ENRE 655 Class Project

Development of the Initial Main Parachute Failure Probability for the Constellation Program (CxP) Orion Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS)

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Abstract

Loss of Crew (LOC) and Loss of Mission (LOM) are two key requirements the Constellation Program (CxP) measure against. To date, one of the top risk drivers for both LOC and LOM has been Orion's Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS). Even though the Orion CPAS is one of the top risk drivers of CxP, it has been very difficult to obtain any relevant data to accurately quantify the risk.

At first glance, it would seem that a parachute system would be very reliable given the track record of Apollo and Soyuz. Given the success of those two programs, the amount of data is considered to be statistically insignificant. However, due to CxP having LOC/LOM as key design requirements, it was necessary for Orion to generate a valid prior to begin the Risk Informed Design process. To do so, the Safety & Mission Assurance (S&MA) Space Shuttle & Exploration Analysis Section generated an initial failure probability for Orion to use in preparation for the Orion Systems Requirements Review (SRR).

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1 Introduction to NASA's Constellation Program (CxP)

The Constellation program has been established to:

- Develop a safe, affordable, reliable and sustainable system to conduct human exploration across the solar system

- Develop an exploration system that will support an extended human mission to the surface of the Moon no later than 2020

- Develop the capability for a sustainable and extensible permanent human presence on the Moon for commercial, national pre-eminence and scientific purposes leading to future exploration of Mars and beyond

- Establish a capability to conduct human expeditions to Mars and beyond.

The CxP Office is developing, integrating, and evolving an architecture to accomplish these needs and goals. The Cx Architecture is currently comprised of spacecraft, launch vehicles, support systems, and destination systems to further these space exploration goals. The Cx Architecture also has several key external interfaces that are critical to the success of Cx missions. Figure 1 illustrates which Cx elements are utilized for the ISS and Lunar missions.[1]

[1] Constellation Program Overview, October, 2006, John F. Connolly, Constellation Program Office, National Aeronautics & Space Administration (NASA)

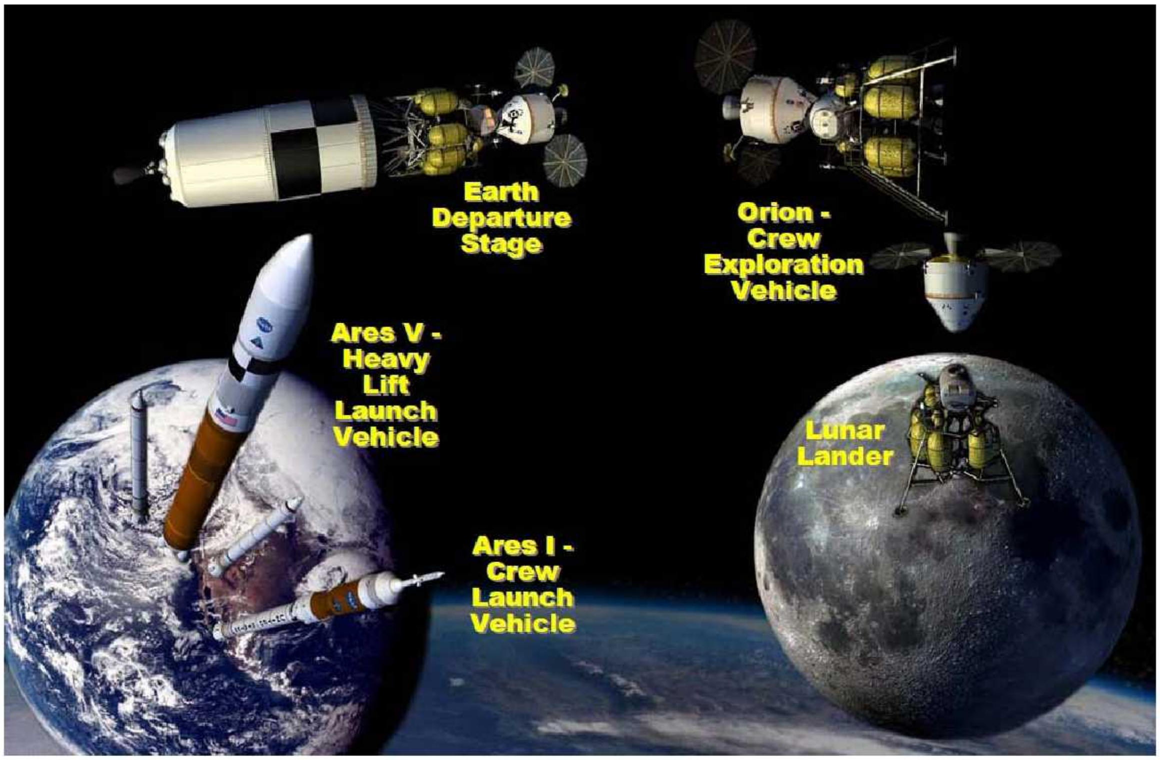

Figure 1: Components of the Constellation Program (CxP)

2 Constellation Program (CxP) Missions

The CxP missions fall into three general categories: missions to the International Space Station (ISS), missions to the Moon, and missions to Mars. The ISS missions consist of ISS crew rotation missions. The Lunar missions demonstrate the capability of the architecture to transport and land humans on the Moon, operate for a limited period on the surface, and safely return them to Earth. Lunar missions also allow for exploration of high-interest science sites or scouting of future Lunar Outpost locations. The Mars missions will demonstrate the capability of the architecture to transport and land humans on Mars, operate for a limited period on the surface, and safely return them to Earth.[2]

3 Applicable Design Reference Missions (DRMs)

The following sections briefly describe each of the applicable CxP DRMs that were planned as of the beginning of the program. There are three major DRMs: the ISS Crewed DRM, the Lunar DRMs, and the Mars DRM. The Lunar DRMs contain three variations: the Lunar Sortie DRM, the Lunar Outpost DRM, and the Lunar Cargo DRM. Of these three DRMs, the Lunar Cargo DRM would not utilize the Orion spacecraft.

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[2] Constellation Program Overview, October, 2006, John F. Connolly, Constellation Program Office, National Aeronautics & Space Administration (NASA)

Thus, the Lunar Cargo DRM would not be applicable in terms of having the Orion CPAS operate.

3.1 *Lunar Design Reference Missions*

3.1.1 Lunar Sortie Crew DRM

Lunar Sortie missions are representative of missions that enable up to four crewmembers to explore a single site anywhere on the Moon with the length of stay limited by the amount of consumables brought by Altair, the Lunar Lander, and Delta-V margins. This type of mission is accomplished independent of pre-positioned lunar surface infrastructure such as habitats or power stations. A Lunar Sortie mission may occur at any time during the CxP Lunar Campaign. The Lunar Sortie mission allows for exploration of high-interest science sites, scouting of future Lunar Outpost locations, or other technology development objectives within the capabilities of the available lunar surface infrastructure. During a sortie, the crew has the capability to perform daily Extravehicular Activities (EVAs).

A Lunar Sortie mission utilizes the following elements for a mission: Ares I, Orion, Ares V, Lander, Mission Systems (MS), Ground Systems (GS), EVA and Portable Equipment. The ascent mission mode for the Lunar Sortie mission is a combination Earth Rendezvous Orbit and Lunar Rendezvous Orbit (ERO-LRO) architecture. The Altair/Earth Departure Stage (EDS) is inserted into ERO with a single Ares V launch followed within 90 minutes by an Ares I launch of the crew and cargo aboard the Orion. Orion and Altair/EDS then rendezvous and dock in ERO. The crew may enter Altair prior to Trans-Lunar Injection/Lunar Orbit Insertion (TLI/LOI). The EDS performs the TLI burn for Altair and Orion and then separates from the stack. The EDS maneuvers to target for a safe disposal away from the Orion/Altair path or any future spacecraft missions. Altair performs any required mid-course correction maneuvers during the trans-lunar cruise. Upon reaching the Moon, Altair then performs the LOI for the two mated elements. Figure 2 illustrates the Lunar Sortie Crew mission. Although this DRM represents the current baseline Lunar Sortie mission, the architecture developed to support this DRM should not preclude the capability to accomplish a Lunar Sortie with a single launch of both crew and cargo on the Ares V.[3]

[3] Constellation Program. (March 21, 2010). In Wikipedia. Retrieved March 30, 2010 from http://en.wikipedia.org/wiki/Constellation_program#Missions

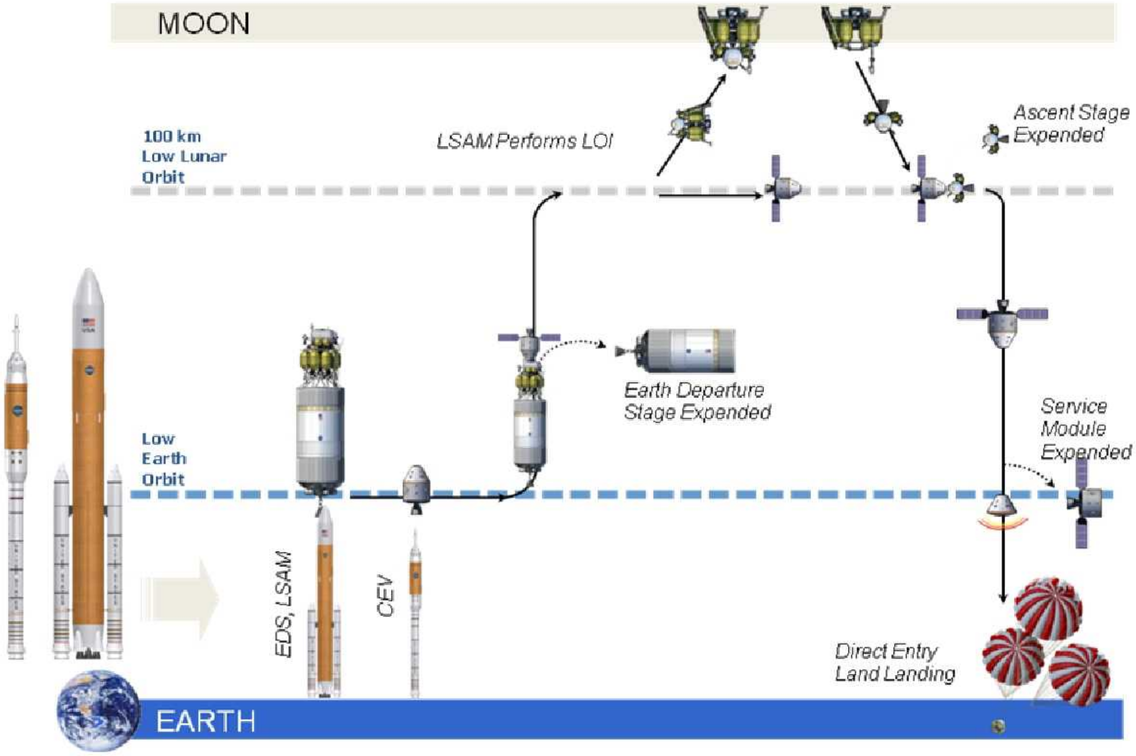

Figure 2: Lunar Sortie Crew DRM

3.1.2 Visiting Lunar Outpost Expedition DRM

The Visiting Lunar Outpost Expedition DRM is representative of a mission with a crew size up to four, where the crew is dependent on the resources from Altair to survive for the duration of the mission; however, as available, some resources from Lunar Surface Systems (LSS) may be used to extend the length of the surface stay. This mission is intended to perform tasks at a Lunar Outpost site that utilize a human's expertise, dexterity, realtime evaluation and ability to improvise. These missions would conceivably be used to construct a Lunar Outpost, or provide needed logistics or repairs to an existing Outpost.

Crew size is determined by the surface operations that are required to accomplish mission objectives. If the crew consists of fewer than four crewmembers, the mass saved may be replaced by additional equipment or small cargo needed for the surface mission. The delivery of cargo on the same vehicle as the crew provides flexibility and optimization to the Outpost construction schedule. These missions incrementally build upon useful infrastructure left behind after the completion of previous missions. The duration of crew surface time for this DRM will vary depending on the Outpost construction and payload/technology objectives.

A Visiting Lunar Outpost Expedition mission utilizes the following systems for a mission: Ares I, Orion, Ares V, Lander, MS, GS, EVA, LSS and Portable Equipment.

The ascent mission mode for the Lunar Outpost Crew mission, just like the Lunar Sortie mission, is a combination ERO-LRO architecture. Altair is pre-deployed with a single Ares V launch to ERO followed within 90 minutes by an Ares I launch of the crew and cargo aboard the Orion. Orion and Altair/EDS then rendezvous and dock in ERO. Figure 4, Lunar Outpost DRM, illustrates the Lunar Outpost Crew mission. Robotic systems perform the function of off-loading crew task overhead and performing activities that would otherwise impact the productivity or safety of the crew.[4]

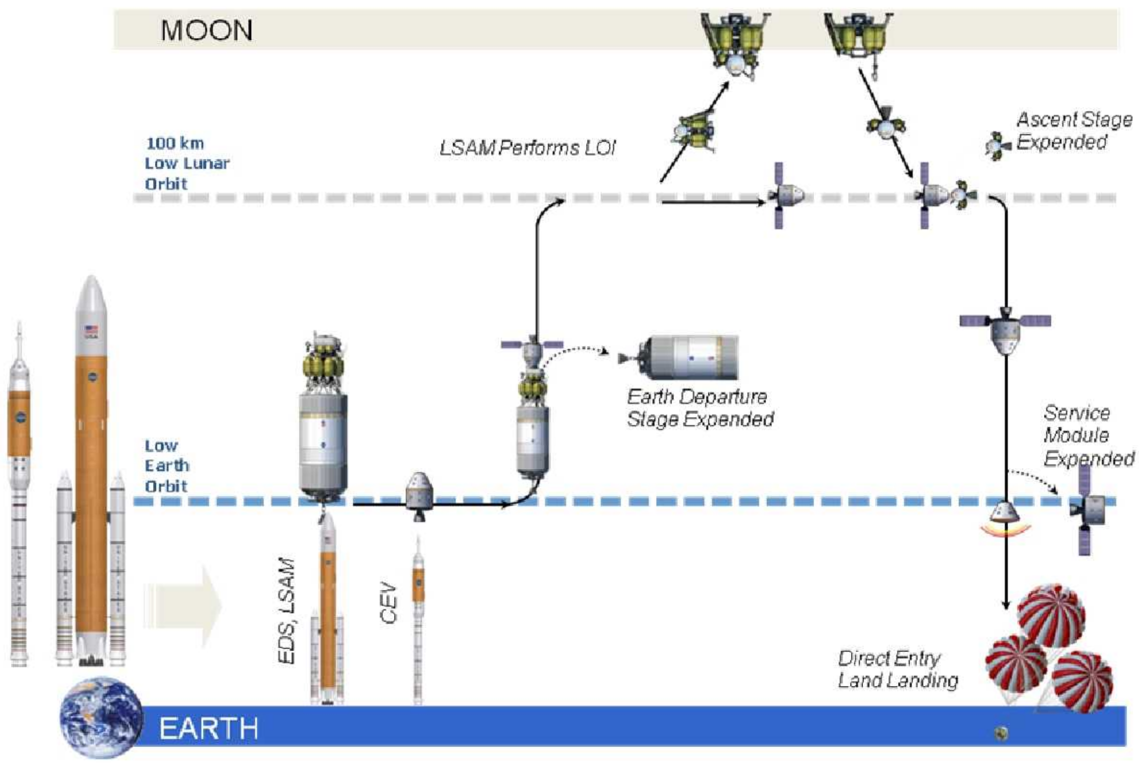

Figure 3: Lunar Outpost - Crew DRM

3.2 *ISS Design Reference Missions*

The ISS DRM supports ISS increment crew rotation and re-supply of the ISS. ISS missions provide a proving ground for Constellations systems while at the same time providing an alternate resource for the support of ISS crewed operations. The presence of a quiescent Orion at the ISS should be included and that the existing ISS crew returns to Earth in the Orion that brought them to the ISS, not in the Orion that brings the replacement crew.

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[4] Constellation Program. (March 21, 2010). In Wikipedia. Retrieved March 30, 2010 from http://en.wikipedia.org/wiki/Constellation_program#Missions

An ISS mission utilizes the following systems for a mission: Ares I, Orion, MS, GS, and Portable Equipment. After separating from the Ares I, Orion performs orbit raising burns per a pre-mission-defined rendezvous phasing profile, modified as necessary to account for actual trajectory conditions, to close in on the ISS. These will be a combination of ground-targeted and onboard-targeted burns, the latter performed once rendezvous navigation sensors acquire the ISS. Any EVA contingency operations originate from the ISS, using ISS resources. The ISS mission involves the launch of Ares I into a 51.6 degree inclination orbit with a crew of three to six destined for a 6-month ISS expedition. Figure 5 illustrates the ISS mission.[5]

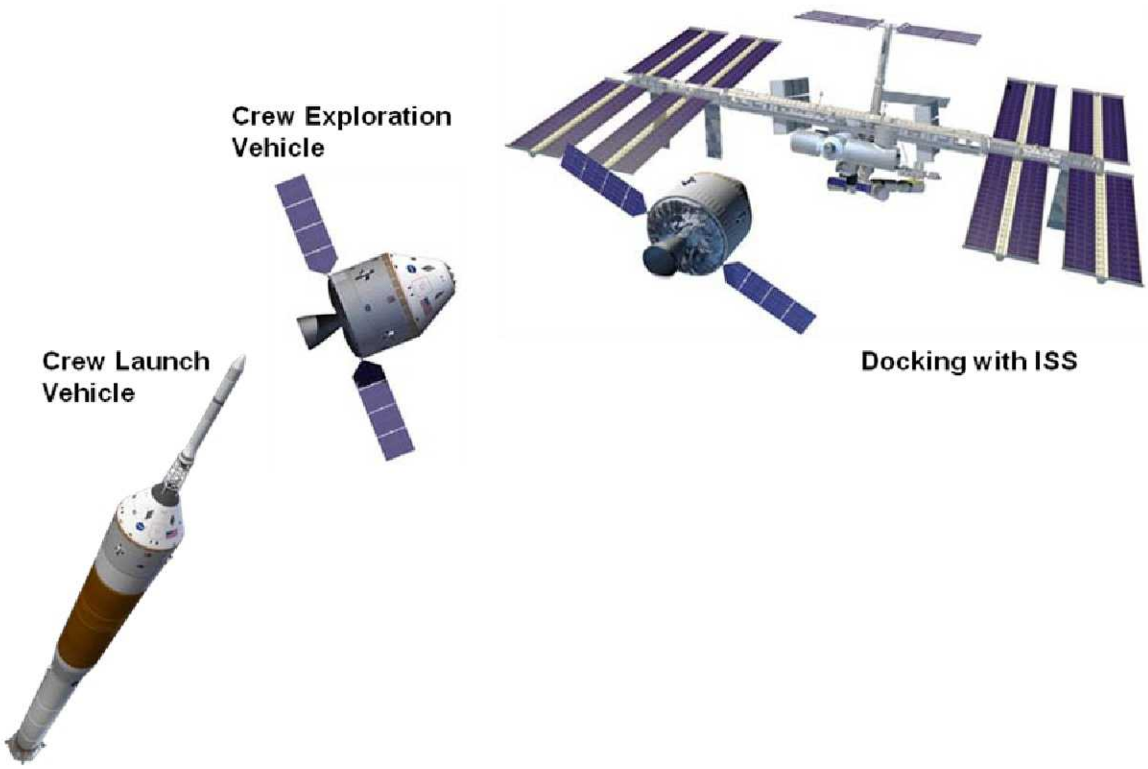

Figure 4: ISS DRM

3.3 *Mars DRM*

The Mars Design Reference Mission employs conjunction-class missions, often referred to as long-stay missions, to minimize the exposure of the crew to the deep-space radiation and zero-gravity environment while at the same time maximizing the scientific return from the mission. This is accomplished by taking advantage of optimum alignment of the Earth and Mars for both the outbound and return trajectories by varying the stay time on Mars, rather than forcing the mission through non-optimal trajectories as in the case of

[5] Constellation Program. (March 21, 2010). In Wikipedia. Retrieved March 30, 2010 from http://en.wikipedia.org/wiki/Constellation_program#Missions

the short-stay missions. This approach allows the crew to transfer to and from Mars on relatively fast trajectories, on the order of six months, while allowing them to stay on the surface of Mars for a majority of the mission, on the order of 18 months. The working assumption for crew size is six, based on previous analysis. The surface exploration capability is implemented through a split mission concept in which cargo is transported in manageable units to the surface, or Mars orbit, and checked out in advance of committing the crews to their mission. The split mission approach also allows the crew to be transported on faster, more energetic trajectories, minimizing their exposure to the deep-space environment, while the vast majority of the material sent to Mars is sent on minimum energy trajectories. Emphasis is placed on ensuring that the space transportation systems are designed to be flown in any Mars injection opportunity. This is vital in order to minimize the programmatic risks associated with funding profiles, technology development, and system design and verification programs.[5]

4 Element Overviews

4.1 Orion

The Orion System consists of a Crew Module (CM), a Service Module (SM), a Launch Abort System (LAS), and a Spacecraft Adapter (SA), and transports crew and cargo to orbit and back. The Orion System will be used in all phases of the CxP. Initially, the Orion transports crew to and from the ISS. It will subsequently transport crew and cargo to and from a lunar orbit for short and extended duration missions. Finally, the Orion or a derivative will support missions to a Mars Transfer Vehicle, and then return the crew and cargo to Earth after separation from the vehicle. There may be unique configurations to accommodate the needs of each defined DRM.

Orion is the spacecraft used to transfer flight crews, cargo, and support equipment from Earth to Low Earth Orbit (LEO) or lunar orbit, and subsequently return the crew to Earth's surface. For a lunar mission, the Orion must first rendezvous with the Earth Departure Stage (EDS)/Altair which will be loitering in LEO. For the trans-lunar portion of the mission the Trans-Lunar Injection (TLI) burn will be performed by the EDS. Subsequent course correction maneuvers will be performed by Altair. In conjunction with Altair and EDS, the Orion delivers the flight crew to Low Lunar Orbit (LLO) and subsequently loiters there without crew onboard while the lunar surface expedition is performed. After returning to orbit with Altair, the crew transfers back to the Orion, and the Orion returns the crew to Earth.

The Orion is comprised of four distinct modules: a Launch Abort System (LAS), a Crew Module (CM), a Service Module (SM), and a Spacecraft Adapter (SA). These modules are seen from left to right in Figure 7.[6]

[6] Constellation Program and Project Overview. Kenneth S. Reightler, Vice President, NASA Program Integration. Lockheed Martin Space Systems Company. November 6, 2007. Retrieved March 30, 2010 from www.californiaspaceauthority.org/.../071106-1300-Reightler.pdf

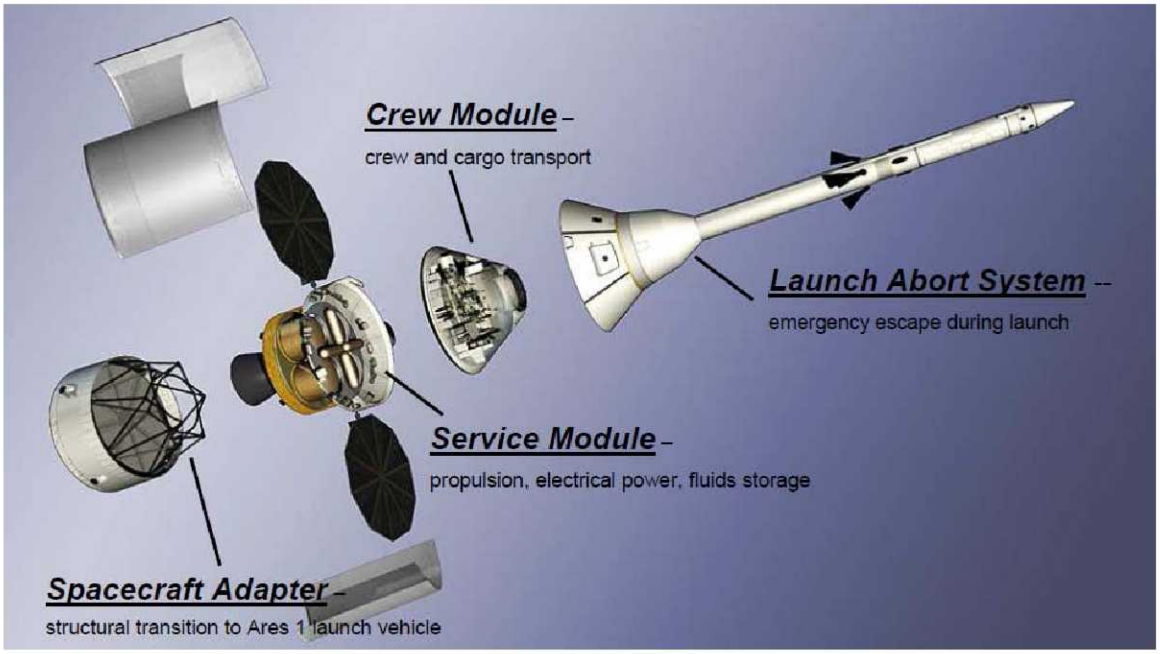

Figure 5: Expanded Orion Layout[7]

5 Overview of the Orion CEV Parachute Assembly System (CPAS)

Prior to the Orion SRR, the Orion CPAS was comprised of three major components: the Forward Bay Cover (FBC), two Drogue parachutes, and three Main parachutes. All components of the Orion CPAS are located in the Forward Bay of the Crew Module (CM).

The purpose of the FBC is to protect the entire Landing & Recovery System (LRS) components through all phases of the mission. Prior to deployment of the Drogue parachutes, the FBC is jettisoned by deploying two Pilot parachutes. Each of the FBC Pilot parachutes are deployed via mortars.

Post-FBC jettison, the two Drogue parachutes were to then be deployed simultaneously via mortars. Each Drogue parachute possessed a single stage of reefing to help manage the aerodynamic loads imposed on the parachutes. After each Drogue parachute completed their respective reefs, they would be used to decelerate and stabilize the Orion Crew Module (CM). Once the CM became stable and achieved a desired dynamic pressure necessary for the Main parachute deployment, the two Drogue parachutes would then be released by pyrotechnic-initiated cutters.

After the Drogue parachutes were released, three Pilot parachutes would simultaneously be deployed via mortars. After the Pilot parachutes inflate, they would independently

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[7] Constellation Program and Project Overview. Kenneth S. Reightler, Vice President, NASA Program Integration. Lockheed Martin Space Systems Company. November 6, 2007. Retrieved March 30, 2010 from www.californiaspaceauthority.org/.../071106-1300-Reightler.pdf

extract each of the Main parachutes from the CM Forward Bay. As with the Drogue parachutes, the Main parachutes were also reefed to help manage the loads. However, the lone difference between the two was that the Main parachutes had two reefing stages as opposed to one for the Drogue parachutes. When the Main parachutes attained full inflation, they would remain attached to the CM until landing either on water or land. Once the CM lands, the three Main parachutes would then be released via pyrotechnic-initiated cutters.[8]

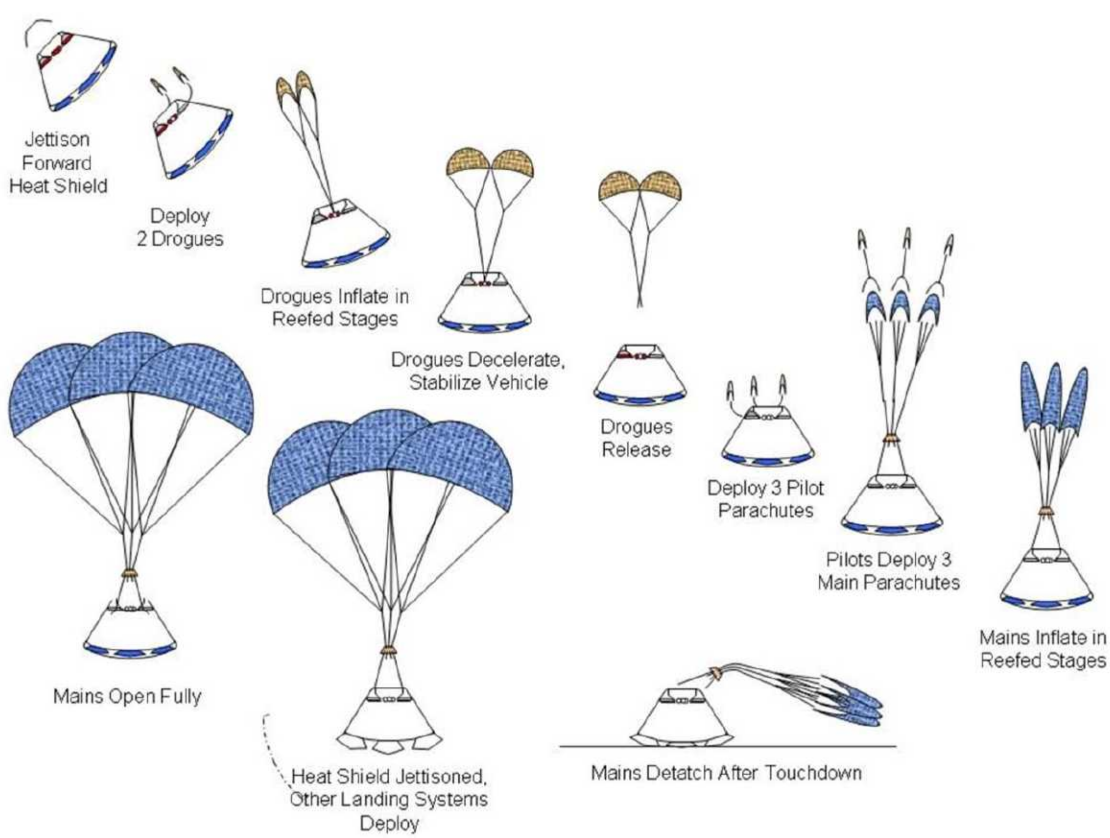

Figure 6: Notional LRS Sequence of Events[9]

6 Development of the Orion CPAS Main Parachute Failure Probability

As part of the Orion Risk Informed Design (RID) process, LOC/LOM probabilities were a key figure of merit used to determine how much system redundancy to place on the vehicle. With human-rated spacecraft, the majority of the systems tend to be similar. Thus, the data used to generate the Orion LOC/LOM probabilities were primarily heritage based numbers from the Space Shuttle Program (SSP) and the International Space Station (ISS) program. Given that Lockheed Martin did not have many of the

[8] Constellation Program. (March 21, 2010). In Wikipedia. Retrieved March 30, 2010 from http://en.wikipedia.org/wiki/Constellation_program#Missions
[9] http://www.nasa.gov/images/content/156596main_Orion_Sequence_500.jpg

Orion spacecraft vendors under contract at the beginning of the RID process, the project agreed to use SSP and ISS heritage based data.

This worked well for many of the Orion system and subsystem trades. However, there were some systems/subsystems that Orion had in their current design that SSP, ISS, or both did not utilize. One of the more obvious subsystem differences was that of the Landing & Recovery System (LRS). Obviously, the ISS does not have a LRS since it is a permanent fixture in Low Earth Orbit (LEO). Since the Orbiter is considered to be a reusable spacecraft, it must have the capability to return to Earth and therefore has a LRS. However, the main difference between the Orbiter and Orion is how each spacecraft lands.

The Orbiter lands very similarly as to how an airplane does. After the Orbiter re-enters the atmosphere, it basically utilizes its two wings and elevons to glide down to the Primary Landing Site (PLS) runway. Once the Orbiter approaches the PLS, the landing gear is deployed. After touchdown, a Drag Parachute is deployed from the aft part of the Orbiter to help decrease its speed after touchdown. Orion's basic design does not include any type of wings as it is a capsule. Thus, Orion has no capability to guide the vehicle to a specific landing site after entry. Once Orion has re-entered the Earth's atmosphere and achieved a certain speed and dynamic pressure, parachutes are used to slow Orion to a safe velocity for landing. Due to the large differences in the Orbiter and Orion landing systems, Orion Safety & Mission Assurance (S&MA) Analysis Section personnel were asked to help develop an initial failure probability for the Orion CPAS Main Parachute. The following sections detail the data used in developing the CPAS main parachute failure probability.

6.1 NASA's Smart Buyer Parachute Failure Probability Estimate

In January, 2006, the Crew Exploration Vehicle (CEV) Smart Buyer Design effort was chartered to develop an in-house design of the CEV. The in-house design was used by the CEV Project to assess driving requirements and alternatives. To accomplish this task, an Agency-wide team was assembled with representatives from all ten NASA Centers and from NASA Headquarters. Due to the short duration of the design effort, the Smart Buyer Team (SBT) concentrated on a limited number of trade study areas. Included as one of the selected trade areas, was the Landing and Recovery System (LRS). As part of the Smart Buyer Design effort, trade studies were conducted on the reliability of the LRS. As a result of the SBD effort, a failure probability for the CEV main parachutes was developed. The resultant failure probability was used by NASA to help generate requirements for the following year.[10] Actual data and results of the SBT parachute failure probability are not included in this paper due to Export Control policy at NASA.

6.2 CxP Main Parachute Failure Probability Estimate

[10] NASA Engineering & Safety Center (NESC) Supporting the Constellation Program. NESC Update: Volume 4. August 2006.

In 2007, after the Smart Buyer Design effort ended, the CxP began to develop preliminary LOC/LOM estimates for the Lunar Sortie and ISS Crewed Design Reference Missions (DRMs). In both DRMs, the Orion spacecraft is utilized which implies the CPAS must operate in order to complete either DRM successfully. In these preliminary stages of evaluating LOC/LOM, analysis personnel adopted the parachute failure probability that was developed by the SBT. This was due in large part to limited resources and a very demanding schedule. However, after consulting with CPAS engineering personnel and Orion LRS personnel, it was decided that the SBT parachute failure probability was not very representative of the Orion CPAS main parachutes. Thus, it was collectively agreed to that NASA S&MA Analysis Section personnel would develop a new failure probability for the Orion CPAS main parachutes.

Instead of using Jeffrey's Non-Informative Prior, CxP Analysis personnel chose to develop the main parachute prior based on Apollo, Soyuz, and Military data. This was due to the fact that the majority of the data had been recorded in roughly the same time period. Once the prior was established in the form of a Beta distribution, it would then be Bayesian updated with the more recent Space Shuttle SRB parachute data using the Beta-Binomial conjugate pair. The following sections detail the data used in that process.

6.2.1 Apollo Parachute History

During the Apollo Program, there were a total of fifteen launches. Eleven of those launches were for a lunar mission and four launches for non-lunar missions. The four non-lunar missions included three to Skylab and one for the Apollo-Soyuz Test Program (ASTP). Each of the fifteen Apollo missions used three main parachutes. This resulted in a total of forty-five demands (15 missions x 3 main parachutes per mission). Out of those fifteen Apollo missions and forty-five demands, there was only one documented parachute failure. That failure occurred during the descent portion of the Apollo 15 mission.11

During the descent portion of the Apollo 15 mission, the three main parachutes had operated properly starting at 3,050 meters and had fully reefed. At approximately 1,825 meters, one of the three main parachute canopies collapsed. This left the Apollo 15 Command Module (CM) with two functioning parachutes. Fortunately, the CM was able to safely land with two of the three main parachutes functioning. The lone parachute canopy that collapsed was never recovered so the exact cause of failure is not exactly known. However, after inspecting one of the two main parachutes that functioned, it was discovered the Reaction Control System (RCS) may be to blame.

[11] Apollo Lunar Surface Journal, Mission Report, Part 6. http://history.nasa.gov/alsj/frame.html

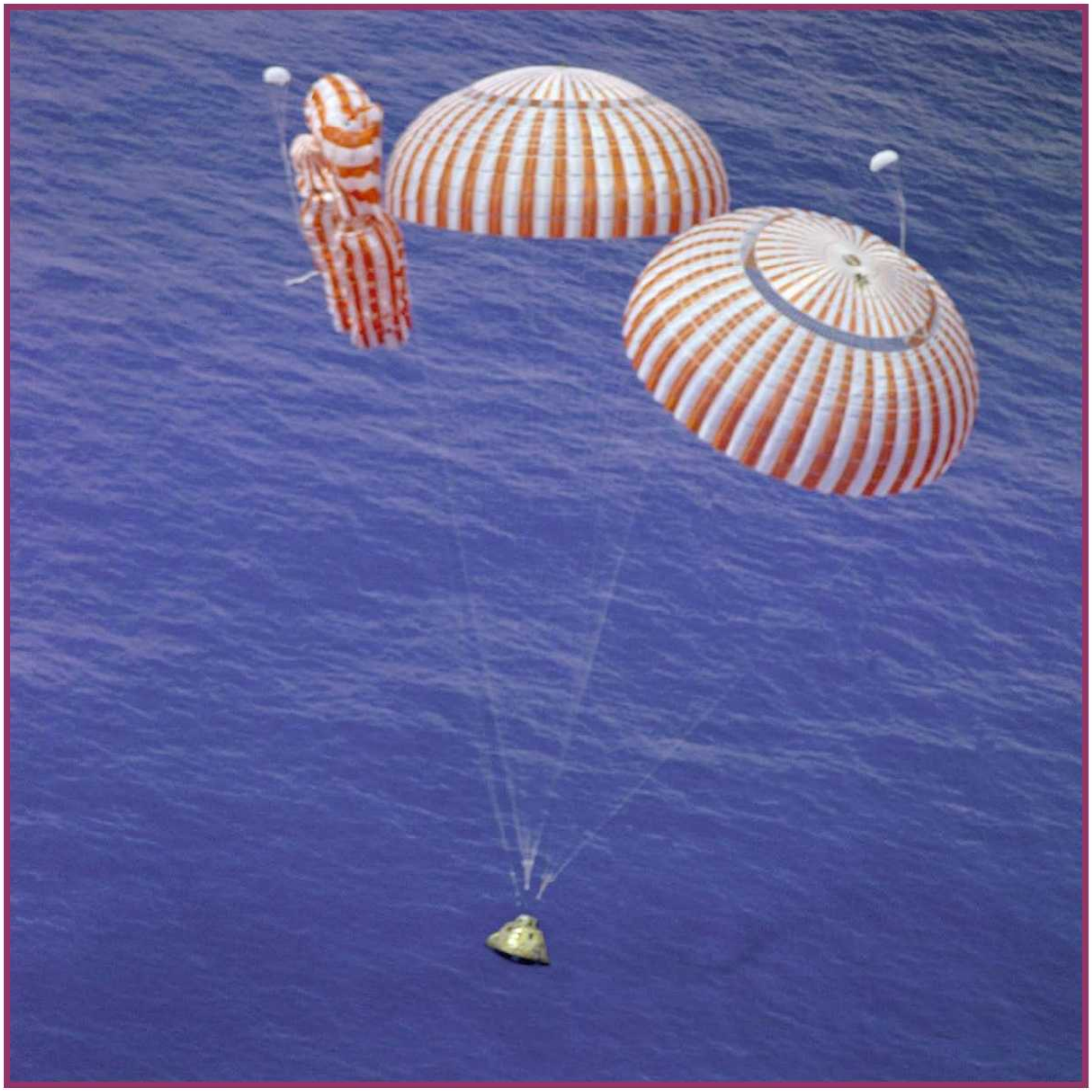

Figure 7: Apollo 15 Main Parachute Failure

Once other possible failure modes were ruled out, it was concluded that RCS fuel was dumped after the main parachutes were fully inflated. A portion of the RCS fuel dump was ignited as it was being expelled and made contact with some of the main parachute riser and suspension lines. This resulted in the riser and suspension lines melting causing the canopy collapse. This failure did not occur to any previous Apollo flights simply because of the main parachute locations during the RCS fuel expulsion. Apollo 15 just happened to have one of the three main parachutes located directly above the RCS engines during this exercise. As a result of the findings, NASA made both material and procedural changes to avoid any potential catastrophic failures in the future. These known changes made to the Apollo parachute system allowed for the analysts to discount

the failure by 90%. Instead of counting a full failure, only .1 failures were counted towards the Apollo parachute data. [12]

6.2.2 Soyuz Parachute History

Between the end of the Smart Buyer Design and CxP developing a new main parachute prior, Soyuz had an additional six launches. Combining these six additional launches with the ninety-three that the SBT considered, CxP assessed a total of ninety-nine Soyuz launches. Of the ninety-nine launches there was only one failure. That failure occurred on Soyuz 1 in 1967.

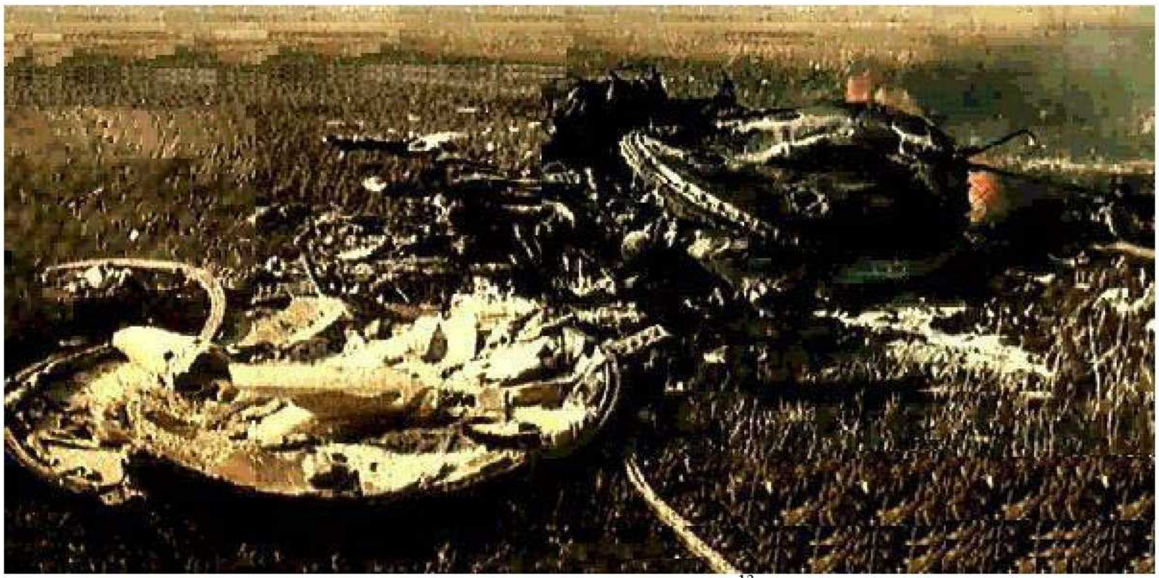

Figure 8: Soyuz 1 Crash Site[13]

Re-entry of Soyuz 1 was successful as was the deployment of the drogue parachute. However, due to a pressure sensor failure, the main parachute did not deploy. After the main parachute failed to deploy on its own, the cosmonaut attempted to deploy the reserve main parachute manually. The reserve main parachute deployed but was soon entangled with the drogue parachute which had not been released. Normally, the drogue parachute would have been released upon deployment of the main parachute. Given the main parachute never deployed, the drogue parachute was never released. Since the Soyuz 1 catastrophe, there have been no known fatal parachute events in the subsequent Soyuz flights. As with the Apollo parachute data, the lone Soyuz parachute failure was discounted. This was accomplished given the fact that there has not been a Soyuz parachute failure since the Soyuz 1 incident. However, unlike Apollo, the Soyuz failure was only discounted by 50% due to the lack of insight as to how the Russians were able

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[12] Arabian, Donald D. and Joseph E. Mechelay, "Apollo 15 Main Parachute Failure." 7th Aerospace Mechanical Symposium, Houston, TX: NASA Lyndon B. Johnson Space Center, 1972. P 137-148.

[13] Soyuz 1, http://www.astronautix.com/flights/soyuz1.htm

to fix/modify the Soyuz parachute system following the Soyuz 1 catastrophe. In this case, only .5 failures counted towards the Soyuz parachute failure probability.[14]

6.2.3 Military Parachute Data

A previous NASA Engineering & Safety Center (NESC) study concerning the Crew Exploration Vehicle (CEV) LRS used eight years (1968-1975) of military data to help assess the main parachute failure of probability. The military data was based on unmanned supply drops and included both procedural and equipment failures. Only the equipment failures were considered for calculating the main parachute prior.

TABLE 6.14 8-YEAR SUPPLY/EQUIPMENT DROP RECORD

	1968		1969		1970		1971		1972		1973		1974		1975	
Number of Drops	23,321		15,102		17,084		15,684		7,649		6,836		5,837		5,475	
Number of Malfunctions	183		126		163		86		68		90		53		70	
Percentage of Malfunctions	0.78		.83		0.95		0.54		0.88		1.31		0.91		1.28	
Malfunction Phases:	EF	IP	EF	IP	EF	IP	EF	IP	EF	IP	EF	IP	EF	IP	EF	IP
Extraction or Ejection	2	91	1	36	3	42	3	15	0	11	0	13	0	4	11	1
Deployment Recovery	5	76	22	58	7	54	6	47	4	43	29	41	13	32	32	18
Release	0	10	1	8	3	5	0	11	2	7	2	5	3	1	5	3

EF = Equipment Failure
IP = Incorrect Procedure

Figure 9: Generic Military Parachute Data

Unfortunately, the state of knowledge regarding the military data is very low. For instance, based on the military data below, it is unclear as to how many parachutes were used in each drop. We also do not know if any design or material changes were implemented to correct any of the failures. Without this knowledge, the analysts were unable to discount any of the recorded equipment failures. However, this set of data does provide a significant number of drops unlike the Apollo, Soyuz, or SSP SRB data.

Assuming each supply/equipment drop is equivalent to one demand, there is a total of ninety-six thousand nine hundred eighty-eight demands over the eight year period. During the eight year span, there were also a total of one hundred fifty-four equipment failures. The resulting parachute failure probability over the eight year period equated to 1.6E-03.[15]

6.2.4 Space Shuttle Program (SSP) Solid Rocket Booster (SRB) Parachute History

Every Space Shuttle launch utilizes two Solid Rocket Boosters (SRBs) during the Ascent portion of the mission. Each of the SRBs is equipped with a parachute system so they

[14] MIR Hardware Heritage, Part 1. http://spaceflight.nasa.gov/history/shuttle-mir/references/r-documents.htm

[15] Recovery Systems Design Guide. Air Force Flight Dynamics Laboratory AFFDL-TR-78-151. Wright-Patterson AFB, OH. Irvin Industries Inc. Gardena, CA. December 1978.

can be recovered and refurbished for future launches. The SRB parachute system consists of a drogue parachute and three main parachutes. Below, Figures 10 and 11 displays what a typical SRB looks like during descent and at splashdown.

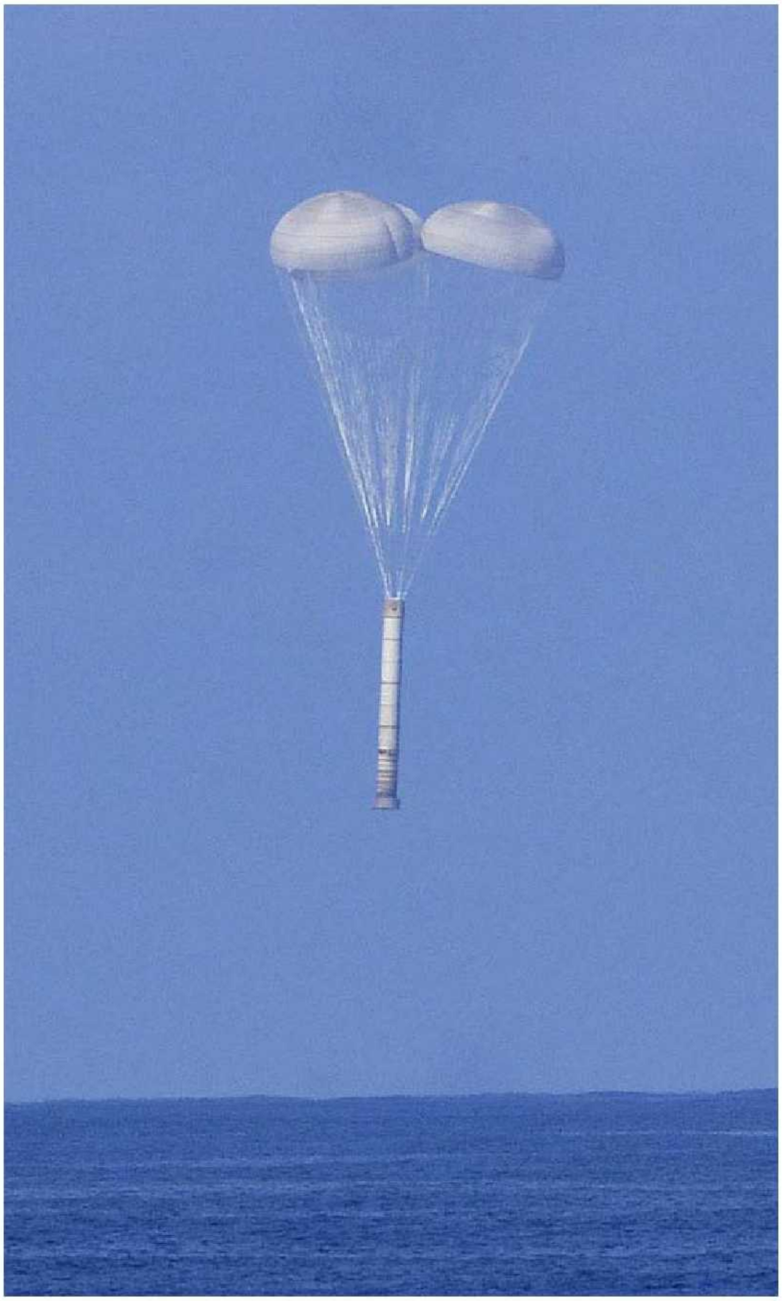

Figure 10: Typical SRB Descent[16]

[16] http://gcaptain.com/maritime/blog/interesting-ship-week-nasa-recovery/

Figure 11: Typical SRB Splashdown[17]

At the time of this analysis, Space Shuttle launches STS-1 thru STS-124 were considered as relevant data. This set of launch data did not include STS-51L (Challenger) due to the catastrophe suffered during Ascent. After discussions with SRB Reliability personnel, it was noted that many upgrades had been made to the SRB parachutes over the years. Primarily, the majority of the updates occurred prior to the Challenger accident. As a result the SRB main parachute failure rate has decreased over the years. To account for the decrease in failure rate, only the SRB main parachute data post-Challenger was considered. Prior to Challenger, there were a total of twenty-five Space Shuttle launches. Subtracting those away from the total number of launches left a total of ninety-eight launches to assess. To get the likelihood of a single SRB main parachute, the total number of failures, post-Challenger, was divided by the total number of demands. The total number of demands is equates to 98 missions x 2 SRBs x 3 main parachutes per SRB. This resulted in a total of five hundred eighty-eight demands. In order to comply with Export Control policy, the z = total number of SRB failures in the ninety-eight missions.

With the given data, the SRB main parachute Likelihood can be calculated by dividing the number of failures considered, z, by the total number of demands (588). Doing so produced a Likelihood value of $(z/588)$per demand.

7 Calculating the CPAS Main Parachute Prior & Posterior

[17] http://gcaptain.com/maritime/blog/interesting-ship-week-nasa-recovery/

As mentioned above, the course of action to produce a failure probability for the CPAS Main parachute was to develop a prior based on discounted-Apollo, discounted-Soyuz, and Military data. Given the sets of data reflected demand events, the resulting prior distribution was a Beta with $\alpha = 0.2$ and $\beta = 82.7$. The prior data and data sources are summarized below in Figure 14.

The generic data sources:

Source	Comments	Failures	Demands	Mean	Variance
Soyuz	One discounted failure	0.5	99	5.1E-03	5.1E-05
Apollo	One discounted failure	0.1	45	2.2E-03	4.9E-05
AFFDL-TR-78-151	Nine years of Army drops	154	96,988	1.6E-03	1.6E-08

The resulting prior:

Distribution	Mean	Mean^{-1}	α	β	"EF"
Beta	2.95E-03	339	0.2	82.7	8.1

Figure 12: CPAS Main Parachute Prior Summary

Now that the CPAS Main parachute prior distribution has been established as a $\beta(0.2, 82.7)$, the Beta-Binomial conjugate pair can be used to determine the posterior distribution. This is the same process as used in the SBT Bayesian update for the CEV Main parachute failure probability (Section 6.1).

To re-iterate, the Beta-Binomial conjugate pair states that if the prior distribution, π_o, is a Beta distribution with α and β as the parameters, one can Bayesian update π_o with Likelihood data in the form of a Binomial distribution where x = total number of failures and N = total number of trials. The resulting posterior distribution, π_1, is in the form of a Beta distribution with the parameters of α + x and β + N – x. The mean of π_1 can be calculated as $\bar{x} = (\alpha + x)/(\alpha + \beta + N)$. In this case, $\alpha = 0.2$, $\beta = 82.7$, x = z, and N = 588.

Now with a Beta distribution as the prior, and a Binomial distribution as the Likelihood, the posterior distribution for the CPAS main parachute can be formed as a Beta distribution. The resulting posterior Beta distribution parameters would be $\alpha' = .2 + z$ and $\beta' = 82.7 + 588 - z$. The resulting mean of the posterior distribution would be calculated as follows:

$$\bar{x} = [(.2 + z)/(.2 + 82.7 + 588)]$$

7.1 Issues with the Results

As the results shown above in Figure 16 were presented to the CPAS Project, several concerns were raised regarding the relativity of the data. Two of the four data sources used (Military data and SRB data) utilized parachute systems that were not human-rated. The Soyuz is considered a human-rated vehicle. However, the parachute system uses a single main parachute as opposed to a cluster of three. However, out of all the human-rating and configuration deltas, the largest concern was the lack of Apollo data. There were only a total of fifteen missions, or forty-five demands. As a result of this concern, an effort was launched to try and find all of the test data from the Apollo parachute system. Several documents were found to have Apollo parachute test data recorded. However, the data was recorded in such a manner, that the analysts were unable to tell which configuration was tested and exactly what component failed during the test. To date, CPAS engineering personnel are still attempting to find relevant Apollo parachute test data with no success thus far.

8 Summary

With any future, human-rated spacecraft NASA develops, finding appropriate data to help quantify a system/sub-system/component risk will be necessary. Unfortunately, due to the cost of human spaceflight and all of the associated testing, there will always be a shortage of useful data. As a result, NASA will continue to use surrogate data to develop prior distributions and initial posterior distributions. The work done to quantify the initial CPAS main parachute has been instrumental in educating the engineering directorates about Bayesian updating. Multiple lessons learned have also been taken from this exercise in hope of refining the techniques for quantifying other system/sub-system/components located on future human spaceflight vehicles.