following the Columbia accident (STS-107), the decision was made to remove the HST SM4 from the Shuttle manifest for several reasons including the belief that the risk of flying the HST mission would be too high, because at the time, there was no stand-alone repair technique or crew rescue capability. Following return-to-flight, NASA revisited the decision to reinstate the HST SM4 because of improvements in the ascent debris environment, the ability to perform stand-alone repairs with the Orbiter Boom Sensing System (OBSS), and the potential to provide a crew rescue capability. This paper focuses on quantifying the HST mission loss of crew rescue capability using Shuttle historical data and various power down strategies to conserve Orbiter consumables; thus, extending the mission lifetime of the Orbiter. The results from this effort supported NASA's decision to proceed with the HST SM4 a.k.a. STS-125, which was successfully completed on May 24th 2009.

2. METHODOLOGY

The HST SM4 crew rescue risk was calculated utilizing a Discrete Event Simulation (DES) built with Rockwell Software's Arena Discrete Event Simulation Software [1]. A model already in use by NASA, the Space Shuttle Manifest Assessment Simulation Tool (MAST), served as the starting point for building the HST crew rescue risk simulation [2]. The Arena simulation model of the HST Service Mission LON scenario includes the timeframe from HST Service Mission launch through rescue and re-entry of the LON mission. The ground timeline for the LON vehicle, also referred to as STS-400, was provided by NASA Kennedy Space Center (KSC), and the flight timeline was provided by NASA Johnson Space Center (JSC) Mission Operation Directorate (MOD). These timelines will be discussed in further detail in Section 3.1. The underlying premise of this analysis is that past performance,

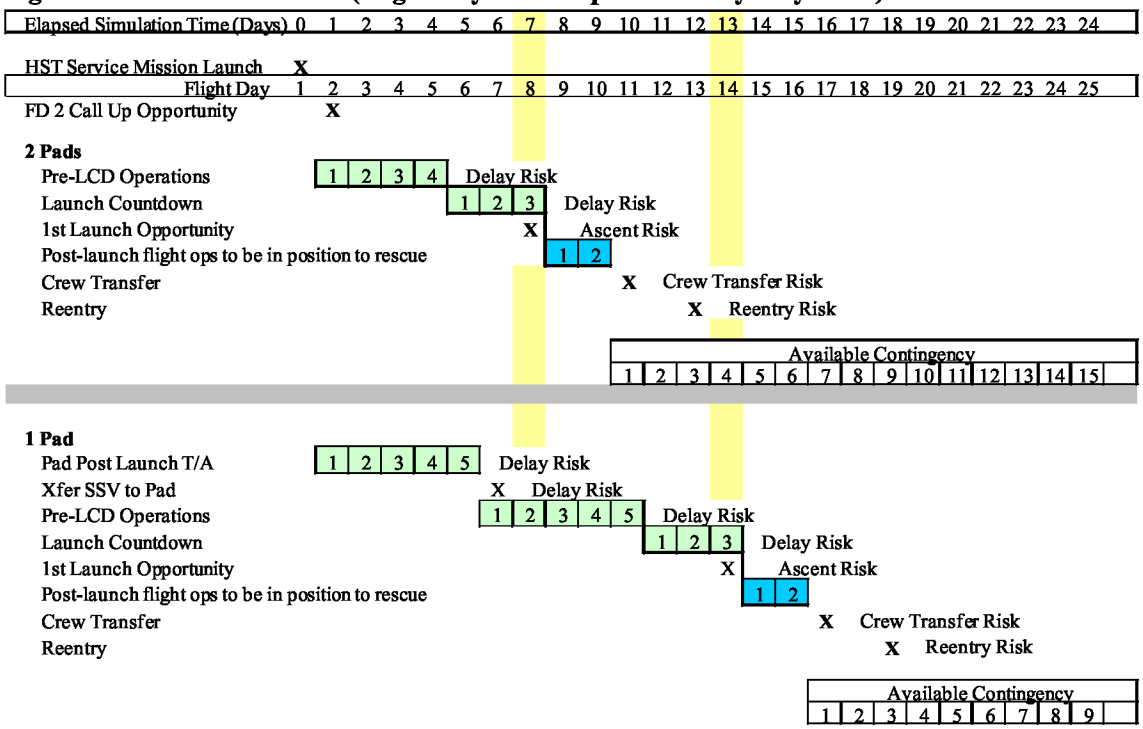
* *Teri.L.Hamlin@nasa.gov*

expert opinion, and the results from other analyses may be used in conjunction with discrete event simulation modeling to help predict future performance i.e., the probability of mission success. Historical data regarding the Mobile Launch Platform (MLP), Crawler Transporter (CT), Vehicle Assembly Building (VAB), pad, and launch was used to derive delay probabilities and delay distributions. Event probabilities for ascent risk, crew transfer risk, and re-entry risk were based upon historical data. The model has the option to exclude or include each risk. The results are based upon 5,000 replications, and sensitivities to model assumptions were performed.

To understand the crew rescue timeline, some background information on Shuttle risk is necessary. Following the Columbia accident, which was the result of ascent debris impacting the Orbiter and damaging its Thermal Protection System (TPS), the Shuttle Program initiated on-orbit inspections on Flight Day (FD)2 to inspect for critical ascent damage before re-entering the atmosphere and challenging the TPS. A later inspection was also added towards the end of the mission to inspect for Micrometeoroid and Orbital Debris (MMOD) critical damage. Critical damage is defined as damage to the TPS that will result in Loss of Crew and Vehicle (LOCV) during re-entry if action is not taken. The timing of the latter inspection varies mission to mission; and for the HST mission, it was scheduled for FD9. These two Shuttle risks (ascent debris and MMOD) constitute a significant portion of the Shuttle risk (~50%). To mitigate the risk of detected critical damage, the Shuttle Program developed repair techniques and a crew rescue capability if a repair cannot be accomplished. For International Space Station (ISS) missions, this crew rescue capability relied on the ability to shelter the crew on the ISS until a rescue mission could be launched; however, no special processing for the LON vehicle occurred until the rescue mission was called up. The ISS provides the capability for a stranded crew to wait for an extended period of time for a rescue. Since the HST mission was incapable of docking to the ISS due to orbital mechanics, the HST mission's capability to remain on Orbit was limited by the Orbiter's small supply of consumables. For example, an Orbiter typically must return to Earth after about 12-14 days. Provisions were necessary to maximize the HST mission's rescue capability, including manifesting additional LiOH, which absorbs CO_2, and planning for contingency power downs, which extend the Orbiter's stay time by minimizing the use of consumables for electric power generation. The contingency power downs analyzed were limited to those that were already proceduralized, specifically the Group B power down, Modified Group C power down, and Group C+ power down. The Group B power down was part of the nominal flight plan to conserve power without impacting the HST mission. The Modified Group C power down retained nominal entry capability, while providing additional stay time. For the Group C+ power down, nominal entry capability was lost and could not be recovered due to powering off the Auxiliary Power Unit (APU) and hydraulic heaters. In both the Modified Group C and Group C+ power downs, the capability to dispose of the HST Orbiter via a controlled re-entry to a minimal risk area was maintained, which protects the public from re-entry debris. More extensive power downs could be performed, but these would have additional unknown risks, including potentially exposing the public to re-entry debris.

Two potential options for LON capability were explored: (1) a dual pad option where the LON vehicle would be processed and launched from Launch Complex 39-B, which was the alternate launch pad for the HST mission and (2) a single pad option where the LON vehicle would be processed and launched from Launch Complex 39-A, which is the same launch pad used for the HST mission. Both options were considered to preserve launch capability for the Constellation Program's Ares I-X, which was scheduled to launch from Launch Complex 39-B. An example timeline for dual pad and single pad options is shown in Figure 1. Risk trades evaluating single pad verses dual pad were preformed several times leading up to the launch of STS-125. The final decision was to use dual pad operations, which increased the margin between first LON opportunity and STS-125 maximum stay time, improving overall probability of success and operational flexibility. Single pad operations incurred additional risks such as: reduced margins by delaying first launch opportunity of LON until FD14, increased the risk from potential STS-125 launch damage to pad, and included Space Shuttle Vehicle (SSV) transfer to pad and pad turnaround.

Figure 1: Planned Timelines (Flight Day 2 Call-Up and 24-Day Stay Time)



3. MODEL INPUTS

The inputs to the Arena model include mission timelines and risks for completing the crew rescue and LON actions prior to depleting the HST Orbiter consumables. For dual pad crew rescue, the following risks were considered: post-launch ascent, crew transfer, re-enty risks, launch countdown risk, and pad operations flow prior to launch countdown (Pre-LCD) risks. The single pad analysis included all the dual pad analysis risks plus risks for pad turnaround (T/A) and transferring the rescue SSV from the VAB to the launch pad. These inputs will be discussed in detail in the following subsections.

3.1. Timelines

There are two timelines of importance. The first timeline is the LON vehicle timeline, which includes ground processing time and the time it takes to rendezvous with the HST vehicle and transfer the crew. The second timeline is the HST mission timeline, which includes when inspections and power downs occur.

The dual pad LON baseline timeline is seven days launch to launch as shown on Figure 1. This includes four days of pad operations flow and three days of launch countdown. Following a successful launch and ascent, it takes two days to rendezvous with the HST vehicle and transfer the crew, assuming an accelerated crew transfer. Nominal rendezvous and crew transfer takes approximately three days six hours. Once the HST vehicle launches, the LON vehicle will proceed with pad operations flow activities until they are complete and the vehicle is at Launch minus three days (L-3). The LON vehicle was assumed to be held at L-3 in the baseline analysis; however, Launch minus four days (L-4) was analyzed as well. Processing the LON vehicle to L-3 requires loading cryogenic hydrogen and oxygen for the Orbiter's electric power generating fuel cells, which exposes the ground personnel and vehicle to Composite Overwrapped Pressure Vessel (COPV) rupture. In addition, holding at L-4 would make it easier to reconfigure the LON vehicle into STS-127, which was to be launched off of Pad 39A following the HST mission.

As discussed in the Background section, there are two important mission events that determine whether a crew rescue will be needed, the FD2 inspection and the late inspection.

As the name implies, FD2 inspection occurs on flight day 2 of the HST mission. However, to confuse matters, the Mission Elapsed Time (MET) is ~18 hours; therefore, the inspection occurs at launch plus 18 hours. Both MET and FD timelines will be used in this discussion. If the FD2 inspection detects critical TPS damage, there are two possible outcomes: the critical damage is determined to be irreparable or the critical damage is determined to be repairable. If the critical damage is considered to be irreparable, the LON vehicle will be "called up" on FD2, with the earliest launch of the LON vehicle on FD8 (MET 7) as shown on Figure 1. Depending upon whether the Orbiter performs a Modified Group C power down or a Group C+ power down at that time, the HST Orbiter can either last until FD19 (MET 18) or FD25 (MET 24). If the critical damage is not immediately determined to be irreparable, some additional time is needed to consider whether a repair is necessary. If it is determined that a repair is necessary, a Modified Group C power down will be performed on FD3 (MET 2), with the repair being performed on FD 7 (MET 6). During the repair, it is possible for the Extravehicular Activity (EVA) crew to decide the repair is unsuccessful; in this case, the LON vehicle will be "called up" on FD7 (MET 6) and begin the launch countdown with the earliest possible launch on FD 10 (MET 9). If the EVA crew successfully completes the repair, an inspection will be performed to determine if the repair is acceptable for re-entry. At that time, either the vehicle will remain in a Modified Group C power down or go to a Group C+ power down, which will extend the Orbiter mission time to either FD18 (MET 17) or FD20 (MET 19).

Late inspection occurs on FD9 (MET 8), and there is limited capability to extend the mission at that point. If the late inspection detects critical damage, similar to the FD2 inspection, the damage is either repairable or not. Fortunately, the majority of critical MMOD damage is repairable, since the damages are generally coating loss or small holes. If damage was determined to be irreparable, the LON vehicle would have been "called up" on FD10 (MET 9) and either a Modified Group C power down or a Group C+ power down would have been performed at that time to maintain the HST Orbiter until FD15 (MET 14) or FD18 (MET 17). More severe power downs would be necessary to protect for a failed repair; therefore, the analysis assumed there would be no crew rescue capability in the event of a failed MMOD repair. However, this assumption did not significantly increase the risk, because the majority of the MMOD repair failures are on re-entry, where crew rescue is not an option.

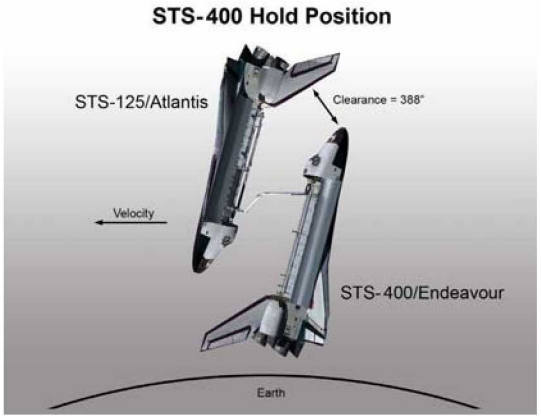
As described in this section, one can see the rescue scenarios are complicated and there are several decision points to consider, which can influence the risk. Therefore, numerous sensitivity calculations were performed.

3.2. Post-Launch Risks

HST crew rescue post-launch risks include ascent abort, ascent LOCV, crew transfer, and re-entry LOCV. The frequency of post-launch risks that were input into the Arena model were simply based on historical data. There were 125 flights prior to launch of the HST mission, 124 of those flights are applicable to abort and entry calculations since Challenger (STS-51L) was destroyed during ascent and did not experience a re-entry. There has been one ascent abort (STS-51F); therefore, the probability of an ascent abort is 1:124. There has been one ascent LOCV (STS-51L); therefore, the probability of ascent LOCV is 1:125. There has been one entry LOCV (STS-107); however, in order to need crew rescue on the HST mission, the HST mission would also be considered and entry LOCV would yield a probability of 2 in 124 or 1:62.

The 1:100 risk associated with crew transfer was based upon a basic Cognitive Reliability and Error Analysis Method (CREAM) [3] calculation as well as engineering judgment and assumed that the risk would be dominated by human error. For crew transfer, the plan was to use the rescue Orbiter's Shuttle Remote Manipulator System (SRMS) to grapple the HST Orbiter; this is shown in Figure 2.

Figure 2: Crew Transfer Position [4]



Approximately three EVAs were required with five Extravehicular Mobility Units (EMUs) available (four on the HST vehicle and one on the LON vehicle). The first EVA would have translated down the SRMS and set up a secondary translation path (concept is rope-like). This is a translation path that is nominally taught for contingencies, and it is much worse than a nominal translation. The remaining HST crew will translate the secondary translation path, except the last translation would be taking the same path as the first (i.e., down the SRMS.) Except for the first and last translation, the majority of the tasks are very basic. Three crewmembers would not be fully EVA trained (Commander (CDR), Pilot (PLT), and SRMS crewmembers); however, they would each have some very basic classes and EMU exposure. The plan was to carry the non-EVA trained crewmembers. The secondary translation path was established because it would be extremely difficult to carry a second person down the SRMS.

3.3. Launch Countdown Risk

Launch probabilities used in the crew rescue simulation were derived from the total Space Shuttle launch experience. Consideration was not given for the potential that the Mission Management Team (MMT) could behave differently during an LON countdown. For example, the question of whether the MMT would be willing to take more risks to achieve a timely launch was not addressed. However, as shown in Figure 3, some of the historical launch delays were scrubbed out as not applicable to an LON missing. For example, a launch delay due to a payload issue was not considered. Overall, the probability of a delay or scrub during launch countdown has been fairly stable since 1991.

Figure 3: Historical Launch Data

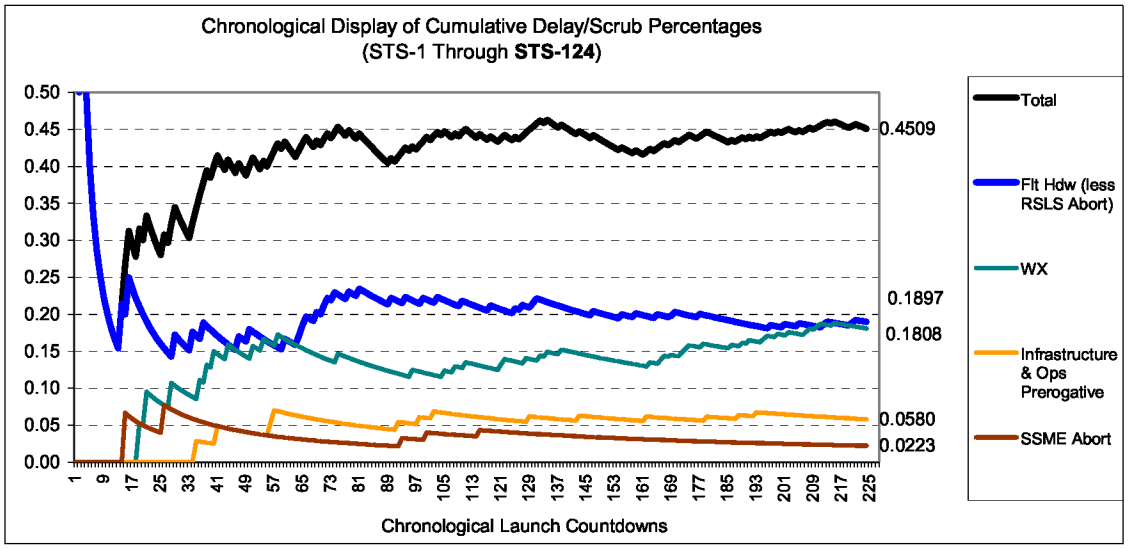
Historical Launch Outcome Percentages

MAST Sim Info		Delays or Scrubs During Launch Countdown (S0007)				
Launch Data Through STS-124 2008_10_15.xls	Launch Occurs	Weather	Flight Hardware (Less Engine Abort)	Infrastructure or Operational Prerogative	Main Engine Abort	Total
From Start of Countdown	54.91%	18.08%	18.97%	5.80%	2.23%	100%

After scrubbing historical data set for applicability to LON Scenario

		Delays or Scrubs During Launch Countdown (S0007)				
Launch Data Through STS-124 2008_10_15.xls	Launch Occurs	Weather	Flight Hardware (Less Engine Abort)	Infrastructure or Operational Prerogative	Main Engine Abort	Total
From Start of Countdown	57.59%	18.08%	17.63%	4.46%	2.23%	100%

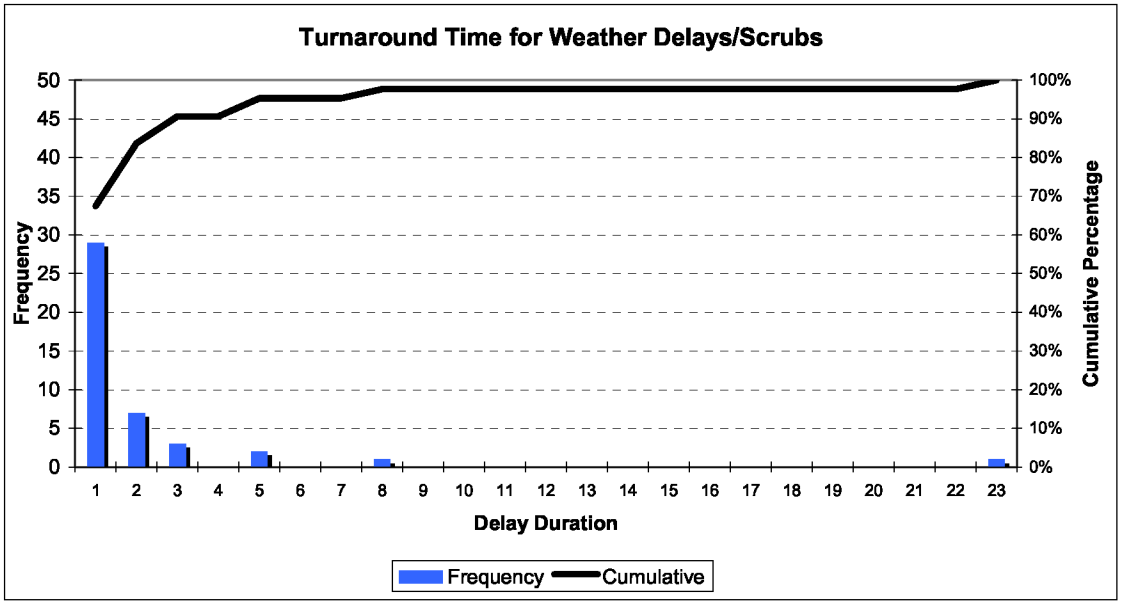
Launch Data Through STS-124 2008_10_15.xls	*HST or ISS LON Sim Info*	*11/6/2008 21:39*
File Name	Worksheet Name	Date & Time



Launch Data Through STS-124 2008_10_15.xls	***Cumulative Run Charts***	***11/6/2008 21:39***
File Name	**Worksheet Name**	**Dynamic Date & Time**

Shuttle historical data was also used to estimate the time between launch attempts. The duration of the delay/scrub until the next launch attempt is dependent upon the reason for the delay/scrub. For example, weather delays/scrubs have a 67% chance of being one day in duration; whereas, flight hardware delays/scrubs are more likely to require a greater number of days. Operational prerogative and infrastructure delays seem to fall between the weather and flight hardware delays in terms of duration; however, the infrequent nature of these delays and the resulting lack of empirical data makes the duration of these delays more difficult to predict with accuracy. Except for the SSME on pad abort, consideration was not given for the potential that the time required to recover from a launch delay/scrub may be reduced during an LON scenario. Figure 4 shows the historical weather delay frequencies; similar distributions were developed for other launch countdown delay contributors.

Figure 4: Weather Delay Duration



Days Delayed	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Frequency	29	7	3	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Probability	0.67	0.16	0.07	0	0.05	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02
Cumulative	0.67	0.84	0.91	0.91	0.95	0.95	0.95	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	1

Arena Representation:
DISC(.6744,1, .8372,2, .9070,3, .9535,5, .9767,8, 1,23)

3.4. Pad Flow Risks

Directly applying historical data for the pre-launch countdown pad delay risk would be overly pessimistic for use in the LON scenario. The HST service mission was not planned to be launched until after the bulk of the LON Shuttle pad flow was accomplished; therefore, the majority of this risk was retired. For this reason, the historical data was manipulated to reflect an assumption that a large percentage of the problems have already been encountered and corrected. To reflect the risk of a delay in the time period of concern, the KSC Critical Path Assessments and the JSC Mission Operations Directorate (MOD) Space Shuttle Mission Summary were reviewed to estimate probability of launch postponements that occur in the final days leading up to launch countdown. Data points that would not have applied in an LON scenario, such as payload-induced delays, were discounted.

3.5. Other Risks

For single pad crew rescue, the risk of a launch delay while transferring the LON vehicle to the pad and pad turnaround had to be considered. With the exception of the potential for increased pad scrutiny in the case of an ascent debris damage, these risks are not considered for dual pad crew rescue since the HST mission wound not have launched without the LON vehicle ready to launch off of Pad 39B. These risks are summarized briefly in this section.

The pad transfer delay risk for the single pad crew rescue operation stems from weather restrictions, infrastructure (e.g., the CT) problems, and flight hardware concerns. The historical data available for review included 91 SSV rollouts (from STS-26 through STS-115). Thirteen cases in which SSV rollout was delayed in a manner that would have been applicable to the LON scenario were identified, nine of which were weather related. Of the nine weather delays, eight occurred during hurricane season (June through November). Since the final HST launch was outside of hurricane season (May

2009), a probability of 0.0549 (5 divided by 91) was used to model the likelihood of an SSV rollout delay outside hurricane season.

Launch pad turnaround is assumed to be initiated prior to LON vehicle call-up, immediately following the HST launch. KSC advertised an 8-day pad wash and refurbish timeline in the Volume II Schedule and Status, Enhancement Analysis KSC Processing, Summary Data (SFOC DRD-1.1.7.c) dated December 12, 2002. An 8-day duration was shown as being under review and was based upon nominal launch damage. However, in the HST LON analysis, an accelerated schedule of approximately four days was assumed based upon the recommendation from KSC. This recommended refurbish time is consistent with the fastest pad turnaround in the post-Challenger era. STS-51 was launched at 7:45 am on September 12, 1993 from Pad 39B. STS-58 arrived on September 17. However, since four days is based upon nominal launch damage, there is also risk of greater than nominal launch pad damage. For post-Challenger launches (STS-107 and STS-96 not included), 4 (or 5) launches out of 90 were identified as having greater than nominal launch damage (STS-124, STS-108, STS-59, STS-26 and STS-70). In cases where the damage has been greater than nominal, the time between launch and next pad usage is known. However, except for the extensive flame trench damage repair required after the STS-124 launch, it cannot be concluded the pad turnarounds spanned the entire durations. It should be noted that it is difficult to analyze pad turnaround risk. In most cases, the time between launch and the next vehicle arrival is greater than eight days, because the launch rate does not necessitate such quick times between launch and next vehicle arrival. Consequently, the time required to accomplish pad turnaround can expand. Additionally, the available historical data does not lend itself to determining when the launch pad was available to accept a vehicle. For this reason, the MLP time on the launch pad was used as an analog.

Consideration was also given to the potential that TPS damage to an Orbiter could prompt increased scrutiny during launch pad turnaround. For example, the source of the damage to the TPS could be debris on the launch pad being kicked up by the engine start sequence or during the initial moments of liftoff. Probabilities for increased scrutiny were based upon engineering judgment. In the case of a FD2 "call up," the probability was assumed to be one and zero in the case of a FD10 call up. Delay to pad turnaround is likely to be minimized by the desire to accomplish LON in a timely fashion. Consequently, there may be no delay to pad turnaround 50% of the time (estimate). Delays would be limited to one day 40% of time (estimate) and two days 10% of the time (estimate).

4. RESULTS

The baseline crew rescue success is shown in Figure 5, which assumes the HST Orbiter does not power down below a Modified Group C power down to protect re-entry capability. Figure 5, shows the probability of crew rescue success significantly increases with the first few days of contingency days available and then starts leveling out. For FD 10 "call ups," there is only a single launch opportunity; and the probability of success is 53%. If three additional days were available, which is the case if a Group C+ power down is performed, the probability of success increases to 74% as shown in Table 1.

Figure 5: Baseline Dual Pad Crew Rescue Results (No C+ Power down)

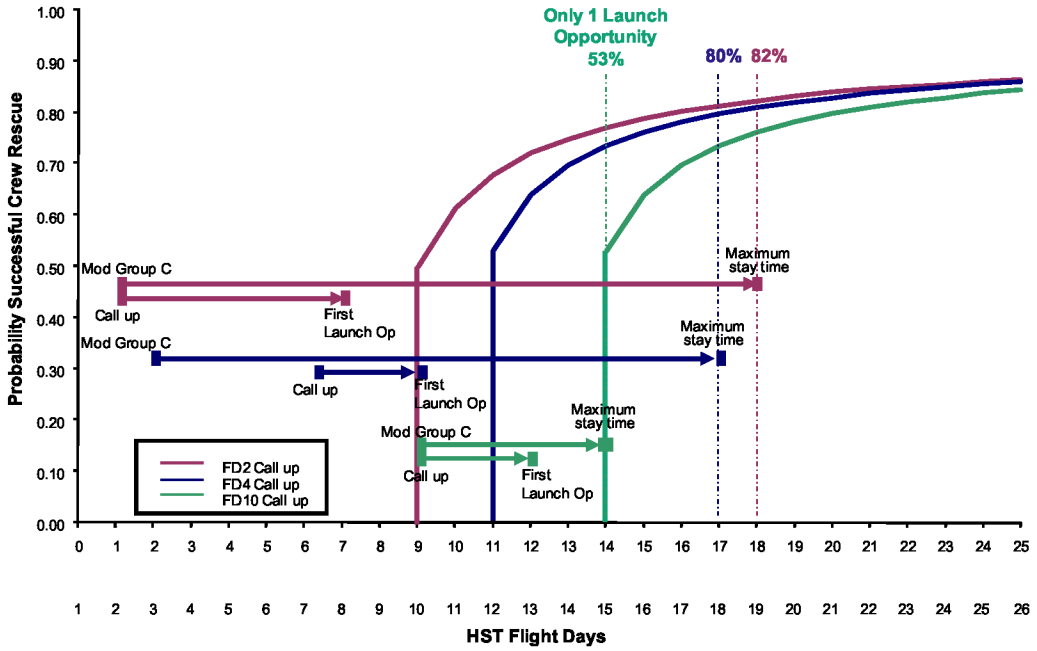


Figure 5 was developed so that risk trades could be accomplished by simply shifting the "maximum stay time" line. In addition, the curves could be shifted to assess the differences in LON launch readiness. For example, the baseline assumes L-3, but the curves could be shifted to the right a day to assume L-4. For a FD2 "call up," this does not change the results at all, because the "call up" occurs before the LON vehicle reaches L-4. For the FD10 "call up," the probability of success is zero without a Group C+ power down. Therefore, if the Shuttle Program decided to keep the LON vehicle at L-4 to hold off on loading cryogenics, the HST vehicle would have to go to a Group C+ power down to maintain a rescue capability. These results are summarized in Table 2.

Table 1: Crew Rescue Comparisons with and without C+ Power down (L-3)

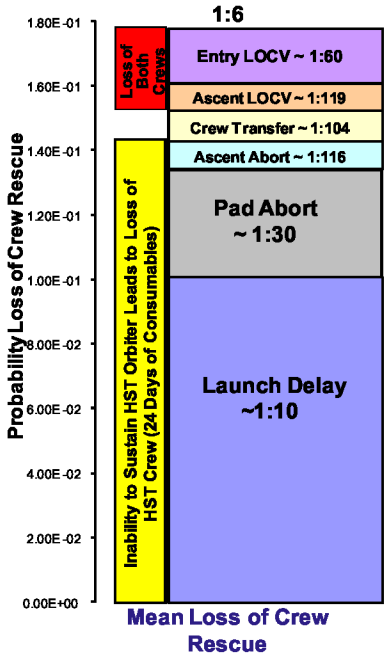
	With C+ Power down		Without C+ Power down	
	Staytime	**Crew Rescue Success**	**Staytime**	**Crew Rescue Success**
FD2	24 days	86%	18 days	82%
FD4	19 days	82%	17 days	80%
FD10	17 days	74%	14 days	53%

Table 2: Crew Rescue Comparisons with and without C+ Power down (L-4)

	With C+ Power down		Without C+ Power down	
	Staytime	**Crew Rescue Success**	**Staytime**	**Crew Rescue Success**
FD2	24 days	86%	18 days	82%
FD4	19 days	81%	17 days	78%
FD10	17 days	70%	14 days	0%

The loss of crew rescue probability for a FD2 "call up" is shown in Figure 6. This is simply 1 minus the probability of success, or 0.18. This probability is represented by the fraction 1:6 when rounded to the nearest whole number. Figure 6 shows that over 50% of the risk is due to launch delays not including pad aborts, with pad aborts providing the second biggest risk driver. It also shows that a fraction ~14% of the risk results in loss of both the HST crew and the rescue crew due to an ascent or entry LOCV.

Figure 6: FD2 Loss of Crew Rescue Probability



5. CONCLUSION

The risk trade space for the HST crew rescue included many variables, including when and to what extent power down procedures were to be implemented, to what extent the LON vehicle should be processed, and initially whether to provide dual pad capability. Crew rescue success needed to be weighed against preserving the ability of the Orbiter to have a landing option in case there was a problem with the LON vehicle. In the end, the HST SM4 was successfully completed on May 24th 2009 and did not require the rescue mission. Had a rescue mission been required, the baseline plan was to remain in the Modified Group C power down to protect the HST Orbiter's capability to land in the event that a rescue mission could not be completed. Although the analysis showed significant improvement going to a Group C+ power down in the case of a FD10 "call up" (53% to 74%), the probability of needing a rescue mission, which was not discussed in this paper, was low—such that the overall increase in risk was minimal.

Acknowledgements

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