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Constellation Program (CxP) Crew Exploration Vehicle (CEV) Project Integrated Landing System

John D. Baker
Jet Propulsion Laboratory, Pasadena, California

Daniel E. Yuchnovicz/NESC
Langley Research Center, Hampton, Virginia

David J. Eisenman and Scott G. Peer
Jet Propulsion Laboratory, Pasadena, California

Edward L. Fasanella
Langley Research Center, Hampton, Virginia

Charles Lawrence
Glenn Research Center, Cleveland, Ohio

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Volume I: Assessment Report

1.0 Notifi cation and Authorization

This assessment was initiated out-of-board by the authority of the NASA Engineering and Safety Center (NESC) Director on October 13, 2006. Julie Kramer White, Crew Exploration Vehicle (CEV) Chief Engineer requested a risk comparison of the Integrated Landing System design developed by NASA and the design developed by Contractor– referred to as the LM 604 baseline. Based on the results of this risk comparison, the CEV Chief engineer requested that the NESC evaluate identified risks and develop strategies for their reduction or mitigation. The assessment progressed in two phases.

A brief Phase I analysis was performed by the NESC team to compare the CEV Integrated Landing System proposed by the Contractor, as defined in the LM 604 baseline, against the NASA TS-LRS001 baseline with respect to risk (safety and reliability).

During the Phase II effort, the NESC team further examined the areas of critical importance to minimizing the overall landing risk, including risk to the crew and the Crew Module (CM) during a nominal land-landing. The areas studied included:

Task 1: Landing System Risk Assessment - Estimate the risk to the crew during landing using the LM 606 baseline and postulated landing attenuation system configurations.

Task 2: Landing System Test and Verification (T&V) Approach - Assess the CEV Project's T&V approach to determine the level of residual risk.

Task 3: Landing Site Accessibility and Availability - Evaluate implications of relying on wind limits to ensure that horizontal velocity at touchdown remains within the CM design capability.

Task 4: CM Roll Control in Preparation for Landing – Assess the requirements and capability of the CM roll control concept to orient the CM for an acceptable landing.

Task 5: Investigate Parachute Effects during Landing - Investigate parachute induced effects on CM stability during landing near or beyond the CM's horizontal velocity capability.

Task 6: Crew Protection System Enhancements – Develop tools to evaluate enhanced crew restraints and develop restraint concepts that would enhance crew safety during high-g impacts or CM tumbling

The key stakeholders for this assessment were Ms. Julie Kramer White at the Johnson Space Center (JSC), and Mr. Christopher Johnson, JSC, who served as the CEV Project Office liaison.

2.0 Signature Page

Submitted by:
Team Signature Page on File – 12/1/09

Mr. John D. Baker Date	Mr. Daniel E. Yuchnovicz Date

Significant Contributors:

Mr. David J. Eisenman Date	Mr. Scott G. Peer Date
Dr. Edward L. Fasanella Date	Dr. Charles Lawrence Date

Signatories declare the findings and observations complied in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analysis, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
John Baker	Team Lead	JPL
David Eisenman	Deputy Lead	JPL
Daniel Yuchnovicz	NESC SEO	LaRC
Scott Peer	Systems Engineering	JPL
Charles Lawrence	Landing Simulation	GRC
Ed Fasanella	Landing & Recovery	LaRC
Consultants		
Brian Bairstow	Systems Engineering	JPL
George Chen	Systems Engineering	JPL
Courtenay Clifford	Safety and Mission Assurance	JSC
Chris Johnson	NASA CEV Project System Engineering	JSC
Wayne Lee	Systems Engineering	JPL
Blake Putney	Risk Assessment	Valador
Malcolm Cohen	Human Factors	NASA, ARC (Retired)
Phil Glynn	Peer Review	SAIC
T.K. Mattingly	Peer Review	Space Planning and Analysis, Inc.
Jerry McCullough	Peer Review	SAIC
Dave Shemwell	Systems Engineering	Space Planning and Analysis, Inc.
Milt Silvera	Peer Review	SAIC
Al Tabiei	SAIC	University of Cincinnati
Bob West	Peer Review	SAIC
Support Personnel		
Lisa McAlhaney	Program Analyst	LaRC
Linda Burgess	Planning & Control Analyst	LaRC, ATK
Christina Cooper	Technical Writer	LaRC, ATK

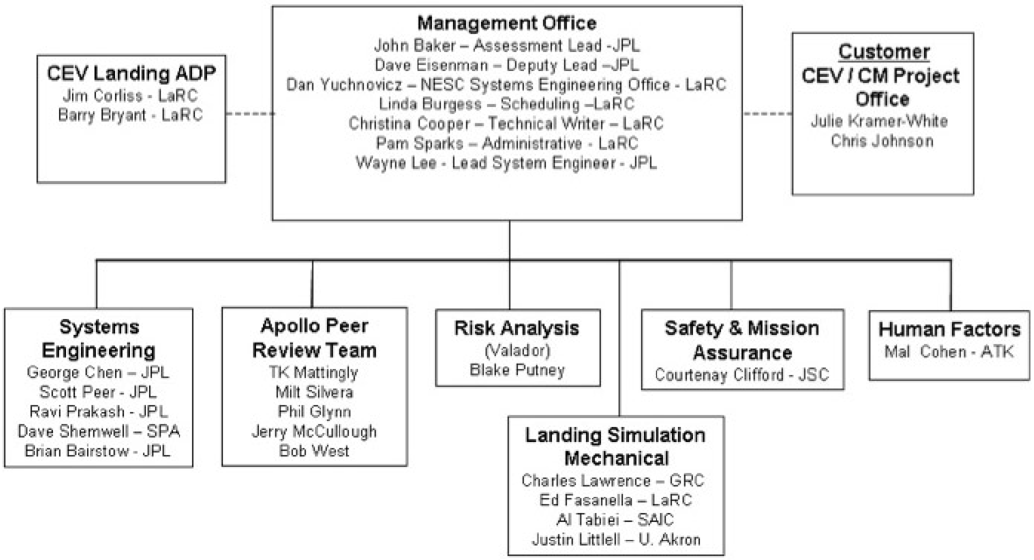
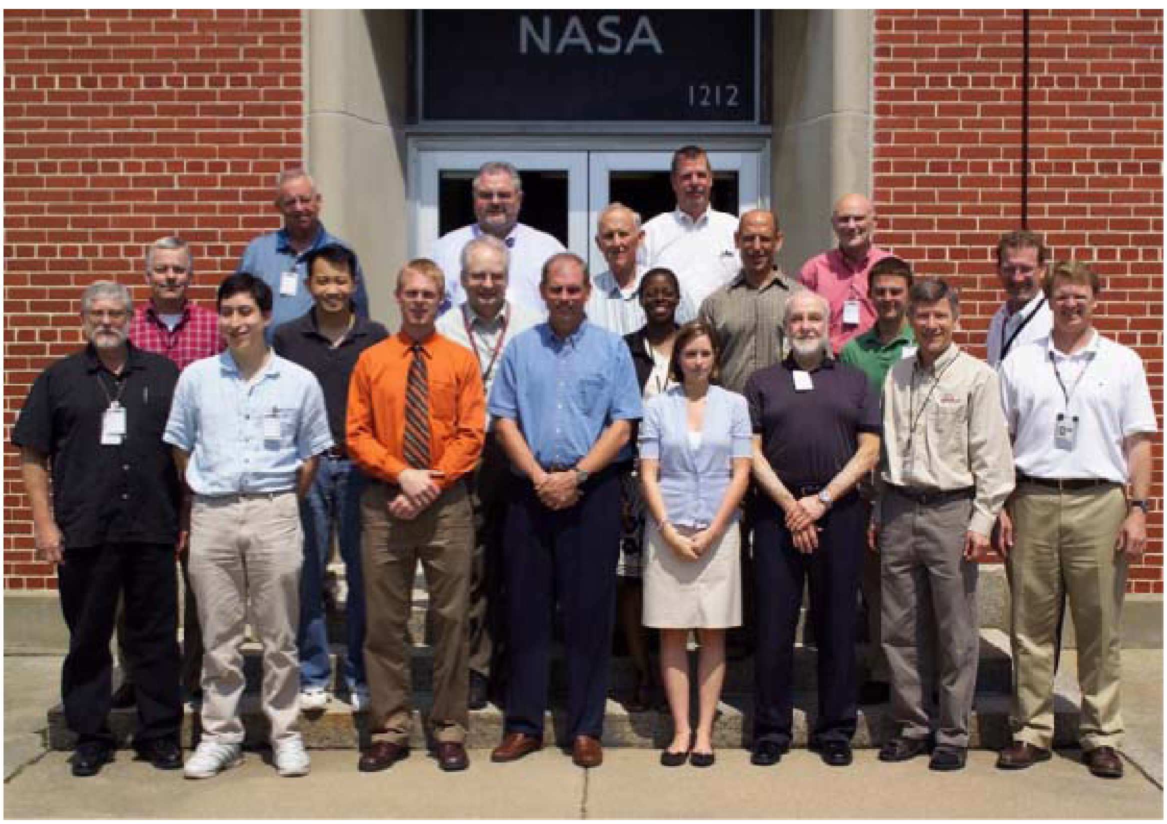


Figure 3.0-1. CEV Integrated Landing Assessment Team Structure



Front row: David Eisenman, Brian Bairstow, Chris Johnson, Blake Putney, Christina Cooper, Mal Cohen, Scott Peer, John Baker
Second Row: Dave Shemwell, Wayne Lee, Ed Fasanella, Bob West, Debora Briggs, Chuck Lawrence, Dan Yuchnovicz
Third Row: Phil Glynn, Jim McMichael, Jeff Cyphert, T.K. Mattingly

4.0 Executive Summary

This assessment was performed in two phases. A brief Phase I analysis was performed by the Water versus Land-Landing Team (NESC Assessment Number 06-020-E) to compare the Crew Exploration Vehicle (CEV) Integrated Landing System proposed by the Contractor, as defined in the LM 604 baseline, against the NASA TS-LRS001 baseline with respect to risk (safety and reliability). A phase II effort examined the areas of critical importance to the overall landing risk, evaluating risk to the crew and to the CEV Crew Module (CM) during a nominal land-landing.

Phase I Results Summary

The Phase I analysis was performed to compare the CEV Integrated Landing System proposed by the contractor Lockheed Martin (LM), as defined in the LM 604 baseline, with the NASA TS-LRS001 baseline with respect to risk factors potentially leading to severe injury or loss of crew (LOC). Due to the early stage of development for both systems, insufficient detail exists for either a numerical risk analysis or reliability calculation, thus the following approach was utilized:

- Focus on potential design reliability - mass, volume, cost, and complexity were secondary considerations unless obvious concern existed.
- Compare the two designs with the proven Apollo Earth Landing System (ELS).
- Use existing design and performance data from NASA and LM CEV teams.
- Do not incorporate preliminary requirements changes from the CEV Project's Requirement Analysis Cycle-3 (RAC-3) because the NESC task was run in parallel with RAC-3 activities.
- Develop a functional description for each baseline (functional block/event sequence diagram).
- Quantify/evaluate the relative risks of each function.

The end result of the comparison/evaluation is summarized in Figure 4.0-1. A list of ten concerns (C1–C10) and associated NESC recommendations were generated. The major concerns included:

- C1 - LM 604 - Use of a single drogue to extract all the main parachutes was viewed as a critical single point failure.

- C2, C4 LM 604 - 600 lbm confluence retro-rocket pack mounted at the confluence point on the main parachute harness is viable, but will require an extensive development and validation program. Primary concerns include deployment without contacting CM retrorocket plume impingement, parachute risers, and retrorocket pack (200 lbm) re-contact with CM after touchdown.

- C3 - LM 604 - The use of horizontal wind velocity limits for LM 604 was unproven for effectiveness. Insufficient data had been produced to demonstrate that relying on operational wind limits without horizontal retrorockets was a viable design option.

C5 - LM 604, TS-LRS001 – The reliability and robustness of the apex/Forward Bay Cover (FBC) separation system needs to be improved to ensure high reliability and adequate clearance with the CM during the mission descent phase. Failure to deploy the FBC would result in LOC.

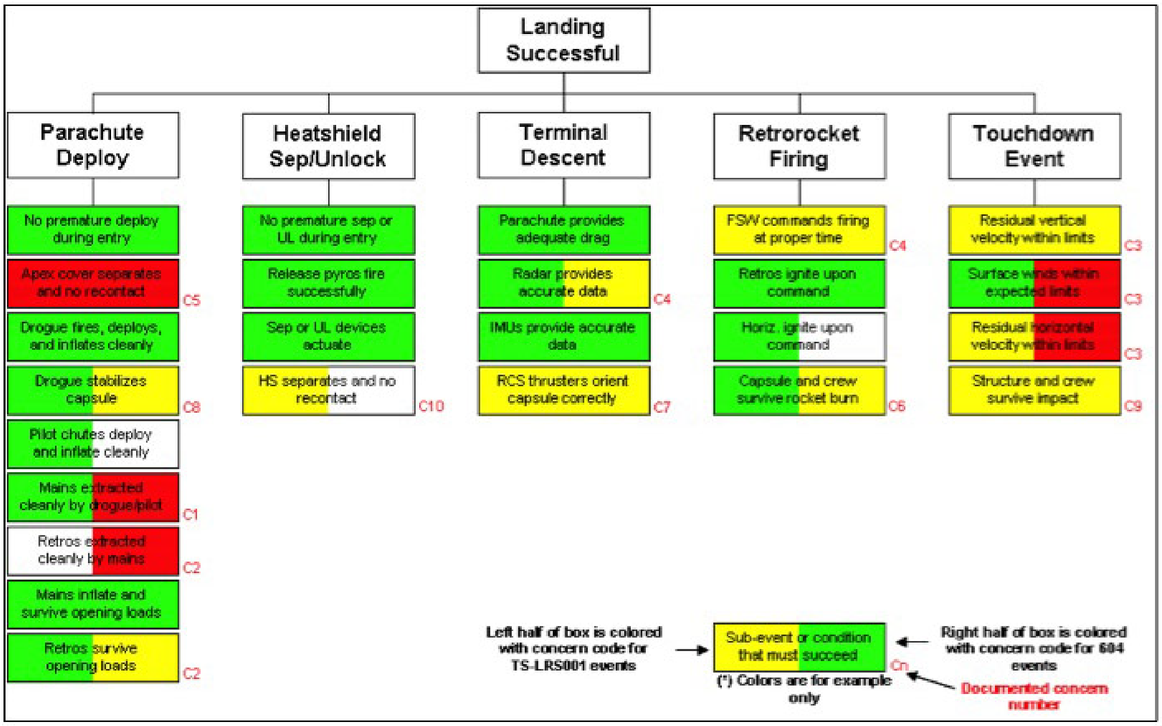


Figure 4.0-1. Risk Comparison of the NASA TS-LRS001 and LM 604 Landing and Recovery System Baselines

The findings were presented to Julie Kramer White and the CEV Project Configuration Control Board (CPCB) on December 2006. Key team members of the NESC Water versus Land-Landing Assessment were used to perform this task and were critical in influencing the CEV Project and Contractor decision to adopting the NASA TS-LRS001 design as the baseline configuration.

Phase II Results Summary

A systems approach was required to assess the overall risks since the Landing System design can affect multiple CEV subsystems and will operate in a range of landing environments. Figure 4.0-2 summarizes the six tasks and their relationships.

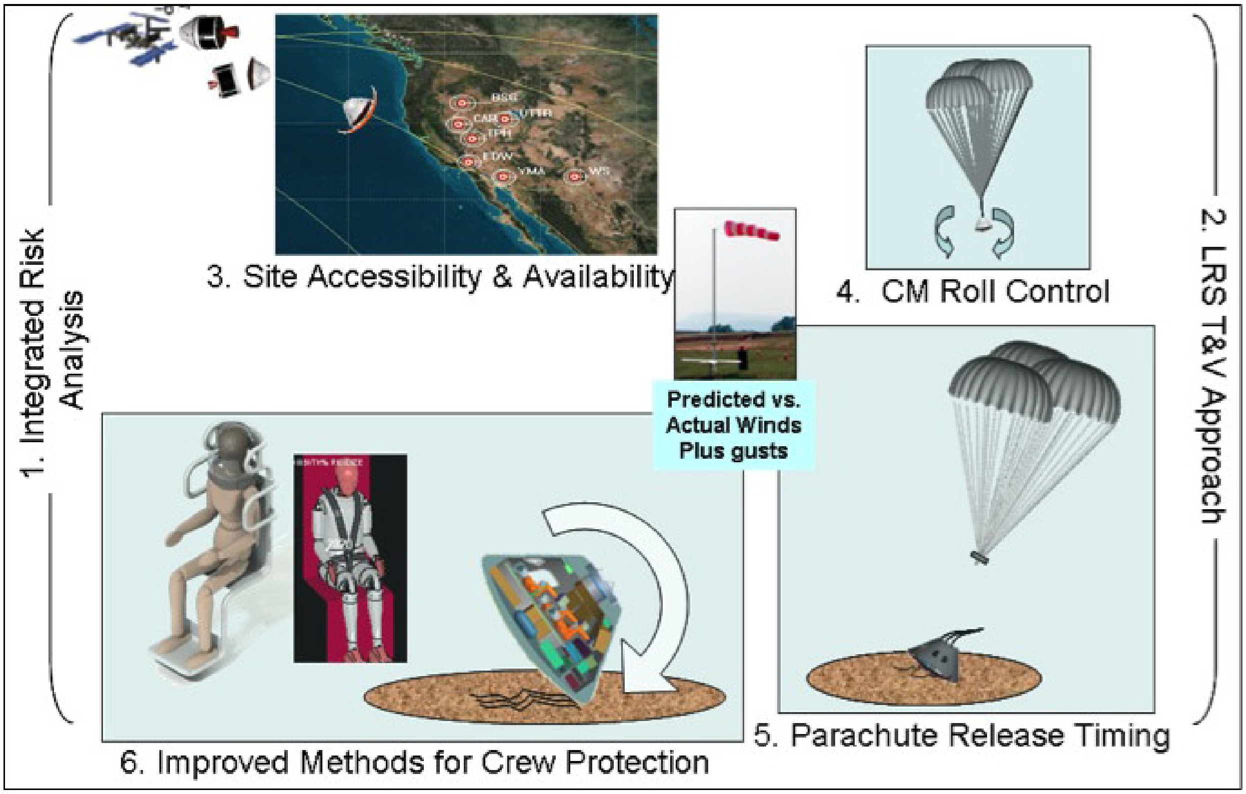


Figure 4.0-2. Systems Approach to the Integrated Landing and Recovery System Risk Assessment

Phase II Study Task Areas

Task 1: Integrated Risk Analysis Summary

The purpose of the Task 1 risk assessment was to identify the risk drivers of different CM landing configurations and provide overall risk comparisons of the alternatives. Several spacecraft landing configuration baselines were examined including: the LM 606, Zero Based Vehicle (ZBV): and a water-lander based on the ZBV with minor modifications, with/without vertical / horizontal retrorockets, roll control, and air bags.

The NESC recommendations included:

- Improve the FBC release (Apex Cover) to minimize interference with drogue parachute deployment.
- Increase the horizontal velocity attenuation to protect against under predicted horizontal winds at land-landing site, increase stability of the CM during landing, and increases landing availability.
- Improve crew occupant protection systems as functional redundancy to any landing attenuation system failures.

Task 2: Landing System Test and Verification (T&V) Summary

This task was designed to investigate the completeness of the Landing System T&V plan. A landing event sequence diagram was developed and used as the basis of the investigation. The major NESC recommendations included:

- Explicitly add a test program to exercise end-to-end performance of the Landing and Recovery System (LRS) with emphasis on interactions between subsystems.
- Formulate a working group charged with the responsibility for verification of end-to-end LRS performance with emphasis on subsystem-to-subsystem and subsystem-to-CM interactions.
- Adopt a strategy of developing specific LRS tests based on evaluation and verification needs as opposed to forcing the verification plan to conform to already existing "all encompassing" tests.
- Develop T&V scenarios to test the FBC release, parachute extraction and deployment, main heat shield jettison (if required), and active controls used for impact attenuation or control during descent, landing, and airbag inflation (if used).

Task 3: Landing Site Accessibility and Availability Summary

The terrestrial landing site availability from Low Earth Orbit (LEO) task addressed the interaction of continental United States (CONUS) landing accessibility and availability. Accessibility is the number of times a given landing site can be physically reached from the initial orbit. Availability is defined as the number of times opportunities can be utilized in the presence of operational constraints. This study covered accessibility based on orbital mechanics, landing site location and CM lift to drag ratio (L/D). Availability topics studied included day/night, ascending/descending orbit pass constraints, surface wind conditions and thresholds, gust conditions, and Service Module (SM) disposal footprints.

The task also determined that water-landings were a viable back-up to CONUS-based land-landings and could also be used as standalone landings. Suggestions included choosing a water based location that takes advantage of ascending and descending pass opportunities (e.g., off the coast of California). In addition, because of the flexibility of water-landings – through ship movement – additional opportunities for vehicle return become apparent. There were no obvious CONUS-based land-landing opportunities for the 28.5 degree inclination orbit. CONUS sites are accessible if an inclination change orbit maneuver is performed.

The major NESC recommendations included:

- Implement improved wind forecasting at the landing sites because current wind forecasting is not sufficiently accurate at the relatively low velocity constraints that are important to CM stability.
- Improve crew protection to guard against misforecast winds or gusts, and to avoid over constraining wind placards.
- Develop a flight test program that can support International Space Station (ISS) schedules and be prepared to capitalize on performance envelope expansion opportunities as they

emerge. The initial flight test program will be paced by limited opportunities to satisfy initial land-landing wind placards.
- Preplanned water-landing sites can backup missed or unavailable land-landing site opportunities.

Task 4: CM Roll Control in Preparation for Landing Summary

The use of roll control can optimize the orientation of the crew seat attenuation system for land- or water-landings. CEV Project tests show that the CM Reaction Control System (RCS) has sufficient torque to meet the ± 30 degree roll requirement with current parachute harness / riser designs. The NESC recommendations from the NESC CEV Water versus Land-Landing Assessment endorsed the use of roll control, and the recommendation remains applicable because:
- Some form of roll control is useful to orient the CM Z plane with the direction of travel to maximize crew safety.
- There is limited cabin volume and minimal human impact acceleration tolerance in the Y axis (lateral impacts).
- During water-landings, the CM can be oriented to minimize crew impact accelerations. This supports meeting reduced impact acceleration requirements for de-conditioned crew.

Task 5: Main Parachute Release Times during Land-Landing Summary

The effectiveness of releasing the parachute from the CM at different release times post touchdown was examined for a vertical and horizontal landing velocity of 26 and 37 fps, respectively. A 37 fps horizontal velocity was used since this velocity represents one of the more extreme conditions and is most likely to cause CM rollover.

For landing conditions where there is a horizontal wind, retaining the parachutes has a detrimental effect on CM stability since the drag force on the parachutes can pull the vehicle over. The effect of rigging and parachute flexibility has minimal effect on the acceleration and roll response so that the trends reported here should be applicable to most parachute system designs. Peak accelerations occur early at touchdown where the parachutes have negligible effect. Rollover which occurs after touchdown is not significantly affected by the parachutes since the parachutes are either slack or have minimal tension, thus applying little or no forces on the CM.

Some form of automated parachute release should be a requirement since in the presence of horizontal winds with an attached parachute may cause the CM to be dragged and tumble. This is true for both water and land-landing events.

- An automated system should be required since the release may be required to occur within 0.50 seconds of touchdown, which is not sufficient time for a crew operated manual release.

- An automated release system would be a critical function that must ensure no unplanned release events.

Task 6: Crew Protection System Enhancements Summary

This task explored the utility of using Finite Element Model (FEM) techniques as a method for improving overall understanding of the effects and effectiveness of advanced or modified crew restraint systems. While in many aspects simplified, the results of this task indicate that the technique is useful and traceable to appropriate and well anchored approaches. This task also explored the specific case of incorporating lateral supports to improve the crew's tolerance to high Y-axis accelerations. Simulations indicated that substantial reductions in neck moments, cited as being most responsible for severe injury for these sorts of crashes, while showing increases in some other forces throughout the body. In particular these simulations indicate that substantial improvement in crew safety can be effected, with the caution that care must be taking in the detailed design to avoid transferring injurious loads to other parts of the body. Concepts were also developed that would allow implementation of suitable restraints.

The major results of Task 6 included:

- The Finite Element Analysis (FEA) modeling approach shows promise as a tool for seat designers. In this task, lateral supports were studied and could be used to improve crew survivability for landings with increased Y-axis accelerations. FEA models can provide a design engineering means to understand the effect of these restraints. In addition to developing tools, it is important that a practical means exist for implementing design solutions.

- Lateral Seat Support - The use of rigid lateral supports of the type found currently in race cars were not directly applicable since these designs would likely be impractical during crew ingress and egress. In order for lateral restraints to be used in space flight applications, a practical means for implementation with reasonable crew ingress, and rapid egress must be developed. In addition the restraint system must be flexible in its ability to accommodate crew members of different sizes. During this subtask, several lateral restraint concepts were examined.

- Assuming that the potential for unplanned landings on land cannot be eliminated for a CM configured for water penetration or other compromised landing configurations, additional crew protection is desirable.

- The Brinkley Dynamic Response Method criteria define an acceptable environment for crews restrained in a specific way. However, it does not provide insight into additional or modified crew restraint systems.
- The use of FEA and anthropomorphic test devices (ATD) tests can allow designers to evaluate the effectiveness of alternate restraint systems that can provide crews with Brinkley Dynamic Response Method levels of protection in substantially harsher

environment. Additional evaluation of industry standard injury criteria should be initiated to ascertain the applicability of these criteria to crew protection.

- Based on the work performed to date, further development and adoption of these contemporary design tools and techniques is recommended.

- Practical methods for implementing additional crew protection appear realistic and should be developed.

Space flight inherently poses risk to the crew during dynamic flight phases. This assessment was performed to address specific risk areas identified during the previous study on Water versus Land-Landings (NESC Assessment Number 06-020-E) involving the descent and landing phase of the mission. New findings and recommendations for the CM parachute architecture, occupant protection system, landing attitude, and operational approaches were identified and implemented. The Apollo CM remains as a solid reference, which when combined with the NESC team experience, allowed the understanding and then improvement on what Apollo had accomplished. Finally, additional lessons learned from Apollo Program experience were made to reduce risk as part of the T&V program. Given the state of maturity of the CEV Project at this time, those recommendations have not yet been implemented.

5.0 Ass essment Plan

5.1 Charter and Background

The CEV Project Chief Engineer requested that an integrated risk assessment and various associated studies be performed on the CEV Integrated Landing System – referred to as the LM 604 baseline. The Chief Engineer requested the independent study as preparation for the CEV Project's decision to baseline the LRS.

A brief Phase I analysis was performed by the Water versus Land-Landing Team (NESC Assessment Number 06-020-E) to compare the CEV Integrated Landing System defined in the LM 604 baseline, against the NASA TS-LRS001 baseline with respect to risk factors potentially leading to severe injury or LOC. This assessment covers CM and crew recovery, but does not include post-landing operations.

The Phase I effort resulted in the requestor asking the NESC to perform an in-depth analysis of potential risk to the crew in the Integrated Landing System of the LM 606 baseline as described in the following section.

5.2 Scope

The scope of this task is limited to an evaluation of potential risks found in the LM CEV Integrated Landing System as described in LM 606 baseline. Initially, the NESC 06-020-E Water versus Land-Landing study evaluated the Integrated Landing System risks to the proposed LM 604 CEV baseline. As the CEV design has matured and many design assumptions have changed, the NESC was requested to investigate areas of potential risk in the LM 606 baseline.

The Phase II study focused on areas of risk associated with the flight terminal phase for the CM and developed strategies for reducing or mitigating inherent risks. Risk was evaluated in terms of risk to the crew during a nominal land-landing. Additionally the CEV Integrated Landing System testing approach was evaluated.

6.0 Description of the Problem and Approach

The problem description and approach for the Phase I portion are presented in Section 6.1 and the Phase II problem description and approach are presented in Section 6.2. Note: each of the problems and approaches has a corresponding data analysis section and paragraph number in Section 7.0.

6.1 Phase I - Comparison of LM 604, TS-LRS001, and Apollo LRS – Problem and Approach

The CEV Project Office requested a risk comparison of the LRS proposed by LM with the design developed internally by NASA as shown in Figure 6.1-1.

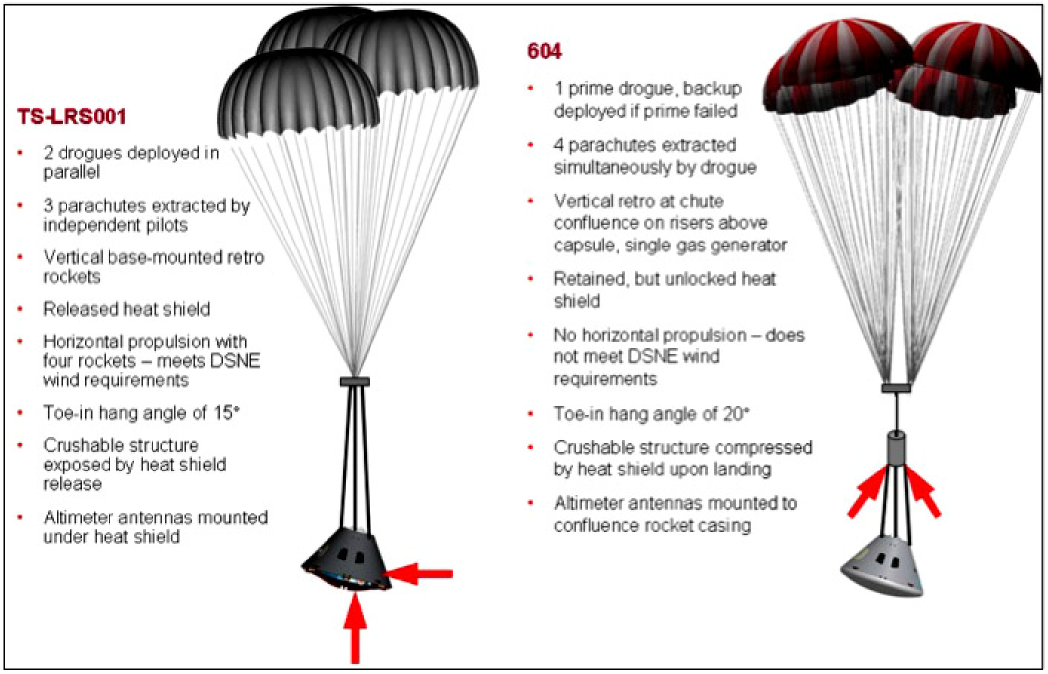


Figure 6.1-1. NASA and LM Landing and Recovery Baselines used for Comparison in Phase I

The primary focus for the Phase 1 task was reliability. Mass, volume, cost, and complexity were considered only if an obvious concern existed. The CEV Project's RAC-3 results were not factored into the assessment because this task was run in parallel with RAC-3 activities. A qualitative risk assessment was performed because insufficient detail existed for a quantitative risk analysis or reliability prediction.

This assessment relied on existing design and performance data from the NASA (TS-LRS001) and LM604 CEV teams primarily from the September – October 2006 timeframe. There were no existing formal design documents. Mr. Jim Corliss, Chief Engineer for the CEV Landing System Advanced Development Project, provided presentation material regarding landing systems from the weekly CEV Government Equipment and Materials (GEM) Office project control panel status meetings at JSC. LM data were culled from presentation packages and from technical interchange meetings (TIMs) to discuss the status of the LRS design. Additionally, the NESC assessment team visited the LM Denver site in October 2006 for a TIM.

The paradigm for the evaluation procedure was as follows: Entry, Descent, and Landing (post-entry) was decomposed into five major sequences, all of which must succeed:

- Parachute deployment
- Heat shield unlock or jettison
- Terminal descent
- Retrorocket firing
- Touchdown

Each of the five sequences was further decomposed into a set of sub-events or conditions, all of which must succeed for the overall sequence to be successful. Each sub-event was evaluated for design vulnerabilities with the potential to cause severe injury or LOC. Four categories of design vulnerabilities were considered in the qualitative evaluation process. The design vulnerabilities were:

- Brittleness (sensitivity to design assumptions) of performance to flight dynamics, environmental factors, or operating conditions.
- Potential to be a common-cause failure source or susceptibility to a common-cause failure.
- Lack of redundancy coupled with potential reliability issues.
- Steep drop-off in performance under off-nominal conditions.

A color code was assigned to each sub-event based on the level of concern relative to the list of vulnerabilities. The colors assigned to the sub-events assume that all previous sub-events and sequences are successful. Vulnerability concerns by color codes were:

- Green = low concern (function deemed to be robust).
- Yellow = moderate concern (design concept may be adequate but robustness improvements should be considered).
- Red = active concern (recommend proactive measures to increase robustness and/or change the design).
- White (no color) = function not applicable to the design.

Color code assigned to each sub-event based on level of concern relative to the list of vulnerabilities as shown in Figure 6.1-3.

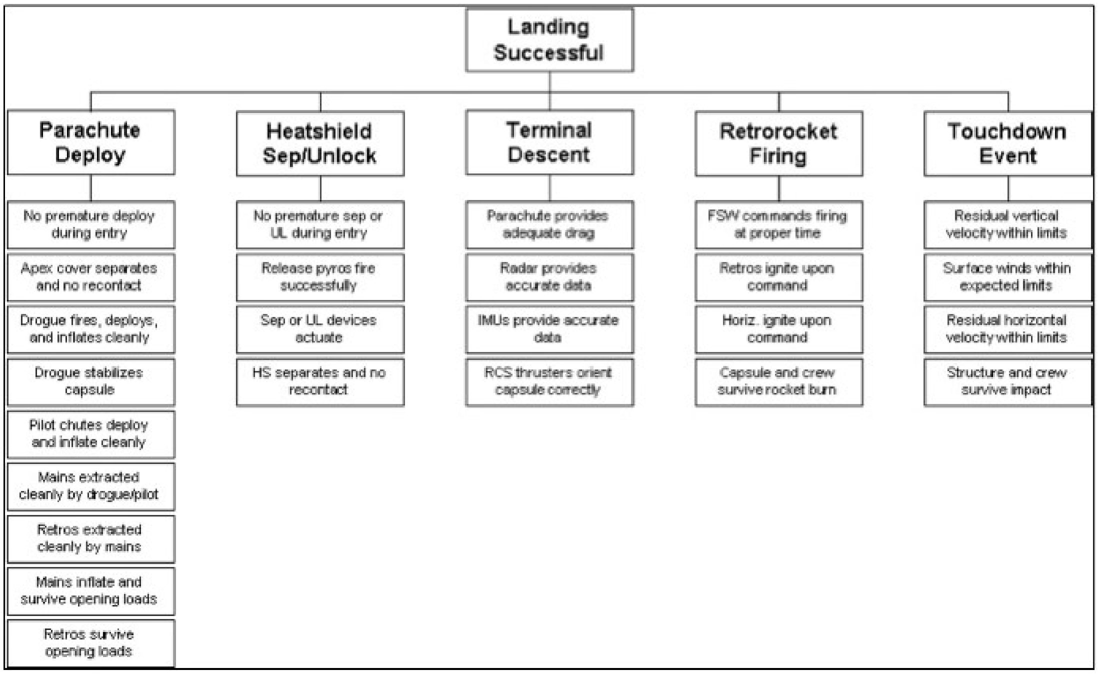


Figure 6.1-2. Post-Entry Descent and Landing Event Sequence (Functional Decomposition of Main Events) for a Successful Landing

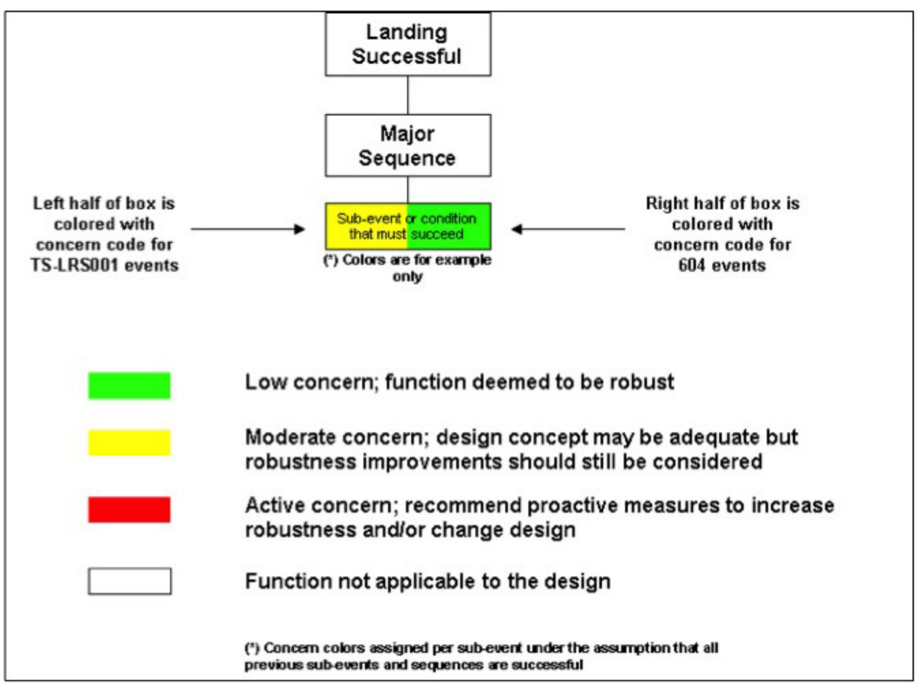


Figure 6.1-3. Vulnerability Concern Color Code: Concern Colors Are Assigned per Sub-Event with the Assumption that All Previous Sub-Events and Sequences Are Successful

6.2 Phase II -Integrated LRS Risk Assessment – Problem and Approach

The Phase II study focused on determining the areas of risk associated with the terminal phase of flight for the CM and developed strategies for reducing or mitigating risks inherent in this phase. A systems engineering approach was used to investigate the overall landing risk by investigating multiple areas of risk and suggested strategies for reducing or mitigating the risks.

Analysis of the problem by the NESC assessment team and working with the CEV Chief Engineer resulted in six individual tasks that encompassed specific, but related portions of the overall landing system concept. The tasks were developed to assess the risk to the crew of operating various vehicle configurations in the anticipated nominal descent and nominal land-landing environments, and investigate specific landing risk mitigation strategies. The overall systems approach is depicted in Figure 6.2-1.

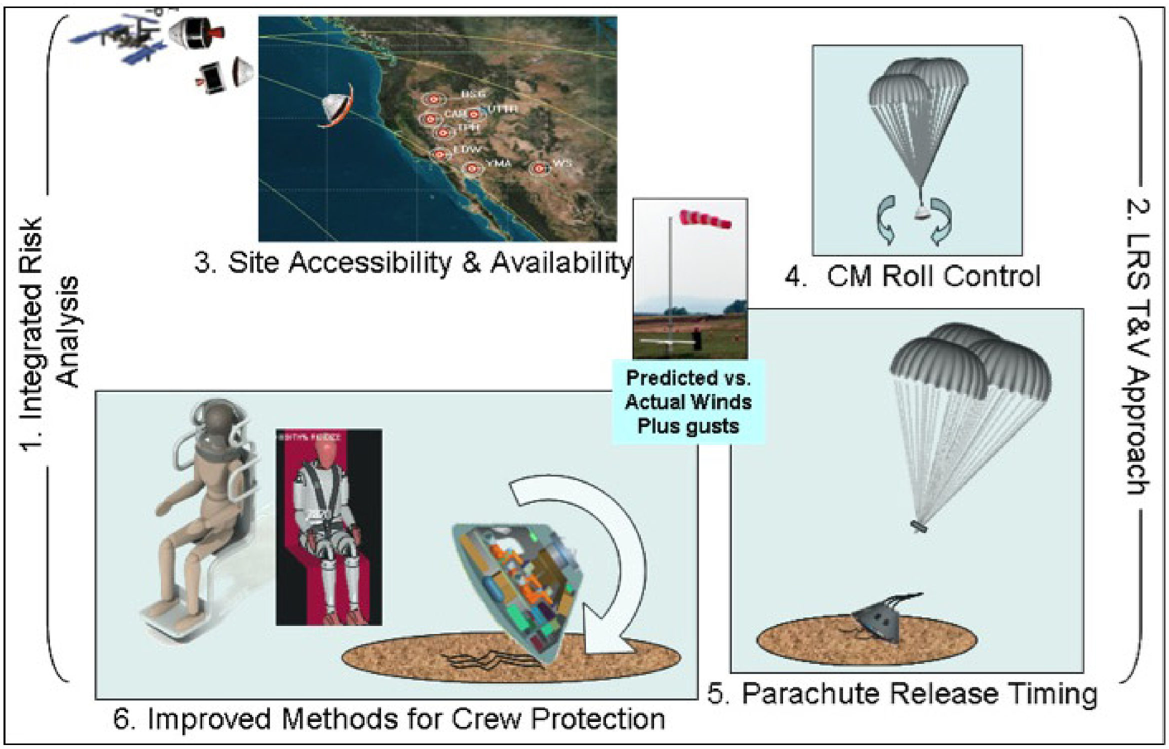


Figure 6.2-1. Systems Approach to the Integrated LRS Risk Assessment

The tasks and approach are summarized in the following sections.

6.2.1 Task 1: Entry, Descent, and Landing System Quantitative Risk Assessment Problem and Approach

The NESC assessment team's objective was to estimate the risk to the crew during landing using the LM 606 LRS baseline. The team's approach was to update the Integrated Risk Matrix from the CEV Water versus Land-Landing Study, which provided a quantitative risk assessment of landing. The analysis began with undock through entry, descent, and landing, and included various landing configurations (e.g., with and without CM horizontal retrorockets) and site conditions.

Figure 6.2-2. Phases of the Entry, Descent, and Landing Included in the Integrated Risk Assessment

6.2.2 Task 2: Landing System Test and Verification (T&V) Problem and Approach

The NESC assessment team assessed the CEV Project's T&V approach with respect to design qualification and certification. The original request was to provide an independent assessment regarding the CEV Project's T&V strategy for the CM LRS with respect to design qualification and certification. The team found that it was difficult to evaluate strategy since the CEV Project T&V planning is still in initial stages. Historically, T&V plans are not developed until the Preliminary Design Review (PDR) time frame or after. Early work on T&V planning is also problematic because design requirements are in an evolutionary state.

The team's opinion was that historical experience should be used to make recommendations because the LRS design has heritage from Apollo and Mars exploration programs – while still recognizing that the CEV has unique requirements.

The team restructured the Task 2 objective to develop a recommended set of T&V activities based on the team's experience with similar systems and available knowledge of the efforts to date. The goals were to:

- Develop a set of activities that would comprise a comprehensive entry, descent, and landing T&V plan.
- Provide Project with sufficient T&V information for use as a guide during their T&V task planning process.
- Utilize event-tree methodology to expose the items that must be verified in the absence of requirements.

For each activity, the following was provided:

- A brief, qualitative description of the activity.
- Whether the activity should cover exhaustive, bounding, or representative scenarios.

- External variables that should be examined.
- Fidelity of the interfaces to other subsystems or components that interact with the prime target of verification.

6.2.3 Task 3: Landing Site Accessibility and Availability Problem and Approach

The NESC assessment team's objective of this analysis was to identify significant trends in availability and develop a relative measure of sensitivity for those of special interest. The goal was to identify factors that warrant additional attention, not to make probability assessments or recommend design or operations criteria. Further, the team was to evaluate implications of relying on wind limits to ensure that horizontal velocity at touchdown remains within the CM design capability.

The team addressed the operational implications of implementing various landing scenarios for CM return from an ISS orbit. Two quantifiable attributes, accessibility and availability, have been defined to guide this evaluation (Figure 6.2-3).

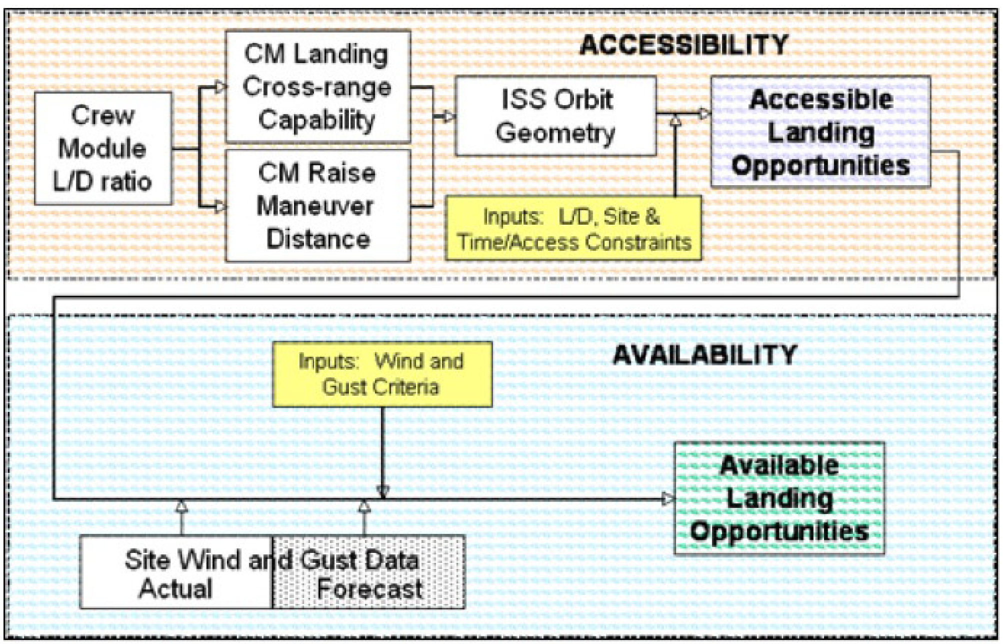


Figure 6.2-3. Approach to determining Landing Site Accessibility and Availability

Accessibility is defined as the number of times a given landing site can be physically reached from the initial orbit. It reflects the classic Return to Earth (RTE) targeting problem, achieving an inertial trajectory that will transition to an earth based coordinate system at a specific time of landing and geographic location. This evaluation identifies opportunities to land at a given site during a period of interest.

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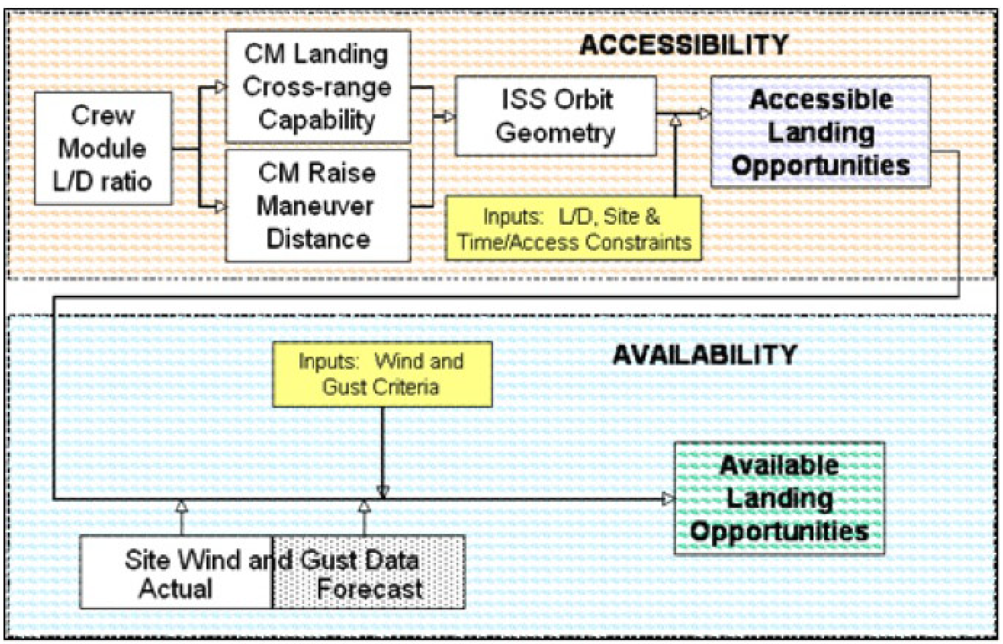

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            iii. inclination 51.63 degree
        b. Edwards Air Force Base (EAFB) wind/gust data for 2006
2. Multiple site weather from National Oceanic and Atmospheric Administration (NOAA) for 2004 [ref. 14]. Geographic data and orbital tracks were derived from Analytical Graphics, Inc's Satellite Toolkit (STK) orbital model
3. Day-time are initially defined as 0600-1800 local time
4. Landing opportunities are assumed possible whenever the ISS model flies through a cylinder with a radius equal to the CM cross range, projected vertically from the center of the landing area (ignores the delta times due to actual reentry timeline)
5. Toe of SM debris footprint ranges from 370 nm short of landing site in orbital plane with no raise maneuver to 1,300 nm with a maximum raise maneuver of 55 fps for L/D 0.35, and 230 nm and 1160 nm for L/D 0.30
6. No attempt was made to assess the suitability of landing sites, capabilities of specific CM designs, compatibility of CM designs with landing site surfaces, or availability of more accurate wind forecasting tools.
7. Analysis is focused on land-landings associated with returns from LEO since they are a precursor to lunar operations and must accommodate unique flight test and operational constraints.

Availability is defined as the number of times that accessible opportunities can be utilized in the presence of operational constraints. The consideration of operational constraints can only reduce the number of potential landing opportunities, this study addresses those concerns. Key considerations included were:

- Surface winds and gust conditions
- Day/night restrictions
- Ability to ensure SM debris footprints remain off shore

A deterministic approach was used to determine landing site availability that included:

- Collect and evaluate 2006 recorded and forecast wind data for EAFB.
- Identify EAFB landing opportunities for various forecast criteria and evaluate outcomes for each using appropriate wind reports.
- Consider potential correlation among EAFB, Carson Sink, NV, and the Utah Test Range wind data.
- Consider potential flight demonstration build up plan.

A statistical approach was also used to determine landing site availability that included an examination of the weather forecasts (primarily horizontal winds and gusts) versus the measured winds exceeding the CM's horizontal wind landing capability.

Additional concerns not addressed were: landing surface conditions, terminal area weather (snow, rain), and weather forecasting confidence. While these are broad assumptions, their use allows for identification of significant trends and sensitivities in key design drivers (i.e., orbital mechanics and weather patterns and may lead to a more detailed evaluation). The complexity of this environment and large number of conditions that merit examination, led to the development of an analog evaluation tool, Spacecraft Landing Accessibility and Availability Model (SLAAM). SLAAM was created in multiple steps starting with using the simulated orbit data modeled in AGI's STK, tracking the times when the orbiting satellite (ISS) would pass over the landing areas specified by the CM L/D and exporting this data into Microsoft® Excel ®. This data was then sorted and adjusted for local time, ascending or descending pass types, landing location, and SM disposal method. Weather data for EAFB was added in a separate database. Lastly, the tool mainly allows the user to sort the data based on their desired inputs. This model displays data in both daily and daily/hourly calendar format and geometrically accessible landing times while allowing for various user-imposed constraints. Those landing opportunities that fail the constraint from the display are removed from consideration. Figure 6.2-5 shows an example of the SLAAM user interface along with the sample output.

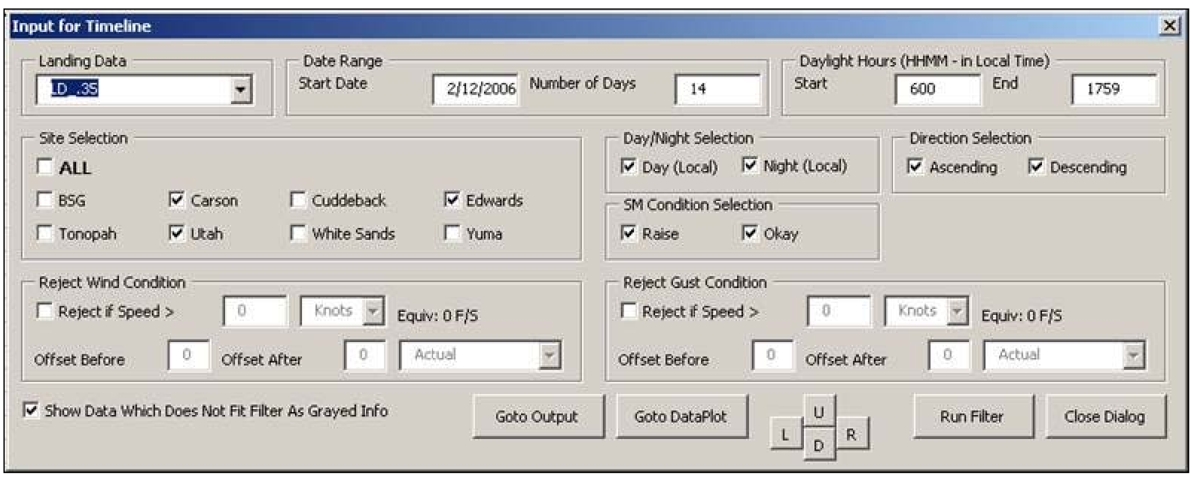

Figure 6.2-5. SLAAM User Interface

6.2.4 Task 4: CM Roll Control in Preparation for Landing Problem and Approach

The NESC assessment team's objective was to evaluate the requirements and capability of the CM roll control concept to orient the vehicle for an acceptable landing. The approach was to determine the previous Apollo missions roll control requirements, the current CM requirements for the roll control system, and then:

- Compare Apollo and CEV CM requirements.
- Determine what the requirements should be on the roll control system, and identify the simplest approach using a combination of modeling and simulation, design, and peer review.
- Deployment altitude, descent times, and range of wind conditions including cross winds as function of altitude.
- Analyze the RCS impulse performance and fuel allocation.
- Identify accepted range of roll alignment requirement (with confidence of specified requirement) for landing.

- Estimate torque requirement for range of bearing diameters and compare with RCS torque output.
- Size riser length and thickness requirement based on estimated peak deployment loads
- Estimate oscillation frequencies, magnitude, and dampening of the CM/parachute system.

6.2.5 Task 5: Investigate Parachute Release Times during Land-Landing Problem and Approach

The NESC assessment team investigated parachute induced effects on CM stability during landing near or beyond the vehicle's horizontal velocity capability. A concern of the CM landing is that structural accelerations will be large causing vehicle damage and/or crew injuries. Winds at the landing site could exceed the predicted values and thus exceed the CM capability (i.e., environment exceeds capability). Also, the CM accelerations could be large causing vehicle and/or crew injuries. The parachute effects are thought to have the potential to pull the CM over during conditions such as higher winds, or in some cases to stabilize the vehicle by preventing the motion after touchdown.

The effect of releasing the parachutes at different times after touchdown was investigated in terms of CM accelerations and rollover in various horizontal wind conditions. A simplified parachute model was developed and coupled to a CM structural model. Simulations were performed with vertical and horizontal landing initial conditions and horizontal winds expected at the landing sites.

6.2.5.1 Parachute Model

The LS-DYNA® FEM originally created for the CM was extended to include the parachutes and parachute lines. While CM is expected to utilize three primary parachutes for landing, for the purposes of this study the effects of the parachutes and lines are simplified by combining the effects into a single parachute concept (Figure 6.2-6). The parachute is modeled as a lumped mass whose weight is equal to the total expected parachute weights. The connecting lines are modeled as a single line with elastic properties and pre-tensioning. The line is preloaded with an initial tension equal to the CM weight so that the coupled vehicle-parachute system is in equilibrium just before touchdown. The "cable" element available within LS-DYNA® is used to model the line so that the line transmits load when the line is in tension and carries no load when the line is slack. The weight of the line is distributed along the length and the mass of the parachute is concentrated at the top of the rigging.

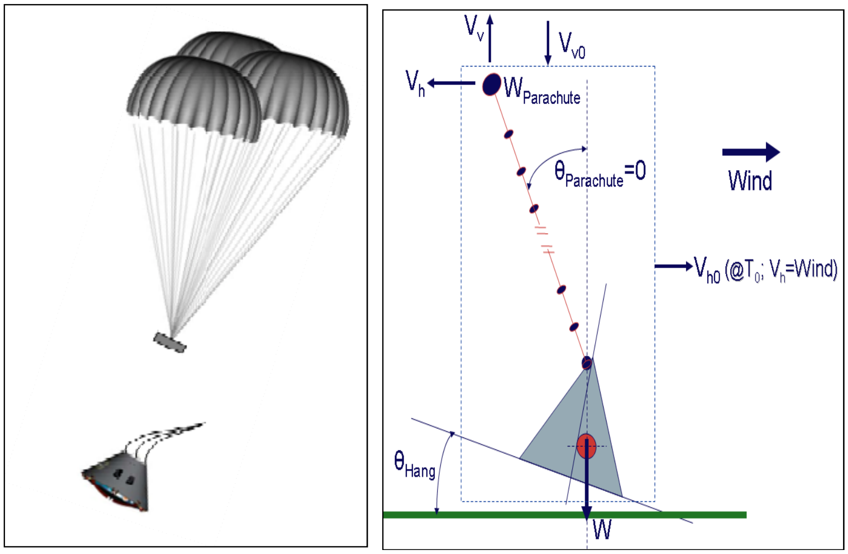

Figure 6.2-6. Conceptual Automatic Parachute Separation on Landing to Prevent CM Tumbling (left) and Simplified LS-DYNA® Model (right)

The parachute force is applied at the location of the parachute mass. The parachute force is computed from the simple drag equation:

$$F = C \times V^2$$

Where F is the parachute force, V is the velocity of the parachute mass, and C is the parachute coefficient. C may be determined from the relationship:

$$C = \frac{1}{2} \times \rho \times C_d \times A$$

Where ρ is the air density, A is the area of the parachutes, and C_d is the drag coefficient of the parachute. An alternative approach to computing the parachute force is to use the equilibrium conditions for a nominal landing to compute the coefficient, C. For a nominal landing, the parachute force must equal the CM weight so that:

$$W = C \times V^2$$

For this assessment, the nominal vertical velocity was 26 fps and the CM weight was 13,046 lbs leading to a parachute coefficient of 0.134. For the present assessment, this coefficient was used for both the vertical and horizontal directions. This was a reasonable approximation to the actual parachute forces since the parachutes tend to orient themselves so that they efficiently oppose the direction of the wind and vehicle motions. Currently, tests are being performed on CM parachute systems and as this data is processed a better understanding of the parachute forces will be defined. However, for the present study this simplified model of the parachute system and forces was sufficient to explore the effects of the parachutes once the CM touches the ground.

The parachute force was implemented into the LS-DYNA® simulation via a series of lookup tables for various wind conditions. During each time step in the transient simulation, the computed vertical and horizontal velocity at the location of the parachute mass was used with the lookup tables to extract a parachute force in each of the horizontal and vertical directions. These forces were then applied at the parachute mass location and used to compute the structural response for the step time step. When there was a horizontal wind present, the horizontal wind force was added to forces generated from the transient motion of the parachute mass.

The vertical parachute force is defined as:

$$F_v = 0.134 \text{ x } V_v^2 \quad \text{lbs}$$

And the horizontal force is defined as:

$$F_h = 0.134 \text{ x } (V_{wind}^2 + V_h^2) \quad \text{lbs}$$

Where V_v and V_h are the vertical and horizontal velocities of the finite element node at the location of the parachute mass.

Figure 6.2-7 shows a comparison between the parachute forces computed using the identified formulation and the vertical parachute force obtained using the parameters supplied by LM in memorandum CEV-LRS-07-001. For descent velocities within those expected for the CM, there was close agreement between the LM and NESC assessment team's predictions. At higher than expected velocities there is a divergence between the parachute forces since the LM formulation used a parachute drag coefficient that increases with descent velocity (thus increasing the drag force) while the team's formulation employed a constant drag.

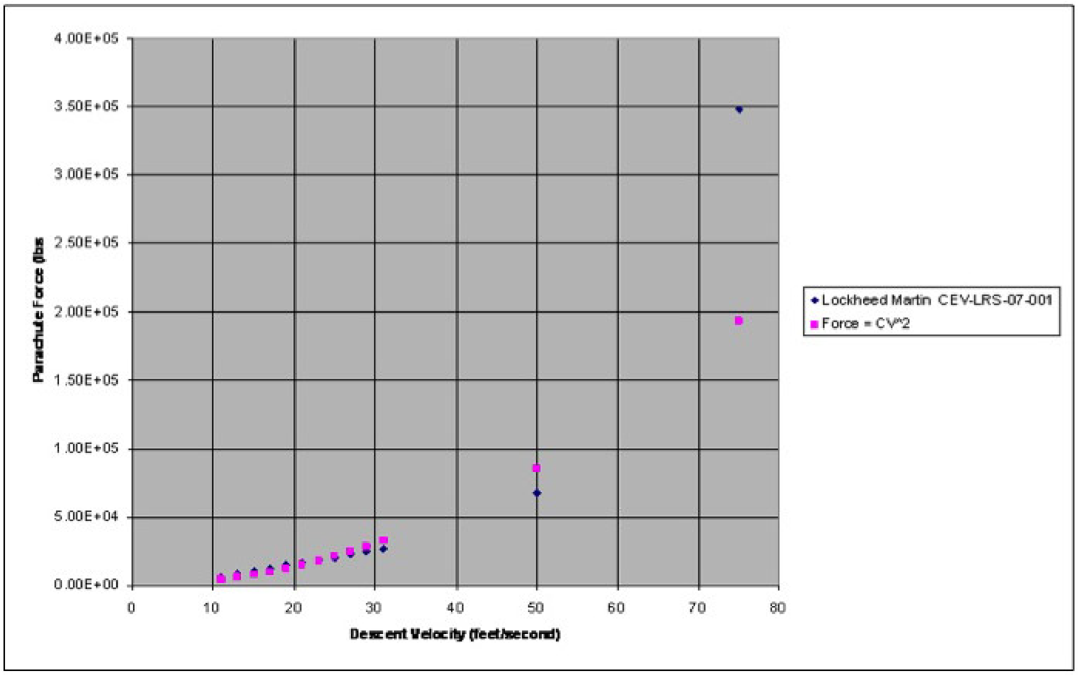

Figure 6.2-7. Comparison of Results of Parachute Forces from Two Different Computational Methods

LS-DYNA® was used to perform the analysis of CM landings with parachute attachments. This program was selected because of its ability to simulate the complex transient dynamic behavior of the CM impacting a landing surface. The CM model consisted of a collection of structural parts as depicted in Figure 6.2-8. The main portion of the CM, which consists of the pressure vessel, associated structure, and internal components, was modeled as a rigid part having inertia properties equivalent to the LM 604 CM design. The total weight of the vehicle was 13,046 lbs which is lighter than the currently projected design, but was an adequate value for the purposes of the present study.

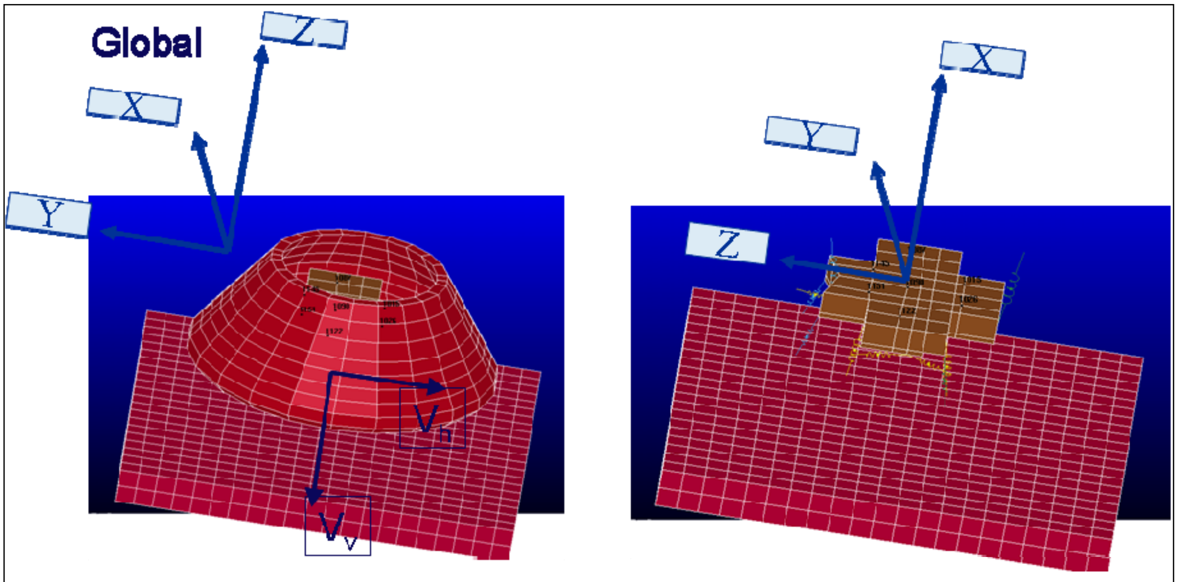

Figure 6.2-8. CM Structural Parts used in the Model

Inside of the CM pressure vessel is the crew pallet. The pallet supports the seats and is supported by fifteen energy absorbing landing struts. A portion of the CM inertia properties are allocated to the pallet (modeled as a rigid part) to account for the crew and seat weights. While the pressure vessel and pallet are modeled as structurally rigid and non-energy absorbing, the pallet struts are modeled as energy absorbing since they provide the primary source of landing load attenuation.

The parachute and rigging are attached to the CM FEM so that the parachute attachment point passes through the center-of-gravity with the vehicle oriented at the desired hang angle shown in Figure 6.2-9. The parachute is attached approximately 190 feet from the attachment point. The CM model shown includes a triangular shaped parachute used for visualization purposes only as the parachute is modeled as a concentrated mass.

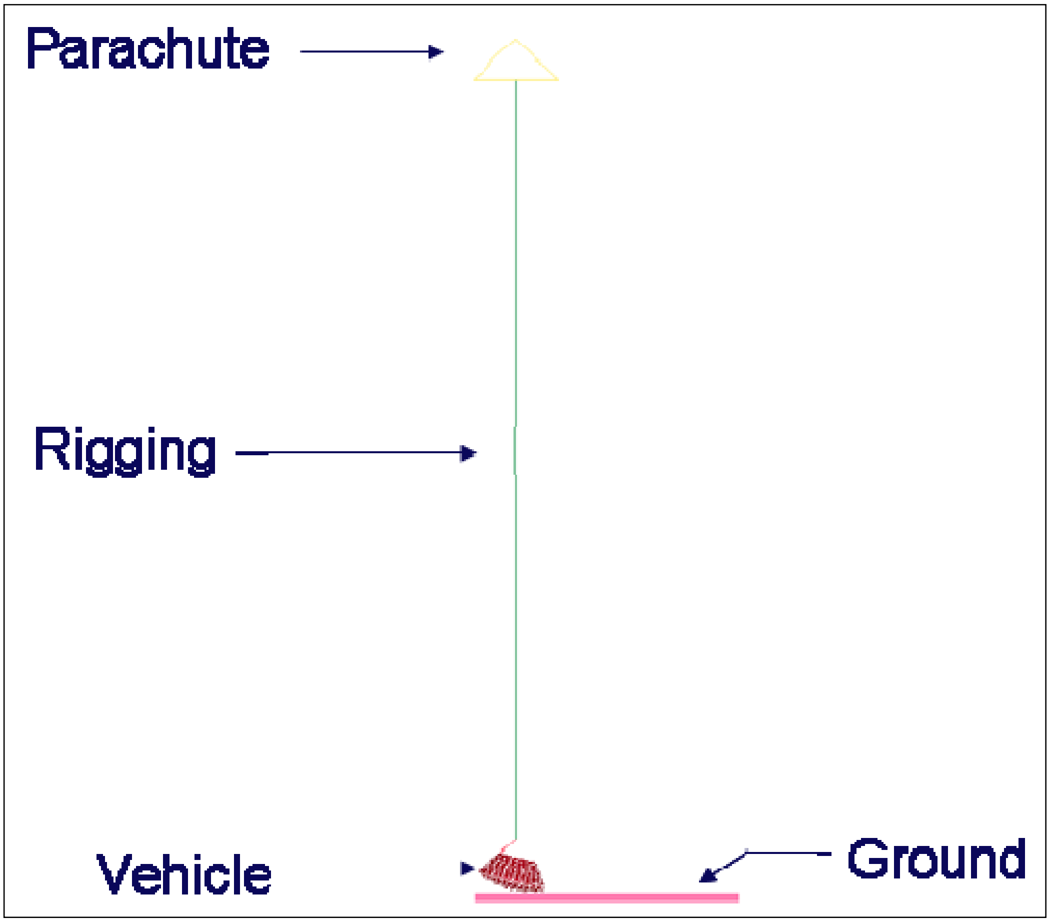

Figure 6.2-9. Overview of the Complete Finite Element Model

For the purpose of the present study the landing surface is assumed to be a relatively "soft" soil. The soft soil model has the effect of lessoning the resulting CM accelerations compensating for the fact that most of the vehicle structure is modeled as rigid. A coefficient of friction of 0.60 is used to model the contact friction between the CM and soil surface.

6.2.5.2 Parachute System Elasticity

Before proceeding with the assessment of the effect of parachute release times, it is important to measure the significance of the effect of the parachute system elasticity. For example, if a stiff rigging configuration responds significantly differently from a soft system, it is important to identify these differences and to either model the system as closely as possible to the actual "to be built system", or to identify differences so that relevant information is available to subsequent designers.

The overall parachute system elasticity is a combination of the elasticity contributed from the harness, riser, parachute suspension lines, and the air embedded inside the inflated parachute. To assess the overall effect from these components they may be viewed as a single spring that connects the parachute to the CM. When the parachute pulls on the vehicle, the air inside the chute compresses and, along with the rigging lines and riser, provides system flexibility. While the parachute design may utilize materials such as nylon or Kevlar® which are readily characterized, the total system elasticity is more difficult to calculate since it is a combination of rigging material, geometry, and aerodynamics. In fact, the compression of the air inside the parachute may provide more elasticity than all of the rigging materials combined.

To provide a reasonable assessment of the system elasticity, or to at least determine if elasticity considerations are even a significant issue, three different system stiffness's were examined for their effect of the overall system response. The three stiffness's are a relatively stiff system where the entire parachute/rigging elongates only 1 percent of its length when the CM weight is hung from the parachute (i.e. 13,046 lbs hung from a 190 foot parachute system stretches the system ~2 feet), a medium system (2 percent elongation), and a relatively soft system where the elongation is 5 percent.

The CM rotation and acceleration resulting from a vertical and horizontal landing velocity of 26 fps and 37 fps is shown in Figures 6.2-10 and 6.2-11, respectively, for the three levels of stiffness. The hang angle is 0 degrees. For all three stiffness's the parachute is kept attached to the CM for the duration of simulation. As depicted in the figures, the CM rolls over regardless of the system stiffness, which is an expected response for a 0 degree hang angle and horizontal velocity. Furthermore, there is no significant different among the three levels of stiffness. The simulation resulting from the softest stiffness does rollover slightly less than the other two simulations, but the difference in rollover angle is not large. The accelerations at the location where the crew are seated are almost identical regardless of the stiffness level. The medium stiffness level was used for subsequent simulations since this level is thought to be the most reasonable characterization of the actual stiffness.

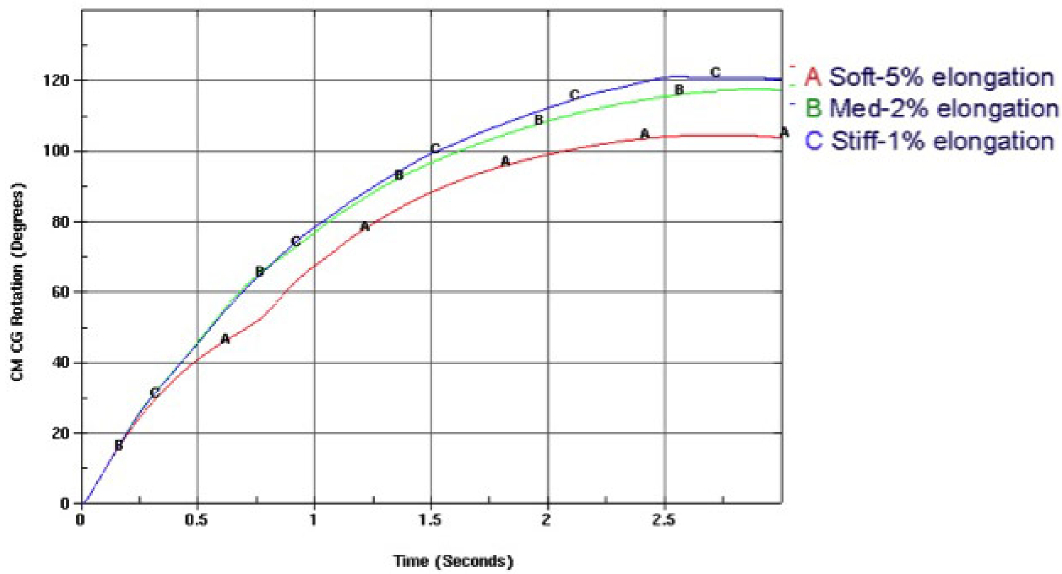

Figure 6.2-10. Effect of Rigging Stiffness on CM Rollover (0 degree hang, Parachute Remains Attached)

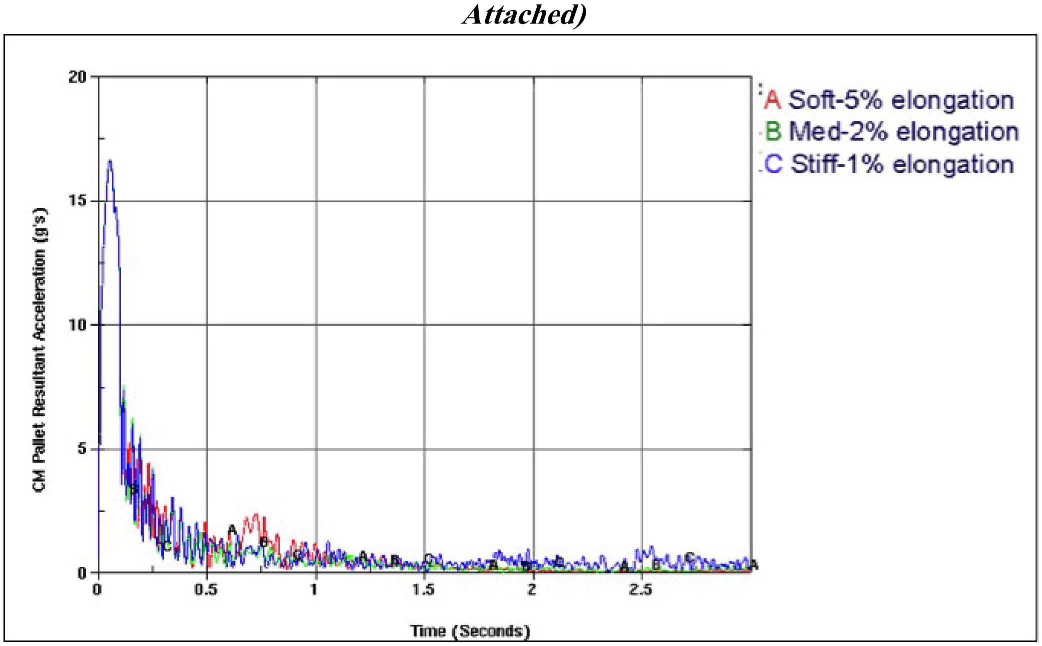

Figure 6.2-11. Effect of Rigging Stiffness on Pallet Acceleration (0 degree hang, Parachute Remains Attached)

6.2.6 Task 6: Crew Protection System Enhancements Problem and Approach

During the course of this assessment, tools were developed to:

- Evaluate enhanced crew restraints and to develop restraint concepts that would enhance crew safety during high-g impacts or CM rollover.
- Investigate the use of FEA techniques to model the biodynamic effects of high-g impacts with various seat and restraint systems.
- Establish correlation between the FEA technique and standard methods (e.g., Brinkley Dynamic Response Method Model) for the case of standard restraints.
- Employ FEA to explore one type of advanced crew restraint system.

At the conclusion of this assessment, these tools were provided to the CEV Project for use in evaluating alternative crew seats.

The effects of crew restraint options on the LM 604 seat strut and seat pallet concept designs using traditional "whole body" dynamic response models, and FEA models of (ATDs (e.g., crash test dummies) were investigating. The NESC team:

- Investigated the basic crew seat configuration (legacy) versus race car seat.
- Determined if FEA ATD models can be developed into design tool that will be predictive for advanced crew protection seats.
- Performed FEA simulations of impacts in the Y- and Z-axis directions (most sensitive for crew injury).
- Compared FEA to Brinkley Dynamic Response Method and biological data.
- Developed and compare crew seat impact attenuation improvement concepts.
- Found opportunity to add additional value that involved validating the FEA model with recent sled results run by the CEV Project and the Suit Project at Wright Patterson Air Force Base.

7.0 Dat a Analysis

The data analysis for the Phase I portion is presented in Section 7.1 and the Phase II data analyses are presented in Section 7.2.

7.1 Phase I - Comparison of 604, TS-LRS001, and Apollo LRS Data Analysis

The NESC team compared the configurations of the reference designs and developed an architecture comparison of these designs with the Apollo ELS. Table 7.1-1 lists the points of architecture comparison with the Apollo system.

Table 7.1-1. Areas of Comparison between the Apollo ELS and the LM and NASA CM LRSs

Feature	Apollo	604	TS-LRS001
Parachue			
Drouge Chute	2 deployed in parallel via mortars	1 prime via mortar, backup drogue deployed if FSW detects prime has failed	2 deployed in parallel via mortars
Main Chutes	3 ring sails, 83.5' diameter	4 ring sails	3 ring sails, 122.6' diameter
Main Deployment	Extracted by 3 independent mortar-fired pilots	Extracted simultaneously by single drogue	Extracted by 3 independent mortar-fired pilots
Heatshield			
Type	Avcoat	PICA	PICA
Retainment	Retained for splashdown, load path same as for entry	Retained for touchdown, but unlocked from entry load path prior to touchdown	Jetttisoned after main chute deployment
Terminal Descent ACS			
Type	Passive	Active orientation required, uses swivel at chute confluence	Active orientation required, swivel TBD
Radar			
Altimetry	N/A	(TBD) Radar	(TBD) Radar or LIDAR
Velocimetry	N/A	(TBD) Doppler or GPS	(TBD) Doppler or GPS
Avonics Location	N/A	Within capsule	Within capsule
Antenna Location	N/A	At chute confluence, mounted to retrorocket casing	At bottom of capsule, under the heatshield
Retrorockets			
Vertical	N/A	1 rocket w/ 6 nozzles, (TBD) thrust	4 rockets, 7000 lbs thrust each
Horizontal	N/A	N/A	4 rockets, 9400 lbs thrust each
Mounting Location	N/A	On risers, at parachute confluence point above capsule	At base of capsule, under the heatshield

The Apollo ELS Subsystem Manager was an integral part of the NESC team and identified the areas of design challenge in the Apollo ELS applicable to the LM and NASA LRS baselines.

A vulnerability concern map that evaluated risk was prepared of sub-events/conditions mapped to the five major sequences outlined in paragraph 6.1. Concern colors for each of the reference designs were indicated for each sub-event. The 10 concerns, numbered C1 through C10, were associated with the sub-event or sub-events. They are:

C1 (LM 604) - Main Chute Extraction

C2 (LM 604) - Retrorocket Extraction

C3 (LM 604) - Winds and Residual Horizontal Velocity

C4 (LM 604 and TS-LRS-001) - Retrorocket Firing Chain

C5 (LM 604 and TS-LRS-001) - Apex Cover Separation

C6 (LM 604) - Retrorocket Plume Impingement

C7 (LM 604 and TS-LRS-001) - Capsule Orientation Event

C8 (LM 604) - Drogue Stabilization

- C9 (TS-LRS-001) - Impact Survivability
- C10 (TS-LRS-001) - Heat shield Separation

An additional level of categorization was also applied to the concerns:

- 1st Tier — Considered the most serious and challenging and has architectural ramifications for the design: C2, C3, and C4.
- 2nd Tier — Considered challenging, but fixable. Does not necessarily have cascading effects through the architecture: C1 and C5.
- 3rd Tier — Considered to have relatively straightforward fixes: C6, C7, C8, C9, and C10.

Figure 7.1-1 illustrates the vulnerability concern map, the concern colors for each design, the numbered concerns associated with entry, descent, and landing sequences, and the 1st, 2nd, and 3rd Tier concerns.

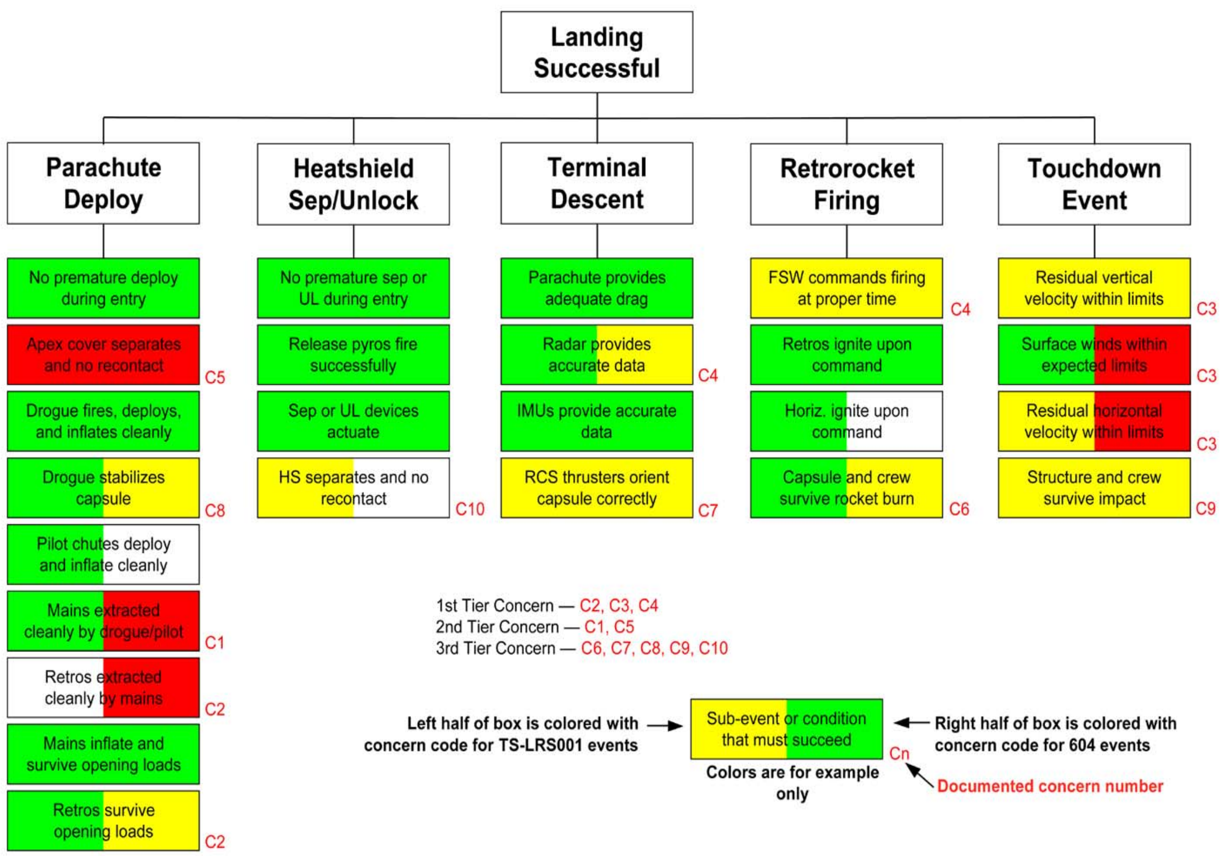

Figure 7.1-1. Vulnerability Concern Map

7.2 Phase II - Integrated LRS Risk Assessment Data Analysis

This section presents the data analysis of the six tasks included in the Phase II assessment.

7.2.1 Task 1: Data Analysis for Entry, Descent, and Landing System Quantitative Risk Assessment Data Analysis

The purpose of the risk assessment was to identify the risk drivers of different configurations, and provide comparisons of the overall risk of the alternatives. This work was an extension of a previous NESC assessment that evaluated the risks of landing the CM on water versus land. This previous assessment did not analyze specific vehicles and assumed that key risk mitigating features were in place. The current assessment extended the previous analysis to evaluate specifics of the current CEV design concepts. The risk metric chosen for this analysis was probability of LOC (PLOC).

7.2.1.1 CM Landing System Configurations Assessed

Several candidate CM configurations were assessed and compared, which include:

- LM 606 was the baseline configuration in the Spring of 2007. It is a primary land-lander with airbags and horizontal retrorockets. It did not meet weight allowances, so variations were considered.
- The ZBV was based on the LM 606, but had numerous parts removed (e.g., landing system and some redundant components) in order to meet the weight allowance. This was the starting point for alternative configurations assessed. It is also the starting point for the PDR point of departure (POD) vehicle design (currently scheduled to be approved in mid-November 2009).
- Water-lander, which is essentially the ZBV with minor accommodations for water-landing, including roll control.
- Vertical retrorockets with no horizontal retrorockets on dry soil.
- Vertical retrorockets with no horizontal retrorockets on wet soil.
- Vertical and horizontal retrorocket land-lander (soil type does not significantly affect outcome), which is equivalent to the LM 606 configuration.
- Airbags with no horizontal retrorockets on dry soil.
- Airbags with no horizontal retrorockets on wet soil.
- Airbags with horizontal retrorockets (soil type does not significantly affect outcome).

In the ZBV, some multi-level redundancy was removed. For example, some avionics electronics was previously multiple fault-tolerant, but was reduced to single fault tolerance (e.g., three computers were reduced to two). The NESC team's calculations determined the reduction in the number of computers made a negligible difference because of the used of a common cause failure rate of 10 percent of the independent failure rate, so the third unit typically reduces the failure rate by less than 1 percent. It was not clear if all manual backup modes were maintained in the ZBV, but the team assumed that they were. Similarly, ballistic mode and some trajectories were removed from the ZBV. The team did not analyze in detail the risk impact, but instead assumed that it would have a minimal impact (i.e., other design features would be used to mitigate new risks that arose from the change). It was also assumed that there would be roll control. The importance of roll control for water-landing was not analyzed in detail, but it is crucial for land-landings.

The airbag systems assessed were the Generation 1 airbags by Airborne Systems and the Generation 2 biased airbags by Boeing. Boeing's biased airbags have different pressures in the front and rear bags to counteract the center-of-gravity offset, but was not optimized in order to maintain acceptable stability at all landing orientations (roll). Generation 2 airbags showed improvement over the Generation 1 airbags, thus only the Generation 2 airbags results are presented in this study.

It should be noted that for a given primary land-lander CM configuration, the risk can vary widely based on the landing site and landing wind criteria. Section 7.2.3details the analysis that was done in selecting landing criteria and the influence of that on landing availability. In this section, the primary landing site was EAFB (with backup sites), and the wind forecast go-for-landing criteria was 18 fps. In this case tumbling is the number one entry, descent, and landing risk for land-landing configurations except for airbags with horizontal retrorockets. At the same time, for day landings with three sites, there would be a 10 percent chance of having to wait 200 hours to land for an ISS return (i.e., landing availability is not likely to be reduced further in order to reduce risk).

7.2.1.2 Mission Risk Description and Design Impacts

The risk analysis was focused on the landing systems. The mission segments considered was the entry, descent, and landing for an ISS mission. This mission segment is shown in Figure 7.2-1, along with risk drivers, and key design features that differentiate the LM 606 design from the idealized land-landing design previously analyzed. The reentry risk drivers are:

- Entry
  - Guidance Navigation and Control (GN&C) System Fault After Entry: This failure mode represents failure of the system to deliver the vehicle to the proper landing site. If the CM does not land on a relatively smooth, flat surface it may be subject to tumbling. This failure mode applies only to land-landing.
  - Thermal Protection System (TPS) Failure: TPS failure could cause catastrophic failure to the CM, or cause the structure to become overheated and weakened. The weakened structure could cause the vehicle to sink during a water-landing.
  - FBC Release Mechanism: Failure of this mechanism and drogue parachute could cause the FBC to interfere with deployment of the drogue parachutes.
- Parachute Descent
  - Two Drogue Chute Deployment Failure: This failure prevents the initial CM deceleration and stabilization to allow for successful deployment of the main parachutes.

- Two Main Chute Deployment Failures: This failure prevents the CM from decelerating to safe limits. This failure could result from system faults, or a postulated situation where the drogues are released at a time when there are sufficient rates to cause the CM to be inverted when the main parachutes are deployed causing failure of the deployment. This concept is being evaluated by the CEV Project and is not expected to be in the final CM configuration.
- Apex Cover Re-contact: Once the apex cover is clear of the CM, it is possible for re-contact if its drogue chute does not deploy.

- Landing Risk Drivers
  - Land-Landing
    - No Heat Shield Separation: The land-landing systems are designed such that the heat shield must be jettisoned to allow for operation of the active attenuation systems (retrorockets/airbags). Failure of this system will cause the capability of the seat attenuation system to be exceeded, or make the CM susceptible to tumbling. The idealized vehicle in the previous study was assumed to be designed to have a possibility of survival.
    - Altimeter or Retro Failure (Retro Systems): This failure results in an early, late, or no actuation of the Retro System. Failure of this system will cause the capability of the seat attenuation system to be exceeded, or make the vehicle CM to tumbling. This type of system requires a narrow timing window for actuation (approximately 1 second), with no back-up. The idealized vehicle in the previous study was assumed to be designed to have a possibility of survival.
    - Airbag Failure to Inflate or Deflate Properly (Airbag Systems): A failure in this system will cause the capability of the seat attenuation system to be exceeded, or possibly make the CM tumble. Timing of the actuation of this system is not as critical as for retrorockets. The idealized vehicle in the previous study was assumed to be designed to have a possibility of survival.
    - Mispredicted Surface Winds: This failure mode is applicable to systems that do not have the capability to remain upright in high surface winds (either by design or through active systems such as horizontal retrorockets). These systems will typically require that the winds be placarded to ensure the capability of the system is not exceeded. This failure mode represents the possibility that the weather prediction meets the placard, but the actual winds at time of landing can cause the CM to tumble. The idealized vehicle in the previous study was assumed to be designed to have a possibility of survival.

- Water-Landing (Cabin Flooding/high leak rate)
  - Pressure Relief Valve/Vent Failure: This failure would cause the CM to take on water and begin t sink. Requiring crew emergency egress if the recovery is not prompt.
  - Structural Failure (due to TPS failure): This failure represents the possibility of a TPS failure causes overheating (but not destruction) of the CM such that it fails during water impact. This failure is assumed to be severe enough to cause immediate sinking.

Another potential risk driver was the contribution of the landing system during a pad abort. There is the possibility of a pad abort occurring when there are sufficient winds to blow the vehicle back on land.

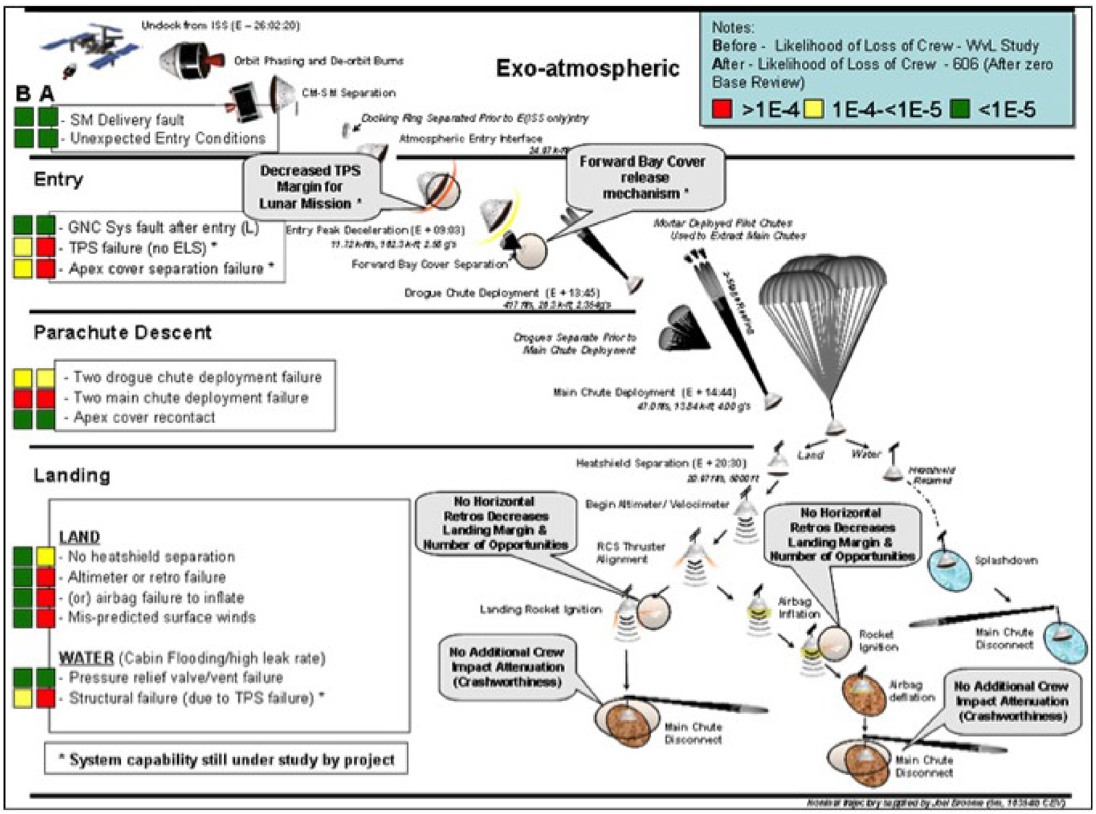

Figure 7.2-1. Summary of Risk Drivers for the Nominal ISS Return Mission – Updated from the NESC CEV Water Versus Land-Landing Study (Before and After)

7.2.1.3 Risk Quantification Updates

Each of the risk drivers that had new information was re-quantified for the LOC end state. The overall risk matrix is shown in Appendix A. The results of this are summarized in qualitatively in Figure 7.2-2 and Table 7.2-1. Rationale for the quantification is provided in the following sub-sections.

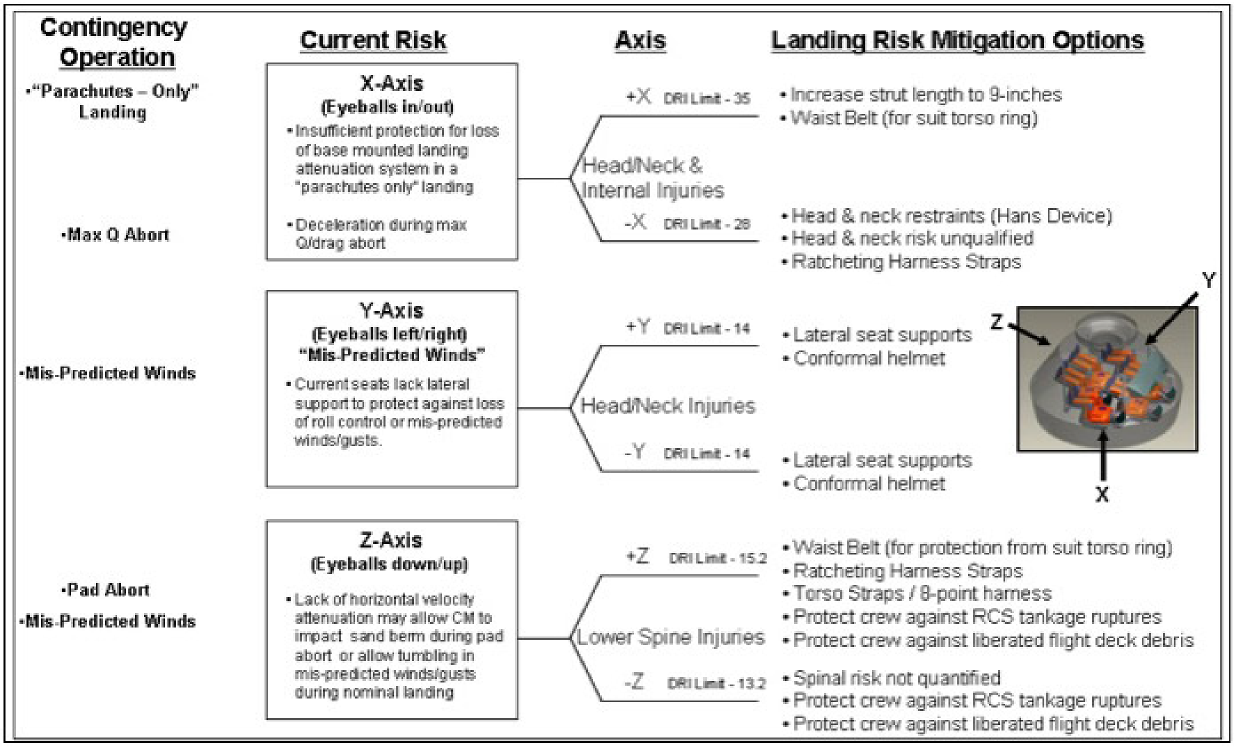

Figure 7.2-2. Results of the Risk Update

Table 7.2-1. PLOC for Risk Driver (Tabular)

	Vehicle Analyzed					
Updated Risk Driver	WvL Land (Vertical, Horizontal Retrorockets)	LM 606 with Airbags (dry soil)	LM 606 with Airbags and Horizontal retrorockets	LM 606 Water-Landing Only	LM 606 with Vertical and Horizontal retrorockets	LM 606 with Vertical retrorockets Only (dry soil)
Pad Abort	8E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5
TPS Failure	2.6E-5	2.7E-5	2.7E-5	2.7E-5	2.7E-5	2.7E-5
GNC and Other Entry	1.1E-5	1.5E-5	1.5E-5	1.5E-5	1.5E-5	1.5E-5
Apex Cover Separation	1E-4	2E-4	2E-4	2E-4	2E-4	2E-4
Heat Shield Separation Fault	0	8.8E-5	8.8E-5	0	8.8E-5	8.8E-5
Parachute Failure	2.6E-4	2.6E-4	2.6E-4	2.6E-4	2.6E-4	2.6E-4
Roll Control Failure	1E-6	4.2E-5	4.2E-5	1.1E-5	4.2E-5	4.2E-5
Retro System Failure	0	0	0	0	2E-4	2E-4
Airbag System Failure	5E-6 (airbag alternative)	1.6E-4	1.6E-4	0	0	0
Mispredicted Winds	0	1E-4	0	0	1E-3	1.5E-2
Structural Failure due to Overheat (Water-Landing)	4.4E-5	0	0	2.3E-5	0	0

Heat Shield Failure

Several faults can lead to heat shield failure resulting in LOC. For ISS missions this is dominated by Micro Meteoroid Orbital Debris (MMOD) damage during extended stays at the ISS. This analysis assumed no covering of the heat shield shoulder region that is above the SM. The damage leads to increased turbulence during entry and catastrophic failure (LOC).

Less severe MMOD damage can lead to weakening of the structure that can cause CM sinking. For land-landing, similar damage could lead to overheating the landing system, but this was assumed to be less likely. An additional, but less probable cause of sinking is structural failure due to insufficient margins.

Heat shield failure during lunar return was also analyzed, but not included because most risks do not differ between lunar and ISS cases and ISS return is more frequent. Due to the high heat loads for lunar return. Heat shield failure leading to LOC is more likely with a probability of 1.3E-4. Sinking due to heat shield overheating is also more likely at 2.6E-4.

Apex Cover Separation

Risk of apex cover/FBC separation failure increased from the Water versus Land-Landing Assessment, mostly due to new concerns about interference with the drogue chutes.

Heat Shield Separation

Heat shield separation faults do not apply to the water-lander because it retains the heat shield. The driving failure modes are early separation (which results in LOC in all cases) and no separation. In the Water versus Land-Landing Assessment, heat shield failure to separate was not considered to cause LOC due to the enhanced seat system, and early separation was not considered. In the current study, both cases result in LOC, although early separation was given a 0.75 weighting due to non-fatal cases (i.e., early separation and cases where the aerodynamic loads keep the heat shield in place until parachute deployment).

Roll Control Failure

Roll control/RCS thruster alignment failure has the same probability of system failure for the Water versus Land-Landing investigation and this assessment. However, in the earlier study the system failure did not lead to as high of a PLOC due to the superior seat system. Roll control is not as critical for water-landing, but there is some risk due to the asymmetric CM structure design and the increased risk of sinking at off-nominal roll angles.

Retro System Failure

Vertical retrorocket system failure applies only to that particular system, and is a significant discriminator between CM configurations. In this study all retrorocket failures were presumed to result in LOC, whereas in the Water versus Land-Landing Assessment the seats mitigated the fault completely.

Airbag System Failure

Airbag system failure applies only to that particular system, and is a significant discriminator. In this study airbag failures were presumed to lead to LOC, whereas in the Water versus Land-Landing Assessment the seats mitigated all failure modes except for the pressure release valve failure, which was 95 percent mitigated.

Mispredicted Winds at Landing Site

The possibility of choosing to land based on acceptable wind forecasts at the time of the go/no-go decision, but encountering high winds upon landing was not considered during the Water versus Land-Landing Assessment. This was partly because the baseline design included horizontal retrorockets that would counteract the winds at the time of landing. However, during the current study it was found to be the dominant risk in several vehicle configurations. Details about the variability of the winds and landing criteria are provided as part of the separate wind task; only the effect on PLOC is discussed here.

The CM's horizontal velocity at impact is roughly equal to the surface wind speed. Water-landing is not affected by horizontal winds. Airbag systems have been demonstrated to handle higher horizontal velocity without tumbling than vertical retrorocket systems. This was achieved by timing the pressure release of the outer bag and shaping the airbags to behave like skids. It was also found through simulation that the CM will tumble at a lower horizontal velocity on wet than on dry soil. In all cases it was assumed that tumbling results in LOC (unlike Soyuz or the Water versus Land-Landing Assessment vehicles with their improved seat attenuation).

These effects led to the CM configuration with vertical retrorockets, but no horizontal retrorockets to have unacceptable PLOC of over 1 percent. Airbag systems without horizontal retrorockets are marginal (especially when the landing soil is wet and soft). While the risk could be reduced with increased landing constraints, those constraints would probably be unacceptable due to the resulting loss of landing opportunities (i.e., there could be many days with no landing opportunities). Vertical retrorocket systems with horizontal retrorockets have similar performance to airbag systems without retrorockets. In this study, it was found that winds are handled well by only the airbag system with horizontal retrorockets and the water-lander.

Structural Failure Due to Overheat

Structural failure can lead to sinking of a water-lander, which has a high probability of causing LOC in a CM with up to six crew members. Although early Apollo tests resulted in sinking under nominal conditions, it is assumed that for the CEV Project the main cause of sinking would be TPS failure to meet temperature requirements, leading to a weakened pressure vessel and high leak rate upon splashdown.

7.2.1.4 Risk Observations and Results

Role and Benefit of Quantitative Risk Assessment to the Process

The quantitative risk assessment process goes beyond a reliability and safety analysis and is based on an evaluation of the entire mission to identify scenarios that could lead to LOC. This analysis integrates hazards and equipment reliability with the physics of the scenarios. It may be difficult to validate the estimates generated by this process. However, the discipline of developing, justifying, and comparing estimates for internal consistency helps keep the project focused on appropriate risk drivers. Opening the analysis beyond the standard safety and reliability framework provides the opportunity to analyze situations that go beyond hardware failure (i.e., mispredicting winds), and considering the possibility of failures due to design problems and unknown unknowns that have occurred in the past (i.e., failure of the retrorocket system to actuate in the less than 1 second window).

The risk assessment made it possible to link the CM design features to the mission. In this way it was possible to understand the benefit of crash protection in the context of the landing system failure modes. Furthermore the analysis helped expose the difference between a land-landing capability (on a smooth, flat, dry surface with low horizontal velocities), and land-landing survivability during a pad abort. This distinction helps to make visible the capabilities of the land-landing vehicle, and understand the benefit of crash protection for any system type.

Qualitative Results

It was recognized that the risk analysis is subject to large uncertainties. In order to provide a high level interpretation of the results, the risks were color coded to reflect the rough order of magnitude of their likelihood. The risks shown in Figure 7.2-1 are: Before (B) representing the risk of idealized landing systems (used in the earlier Water versus Land-Landing Assessment), and After (A) representing the LM606 configuration.

Figure 7.2-1 shows an increase in failure from TPS and apex cover separation. These risks are currently under design so they may change. But if the apex cover separation requires a parachute system to mitigate the risk, then it may remain high along with the other parachute systems (yellow to red risk).

The risks during descent have remained the same. The landing phase shows a risk increase for land-landing systems due to the lack of capability to protect the crew during a hard landing (resulting from system failure), or after tumbling (due to mispredicted winds). The mispredicted surface winds became red due to the lack of horizontal retrorockets that were assumed to prevent tumbling in high wind conditions.

Quantitative Results

The total risk for each CM configuration was computed by adding the PLOC for each risk item. This approach is viable because the fault probabilities are relatively independent and low. Airbag and vertical retro systems without horizontal retrorockets were evaluated for both wet and dry soils due to the significantly different tumbling velocities for the soil types. The results are presented in Figures 7.2-3 and 7.2-4.

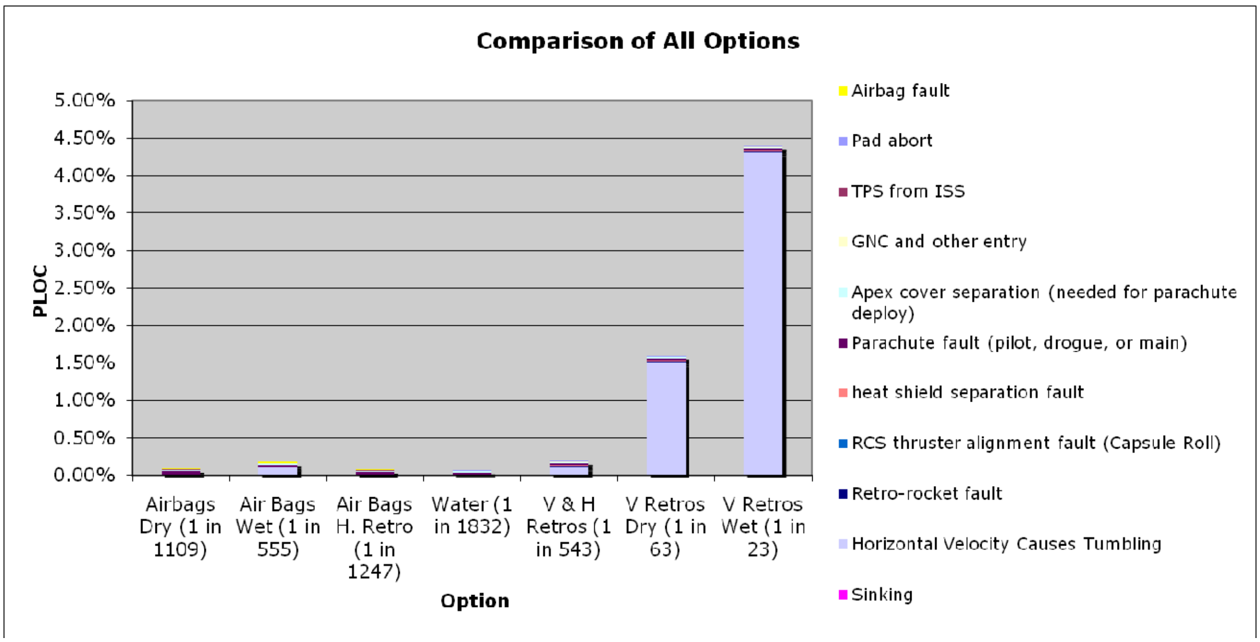

Figure 7.2-3. Comparison of All Options (Uses Generation 2 Airbags)

Mispredicted wind (landing with high horizontal velocity) was found to dominate risk for vertical retro systems without horizontal retrorockets. This risk was unacceptable and tended to saturate the bar chart used to compare options. After the vertical retro systems without horizontal retrorockets were removed, a new bar chart was generated (Figure 7.2-4) to compare the remaining options.

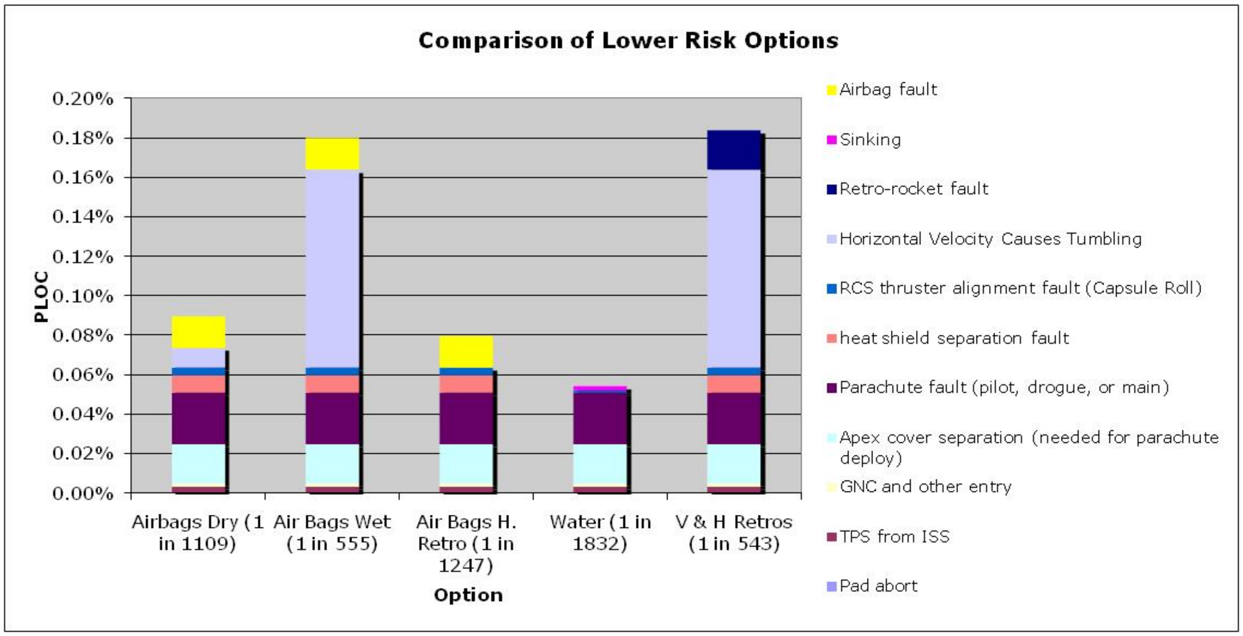

Figure 7.2-4. Comparisons of Lower Risk Options with Generation 2 Airbags (bottom)

When using the Generation 2 airbags, failure rates within an order of magnitude (PLOC = 1.8 E-3 to 9.4 E-4) indicated that they were relatively close considering the order of magnitude uncertainty attached to most of the constituent probabilities. Water-landers had the best risk (PLOC = 5.3 E-4) due to their insensitivity to wind, soft landing surface, and simplicity (no landing mechanisms or retrorockets). Airbags with horizontal retrorockets have the next best risk, and are similar to water-landers, but with some added risk for the landing system.

Airbag systems without horizontal retrorockets on dry soil and vertical retro systems with horizontal retrorockets were found to have similar risk, with similar increases in risk over the airbag/horizontal retro system due to having similar (decreased) wind speeds for tumbling. However, airbag systems without horizontal retrorockets tumble at a lower wind speed than those options on wet soil, and so have higher risk. Because it is likely that most landing sites would have wet soil at the same time (during rainy winter months), this risk must be considered to be an integral part of the risk for the airbag/no horizontal retrorocket CM configuration.

Overall, mispredicted winds (high surface winds) were found to be the dominant risk due to resultant vehicle tumbling. If this risk is mitigated (e.g., using horizontal retrorockets or improved seat systems), all of the options are found to have similar risk magnitude considering their uncertainties.

7.2.2 Task 2: Landing System Test and Verification (T&V) Data Analysis

The data analysis effort is summarized in Appendix B. Figure 7.2-5 depicts the events and sub-events that were examined.

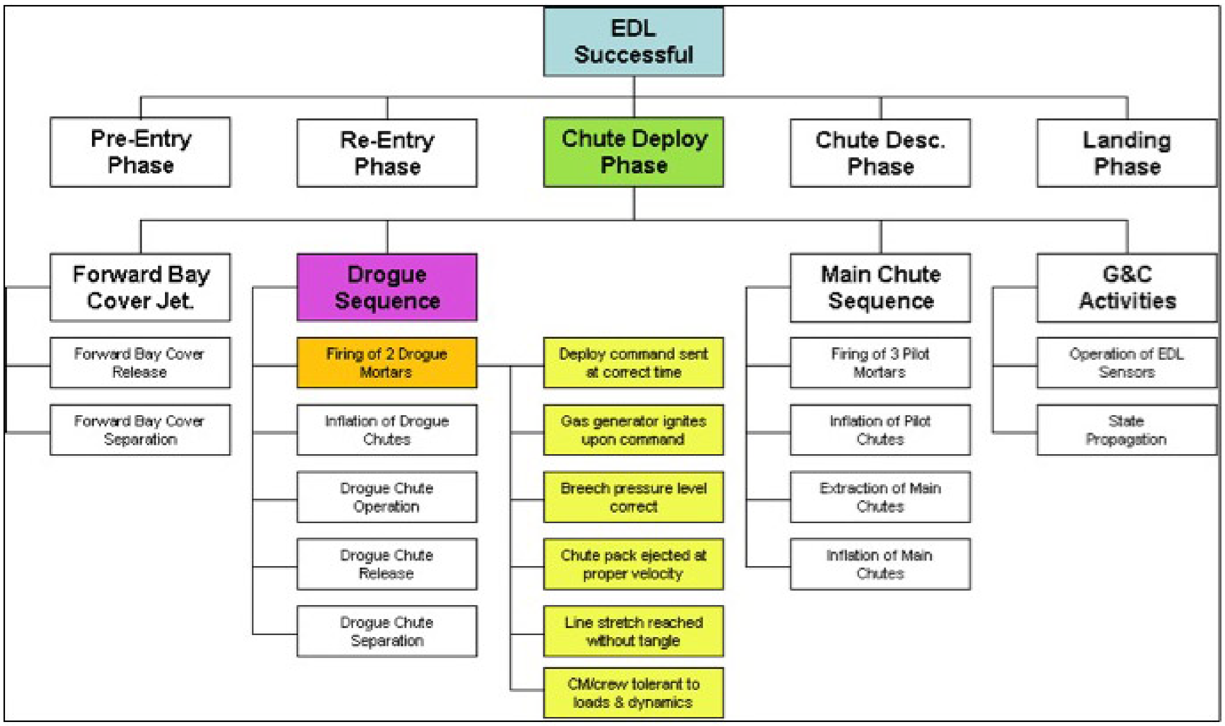

Figure 7.2-5. CM Event Sequence Diagram Used to Investigate the Completeness of the CEV Project's T&V Approach

7.2.3 Task 3: Landing Site Accessibility and Availability Data Analysis

The land-landing site availability from LEO assessment addressed the interaction of CONUS landing accessibility and availability as discussed in the following sections.

7.2.3.1 Landing Site Accessibility

Land-landing site accessibility was based on numerous factors. Each of these factors is discussed, followed by an integrated graphical representation. A landing opportunity was assumed possible when the ISS ground track fell within a specified cylinder projected vertically from the center of the landing target. The cylinder radius was equal to the CM cross range defined by its anticipated L/D capability.

CM Lift to Drag Ratio (L/D)

For this analysis, two L/Ds were under consideration, 0.30 and 0.35. This analysis looked at each ratio; the cross range possibilities each presented and determined the sensitivity of L/D design. The cross range possibilities for the 0.30 and 0.35 L/D are 60 and 85 nm, respectively.

Using a one site landing location as a baseline, this analysis determined how many landing opportunities were presented for 180 contiguous days. The cross range capabilities meant that the ISS did not need to be directly over a landing site for a landing opportunity to occur, but rather the ground track must intersect the cylinder projected vertically from the landing site, thus allowing the CM to be guided to the landing site on that orbital track.

Table 7.2-2 shows the SLAAM output for landing opportunities over a 14 day period, but the total passes and average pass per day show the amounts for the180 days calculated by the model. This model displays data in both daily and daily/hourly calendar format and all geometrically accessible landing times while allowing for various user imposed constraints. Those landing opportunities that fail the constraint from the display are removed from consideration. In addition, the SLAAM results displayed represent 180-day periods, starting on January 1, 2006. It is reasonable to allow for trends in the 180-day data to represent yearly data. The SLAAM display in the table uses following nomenclature:

- 'a' – ascending pass
- 'd' – descending pass
- 'OK' – raise maneuver not necessary
- 'R' – raise maneuver necessary

Table 7.2-2. Comparison of L/D 0.30 and 0.35 for EAFB (Edwards) landing site, all options available (day and night), 180 days (first 14 days shown)

L/D = 0.35

Start Date	1/1/2006														
Number of Days	180														
Site Name	Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	1	1	1	1	0	1	0	0	0	1	0	1	1
# of Landings	**Total Passes**	76													
	Ave Pass Per Day	0.4													

L/D = 0.30

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR			aOK						dR		dR	
Edwards	Pass 2														
	Day Total	0	1	0	0	1	0	0	0	0	0	1	0	1	0
# of Landings	**Total Passes**	56													
	Ave Pass Per Day	0.3													

Decreasing the L/D by 0.05 (from 0.35 to 0.30) decreases the CM cross range capability from 85 to 60 nm with a corresponding reduction in the amount of landing opportunities from 76 to 56, a loss of approximately 26 percent. Some sites are available twice per 24 hour period (Pass 1 and Pass 2) while on some days the site is not available due to orbital mechanics and the CM cross range capability (Figure 7.2-6). An additional note is that some land-landing sites require the raise maneuver, shown in Figure 7.2-7. The reentry trajectory targets a SM disposal area off the US western coast. After SM jettison, the CM must perform an RCS burn lasting up to 50 seconds to extend the trajectory downrange to clear the intervening mountains and achieve the desired landing site.

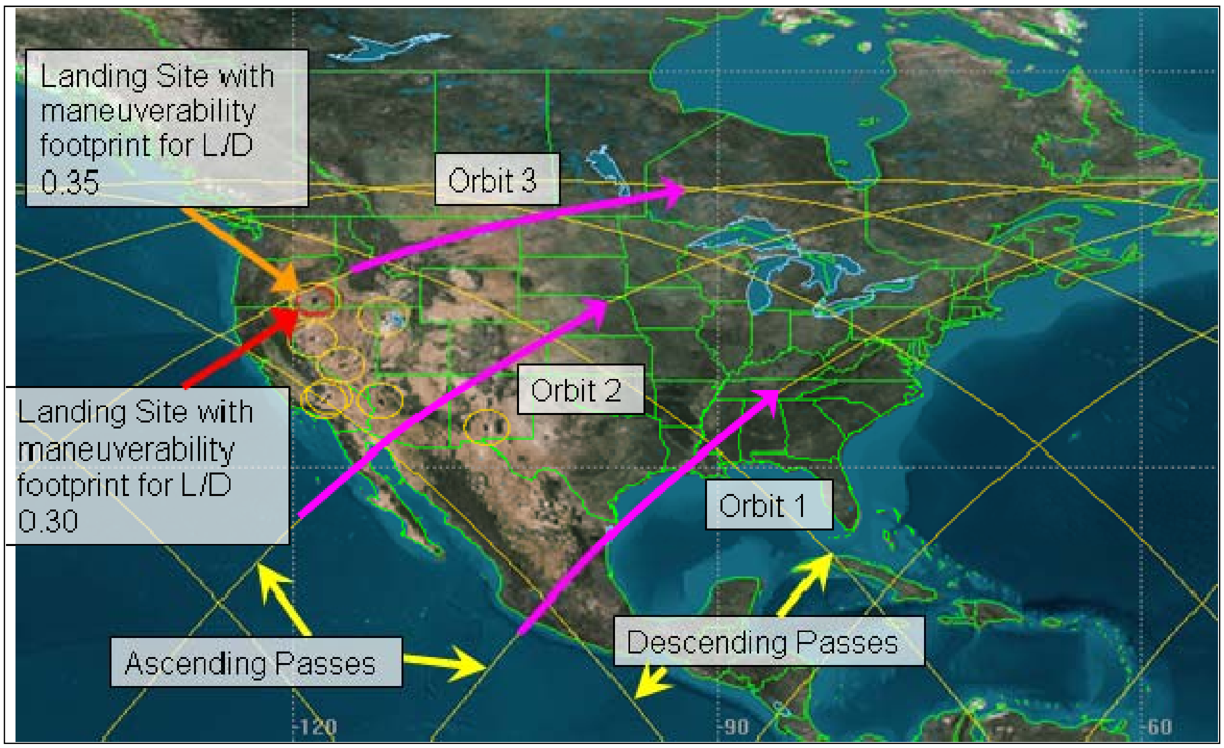

Figure 7.2-6. Problem geometry: illustration of cross range options, ascending and descending passes and 3 orbit ground trace

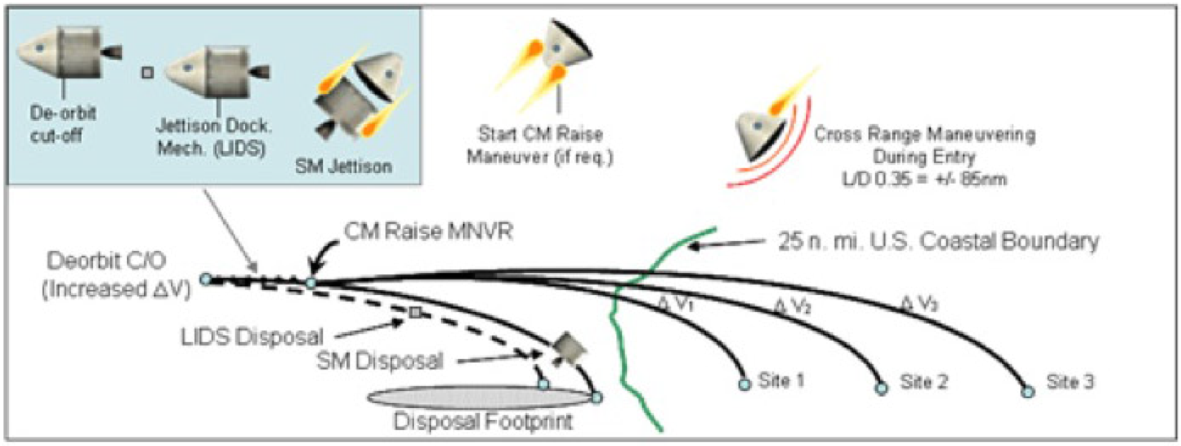

Figure 7.2-7. Concept of Operations: CM Disposal and Raise Maneuver

Ascending or Descending Passes

The latitude of the landing site greatly influences the ascending/descending pass time spread. The closer the landing site to the equator, the more evenly spaced the landing opportunities become and conversely, the further toward either pole, the shorter the time between ascending to descending passes. For most of the sites chosen for this study, the ascending/descending time spread is approximately 16/8 hours (i.e., 16 hours between descending to ascending passes, and 8 hours between ascending to descending passes). While this aspect of orbital geometry may not directly influence landing accessibility, whether or not a pass is ascending or descending might, depending on what occurs in each of those scenarios. For example, there may be landing sites where all the ascending passes mean a particular SM deorbit procedure is required, therefore sorting on ascending or descending was deemed a necessary study tool. The model shows that choosing to sort for either ascending only or descending only passes results in a 50 percent reduction of landing opportunities.

Landing Network

As shown previously in Table 7.2-2, having one landing site has significant limitations. One relatively simple idea to increase landing accessibility is to have a network of landing sites. Table 7.2-3 displays the results for a representative network of three US western coast landing sites: Carson Sink, NV (Carson), EAFB (Edwards), and the Utah Test Range (Utah). Having two additional landing sites increases accessibility over one site by 241 percent.

Table 7.2-3. Landing accessibility for NASA's landing site network, all landing options available, 180 days.

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Carson	Pass 1						aOK		aOK		aOK				
Carson	Pass 2						dOK		dOK		dOK				
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
Utah	Pass 1	aR		dR		dR		dR	aR		aR		aR		dR
Utah	Pass 2														
	Day Total	1	1	2	1	2	2	2	3	0	3	1	1	1	2
	Total Passes	259													
	Ave Pass Per Day	1.4													

7.2.3.2 Landing Site Availability

As mentioned previously, landing site availability is the number of times that accessible landing opportunities can be utilized in the presence of operational constraints. The operational constraints studied were SM deorbit, day/night landing preferences, wind velocity threshold, gust conditions, and the use of water as a CONUS landing site backup is described in the following sections.

Day/Night Constraints

In certain circumstances and locations, landing either at night only or day only may be preferable. Table 7.2-4 shows the differences for day and night only landings, with day and night-time each containing 12 hours. For January of 2006, day and night also coincide with descending and ascending passes respectively, which is not the case throughout the year. For example, in June 2006 day only passes for EAFB opportunities occur on both ascending and descending passes.

Table 7.2-4. Landing site availability for Edwards with day landing only constraint

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR		dR							dR		dR	
Edwards	Pass 2														
	Day Total	0	1	0	1	0	0	0	0	0	0	1	0	1	0
	Total Passes	38													
	Ave Pass Per Day	0.2													

Surface Wind Constraints

Past studies indicated that landing systems were sensitive to surface wind speeds. In this analysis, the objective was to study landing sensitivity to various wind speed thresholds, diurnal and seasonal effects, and site to site wind correlations

The data for the threshold sensitivity, diurnal, seasonal studies were obtained from the EAFB staff meteorologist and included observation and forecasted data for each hour recorded and gust conditions. The data for the site correlation study came from Jet Propulsion Lab (JPL) and NOAA.

Diurnal Study

The diurnal study was completed by examining the hourly wind speed observation data for EAFB in 2006, sorting the observations into six 4-hour time blocks, and taking the average wind speed for each time block for the year. This study indicated that there are diurnal effects at EAFB and the 1600 – 1900 time block has the highest average wind speed. Final results are shown in Figure 7.2-8. It is worth noting that while diurnal effects were seen, there were many instances of wind variability at all times of day. This study has shown that avoiding certain times of day for landing due to diurnal effects is not an effective remedy to the wind situation.

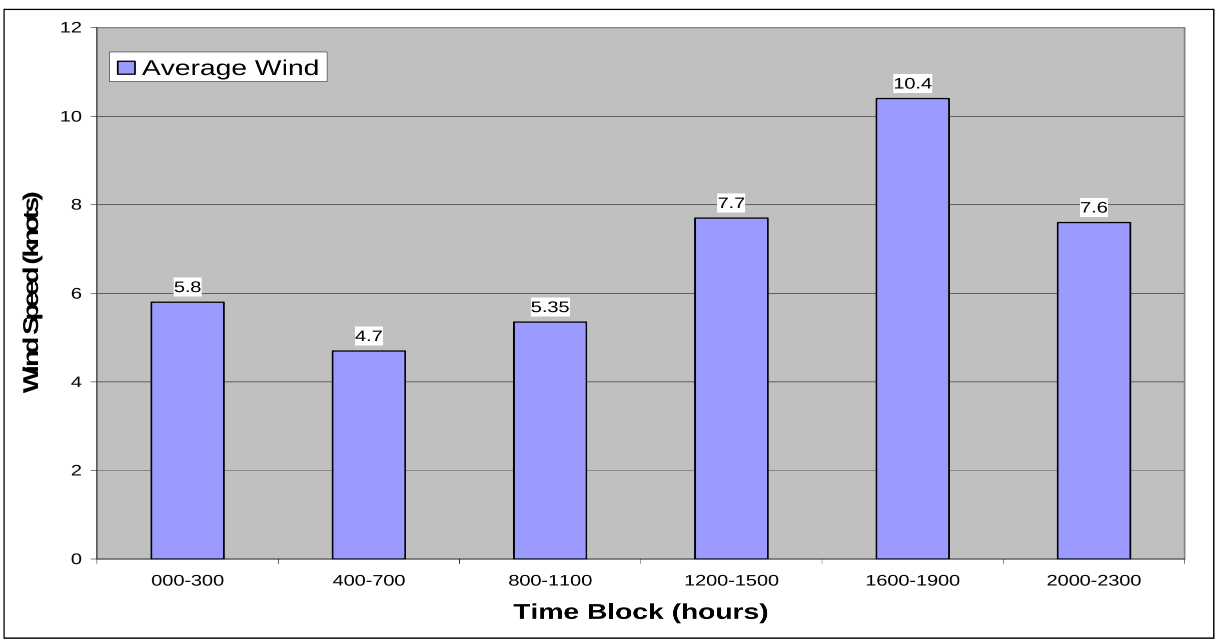

Figure 7.2-8. Diurnal wind study results, Edwards 2006

Seasonal Wind Study

This study examined the recorded data for seasonal variations. Data for 2006 in the 1600-1900 time block was used. The year was broken into seasons by month and the average seasonal wind speeds were compared with the average yearly wind speed for the chosen time block. The seasonal study also indicated that while the average wind speeds tend to be benign, the data shows that averages can be misleading. Figure 7.2-9 shows the results for summer 2006. See Appendix B for all seasons. Because this analysis is only for the 1600-1900 time block, the annual average differs from the total annual average.

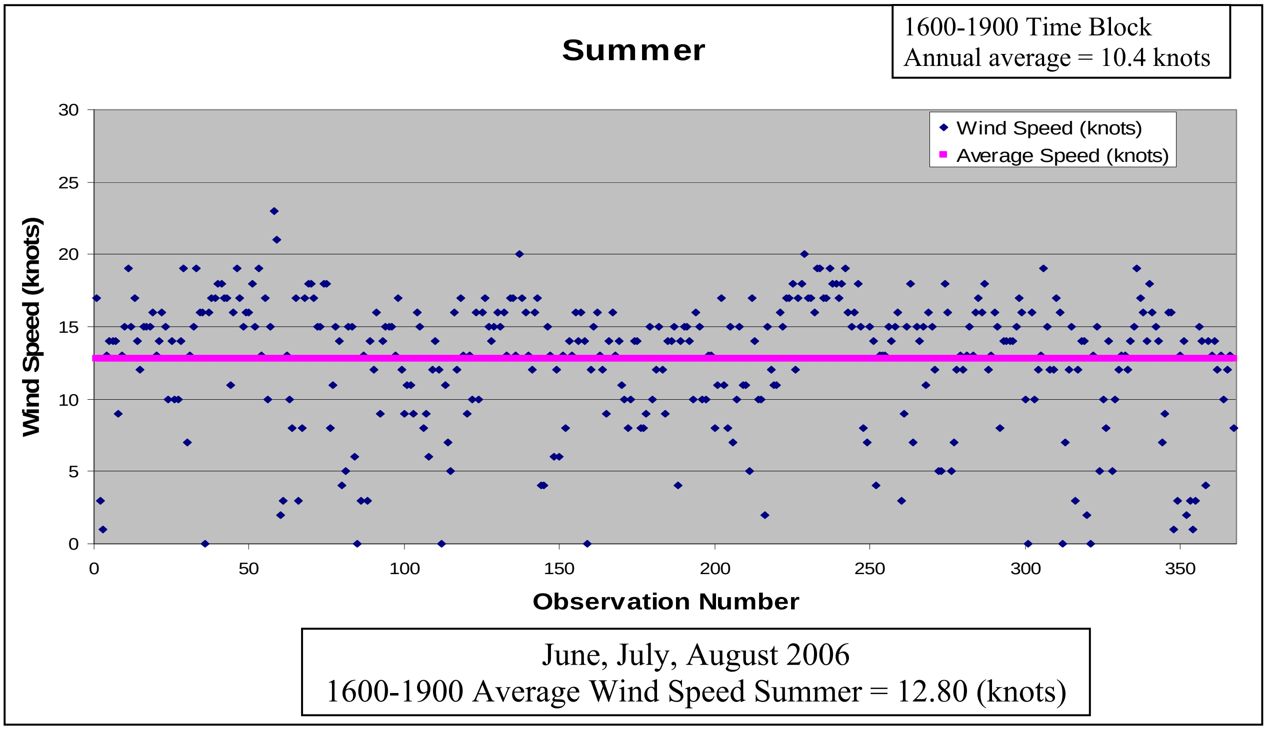

Figure 7.2-9. Seasonal Study: Summer 2006, EAFB

Wind Threshold Sensitivity Study

The purpose of the wind threshold sensitivity study was to determine what happens to landing availability when winds above certain thresholds are eliminated. SLAAM has the capability to take wind threshold as a user input and sort accordingly. As the wind threshold increases, landing availability increases. Table 7.2-5 through 7.2-8 through show the results for 5, 10, 15 and 20 knot thresholds at EAFB for 180 days.

Table 7.2-5. 5 knot wind threshold (8.4 fps)

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1			aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	0	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	40													
	Ave Pass Per Day	0.2													

Table 7.2-6. 10 knot wind threshold (16.8 fps)

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	55													
	Ave Pass Per Day	0.3													

Table 7.2-7. 15 knot wind threshold (25.3 fps)

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	69													
	Ave Pass Per Day	0.4													

Table 7.2-8. 20 knot wind threshold (33.7 fps)

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	75													
	Ave Pass Per Day	0.4													

Figure 7.2-10 shows how the cumulative wind speed capture percentage compares with the wind speed at EAFB for 2006. The data shows that if a CM is designed to withstand a wind speed listed on the y-axis, one can note the percentage of observations, based on the year's wind data that the vehicle could be expected to accommodate.

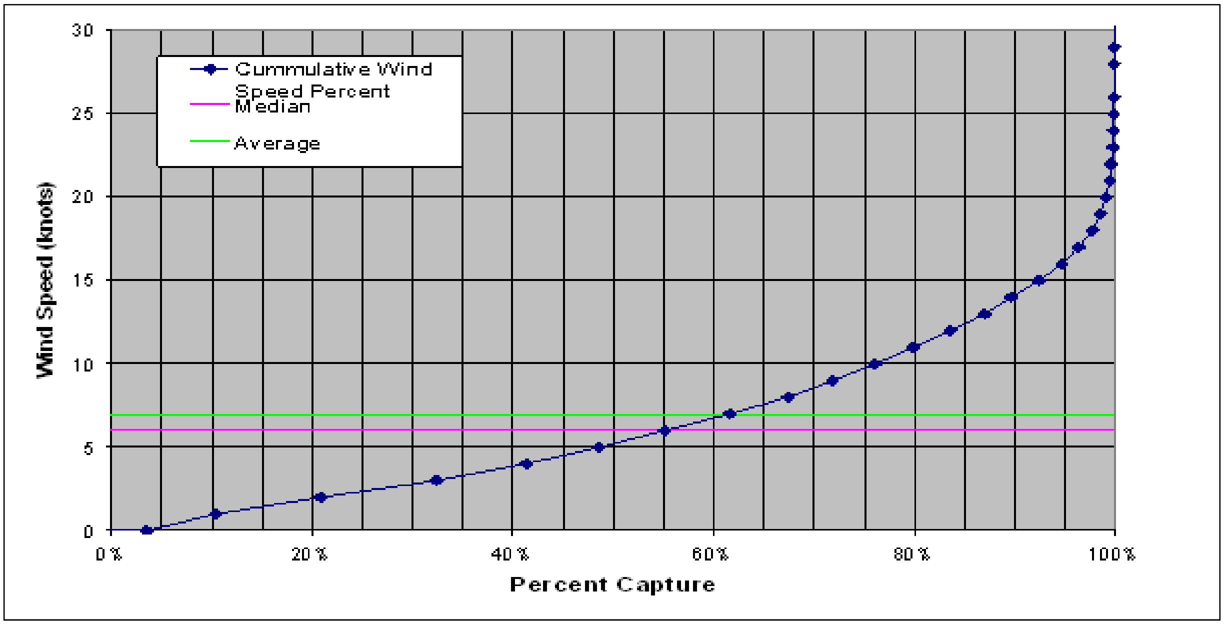

Figure 7.2-10. Percent Capture versus Wind Speed (knots)

Because wind gusts can cause CM oscillations, this analysis investigated what happens to landing availably with gust conditions. Using gust data for the same time period (EAFB 2006), SLAAM was used to determine landing availability based on whether there were or were not gust conditions only. Shown in Table 7.2-9 are the results for gust elimination at EAFB for 180 days.

Table 7.2-9. Gust elimination, No wind threshold, EAFB 2006

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Day Total	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	63													
	Ave Pass Per Day	0.4													

Wind threshold and gust elimination can have a significant effect on landing availability. Wind thresholds can decrease availability by up to 49 percent with a 5 knot threshold. Gust elimination alone can decrease availability by 17 percent. Due to the variability of gusts and the unpredictable nature of gusts elimination, an operational constraint may be necessary.

Forecast Versus Actual Wind

The differences between actual and forecast wind conditions are worth noting. This assessment looked at both forecast and actual data for 2006 at EAFB. In all, there were over 8,500 hourly wind and gust observations with two daily forecasts. The actual wind speed exceeded the forecast approximately 1,200 times and there were approximately 200 occasions where there were non-forecast gust conditions or gusts that exceeded the forecast. This showed that forecasts tend to be more conservative, but actual wind and gust conditions frequently exceed the forecast. Due to the nature of gust and wind recording methods, there may be situations where gust conditions exist or various wind speeds occur, but are not recorded. Reported wind data is the latest two-minute average wind speed for the previous hour, and gust data is the highest two-minute wind speed average for the last 10 minutes of the previous hour. This data reporting method shows how vital information can be non-recorded.

Wind/Gust Offset

Because of the nature of weather forecasting and the methods for determining wind and gusts speeds, a data-offset capability was introduced into the model. This offset allows the user to use the highest value of either wind and/or gust velocity, forecast or actual data for their analysis based on time. For example, if a user wanted to use the tool to determine landing opportunities with a wind threshold, but wanted to include information on the wind forecast from six hours before landing they would have that option. The examples in Tables 7.2-10 and 7.2-11 show the impact of using the offset option.

Table 7.2-10. Offset Example, 20 knot threshold, no pre- or post-offset, forecast data

Start Date	1/1/2006														
Number of Days	180														
Data Used	LD_.35														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Daily Availability	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	74													
	Ave Pass Per Day	0.4													

Table 7.2-11. Offset Example, 20 knot threshold, 6-hour-pre- and 3-hour-post-offset, forecast data

Start Date	1/1/2006														
Number of Days	180														
Data Used	LD_.35														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1		dR	aOK	dR	aOK		aOK				dR		dR	aOK
Edwards	Pass 2														
	Daily Availability	0	1	1	1	1	0	1	0	0	0	1	0	1	1
	Total Passes	68													
	Ave Pass Per Day	0.4													

Due to the offset uses for the highest wind value for the time period specified, the result is a more conservative prediction of availability. The offset works similarly for the gust criterion. For more information about the offset option, see Appendix B.

Site-To-Site Correlation

Based on top level statistical analysis, this study showed that there is some correlation between the three previously discussed land network sites: Carson Sink, NV; EAFB, and the Utah Test Range. The correlation coefficients for the three pairs are listed below:

1. Wind speed correlation for Carson and Edwards = 0.5460
2. Wind speed correlation for Carson and Utah = 0.5039
3. Wind speed correlation for Edwards and Utah = 0.5071

A correlation of 0.5 indicates a generally positive relationship between wind speeds at both locations. This means that the plot of wind speed at one location versus wind speed at the other location tend to fall along a line with positive slope. The closer the correlation coefficient is to 1, the closer the points in the plot will fall on a straight line. So, if the wind speed is high at Carson, a similarly high wind speed is expected at EAFB. This is not to say that a lower wind speed at EAFB is not possible, but the probability of a lower wind speed is smaller than a higher wind speed. Table 7.2-12 shows the 2006 site winds for Carson Sink, NV, EAFB, and the Utah Test Range, respectively.

Table 7.2-12. 2006 Winds, Reported in Knots, at Representative Landing Sites

2006 Winds, Reported in Knots, at Representative Landing Sites

CAR			EDW			UTTC		
6	Ave		7	Ave		6	Ave	
33	Max		29	Max		38	Max	
33	Percentile	100%	29	Percentile	100%	38	Percentile	100%
15		95%	17		95%	17		95%
12		90%	15		90%	14		90%
10		85%	14		85%	11		85%
9		80%	12		80%	9		80%
8		75%	11		75%	8		75%
7		70%	10		70%	8		70%
6		65%	9		65%	7		65%
6		60%	8		60%	6		60%
5		55%	7		55%	6		55%
5		50%	6		50%	5		50%

SM Deorbit Method Constraint

In order to reduce the likelihood of SM debris hitting land, sorting for raise and non-raise maneuvers was incorporated into SLAAM. Using the SM debris footprint, Table 7.2-13 was developed to classify the ascending and descending passes for each site based on L/D and SM debris footprint. “Raise” means a raise maneuver is necessary for landing and “okay” means no raise maneuver is necessary.

Table 7.2-13. Raise maneuver classification

Site Name	Approach	L/D 0.30	L/D 0.35
Carson Sink, NV	Ascending	Raise	Okay
	Descending	Raise	Okay
EAFB	Ascending	Okay	Okay
	Descending	Raise	Raise
Utah Test Range	Ascending	Raise	Raise
	Descending	Raise	Raise

Eliminating opportunities that require raise maneuvers reduces availability at EAFB by 51 percent as shown by the loss landing opportunities shown in Table 7.2-14.

Table 7.2-14. Availability at EAFB without Raise Maneuvers

Start Date	1/1/2006														
Number of Days	180														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Edwards	Pass 1			aOK		aOK		aOK							aOK
Edwards	Pass 2														
	Day Total	0	0	1	0	1	0	1	0	0	0	0	0	0	1
	Total Passes	37													
	Ave Pass Per Day	0.2													

This analysis also quantified what impact the SM deorbit method constraint had on the landing site network. Eliminating opportunities that require raise maneuvers for the land-landing network decreased the availability by 52 percent, shown in Table 7.2-15.

Table 7.2-15. Availability at Carson Sink, NV. EAFB, and the Utah Test Range without Raise Maneuvers

Start Date	1/1/2006														
Number of Days	180														
Data Used	LD_.35														
Site Name		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Carson	Pass 1						aOK		aOK		aOK				
Carson	Pass 2						dOK		dOK		dOK				
Edwards	Pass 1			aOK		aOK		aOK							aOK
Edwards	Pass 2														
Utah	Pass 1														
Utah	Pass 2														
	Daily Availability	0	0	1	0	1	2	1	2	0	2	0	0	0	1
	Total Passes	124													
	Ave Pass Per Day	0.7													

Statistical Analysis of Landing Site Data to Determine Site Availability

Landing site availability was determined statistically by an examination of the weather forecasts (primarily horizontal winds and gusts) versus the measured winds exceeding the vehicle capability. Weather forecast data from EAFB was used as input to a Monte Carlo analysis. Figure 7.2-11 shows a flow chart of the analysis.

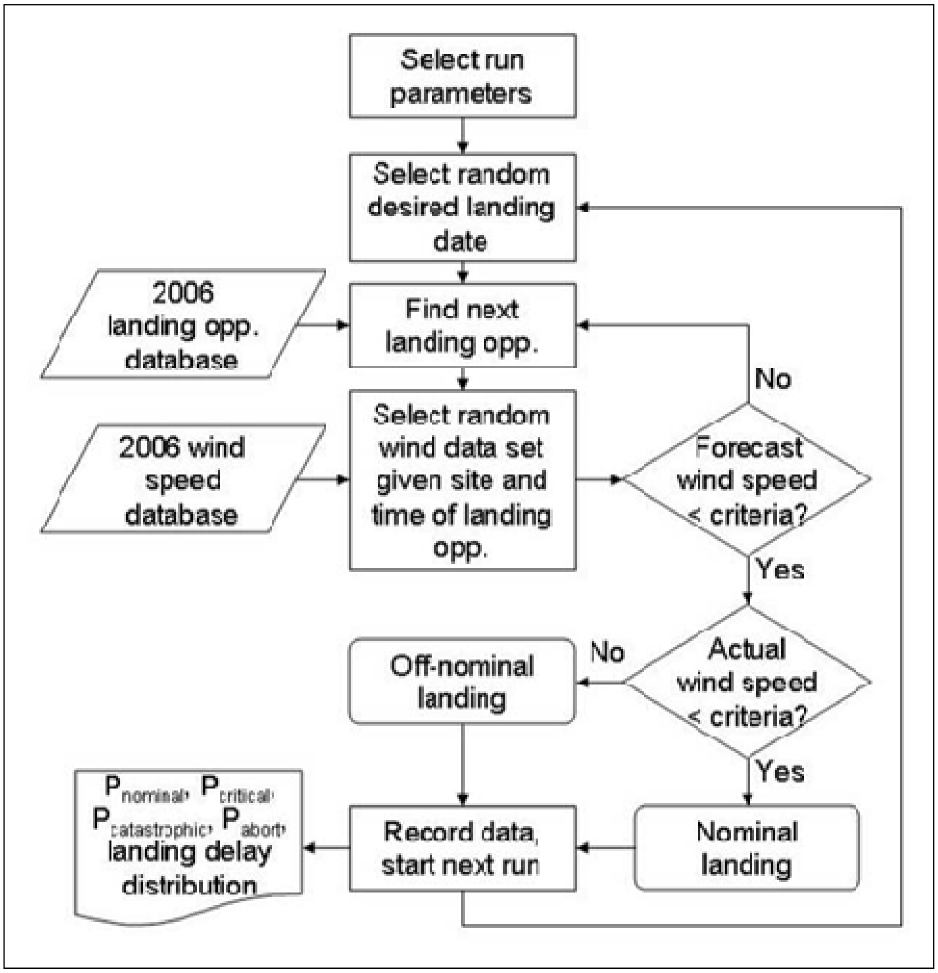

Figure 7.2-11. Monte Carlo Simulation Flow Chart for Statistical Weather Analysis

The simulation began by setting the parameters such as the landing, critical, and catastrophic criteria. The criteria determined if the CM would attempt to land in the estimated wind conditions, and whether the vehicle landed nominally under the experienced wind conditions. If the forecasted wind speed is lower than the landing criteria, then the CM could attempt to land. If the actual wind speed is higher than the critical criteria, then the CM could experience tipping, and if the actual wind speed is higher than the catastrophic criteria then the CM will tumble and LOC was assumed.

Different values correspond to different CM configurations. The baseline landing criteria used for previous studies was 18 fps, according to the operational number presented by Marshall Space Flight Center (MSFC) in May. The baseline CM configuration used was a vehicle with airbags, no horizontal retrorockets, and landing on dry soil. The corresponding critical criteria was 38 fps, and the catastrophic criteria was 47 fps.

Another parameter was wind gust chance. The gust data used in the studies only gave the maximum gust speed experienced during a ten-minute period in an hour, and no information about gust length or frequency. Thus, if conditions were gusty, the gust chance parameter represented the probability that a gust would happen during the critical landing period. The baseline value used in the studies was 20 percent, which is an approximation based on the characterization of gusts as roughly sinusoidal. This 20 percent number meant that landing vehicle was estimated to experience gusty wind speeds rather than average wind speeds 20 percent of the time.

The user could also select the available landing sites. Cases with one site used EAFB, while cases for three sites used EAFB, Carson Sink, NV, and the Utah Test Range. The NESC team only had gust data for EAFB and was used as a reasonable proxy at low fidelity for the two other sites. The other sites provide additional landing opportunities based on orbital analysis.

The user was able to select the forecast time. This is the length of time prior to touchdown that the go/no-go landing decision has to be made. Thus this describes how old the wind forecast data will be by the time the landing takes place. This value is typically a product of the operational setup, and the value of three hours was used as a baseline. This means that the landing decision will be made based on the forecast in effect three hours before the scheduled landing.

After framing the problem, the simulation performed runs up to the specified amount, usually about 10^6 runs. For each run the simulation selects a random day to be the first day in which a landing is desired. The next landing opportunity is determined from a database of orbital accessibility times (assuming a CM L/D of 0.3). Then a set of wind data is chosen randomly from the wind speed database according to time of day and time of year of the landing opportunity. The data is binned by hour and month, but in order to increase the number of data points to choose from the simulation can select from data sets one hour earlier or later; and from data sets one month earlier or later. Thus for a landing at 13:00 in May, the simulation would select data from the hours of 12:00, 13:00, and 14:00, and from the months of April, May and June. Each set of wind data includes the forecasted maximum wind speed, the actual observed average wind speed from the end of the hour, and the maximum gust speed in that hour. The forecasted data, actual data, and the gust data come from the same hour.

The forecasted wind speed is then compared to the landing criteria speed. If the forecasted speed is too high then the landing is delayed until the next landing opportunity. If the forecasted speed is acceptable, then the landing is attempted. To determine the outcome of the landing, the actual wind speed (or gust speed depending on the gust chance) is compared to the critical and catastrophic criteria. If those criteria are not exceeded then it is a nominal landing, and if they are exceeded, then the landing is critical or catastrophic. The data is recorded and the next run is completed.

After completing all runs, the probabilities of nominal, critical, and catastrophic outcomes can be examined. Also the probability of landing delay, and the total delay times for each run can be analyzed.

Critical and catastrophic criteria were chosen for several CM configurations seen in Table 7.2-16. These values are for a three hour forecast time (i.e., a forecast in effect three hours before the scheduled landing) and 20 percent gust chance (with 0 percent gust chance in parentheses). The landing criteria was kept constant for comparison. The tumbling capabilities affect the risk directly, with higher capability being better.

Table 7.2-16. Results from the Monte Carlo Weather Analysis

	Air-Bag Dry Soil **(no horizontal retrorocket)**	Air-Bag Wet Soil **(no horizontal retrorocket)**	Air-Bag (with horizontal retrorocket)	Retro Dry Soil **(no horizontal retrorocket)**	Retro Wet Soil **(no horizontal retrorocket)**	Retrorocket (with horizontal retrorocket)
Go for Landing Forecast Criteria, fps (kts)	18 (11)	18 (11)	18 (11)	18 (11)	18 (11)	18 (11)
Actual Landing Tipping Criteria, fps (kts)	38 (22)	30 (18)	54 (32)	22 (13)	14 (8.5)	38 (22)
Actual Landing Tumbling Criteria, fps (kts)	47 (27)	38 (22)	61 (36)	30 (18)	22 (13)	47 (27)
Probability of Tipping, Percent	0.3 (0.2 - no gusts)	1.1 (1.1 - no gusts)	0.04 (0 - no gusts)	2.8 (2.8 - no gusts)	13 (13 - no gusts)	0.3 (0.2- no gusts)
Probability of LOC, Percent (Tumbling Criteria Exceeded)	0.1 (0.04 - no gusts)	0.4 (0.2 - no gusts)	0.01 (0 - no gusts)	1.5 (1.3 - no gusts)	4.3 (4.1 - no gusts)	0.1 (0.04- no gusts)

The Monte Carlo was run for a range of landing criteria in order to examine the sensitivity of the landing delay chance and crew risk to that parameter. The assumptions were airbags, no horizontal retrorockets, dry soil (38 fps critical, 47 fps catastrophic), 20 percent gust chance, three possible landing sites, and a three hour forecast. The results are in Figures 7.2-12 and 7.2-13.

The baseline case is 18 fps for comparison. The PLOC is at about 1e-3 for the baseline, and goes above 1e-2 at about 50 fps landing criteria. The chance of abort is 47 percent at 18 fps.

As the landing criteria value is increased, the CM is allowed to land under rougher conditions. This decreases the chance of landing delay while increasing the chance of crew injury. As the landing criteria value is decreased, the operational procedure becomes stricter. The chance of delayed landing goes up since it is less likely the conditions will be acceptable, but the risk to the crew goes down since the winds would have to exceed their forecast to a greater degree to be dangerous. Thus this is a trade between landing availability and crew injury risk.

To decrease risk without decreasing availability, it is necessary to improve forecasting to avoid being surprised by high winds or to increase the CM capability. The CM capabilities were varied to examine the results. The assumptions were landing criteria of 18 fps, 20 percent gust chance, and a 3 hour forecast. The results are in Figure 7.2-14.

Figure 7.2-14 illustrates that increasing the CM capability decreases risk. When the tumbling criteria was increased, the CM sees more severe winds in order to roll and injure its occupants. When the tumbling critieria is decreased, the CM will be dangerous in a greater range of wind speed. The baseline tumbling criteria for an airbag system without horizontal retrorockets landing on dry soil is 47 fps.

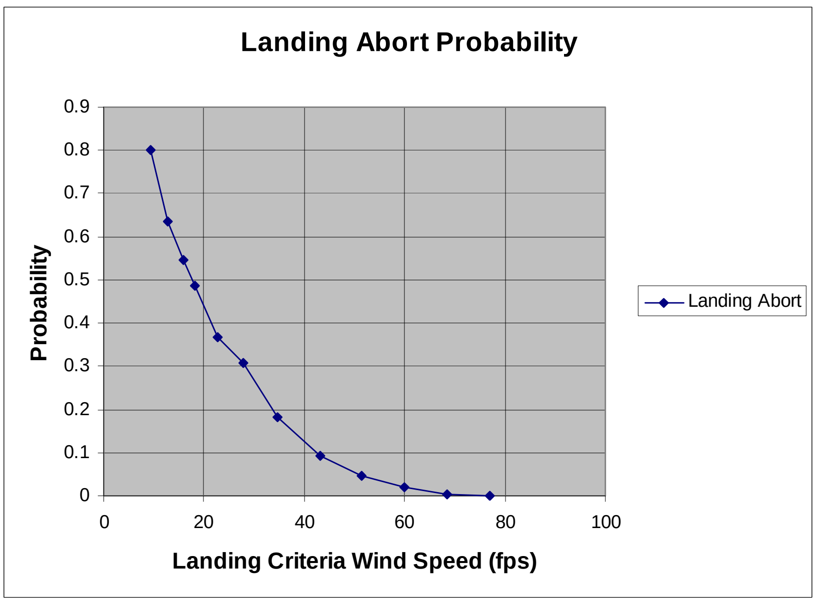

Figure 7.2-12. Landing delay risk - Chance of abort is 47 percent for the 18 fps baseline case

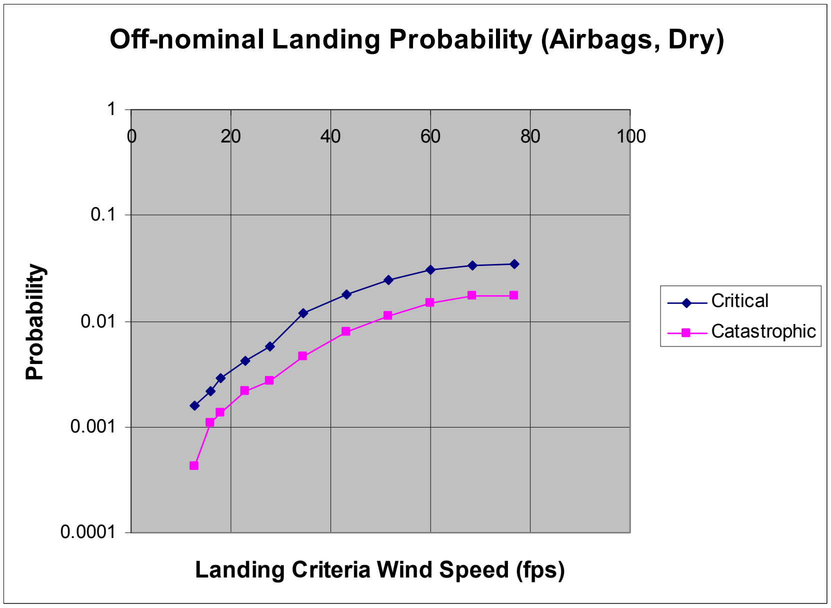

Figure 7.2-13. Logarithmic plot of risk of LOC over criteria

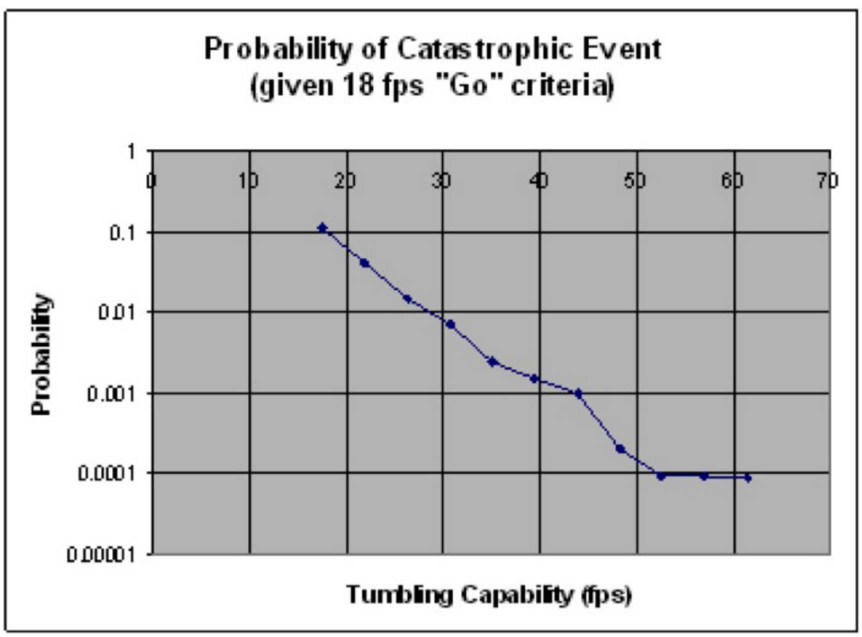

Figure 7.2-14. Logarithmic plot of risk of LOC over capability

Another interesting output was the amount of delay before landing for each run. The time between the first available landing opportunity and the actual landing was recorded for every run, with some landing immediately and some being repeatedly delayed (these delays being independent). Due to orbital tracks, these attempts can be separated by days or weeks. This data can be visualized as a cumulative probability chart, where each point in the chart gives the probability that the CM would have landed with that much delay or more. The assumptions used are a CM with an L/D of 0.3 (which effects site accessibility), 20 percent gust chance, and three hour forecast. Some of the characteristics that were varied were time of day (any time or daytime only), number of sites (one or three), and landing criteria. The results are in Figures 7.2-15 through 7.2-19.

For the case of 1 site, 18 fps, and any time landing, there is an approximate10 percent chance that the CM will not have landed after 10 days. If 3 sites are used, then the change of landing drops slightly more than an order of magnitude. For the case of 1 site, 18 fps, and daytime landing only, there is an approximate10 percent chance that the CM will not have landed after 25 days. Allowing three landing sites changes with 90 percent confidence time to 10 days. For the strictest case (1 site, 13 fps, daytime only) it takes over 40 days of landing delay to achieve 90 percent confidence that the CM would have landed.

Ways to improve these values and lessen the landing delay are to increase the landing criteria, allow landing under a wider variety of conditions, or to increase the accessibility of landing sites by increasing the number or improving the CM landing range.

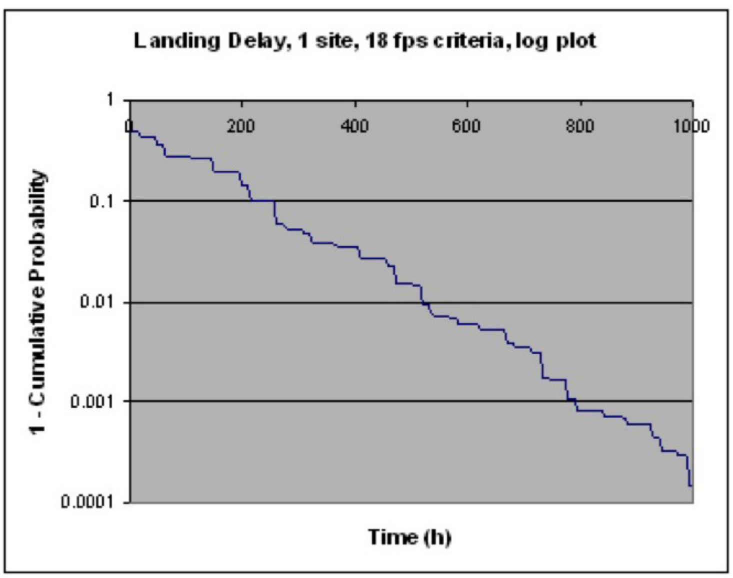

Figure 7.2-15. Landing delay cumulative probability, 1 site, 18 fps

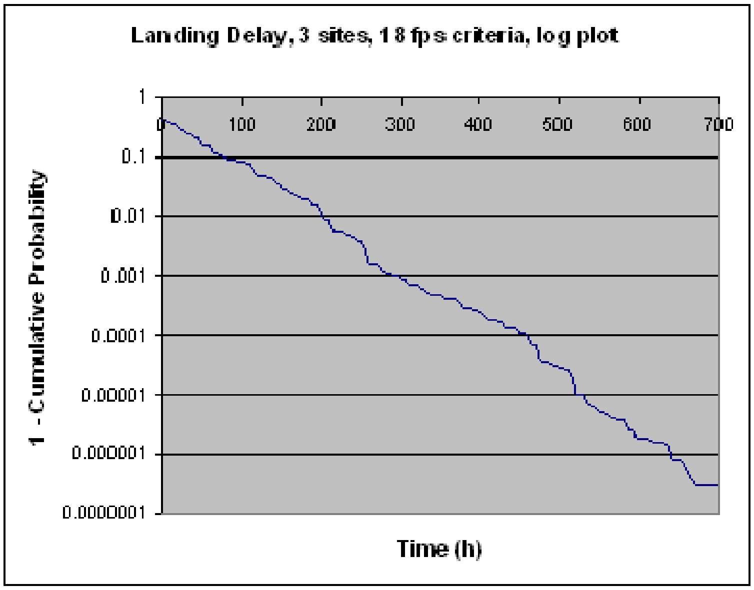

Figure 7.2-16. Landing delay cumulative probability, 3 sites, 18 fps

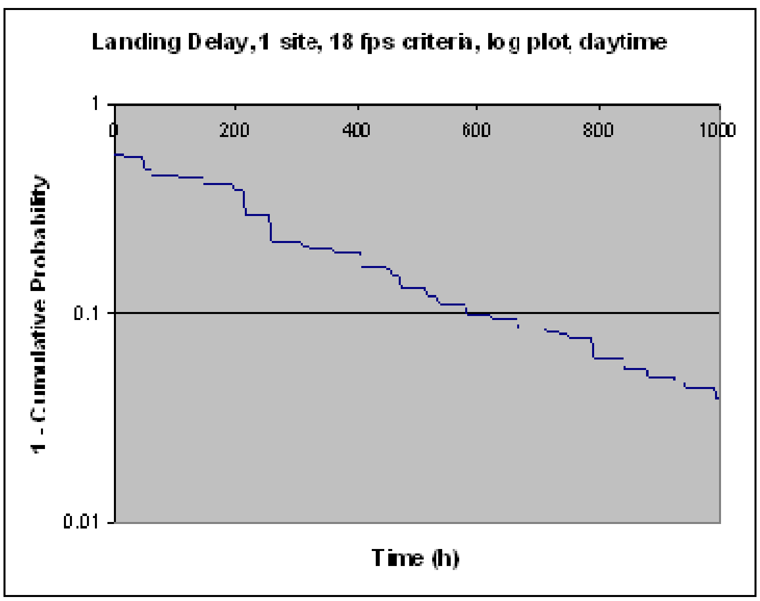

Figure 7.2-17. Landing delay cumulative probability, 1 site, 18 fps, daytime

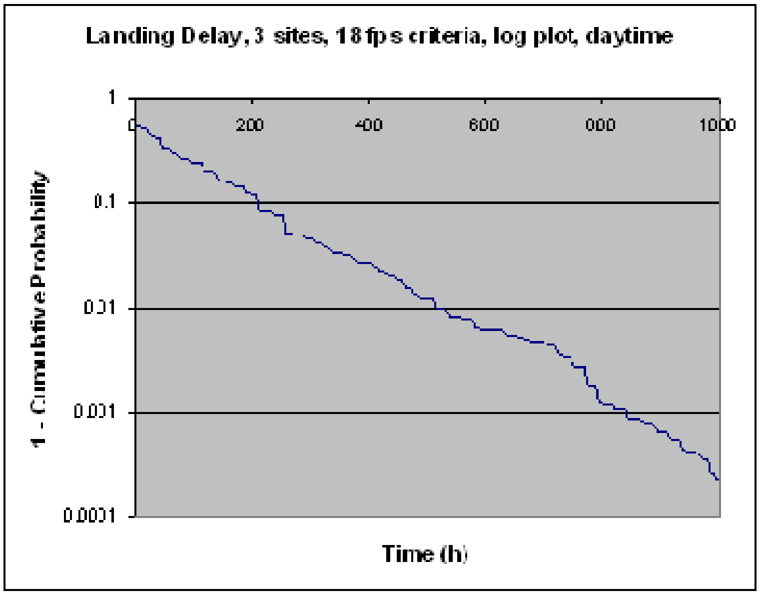

Figure 7.2-18. Landing delay cumulative probability, 3 sites, 18 fps, daytime

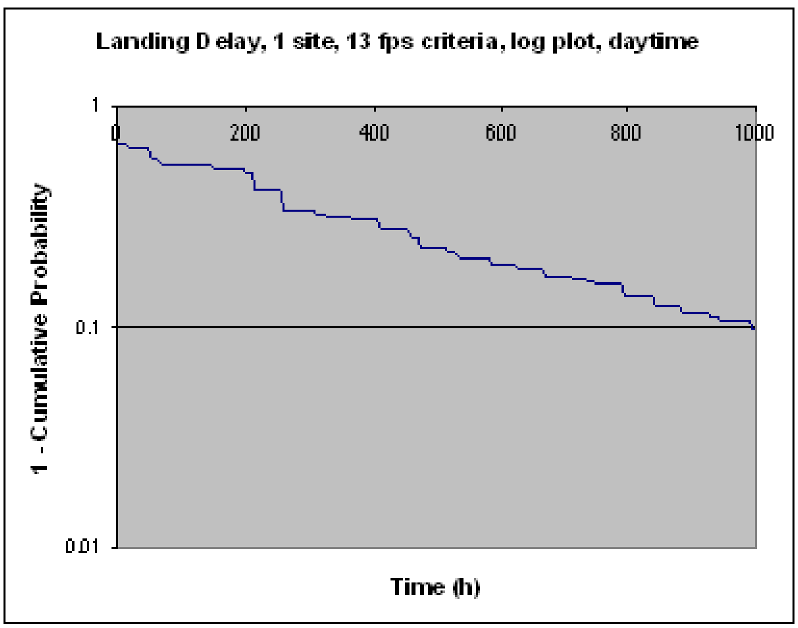

Figure 7.2-19. Landing delay cumulative probability, 1 site, 13 fps, daytime

Another Monte Carlo simulation was run to judge the effectiveness of the Generation 2 airbags. The results are summarized in Table 7.2-17. The PLOC for an airbag equipped CM on soil is near zero in this simulation when compared with Table 7.2-16.

Table 7.2-17. Monte Carlo Results Incorporating Increased Capability of Generation 2 Airbags

	Air-Bag Hard Soil **(no horizontal retrorocket)**	Air-Bag Soft Soil **(no horizontal retrorocket)**	Retro Dry Soil **(no horizontal retrorocket)**	Retro Wet Soil **(no horizontal retrorocket)**	Retrorocket (with horizontal retrorocket)
Go for Landing Forecast Criteria	18 FPS (11 KTS)	18 FPS (11 KTS)	18 FPS (11 KTS)	18 FPS (11 KTS)	18 FPS (11 KTS)
Actual Landing Tipping Criteria	60 FPS (36 KTS)	40 FPS (24 KTS)	22 FPS (13 KTS)	14 FPS (8.5 KTS)	38 FPS (22 KTS)
Actual Landing Tumbling Criteria	70 FPS (41 KTS)	50 FPS (30 KTS)	30 FPS (18 KTS)	22 FPS (13 KTS)	47 FPS (27 KTS)
Probability of Tipping	0.01% (0% - no gusts)	0.3% (0.2% - no gusts)	2.8% (2.8% - no gusts)	13% (13% - no gusts)	0.3% (0.2%- no gusts)
Probability of Tumbling	0% (0% - no gusts)	0.1% (0.02% - no gusts)	1.5% (1.3% - no gusts)	4.3% (4.1% - no gusts)	0.1% (0.04%- no gusts)

Shown in Figure 7.2-20 is an update risk trade of landing opportunities versus risk. An analysis of the Generation 2 airbag system resulted in using 70 fps for the tumbling criterion on hard soil, and 50 fps for the tumbling on soft soil. The CM tipping criteria was set to 10 fps less than the tumbling criteria based on CEV Project provided data. The plots in Figure 7.2-20 were based on: Generation 2 airbags, hard soil, 20 percent gust, three sites, day landings only, and a three hour forecast. As a result, the 18 fps 'Go for Landing' criterion resulted in and average of two opportunities per week, and a 1E-3 PLOC.

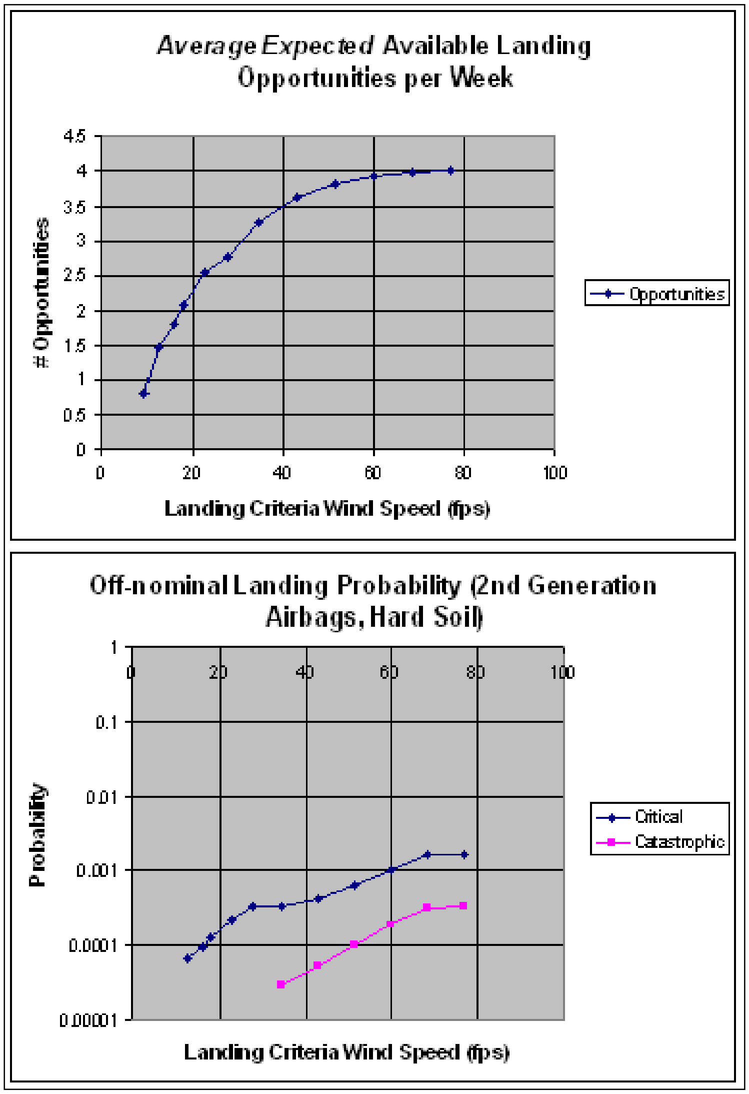

Figure 7.2-20. Updated Landing Opportunities versus Risk

7.2.3.3 Water-Landing Possibilities

The purpose of this portion of the analysis was to determine how water-landing availability could work with accessibility. In addition, this analysis was used to determine if and how water could be used as a backup to land-landings.

Water Accessibility

Water-landing accessibility is similarly based on geometry. However, choosing a location that maximized the opportunity for landing is easier in the water due to ship mobility and lack of SM debris constraints. Day/night constraints may still play a part. As an assumption to the water accessibility study, a ship was placed strategically to support an ascending and descending landing opportunity. Also, it was assumed that this ship could travel at a speed of 15 knots. The ship's motion, in combination with the CM cross range capability meant a large surface area would be considered for landing opportunities as shown in Figure 7.2-21.

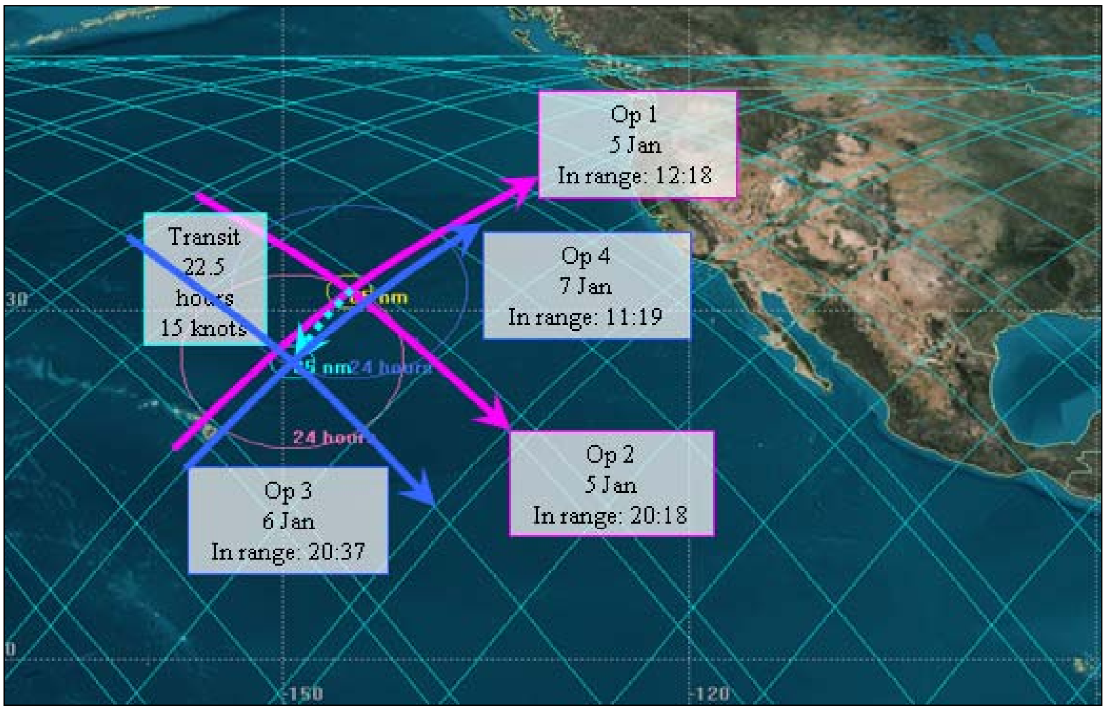

Figure 7.2-21. Water-landing illustration

For example, a ship could be placed at the intersection of the magenta passes and if Opportunity 1 and Opportunity 2 were missed, could be moved to the intersection of the purple passes with sufficient time to "catch" Opportunities 3 and 4. This pattern could be propagated reasonably for days and various landing opportunities. For situations where water-landings were limited to day or night only, the corresponding number of opportunities would be reduced by approximately 50 percent.

Water As Land-Landing Backup

Due to the flexibility of water-landings and the ability to move the starting point, water-landings could readily make the transition from primary to backup landing. For example, in Figure 7.2-22, the yellow arrow shows an opportunity to land at EAFB. If this opportunity was missed, the subsequent water passes could act as a feasible backup until another land opportunity occurred.

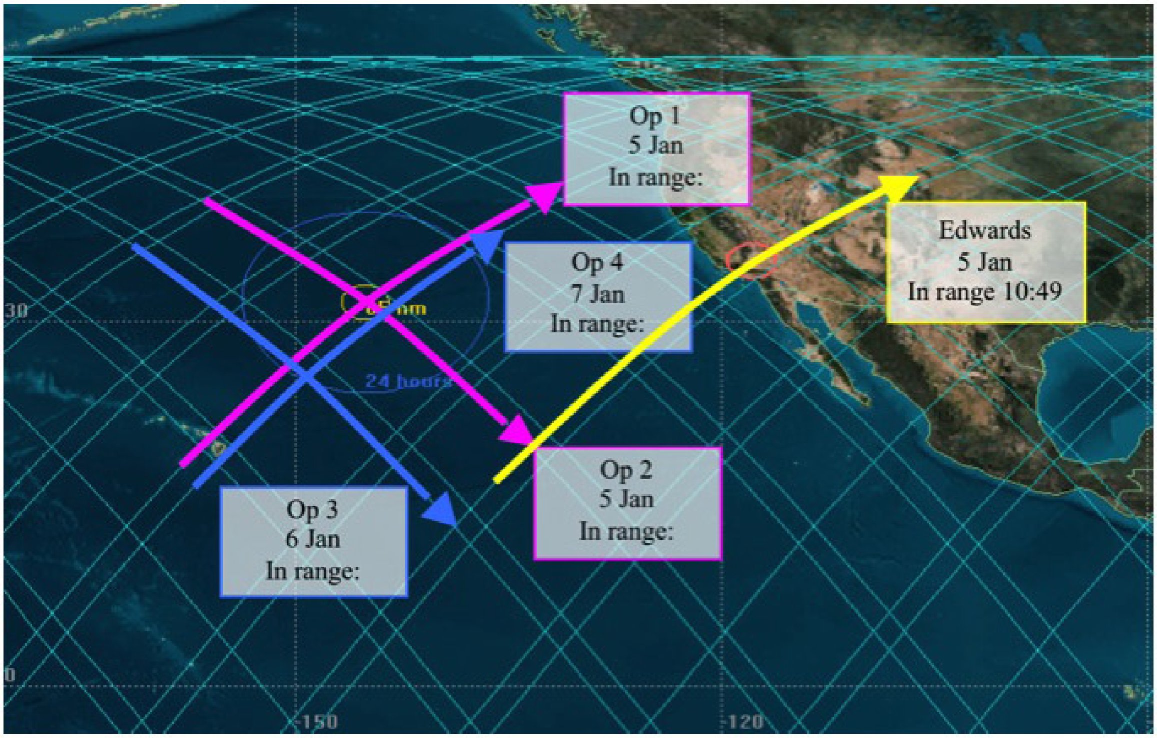

Figure 7.2-22. Water as back up to Edwards on 1/5

To complete this analysis of investigating water as a backup to land passes, SLAAM was adjusted to output data in both hours and days to provide the information in a more readable format. Figure 7.2-23 shows landing opportunities in relation to each other over time. This is the same information in Table 7.2-17

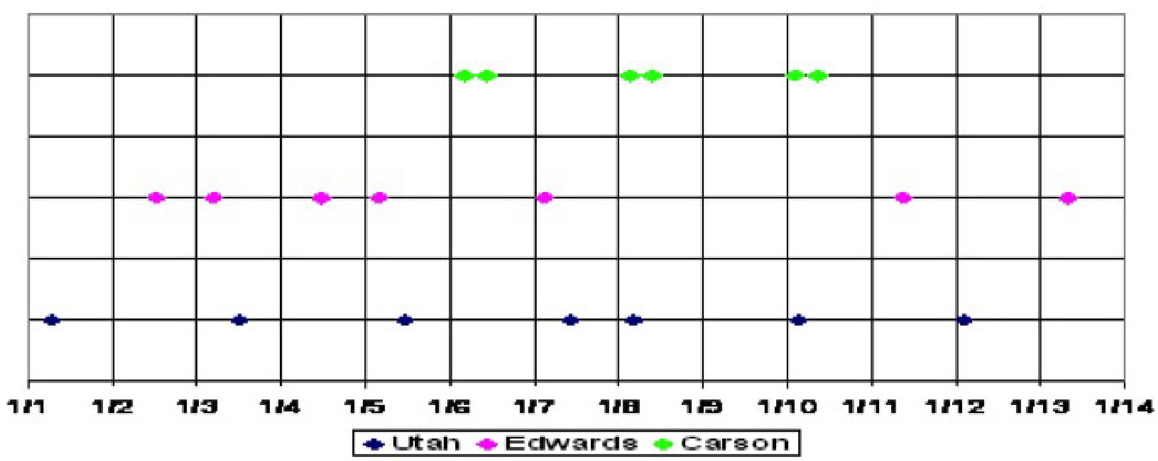

Figure 7.2-23. Landing accessibility for the landing site network, all landing options available, 180 days (14 days shown for clarity), in hours and days

Figure 7.2-24 shows how the opportunities to land change with water as a backup to EAFB pass on January 1 and 11. Note how the water-landing site fills in the gaps left by EAFB passes.

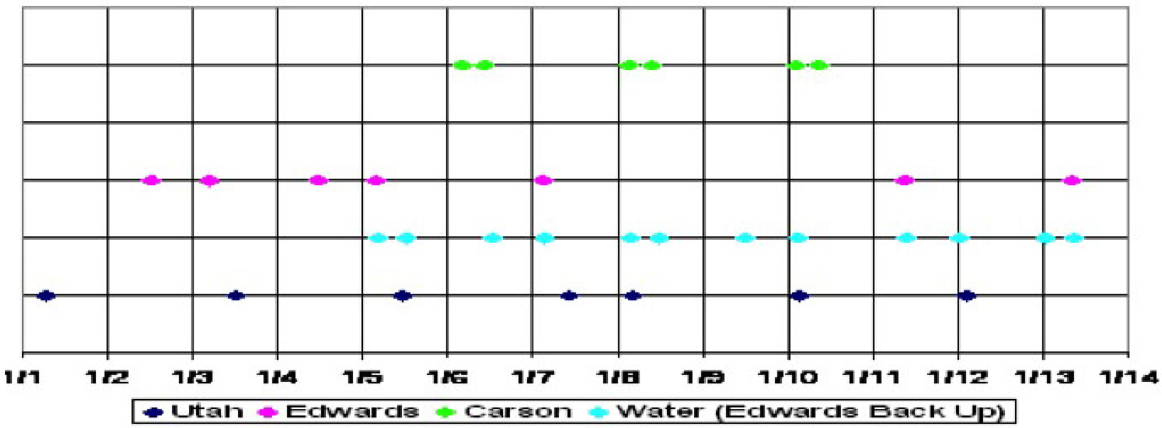

Figure 7.2-24. Water as back up to EAFB

CONUS for 28.5 Degree Inclination Orbit

The purpose of looking at the 28.5 degree inclination orbit was to determine if any CONUS landing opportunities existed. As illustrated in Figure 7.2-25, there are no CONUS land-landing sites available for 28.5 degree inclination orbits. Figure 7.2-25 also shows an example landing location in the Pacific Ocean, with a circle reporting the radius of where a ship could move in 24 hours to support a landing opportunity. This study did verify that if an appropriately sized delta-velocity was applied to the CM for an inclination change, a CONUS based landing site could be reached.

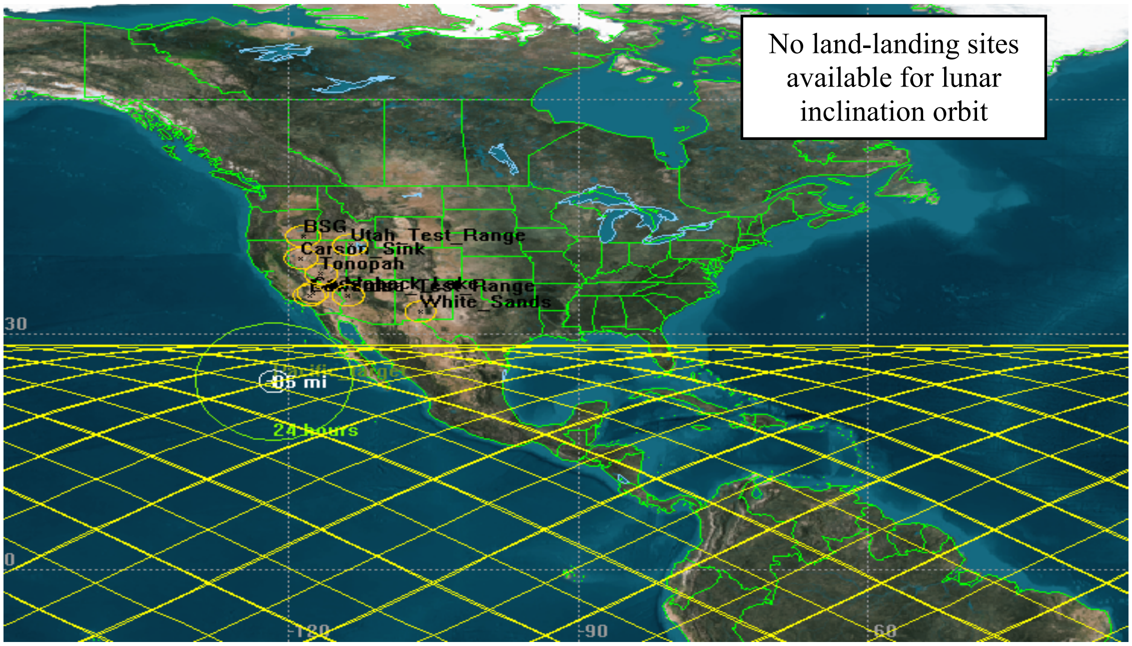

Figure 7.2-25. Lunar inclination CONUS landing evaluation

7.2.4 Task 4: CM Roll Control in Preparation for Landing Data Analysis

While roll control was included in the original Apollo specification, it was ultimately not included as a capability for use during landing. However, the CM was required to land in any possible roll orientation. Roll control was referenced in the original Apollo Program requirements. Although the potential advantages of roll control were recognized, no attempts were made to implement roll control for landing. Apollo had requirements for both nominal and emergency crew acceleration limits and onset rates (Figure 7.2-26). When it was determined that these levels could not be met during a land-landing, the Apollo Program accepted the risk based on the low probability of a pad abort.

The NESC team found that there should be sufficient capability in the RCS to orient the CM per the CEV Project requirements with low riser angles. The CEV Project had performed parachute riser / attachment torque tests to verify the capability. The CEV Project found torque resistance of baseline riser /attachment design needed to be reduced, and subsequently tested designs with sufficiently low torque resistance (with margin). The results of these tests are provided in Figure 7.2-27.

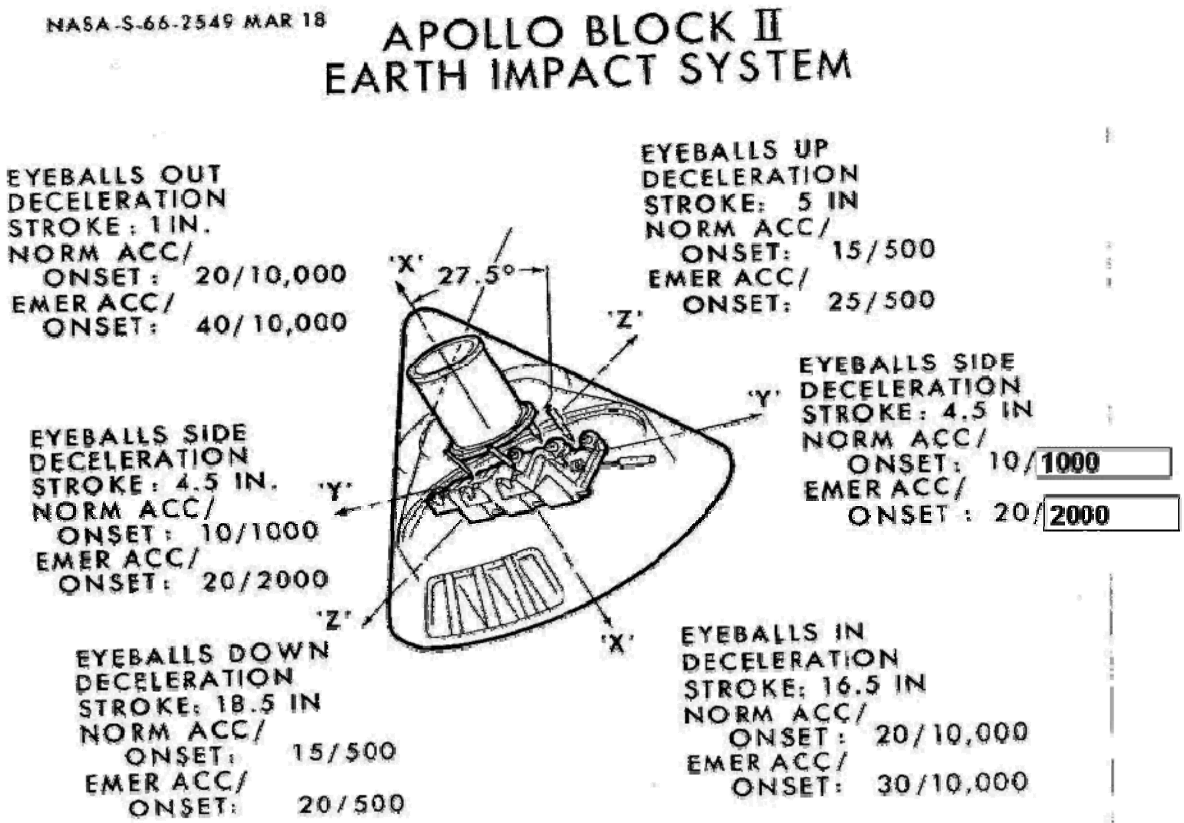

Figure 7.2-26. Crew Acceleration Limits for the Apollo Command Module

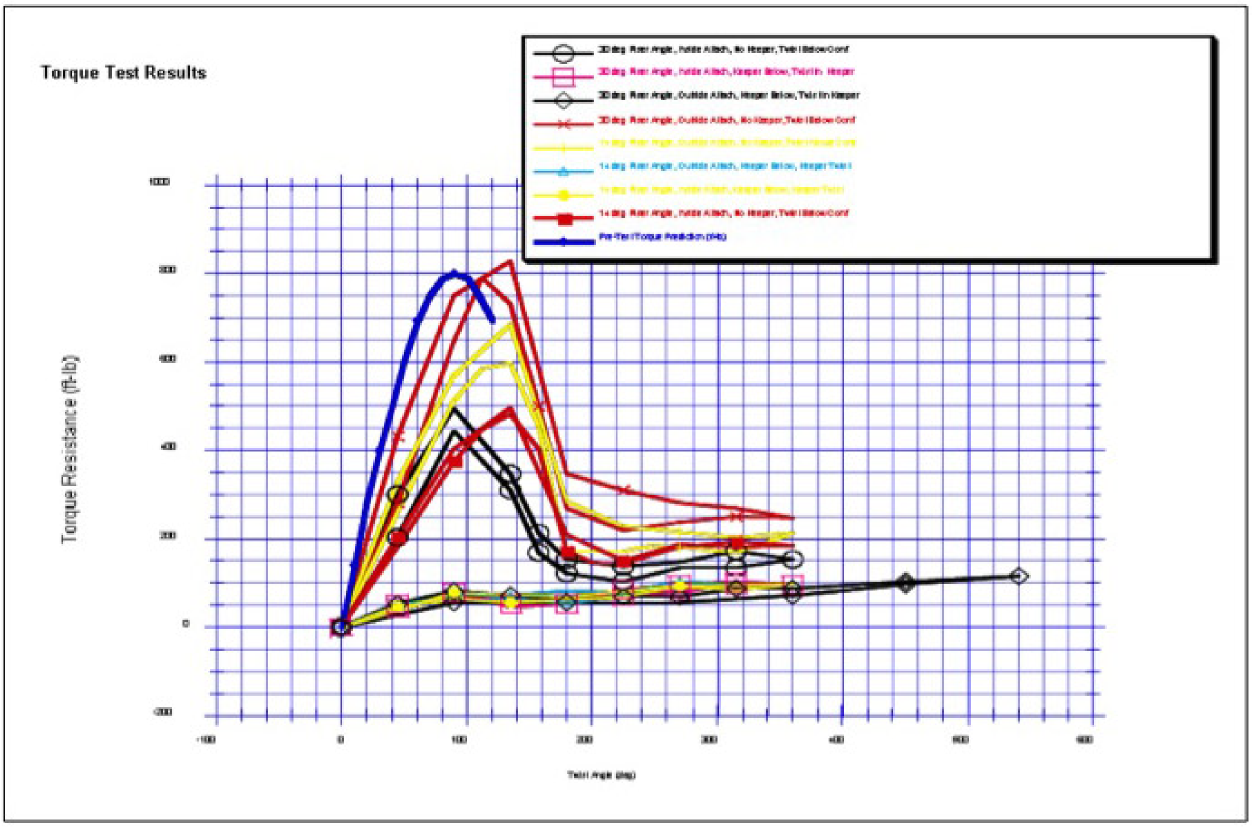

Figure 7.2-27. CM Roll Torque Capability Under Main Parachutes

The CEV Project tests show that the CM RCS has sufficient torque to meet the ±30 degree roll requirement with current parachute harness / riser designs

7.2.5 Task 5: Investigate Parachute Release Times During Land-Landing Data Analysis

The effectiveness of releasing the parachute from the CM at different release times post touchdown is examined for a vertical and horizontal landing velocities of 26 and 37 fps, respectively. A 37 fps horizontal velocity was used since this velocity represents one of the more extreme conditions which is most likely to cause higher rollovers. The 15 degree hang angle is fairly optimal for CM stability in the presence of a horizontal landing velocity, while a flat 0 degree hang angle may be advantageous for a purely vertical landing.

The transient rigging force is shown in Figure 7.2-28. The force starts at 13,046 pounds which is the CM weight and the initial tension in the rigging just before touchdown. Upon touchdown the rigging force quickly decreases as the ground stops the CM from further motion and the parachute continues to descend. At 0.17 seconds the rigging goes completely slack and remains slack until near 0.4 seconds where the tension begins to increase as the horizontal wind load drags the parachute beyond where the CM is contacting the ground.

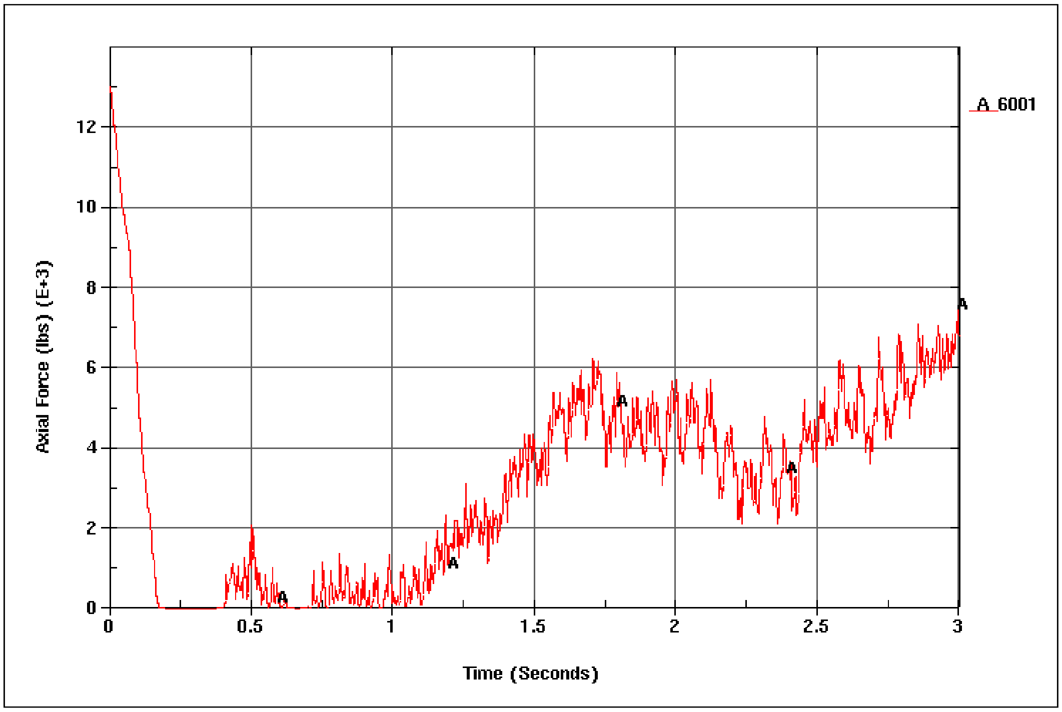

Figure 7.2-28. Rigging Force without Chute Release at a 15 degree Hang Angle

Figure 7.2-29 depicts the effect on CM roll of releasing the parachute at different times beyond initial ground contact. When the parachute is released at touchdown (chute quick release), the CM roll is a minimum compared to all of the other release times examined. When the release time is at 0.17 (when the rigging first becomes slack), 0.08, and 1.00 seconds, the CM roll is similar and is greater than when the parachute is released at 0 seconds. When the parachute is kept attached for the duration, the horizontal wind force on the parachute dominates and the CM tumbles.

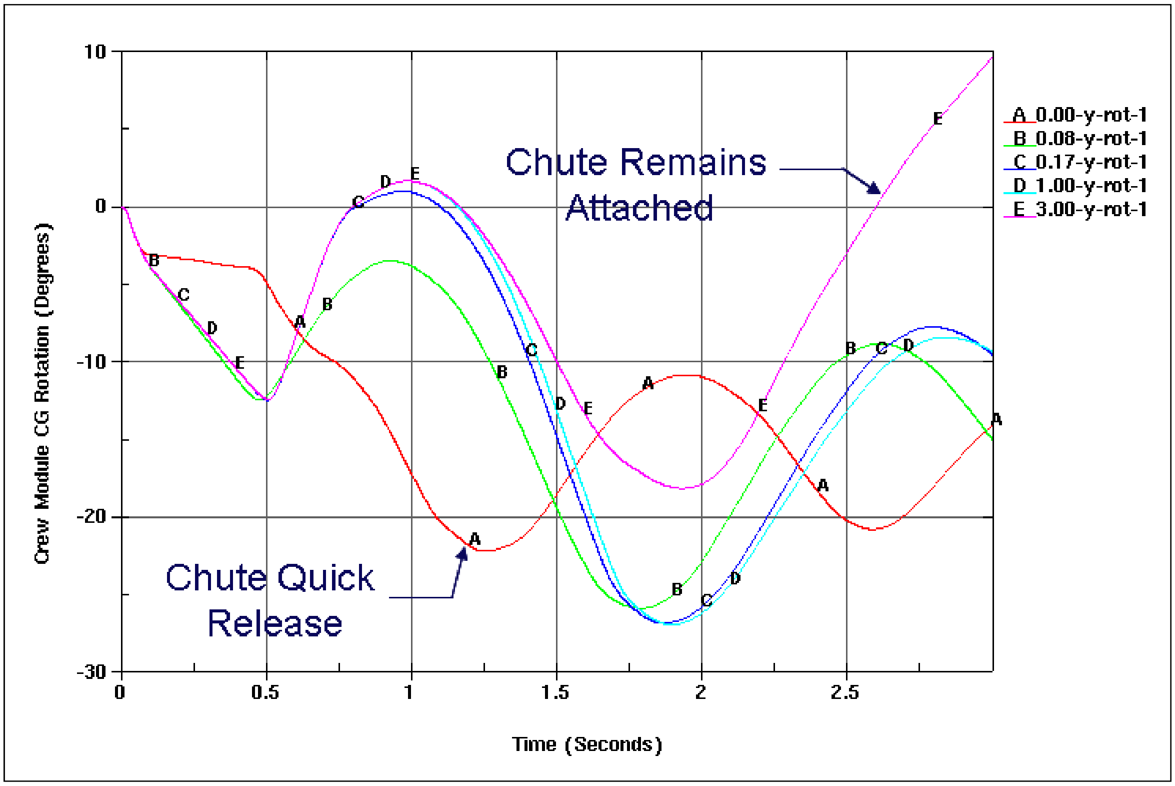

Figure 7.2-29. Effect of Parachute Release Time on CM Roll - 15 degree Hang Angle, CM does not rollover when chute released before 1.0 seconds.

Figure 7.2-30 shows the resultant acceleration at the location of the crew members for the different values of parachute release times. The maximum acceleration occurs below 0.20 seconds. Beyond the peak acceleration, the acceleration profiles are similar for all release times except for the case where the parachute is not released. For this case the second peak in the acceleration profile near 0.50 seconds is larger than for the rest of the cases. This peak occurs after the CM "bounces" and incurs a second landing. The peak is larger for the parachute without release since the parachute pulls the CM higher off the ground than for the other cases where the parachute is released.

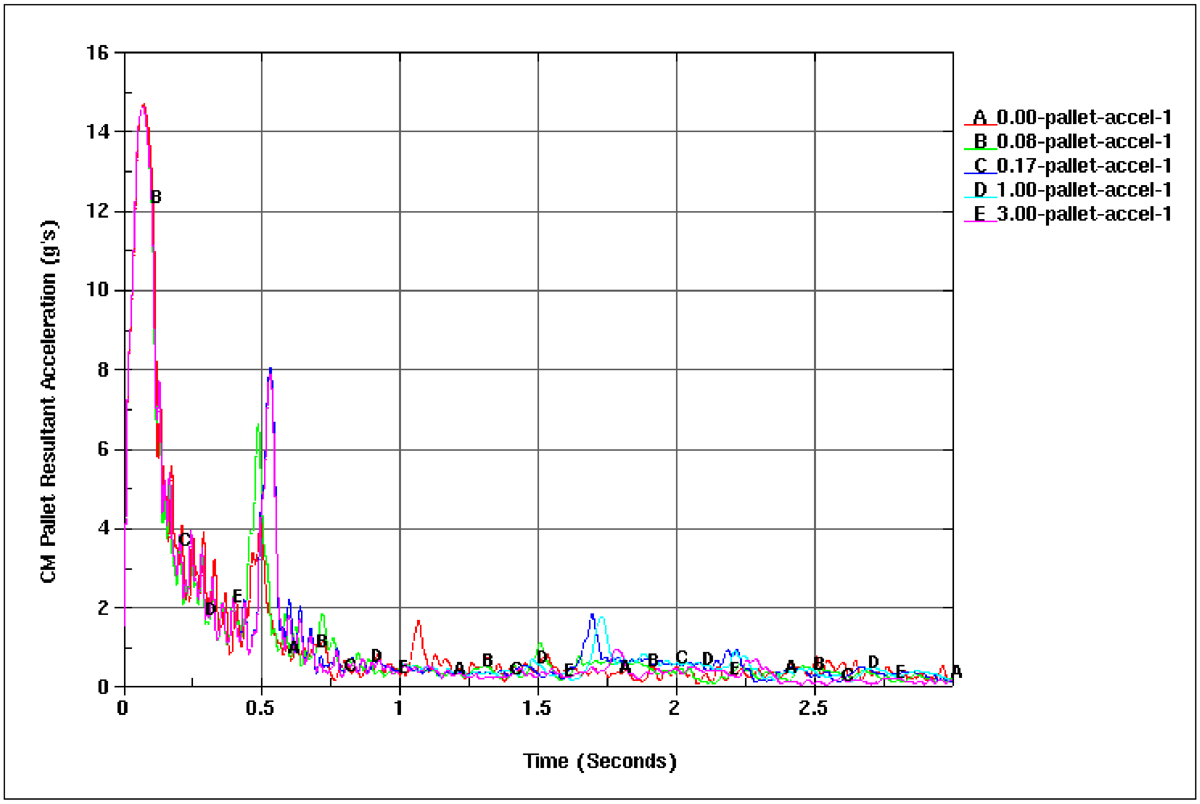

Figure 7.2-30. Effect of Parachute Release Time on Pallet Acceleration 15 degree Hang Angle

Figure 7.2-31 shows a CM cross section for the 0 degree hang angle. For this angle the parachute attachment point is moved to directly above the center-of-gravity.

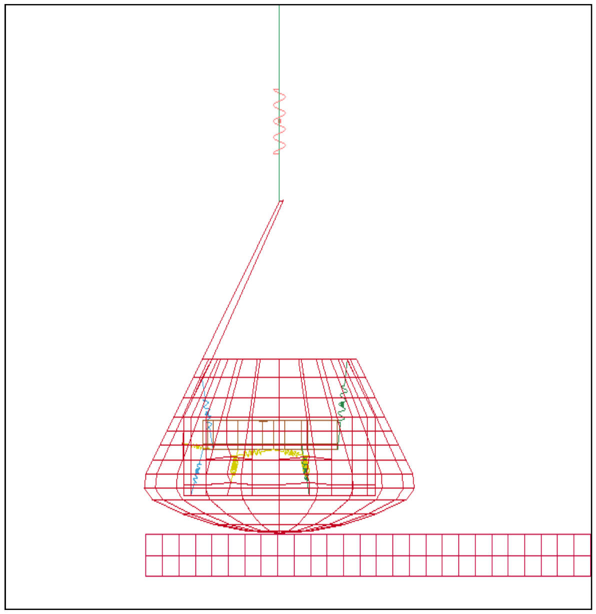

Figure 7.2-31. 0 Degrees Hang Angle (Rigging Attachment Located to Maintain Hang Angle)

Figure 7.2-32 shows the transient rigging force for the case where the parachute is not released. Similarly to the 15 degree hang angle results, the force starts at 13,046 pounds and upon touchdown the rigging force quickly decreases then the tension increases as the horizontal wind load drags the parachute. For the 0 degree hang angle the parachute first becomes slack at 0.16 seconds.

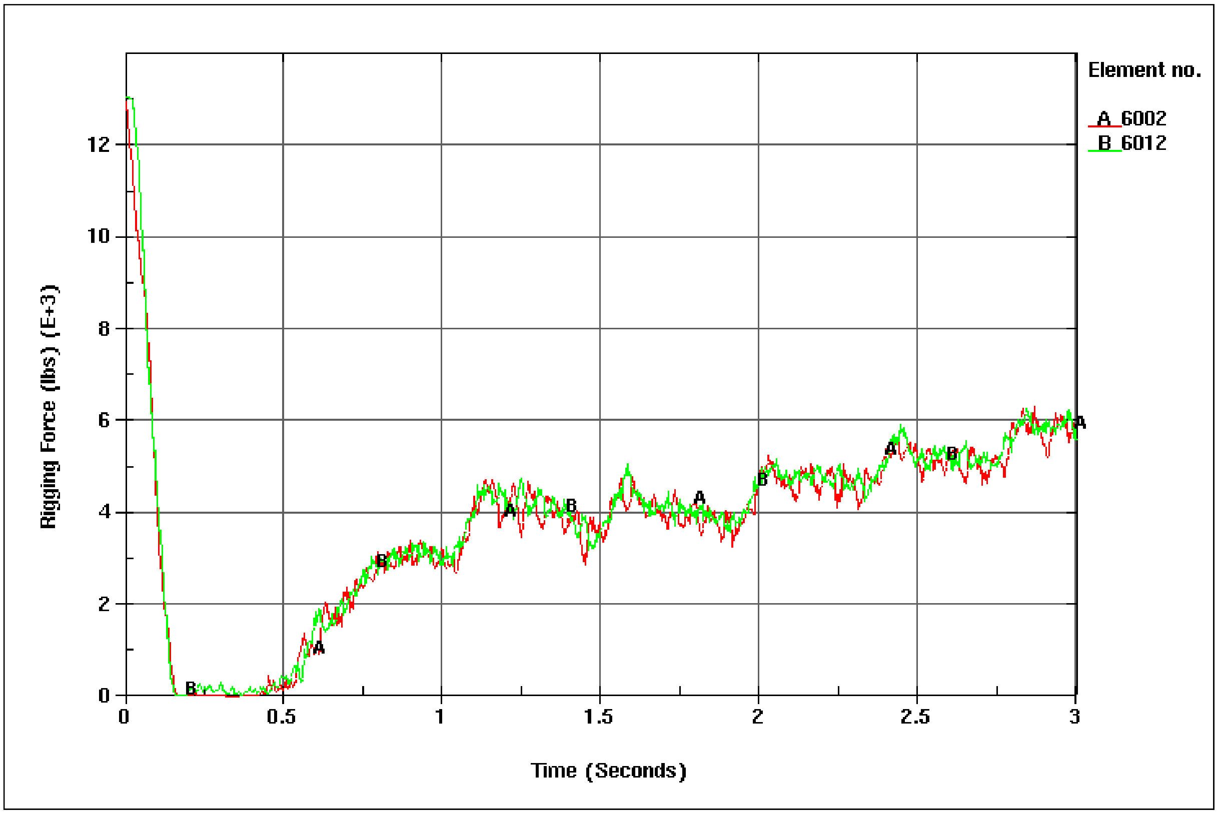

Figure 7.2-32. Rigging Force without Chute Release 0 degree Hang Angle

Figure 7.2-33 depicts the effect on CM roll of releasing the parachute at different times beyond the time of initial ground contact. In general, the CM roll is similar regardless of the release time. When the parachute remains attached for the duration, the CM roll is slightly less than for the other cases for part of the response but converges to the same roll at the end of the simulation. All the cases converge to the same roll since the CM has rolled over and is resting on its top. Figure7.2-34 shows the resultant accelerations for the different release times and similar to the roll profiles the acceleration profiles are similar for each case with a peak acceleration near 0.20 seconds then a second spike in the acceleration when the CM rolls over and the top strikes the ground.

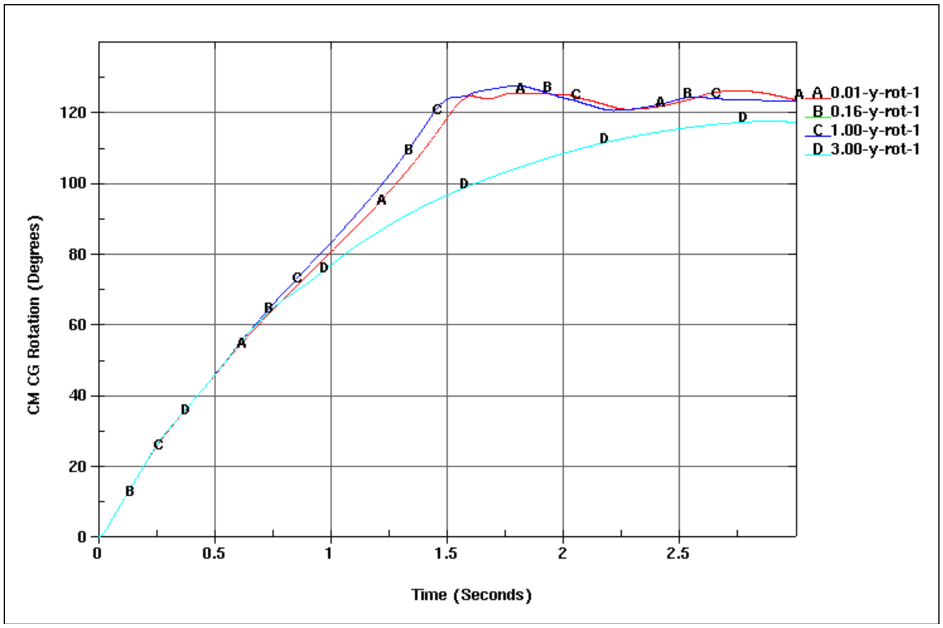

Figure 7.2-33. Effect of Parachute Release Time on CM Roll 0 degree Hang angle, Vehicle rolls over for all cases

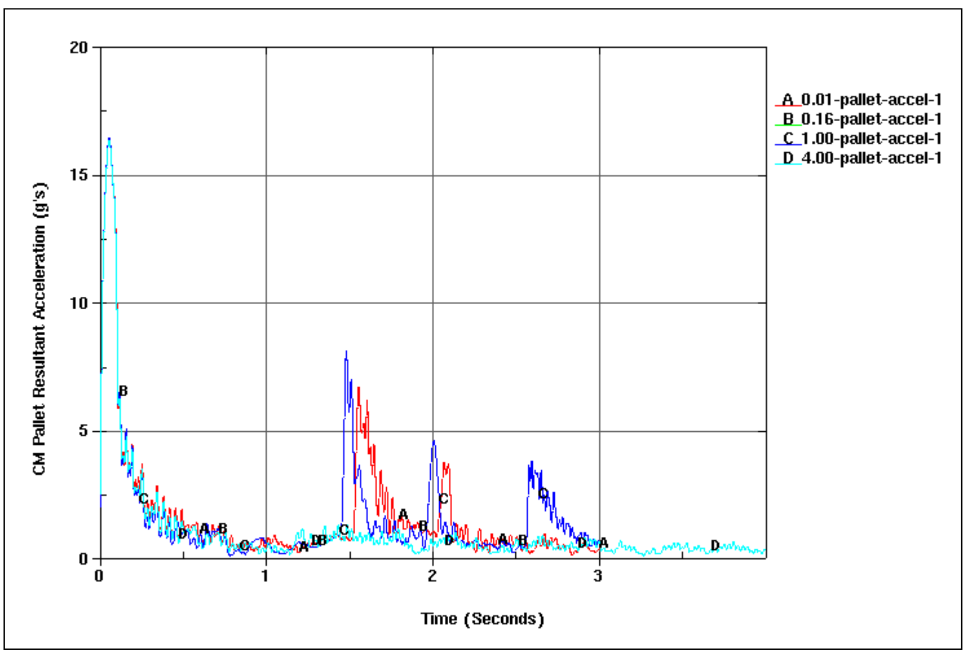

Figure 7.2-34. Effect of Parachute Release Time on Pallet Acceleration 0 degree Hang Angle

Figure 7.2-35 shows the effect of horizontal landing velocity and parachute release time on CM rollover. Figure 7.2-36 are for a CM with a 0 and 15 degree hang angle, respectively. In the presence of a horizontal landing velocity the 15 degree hang angle is more stable. While the vehicle with a 15 degree hang angle can accommodate a horizontal landing velocity of close to 65 fps, the CM with a 0 degree hang angle rolls over when the horizontal velocity is 30 fps. Note that these rollover velocities are relative and additional study is needed to determine values that are more absolute. As depicted in the figures, parachute release time has minimal effect on CM rollover. For the 15 degree hang angle the release time has no effect on rollover so long as the parachute is released before 0.18 seconds. For the 0 degree hang angle the allowable horizontal velocity before rollover occurs is slightly higher when the parachute is released at touchdown. However, similarly to the 15 degree results release time does not significantly affect rollover. Release times beyond 0.18 seconds because the rigging goes back into tension the tension is a result of the horizontal wind always has a detrimental effect on rollover. Thus, the parachute should always be released before the rigging regains tension.

A CM employing airbags for landing load attenuation has conflicting requirements with a vehicle configuration striving to minimize rollover potential. Airbags are most effective for a flat (0 degree hang angle) landing and are less effective when there is a horizontal landing velocity or the vehicle lands with a hang angle. However, there can be situation when there is a horizontal landing velocity and if the CM hang angle is 0 degrees to optimize the airbags effectiveness, the vehicle will be more prone to rollover than if the hang angle was 15 degrees.

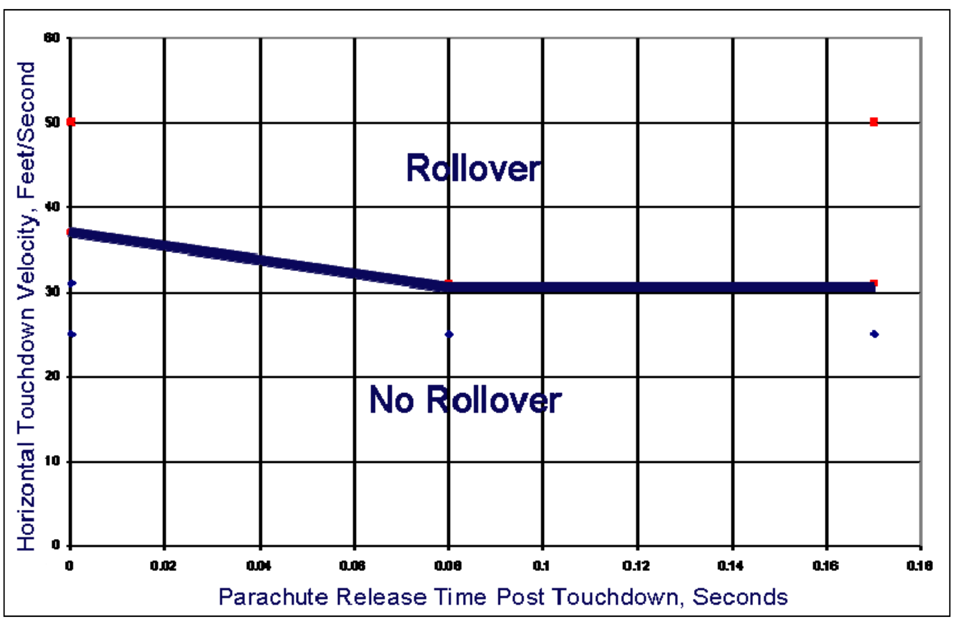

Figure 7.2-35. Effect of Horizontal Velocity on Rollover 0 degree Hang Angle, Vertical velocity = 26 fps, No Roll

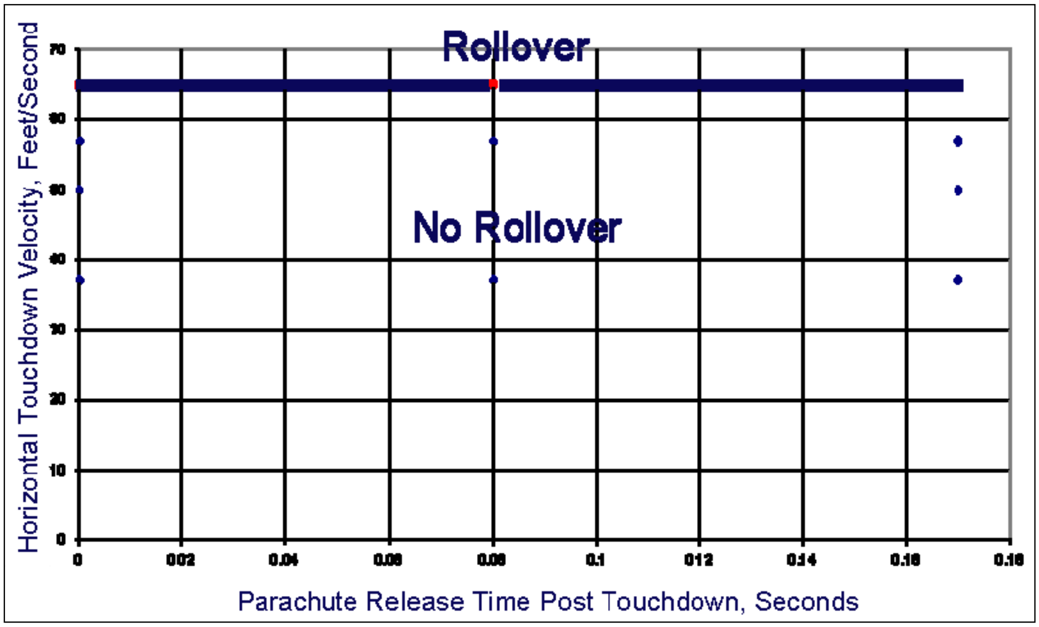

Figure 7.2-36. Effect of Horizontal Velocity on Rollover 15 degree Hang Angle, Vertical Velocity = 26 fps, No Roll

7.2.6 Task 6: Crew Protection System Enhancements Data Analysis

The last phase of all manned space missions is the landing and recovery phase. The CM will descend to earth with a parachute and should be capable of a primary land-landing and water-landings. Consequently, landing systems must be designed for multi-terrain impacts. Earth terrain is highly variable, with soil at proposed landing sites at EAFB typically very hard and soil at Carson Sink, NV often very soft.

To keep the size of parachute systems reasonable and to optimize the weight of the landing system, the terminal velocity of most parachute recovery systems is approximately 25 to 40 fps (17-27 miles/hour). In addition to the terminal sink (vertical) velocity, the parachute and capsule will move horizontally with the air mass depending on the wind speed. The velocities of the CM at touchdown are typical of crash impact velocities of small aircraft and helicopters. Thus, these impact velocities will produce injuries without some type of mitigation for impacts onto land. Water-landings do not require additional mitigation for nominal landings since the water acts as a natural impact attenuator. The Apollo capsule was designed to impact the water with a hang angle of 27 degrees. Since the Apollo capsule entered the water pitched at an angle (thus giving it a wedge shape), the acceleration experienced was nominally 10 g or less for a 30 fps impact [ref. 1]. The Apollo spacecraft also had crushable ribs and a crew seat pallet with stroking energy absorbers to alleviate off-nominal impacts. However, either a land-landing in an abort condition or a flat 0-degree attitude water impact with one chute out was expected to result in occupant injuries. Since the probability of a pad abort with a land impact was considered to be low, the Apollo Program accepted those risks.

Under ideal nominal conditions, either a land-landing with retrorockets or airbags, or a water-landing will result in tolerable accelerations to the crew if the seats and restraint systems are adequately designed. For off-nominal landing conditions, a stroking seat pallet similar to the Apollo design is planned for CEV Project CM should reduce the impact accelerations to limits that are tolerable and prevent crew injury. However, some mitigation for more severe off-nominal impacts can be designed with little weight penalty if a systems approach is taken early in the design phase.

With properly designed seats (i.e., with side supports and restraints), relatively high accelerations can be tolerated with no or minimal injury, especially for impacts with the crew lying on their backs in a seat oriented as shown in Figure 7.2-37. The local axis system has the +X-axis upward, the +Z-axis pointed toward the head, and the +Y-axis to the right. Note that the axis system typically used for a seat is a left-handed system. For accelerations along the +X-axis, which would occur for a flat impact, the acceleration in the spine-to-chest direction is commonly called "eyeballs in." An acceleration along the –X-axis (chest-to-spine) is called "eyeballs out." An acceleration from pelvis-to-head along the +Z-seat axis is called "eyeballs down," and an acceleration pointing in the –Z-axis is "eyeballs up." The seat coordinate system is a local system, and is a non-inertial axis system. Hence, any angular rotations with respect to an inertial system must be considered.

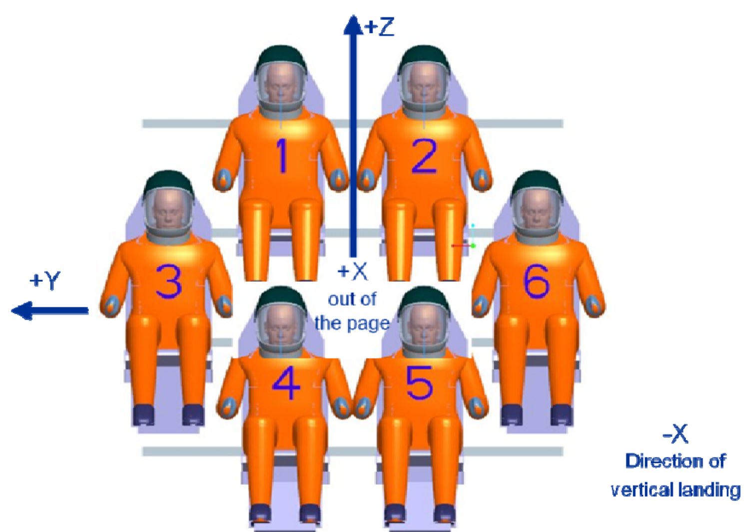

Figure 7.2-37. Six Crew Configuration with local X, Y, and Z-Axis

Human tolerance to impact has been studied continuously since the advent of the automobile and airplane. During the Apollo Program, over 288 impact tests were conducted for NASA on 79 male volunteers using the Holloman Daisy Accelerator [ref. 2]. The acceleration onset rates ranged from 300 to 2500 g per second. In general, lower onset rates are better tolerated. These tests were designed to help understand the effects of water impact on the crew.

The US Air Force and Navy have conducted impact test programs in an effort to make ejection seats as safe as possible. Sled impact testing of volunteers has been conducted for low, non-injurious accelerations. Cadavers, animal surrogates, and ATD's, such as the Hybrid II and III have been used in sled tests to help determine the threshold of moderate and severe injuries. A comprehensive compilation of many of these tests that provides summary charts with regions of uninjured, moderate, and severe injuries versus maximum continuous sled acceleration and duration was produced by Eiband at NASA Lewis [ref.3]. The testing performed in this work is relevant to orientations where the loading is directly up through the spine from the buttocks to head and is less relevant to CM landings where the nominal loading is in the eyeballs out direction.

7.2.6.1 Mathematical Lumped Mass Injury Models

In order to reduce injuries produced during ejection from military aircraft, relatively simple but effective mathematical representations of a seated human were developed. Ejection seats were first designed based on acceleration limits in the +Z-direction and acceleration onset rates. Early on, it was determined that accelerations were better tolerated by aviators if the ejection acceleration onset rate was as low as practical. As ejection seats evolved and became more complex (i.e., those with thrust vectoring rockets and encapsulated seats in the B-70 and F-111), peak acceleration and onset rate proved ineffective for evaluating their performance. New design tools became necessary. The impact tolerance charts produced by Eiband were useful, however their application to an arbitrary acceleration pulse that includes accelerations along all three axes (X, Y, and Z) is subjective. An example of an Eiband chart for accelerations along the spine (+Z, eyeballs-down) is shown in Figure 7.2-38. A modified chart [ref. 4] with ejection seat design limits added is illustrated in Figure 7.2-39.

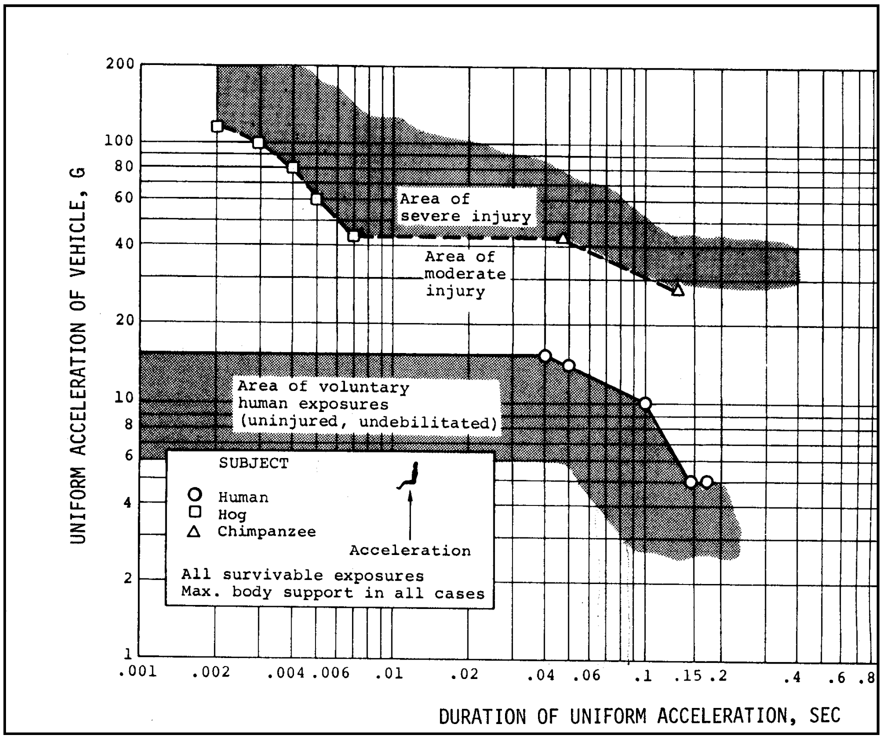

Figure 7.2-38. +Z Acceleration Tolerance with Ejection Seat Data Omitted

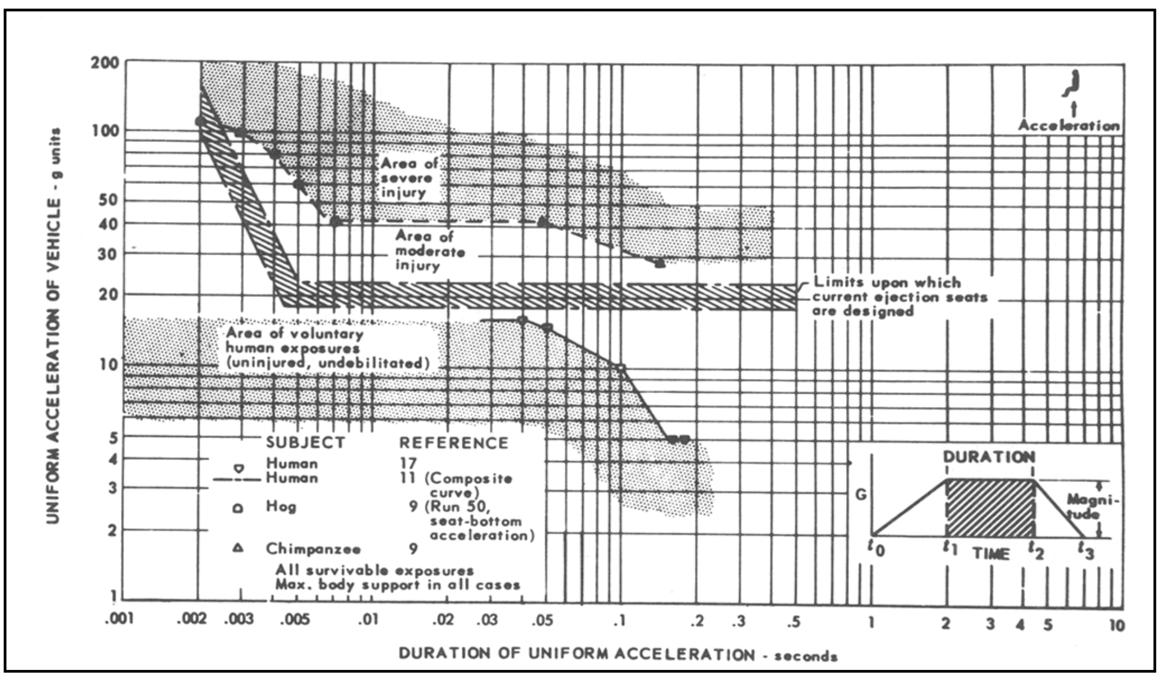

Figure 7.2-39. +Z-Human Tolerance Limits showing Ejection Seat Design Limits

There are three areas to consider on each chart. The *Area of Voluntary Human Exposures* is the bottom-shaded area. In this region, all exposures were uninjured. For example, a maximum acceleration of approximately 14 g could be tolerated (uninjured) for up to 0.04 seconds (40 milliseconds). The other shaded area at the top of the chart is the *Area of Severe Injury*. For example, acceleration above 100 g for longer than 3 milliseconds produces severe injury. The area between the two darkened areas is the *Area of Moderate Injury*.

7.2.6.2 The Dynamic Response Index (DRI) Model

The most effective human model for early ejection seat design was the DRI described by Stech and Payne in 1969 [ref. 5]. This work was performed at what is now called the Wright-Patterson Armstrong Aerospace Medical Research Laboratory (AAMRL) and was based on pioneering work in human biodynamics by von Gierke [ref. 6]. The DRI model was verified by comparison with actual ejection seat data (see Figure 7.2-40) by Brinkley [ref. 7]. For many years the US Air Force used the lumped mass-spring DRI model and only considered the +Z-axis. The DRI model was developed to estimate the probability of spinal fractures for accelerations in the pelvis-to-head or +Z direction. In Figure 7.2-40, the abscissa should be marked DR+Z as only the +Z component is considered in the DRI.

The DRI method was generalized by Brinkley to include the other local orthogonal axes (-Z, +X, -X, +Y, -Y) [ref. 8]. A brief description of the Dynamic Response Method (referred to as the Brinkley Dynamic Response Model) follows.

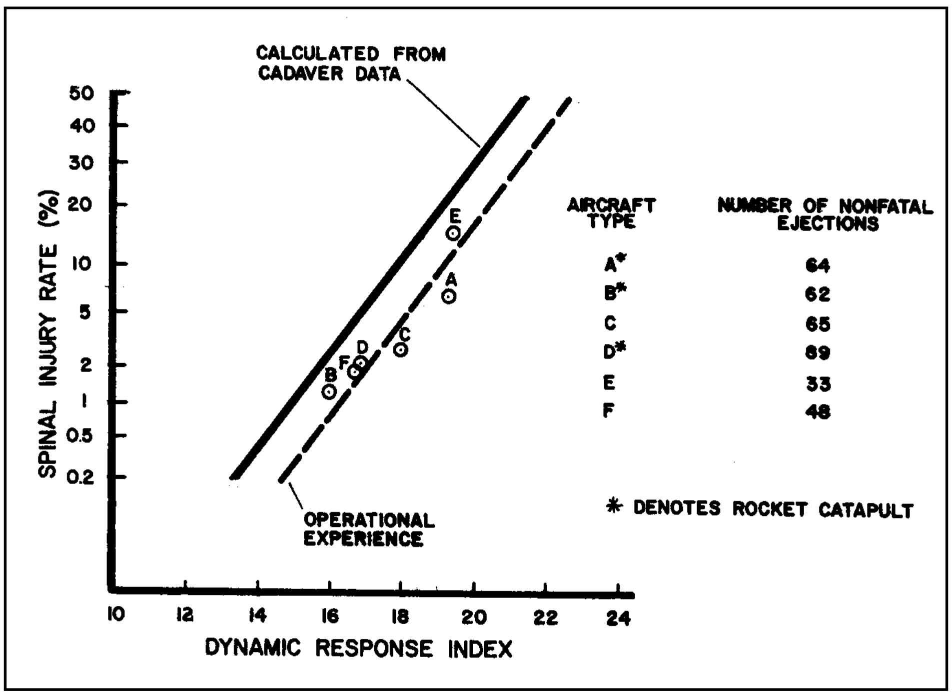

Figure 7.2-40. DRI+Z Related to Probability of Spinal Injury for Ejection Seats
(Note that cadaver data was over conservative.)

The equations of motion of the human body modeling as a lumped mass are three second-order differential equations. Each equation is familiar as simply a forced spring-mass harmonic oscillator with damping. The forcing function "A" in Eq. 1 is the measured acceleration along each of the three seat axes. As a simplifying condition, the three equations are considered to be uncoupled. The second-order differential equation for the Brinkley Dynamic Response model is given by Eq. 1. This equation was given in the Constellation Program (CxP) specification CxP 70024 Human System Integration Requirements (HSIR) December 2006:

$$\ddot{x} + 2\xi\omega_n\dot{x} + \omega_n^2 x = A \qquad \textbf{EQ. (1)}$$

where:

$\ddot{x}$ is the relative acceleration of the dynamic system mass with respect to the accelerometer location in the given axis system (X, Y, or Z).

$\dot{x}$ is the relative velocity of the mass with respect to the accelerometer location in the given axis system.

x is the deflection of the mass with respect to the critical point in the given axis system. A positive value represents compression.

ξ is the damping coefficient ratio.

ω_n is the undamped natural frequency of the dynamic system.

A is the component of the measured acceleration along the specified axis. Since the seat axis is not an inertial frame, rotational acceleration must be considered.

The dynamic response for each axis is given by:

$$DR = \omega_n^2\, x / g \qquad \textbf{EQ. 2}$$

Where Dynamic Response (DR) (t) is the response of the dynamic system and g is the acceleration of gravity. Note that DR is dimensionless. The value "x" when used along the +Z axis is the compression of the spine. Note that DR(t) is essentially the normalized response of the occupant to the input acceleration in g's. The maximum value of DR(t) for any axis should be less than the limiting value. Thus, DR(t) can be plotted versus the input acceleration time history. The maximum of the response DR(t) can be greater or less than the maximum of the input acceleration A(t) depending on whether the simple harmonic oscillator amplifies or attenuates the driving acceleration. The following values for ω_n and ξ were used:

$\omega_{nx} = 62.8$

$\omega_{ny} = 58.0$

$\omega_{nz} = 52.9$

$\xi_x = 0.2$

$\xi_y = 0.09$

$\xi_z = 0.224$

Limiting values of DR levels have been set by NASA for the CEV Project and are listed in Table 7.2-18. These values are also provided in CxP 70024 HSIR. The Very low (nominal) limits were derived by Brinkley [ref.9] from studies initiated in the 1980's for NASA to accommodate a "deconditioned" crew member who had been in space for a considerable time. The Low (off nominal) DR limit is the same as provided in [ref. 8]. The limits also consider DR levels for moderate and high risk [ref. 8]. This data is shown in Table 7.2-19. Side restraints raise the dynamic response limits for the Y-direction as shown in Table 7.2-19. Note that side restraints are not mentioned in the CxP HSIR specification.

Table 7.2-18. Brinkley Dynamic Response Limits (NASA HSIR Specification for the CEV Project)

DR level	**X (eyeballs out, in)**		**Y (eyeballs right, left)**		**Z (eyeballs up, down)**	
	$DR_x < 0$	$DR_x > 0$	$DR_y < 0$	$DR_y > 0$	$DR_z < 0$	$DR_z > 0$
Very low (nominal)	-22.4	31	-11.8	11.8	-11	13.1
Low (off-nominal)	-28	35	-14	14	-13.4	15.2

Table 7.2-19. Dynamic Response Limits from Brinkley and Moser [Ref. 8]

DR level	**X (eyeballs out, in)**		**Y (eyeballs right, left)**		**Z (eyeballs up, down)**	
	$DR_x < 0$	$DR_x > 0$	$DR_y < 0$	$DR_y > 0$	$DR_z < 0$	$DR_z > 0$
Low (same as NASA spec)	-28	35	-14	14	-13.4	15.2
Moderate	-35	40	-17	17	-16.5	18
High Risk	-46	46	-22	22	-20.4	22.4

Also note that if side restraints are used, the DR levels for Y increase to -15 and +15 (Low), -20 and +20 (Moderate), and -30 and +30 (High Risk). Caution – These values are not listed in CxP 70024.

The limiting value of the DR^{lim} in each axis from Table 7.2-18 is used in Eq. 3 to assess Very Low or Low risk. The value of beta, β, in Eq. 3 must be less than one to pass the Brinkley Dynamic Response Method criteria for very low or low risk. Note that beta could lag the input acceleration in time since the resonant frequencies of the lumped mass system are on the order of 10 Hz. Consequently, DR should be calculated until the maximum for each direction has been identified.

$$\beta = \sqrt{\left(\frac{DR_x(t)}{DR_x^{\lim}}\right)^2 + \left(\frac{DR_y(t)}{DR_y^{\lim}}\right)^2 + \left(\frac{DR_z(t)}{DR_z^{\lim}}\right)^2} < 1 \quad \textbf{EQ. 3}$$

In the single +Z axis DRI model, the human body was modeled as a single lumped mass with a spring and damper representing the spine for Z-direction impacts. Thus DRz (t) is the non-dimensionalized response of the lumped mass of the torso to a forced acceleration input along the Z-axis. In general for multi-axis accelerations, the linear second-order differential damped oscillator given by Eq. 1 is solved independently for each direction. The input acceleration for the model should ideally be the acceleration of the seat. For an ejection seat, the primary acceleration would be eyeballs down, or in the +Z direction. Note that unlike Apollo where the crew was laying on their back in the seat, in a fighter jet the seat would be oriented with the Z-axis pointing up. From operational data, the DRI for Z-direction from Eq. 2 was correlated to injury using the data shown in Figure 7.2-40. From the chart, most of the maximum DR values from operational data ranged from a low of 16 to a high of 20. Any DR greater than 22 or 23 was correlated to a spinal injury rate above 50 percent. Note that the DR+z limit (DR_{+Z}^{lim}) in Equation 3, shown in Table 7.2-18 for off nominal in the +Z direction is 15.2, which corresponds to an injury probability of less than 1 percent. The DR+z nominal from Table 7.2-20 is 13.1. Although the Brinkley Dynamic Response Method model has had success in predicting injury, it is a simplified model of a complex dynamic system (i.e., the human body). Also, the method of combining the results of accelerations in the X, Y, and Z-directions is not verified as most test data were gathered for a single acceleration direction. Insight is obtained by examining the DR for each direction before combining the results to obtain Beta in Equation 3. Finally, note that the Brinkley Dynamic Response Method model is only used as a predictive tool for injury. It is not correlated with fatalities. The threshold for fatalities is difficult to predict.

Table 7.2-20. Vertical Velocity and Brinkley Dynamic Response Method Injury Landing Vertical Velocity (fps)/Brinkley DRI

	Eyes In/Out	Spinal	Sideways
Low Injury Risk	33 fps/29	25 fps/13	17 fps/9.2
Medium Injury Risk	42 fps/35	29 fps/15.8	25 fps/17.4
High Injury Risk	58 fps/43.9	33 fps/19.2	33 fps/23.2

In summary, the US Air Force Research Laboratories developed human tolerance models that were grounded in previously developed models to assist in the design and evaluation of ejection seats. Both human volunteers and ATDs were used along with operational ejection seat data to validate these models. The Brinkley Dynamic Response Method is a generalization from +Z impacts to impacts in all orthogonal directions. The model has proved to be extremely useful and is included in the military specifications for aircraft crew escape systems.

In contrast to the US Air Force, the US Army developed design guides requiring features such as crashworthy cockpits and seats to protect the crew in the event of a “survivable crash” [ref. 10]. The automobile industry was faced with Federal regulations to design and build safer cars. ATDs with more human impact fidelity such as the Hybrid III were developed as instrumented passengers for controlled crash tests. The National Highway Traffic Safety Administration (NHTSA) regulates automobile safety and also sponsors research to make automobiles safer.

The Brinkley Dynamic Response Method is limited in that it uses a simplified mechanical model of the human body. In this case the entire body is modeled as a point mass located at the center of mass of the human body and attached with a damped spring oscillator with an approximately 10 Hz resonance frequency. A schematic of the physical layout of the Brinkley model, showing the central mass located in the mid-thorax, is shown in Figure 7.2-41.

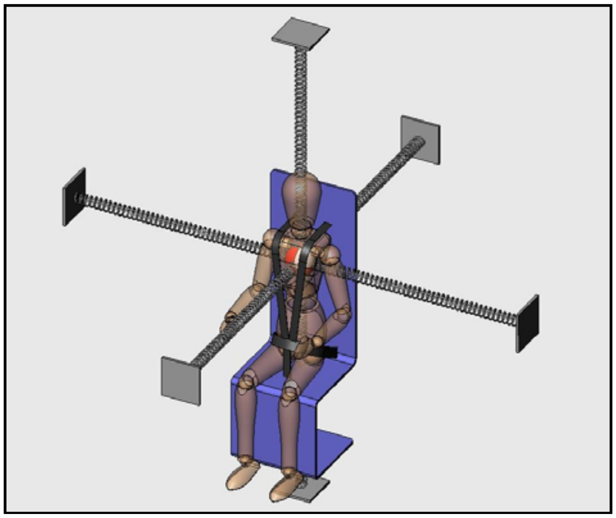

Figure 7.2-41. Central Mass Located in the Mid-Thorax (Brinkley Dynamic Response Method Model)

The nature of the Brinkley Dynamic Response Method model and its representation of the human body as a single mass preclude the model from distinguishing relative movement of individual body parts. Instead, the human body parts are all modeled as moving together as a point mass. While this model works reasonably well for vertical Z-axis loads, such as those of an ejection seat, where the major injury location is in the lower spine and the human body moves as a unit, it does not properly physically model some other impacts, such as side impacts, where sections of the body like the head relative to the body center of mass. In addition to the Brinkley Dynamic Response Method model not having the capability to discern different types of injuries, the Brinkley model cannot provide insight into the effect of any advanced restraint system that provides additional restrictions or protection to the head or other parts of the body.

The current state of the art does not allow the direct modeling and simulation of a human body subjected to injurious high acceleration loading or impact conditions. To address this limitation the automotive industry has attempted to generate a relationship between the physical behavior of the various ATDs and the human body. This has been attempted via a combination of cadaver, sub-injury level testing on human volunteers, animal experimentation, and data gathering from actual accidents. The degree to which the ATD simulates the actual behavior of the human body is referred to as its "bio-fidelity". This is a difficult mechanical engineering problem and the ATD have gone through an evolution and characterization to improve and understand their bio-fidelity.

The general mechanical difficulty in developing a single three-direction ATD that has adequate levels of bio-fidelity has proven to be challenging and has motivated the automotive industry to develop a series of ATDs specific to various types of automobile impact conditions. The three main types of ATD types of interest are: frontal collision full body motion, rear impact, and side impact. For frontal impacts the industry utilizes the Hybrid III ATD as the standard. This ATD has been calibrated with years of test data and is considered a good indicator for whole body motion for frontal impact. The HYBRID III, however, is considered to be inadequate for rear impacts so the industry has developed a number of rear impact ATDs. The rear impact ATDs have more accurate head and neck mechanisms and are better able to predict neck and whiplash types of injuries. The Rear Impact Dummy (RID) series of ATDs include RID1, bio-RID, RID2 and Bio-RIDII. The most important aspects of these ATDs are the additional attention to the mobility of the spine particularly in the neck region and also in the area near the hips. The third type of ATD is the Side Impact Dummy (SID). The SID's are similar to the RID's but with additional fidelity for spinal motion in the sideways, Y-axis, direction. To reduce reliance on crash testing the industry has developed FEMs of the various ATDs.

In the present effort, the Hybrid III FEM was selected as the baseline. This is the most commonly used ATDs and was thought to be a good starting point for comparing the results from the ATDs to those from the Brinkley Dynamic Response Method model. It was also thought that the Hybrid III was a reasonable ATD for assessing alternate crew protection concepts. It is recognized that for situations such as side and rear impact, models such as the SID or RID are more suitable.

In order to directly relate the results of the FEA simulations (which provide forces and moments in strategic locations throughout the model) and actual injury, the nature of specific relevant injury, and the forces or moments that produce it must be understood. Both the US Air Force and the Navy have active programs in the area of biomechanics and injury potential of ejection seats. Much of this work is summarized in a 1993 study entitled "Aircrew Ejection Injury Analysis and Trauma Assessment Criteria" published by the University of Michigan Transportation Research Institute [ref. 11]. This work was commissioned by the US Navy as part of an effort to better understand the use of ATDs in the evaluation of escape systems. This paper is a survey of the state of the art in understanding the effect of ejection seat g forces on the human body. In particular the data indicates that injuries that are experienced at these acceleration levels (+ or -Z axis only) are almost always related to injuries of one type or another to the spinal column. Serious injuries to soft tissue that are not directly related to impact are effectively nonexistent. This fact is important to the CM effort since it indicates that the focus, at least in the Z-axis direction, can be primarily on predicting and preventing spinal column injuries.

7.2.6.3 Finite Element Anthropomorphic Test Device (FE ATD) Simulations

The CM (version 604), Figure 7.2-42 was used to generate vehicle responses so that a comparison could be made between injury predictions from the Brinkley Dynamic Response Method model and predictions from the FE ATD. To generate the response, the CM was oriented in three primary human body directions; eyes in/out (Z-axis), sideways (Y-axis), and the spinal (Z-direction). The CM was given an initial velocity just before impact with the ground. These orientation exaggerate realistic landing scenarios, however, they provide extreme cases for comparing the Brinkley Dynamic Response Method model to the ATD results.

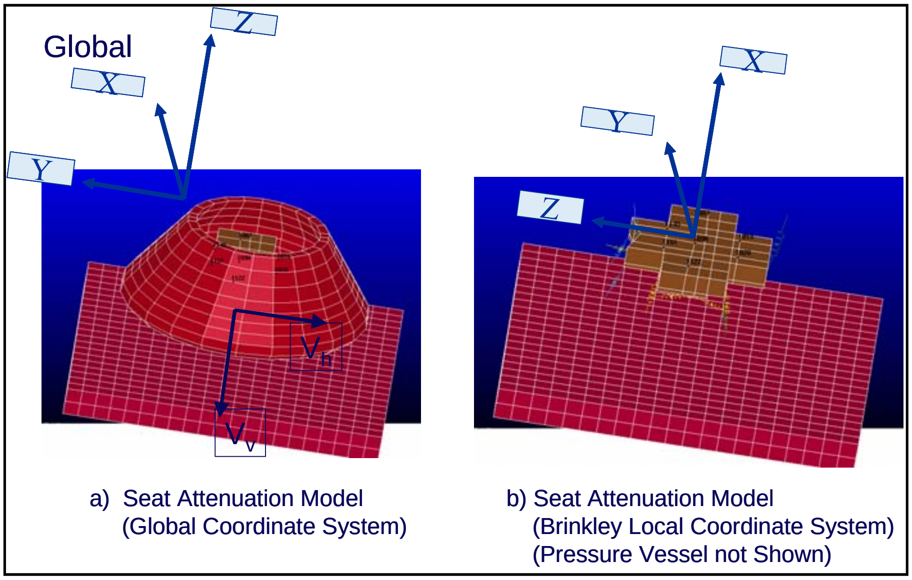

Figure 7.2-42. CM 604 Seat Attenuation Model

LS-DYNA® was used to perform the analysis of the CM impacting ground and resulting acceleration profiles were computed and extracted at the location of the crew members' center of mass. The extracted acceleration profiles were then input into the Brinkley Dynamic Response Method model and the level of injury was computed using the Brinkley injury criteria. The initial impact velocities were adjusted until they corresponding to high, medium and low injury risk were identified (refer back to Table 7.2-20).

Once the impact velocities corresponding to the three levels of Brinkley Dynamic Response Method injury were determined and the acceleration profiles were generated (Figures 7.2-43 through 7.2-54) a separate LS-DYNA® model was created that included only the FE ATD constrained in a seat with a five point harness. The acceleration profiles were then applied to the seat in this model, simulations were run, and a comparison was made between the Brinkley Dynamic Response Method injury criteria and the response extracted from the FE ATD.

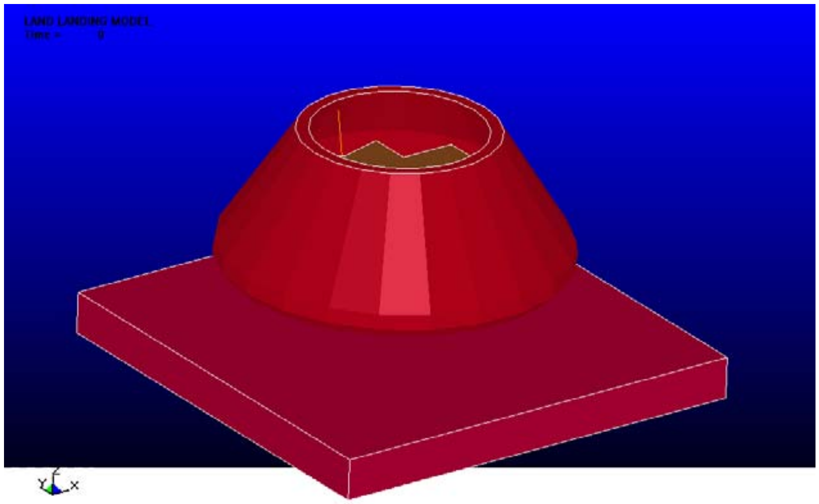

Figure 7.2-43. Configuration for X Acceleration (eyes in/out DRI)

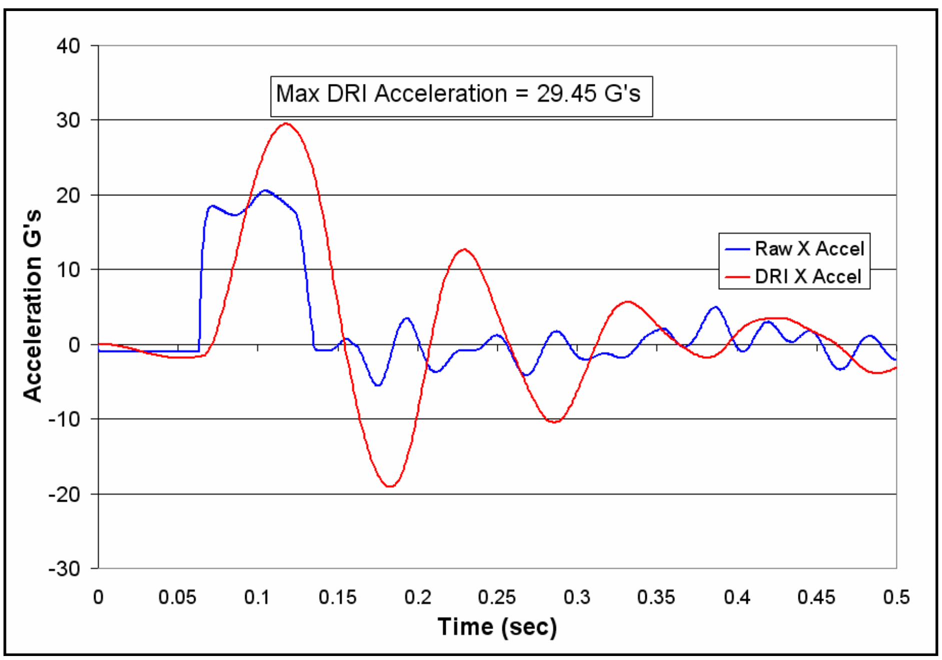

Figure 7.2-44. Acceleration Profile for Low Eyes In/Out DRI (Vn=33.3 fps)

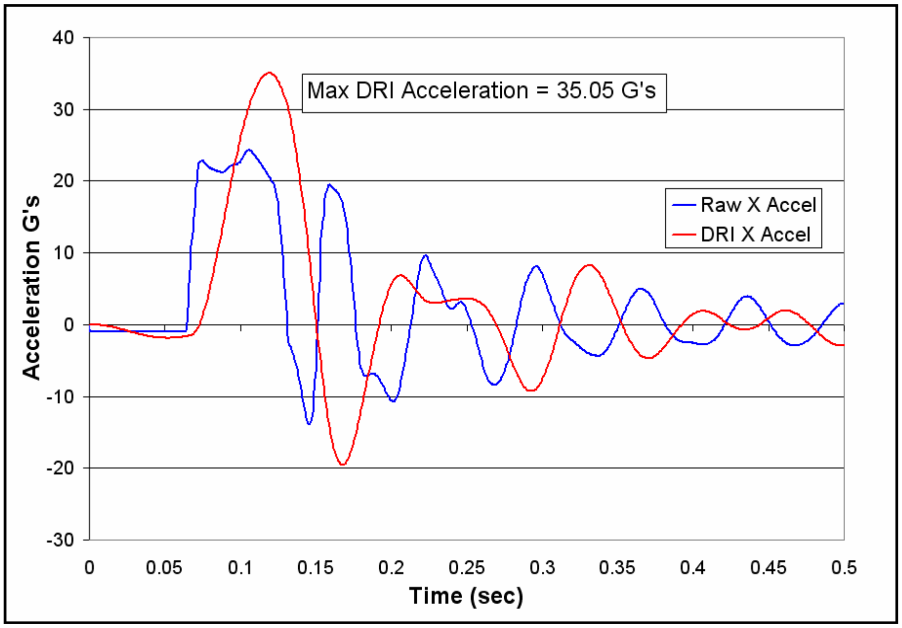

Figure 7.2-45. Acceleration Profile for Moderate Eyes In/Out DRI (Vn=41.67 fps)

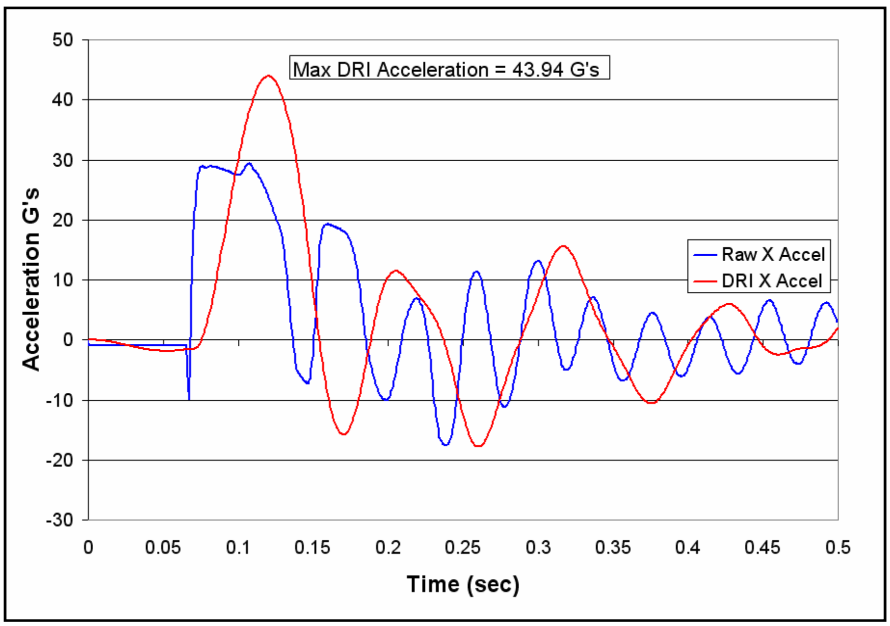

Figure 7.2-46. Acceleration Profile for High Eyes In/Out DRI (Vn=58.33 fps)

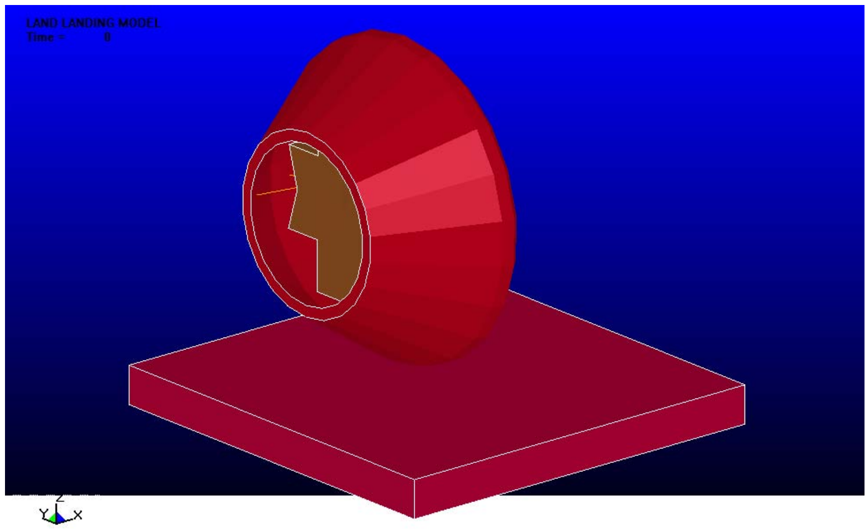

Figure 7.2-47. Configuration for Y Acceleration (sideways DRI)

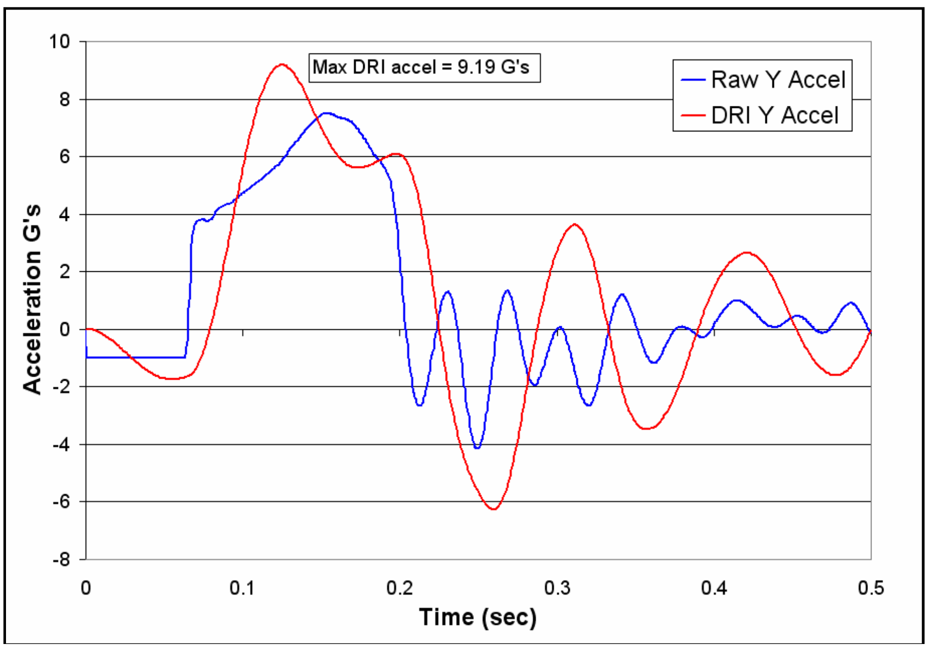

Figure 7.2-48. Acceleration Profile for Low Sideways DRI (Vn=16.66 fps)

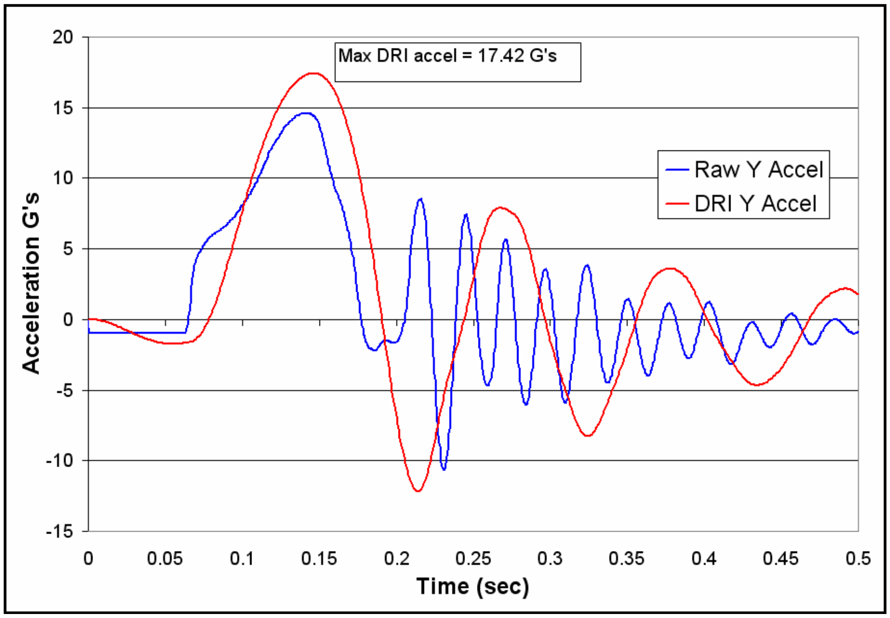

Figure 7.2-49. Acceleration Profile for Moderate Sideways DRI (Vn= 25 fps)

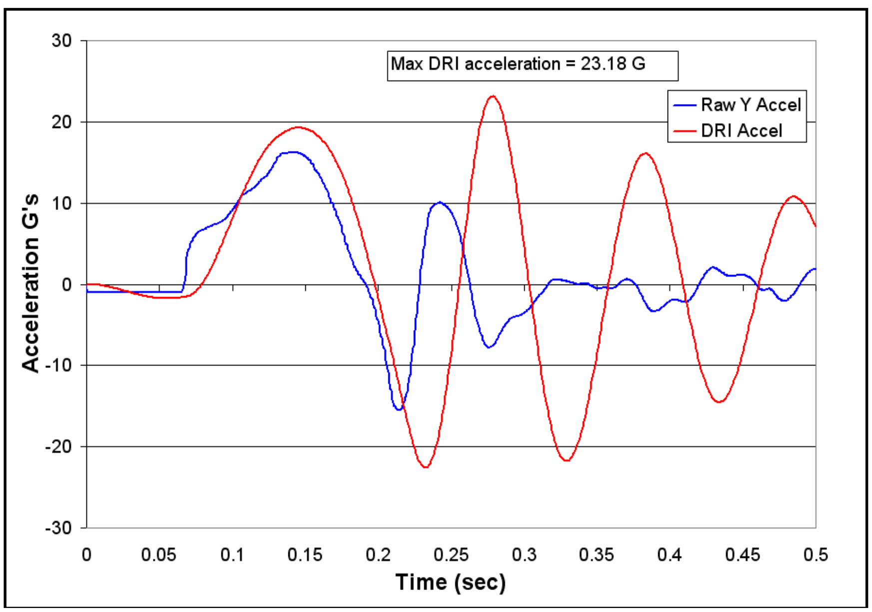

Figure 7.2-50. Acceleration Profile for High Sideways DRI (Vn= 33.3 fps)

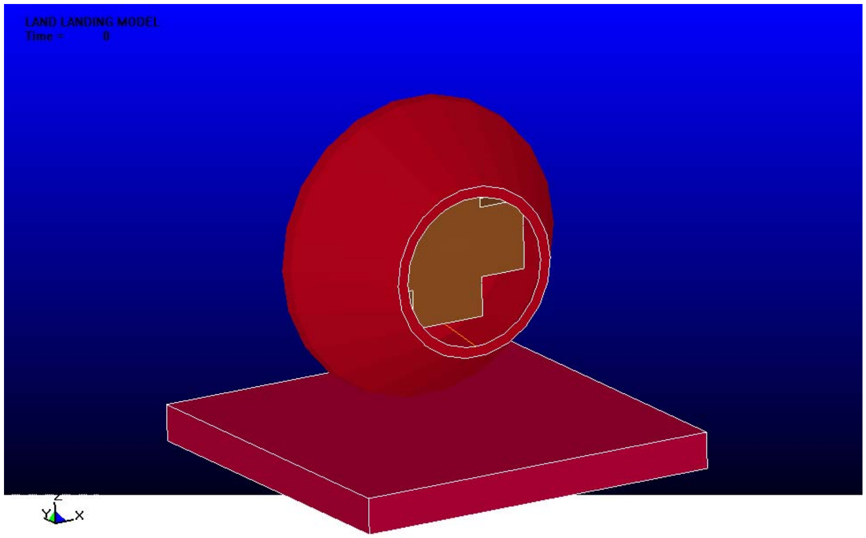

Figure 7.2-51. Configuration for Z Acceleration (spine DRI)

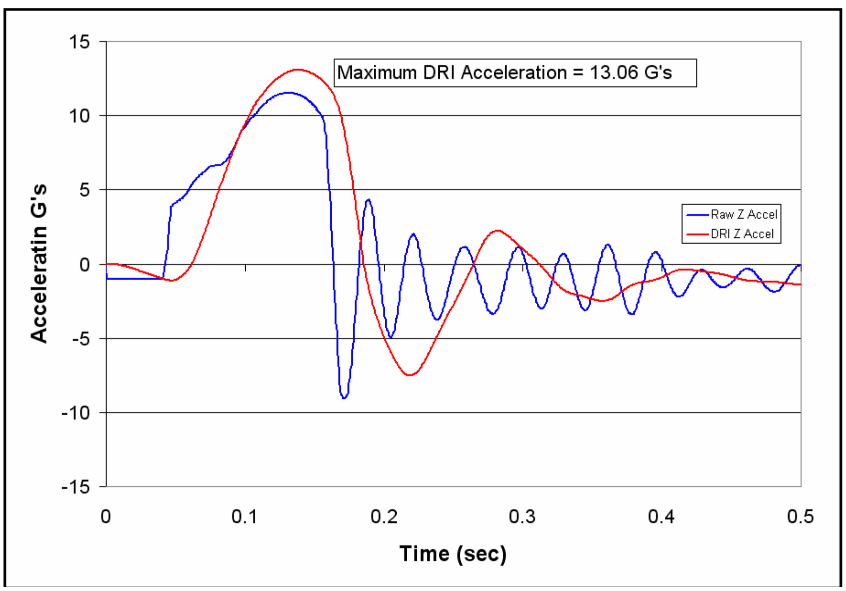

Figure 7.2-52. Acceleration Profile for Low Spine DRI (Vn= 25 fps)

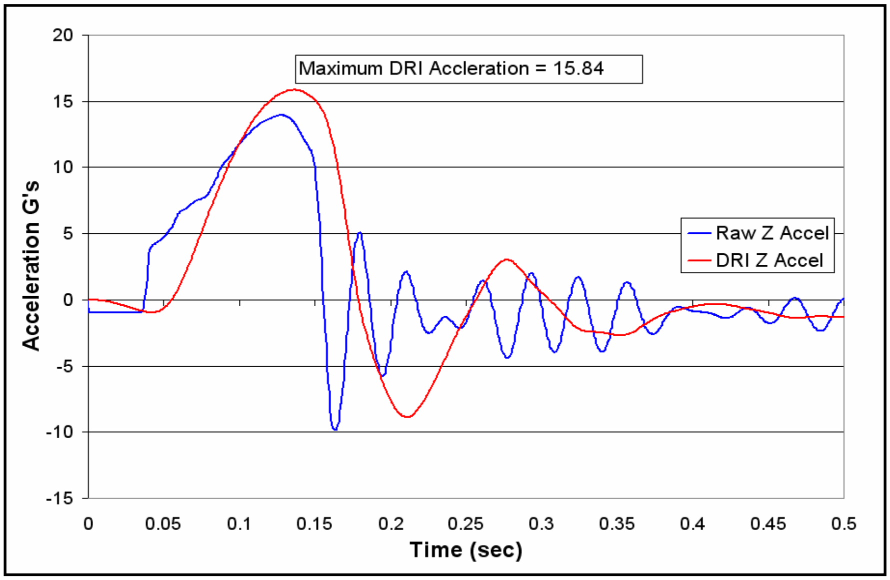

Figure 7.2-53. Acceleration Profile for Moderate Spine DRI (Vn= 29.2 fps)

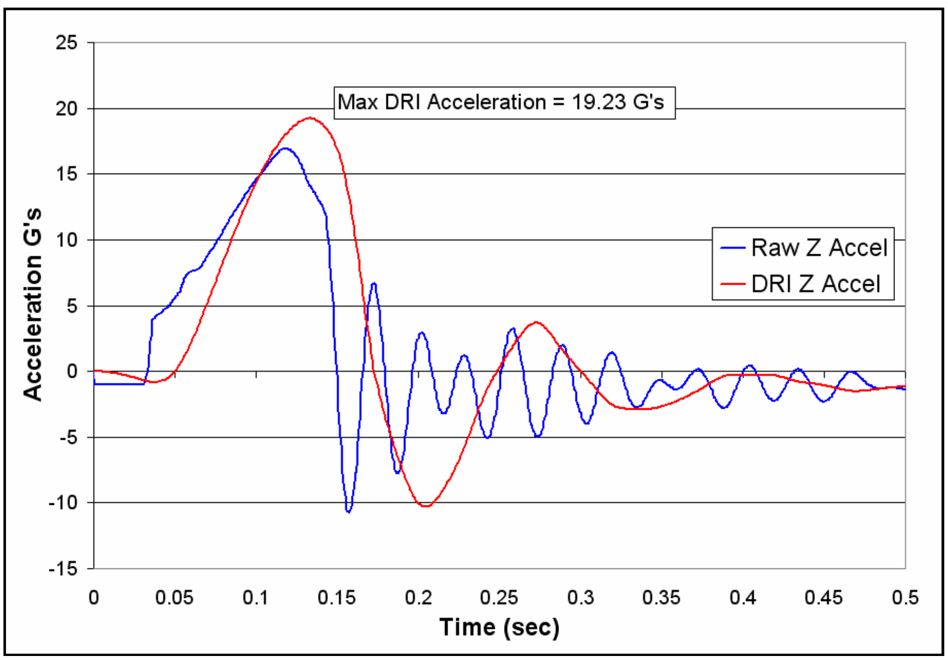

Figure 7.2-54. Acceleration Profile for High Spine DRI (Vn= 33.3 fps)

The FE ATD provides a greater amount of information concerning human body response including actual motions of the body such as limb flailing, head motion, and loads within the body (e.g., acceleration levels at specific locations in the body and forces on individual body parts). Figures 7.2-55 through 7.2-62 show details of the Hybrid III ATD and some of the locations in the model where data is extracted. Figures 7.2-55 through 7.2.6-57 show the location of where accelerations were extracted in the head, pelvis, and thorax. Accelerations at these locations are important since considerable research has been performed and injury criteria have been developed that provide correlations between acceleration levels and likelihood of injury. Figures 7.2-58 and 7.2-59 depict the lower lumbar region of the FE ATD model and where these forces and moments are extracted, while Figures 7.2-60 through 7.2-62 depict the neck region and locations where neck forces and moments are extracted. Similarly to the ATD accelerations, industry standards have been established that minimize injuries by limiting allowable predicted forces and moments in the ATD.

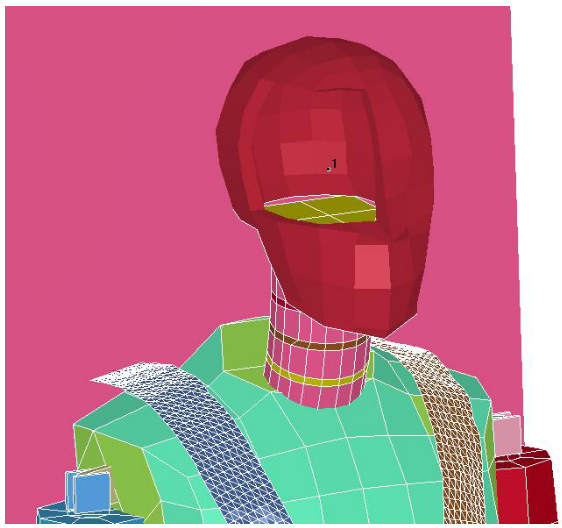

Figure 7.2-55. Location of Head Acceleration

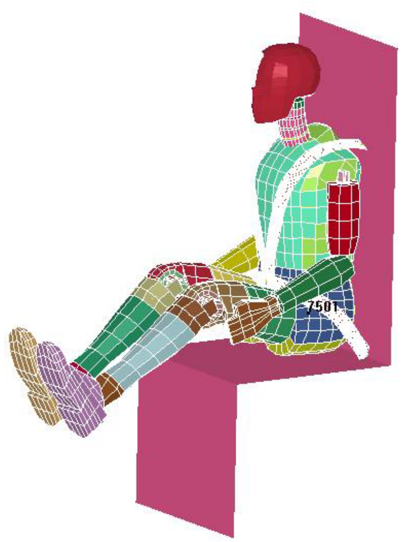

Figure 7.2-56. Location of Pelvis Acceleration

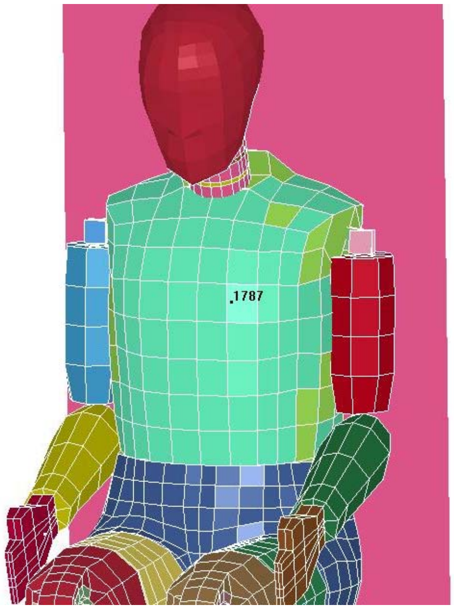

Figure 7.2-57. Location of Thorax Acceleration

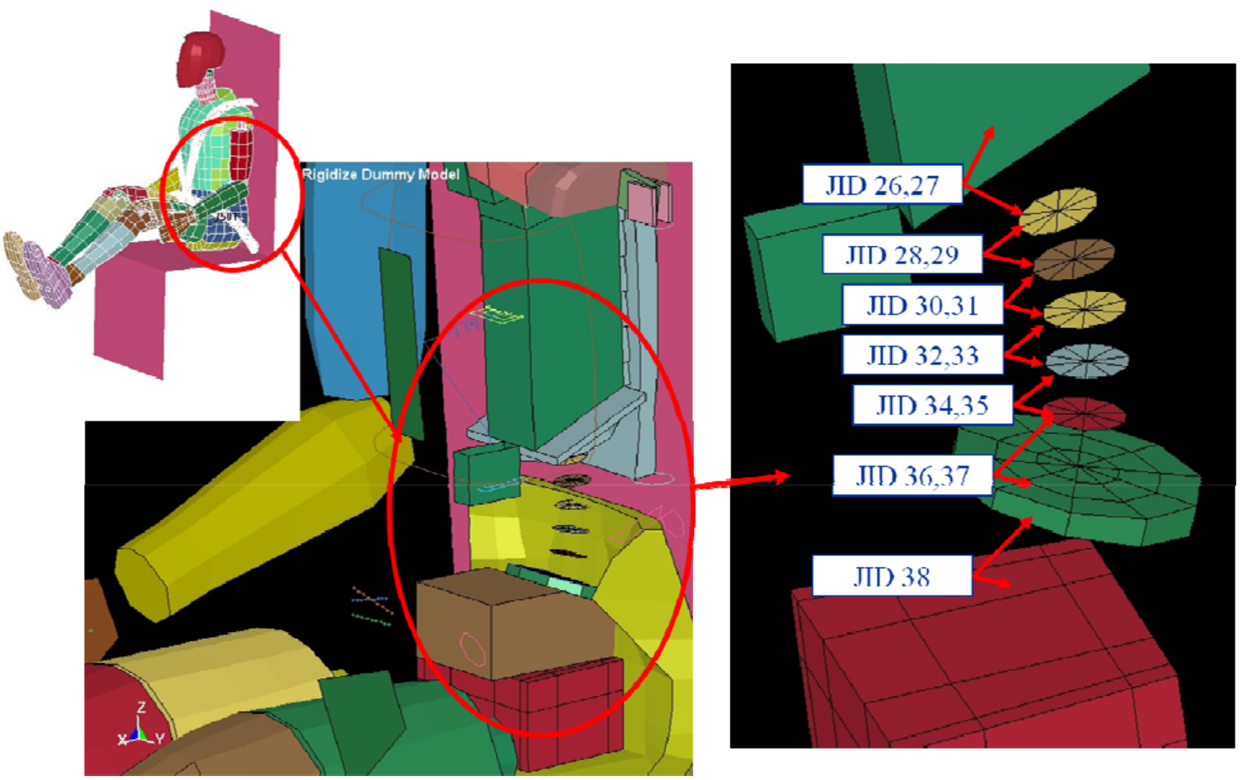

Figure 7.2-58. Location of Lower Lumbar Spine Force

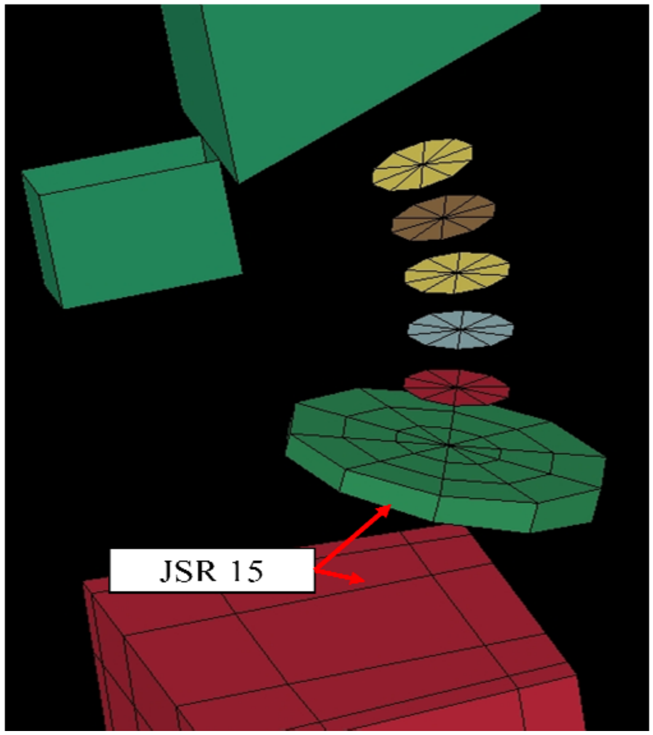

Figure 7.2-59. Location of Lower Lumbar Spine Moment

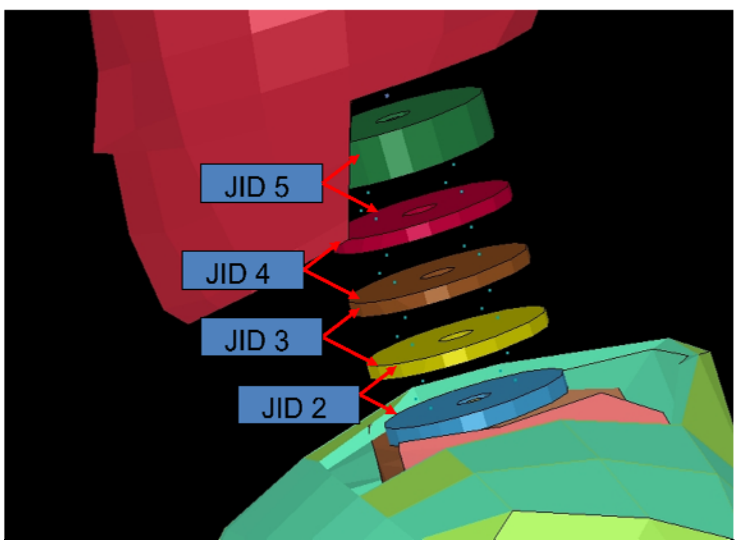

Figure 7.2-60. Location of Neck Joints

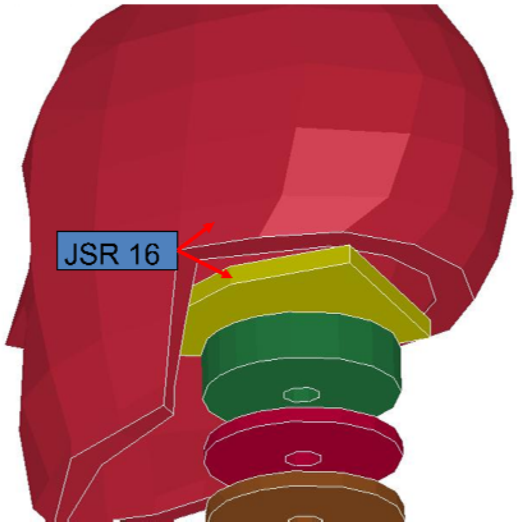

Figure 7.2-61. Location of Upper Neck Moment

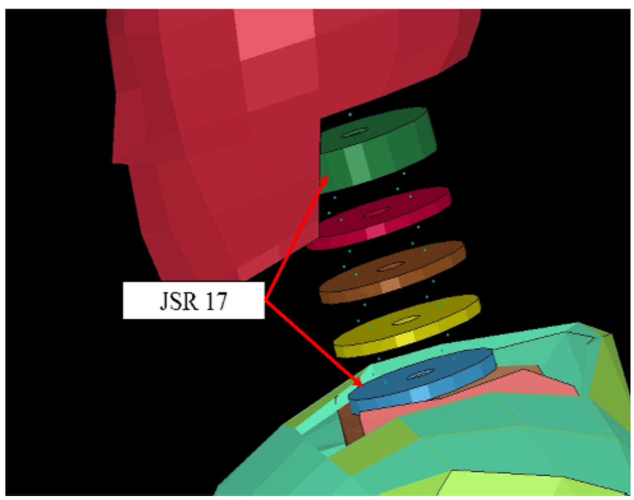

Figure 7.2-62. Location of Lower Neck Moment

As previously mentioned in this report, it is important to note that many of the industry accepted standards have been developed for the automotive industry or ejection seats, and may not be directly applicable to the type of conditions and injuries expected for the CM crew members. It is also important to note that the FE ATD is an analytical model of the physical simulator, which is made up of non-human parts made from materials such as steel, aluminum, rubber, and plastic. The FE ATD is designed to predict the response of the physical simulator, which in turn is designed to mimic how a human might respond during an actual impact.

7.2.6.4 Z-Axis (Spinal) Acceleration Simulations and Results

Loading in the Z-axis (spinal) direction was examined since this is the loading direction that the Brinkley Dynamic Response Method model was originally designed to address and where the model is most accurate. Since the results of the Brinkley model are anchored in actual data for loading in the spinal direction, it was useful to compare the Brinkley predictions to the results generated from the FE ATD and to industry accepted injury criteria. Figure 7.2-63 shows the FE ATD in a five-point harness. This harness was used since the five-point harness is the harness used for the development of the Brinkley model. The harness was composed of 2 inch nylon webbing. The harness was attached to a relatively rigid steel simplified seat and base accelerations were applied to the seat in the Z-axis direction (from the pelvis upwards towards the head). The commercially available Hybrid III FE ATD model and LS-DYNA® were used to generate the transient response.

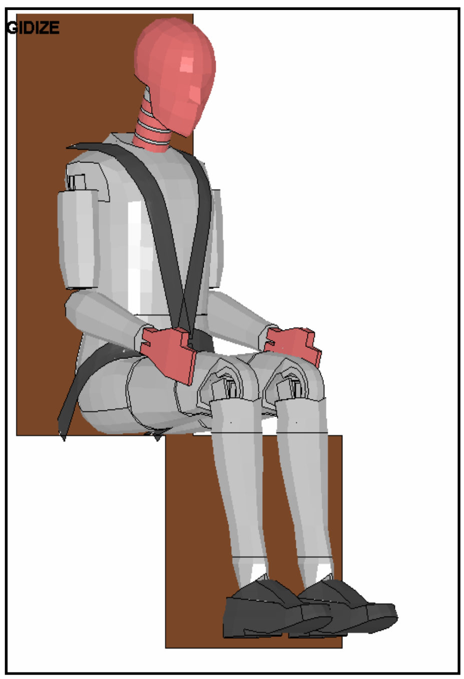

Figure 7.2-63. Hybrid III ATD Constrained with Five Point Harness

Figure 7.2-64 and Table 7.2-21 provide representative output from the LS-DYNA® simulations. Figure 7.2.6-28 shows two intermediate time steps from the simulation. The first frame shows the maximum head flexion, which occurs just after ground impact, and the second frame shows maximum head extension which occurs during the time period where the CM rebounds off of the ground. Table 7.2.6-4 provides a comparison among the three Brinkley Dynamic Response Method injury levels and a collection of injury criteria [ref. 12]. Allowable limits for the injury criteria are included in the table and conditions where the limits are exceeded are identified by red.

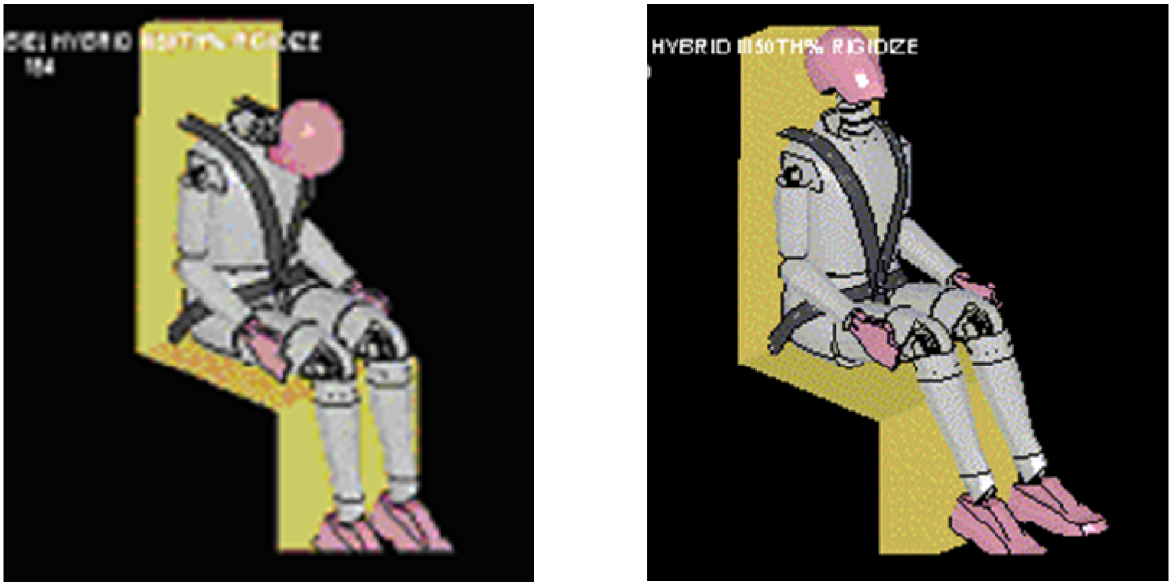

Figure 7.2-64. Hybrid III ATD Response at Intermediate Time Steps

Table 7.2-21. Hybrid III Response and Brinkley Dynamic Response Method Injury Levels Z-Axis (Spinal) Excitation

Criteria[1]	Location	Allowable	Brinkley Low Injury	Brinkley Medium Injury	Brinkley High Injury
Head Injury Criteria (HIC)	N# 1 HIC	700	3.4	4.57	59.54
Chest Severity Index (CSI)	N# 1787 CSI	700	31.6	43	64.49
Thorax G's	N# 1787 -resultant	60 G's	46.17 G's	75.27 G's	127.7 G's
Pelvis G's	N# 7501 - resultant		32.7 G's	49.42	41.9 G's
Lumbar Force	JT# 26-37 -resultant	6672 N	2804 N	4037 N	4545 N
	JT# 38 -resultant	6672 N	4080 N	4500 N	5500 N
Lumbar Moment	JSR# 15 -		131.4 NM	143 NM	124.3 NM
Neck Force	JT# 2-5 - resultant	6806 N	887 N	698 N	1277 N
Neck Moment Flexion (-)	JSR# 16 -	310 NM	66.42 NM	78.6 NM	79.42 NM
Neck Moment Extension (+)	JSR# 17 -	135 NM	108.6 NM	130 NM	184 NM

The Brinkley Dynamic Response Method injury criteria are consistent for low levels of injury in that none of the injury criteria allowable are exceeded. For medium Brinkley injury the allowable thorax acceleration limit is exceeded, while the remainder of the injury criteria is within allowable limits. For high Brinkley injury the thorax acceleration is close to double the allowable limit and the neck moment extension allowable limit is exceeded. It is not surprising that the allowable neck moment is exceeded considering the head is not constrained and is predicted to undergo considerable motion during impact. It is interesting that the lumbar force is within allowable limits for all three Brinkley Dynamic Response Method injury levels considering that for this direction of loading spinal cord injuries, particularly in the lumber region, are prevalent.

Many of the automotive injury criteria were developed for frontal impacts where the human body rapidly decelerates and body parts such as the head impacts some part of the automobile interior. Similarly, aircraft ejection seat criteria are designed for an upright seated pilot being ejected vertically through the aircraft canopy where the primary loading is up through the spine. For CM nominal landings, the crew members will be seated on their backs and the primary loading will be in a direction from the crew member's back towards the chest. Further studies are necessary before existing industry accepted injury criteria be used to assess CEV Project crew member injury.

7.2.6.5 Y-Axis (Sideways) Acceleration Simulations and Results

Results of FEA simulations for the standard five-point harness were compared with simulations that contained a variety of lateral supports inspired by a modern race car seat. Modern race car seats provide excellent driver protection during impacts that might normally be fatal with a more traditional seat design. These seats provide a higher level of protection through the use of lateral supports, and head and neck restraint systems, and improved harnesses. A typical modern race seat is shown in Figure 7.2-65 alongside the seats from the Apollo Program. The differences in lateral support between the two seat designs are evident. Much of the improvements that have been realized in race car seats are the results of trial and error combined with results obtained during actual operations and accidents. CM seat designs have limited opportunities for development tests and therefore must take advantage of improvements in restraint or seat designs and subscale test using FE ATDs.

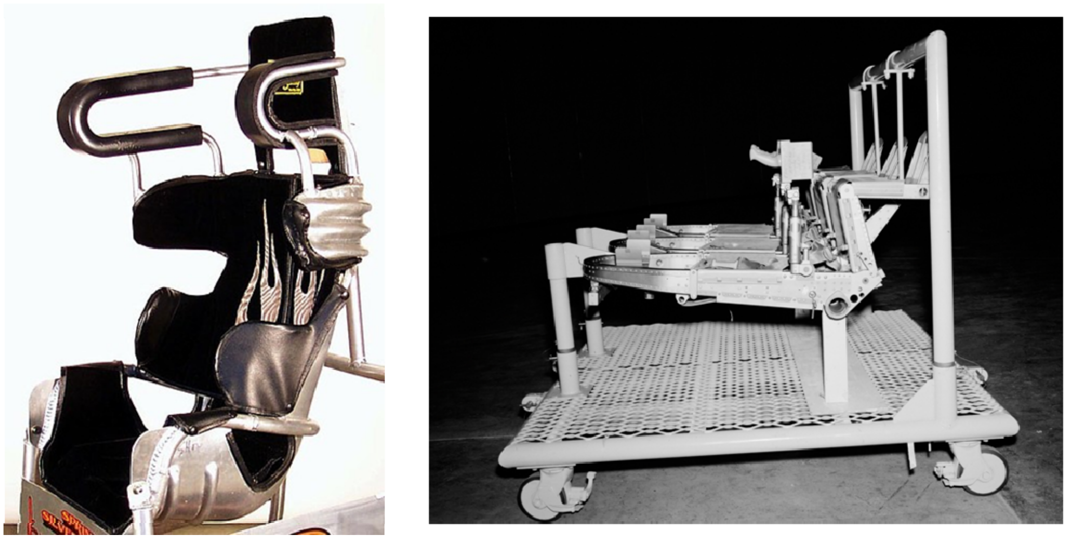

Figure 7.2-65. Modern Race Car Seat with Lateral Supports (left) and Apollo CM seats (right)

The use of lateral supports of the type found in race car seats may not be directly applicable to the CEV Project since these seats may be impractical for crew ingress and egress, and for stowage during flight. In order for lateral restraints (or any other restraint or crew protection system) to be used in space flight applications the system must provide for a practical means for ingress, and rapid egress, and stowage when the system is not in use. In addition the restraint system must be flexible in its ability to accommodate crew members of different sizes and weights.

In a standard seat such as that used in Apollo CM there is no lateral support other than that provided by the harness. There was a slight depression that the crew member sits, but the dish shape provided no real restraint during high g Y-axis accelerations. In the case of CEV Project CM there is the additional complication of having two distinct decks of seating, with two crew members placed in a second row. If permanent lateral restraints are added to the seats, they will most likely make it difficult or impossible to get in and out of the seats.

One system that shows particular promise is a series of side airbags mounted on panels that are linked together and can be quickly extended and retracted by the crew for ingress and egress, see Figure 7.2-66. The illustration on the left shows the airbag pallets in the extended position and the illustration on the right shows the pallets in the stowed position. In this concept there is a retractable arrangement of airbags on each side of the individual seats. The airbags are mounted so that they pivot about one corner, and there is a mechanical linkage that connects them so that they move together as a group. In the up position they are held by a spring clip and by manually pushing any one of the airbags down the entire group can be quickly stowed. The airbag position can be changed for taller or shorter crew members by using an adjustable length linkage between airbag pallets. By adjusting the length of the linkage (Figure 7.2-67) the erect position of the paddle can be pivoted up and down for different crew member sizes. This would allow the seating system to be adjusted in flight or on the ground to accommodate changing crew sizes.

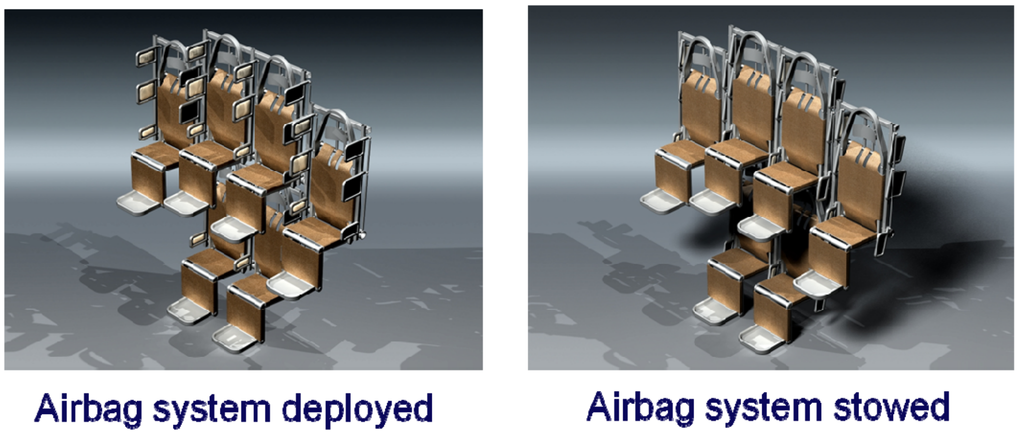

Figure 7.2-66. Airbag Concept shown in a CEV Six-Seat Configuration

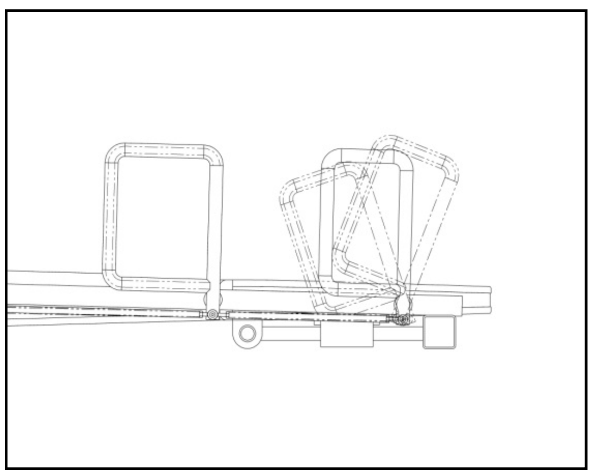

Figure 7.2-67. Airbag Sketch of Adjustable Length Linkage

Simulations for impacts in the Y-axis direction were conducted using the Hybrid III FE model, harness, and seat as was used for the Z-axis study in the previous section. The purpose of performing simulations in the sideways direction was to evaluate the effect of various combinations of side impact constraint devices on crew member injury, and to assess the general effectiveness of the FE ATD for performing this type of study. The Hybrid III FE ATD is not ideally suited for simulating side impacts; however, since this model was already generated for the work performed in the previous section it was expedient to re-use the model for side impacts. The results presented in this section may not be as accurate as if they had been computed with a better-suited ATD such as the SID. However, for performing a first order comparison of the effect of side constraints, this model was adequate.

Figure 7.2-68 shows the four of the five configurations that were used to assess the effectiveness of side impact constraints. The baseline configuration was an unconstrained crew member in the five-point harness. The second configuration was comprised of thin pads with a three-inch gap between the crew member's head and shoulders. The third configuration (not shown in the figure) was thicker pads with a one-inch gap between the crew member's head and shoulder. The fourth configuration was comprised of thick pads in direct contact with the crew members head and shoulders, and the fifth configuration was identical to the fourth with hand and feet constraints added to retain the crew member's arms and legs from significant flaying. For this preliminary study the pads properties and thicknesses were not optimized and the results are only indicative of overall trends. All of the simulations performed in this section were done using the input acceleration profile that generated a high Brinkley Dynamic Response Method injury in the sideways direction.

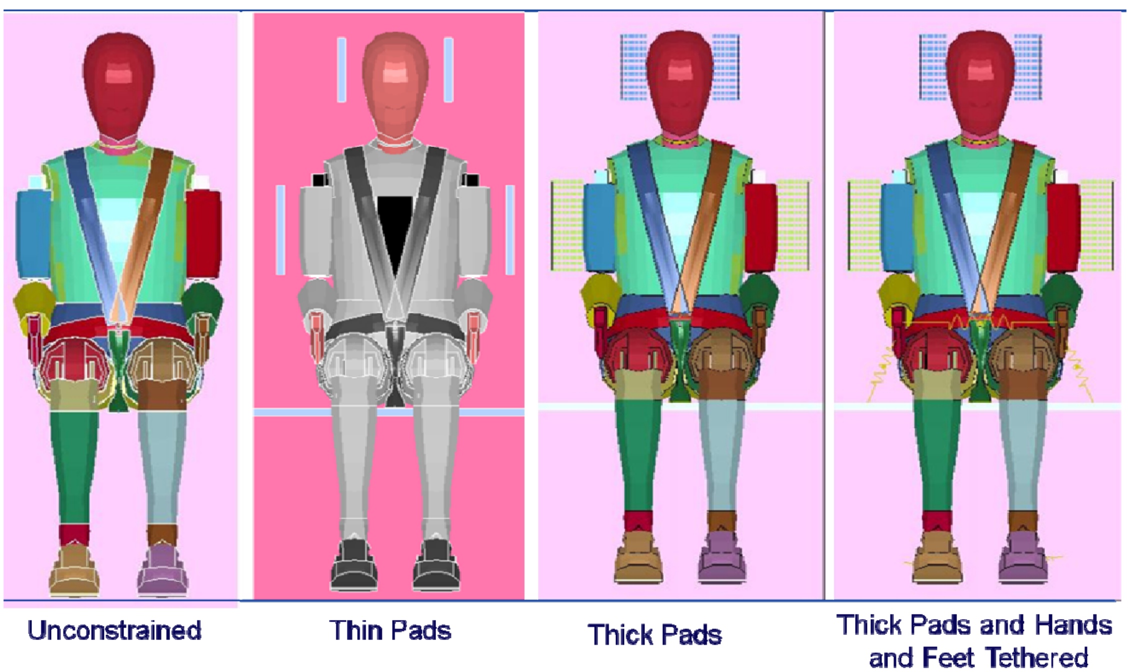

Figure 7.2-68. Comparison Among Padded and Constrained Crew Member for Sideways Loading

Figure 7.2-69 and Table 7.2-22 show the results for the first configuration. Figure 7.2-69 shows the ATD response at three intermediate time steps for the model without any side padding. Large excursions of the head, arms, and legs are shown during both the initial impact and the rebound. The results in Table 7.2-22 agree with the Brinkley Dynamic Response Method prediction of high injury considering that four of the seven injury criteria are exceeded including the Chest Severity Index (CSI), the thorax maximum allowable g level, and the neck flexion and extension. It is important to note that the neck injury criteria are intended for frontal impacts and have been loosely applied to the present side impact application. For side impact there are no clearly defined neck moment criteria available from industry or defined in CxP specifications.

However, the NESC team felt that the industry frontal impact neck criteria could be reasonably applied, as an approximation, to side impacts. Additional study of neck injury criteria is required before firm criteria can be established by the CxP.

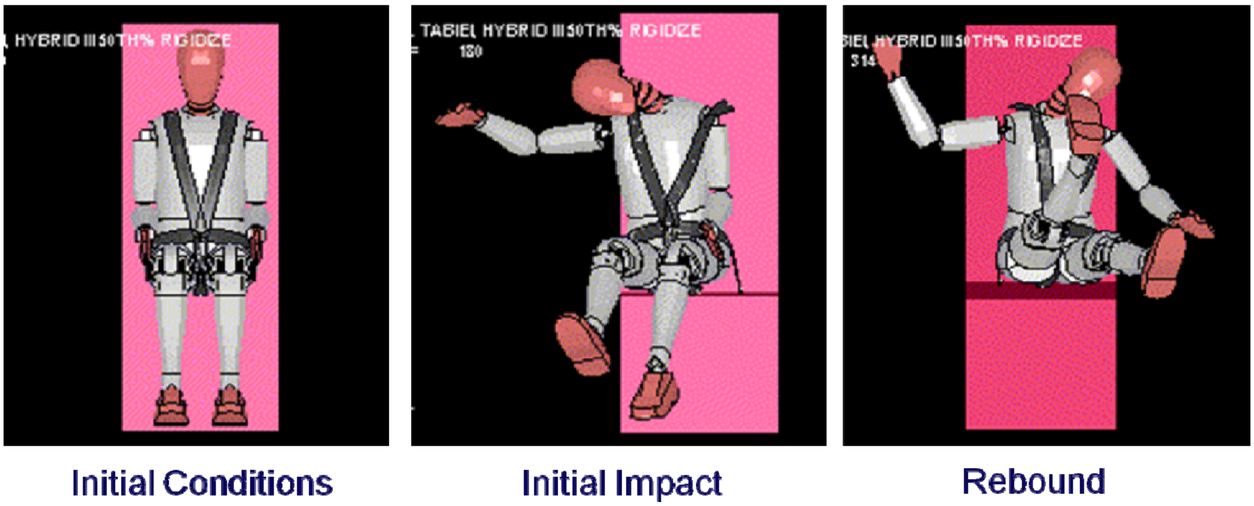

Figure 7.2-69. Hybrid III ATD Response at Intermediate Time Steps for Side Impact (No Side Padding)

Figure 7.2-70 and Table 7.2-22 show the results for the second configuration. This type of support is similar, in concept, to what is currently used for race car seat side supports, and has been proven highly successful in reducing injury during relatively violent high-speed race car crashes and was thought to have similar benefits for CM crew members also undergoing side impact loadings. Figure 7.2-70 shows the ATD response at three intermediate time steps for the model with thin side padding. The large excursions of the head, arms, and legs that were seen for the configuration without side padding is eliminated with the thin pad configuration.

Table 7.2-22. Comparison Among ATD Configurations Using Input Acceleration Profile that Produces High Brinkley Dynamic Response Method Injury in Lateral (Sideways) Direction

	Allowable	Five Point Harness*	Thin pads	Thicker pads 1" gap	Thick pads	Thick Pads and hand and Feet Constraints
HIC (Node 1)	700	225	4050	256	174	92
CSI (Node 1787)	700	965	1960	1965	1211	1559
Thorax g's (Node 1787 filtered @180Hz)	60 g's	78 g's	90 g's	62 g's	71 g's	81 g's
Pelvis g's (Node 7501 filtered @180Hz)	130 g's	90 g's	120 g's	90 g's	161 g's	126 g's
Neck force (Max JT2-5 filtered @180Hz)	6806 N	3950 N	3500 N	3950 N	3264 N	3283 N
Neck moment flexion (Max +JSR17 phi, theta, psi filtered @180Hz)	310 Nm**	315 Nm	165 Nm	142 Nm	123 Nm	84 Nm
Neck moment extension (Max +JSR17 phi, theta, psi filtered @180Hz)	135 Nm**	180 Nm	130 Nm	125 Nm	132 Nm	96 Nm

* All configurations utilize five point harness
** Frontal impact criteria used for lateral direction

The results in Table 7.2-22 show that the thin side pads help to reduce the neck moments, which was expected since the side pads prevent the head from bending over. However, the Head Injury Criteria (HIC), CSI, thorax, and pelvis acceleration criteria all exceed their allowable limits and are considerably larger than for the configuration without any pads. These results were also expected since the crew member head and chest impact into the relatively thin and stiff pads leading to short durations of large accelerations.

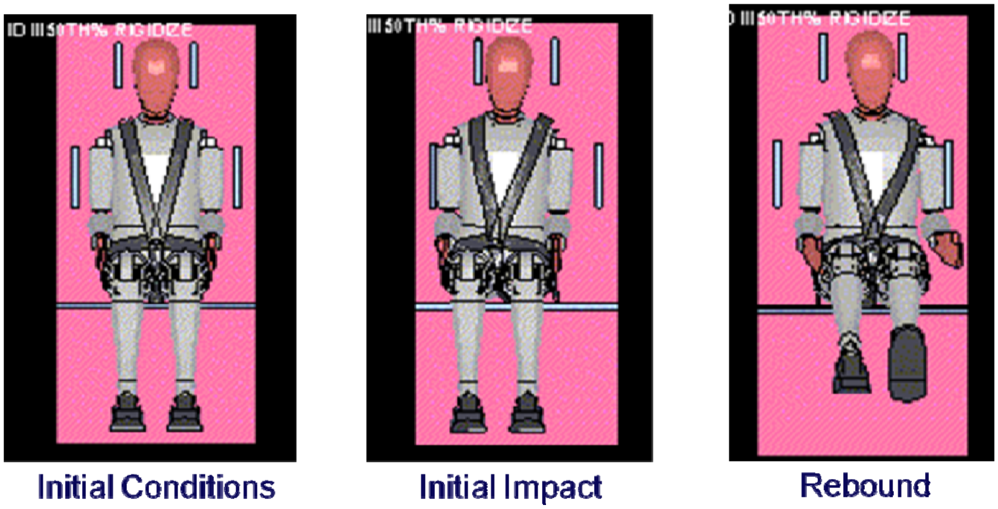

Figure 7.2-70. Hybrid III ATD Response at Intermediate Time Steps for Side Impact (Thin Side Padding)

The configuration with the thicker pads and one-inch gap between the pads and head and chest provides a higher level of injury protection than the previous two cases. For this configuration, only the CSI and the thorax maximum allowable acceleration were exceeded. The thicker pads provide so much reduction in head acceleration that the head injury criterion is reduced by an order of magnitude over the configuration with thin pads. For the thick pad configuration where the pads are in contact with the head and shoulders, the head injury criteria and the CSI are further reduced. However; the pelvis acceleration is increased and is beyond the allowable limit. For the thick pads and constrained arm and leg configuration, all of the observed injury criteria are reduced compared to the other configurations except for the CSI and the thorax acceleration. Both of these criteria exceed their allowable limits.

In general, introduction of the side supports eliminates the large head excursion and neck hyperextension. Neck hyperextensions are the main cause of severe injury for the case without lateral support, so it appears promising that lateral support will improve survivability for Y-axis direction impact. However, the body must still mitigate the crash, so while neck forces are reduced due to reduced head and neck extension, other body forces and moments may show increases. This is supported by the fact that padding had the effect of reducing the neck moment while increasing the CSI. The key design goal is to keep any individual force, moment or acceleration from exceeding the allowable injury level, which will require tradeoffs in the design. With further design improvements it may be possible to reduce the chest and thorax loadings to within allowable limits; however, for the designs that were considered, both the Brinkley Dynamic Response Method model and the FE ATD predicted high levels of injury.

A significant difference between the Brinkley Dynamic Response Method model and the FE ATD is that the Brinkley model cannot directly determine the effects of adding constraints such as side padding while the FE ATD can simulate somewhat realistically the distributed motion of the body and predict accelerations and loads at discrete body locations. Furthermore, the Brinkley model only predicts the level of injury, not the injury location or type. The FE ATD provides a major advantage over the Brinkley model in that the ATD may be used to assess the effects of different seat designs, constraint systems, helmets, and crew protection systems.

7.2.6.6 X-Axis (chest in/out) Acceleration Simulations and Results

A comparison between the Brinkley Dynamic Response Method model and the FE ATD was made in the X-axis direction using an applied acceleration profile obtained from a maximum drag abort situation. This situation occurs when an emergency occurs during ascent and the CM must be separated from the launch vehicle using the Launch Abort System (LAS). When the LAS is activated, the crew members are pushed into their seat backs. Once the LAS rocket's fuel is depleted the aerodynamic drag reverses the acceleration on the crew members and they are pulled out of their seats in the opposite direction. The Hybrid III FE ATD is probably most suited for loadings in the X-axis direction since this is the direction where the ATD was originally designed for automotive frontal impacts. The acceleration profile for the maximum drag abort and the corresponding FE ATD response at intermediate time steps is shown in Figures 7.2-71 and 7.2-72, respectively.

As expected, during LAS rocket firing the crew member is pushed into their seat and there is minimal motion of the head, arms, or legs. In the later stage when aerodynamic drag is dominant and the crew member is pulled out of his seat, both the head and arms and legs are extended leading to the potential for larger neck forces and head accelerations. Note, this particular model contained overly stiff elbow joints which explains the limited extension of the arms. Additionally, flailing of the arms and legs in the close confines of CM could be an issue since the arms and legs may impact surrounding structures or strike other crew members. To compensate for flailing, hand and foot restraints will be an important design consideration. The large head movement could also be an issue and some type of head/helmet constraint may be required.

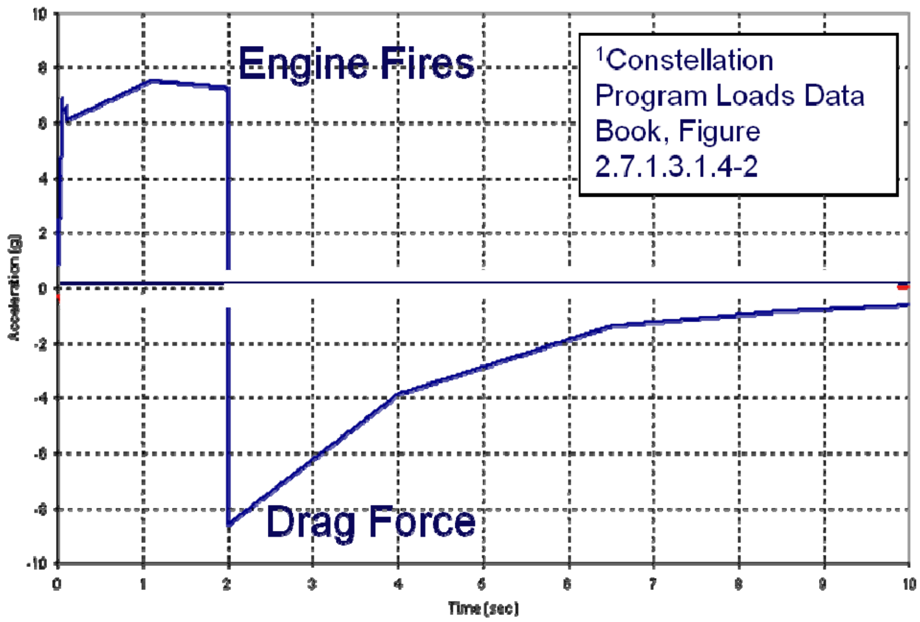

Figure 7.2-71. Acceleration Profile for Maximum Drag Abort

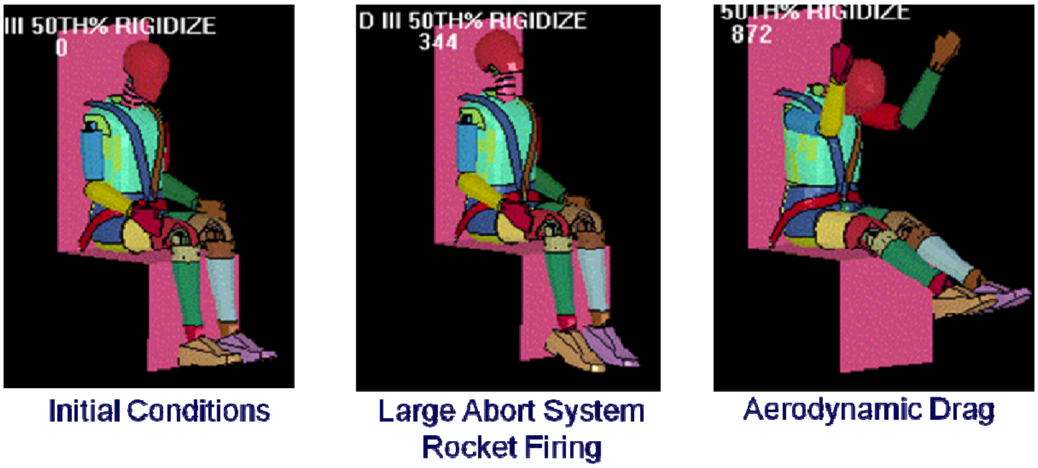

Figure 7.2-72. Hybrid III ATD Response at Intermediate Time Steps for Maximum Drag Abort

Figure 7.2-73 shows the maximum drag abort acceleration that was applied to the crew member seat along with the resulting Brinkley Dynamic Response Method and the FE ATD response in the X-axis direction. Both the Brinkley and the ATD response follow, reasonably close, both the input acceleration shape and magnitude. The Brinkley response closely tracks the input acceleration profile during the rocket-firing phase then oscillates about the input acceleration during the aerodynamic drag phase. The Brinkley model employs an approximately 10 Hz oscillator, so it is expected that the response after the load reversal would oscillate and that the oscillations would be near 10 Hz. The maximum Brinkley dynamic response is 20 g, which is within the Brinkley low risk of injury range for X-axis (chest in/out) accelerations. The FE ATD response is within the same general range as the Brinkley response except for numerous short duration acceleration spikes through the transient response. The ATD response has been filtered to eliminate response above 180 Hz and further reductions, or elimination, of at least some of these acceleration spikes could be minimized by adding more damping to the ATD model, and model refinement through the inclusion of a higher fidelity seat model and seat padding. Even with these outlying acceleration peaks, the computed CSI is below the allowable limit (212 < 700) leading to a consistent result with the Brinkley Dynamic Response Method prediction of a low probability of injury.

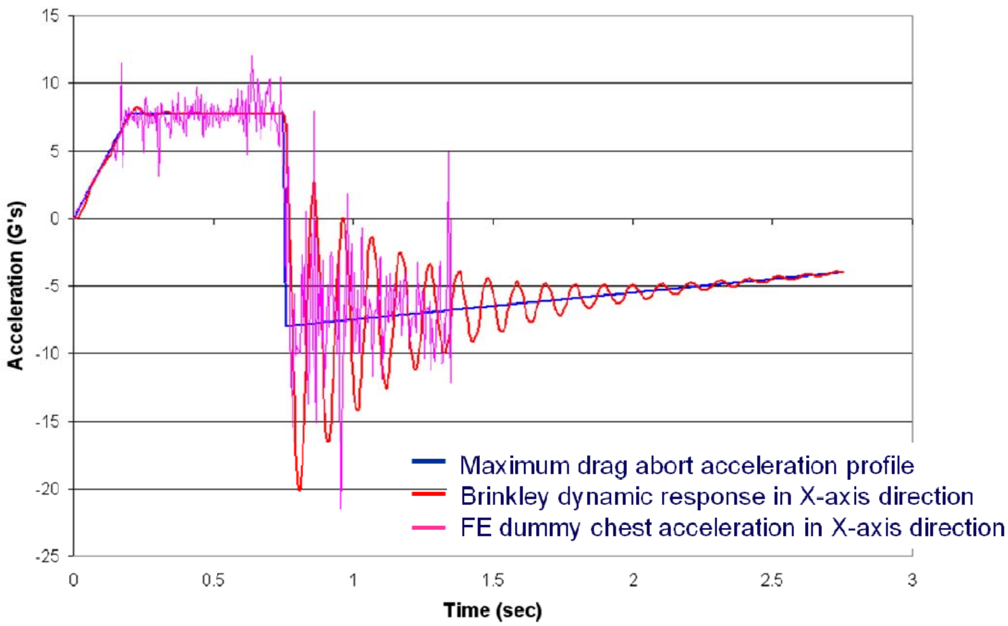

Figure 7.2-73. Acceleration Profile for Maximum Drag Abort, Brinkley Dynamic Response Method and FE ATD Chest Acceleration

7.2.6.7 Applicability of FE ATDs

The FE ATD used in conjunction with the Brinkley Dynamic Response Method provides a useful set of tools for predicting potential crew injuries during CM landings. In addition these tools enable the design and evaluation of alternate crew protection systems. Specifically:

- The Brinkley Dynamic Response Method reasonably ensures an acceptable environment for crew members in a five point harness. However, it has limited ability to provide insight into additional or modified crew restraint and protection systems. The Brinkley model has been modified to include the general effect of sideways crew member support. However, the Brinkley Model does not distinguish between types of support or their differences in effectiveness in preventing injury.
- FE analysis and ATD tests are capable of providing insight into alternate crew member injury protection systems. The FEA model and the physical ATDs can be used to assess the effects of variations of restraint and support in a comparative manner and if validated with human response data, can provide quantitative assessments of crew injuries.
- Additional evaluation of industry standard injury criteria should be initiated to ascertain the applicability of these criteria to crew member protection.
- Practical methods for implementing additional crew protection appears viable and should be further developed.

8.0 Findings and Recommendations

The Findings and NESC Recommendations first for the Phase I and Phase II portions of this study are presented.

8.1 Phase I - Comparison of 604, TS-LRS001, and Apollo LRS

8.1.1 Findings / Observations for Phase I - Comparison of 604, TS-LRS001, and Apollo LRS

Note: This material was extracted from Appendix A, which represents the only documentation of Phase I. Pertinent sections of this appendix were brought forward into the body of this report.

F-1. C2 (LM 604) - Retrorocket Extraction - Design susceptible to retrorocket/capsule contact and damage during extraction, especially under high body-rate conditions:

- Risk of damage to radar antennas, retrorocket body/nozzles, and other components mounted near the CM apex.
- Risk of severing pyro firing lines, radar avionics to antenna RF transmission lines, and parachute risers.
- Extraction failure would result in failure of main chute to deploy properly due to series connection between the two subsystems.
- Mars lander heritage benefits toward concept feasibility not applicable due to utilization of rate-limiting devices to lower the lander from confluence rockets after chute inflation.

F-2. C3 (LM 604) - C3 - Winds and Residual Horizontal Velocity - Insufficient data has been produced to demonstrate that not including horizontal retrorockets in the design is viable.

- Operational limit of 31 fps is too close to CM limits for crew safety and is relatively low; DSNE requirement > 45 fps.
- Consequences of CM rollover are not well understood and could be potentially severe.

Without horizontal velocity abatement, crew safety is critically dependent on the accuracy of a 3-hour weather forecast.

- If weather forecast was 99.9 percent accurate, still non-trivial risk for possible rollover and threat to crew safety.

Use of horizontal retrorockets on the TS-LRS001 is not risk free.

- Mars lander experience is that performance dispersions and failure modes with horizontal retrorockets have potential to compound the problem.

F3: **C4 (LM 604 and TS-LRS-001) - Retrorocket Firing Chain –** Applicable to both baselines. Dispersions on retrorocket burn completion conditions have potential to cause load limits to be exceeded.

- Difficult to control performance using high-impulse solids to deliver the CM to near-zero velocity near the ground.
- Small knowledge errors in parameters such as thrust profile, altitude/velocity state, and attitude/rate state may lead to late firing, including impact prior to ignition.

Retrorocket firing time critically dependent on accuracy of altitude and velocity sensors.

The LM 604 radar antenna location on the retrorocket pack may result in degraded accuracy with potential to degrade ignition time calculations.

F-4. **C1 (LM 604) - Main Chute Extraction -** Use of a single drogue to extract all main chutes in the current design involves rigging the mains together in a way where hang-up of a single chute has the potential to fail the extraction of all the others resulting in LOC.

F-5. **C5 (LM 604 and TS-LRS-001) – Apex/FBC Separation** - Post separation impact with CM has potential to cause severe damage:

- Current design is based on Apollo heritage of separation thrusters and pilot parachute.
- The Apollo Program was only able to provide limited satisfaction in meeting the requirements of no re-contact, even after extensive work.

F-6. **C6 (LM 604) - Retrorocket Plume Impingement -** Exhaust plume may be swept into riser lines or across the top of the capsule potentially resulting in safety related damage.

F-7. **C7 (LM 604 and TS-LRS-001) CM Orientation Event** - Dispersions in ability to orient the CM correctly for touchdown may result in unacceptable crew loads:

- Unclear if dynamics due to issues such as swivel friction, parachute dynamics, hang angle, and available thruster torque are acceptable.
- Not yet demonstrated acceptable Y-axis (cross spine) accelerations for all crew members.

F-8. **C8 (LM 604) - Drogue Stabilization** - During a pad abort scenario, timeline may be insufficient to detect a failed drogue to allow deployment of the back-up drogue:

- Residual attitude and rates, potentially high due to pad abort, may hamper deployment of main chutes.
- Detection scheme for failed drogue is unclear.

F-9. **C9 (TS-LRS-001) - Impact Survivability** – The TS-LRS001 baseline could sustain impact or puncture from ground terrain that may damage critical aft bay components and pose safety risk and/or egress hazard.

- Tanks and unfired retrorockets may be vulnerable to puncture due to jettison of heat shield which would have served as a protective barrier

The LM604 retrorocket pack may re-contact the capsule and pose safety risk

- Retrorockets (used or unspent) may damage up-righting devices, location aids, or egress hatch.

F-10. **C10 (TS-LRS-001) – Heat Shield Separation -** Potential for heat shield contact and damage of retrorocket nozzles on pad abort scenarios:

- Mars lander heritage heat shield separation technique had low clearance margins at high attitude rates.

Radar may track heat shield for up to 1,300 feet after separation and may prevent timely lockup on ground for an on pad abort scenario.

8.1.2 NESC Recommendations for Phase I - Comparison of 604, TS-LRS001, and Apollo LRS

R-1. C2 (LM 604) - Retrorocket Extraction – If the retrorocket system is to remain as part of the Project baseline, then utilize ejection mechanisms or other deployment aids; increase volume available to this system in the forward bay in order to accommodate devices. **(F-1)**

- Consider strong design bias toward storing (and therefore deploying) retrorocket in an upright position in the forward bay in order to minimize deployment complexity.
- Consider placement of retrorockets in location that does not require dynamic deployment.

However, the NESC team strongly recommends that the Apollo parachute architecture be used since it is better understood and characterized based on its heritage.

R-2. C3 (LM 604, TS-LRS-001) - Winds and Residual Horizontal Velocity - Conduct forecast reliability study. ***(F-2)***

- Wind speeds restrictions may need to be reduced below 31 fps to reduce the risk of an incorrect forecast.
- Evaluate whether the CxP paradigm of having at least (1 of 6) sites available still holds with more stringent wind forecast restrictions.
- Implement LRS architecture that restricts landings to low winds, but design CM to be more tolerant to winds.
- Decision not to use retrorockets for pad abort is inconsistent with NESC Land versus Water Assessment recommendation to preserve land-landing and ensure crew safety.
- Perform thorough analysis of the LM 604 retrorocket firing dynamics to understand potential impact of further aggravating horizontal velocity situation. Conduct study

of the TR-LRS001 regarding performance dispersions on horizontal retrorockets, consider limiting use to high winds.

R-3. C4 (LM 604 and TS-LRS-001) - Retrorocket Firing Chain **-** Perform error budget analysis, and chose ignition altitude and proper retrorocket sizing to ensure proper touchdown conditions across range of dispersions. ***(F-3)***

- Verify that CM impact attenuation system capable of absorbing dispersions in an acceptable manner.
- Consider sustainer retrorocket burn, thrust tailoring, or thrust termination techniques.
- Develop requirements for radar (or equivalent) as soon as possible.
- Ensure proper field of view for sensor elements.
- Consider use of retrorockets for pad abort to avoid crew injury for contingency land-landing scenarios.

R-4. C1 (LM 604) - Main Chute Extraction Recommendation - Consider independent extraction for each of the main canopies. ***(F-4)***

R-5. C5 (LM 604 and TS-LRS-001) - Apex Cover Separation **-** Design separation scheme to ensure that cover will clear capsule without contact, and then be laterally translated out of wake flow. ***(F-5)***

- If a pilot chute is required, consider a time delay method in mortar firing to allow it to clear the docking tunnel.
- Conduct study to determine possible safety risks to ground crew and civilian population.

R-6. C6 (LM 604) - Retrorocket Plume Impingement **-** Conduct exhaustive plume analysis, including acoustics, and determine adequacy of separation distance between capsule and retrorockets. ***(F-6)***

- Verify adequacy of riser attachment locations relative to the retrorocket nozzles
- Consider adding requisite retrorocket plume protective devices for riser lines and exposed components on forward deck.

R-7. C7 (LM 604 and TS-LRS-001) CM Orientation Event - Accelerate modeling efforts and testing to define system design requirements in this area. ***(F-7)***

R-8. C8 (LM 604) - Drogue Stabilization - Revisit Apollo Program heritage data. ***(F-8)***

- Dual drogue deployment is not materially more susceptible to deployment entanglement than single drogue system.
- Consider parallel drogue deployment at divergent angles consistent with the heritage Apollo parachute subsystem design.

R-9. C9 (TS-LRS-001) - Impact Survivability **-** Consider protective structural elements to mitigate risk of impact to aft-bay or consequences of retaining heat shield. ***(F-9)***

- Consider design of protective elements that allow for "high" horizontal velocity, even with use of horizontal retrorockets.
- Consider method to safe unfired pyros at time of touchdown.

R-10. C10 (TS-LRS-001) - Heat shield Separation **-** Increase energy in separation devices to be robust to high attitude rates. ***(F-10)***

- Add protection bumpers or other guards near retrorocket nozzle locations and consider heat shield lockup scenario when selecting altimetry architecture.

8.2 Phase II - Integrated LRS Risk Assessment

The Findings, Observations, and NESC Recommendations for each of the six Phase II tasks are presented.

8.2.1 Task 1: Entry, Descent, and Landing System Quantitative Risk Assessment Findings, Observations, and NESC Recommendations

8.2.1.1 Task 1 Findings and Observations

F-1. The 606 design uses parachutes to make sure that the FBC is out of the way for drogue parachute deployment. Parachute system reliability is a risk driver and having a requirement for such a system significantly increases the risk to the CM.

F-2. Task 3 of this assessment presented the predictability of horizontal winds at the landing site poses some risk in that the CMs horizontal landing speed could be exceeded due to mispredicted winds, potentially contributing to an increased PLOC.

F-3. The landing systems may experience reduced capability due to failures.

8.2.1.2 Task 1 NESC Recommendations

R-1. Improved FBC Release (Apex cover) - Ensure the FBC will not interfere with drogue chute deployment with adequate reliability (i.e., without parachutes) and prevents CM re-contact (including main parachutes). ***(F-1)***

R-2. Increased Horizontal Velocity Attenuation - Protect against unpredicted high horizontal winds / gusts. ***(F-2)***

- Horizontal velocity attenuation or increased CM capability will reduce the main risk driver for land landing systems, and provide margins that could be used to increase stability of the CM during landing.

R-3. Improved Occupant Protection – Improve crew protection as a functional redundancy for landing system faults (e.g., heat shield separation, retrorockets, airbags, etc.). ***(F-3)***

- Risk analysis has shown that active landing attenuation systems are susceptible to failure. Improved protection for the crew provides additional safeguards for unforeseen failure modes that may occur.

8.2.2 Task 2: Landing System T&V Data Analysis

8.2.2.1 Task 2 Findings

F-4. Logical evolution of early test plans in place for parachute and airbag subsystems will likely result in a robust T&V strategy for design certification of those individual subsystems:

- Current focus is on early developmental testing to understand design space, not on long-term T&V planning.
- Early developmental testing strategy appears to be robust and well conceived.

F-5. Further investigation is warranted in the area of *integrated* LRS evaluation:

- Unclear to as to which Orion Project element (either NASA or LM) has been charged with evaluating end-to-end LRS performance, including interactions between subsystems and environments.
- Current plans to evaluate end-to-end performance of LRS are dependent on the utilization of a few major flight test opportunities (e.g., PA-1, AA-1, etc.).
  - Although these flight tests are valuable, they will not provide enough opportunities to exercise integrated LRS system under expected range of dynamic conditions.
  - Unclear if Orion Project has plans to add additional flight-like test opportunities dedicated toward evaluation of integrated, end-to-end LRS performance.

8.2.2.2 Task 2 NESC Recommendations

R-4. Explicitly add a test program to exercise end-to-end performance of LRS with emphasis on interactions between subsystems: ***(F-4 and F-5)***

- Utilize air drops of LRS and CM hardware with flight realistic geometry and performance characteristics.
- Executed across a wide range of dynamic conditions bounding expected attitudes, rates, and winds for nominal and abort landings to demonstrate system design margins.
- Coupled to an integrated performance modeling task to extend the number of cases that can be evaluated.

R-5. Formulate a working group charged with the responsibility for verification of end-to-end LRS performance with emphasis on subsystem-to-subsystem and subsystem-to-CM interactions. ***(F-4 and F-5)***

R-6. Adopt a strategy of developing specific LRS tests based on evaluation and verification needs as opposed to forcing the verification plan to conform to already existing "all encompassing" tests. ***(F-4 and F-5)***

R-7. T&V Scenario for FBC Release: ***(F-4 and F-5)***

- Ensure that FBC can separate without striking and damaging forward bay components.
- Ensure that FBC does not come back and strike capsule at a later time.
- Ensure that FBC release does not induce adverse attitude rates on capsule that may affect downstream events such as parachute deployment.

R-8. T&V Scenario for Parachute Extraction and Deployment: ***(F-4 and F-5)***

- Ensure that capsule attitude, rates, physical configuration, and operating characteristics do not interfere in any way with chute extraction and deployment
- Ensure that drogue parachute can stabilize capsule.
- Ensure that capsule and components on upper deck can still function after exposure to parachute opening loads.
- Ensure that parachute deployment chain of events does not result in adverse attitude or rates affecting downstream events.
- Ensure that each component of the LRS satisfies its design requirements.

R-9. T&V Scenario for heat shield Jettison (if required): ***(F-4 and F-5)***

- Ensure that heat shield can separate without striking and damaging aft bay components.
- Ensure that heat shield does not come back and strike the capsule at a later time.
- Ensure that the jettisoned heat shield does not interfere with downstream events such as radar acquisition of the ground.

R-10. T&V Scenario for Parachute Descent: ***(F-4 and F-5)***

- Ensure that capsule attitude and dynamics under parachute does not result in adverse conditions for landing.
- Ensure that RCS thruster firings are effective in orienting capsule
- Ensure that RCS thruster firings and/or venting of residual gasses does not damage or degrade the parachute or airbag materials.

R-11. T&V Scenario for Airbag Inflation (if required): ***(F-4 and F-5)***

- Ensure that airbags can be extracted and inflated without damaging components in the aft bay

- Ensure that the inflated airbags do not interfere with other component functions in the aft bay and vice versa.

R-12. T&V Scenario for Landing and Impact (for water or land): ***(F-4 and F-5)***

- Ensure that impact loads are handled properly by entire end-to-end attenuation chain (e.g., airbags, structure, crew couch, and suit).
- Ensure that impact does not compromise structural integrity.
- Ensure that parachute dynamics during landing and impact process do not result in unexpected and adverse consequences.
- Determine through test and analysis system performance in off- nominal and failure case conditions.

8.2.3 Task 3: Landing Site Accessibility and Availability Data Analysis Findings, Observations, and NESC Recommendations

8.2.3.1 Findings

F-6. The CxP's land-landing site network provides high degree of physical access.

F-7. 14 percent reduction in L/D results in 25 percent to 30 percent loss of individual site access.

F-8. Raise maneuvers enable a significant portion of network access:

- 50 percent for L/D of 0.35, 85 percent for L/D of 0.30.
- Raise required for docking module disposal - otherwise, SM deorbit would be preferred.

F-9. Night restrictions will reduce access and create periodic network gaps.

F-10. Separation between landing opportunities for ISS missions is generally measured in days:

- Requires treating each access as a unique opportunity.
- ISS support missions unlikely to undock without high probability of deorbit.

F-11. No obvious CONUS land sites to support return from 28.5 degree orbits assuming no delta-v available from SM.

F-12. The SLAAM tool allows the weather (primarily horizontal winds and gusts) to be included to show effects on landing opportunities.

8.2.3.2 NESC Recommendations

R-13. Implement forecasting tools and procedures at each candidate land-landing to ensure capability is understood when operations are required. ***(F-6 through F-12)***

R-14. Consider implementing additional crew protection in anticipation of misforecast of landing site winds / gusts. ***(F-6 through F-12)***

R-15. Evaluate supplemental contingency crew protection as a means of avoiding operationally over constraining wind placards in the near term. ***(F-7, F-8)***

R-16. Develop a test program that can accommodate ISS support schedules and be prepared to capitalize on performance envelope expansion opportunities as they emerge. ***(F-7, F-11)***

R-17. Select water based landing location that takes advantage of ascending and descending pass opportunities. ***(F-7, F-11)***

8.2.4 Task 4: CM Roll Control in Preparation for Landing Data Analysis Finding and NESC Recommendation

8.2.4.1 Task 4 Finding

F-13. Program tests show that the CEV Project CM RCS has sufficient torque to meet the ±30 degree roll requirement with current parachute harness / riser designs.

8.2.4.2 Task 4 NESC Recommendation

R-18. Endorsed the use of roll control: ***(F-13)***

- Some form of roll control is useful to orient the vehicle Z plane with the direction of travel to maximize crew safety
- Limited cabin volume and minimal human impact acceleration tolerance in the Y axis (lateral impacts)
- During water-landings the CM can be oriented to minimize crew impact accelerations, which supports meeting reduced impact acceleration requirements for de-conditioned crew.

8.2.5 Task 5: Parachute Release Times during Land-Landing Findings and NESC Recommendation

8.2.5.1 Findings

F-14. For landing conditions where there is a horizontal wind, retaining the parachutes has a detrimental effect on CM stability since the drag force on the parachutes can pull the vehicle over.

F-15. The effect of rigging and parachute flexibility has minimal effect on the acceleration and roll response so that the trends reported should be applicable to most parachute system designs.

8.2.5.2 Task 5 NESC Recommendation

R-19. Require an automated parachute release system. ***(F-14 and F-15)***

- An automated system is required since the release may be required to occur within 0.50 seconds of touchdown, which is not enough time for a crew operated manual release.
- An automated release system would be a critical function which must ensure no unplanned release.

8.2.6 Task 6: Crew Protection System Enhancements Data Analysis Findings and NESC Recommendations

8.2.6.1 Findings

F-16. The FEA modeling approach shows promise as a tool for seat designers.

F-17. In addition to developing tools, it is important that a practical mean exist for implementing these design solutions.

F-18. The Brinkley Dynamic Response Method criteria define an acceptable environment for crews restrained in a specific way. It does not provide insight into additional or modified crew restraint systems.

8.2.6.2 Recommendations

R-20. Development and adoption of contemporary design tools and techniques is necessary. ***(F-16)***

- The Brinkley Dynamic Response Method criteria define an acceptable environment for crews restrained in a specific way. It does not provide insight into additional or modified crew restraint systems.
- Use of FEA and ATD tests allow designers to evaluate the effectiveness of alternate restraint systems.

R-21. Assuming that the potential for unplanned landings on land cannot be eliminated for a CM configured for water penetration or other compromised landing configurations, additional emergency crew protection is highly desirable. ***(F-17)***

R-23. Develop practical methods for implementing additional crew protection appear realistic and should be developed (e.g., lateral support). ***(F-17)***

9.0 Alternat e Viewpoints

There were no alternate viewpoints.

10.0 Other Deliverables

There were no other deliverables.

11.0 Lessons Learned

There were no lessons learned.

12.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

13.0 Acronyms List

AAMRL	Armstrong Aerospace Medical Research Laboratory
AFB	Air Force Base
ATD	Anthropomorphic Test Devices
CEV	Crew Exploration Vehicle
CEVPO	CEV Project Office
CM	Crew Module
CSI	Chest Severity Index
CxP	Constellation Program
DR	Dynamic Response
DRI	Dynamic Response Index
FBC	Forward Bay Cover
FEA	Finite Element Analysis
GEM	Government Equipment and Materials
GN&C	Guidance Navigation and Control
HSIR	Human System Integration Requirements
JPL	Jet Propulsion Lab
L/D	Lift to Drag Ratio
LAS	Launch Abort System
LEO	Low Earth Orbit
LM	Lockheed Martin
LOC	Loss of Crew
LRS	Landing and Recovery System
MMOD	Micro Meteoroid Orbital Debris
NESC	NASA Engineering and Safety Center
NM	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
NRB	NESC Review Board
PDR	Preliminary Design Review
PLOC	Probability of Loss of Crew
RAC-3	Requirements Analysis Cycle-3
RCS	Reaction Control System
RID	Rear Impact Dummy
RTE	Return to Earth
SID	Side Impact Dummy
SLAAM	Spacecraft Landing Accessibility and Availability Model
SM	Service Module
STK	Satellite Toolkit
T&V	Test and Verification
TIM	Technical Interchange Meeting
ZBV	Zero Based Vehicle

14.0 Ref erences

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Volume II Appendices

Appendix A. Crew Exploration Vehicle Integrated Landing and Recovery Evaluation

Appendix B. Task 2 T&V Assessment

Appendix C. Task 1 Integrated Entry, Descent and Landing Risk Matrix

Appendix A. Crew Exploration Vehicle Integrated Landing and Recovery Evaluation

06-060-E
Crew Exploration Vehicle Integrated Landing and Recovery Evaluation
(Phase 1, 604 vs. TS-LRS001)

John Baker

Wayne Lee

7 December 2006

This briefing is for status only and does not represent complete engineering data analysis

Agenda

- Team Composition
- Task Charter and Assumptions
- Executive Summary
- Background Information on Evaluated Configurations
- Methodology of Approach
- Detailed Discussion of Concerns
- Summary

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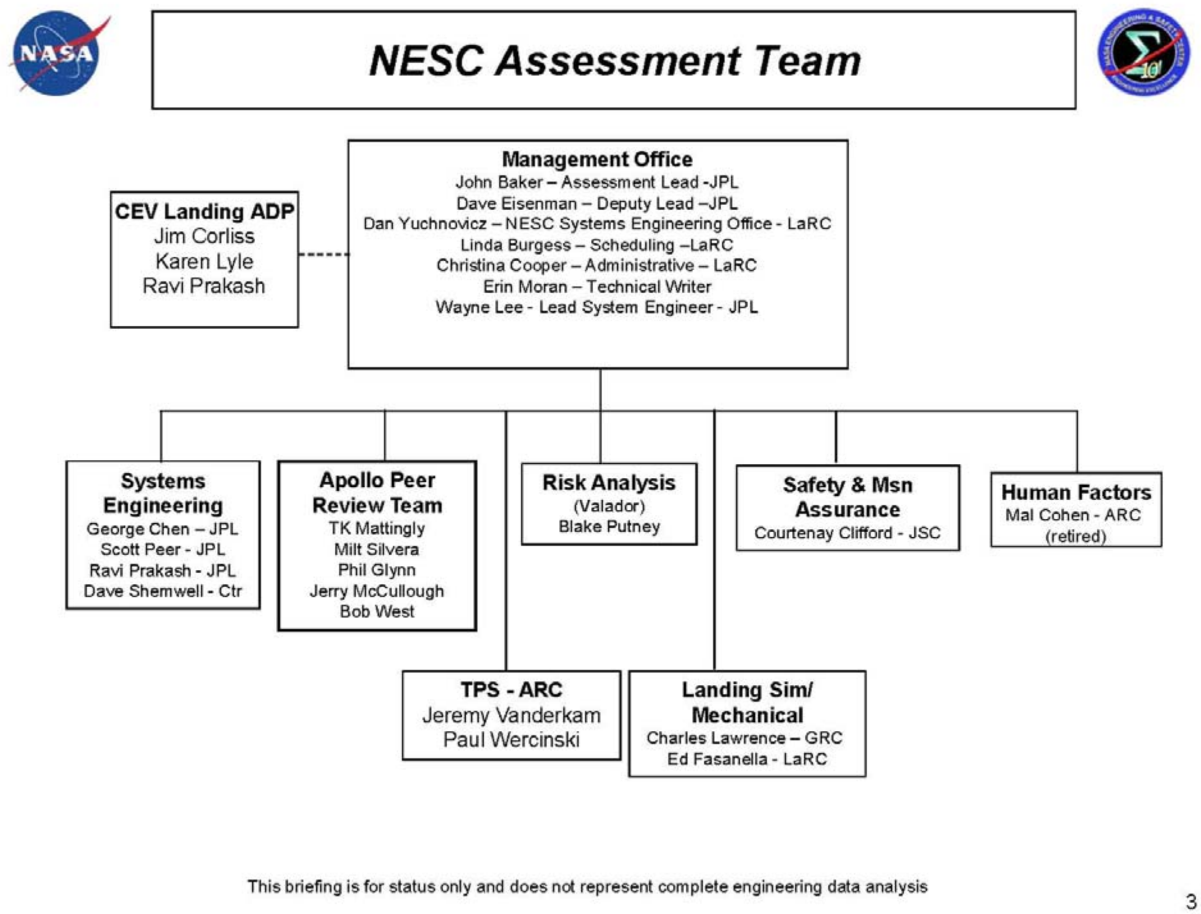
NESC Assessment Team
Management Office
John Baker – Assessment Lead -JPL
Dave Eisenman – Deputy Lead –JPL
Dan Yuchnovicz – NESC Systems Engineering Office - LaRC
Linda Burgess – Scheduling –LaRC
Christina Cooper – Administrative – LaRC
Erin Moran – Technical Writer
Wayne Lee - Lead System Engineer - JPL
CEV Landing ADP
Jim Corliss
Karen Lyle
Ravi Prakash
Systems Engineering
George Chen – JPL
Scott Peer - JPL
Ravi Prakash - JPL
Dave Shemwell - Ctr
Apollo Peer Review Team
TK Mattingly
Milt Silvera
Phil Glynn
Jerry McCullough
Bob West
Risk Analysis
(Valador)
Blake Putney
Safety & Msn Assurance
Courtenay Clifford - JSC
Human Factors
Mal Cohen - ARC
(retired)
TPS - ARC
Jeremy Vanderkam
Paul Wercinski
Landing Sim/ Mechanical
Charles Lawrence – GRC
Ed Fasanella - LaRC
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Task Objectives and Assumptions

- Objective was to assess TS-LRS001 and 604 designs for the CEV landing system with respect to risk factors potentially leading to severe injury or loss of crew
- Focus was on reliability; mass, volume, cost, complexity were secondary considerations unless obvious concern existed
- RAC-3 (requirements analysis cycle) results not yet factored because task was run in parallel with RAC-3 activities
- Assessment relied on existing design and performance data from NASA and LM CEV teams; insufficient time for independent analysis
- Due to the early stage of development, insufficient detail exists for a numerical risk analysis or reliability calculation; two designs compared qualitatively for risk concerns

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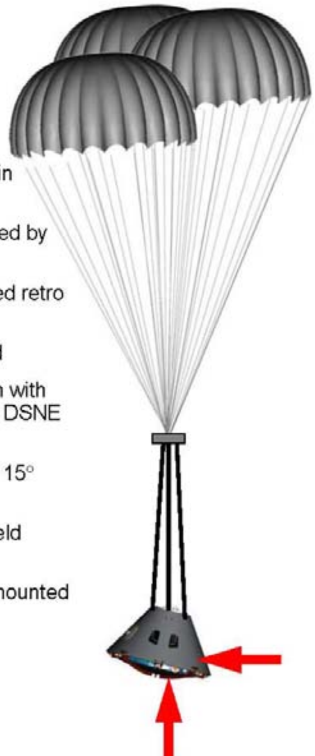
Configuration Comparison

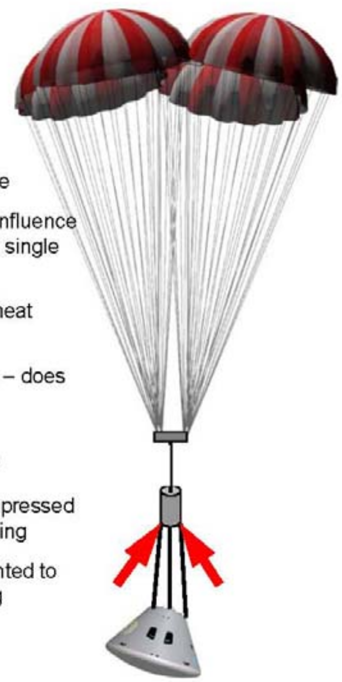
TS-LRS001

- 2 drogues deployed in parallel
- 3 parachutes extracted by independent pilots
- Vertical base-mounted retro rockets
- Released heat shield
- Horizontal propulsion with four rockets – meets DSNE wind requirements
- Toe-in hang angle of 15°
- Crushable structure exposed by heat shield release
- Altimeter antennas mounted under heat shield



604

- 1 prime drogue, backup deployed if prime failed
- 4 parachutes extracted simultaneously by drogue
- Vertical retro at chute confluence on risers above capsule, single gas generator
- Retained, but unlocked heat shield
- No horizontal propulsion – does not meet DSNE wind requirements
- Toe-in hang angle of 20°
- Crushable structure compressed by heat shield upon landing
- Altimeter antennas mounted to confluence rocket casing



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Architecture Comparison with Apollo

Feature	Apollo	604	TS-LRS001
Parachue			
Drouge Chute	2 deployed in parallel via mortars	1 prime via mortar, backup drogue deployed if FSW detects prime has failed	2 deployed in parallel via mortars
Main Chutes	3 ring sails, 83.5' diameter	4 ring sails	3 ring sails, 122.6' diameter
Main Deployment	Extracted by 3 independent mortar-fired pilots	Extracted simultaneously by single drogue	Extracted by 3 independent mortar-fired pilots
Heatshield			
Type	Avcoat	PICA	PICA
Retainment	Retained for splashdown, load path same as for entry	Retained for touchdown, but unlocked from entry load path prior to touchdown	Jetttisoned after main chute deployment
Terminal Descent ACS			
Type	Passive	Active orientation required, uses swivel at chute confluence	Active orientation required, swivel TBD
Radar			
Altimetry	N/A	(TBD) Radar	(TBD) Radar or LIDAR
Velocimetry	N/A	(TBD) Doppler or GPS	(TBD) Doppler or GPS
Avonics Location	N/A	Within capsule	Within capsule
Antenna Location	N/A	At chute confluence, mounted to retrorocket casing	At bottom of capsule, under the heatshield
Retrorockets			
Vertical	N/A	1 rocket w/ 6 nozzles, (TBD) thrust	4 rockets, 7000 lbs thrust each
Horizontal	N/A	N/A	4 rockets, 9400 lbs thrust each
Mounting Location	N/A	On risers, at parachute confluence point above capsule	At base of capsule, under the heatshield

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Executive Summary

- **Confluence retrorocket pack is viable, but will require extensive development and validation program**
  - Primary concerns include deployment without contacting crew module, rocket plume impingement, and retro recontact after touchdown
  - Base mounted system preferred to reduce implementation risks, but may result in slight increase in risk at impact if heatshield jettison option is chosen
- **Current state-of-the-art techniques for pyrotechnic safe and inhibits can reliably prevent premature heatshield separation**
  - Reliability of planned heatshield separation is not a discriminator between the two design concepts
- **Insufficient data has been produced to demonstrate that not including horizontal rockets, and relying on operational wind limits, is a viable design option**

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Executive Summary (cont.)

- Reliability and robustness of apex cover separation and CM clearance system needs to be improved
- Use of single extraction device for all main chutes viewed as potential single point failure
  - Recommend each main chute be independently deployed
- No obvious safety related discriminators found in the use of 3 vs. 4 main chutes

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8

Evaluation Paradigm

- **EDL (post-entry) decomposed into 5 major sequences all of which must succeed**
  - Parachute deploy sequence
  - Heatshield unlock or jettison sequence
  - Terminal descent sequence
  - Retrorocket firing sequence
  - Touchdown
- **Each sequence was further decomposed into set of sub-events or conditions, all of which must succeed in order for the sequence to be successful**
- **Each sub-event was evaluated for design vulnerabilities with the potential to cause severe injury or loss of crew**

Evaluation Paradigm (cont.)

- **Design vulnerabilities considered in the qualitative evaluation process include:**
  - Brittleness (sensitivity to design assumptions) of performance to flight dynamics, environmental factors, or operating conditions
  - Potential to be a common cause failure source or susceptibility to a common cause failure
  - Lack of redundancy coupled with potential reliability issues
  - Steep drop off in performance under off-nominal conditions
- **Color code assigned to each sub-event based on level of concern relative to the above list of vulnerabilities**

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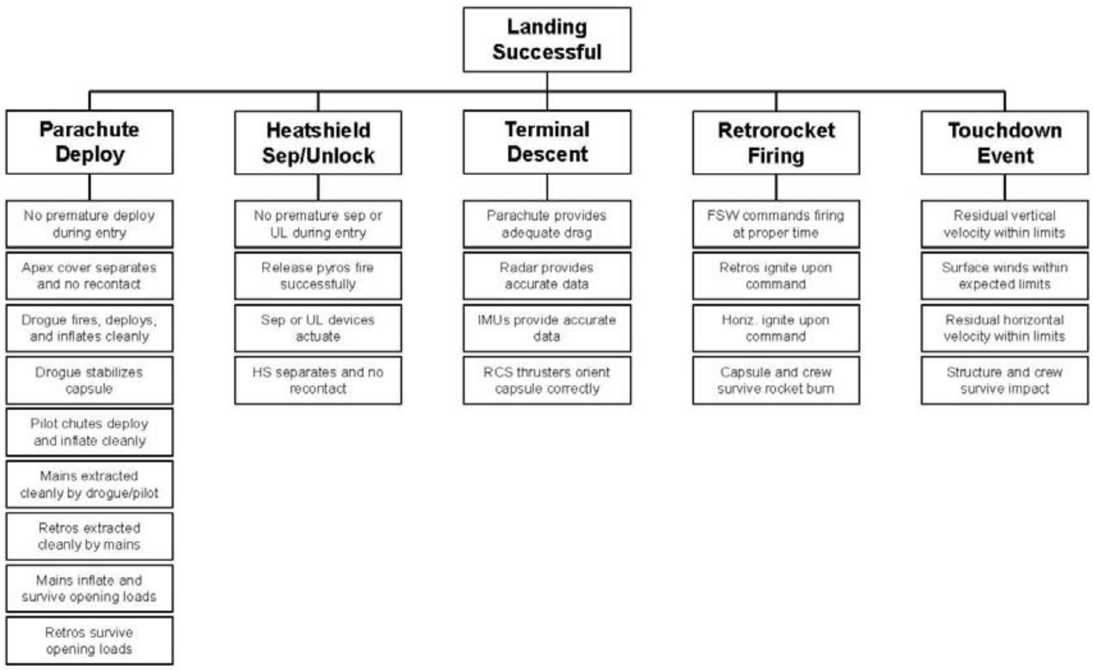
Functional Decomposition Map



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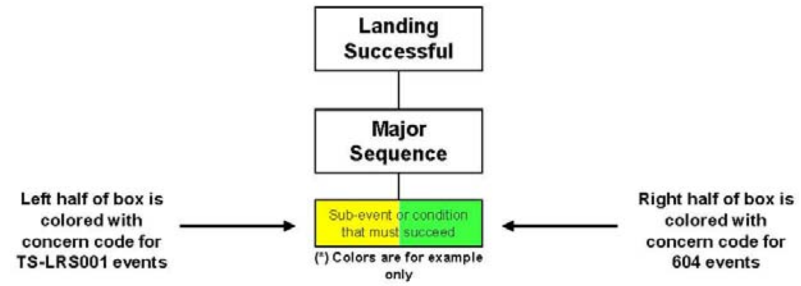
Vulnerability Concern Color Code



- Green: **Low concern; function deemed to be robust**
- Yellow: **Moderate concern; design concept may be adequate but robustness improvements should still be considered**
- Red: **Active concern; recommend proactive measures to increase robustness and/or change design**
- White: **Function not applicable to the design**

(*) Concern colors assigned per sub-event under the assumption that all previous sub-events and sequences are successful

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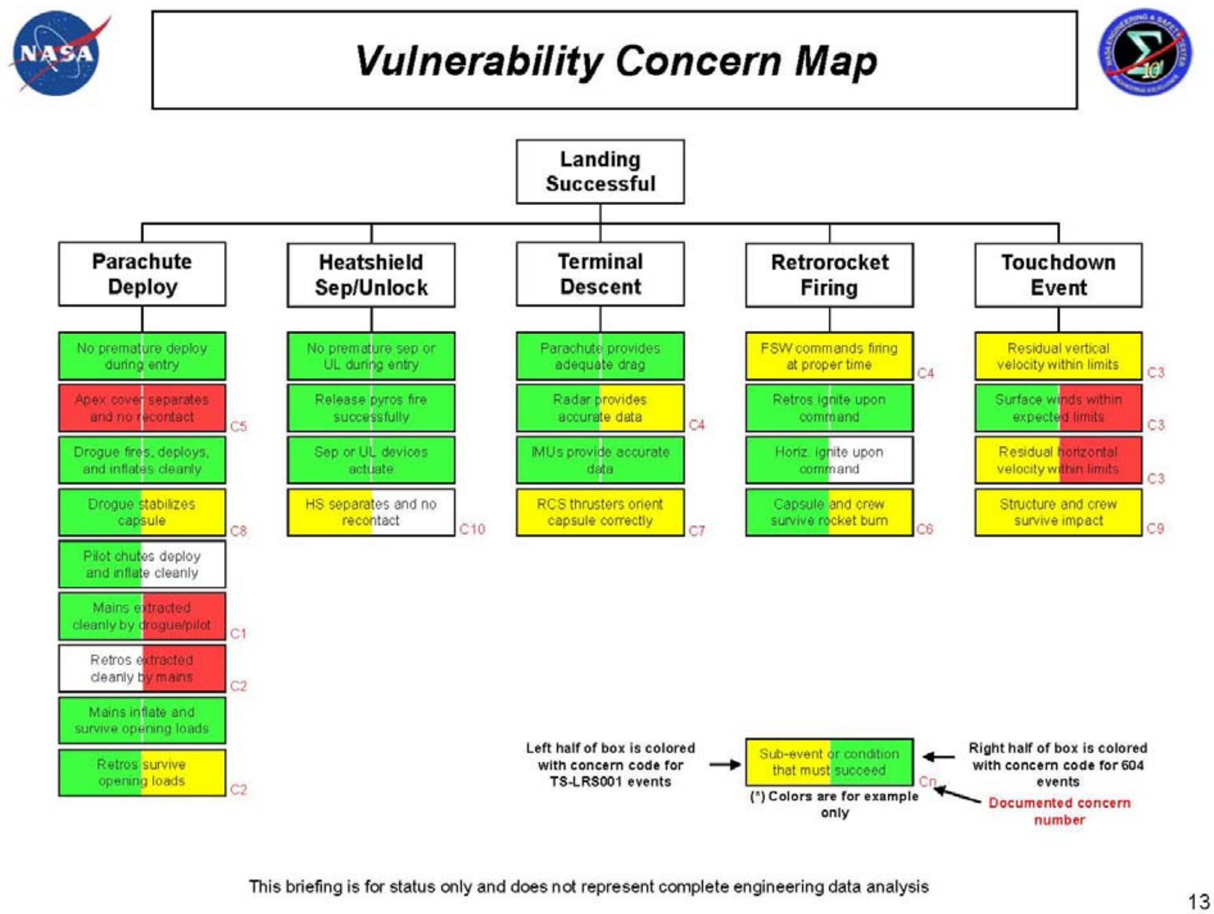
Vulnerability Concern Map
Landing Successful
Parachute Deploy
Heatshield Sep/Unlock
Terminal Descent
Retrorocket Firing
Touchdown Event
No premature deploy during entry
Apex cover separates and no recontact
C5
Drogue fires, deploys, and inflates cleanly
Drogue stabilizes capsule
C8
Pilot chutes deploy and inflate cleanly
Mains extracted cleanly by drogue/pilot
C1
Retros extracted cleanly by mains
C2
Mains inflate and survive opening loads
Retros survive opening loads
C2
No premature sep or UL during entry
Release pyros fire successfully
Sep or UL devices actuate
HS separates and no recontact
C10
Parachute provides adequate drag
Radar provides accurate data
C4
IMUs provide accurate data
RCS thrusters orient capsule correctly
C7
FSW commands firing at proper time
C4
Retros ignite upon command
Horiz. ignite upon command
Capsule and crew survive rocket burn
C6
Residual vertical velocity within limits
C3
Surface winds within expected limits
C3
Residual horizontal velocity within limits
C3
Structure and crew survive impact
C9
Left half of box is colored with concern code for TS-LRS001 events
Sub-event or condition that must succeed
Cn
(*) Colors are for example only
Right half of box is colored with concern code for 604 events
Documented concern number
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C1 - Main Chute Extraction

- **Concerns (604)**
  - Use of a single drogue to extract all main chutes in current design involves rigging the mains together in a way where hang-up of a single chute has the potential to fail the extraction of all the others
- **Recommendations (604)**
  - Consider independent extraction for each of the main canopies

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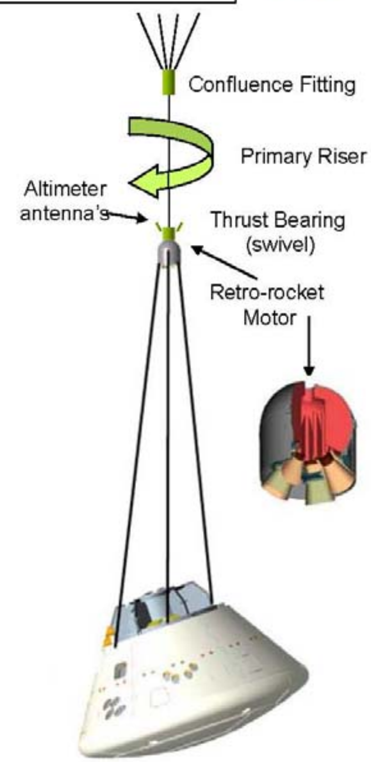
C2 - Retrorocket Extraction

- **Concerns (604)**
  - **Design susceptible to rocket/capsule contact and damage during extraction, especially under high-rate conditions**
    - Risk of damage to radar antennas, rocket body/nozzles, and other components mounted near apex of vehicle
    - Risk of severing pyro firing lines and radar avionics to antenna RF transmission lines
  - **Extraction failure may result in failure of main chute to deploy properly due to series connection between the two subsystems**
  - **Mars heritage benefits toward concept feasibility not applicable due to utilization of rate-limiting devices to slowly lower Mars lander away from confluence rockets after chute inflation**



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C2 - Retrorocket Extraction (cont.)

- **Recommendations (604)**
  - Utilize ejection mechanisms or other deployment aids; increase volume available to this system in the forward bay in order to accommodate devices
  - Consider strong design bias toward storing (and therefore deploying) retrorocket in an upright position in the forward bay in order to minimize deployment complexity
  - Consider placement of retrorockets in location that does not require dynamic deployment
  - Evaluate scope and schedule implications for test and verification program; likely to be both extensive and expensive

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C3 - Winds & Residual Horiz. Velocity

- **Concerns (604)**
  - Insufficient data has been produced to demonstrate that not including horizontal rockets in the design is viable
    - Operational limits of 31 ft/s (18 knots) is too close to vehicle limits for crew safety and is relatively low; DSNE requirement > 45 fps
    - Consequences of roll over are not well understood and will be potentially severe
  - Without horizontal velocity abatement, crew safety critically dependent on accuracy of 3-hour weather forecast
    - If weather forecast was 99.9% accurate, still non-trivial risk for possible roll over and threat to crew safety
  - (TS-LRS001) Use of horizontal rockets is not risk free
    - Mars experience is that performance dispersions and failure modes with horizontal rockets have potential to compound problem

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C3 - Winds and Horiz. Velocity (cont.)

- **Recommendations (Both)**
  - Conduct forecast reliability study
    - Wind speeds restrictions may need to be reduced below 31 ft/s in order to reduce risk of incorrect forecast
    - Evaluate whether paradigm of having at least 1 (out of 6) sites available still holds with more stringent wind forecast restrictions
  - Implement LRS architecture that restricts landings to low winds, but design capsule to be more tolerant to winds
    - Decision not to use retros for pad abort is inconsistent with NESC Land vs. Water study recommendation to preserve land landing
  - (604) Perform thorough analysis of retro firing dynamics to understand potential impact of further aggravating horizontal velocity situation
  - (TR-LRS001) Conduct study regarding performance dispersions on horizontal retrorockets, consider limiting use to high winds

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C4 - Retrorocket Firing Chain

- Concerns (Both)
  - Dispersions on retro burn completion conditions have potential to cause load limits to be exceeded
    - Difficult to control performance using high-impulse solids to deliver vehicle to near-zero velocity near the ground
    - Small knowledge errors in parameters such as thrust profile, altitude/velocity state, and attitude/rate state may lead to late firing, including impact prior to ignition
  - Retro firing time critically dependent on accuracy of altitude and velocity sensors, but viable device not yet selected
    - NESC understanding is that work is underway on this topic
  - (604) Radar antenna location on retro pack may result in degraded accuracy with potential to spoof ignition time calculation
    - Degradation due to antenna cant angle precluding nadir view of ground

Confluence Point Retro Firing

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C4 - Retrorocket Firing Chain (cont.)

- **Recommendations (Both)**
  - Perform error budget analysis, and chose ignition altitude and proper rocket sizing to ensure proper touchdown conditions across range of dispersions
  - Verify that capsule impact attenuation system capable of absorbing dispersions in an acceptable manner
  - Consider sustainer rocket burn, thrust tailoring or thrust termination techniques
  - Develop requirements for radar (or equivalent) as soon as possible
  - Ensure proper field of view for sensor elements
  - Consider use of retros for pad abort to avoid hard impact for land landings

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C5 - Apex Cover Separation

- Concerns (Both)
  - Post separation impact with vehicle has potential to cause severe damage
    - Current design is based on Apollo heritage of separation thrusters and pilot parachute
    - Apollo team was only able to provide limited satisfaction in meeting the requirements of no re-contact, even after extensive work
- Recommendations (Both)
  - Design separation scheme to ensure that cover will clear capsule without contact, and then be laterally translated out of wake flow
  - If a pilot chute is required, consider a simple time delay method in mortar firing to allow it to clear the docking tunnel first
  - Conduct study to determine possible safety risks to ground crew and civilian population

Extraction of apex cover from forward bay

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C6 - Plume Impingement

- **Concerns (604)**
  - Exhaust plume may be swept into riser lines or across the top of the capsule potentially resulting in safety related damage
- **Recommendations (604)**
  - Conduct exhaustive plume analysis, including acoustics, and determine adequacy of separation distance between capsule and retrorockets
  - Verify adequacy of riser attachment locations relative to the rocket nozzles
  - Consider adding requisite protective devices for riser lines and exposed components on forward deck

Plume impingement during test of LAARS system

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C7 - Capsule Orientation Event

- **Concern (Both)**
  - Dispersions in ability to orient capsule correctly for touchdown may result in unacceptable loads on crew
    - Unclear if dynamics due to issues such as swivel friction, parachute dynamics, hang angle and available thruster torque are acceptable
    - Not yet demonstrated acceptable y-axis (cross spine) accelerations for all six astronauts
- **Recommendations (Both)**
  - Accelerate modeling efforts and testing to define system design requirements in this area

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C8 - Drogue Stabilization

- **Concerns (604)**
  - During a pad abort scenario, timeline may be insufficient to detect a failed drogue and then deploy the back-up drogue
    - Residual attitude and rates, potentially high due to pad abort, may hamper deployment of main chutes
    - Detection scheme for failed drogue is also unclear
- **Recommendations (604)**
  - Revisit Apollo heritage data
    - NESC team opinion is that dual drogue deployment is not materially more susceptible to deployment entanglement than single drogue system
  - Consider parallel drogue deployment at divergent angles

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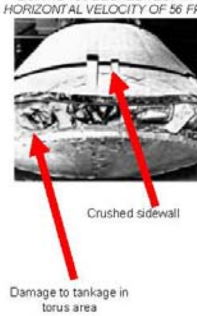
C9 - Impact Survivability

- Concerns
  - (TS-LRS001) Impact or puncture from rocks may damage critical aft bay components and pose safety risk and/or egress hazard
    - Tanks and unfired rockets may be vulnerable to puncture due to jettison of heatshield which would have served as protective barrier
  - (604) Retro pack may fall onto top of capsule and pose safety risk
    - Unspent retros (> 200 lbs) on water landing, or spent retros, may damage uprighting devices, location aids, or egress hatch

IMPACT DAMAGE TO CM 011 DURING 180 DEGREE TEST AT HORIZONTAL VELOCITY OF 56 FPS



- Recommendations (TS-LRS001)
  - Consider protective structural elements to mitigate risk of impact to aft-bay or consequences of retaining heatshield
  - Consider design of protective elements that allow for “high” horizontal velocity, even with use of horizontal rockets
  - Consider method to safe unfired pyros at time of touchdown

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C10 - Heatshield Separation

- **Concerns (TS-LRS001)**
  - Potential for heatshield contact and damage of retrorocket nozzles on pad abort scenarios
    - Mars heritage heatshield separation technique have had low clearance margins at high attitude rates
  - Radar may track heatshield for up to 400 meters after separation and may prevent timely lockup on ground on pad abort scenario
- **Recommendations (TS-LRS001)**
  - Increase energy in separation devices to be robust to high attitude rates
  - Add protection bumpers or other guards near rocket nozzle locations
  - Carefully consider heatshield lockup scenario when selecting altimetry architecture

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Summary

- Confluence retrorocket pack is viable, but will require extensive development and validation program
- Safety of heatshield separation is not a discriminator between the two design concepts
- Insufficient data has been produced to demonstrate that not including horizontal rockets, and relying on operational wind limits, is a viable design option
- Robustness of apex cover separation scheme should be improved
- Use of a single drogue to extract all main chutes is a potential single-point failure

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Appendix B. Task 2 T&V Assessment

Test and Verification Task Update - Orion LRS (06-060-E)

Phil Glynn
Christian De Jong
Wayne Lee
Jerry McCullough
Chester Ong
Bob West

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Background

- Purpose of task is to provide an independent assessment to the Orion project as to the set of activities that would comprise a complete T&V plan for EDL
- Project will be able to utilize the assessment as a guide during their task planning process
- Historically, T&V plans are not developed until the PDR time frame or after, but experience has demonstrated that early T&V planning can reduce overall risk
  - Reliability and scope/cost growth risk may be reduced if T&V assessment uncovers activities not previously identified
  - Design and schedule risk may be reduced if T&V assessment uncovers aspects of design that are difficult to verify
- Early work on T&V planning can be problematic due to lack of firm design requirements
  - T&V planning is further complicated by the fact that verification that all written requirements have been satisfied never leads to a complete verification story
- This task will utilize event-tree methodology to expose the items that must be verified in the absence of requirements

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Background (cont.)

- **Although EDL design for Orion will be unique, historical experience can be used to recommend verification activities because concepts under consideration have been used either on Apollo or at Mars**

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Verification Assumptions

- **Different types of verification exist**
  1. **Conducting activities to determine whether requirements make sense and that a concept is feasible**
  2. **Conducting activities to corroborate that the presumed external conditions encountered during flight are valid**
  3. **Conducting activities to determine whether the chosen design instantiation can withstand encountered flight environments**
  4. **Conducting activities to be certain that the chosen design instantiation has met its functional performance requirements**
  5. **Conducting activities to determine that the quality of a delivered flight article is such that it can be flown**
  6. **Conducting activities to ensure that simulation tools used for all of the above produce valid results**

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Verification Assumptions (cont.)

- **Although all types of verification are important, this task will primarily address type #4**
- **Verification types #2 and #3 will be addressed to the extent that the environments are central to the functional performance of the EDL hardware**
  - **Examples include aerodynamics, aerothermal, and winds**
  - **But not EMI/EMC, radiation, vibrations, etc.**

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Event Tree Methodology

- The event tree is a hierarchical method of functionally decomposing EDL into events and enumerating all the successful conditions required for "success"
  - Utilized by the Mars program because it was deemed not practical to enumerate EDL success using requirements
- EDL is first exapnded into major phases
  - Each phase is a regime of flight differentiated from the others based on similarity of the governing mode of motion
  - Pre-entry, Entry, Parachute Deployment, Parachute Descent, Landing
- Each phase is expanded into sequences
  - Sequences are high-level functions of the vehicle that typically require several subsystems working together to accomplish
  - Drogue deploy, heatshield separation, landing set-up, etc.

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Methodology (cont.)

- **Each sequence is expanded into discrete events**
  - **Events are typically subsystems performing a specific action**
  - **Canopy inflation, mortar firing, thruster firing, etc**
- **Each event is expanded into a set of conditions, all of which much succeed, in order for the event to succeed**
  - **For example, for pilot mortar firing, a required condition is that the parachute pack must be ejected at the proper velocity**
  - **In the absence of formal requirements, these conditions form a set of de facto requirements**
  - **Conditions are qualitative because design has not been finalized**

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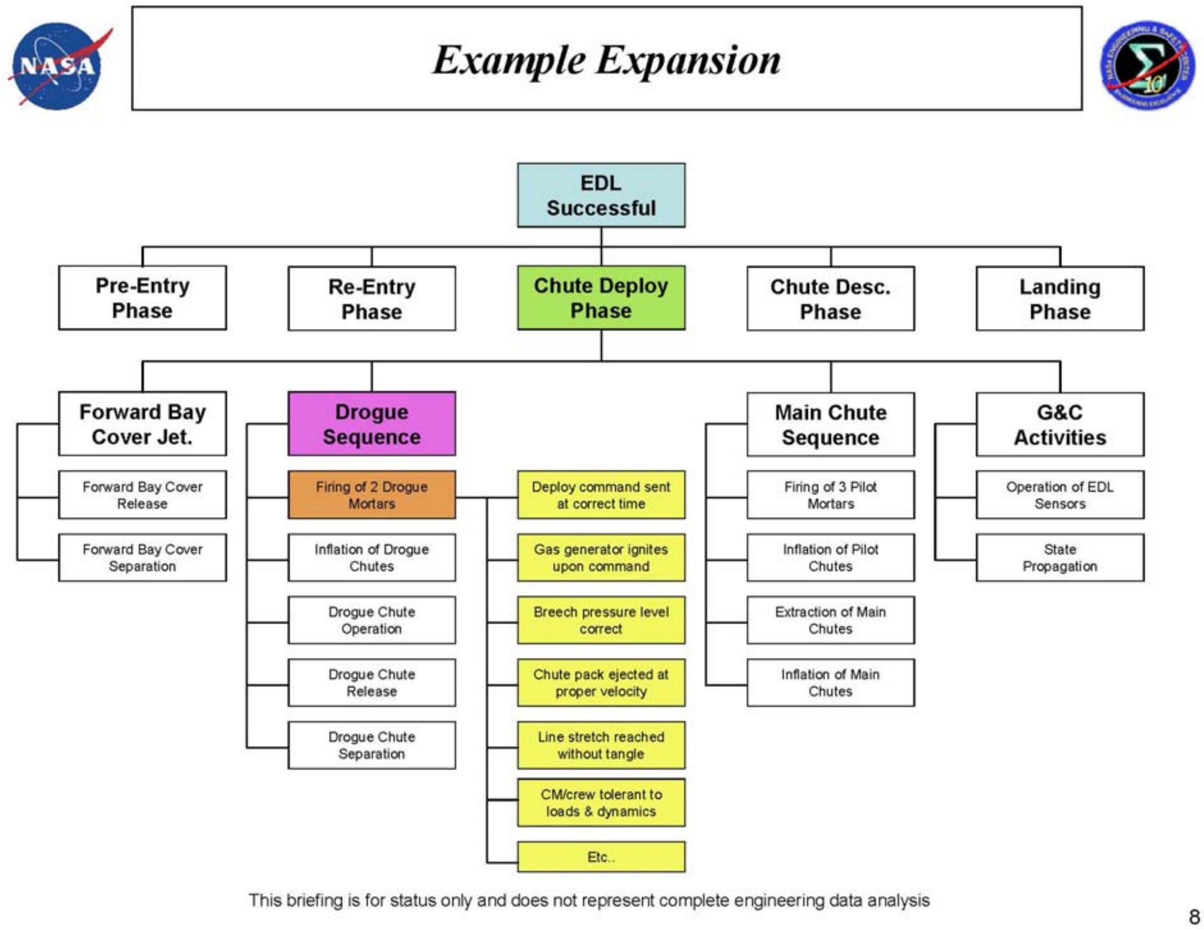

Example Expansion
EDL Successful
Pre-Entry Phase
Re-Entry Phase
Chute Deploy Phase
Chute Desc. Phase
Landing Phase
Forward Bay Cover Jet.
Forward Bay Cover Release
Forward Bay Cover Separation
Drogue Sequence
Firing of 2 Drogue Mortars
Inflation of Drogue Chutes
Drogue Chute Operation
Drogue Chute Release
Drogue Chute Separation
Deploy command sent at correct time
Gas generator ignites upon command
Breech pressure level correct
Chute pack ejected at proper velocity
Line stretch reached without tangle
CM/crew tolerant to loads & dynamics
Etc..
Main Chute Sequence
Firing of 3 Pilot Mortars
Inflation of Pilot Chutes
Extraction of Main Chutes
Inflation of Main Chutes
G&C Activities
Operation of EDL Sensors
State Propagation
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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
Chute Deploy					
	Upper Cone Jettison				
		Forward Bay Cover Release			
			Retention release command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	1001
			Retention device actuated upon command	(B,A) Retention device performance and characterization test	1002
			Sep devices actuate and impart desired velocity	(A) Sep device component performance and characterization test (B) Forward bay cover separation analysis (R) Full scale forward bay cover separation test	1003
			CM and crew tolerant to release forces and related dynamics	(B) Forward bay cover release shocks and loads transference analysis (A) Forward bay cover release shocks and loads transference test	1004
		Forward Bay Cover Separation			
			Cover clears capsule without contact	(A) Sep device component performance and characterization test (B) 6-DOF cover separation analysis (R) Full scale first motion separation test (R) Full scale dynamical aerial separation test	1005
			Cover flies away from capsule and no subsequent recontact	(B) Cover/vehicle trajectory analysis (B,R) Full scale dynamical aerial separation test	1006
	Drogue Sequence				
		Drogue Mortar Firing			
			Drogue deployment command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	2007
			Gas generator ignites and performs	(B) Gas generator characterization and performance test	2008
			Breech pressure within the mortar reaches the proper level within the allocated time	(B) Mortar closed bomb firing test	2009
			Chute pack ejected from mortar at proper velocity	(B) Mortar static fire test with cover (B) Mortar performance analysis (R) Drogue aerial deployment test	2010
			Drogue mortar cover clears capsule without contact	(B) Mortar cover stress analysis (B) Mortar static fire test with cover and upper cone mock up	2011
			Drogue mortar cover flies away from capsule and no subsequent recontact	(B) Cover/vehicle trajectory analysis (B) Drogue aerial deployment test	2012
			Chute pack reaches line stretch without hangup, tangle, or interference	(B) Mortar static fire test (B) Drogue aerial deployment test	2013
			Bag strips off properly	(B) Drogue aerial deployment test	2014
			Chute pack survives snatch load	(B) Drogue aerial deployment test (B) Drogue deployment loads analysis	2015
			Capsule and crew tolerant to mortar reaction loads and related dynamics	(B) Drogue ejection shocks and loads transference analysis (A) Drogue ejection shocks and loads transference test	2016
		Drogue Inflation			
			Drogues open and achieves full inflation under expected M/Q/AOA	(B) Drogue aerial deployment test	2017
			Drogues survive opening loads	(B) Drogue aerial deployment test	2018
			Capsule and crew tolerant to drogue opening loads and related dynamics	(B) Drogue inflation shocks and loads transference analysis (A) Drogue inflation shocks and loads transference test	2019

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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
		Drogue Operation			
			Drogue drag properties as expected	(B) Drogue aerodynamics performance characterization test	2020
			Drogues do not interfere with each other	(B) Drogue aerodynamics performance characterization test	2021
			Drogues stabilize capsule	(B) High fidelity terminal descent multi-body attitude dynamics analysis (R) Drogue/capsule interaction drop test	2022
		Drogue Release			
			Drogue release commanded at proper time	(B) Integrated avionics test bed and flight software sequence timing test	2023
			Line cutters actuate upon command and sever risers	(B) Line cutter performance and characterization test (B) Drogue aerial separation test	2024
		Drogue Separation			
			Risers clear capsule without hangup	(B) Drogue aerial separation test	2025
			Drogue parachute assembly flies away from capsule and no subsequent recontact	(B) Drogue aerial separation test	2026
	Main Chute Sequence				
		Pilot Mortar Firing			
			Pilot chute deployment command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	3027
			Gas generator ignites and performs	(B) Gas generator characterization and performance test	3028
			Breech pressure within the mortar reaches the proper level within the allocated time	(B) Pilot mortar closed bomb firing test	3029
			Chute pack ejected from mortar at proper velocity	(B) Pilot mortar static fire test with cover (B) Pilot mortar performance analysis (R) Pilot aerial deployment test	3030
			Pilot mortar cover clears capsule without contact	(B) Pilot mortar cover stress analysis (B) Pilot mortar static fire test with cover and upper cone mock up	3031
			Pilot mortar cover flies away from capsule and no subsequent recontact	(B) Cover/vehicle trajectory analysis (B) Pilot aerial deployment test	3032
			Chute pack reaches line stretch without hangup, tangle, or interference	(B) Pilot mortar static fire test (B) Pilot aerial deployment test	3033
			Bag strips off properly	(B) Pilot aerial deployment test	3034
			Chute pack survives snatch load	(B) Pilot aerial deployment test (B) Pilot deployment loads analysis	3035
			CM and crew tolerant to reaction loads and related dynamics	(B) Pilot ejection shocks and loads transference analysis (A) Pilot ejection shocks and loads transference test	3036
		Pilot Inflation			
			Chute fills with air under expected M/Q/AOA conditions and survives opening loads	(B) Pilot aerial deployment test	3037
			Pilot survives opening loads	(B) Pilot aerial deployment test	3038

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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
			CM and crew tolerant to pilot snatch and opening loads and related dynamics	(B) Pilot inflation shocks and loads transference analysis (A) Pilot inflation shocks and loads transference test	3039
		Main Extraction			
			Pilot chutes extract main chutes from forward bay and line stretch is achieved with no interference or entanglement	(B) Pilot/main aerial deployment test	3040
			Main pack survives snatch load	(B) Main aerial deployment test (B) Main deployment loads analysis	3041
		Main Inflation			
			Reefing cutter lanyards properly actuate the pyrotechnic delay functions, and cutters sever reefing lines	(B) Reefing cutter performance characterization test (B) Main aerial deployment test	3042
			Main chutes inflate properly during each reefing stage under expected M/Q/AOA conditions and survive opening loads	(B) Main aerial deployment test	3043
			CM and crew tolerant to main snatch and opening loads and related dynamics	(B) Main inflation shocks and loads transference analysis (A) Main inflation release shocks and loads transference test	3044
	GNC Activities				
		Sensor Operation			
			EDL sensors generate accurate data when subjected forces and dynamical transients during chute deploy phase	(A,B) IMU performance characterization test (R) IMU performance characterization analysis (B) Parachute to IMU loads transference analysis (A,R) Parachute deployment shock and loads characterization test	4045
		State Propagation			
			Attitude and pos/vel states propagated or estimated correctly when subjected forces and dynamical transients during chute deploy phase	(R) Integrated avionics test bed and flight software sequence test (B) Algorithm/software test bed (R) Parachute descent phase dynamics characterization test	4046
Chute Descent					
	Subsonic Flight				
		Chute Deceleration			
			Drag performance of main canopies is as expected, including canopy interference issues	(B) Main canopy aerodynamics performance characterization test	5047
			Stability of main chute cluster is as expected	(B) Main canopy aerodynamics performance characterization test	5048
			CM attitude and rates within tolerance within vicinity of ground	(B) High fidelity terminal descent multi-body attitude dynamics analysis (R) Parachute/capsule interaction drop test	5049
	Heatshield Jettison				
		Heatshield Release			
			Retention device activation command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	6050
			Retention device activates upon command	(B,A) Retention device performance and characterization test	6051
			Sep devices actuate and impart desired velocity	(A) Sep device component performance and characterization test (B) Heatshield separation analysis (R) Full scale heatshield separation test	6052

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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
			CM and crew tolerant to release forces and related dynamics	(B) Heatshield shocks and loads transference analysis (A) Heatshield shocks and loads transference test	6053
		Heatshield Separation			
			Heatshield clears capsule without contact	(A) Sep device component performance and characterization test (B) 6-DOF heatshield separation analysis (R) Full scale first motion separation test (R) Full scale dynamical aerial separation test	6054
			Heatshield flies away from capsule with no subsequent recontact, and moves far enough away within the allocated time to preclude ground sensing interference	(B) Heatshield/vehicle trajectory analysis (B,R) Full scale heatshield separation test	6055
	Landing Prep				
		Sensor Acquisition			
			Alt/vel sensors commanded to activate at the proper time	(B) Integrated avionics test bed and flight software sequence timing test	7056
			Alt/vel sensors achieve unambiguous lock on the ground within allocated time	(B) Radar characterization field test (B) Radar performance characterization laboratory test	7057
		Sensor Operation			
			Alt/vel sensors generate data that meets accuracy requirements in the presence of terrain effects and capsule dynamics	(B,A) Radar characterization field test (B,A) Radar performance characterization laboratory test (B) Modeled radar performance simulation	7058
		Roll Orientation Selection			
			GNC computes direction of horizontal motion and selects appropriate landing attitude	(B) Algorithm/software test bed (B) Comprehensive EDL trajectory and dynamics simulations (R) Integrated avionics test bed and flight software sequence test	7059
		Thruster Firing			
			Thruster firing command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	7060
			Thruster ISP and thrust properties are as expected	(B) ACS thruster characterization and performance test stand firings	7061
			No adverse plume impingement effects on CM	(B) Capsule plume impingement and vehicle configuration analysis (B) ACS thruster characterization and performance test stand firings (R) Thruster/capsule interaction test firing	7062
			Resultant torque on vehicle is as expected, including effects from chute risers	(B) High fidelity terminal descent attitude dynamics analysis (A) Thruster/capsule/riser interaction test	7063
			GNC control logic performs correctly in targeting and achieving final attitude conditions	(B) Algorithm/software test bed (B) High fidelity terminal descent attitude dynamics analysis (R) Integrated avionics test bed and flight software sequence test	7064
		Trigger Computation			
			GNC computes correct altitude/time to inflate airbags	(B) Algorithm/software test bed (B) Comprehensive EDL trajectory and dynamics simulations (R) Integrated avionics test bed and flight software sequence test	7065
			GNC computes correct altitude/time to fire horizontal rockets	(B) Algorithm/software test bed (B) Comprehensive EDL trajectory and dynamics simulations (R) Integrated avionics test bed and flight software sequence test	7066

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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
		Airbag Inflation			
			Retention release command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	7067
			Retention device actuated upon command	(B,A) Retention device performance and characterization test	7068
			Gas generator ignition or activation command sent at proper time	(B) Integrated avionics test bed and flight software sequence timing test	7069
			Inflation device ignites or activates upon command	(B,A) Inflation device performance and characterization test	7070
			All bags fill to desired level of pressure within allocated time	(B) Airbag inflation test	7071
			Airbags maintain proper pressure level until ground impact is achieved	(B) Airbag inflation and leak test	7072
			CM and crew tolerant to loads and dynamics associated with inflation	(B) Airbag shocks and loads transference analysis (A) Airbag shocks and loads transference test	7073
	GNC Activities				
		Sensor Operation			
			EDL sensors generate accurate data when subjected to forces and dynamical transients during chute descent phase	(B) IMU performance characterization test (R) IMU performance characterization analysis (B) Radar performance characterization field test (R) Radar performance characterization analysis	8074
		State Propagation			
			Attitude and pos/vel states propagated or estimated correctly when subjected forces and dynamical transients during chute descent phase	(R) Integrate avionics test bed and flight software sequence test (B) Algorithm/software test bed (R) Parachute descent phase dynamics characterization test	8075
Landing					
	Terminal Deceleration				
		Horizontal Velocity Reduction			
			Horizontal rockets commanded to ignite at the proper time	(B) Integrated avionics test bed and flight software sequence timing test	9076
			Horizontal rockets ignite upon command	(B) Horizontal rocket characterization and performance test stand firings	9077
			Horizontal rocket thrust and ISP profile are as expected	(B) Horizontal rocket characterization and performance test stand firings	9078
			Horizontal rockets decelerate capsule to velocity limits prior to impact	(R) Parachute/capsule horizontal rocket interaction firing test (B) Capsule response dynamics analysis	9079
			Post-burn attitude and rates within tolerance	(R) Parachute/capsule horizontal rocket interaction firing test (B) Capsule response dynamics analysis	9080
			CM and crew tolerant to loads and dynamics associated with rocket burn	(A) Horizontal rocket/capsule interaction test firing (B) Horizontal rocket firing shocks and loads transference analysis	9081
			No adverse plume impingement effects on CM	(B) Capsule plume impingement and vehicle configuration analysis (B) Horizontal rocket characterization and performance test stand firings (R) Horizontal rocket/capsule interaction test firing	9082
	Touchdown				
		Airbag Operation			
			Airbag stroke capability and performance as expected	(B,A) Airbag characterization bounding test (B) Airbag pressure and stroke analysis	1183
			Airbags vented at the proper time	(B) Integrated avionics test bed and flight software sequence timing test (B) Sensor characterization and qualification test (B,A) Controlled laboratory venting test (R) Airbag performance characterization drop test (B) [illegible]	1184

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Preliminary Event Tree Expansion

Phase	Sequence	Event	Conditions	Verification Activities	PPT #
			Airbags integrity not compromised by interaction with terrain	(B) Airbag terrain interaction drop test (B) Airbag materials qualification test (B) Landing site investigation	1185
		Impact Attenuation			
			Crew seat restraint and stroke capability and performance as expected	(B) Crew seat and loads impact analysis (B) Crew seat laboratory loads test (A) High fidelity capsule impact test	1186
			Load transmitted to crew due to impact is as expected	(B) Landing impact load transmission analysis (A) High fidelity capsule impact test	1187
			Post-impact attitude and rates are as expected	(B) Impact dynamics analysis (B,A) High fidelity landing dynamics test	1188
			Capsule maintains appropriate structural integrity and unconsumed volatiles not released	(B) Impact loads and dynamics analysis (B,A) High fidelity capsule impact test	1189
			Ground and terrain characteristics are as expected	(B) Landing site terrain survey	1190
			Wind speeds at the time of landing are as expected	(B) Historical wind forecast reliability analysis	1191

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Identification of Verification Activities

- Each condition is evaluated to determine a recommended set of verification activities (test, simulation, analysis) to prove that the condition is satisfied
- For each activity, the following will be recommended
  - A brief, qualitative description of the activity
  - Whether the activity should cover exhaustive, bounding, or representative scenarios
  - External variables that should be varied
  - Fidelity of the interfaces to other subsystems or components that interact with the prime target of verification
- Collection of activity descriptions will form the nucleus of the delivered product

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Forward Bay Cover Release

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1001: Retention release command sent at proper time

- **Element Description**
  - **Retention release command sent at proper time**
    - Untimely retention release may result in subsequent chute stages inflating at improper M/Q/AOA.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment.
    - Will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Should be run across a bounding set of cases representing the extremes of dynamics encountered by the vehicle.

1002: Retention device command

- **Element Description**
  - **Retention device actuated upon command**
    - Failure to operate the retention device will result in cover retention and failure to release deploy parachute system.

- **Verification Approach**
  - **Retention device performance and characterization test**
    - Test involves operating the retention release device in a controlled setting to verify that release occurs in a reliable fashion.
    - A sufficient number of trials is needed to gain statistical confidence and should be executed across a bounding set of conditions such as temperature and pre-load.

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1003: Cover sep devices

- **Element Description**
  - **Sep devices actuate and impart desired velocity**
    - Failure in the sep devices will result in cover retention and failure to release deploy parachute system.

- **Verification Approach**
  - **Sep device component performance and characterization test**
    - Test involves operating the separation device in a controlled setting to verify that release energy meets specification.
    - A sufficient number of trials needed to gain statistical confidence should be executed across bounding set of conditions such as temperature and pre-load.
  - **Forward bay cover separation analysis**
    - Activity involves use of a dynamical simulation capable of modeling objects of arbitrary shape, their motion due to relative forces, and whether contact occurs.
    - Cases should be run for an exhaustive set of conditions including variations in separation device performance and initial attitude and rates of the capsule.
    - Model of separation device used in the simulation will be calibrated by the device characterization test.
  - **Full scale forward bay cover separation test**
    - Test involves firing a flight-like separation device on a full-scale mock-up of the forward cover attached to a mock-up of the upper cone area of the capsule in a controlled setting.
    - Only need to execute several times under representative conditions to confirm validity of the simulation

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1004: Forward cover release loads and dynamics

- **Element Description**
  - **CM and crew tolerant to release forces and related dynamics**
    - Structural damage and injury to crew may result from higher then expected cover release loads and associated dynamics.

- **Verification Approach**
  - **Forward bay cover release shocks and loads transference analysis**
    - Activity involves an analysis to determine that the amount of attenuation of shock and loads generated from release of the forward bay cover, as transferred through the structure, results in acceptable level seen at the attach points for critical components and the crew.
  - **Forward bay cover release shocks and loads transference test**
    - Test involves measurement of forward bay cover release shock and loads on a flight-like structure at critical attachment points along the structure.
    - Only need to execute a few representative cases to both confirm the validity of the shock transfer analysis, and to gather accelerometer data to calibrate the structural attenuation model used in the analysis

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Forward Bay Cover Separation

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1005: Cover near term recontact (1/2)

- **Element Description**
  - **Cover clears capsule without contact**
    - The cover contacting in the near term may impair future drogue chute deployment.

- **Verification Approach**
  - **Sep device component performance and characterization test**
    - Test involves operating the separation device in a controlled setting to verify that release energy meets specification.
    - A sufficient number of trials needed to gain statistical confidence should be executed across bounding set of conditions such as temperature and pre-load.
  - **6-DOF cover separation analysis**
    - Activity involves use of a dynamical simulation capable of modeling objects of arbitrary shape, their motion due to relative forces, and whether contact occurs.
    - Cases should be run for an exhaustive set of conditions including variations in separation device performance and initial attitude and rates of the capsule.
    - Model of separation device used in the simulation will be calibrated by the device characterization test.
  - **Full scale first motion separation test**
    - Test involves a flight-like forward bay cover and geometrically realistic mock-up of the upper cone area of the capsule that are slowly "walked" away from each other.
    - Will verify that no obvious mechanical interferences exist that could hang-up the separation.

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1005: Cover near term recontact (2/2)

- **Verification Approach**
  - **Full scale dynamical aerial separation test**
    - Test involves using flight-like hardware and separating the cover from the capsule under flight-like conditions during an aerial drop test.
    - Will need to execute both nominal and bounding attitude rate cases to confirm validity of separation simulation.

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1006: Cover subsequent recontact

- **Element Description**
  - **Cover flies away from capsule and no subsequent recontact**
    - Cover recontact may damage the CM or impair future chute deployment.

- **Verification Approach**
  - **Cover/vehicle trajectory analysis**
    - Activity involves 6-DOF trajectory propagation to determine the relative motion between the cover and capsule.
    - Cases should be run that span an exhaustive range of bounding initial conditions (e.g. velocity, attitude, attitude rate) and model dispersions such as aerodynamics and atmospheric conditions.
  - **Full scale dynamical aerial separation test**
    - Test involves using flight-like hardware and separating the cover from the capsule under flight-like conditions during an aerial drop test.
    - Will need to execute both nominal and bounding attitude rate cases to confirm validity of separation simulation.

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Drogue Mortar Firing

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2007: Drogue deployment command time

- **Element Description**
  - **Drogue deployment command sent at proper time**
    - Untimely drogue chute deployment may result in chute inflation at improper M/Q/AOA.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment.
    - Will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Should be run across a bounding set of cases representing the extremes of dynamics encountered by the vehicle.

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2008: Gas generator ignition

- **Element Description**
  - **Gas generator ignites and performs**
    - Failure of the gas generator to ignite and perform as expected will result in failed drogue chute extraction.
- **Verification Approach**
  - **Gas generator characterization and performance test**
    - Test involves initiating a statistically significant number of flight-like gas generator cartridges in a controlled environment to verify reliability of ignition.
    - Should be executed across a bounding range of conditions such as initial temperature, atmospheric density, and moisture content.

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2009: Mortar breach pressure at proper level

- **Element Description**
  - **Mortar breach pressure at proper level within allocated time**
    - Insufficient mortar breach pressure may result in partial ejection of drogue chute. Failure to breach pressure within the allocated time may impair the likelihood for success of future parachute events.
- **Verification Approach**
  - **Mortar closed bomb firing test**
    - Test involves firing a statistically significant number of flight-like mortars in a "bomb chamber" in order to verify that the pressure generated in the mortar tube meets expectations.
    - Should be executed across a bounding range of conditions such as initial temperature and atmospheric density.

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2010: Drogue chute pack ejection

- **Element Description**
  - **Chute pack ejected from mortar at proper velocity**
    - Insufficient velocity for the ejected drogue chute pack may result in poor line stretch or tangle, and consequently may impair subsequent drogue chute inflation.
- **Verification Approach**
  - **Mortar static fire test with cover**
    - Test involves live firings of flight-like mortars with flight-like chute packs on a static test stand.
  - **Mortar performance analysis**
    - Activity involves dynamical simulation of the motion of the parachute within the mortar tube as a function of overpressure.
    - Model should be run across the expected bounding range of pressures.
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2011: Drogue mortar cover near term recontact

- **Element Description**
  - **Drogue mortar cover clears capsule without contact**
    - The pilot mortar cover contacting in the near term may impair drogue chute extraction.

- **Verification Approach**
  - **Mortar cover stress analysis**
    - Activity involves an analysis of the breaking strength of the mortar cover and cover hold-down attachment fittings.
    - Analysis will verify that chute pack has overwhelming momentum to cleanly break cover away from attach fittings.
  - **Mortar static fire test with cover and upper cone mock up**
    - Test involves live firings of flight-like chute packs in flight-like mortars attached to a realistic mock-up of the forward bay region of the capsule.
    - Will provide confirmation that no obvious problems exist with respect to FOD from the cover separation.

2012: Drogue mortar cover subsequent recontact

- **Element Description**
  - **Drogue mortar cover flies away from capsule and no subsequent recontact**
    - Drogue mortar cover recontact may damage the CM or impair drogue chute chute inflation.

- **Verification Approach**
  - **Cover/vehicle trajectory analysis**
    - Activity involves 6-DOF trajectory propagation to determine the relative motion between the mortar cover and capsule.
    - Cases should be run that span an exhaustive range of bounding initial conditions (e.g. velocity, attitude, attitude rate) and model dispersions such as aerodynamics and atmospheric conditions.
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2013: Chute pack line stretch

- **Element Description**
  - **Chute pack reaches line stretch without hangup, tangle, or interference**
    - Hangup, tangle, or interference may result impaired drogue chute operation.

- **Verification Approach**
  - **Mortar static fire test**
    - Test involves live firings of flight-like mortars with flight-like chute packs on a static test stand.
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2014: Bag strips off properly

- **Element Description**
  - **Bag strips off properly**
    - Improper removal of the drogue parachute bag may result in partial to zero inflation of drogue chutes.

- **Verification Approach**
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2015: Chute pack snatch load

- **Element Description**
  - **Chute pack survives snatch load**
    - The drogue chute pack must survive the snatch load or subsequent drogue chute inflation will not occur.

- **Verification Approach**
  - **Drogue aerial deployment test**
    - Test involves firing flight-like drogue chute packs from a flight-like mortar during aerial drop tests to verify that the pack integrity is not compromised by the snatch load.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack
  - **Drogue deployment loads analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each can be observed.
    - Case runs should span an exhaustive range of expected conditions.
    - Will be used to confirm that the expected range of snatch loads does not exceed rated capacity of parachute pack.

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2016: Mortar reaction loads and dynamics

- **Element Description**
  - **Capsule and crew tolerant to mortar reaction loads and related dynamics**
    - Structural damage and injury to crew may result from higher then expected mortar reaction loads and associated dynamics.

- **Verification Approach**
  - **Drogue ejection shocks and loads transference analysis**
    - Activity involves an analysis to determine that the amount of attenuation of the mortar initiation shock, as transferred through the structure, results in acceptable level seen at the attach points for critical components and the crew.
  - **Drogue ejection shocks and loads transference test**
    - Test involves measurement of mortar reaction loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Only need to execute a few representative cases to both confirm the validity of the load transfer analysis, and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Probably executed by placing accelerometers in key structural locations during an aerial inflation test.

Drogue Inflation

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2017: Drogue inflation conditions

- **Element Description**
  - **Drogues open and achieves full inflation under expected M/Q/AOA**
    - Failure to fill drogues under design conditions may result in loss of drogue chute or inadequate performance.

- **Verification Approach**
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests to verify that chute inflation occurs cleanly.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2018: Drogues survive opening loads

- **Element Description**
  - **Drogues survive opening loads**
    - Drogue loss will result in failure to stabilize capsule and may result in pilot chute deployment at undesirable conditions.

- **Verification Approach**
  - **Drogue aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests to verify that opening loads do not cause damage to the chute assembly.
    - Will need to execute cases for both nominal and pad abort scenarios spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack

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2019: Drogue opening loads and dynamics

- **Element Description**
  - **Capsule and crew tolerant to drogue opening loads and related dynamics**
    - Structural damage and injury to crew may result from higher then expected drogue opening loads and associated dynamics.

- **Verification Approach**
  - **Drogue inflation shocks and loads transference analysis**
    - Activity involves an analysis to determine that the amount of attenuation of the drogue inflation shock, as transferred through the structure, results in acceptable levels seen at the attach points for critical components and the crew.
  - **Drogue inflation shocks and loads transference test**
    - Test involves measurement of drogue inflation shock loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Only need to execute a few representative cases to both confirm the validity of the load transfer analysis, and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Probably executed by placing accelerometers in key structural locations during an aerial inflation test.

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Drogue Operation

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2020: Drogue drag properties

- **Element Description**
  - **Drogue drag properties as expected**
    - Drogue aerodynamic properties are critical to stabilizing capsule for subsequent parachute stages.

- **Verification Approach**
  - **Drogue aerodynamics performance characterization test**
    - Test involves aerial drops of drogue chutes to verify aerodynamic properties such as drag and stability as a function of angle of attack.
    - Should be executed in both single and dual drogue chute configuration to separate cluster performance artifacts from ideal canopy performance.

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2021: Drogues interference with one another

- **Element Description**
  - **Drogues do not interfere with each other**
    - Drogues interfering with one another may result in off nominal deceleration and performance.

- **Verification Approach**
  - **Drogue aerodynamics performance characterization test**
    - Test involves aerial drops of drogue chutes in flight-like cluster configuration to verify that aerodynamic interaction between the chutes does not interfere with individual chute performance.
    - Should be executed for a bounding range of conditions such as angle of attack, attitude rates, and winds.

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2022: Drogues stabilize capsule

- **Element Description**
  - **Drogues stabilize capsule**
    - Instability following drogue inflation results in off nominal attitude for pilot chute deployment.

- **Verification Approach**
  - **High fidelity terminal descent multi-body attitude dynamics analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between each can be observed.
    - Case runs should span an exhaustive range of expected conditions such as initial angle of attack, attitude and rates, wind gusts, and single/dual drogue configuration.
    - Will be used to dramatically extend the number of cases that otherwise might be impractical to test due to time or schedule limitations.
  - **Drogue/capsule interaction drop test**
    - Test involves utilizing flight-like, mortar-deployed drogue chutes to stabilize attitude rates on a flight-like capsule under realistic flight conditions.
    - Cases executed do not have to be exhaustive, but should be bounding with respect to extreme conditions such as initial angle of attack, attitude and rates, wind gusts, and single/dual drogue configuration.

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Drogue Release

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2023: Drogue release at proper time

- **Element Description**
  - **Drogue release commanded at proper time**
    - Untimely drogue release may decrease the chances for subsequent parachute stages success.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment.
    - Will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Should be run across a bounding set of cases representing the extremes of dynamic encountered by the vehicle.

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2024: Drogue chute line cutters

- **Element Description**
  - **Drogue line cutters actuate upon command and sever risers**
    - Failure to release drogue will hamper main chute deployment.

- **Verification Approach**
  - **Line cutter performance and characterization test**
    - Test involves firing the line cutters in a controlled setting to verify reliability of the device.
    - Should be run across a bounding set of cases including temperature, line pre-load or slack, and line strength.
  - **Drogue aerial separation test**
    - Test involves using flight-like line cutters to sever flight-like drogue lines under a realistic flight environment.
    - Cases should be executed across a bounding set of conditions such as attitude rates and single/dual drogue configuration.
    - Will verify that details related to flight conditions and/or conditions that result only when flight hardware is utilized do not have adverse affect on performance.

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Drogue Separation

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2025: Drogue risers clear capsule

- **Element Description**
  - **Drogue risers clear capsule without hangup**
    - Drogue chute riser hangup may hamper pilot chute deployment.

- **Verification Approach**
  - **Drogue aerial separation test**
    - Test involves using flight-like line cutters to sever flight-like drogue lines under a realistic flight environment.
    - Cases should be executed across a bounding set of conditions such as attitude rates and single/dual drogue configuration.
    - Will verify that details related to flight conditions and/or conditions that result only when flight hardware is utilized do not have adverse affect on cutter performance.

2026: Drogue parachute subsequent recontact

- **Element Description**
  - **Drogue parachute assembly flies away from capsule and no subsequent recontact**
    - Drogue parachute recontact may impair pilot chute inflation and main chute extraction.

- **Verification Approach**
  - **Drogue aerial separation test**
    - Test involves separating flight-like drogue chutes from a flight-like capsule under a realistic environment to verify that drogue chute fly-away performance is adequate.
    - Cases should be executed across a bounding set of conditions such as attitude rates and single/dual drogue configuration.

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Pilot Mortar Firing

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3027: Pilot chute deployment command

- **Element Description**
  - **Pilot chute deployment command sent at proper time**
    - Untimely pilot chute deployment may result in chute inflation at improper M/Q/AOA.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment. Test will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Test should span a bounding set of cases representing the extremes of dynamic encountered by the vehicle.

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3028: Pilot gas generator ignition

- **Element Description**
  - **Pilot gas generator ignites and performs**
    - Failure of the gas generator to ignite and perform as expected will result in failed pilot chute and subsequent main chute extraction.

- **Verification Approach**
  - **Gas generator characterization and performance test**
    - Test involves imitating a statistically significant number of flight-like gas generator cartridges in a controlled environment to verify reliability of ignition.
    - Test should span across a bounding range of conditions such as initial temperature, atmospheric density, and moisture content.

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3029: Pilot mortar breach pressure

- **Element Description**
  - **Pilot mortar breach pressure at proper level within allocated time**
    - Insufficient mortar breach pressure may result in partial ejection of the chute pack. Failure to breach pressure within the allocated time may impair the likelihood for success of future parachute events.
- **Verification Approach**
  - **Pilot mortar closed bomb firing test**
    - Test involves firing a statistically significant number of flight-like mortars in a "bomb chamber" in order to verify that the pressure generated in the mortar tube meets expectations.
    - Test should span across a bounding range of conditions such as initial temperature and atmospheric density.

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3030: Pilot chute pack ejection

- **Element Description**
  - **Pilot chute pack ejected from mortar at proper velocity**
    - Insufficient velocity for the ejected chute pack may result in poor line stretch or tangle, and consequently may impair subsequent pilot chute inflation.

- **Verification Approach**
  - **Pilot mortar static fire test with cover**
    - Test involves live firings of flight-like mortars with flight-like chute packs on a static test stand.
  - **Pilot mortar performance analysis**
    - Activity involves dynamical simulation of the motion of the parachute within the mortar tube as a function of overpressure.
    - Model should run across the expected bounding range of pressures.
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Test needs to cover cases spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack.

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3031: Pilot mortar cover near term contact

- **Element Description**
  - **Pilot mortar cover clears capsule without contact**
    - The pilot mortar cover contacting in the near term may impair main chute extraction.

- **Verification Approach**
  - **Pilot mortar cover stress analysis**
    - Activity involves an analysis of the breaking strength of the mortar cover and cover hold-down attachment fittings.
    - Analysis will verify that chute pack has overwhelming momentum to cleanly break cover away from attach fittings.
  - **Pilot mortar static fire test with cover and upper cone mock up**
    - Test involves live firings of flight-like chute packs in flight-like mortars attached to a realistic mock-up of the forward bay region of the capsule.
    - Test will confirm that no obvious problems exist with respect to FOD from the cover separation.

3032: Pilot mortar cover subsequent recontact

- **Element Description**
  - **Pilot mortar cover flies away with no subsequent recontact**
    - The pilot mortar cover recontacting may impair main chute operations or result in structural damage to the CM.
- **Verification Approach**
  - **Cover/vehicle trajectory analysis**
    - Activity involves 6-DOF trajectory propagation to determine the relative motion between the mortar cover and capsule.
    - Cases should span an exhaustive range of bounding initial conditions (e.g. velocity, attitude, attitude rate) and model dispersions such as aerodynamics and atmospheric conditions.
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Test must cover wide range of conditions for both nominal and pad abort scenarios, including variations in initial velocities, attitude and rates, and angles of attack

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3033: Pilot chute pack line stretch

- **Element Description**
  - **Pilot chute pack reaches line stretch without hangup, tangle, or interference**
    - Hangup, tangle, or interference may result impaired chute operation.

- **Verification Approach**
  - **Pilot mortar static fire test**
    - Test involves live firings of flight-like mortars with flight-like chute packs on a static test stand.
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Test must include wide range of conditions including initial velocities, attitude and rates, and angles of attack.

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3034: Pilot bag strips off properly

- **Element Description**
  - **Pilot bag strips off properly**
    - Improper removal of the parachute bag may result in partial to zero inflation of pilot chutes.

- **Verification Approach**
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests.
    - Test must include wide range of conditions including initial velocities, attitude and rates, and angles of attack.

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3035: Pilot chute pack snatch load

- **Element Description**
  - **Pilot chute pack survives snatch load**
    - The pilot chute pack must survive the snatch load or subsequent chute inflation will not occur.
- **Verification Approach**
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests to verify that the pack integrity is not compromised by the snatch load.
    - Test must include wide range of conditions including initial velocities, attitude and rates, and angles of attack.
  - **Pilot deployment loads analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each can be observed.
    - Case runs should span an exhaustive range of expected conditions.
    - Test will confirm that expected range of snatch loads does not exceed rated capacity of parachute pack.

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3036: *Pilot chute ejection loads and dynamics*

- **Element Description**
  - **CM and crew tolerant to pilot reaction loads and related dynamics**
    - Structural failure and injury to crew may result from higher then expected ejection loads and associated dynamics.

- **Verification Approach**
  - **Pilot ejection shocks and loads transference analysis**
    - Activity involves an analysis to determine that the amount of attenuation of the mortar initiation shock -- as transferred through the structure -- results in acceptable structural health levels (g-load, stress, strain, etc.) experienced by the crew and at the attach points for critical components.
  - **Pilot ejection shocks and loads transference test**
    - Test involves measurement of mortar reaction loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Only a few representative cases required to both confirm the validity of the load transfer analysis and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Placement of accelerometers should lay in key structural locations during an aerial inflation test.

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Pilot Inflation

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3037: Pilot chute inflation conditions

- **Element Description**
  - **Pilot chute fills with air under expected M/Q/AOA conditions and survives opening loads**
    - Failure to fill pilot chute under design conditions may result in pilot chute and subsequent mission loss of success.

- **Verification Approach**
  - **Pilot aerial deployment test**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests to verify that chute inflation occurs cleanly.
    - Tests should vary wide range of conditions including initial velocities, attitude and rates, and angles of attack.

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3038: Pilot chute survivability

- **Element Description**
  - **Pilot survives opening loads.**
    - Pilot chute failure from opening loads will impede main chute extraction.

- **Verification Approach**
  - **Pilot aerial deployment test.**
    - Test involves firing flight-like chute packs from a flight-like mortar during aerial drop tests to verify that opening loads do not cause damage to the chute assembly.
    - Tests should vary wide range of conditions including initial velocities, attitude and rates, and angles of attack.

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3039: Pilot snatch/inflation loads and dynamics

- **Element Description**
  - **CM and crew tolerant to pilot snatch and opening loads and related dynamics.**
    - Extreme forces from pilot snatch, opening loads, and related dynamics places CM and crew at risk.

- **Verification Approach**
  - **Pilot inflation shocks and loads transference analysis.**
    - Activity involves an analysis to determine that the amount of attenuation of the pilot chute inflation shock -- as transferred throughout the structure -- results in acceptable structural health levels (g-load, stress, strain, etc.) experienced by the crew and at the attach points for critical components.
  - **Pilot inflation shocks and loads transference test.**
    - Test involves measurement of pilot inflation shock loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Only a few representative cases required to both confirm the validity of the load transfer analysis and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Placement of accelerometers should lay in key structural locations during an aerial inflation test.

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Main Extraction

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3040: Main chute extraction

- **Element Description**
  - **Pilot chutes extract main chutes from forward bay, and line stretch is achieved with no interference or entanglement.**
    - Entanglement of main chute lines or extraction failure will impede main chute deployment.

- **Verification Approach**
  - **Pilot/main aerial deployment test.**
    - Test involves using flight-like, mortar-deployed pilot chutes to extract flight-like main canopies under realistic flight conditions during aerial drop tests.
    - Tests should span a wide range of conditions including initial velocities, attitude and rates, and angles of attack.
    - Each case may need to be run several times to reduce the risk that success was a result of fortuitous circumstances.

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3041: Main chute snatch load

- **Element Description**
  - **Main pack survives snatch load.**
    - Excessive snatch load may cause pack to sever from risers.
- **Verification Approach**
  - **Main aerial deployment test.**
    - Test involves using flight-like, mortar-deployed pilot chutes to extract flight-like main canopies under realistic flight conditions during aerial drop tests.
    - Tests should vary wide range of conditions including initial velocities, attitude and rates, and angles of attack.
  - **Main deployment loads analysis.**
    - Analysis involves "multi-body" 6-DOF simulation where forces are applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each is observed.
    - Case runs should span an exhaustive range of expected conditions.
    - Analysis will confirm that expected range of snatch loads does not exceed rated capacity of parachute pack.

Main Inflation

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3042: Reefing cutter lanyards and reefing line cutters

- **Element Description**
  - **Reefing cutter lanyards properly actuate the pyrotechnic delay functions, and cutters sever reefing lines**
    - Obstruction of reefing line severance will impair main chute inflation.

- **Verification Approach**
  - **Reefing cutter performance characterization test**
    - Test involves firing the line cutters in a controlled setting to verify reliability of the device.
    - Tests should cover bounding set of conditions including temperature; reefing line pre-load or slack; reefing line strength; and lanyard pull force
  - **Main aerial deployment test.**
    - Test involves using flight-like, mortar-deployed pilot chutes to extract flight-like main canopies under realistic flight conditions during aerial drop tests.
    - Tests should span a wide range of conditions including initial velocities, attitude and rates, and angles of attack.
    - Tests will verify that details related to flight conditions and/or conditions that result only when flight hardware is utilized do not have adverse affect on reefing cutter performance.

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3043: Main chute inflation conditions.

- **Element Description**
  - **Main chute inflates properly during each reefing stage under expected M/Q/AOA conditions and survives opening loads.**
    - Inadequate performance of main chute during deployment, inflation, and operation may endanger CM and crew safety.

- **Verification Approach**
  - **Main aerial deployment test.**
    - Test involves using flight-like, mortar-deployed pilot chutes to extract flight-like main canopies under realistic flight conditions during aerial drop tests.
    - Tests will need to execute cases spanning a wide range of conditions including initial velocities, attitude and rates, and angles of attack.
    - Each case may need to be run several times to reduce the risk that success was a result of fortuitous circumstances.

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3044: Main snatch, opening loads, and dynamics

- **Element Description**
  - **CM and crew tolerant to main snatch, opening loads, and related dynamics.**
    - Extreme forces from main chute deployment may injure CM and crew.

- **Verification Approach**
  - **Main inflation shocks and loads transference analysis.**
    - Activity involves an analysis to determine that the amount of attenuation of the main chute inflation shock -- as transferred through the structure -- results in acceptable structural health levels (g-load, stress, strain, etc.) experienced by the crew and at the attach points for critical components.
  - **Main inflation release shocks and loads transference test.**
    - Test involves measurement of main chute inflation shock loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Tests only need to execute a few representative cases to both confirm the validity of the load transfer analysis and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Placement of accelerometers should lay in key structural locations during an aerial inflation test.

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Sensor Operation

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4045: Chute deploy sensor accuracy

- **Element Description**
  - **EDL sensors generate accurate data when subjected to forces and dynamical transients during chute deploy phase.**
    - Inaccurate data generation may state estimation accuracy and affect touchdown performance.

- **Verification Approach**
  - **IMU performance characterization test.**
    - Test involves subjecting an IMU to an exhaustive set of dynamical conditions in a controlled setting to verify whether performance (accuracy, drift, bias, etc.) meets specification.
    - Tests should cover bounding set of accelerations, angular rates, and temperatures.
  - **IMU performance characterization analysis.**
    - Activity involves use of computer simulation that models the internal mechanisms and software of the IMU to predict its output based on a simulated input.
    - Model is calibrated using data gathered from performance characterization test.
    - Although IMU will be tested under flight-like conditions, the simulation is used to dramatically expand the number of cases that would otherwise be unattainable due to schedule or budget limitations.
  - **Parachute to IMU loads transference analysis**
  - **Parachute deployment shock and loads characterization test.**

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State Propagation

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4046: Chute deploy phase state vector propagation

- **Element Description**
  - **Attitude position and velocity states propagated or estimated correctly as results of forces and dynamical transients during chute deploy phase.**
    - Incorrect state vector calculations may obstruct timely deployment of parachute phase.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test verifies that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Tests only need to cover selected, representative cases.
  - **Algorithm / software test bed.**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated but realistic input streams across all possible ranges of input conditions
  - **Parachute descent phase dynamic characterization test.**
    - Test involves flying a flight-like parachute/capsule system from forward cover separation to main inflation in order to record the dynamical motion experienced by the capsule during the chute deployment process.
    - Test data is used to confirm dynamical models used in GNC and trajectory simulations.
    - Tests need only cover a few representative cases for nominal descent and pad abort.

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Chute Deceleration

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5047: Drag performance of main canopies

- **Element Description**
  - **Drag performance of main canopies is as expected, including canopy interference issues.**
    - Unexpected performance of main canopy drag may break design limits of horizontal rockets and landing airbags which ultimately increases force of ground impact.

- **Verification Approach**
  - **Main canopy aerodynamics performance characterization test**
    - Test involves aerial drops of main chutes to verify aerodynamic properties such as drag and stability as a function of angle of attack.
    - Tests should involve single, dual, and triple canopy configuration to separate cluster performance artifacts from ideal canopy performance.
    - Tests do not explicitly require a flight-like deployment process,but could piggyback on a deployment test

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5048: Stability of main chute cluster

- **Element Description**
  - **Stability of main chute cluster is as expected.**
    - Individual canopies interfering with one another may result in degraded parachute performance.

- **Verification Approach**
  - **Main canopy aerodynamics performance characterization test**
    - Test involves aerial drops of main chutes in flight-like cluster configuration to verify that aerodynamic interaction between the chutes does not interfere with individual chute performance.
    - Test should cover bounding range of conditions such as angle of attack, attitude rates, and winds.
    - Test does not explicitly require a flight-like deployment process but could piggyback on a deployment test

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5049: Pre-landing attitude states

- **Element Description**
  - **CM attitude and rates within tolerance when within vicinity of ground.**
    - Excessive CM attitude and rates may damage vehicle and harm crew.

- **Verification Approach**
  - **High fidelity terminal descent multi-body attitude dynamics analysis.**
    - Analysis involves "multi-body" 6-DOF simulation where forces are applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each is observed.
    - Case runs should span an exhaustive range of expected conditions.
  - **Parachute/capsule interaction drop test.**
    - Test involves dropping a flight-like capsule with flight-like main chutes for the purpose of observing and recording the attitude dynamics of the entire stack.
    - Test need cover only few representative conditions to confirm validity of attitude dynamics analysis.

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Heatshield Release

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6050: Heatshield retention device release

- **Element Description**
  - **Heatshield retention device release commanded at proper time.**
    - Untimely command of heatshield retention device release will jeopardize airbag inflation and horizontal retro-rocket firing sequence.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment.
    - Test will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Should be run across a bounding set of cases representing the extremes of dynamic encountered by the vehicle.

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6051: Heatshield retention device release activation

- **Element Description**
  - **Heatshield retention device releases upon command.**
    - Failure of heatshield retention device activation to release will cripple airbag deployment and increase landing impact forces.

- **Verification Approach**
  - **Retention device performance and characterization test.**
    - Test involves operating the retention release device in a controlled setting to verify that release occurs in a reliable fashion.
    - Sufficient number of trials needed for statistical confidence should span across bounding set of conditions such as temperature and pre-load.

6052: Heatshield separation device performance

- **Element Description**
  - **Heatshield separation devices actuate and impart desired velocity.**
    - Underperformance of separation device may cause heatshield recontact or ground sensing interference from heatshield release.
- **Verification Approach**
  - **Sep device component performance and characterization test**
    - Test involves operating the separation device in a controlled setting to verify that release energy meets specification.
    - Sufficient number of trials needed for statistical confidence should span across bounding set of conditions such as temperature and pre-load.
  - **Heatshield separation analysis.**
    - Activity involves use of a dynamical simulation capable of modeling objects of arbitrary shape; respective motion due to relative forces; and whether contact occurs.
    - Cases should comprise an exhaustive set of conditions including variations in separation device performance; initial attitude; and rates of the capsule.
    - Model of separation device used in the simulation is calibrated by the device characterization test.
  - **Full scale heatshield separation test.**
    - Test involves firing a flight-like separation device on a full-scale mock-up of the heatshield attached to a mock-up of the lower portion of the capsule in a controlled setting.
    - Only cases with representative conditions required to confirm validity of the simulation.

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6053: Heatshield separation forces and dynamics

- **Element Description**
  - **CM and crew tolerant to release forces and related dynamics.**
    - Extreme forces and related dynamics from heatshield release may harm crew and damage CM.

- **Verification Approach**
  - **Heatshield shocks and loads transference analysis.**
    - Analysis is used to determine that the amount of shock attenuation and loads generated from heatshield release -- as transferred through the structure -- results in acceptable structural stress/strain/loads/etc. level experienced by the crew and at the attach points of critical components.
  - **Heatshield shocks and loads transference test.**
    - Test involves measurement of the heatshield release shock and loads on a flight-like structure at critical attachment points along the structure.
    - Only a few representative cases required to both confirm the validity of the shock transfer analysis and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.

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Heatshield Separation

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6054: Heatshield near term recontact (1 of 2)

- **Element Description**
  - **Heatshield clears capsule without contact.**
    - Recontact of heatshield with capsule will damage CM; may cause harm to crew; will alter entry trajectory; and may cause unacceptable attitude dynamics.

- **Verification Approach**
  - **Sep device component performance and characterization test**
    - Test involves operating the separation device in a controlled setting to verify that release energy meets specification.
    - A sufficient number of trials necessary for statistical confidence should cover bounding set of conditions such as temperature and pre-load.
  - **6-DOF heatshield separation analysis.**
    - Activity involves use of a dynamical simulation capable of modeling objects of arbitrary shape; respective motion due to relative forces; and whether contact occurs.
    - Cases should cover exhaustive set of conditions including variations in separation device performance, initial attitude, and rates of the capsule.
    - Model of separation device used in the simulation will be calibrated by the device characterization test.
  - **Configuration obstructions analysis.**
    - Test involves a flight-like heatshield and geometrically realistic mock-up of the lower region of the capsule that are slowly "walked" away from each other.
    - Test will verify that no obvious mechanical interferences exist that could hang-up the separation.

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6054: Heatshield near term recontact (2 of 2)

- **Verification Approach (cont.)**
  - **Full Scale first motion separation test.**
    - Test involves using flight-like hardware and separating the cover from the capsule under flight-like conditions during an aerial drop test.
    - Test runs should include both nominal and bounding attitude rate cases to confirm validity of separation simulation.

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6055: *Heatshield long term separation*

- **Element Description**
  - **Heatshield flies away from capsule with no subsequent recontact, and moves far enough away within the allocated time to preclude ground sensing interference.**
    - Ground sensing interference from released heatshield may obstruct EDL sensors critical to airbag inflation and horizontal rocket firings.

- **Verification Approach**
  - **Heatshield/vehicle trajectory analysis.**
    - Activity involves 6-DOF trajectory propagation to determine the relative motion between the heatshield and capsule.
    - Cases run should incorporate exhaustive range of bounding initial conditions (e.g. velocity, attitude, attitude rate), and model dispersions such as aerodynamics and atmospheric conditions.
  - **Full scale heatshield separation test.**
    - Test involves using flight-like hardware and separating the heatshield from the capsule under flight-like conditions during an aerial drop test.
    - Test executions will include both nominal and bounding attitude rate cases to confirm validity of separation simulation.

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7056: Altitude and velocity sensor activation

- **Element Description**
  - **Altitude and velocity sensors commanded to activate at the proper time.**
    - Delayed activation of altitude and velocity sensors may result in degraded in GNC performance during terminal descent, possibly leading to degraded airbag and retro-rocket performance.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data to mimic response of vehicle to dynamical environment.
    - Test will verify that proper timing of issued commands are not subject to hardware to software timing issues.
    - Test should encompass bounding set of cases representing the extremes of dynamic encountered by the vehicle.

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Sensor Acquisition

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7057: Altitude and velocity sensor lock-up

- **Element Description**
  - **Altitude and velocity sensors achieve unambiguous lock on the ground within allocated time.**
    - Fluctuating sensor lock on ground by will adversely affect GNC calculations (airbag inflation, horizontal rocket firings, final CM attitude).

- **Verification Approach**
  - **Radar characterization field test.**
    - Test requires flying a flight-like sensor from above to below its expected ground acquisition altitude under bounding conditions of drop velocity, attitude rates, and encountered terrain types.
  - **Radar performance characterization laboratory test.**
    - Test requires use of ground support equipment that takes sensor output and applies proper signal delay and distortion prior to feeding signal back to the sensor.
    - Ground support equipment is used to simulate the sensor in the laboratory and allow for an understanding of performance under ideal conditions.

Sensor Operation

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7058: Performance of altitude and velocity sensors

- **Element Description**
  - **Altitude and velocity sensors generate data that meets accuracy requirements in the presence of terrain effects and capsule dynamics.**
    - Inability of alt/vel sensors to operate in all-terrain environment will hinder CM landing site options.
- **Verification Approach**
  - **Radar characterization field test.**
    - Test requires flying a flight-like sensor over all expected terrain types within the selected landing sites to confirm that actual performance meets requirements.
    - Test will involve dropping the sensor across entire range of plausible descent velocities over all expected terrain types.
  - **Radar performance characterization laboratory test.**
    - Test requires use of ground support equipment that takes sensor output and applies proper signal delay & distortion prior to feeding signal back to the sensor.
    - Ground support equipment is used to simulate the sensor in the laboratory and allow for an understanding of performance under ideal conditions.
  - **Modeled radar performance simulation.**
    - Activity involves use of computer simulation that models the output of the sensor; interaction of the sensor's signal with the ground; and internal processing of the signal upon receipt.
    - Simulation is anchored by performance data collected in the field and laboratory.
    - Simulation is critical to dramatically extend (experimental) test case scenarios which are otherwise unattainable due to schedule limitations.

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Roll Orientation Selection

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7059: Landing attitude selection

- **Element Description**
  - **GNC computes direction of horizontal motion and selects appropriate landing attitude.**
    - Errors in GNC computation of horizontal motion and resulting landing attitude may result in degraded airbag and horizontal velocity abatement performance.

- **Verification Approach**
  - **Algorithm / software test bed**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated, but realistic input streams across all possible ranges of input conditions
  - **Comprehensive EDL trajectory and dynamics simulations**
    - Activity involves use of 6-DOF trajectory propagation with embedded virtual, but calibrated sensor models and embedded flight software code in a closed loop simulation.
    - Trajectory cases should exhaustively encompass expected bounding dynamical conditions, and output behavior of GNC algorithms should be inspected for correct behavior.
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Only selected, representative cases necessary for complete test.

Thruster Firings

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7060: Timely command of RCS thrusters

- **Element Description**
  - **RCS thruster firing command sent at proper time.**
    - Mistimed thruster firing commands equates to poor vehicle roll control.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test involves firing flight-like thrusters in a controlled setting to determine whether performance characteristics meet expectations.
    - A sufficient number of trials necessary for statistical confidence should span across bounding set of conditions such as temperature, feed pressure, and pulse duration.
    - Data collected is also used to create accurate thruster models for use in trajectory simulations.

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7061: RCS Thruster performance

- **Element Description**
  - **RCS thruster ISP and thrust properties are as expected.**
    - Poor thruster performance may result in over/under-performance of torque control.

- **Verification Approach**
  - **ACS thruster characterization and performance test stand firings**
    - Test involves firing flight-like thrusters in a controlled setting to determine whether performance characteristics meet expectations.
    - A sufficient number of trials necessary for statistical confidence should span across bounding set of conditions such as temperature, feed pressure, and pulse duration.
    - Data collected is also used to create accurate thruster models for use in trajectory simulations.

7062: Adverse RCS plume impingement

- **Element Description**
  - **No adverse plume impingement effects from RCS thrusters on CM**
    - Adverse plume impingement may cause CM burn-through or parachute riser failure (Apollo 15).

- **Verification Approach**
  - **Capsule plume impingement and vehicle configuration analysis**
    - Activity involves 3-dimensional modeling to determine if expected plume will impinge on capsule or parachutes. Will need to model temperature and velocity of exhaust as a function of distance from the nozzle and compare with sensitivity of vehicle to plume intensity.
  - **ACS thruster characterization and performance test stand firings**
    - Test involves firing flight-like thrusters in a controlled setting to verify shape and size of thruster plume for use in plume impingement analysis.
    - A sufficient number of trials necessary for statistical confidence should span across bounding set of conditions such as temperature, feed pressure, and pulse duration.
  - **Thruster/capsule interaction test**
    - Test involves firing flight-like thrusters attached to a capsule mock-up with flight-like fidelity in exterior geometry, including parachute risers.
    - Only a few representative cases necessary to confirm the validity of the plume impingement analysis.
    - Data collected should also examine that deposited particulates from the exhaust do not pose a hazard to seals, windows, and vents.

7063: Roll torque performance under chute

- **Element Description**
  - **Resultant torque on vehicle is as expected, including effects from chute risers.**
    - Unexpected resultant torque may affect desired final landing attitude conditions.

- **Verification Approach**
  - **High fidelity terminal descent attitude dynamics analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each can be observed.
    - Case runs should span an exhaustive range of expected conditions.
  - **Thruster/capsule/riser interaction test**
    - Test involves hanging a capsule from parachute risers and firing thrusters to rotate the capsule under the risers.
    - Only a few representative cases necessary to verify fidelity of attitude dynamics analysis.
    - Data collected should include performance of the risers (e.g. torsional stiffness, elasticity) to calibrate input parameters in the attitude dynamics analysis.

7064: Final landing attitude targeting by GNC

- **Element Description**
  - **GNC control logic performs correctly in targeting and achieving final attitude conditions.**
    - Errors in GNC control logic will result in missing desired final attitude conditions.

- **Verification Approach**
  - **Algorithm/software test bed**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated, but realistic input streams across all possible ranges of input conditions
  - **High fidelity terminal descent attitude dynamics analysis**
    - Activity involves use of "multi-body" trajectory and attitude propagation with embedded virtual, but calibrated sensor models and embedded flight software code in a closed loop simulation.
    - Cases should exhaustively span expected bounding dynamical conditions, and output behavior of GNC algorithms should be inspected for correct behavior.
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Test need only cover selected, representative cases.

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Trigger Computation

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7065: Airbag inflation time

- **Element Description**
  - **GNC computes correct altitude and time to inflate airbags.**
    - Mistimed airbag inflation could degrade airbag performance.

- **Verification Approach**
  - **Algorithm / software test bed**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated, but realistic input streams across all possible ranges of input conditions
  - **Comprehensive EDL trajectory and dynamics simulations**
    - Activity involves use of multi-DOF trajectory propagation with embedded virtual, but calibrated sensor models and embedded flight software code in a closed loop simulation.
    - Trajectory cases should exhaustively span expected bounding dynamical conditions, and output behavior of GNC algorithms should be inspected for correct behavior.
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment. Will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Test need only cover selected, representative cases.

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7066: Horizontal rocket firing time

- **Element Description**
  - **GNC computes correct altitude and time to fire horizontal rockets.**
    - False predictions of horizontal rocket firings may cause intolerable torques and/or misalign acceptable landing attitude and location.

- **Verification Approach**
  - **Algorithm / software test bed**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated, but realistic input streams across all possible ranges of input conditions
  - **Comprehensive EDL trajectory and dynamics simulations**
    - Activity involves use of 6-DOF trajectory propagation with embedded virtual, but calibrated sensor models and embedded flight software code in a closed loop simulation.
    - Trajectory cases should exhaustively span expected bounding dynamical conditions, and output behavior of GNC algorithms should be inspected for correct behavior.
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Test need only cover selected, representative cases.

Airbag Inflation

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7067: Timely command activation of retention device

- **Element Description**
  - **Retention release command sent at proper time.**
    - Delay in release of airbag retention device may harm CM and crew upon landing.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Test need only cover selected, representative cases.

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7068: Airbag retention device release

- **Element Description**
  - **Airbag retention device released upon command.**
    - Failure in airbag retention device to not release may hinder airbag inflation.

- **Verification Approach**
  - **Retention device performance and characterization test.**
    - Test involves operating the retention release device in a controlled setting to determine if performance meets expectations.
    - A sufficient number of trials necessary for statistical confidence should span bounding set of conditions such as temperature, pre-load, and retention stiffness.

7069: Airbag gas generator ignition

- **Element Description**
  - **Airbag gas generator ignition or activation command sent at proper time.**
    - Untimely activation of gas generator may degrade airbag performance.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test.**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Test will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Test need only cover selected, representative cases.

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7070: Airbag inflation device command

- **Element Description**
  - **Airbag inflation device ignites or activates upon command.**
    - Failure of airbag inflation upon command threatens success of CM and crew landing.

- **Verification Approach**
  - **Inflation device performance and characterization test.**
    - Test involves operating the inflation device in a controlled setting to determine if the pressure and flow rate output meets expectations.
    - A sufficient number of trials necessary for statistical confidence should span bounding set of conditions such as temperature and ambient pressure.

7071: Achieving airbag pressure level

- **Element Description**
  - **All airbags fill to desired level of pressure within allocated time.**
    - Untimely attainment of acceptable airbag pressure level may degrade airbag performance.

- **Verification Approach**
  - **Airbag inflation test**
    - Test involves repeated inflations of flight-like airbags using flight-like inflation devices under nominal and bounding cases of initial temperature.
    - A structural mock-up with an accurate representation of the capsule bottom should be used to verify that no hang-ups occur during the inflation process

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7072: Maintaining airbag pressure level

- **Element Description**
  - **Airbags maintain proper pressure level until ground impact is achieved.**
    - Loss of acceptable airbag pressure levels may degrade airbag performance.

- **Verification Approach**
  - **Airbag inflation and leak test**
    - Test involves inflating the airbags in a controlled setting under nominal and bounding cases of initial temperature to verify that the inflation device can maintain proper operating pressure for the requisite duration of time.
    - Test should also include data collection on airbag leak rate.

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7073: Airbag inflation loads and dynamics

- **Element Description**
  - **CM and crew tolerant to loads and dynamics associated with airbag inflation.**
    - Structural damage and injury to crew may result from higher then expected airbag inflation loads and associated dynamics.

- **Verification Approach**
  - **Airbag shocks and loads transference analysis**
    - Activity involves an analysis to determine that the amount of attenuation of airbag inflation shock and loads, as transferred through the structure, results in acceptable level seen at the attach points for critical components and the crew.
  - **Airbag shocks and loads transference test**
    - Test involves measurement of airbag inflation shock and loads on a flight-like structure at critical attachment points along the structure.
    - Only need to execute a few representative cases to both confirm the validity of the shock transfer analysis, and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.

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Sensor Operation

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8074: EDL sensors during chute descent phase

- **Element Description**
  - **EDL sensors generate accurate data when subjected to forces and dynamical transients during chute descent phase**
    - Subjected to forces and dynamic transients, EDL sensors must perform as expected for timely command of horizontal velocity reduction.

- **Verification Approach**
  - **IMU performance characterization test**
    - Test involves subjecting an IMU to an exhaustive set of dynamical conditions in a controlled setting to verify whether performance (accuracy, drift, bias, etc.) meets specification.
    - Should be executed across bounding set of accelerations, angular rates, and temperatures.
  - **IMU performance characterization analysis**
  - **Radar performance characterization field test**
    - Activity involves use of computer simulation that models the internal mechanisms and software of the IMU to predict its output based on a simulated input.
    - Model will be calibrated using data gathered from performance characterization test.
    - Although IMU will be tested under flight-like conditions, simulation will be used to dramatically expand the number of cases that might otherwise be impractical to test due to schedule or budget limitations.
  - **Radar performance characterization analysis**

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State Propagation

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8075: Chute descent phase state propagation 1/2

- **Element Description**
  - **Attitude and pos/vel states propagated or estimated correctly when subjected forces and dynamical transients during chute descent phase**
    - Failure to correctly interpret and propagate sensor data will result in improper command of horizontal rocket velocity reduction.

- **Verification Approach**
  - **Integrate avionics test bed and flight software sequence test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Only need to be run for selected, representative cases.
  - **Algorithm/software test bed**
    - Activity involves isolated unit testing of relevant GNC algorithms using simulated, but realistic input streams across all possible ranges of input conditions
  - **Parachute descent phase dynamics characterization test**
    - Test involves flying the parachute/capsule system from deployment to low altitudes in order to record the dynamical motion experienced by the capsule while "swinging" under the chutes.
    - Data will be used to confirm dynamical models used in GNC and trajectory simulations.
    - Should be executed for a few representative cases for nominal descent and pad abort.

8075: Chute descent phase state propagation 2/2

- **Verification Approach (cont.)**
  - **Parachute descent phase dynamics characterization test**
    - Test involves flying the parachute/capsule system from deployment to low altitudes in order to record the dynamical motion experienced by the capsule while "swinging" under the chutes.
    - Data will be used to confirm dynamical models used in GNC and trajectory simulations.
    - Should be executed for a few representative cases for nominal descent and pad abort.

Horizontal Velocity Reduction

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9076: Horizontal rockets ignition time

- **Element Description**
  - **Horizontal rockets commanded to ignite at the proper time**
    - Untimely ignition of horizontal rockets will cause unexpected attitude, rates, and velocity of capsule.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Only need to be run for selected, representative cases.

9077: Horizontal rockets ignite

- **Element Description**
  - **Horizontal rockets ignite upon command**
    - Failure of horizontal rocket ignition will hinder airbag performance which may cause dynamically unstable landing conditions.

- **Verification Approach**
  - **Horizontal rocket characterization and performance test stand firings**
    - Test involves firing flight-like rockets in a controlled setting to verify reliability of ignition.
    - Will also generate data on thrust onset rise times to be used in rocket models within trajectory and dynamics simulations.

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9078: Horizontal rocket thrust and ISP

- **Element Description**
  - **Horizontal rocket thrust and ISP profile are as expected.**
    - Unexpected thrust and ISP performance will result in undesirable attitude, rates, and velocity profiles.

- **Verification Approach**
  - **Horizontal rocket characterization and performance test stand firings**
    - Test involves firing flight-like rockets in a controlled setting to determine whether performance characteristics meet expectations.
    - A sufficient number of trials needed to gain statistical confidence should be executed across bounding set of conditions such as grain temperature.
    - Data will also be used to create accurate thruster models for use in trajectory simulations.

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9079: Horizontal rockets decelerate capsule

- **Element Description**
  - **Horizontal rockets decelerate capsule to velocity limits prior to impact**
    - Failure of horizontal rockets to perform as expected will cause unacceptable horizontal velocities and possible capsule roll over.

- **Verification Approach**
  - **Parachute/capsule horizontal rocket interaction firing test**
    - Test involves firing flight-like horizontal rockets during a drop test with flight-like parachutes, and a capsule with the correct mass properties.
    - Will confirm validity of capsule response dynamical analysis and that second-order effects due to parachute interaction with the capsule are adequately modeled.
    - Only needs to be run for a few representative cases.
  - **Capsule response dynamics analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each can be observed.
    - Case runs should span an exhaustive range of expected conditions.

9080: Post-burn attitude and rates

- **Element Description**
  - **Post-burn attitude and rates within tolerance**
    - Expected post-burn attitude and rates assessment is essential to preventing unfavorable CM landing attitudes.

- **Verification Approach**
  - **Parachute/capsule horizontal rocket interaction firing test**
    - Test involves firing flight-like horizontal rockets during a drop test with flight-like parachutes, and a capsule with the correct mass properties.
    - Will confirm validity of capsule response dynamical analysis and that second-order effects due to parachute interaction with the capsule are adequately modeled.
    - Only needs to be run for a few representative cases.
  - **Capsule response dynamics analysis**
    - Analysis involves "multi-body" 6-DOF simulation where forces can be applied to individual components (e.g. capsule, risers, chutes) attached to each other and the constrained motion between of each can be observed.
    - Case runs should span an exhaustive range of expected conditions.

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9081: Rocket burn loads and dynamics

- **Element Description**
  - **CM and crew tolerant to loads and dynamics associated with rocket burn**
    - Structural failure and injury to crew may result from inaccurate prediction of rocket burn loads and dynamics.

- **Verification Approach**
  - **Horizontal rocket firing shocks and loads transference analysis**
    - Test involves measurement of rocket loads and load frequency content on a flight-like structure at critical attachment points along the structure.
    - Only need to execute a few representative cases to both confirm the validity of the load transfer analysis, and to gather accelerometer data to calibrate the structural attenuation model used in the analysis.
    - Measurements should also be gathered to verify that acoustical effects are acceptable.
  - **Horizontal rocket/capsule interaction test firing**
    - Activity involves an analysis to determine that the amount of attenuation of the rocket firing shock, as transferred through the structure, results in acceptable levels seen at the attach points for critical components and the crew.

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9082: Plume impingement on CM

- **Element Description**
  - **No adverse plume impingement effects on CM**
    - An adverse plume impingement may compromise backshell integrity via plume burn through.

- **Verification Approach**
  - **Capsule plume impingement and vehicle configuration analysis**
    - Activity involves 3-dimensional modeling to determine if expected plume will impinge on capsule.
    - Will need to model temperature and velocity of exhaust as a function of distance from the nozzle and compare with sensitivity of vehicle to plume intensity.
  - **Horizontal rocket characterization and performance test stand firings**
    - Test involves firing flight-like rockets in a controlled setting to verify shape and size of thruster plume for use in plume impingement analysis.
    - A sufficient number of trials needed to gain statistical confidence should be executed across bounding set of conditions such as grain temperature and ground effects.
  - **Horizontal rocket/capsule interaction test firing**
    - Test involves firing flight-like rockets attached to a capsule mock-up with flight-like fidelity in exterior geometry.
    - A few representative cases should be run to confirm the validity of the plume impingement analysis.
    - Data should also be collected to verify that deposited particulates from the exhaust do not pose a hazard to seals, windows, and vents.

This briefing is for status only and does not represent complete engineering data analysis

Airbag Operation

This briefing is for status only and does not represent complete engineering data analysis

1183: Airbag stroke performance

- **Element Description**
  - **Airbag stroke capability and performance as expected**
    - Airbag stroke capability outside the design specifications may lead to unacceptable impact loads and unstable mode conditions.

- **Verification Approach**
  - **Airbag characterization bounding test**
    - Laboratory test under controlled conditions to verify stroke performance as a function of velocity on a single bag.
    - Data will also be used to anchor airbag pressure and stroke analysis.
  - **Airbag pressure and stroke analysis**
    - Computer simulation of airbag stroke across entire range of expected initial velocity conditions and expected pressure dispersions

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1184: Airbags vented at proper time 1/2

- **Element Description**
  - **Airbags vented at the proper time**
    - Venting of inflated airbags upon impact (proper time) prevents unstable mode and reduces associated impact energy.

- **Verification Approach**
  - **Integrated avionics test bed and flight software sequence timing test**
    - Test requires execution of flight software on flight-like avionics using simulated GNC sensor data based on 6-DOF trajectory simulation to mimic response of vehicle to dynamical environment.
    - Will verify that no intricate timing issues exist that would cause the GNC software to produce different results when running on hardware as opposed to a simulated environment.
    - Only need to be run for selected, representative cases.
  - **Sensor characterization and qualification test**
    - Test involves characterization of pressure sensors in a controlled environment to verify that performance meets accuracy specifications.
    - Must characterize performance over entire range of expected temperatures and pressures.
  - **Controlled laboratory venting test**
    - Test involves using a flight-like pressure sensor to trigger venting of a flight-like airbag in a controlled setting under an exhaustive set of conditions.
    - Will be used to verify that the precision and repeatability to which venting can be performed is acceptable.

1184: Airbags vented at proper time 2/2

- **Verification Approach (cont.)**
  - **Airbag performance characterization drop test**
    - Test involves dropping a flight-like airbag attached to either a flight-like capsule or equivalent mass simulator under an enveloping set of initial velocity, orientation, and terrain effect conditions.
    - Each test should be analyzed to confirm venting performance.

This briefing is for status only and does not represent complete engineering data analysis

1185: Airbag integrity

- **Element Description**
  - **Airbags integrity not compromised by interaction with terrain**
    - Failure to account for interaction with terrain may compromise airbag integrity.

- **Verification Approach**
  - **Airbag terrain interaction drop test**
    - Test involves dropping a flight-like airbag attached to either a flight-like capsule or equivalent mass simulator under enveloping conditions of velocity, orientation, and terrain features (rocks, plants, etc.)
  - **Airbag materials qualification test**
    - Test involves measuring the abrasion and puncture resistance characteristics of airbag material coupons when exposed to simulated stresses and strains.
    - Will verify that the strength of the material used in the airbags meets specification.
  - **Landing site investigation**
    - Data collection of major landing sites and subsequent terrain map generation.

This briefing is for status only and does not represent complete engineering data analysis

Impact Attenuation

This briefing is for status only and does not represent complete engineering data analysis

1186: Crew seat performance

- **Element Description**
  - **Crew seat restraint and stroke capability and performance as expected**
    - Severe crew injury may result from inadequate performance of crew seat restraint and stroke capability.

- **Verification Approach**
  - **Crew seat and loads impact analysis**
    - Activity involves finite element analysis to determine whether the seat impact attenuation
  - **Crew seat laboratory loads test**
  - **High fidelity capsule impact test**
    - Representative of actual capsule impact conditions
    - Instrumented helicopter or drop tower tests

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1187: Crew impact loads

- **Element Description**
  - **Load transmitted to crew due to impact is as expected**
    - Excessive loads on crew during impact may result in severe injury.

- **Verification Approach**
  - **Landing impact load transmission analysis**
    - Finite element/dynamics analysis performed across bounding range of impact velocities and orientations, with loads transmitted through inflated airbags
  - **High fidelity capsule impact test**
    - Will require flight like capsule with realistic load paths including tanks, airframe, airbags, crew couch, and instrumented human crash test articles
    - Drop scenarios should include a representative range in impact velocities and orientations
    - Needs to include water landing scenarios with or without airbags as appropriate
    - Goal is to provide model and parameter correlation data for the impact loads and dynamics analysis as well as a physical demonstration that simulation results are accurate

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1188: Post-impact attitude and rates

- **Element Description**
  - **Post-impact attitude and rates are as expected**
    - Excessive attitudes and rates after impact may result in capsule roll over.
- **Verification Approach**
  - **Impact dynamics analysis**
    - 6 DOF dynamics analysis performed across bounding range of airbag impact velocities and orientations
  - **High fidelity landing dynamics test**
    - Requires flight configuration airbags, but simulated capsule mass with flight mass properties is sufficient
    - Drop scenarios should include a representative range in impact velocities and orientations
    - Goal is to provide model and parameter correlation data for the impact dynamics analysis

1189: Impact structural integrity

- **Element Description**
  - **Capsule maintains appropriate structural integrity and unconsumed volatiles not released**
    - Failure of structural integrity can result in structural deformation and crew injury.
    - Breach in main pressure vessel may cause capsule to sink.

- **Verification Approach**
  - **Impact loads and dynamics analysis**
    - Finite element/dynamics analysis performed across bounding range of impact velocities and orientations, with loads transmitted through inflated airbags
  - **High fidelity capsule impact test**
    - Will require flight like capsule with realistic load paths including tanks, airframe, airbags
    - Drop scenarios should include a representative range in impact velocities and orientations
    - Needs to include water landing scenarios with or without airbags as appropriate
    - Goal is to provide model and parameter correlation data for the impact loads and dynamics analysis as well as a physical demonstration that the capsule can survive impact

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1190: Terrain characteristics

- **Element Description**
  - **Ground and terrain characteristics are as expected**
    - Absence of accurate knowledge of ground and terrain characteristics will produce a dubious model of the capsule impact simulations.
    - Impact on hazardous terrain may violate acceptable loads

- **Verification Approach**
  - **Landing site terrain survey**
    - Data collection (e.g. ground GPS survey and air-SAR) for all candidate landing sites and subsequent terrain map generation for entire location.
    - Terrain maps should include elevation, slope, and major hazards (at capsule scale)
    - Geomorphology assessment (rock abundance and soil characteristics)

1191: Landing Wind Speeds

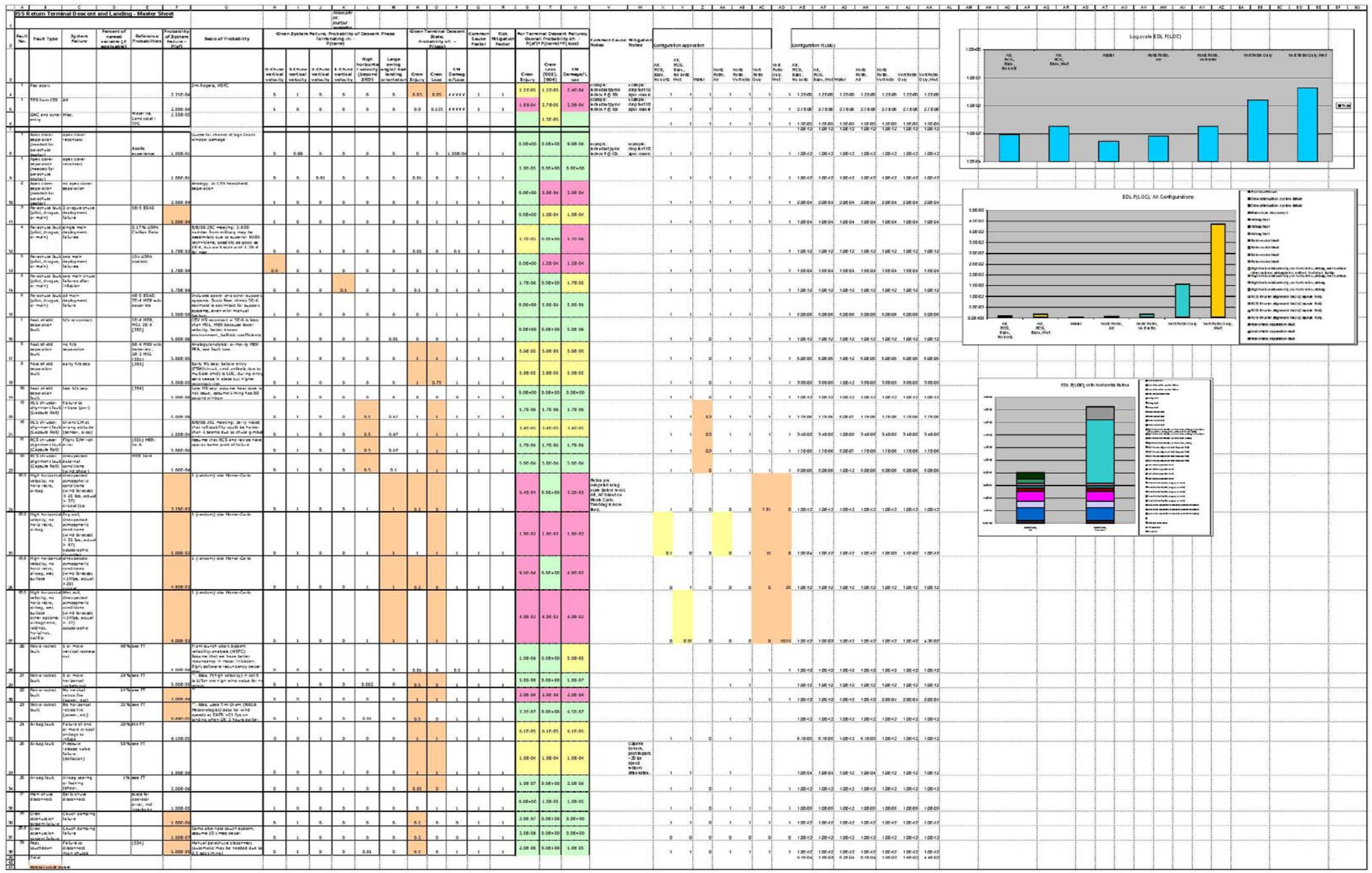
- **Verification Statement**
  - **Wind speeds at the time of landing are expected**
    - Errors in estimated wind speed may provide unacceptable landing environments as well as inaccurate model capsule impact simulations and landing site dispersions.

- **Verification Approach**
  - **Historical wind forecast reliability analysis.**
    - All inclusive study conducted for all landing sites, all seasons, and times of day
    - Confirms that historical expectations of wind speeds is within operational limits
    - Confirms that winds speeds are likely to remain within operational limits given a favorable forecast at the time of the go/no go de-orbit decision

This briefing is for status only and does not represent complete engineering data analysis

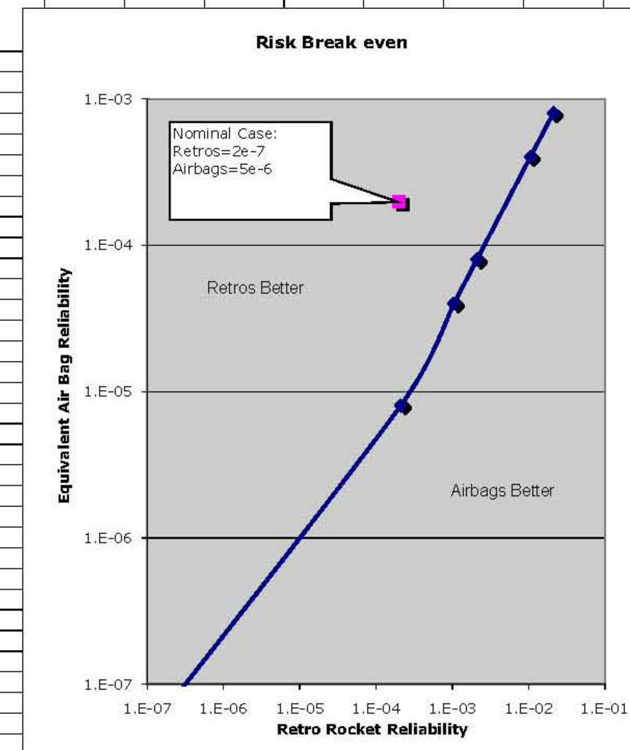
Appendix C. Task 1 Integrated Entry, Descent and Landing Risk Matrix

(Insert 11x17 paper)



Integrated Landing Assessment CM Configurations

Configuration Name	Vertical System	RCS, horiz. Rockets	Seat System	Parachute Separation
Air, no RCS, Base	Airbags	No	Baseline	
Air, RCS, Base	Airbags	Yes	Baseline	
Air, no RCS, Alt	Airbags	No	Alternate	Yes/no
Air, RCS, Alt	Airbags	Yes	Alternate	
Retro, no RCS, Base	Retros in base	No	Baseline	
Retro, RCS, Base	Retros in base	Yes	Baseline	
Retro, no RCS, Alt	Retros in base	No	Alternate	
Retro, RCS, Alt	Retros in base	Yes	Alternate	



Common Design Features and Assumptions

606 configuration with modifications/variations
Land landing after nominal entry
Heatshield separates
3 parachutes
Suit for landing: 3/2007 Constellation Space Suit Element (CSSE) Reference Architecture has rigid bearing rings at torso and limbs
Assume for this study that a standard soft suit will be used instead to reduce risk of injury
Landing site winds have ~1% chance of increasing to >21fps after being OK 3 hours before landing (details elsewhere)

Configuration Details

Airbag 2nd Gen biased system tumbles at horizontal impact velocity of: 61+ fps on dry soil, 50 fps on wet/soft soil
Airbag system tumbles at windspeed over 70 fps with added horizontal retros on dry soil (very unlikely)
Retro (vertical) system tumbles at horizontal impact velocity of: 30 fps on dry soil, 22 fps on wet soil
Retro (vertical) system tumbles at windspeed of 47 fps with added horizontal retros on dry soil
Roll control is in all configurations (if it's not, then add cases to the RCS/Horizontal Rocket column)
Horizontal rockets require roll control since they only point one direction
Seat System: includes seat struts, cushions, harness, etc; plus CM structure and tank placement
baseline = JSC: as of 5/16/07 has 9 passive struts, ±8 inches of stroke in all axes
baseline results in LOC for tumbling cases
altenate partially defined: 1 meter optimized stroke, 6 point harness, shoulder and head side (y axis) restraints
alternate performs similarly to WvL seat assumption: 80% to 100% protection from hard landing and tumbling
Parachute Separation: only needed if some configurations will differ as to separating/staying attached after landing
automatic cutter system may be needed due to 0.5 second timing after impact

Notes

Master sheet has all raw data
Configuration sheets (retro, etc) select rows of data from Master sheet

Questions

Should we consider roll control without rockets? (Bob West parachute line latches or similar)
Seat system is TBD. Baseline is probably passive struts. Alternate may have seat pan allowed to collapse in a controlled fashion or may have active struts.
Does parachute system have multiple configurations? Chutes detach?
Does horizontal or roll control plume impinge on parachute and cause any risk?
Does airbag P(LOC) need to be increased for risk of pad abort to water and airbag (possibly failed) causing leak and CM sinking?
Tumbling CM P(LOC) = ? (used mostly 100%; no one died in Soyuz tumbles but they have long stroke and custom seat liners)

Airbag vs. Retro Comparison Sensitivity

				LOC
Retro	2.11E-04	2.11E-04		
Airbag	2.01E-04	2.01E-04	1.63E-04	1.61E-04
4				
	Retro	Airbag		
0.1	1.00E-08	1.00E-08		
1	0.000210703	8.04E-06		
5	0.001053515	4.02E-05		
10	0.00210703	8.04E-05		
50	0.010535149	4.02E-04		
100	0.021070299	8.04E-04		
	2.00E-04	2.00E-04		

ISS Return Terminal C		0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
Fault No.	Fault Type		Probability of System Failure - P(sf)	0	Configuration Application	0	0	0	0	0	0 Configuration P(LOC)		0	0	0	0	0	0
0	0			Crew Loss	Air, RCS, Base, No horiz	Air, RCS, Base, No horiz, Wet	Water	Horiz Retro, Air	Horiz Retro, Vert retro	Vert Retro Only	Vert Retro Only, Wet	Air, RCS, Base, No horiz	Air, RCS, Base, Wet	Water	Horiz Retro, Air	Horiz Retro, Vert retro	Vert Retro Only	Vert Retro Only, Wet
1	Pad abort		2.35E-04	0.05	1	1	1	1	1	1	1	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175
1	TPS from ISS	All	2.00E-04	0.135	1	1	1	1	1	1	1	0.000027	0.000027	0.000027	0.000027	0.000027	0.000027	0.000027
8	GNC and other entry		1.50E-05	0	1	1	1	1	1	1	1	0.000015	0.000015	0.000015	0.000015	0.000015	0.000015	0.000015
0	0		0.00E+00	0	0	0	0	0	0	0	0	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
1	Apex cover separation (needed for parachute deploy)		1.00E-01	0	1	1	1	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
1	Apex cover separation (needed for parachute deploy)		1.00E-01	0	1	1	1	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	2.00E-04	1	1	1	1	1	1	1	1	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	1.00E-04	1	1	1	1	1	1	1	1	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	Parachute fault (pilot, drogue, or main)		1.70E-03	0	1	1	1	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	1.70E-04	1	1	1	1	1	1	1	1	0.000153	0.000153	0.000153	0.000153	0.000153	0.000153	0.000153
5	Parachute fault (pilot, drogue, or main)		1.70E-04	0	1	1	1	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	5.00E-06	1	1	1	1	1	1	1	1	0.000005	0.000005	0.000005	0.000005	0.000005	0.000005	0.000005
7	heat shield separation fault		5.00E-06	0	1	1	0	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
8	heat shield separation fault	no h/s separation	5.00E-05	1	1	1	0	1	1	1	1	0.00005	0.00005	1E-12	0.00005	0.00005	0.00005	0.00005
9	heat shield separation fault	early h/s sep	5.00E-05	0.75	1	1	0	1	1	1	1	0.0000375	0.0000375	1E-12	0.0000375	0.0000375	0.0000375	0.0000375
10	heat shield separation fault		1.00E-06	0	1	1	0	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
15	RCS thruster alignment fault (Capsule Roll)	Failure to initiate (pwr)	5.00E-06	1	1	1	0.3	1	1	1	1	0.000001675	1.675E-06	5.025E-07	1.675E-06	1.675E-06	1.675E-06	1.675E-06
16	RCS thruster alignment fault (Capsule Roll)	Orient CM at wrong attitude (sensor, prop)	1.00E-04	1	1	1	0.3	1	1	1	1	0.0000335	0.0000335	0.00001005	0.0000335	0.0000335	0.0000335	0.0000335
17	RCS thruster alignment fault (Capsule Roll)	Flight S/W roll error	5.00E-06	1	1	1	0.3	1	1	1	1	0.000001675	1.675E-06	5.025E-07	1.675E-06	1.675E-06	1.675E-06	1.675E-06
18	RCS thruster alignment fault (Capsule Roll)	Unexpected external conditions (wind shear)	1.00E-04	1	1	1	0	1	1	1	1	0.000005	0.000005	1E-12	0.000005	0.000005	0.000005	0.000005
18.5	Horizontal Velocity Causes Tumbling		3.20E-03	0	1	0	0	0	0	7.81	0	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
18.5	Horizontal Velocity Causes Tumbling	Dry soil, Unexpected atmospheric conditions (wind forecast = 21 fps, actual = 47) catastrophic (tumble)	1.00E-03	1	0.1	0	0	0	1	15	0	0.0001	1E-12	1E-12	1E-12	0.001	0.015	1E-12
18.5	Horizontal Velocity Causes Tumbling		4.80E-03	0	0	1	0	0	0	0	25	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
18.5	Horizontal Velocity Causes Tumbling	Wet soil, Unexpected atmospheric conditions (wind forecast =14fps, actual = 37) catastrophic	4.00E-03	1	0	0.25	0	0	0	0	10.75	1E-12	0.001	1E-12	1E-12	1E-12	1E-12	0.043
20	Retro-rocket fault		1.00E-04	0	0	0	0	0	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
21	Retro-rocket fault		5.00E-05	0	0	0	0	1	1	0	0	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
22	Retro-rocket fault	No vertical retros fire (power, etc)	2.00E-04	1	0	0	0	0	1	1	1	1E-12	1E-12	1E-12	1E-12	0.0002	0.0002	0.0002
23	Retro-rocket fault		6.49E-05	0	0	0	0	1	1	0	0	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
24	Airbag fault	Failure of one or more critical airbags to inflate	6.10E-05	1	1	1	0	1	0	0	0	0.000061	0.000061	1E-12	0.000061	1E-12	1E-12	1E-12
25	Airbag fault	Pressure release valve failure (deflation)	1.00E-04	1	1	1	0	1	0	0	0	0.0001	0.0001	1E-12	0.0001	1E-12	1E-12	1E-12
26	Airbag fault		2.00E-06	0	1	1	0	1	0	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
27	Main chute disconnect	Early chute disconnect	1.00E-05	1	1	1	0	1	1	1	1	0.00001	0.00001	1E-12	0.00001	0.00001	0.00001	0.00001
28	Crew attenuation system failure		1.00E-06	0	1	1	0	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
28.5	Crew attenuation system failure		1.00E-07	0	0	0	0	0	0	0	0	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
29	Post touchdown		1.00E-05	0	1	1	0	1	1	1	1	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12	1E-12
0	Total	Configuration P(LOC)	0	0	0	0	0	0	0	0	0	0.0009121	0.0018121	0.00052281	0.0008121	0.0018511	0.0158511	0.0438511

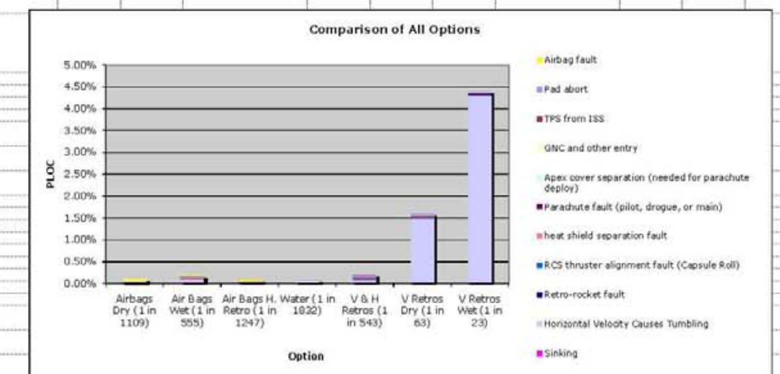
	Airbags Dry	Air Bags Wet	Air Bags H. Retro	Water	V & H Retros	V Retros Dry	V Retros Wet	
	Airbags Dry (1 in 1109)	Air Bags Wet (1 in	Air Bags H. R	Water (1 in 1832)	V & H Retros	V Retros Dry (	V Retros Wet (1 in 23)	
Pad abort	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175	0.00001175	
TPS from ISS	0.000027	0.000027	0.000027	0.000027	0.000027	0.000027	0.000027	
GNC and other entry	0.000015	0.000015	0.000015	0.000015	0.000015	0.000015	0.000015	
Apex cover separation (needed for parachute deploy)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
Parachute fault (pilot, drogue, or main)	0.000258	0.000258	0.000258	0.000258	0.000258	0.000258	0.000258	
heat shield separation fault	8.75E-05	8.75E-05	8.75E-05	4E-12	8.75E-05	8.75E-05	8.75E-05	
RCS thruster alignment fault (Capsule Roll)	0.00004185	0.00004185	0.00004185	1.1055E-05	0.00004185	0.00004185	0.00004185	For airbags, different roll orientations improve stability
Horizontal Velocity Causes Tumbling	0.0001	0.001	4E-12	4E-12	0.001	0.015	0.043	2nd gen airbags reduced risk
Retro-rocket fault	4E-12	4E-12	4E-12	4E-12	0.0002	0.0002	0.0002	
Airbag fault	0.000161	0.000161	0.000161	3E-12	3E-12	3E-12	3E-12	
Sinking	0	0	0	2.30E-05	0	0	0	
Total PLOC	0.0009021	0.0018021	0.0008021	0.000545805	0.0018411	0.0158411	0.0438411	
PLOC as 1-in-X format (inverse of total PLOC)	1108.524537	554.9081584	1246.72732	1832.156106	543.153545	63.1269293	22.8096466	

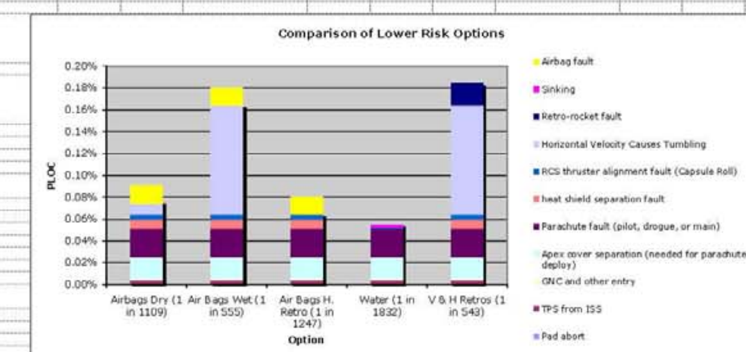
Note: "Horizontal Velocity Causes Tumbling" is based on choice of operational constraint combined with the design.
It could be reduced at the expense of low landing availability.
Case used was 18FPS go-for-landing wind, for 3 landing sites:

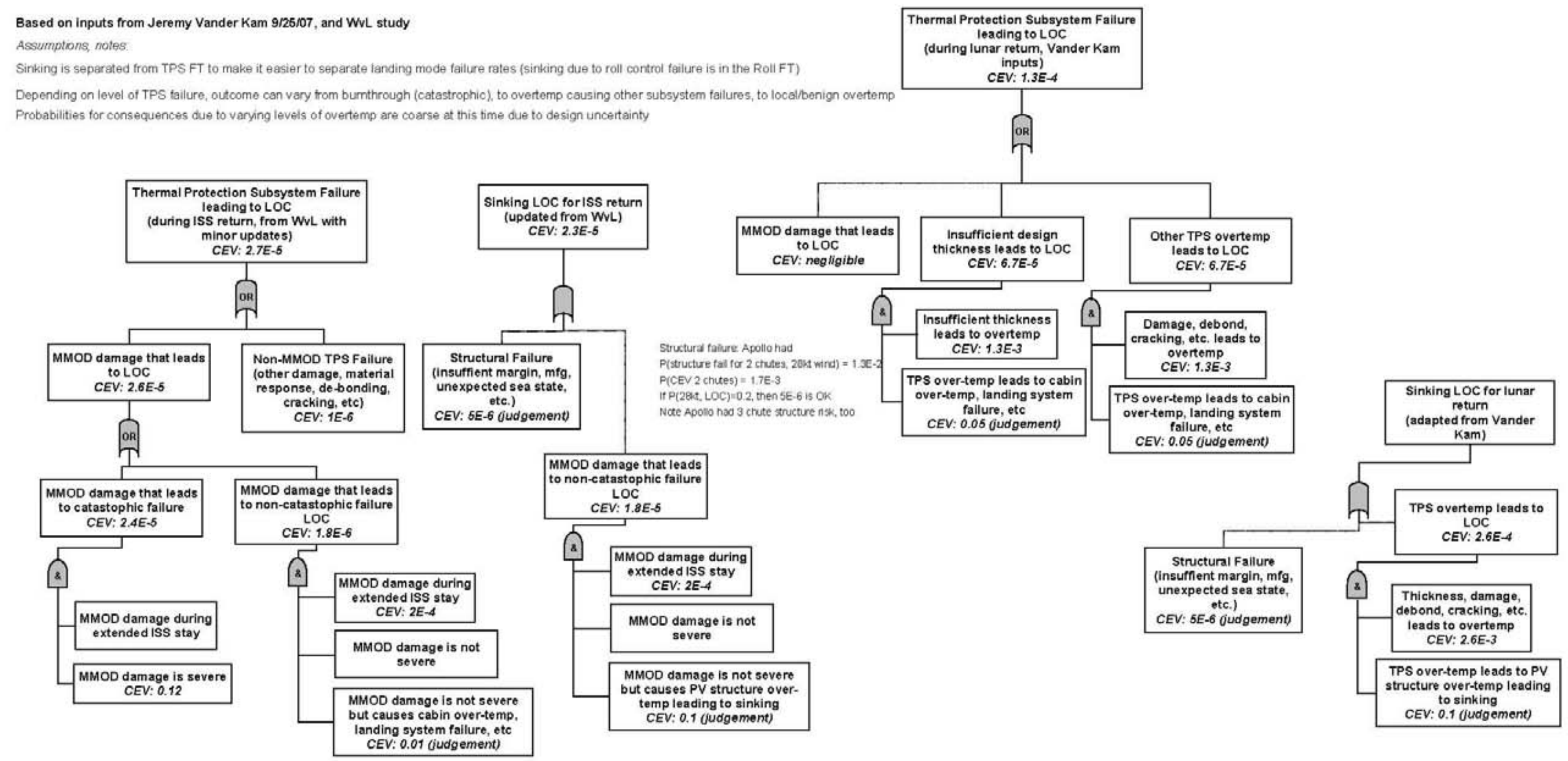
P(first chance is OK) = 0.45
P(OK within 80 hours) = 90%
P(OK within 200 hours) = 99%

P(OK within 200 hours day only) = 90%

P(OK within 500 hours day only) = 99%







Based on inputs from Jeremy Vander Kam 9/25/07, and WvL study
Assumptions, notes:
Sinking is separated from TPS FT to make it easier to separate landing mode failure rates (sinking due to roll control failure is in the Roll FT)
Depending on level of TPS failure, outcome can vary from burnthrough (catastrophic), to overtemp causing other subsystem failures, to local/benign overtemp
Probabilities for consequences due to varying levels of overtemp are coarse at this time due to design uncertainty
Thermal Protection Subsystem Failure leading to LOC (during ISS return, from WvL with minor updates) CEV: 2.7E-5
OR
MMOD damage that leads to LOC CEV: 2.6E-5
Non-MMOD TPS Failure (other damage, material response, de-bonding, cracking, etc) CEV: 1E-6
OR
MMOD damage that leads to catastophic failure CEV: 2.4E-5
&
MMOD damage during extended ISS stay
MMOD damage is severe CEV: 0.12
MMOD damage that leads to non-catastophic failure LOC CEV: 1.8E-6
&
MMOD damage during extended ISS stay CEV: 2E-4
MMOD damage is not severe
MMOD damage is not severe but causes cabin over-temp, landing system failure, etc CEV: 0.01 (judgement)
Sinking LOC for ISS return (updated from WvL) CEV: 2.3E-5
Structural Failure (insuffient margin, mfg, unexpected sea state, etc.) CEV: 5E-6 (judgement)
MMOD damage that leads to non-catastophic failure LOC CEV: 1.8E-5
&
MMOD damage during extended ISS stay CEV: 2E-4
MMOD damage is not severe
MMOD damage is not severe but causes PV structure over-temp leading to sinking CEV: 0.1 (judgement)
Structural failure: Apollo had
P(structure fail for 2 chutes, 28kt wind) = 1.3E-2
P(CEV 2 chutes) = 1.7E-3
If P(28kt, LOC)=0.2, then 5E-6 is OK
Note Apollo had 3 chute structure risk, too
Thermal Protection Subsystem Failure leading to LOC (during lunar return, Vander Kam inputs) CEV: 1.3E-4
OR
MMOD damage that leads to LOC CEV: negligible
Insufficient design thickness leads to LOC CEV: 6.7E-5
&
Insufficient thickness leads to overtemp CEV: 1.3E-3
TPS over-temp leads to cabin over-temp, landing system failure, etc CEV: 0.05 (judgement)
Other TPS overtemp leads to LOC CEV: 6.7E-5
&
Damage, debond, cracking, etc. leads to overtemp CEV: 1.3E-3
TPS over-temp leads to cabin over-temp, landing system failure, etc CEV: 0.05 (judgement)
Sinking LOC for lunar return (adapted from Vander Kam)
TPS overtemp leads to LOC CEV: 2.6E-4
Structural Failure (insuffient margin, mfg, unexpected sea state, etc.) CEV: 5E-6 (judgement)
&
Thickness, damage, debond, cracking, etc. leads to overtemp CEV: 2.6E-3
TPS over-temp leads to PV structure over-temp leading to sinking CEV: 0.1 (judgement)

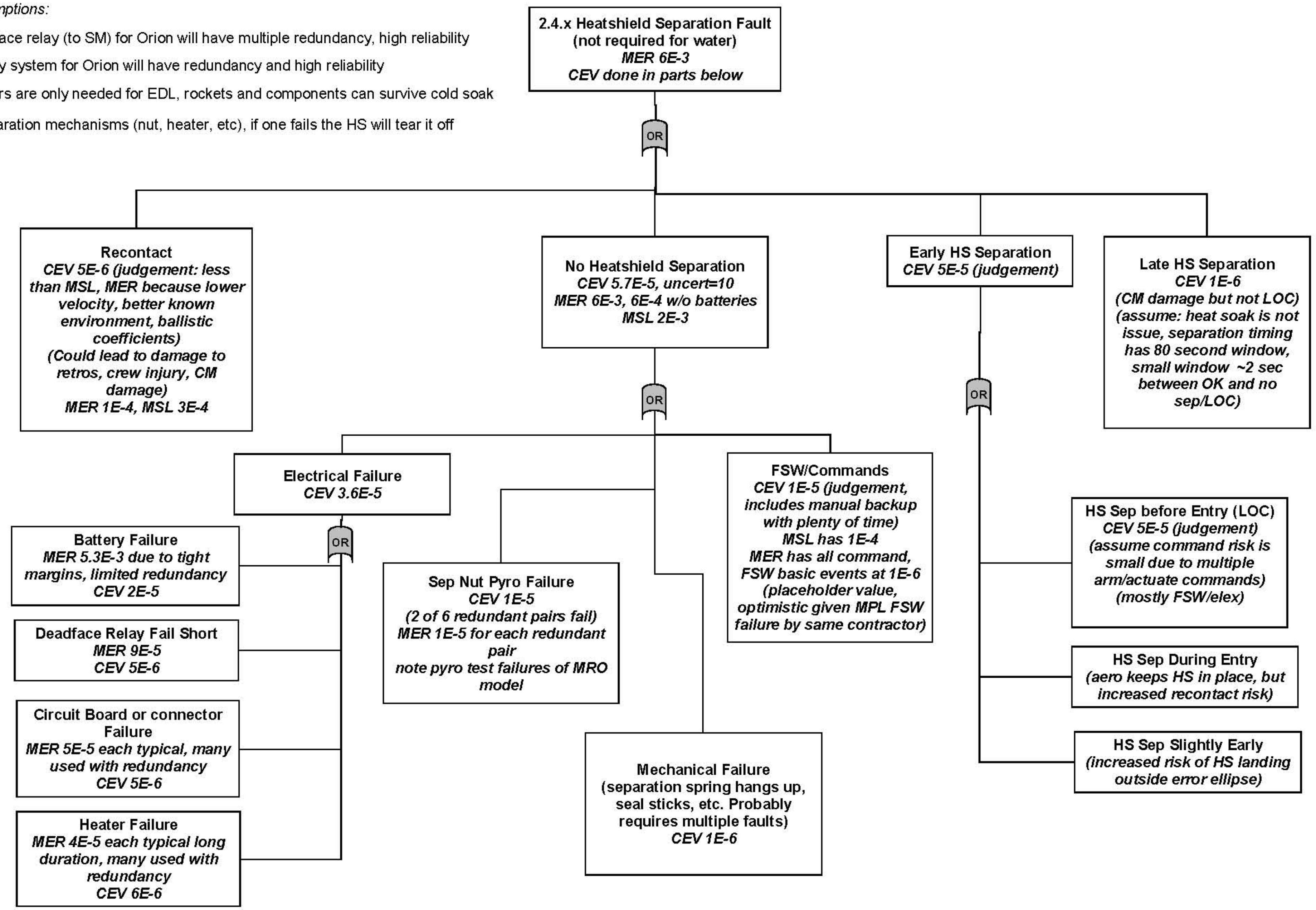
Assumptions:

Deadface relay (to SM) for Orion will have multiple redundancy, high reliability

Battery system for Orion will have redundancy and high reliability

Heaters are only needed for EDL, rockets and components can survive cold soak

6 separation mechanisms (nut, heater, etc), if one fails the HS will tear it off



File: Landing_Assessment_Risk_Matrix_2007-10-31-(9-22-09).xlsx; HS Sep FT

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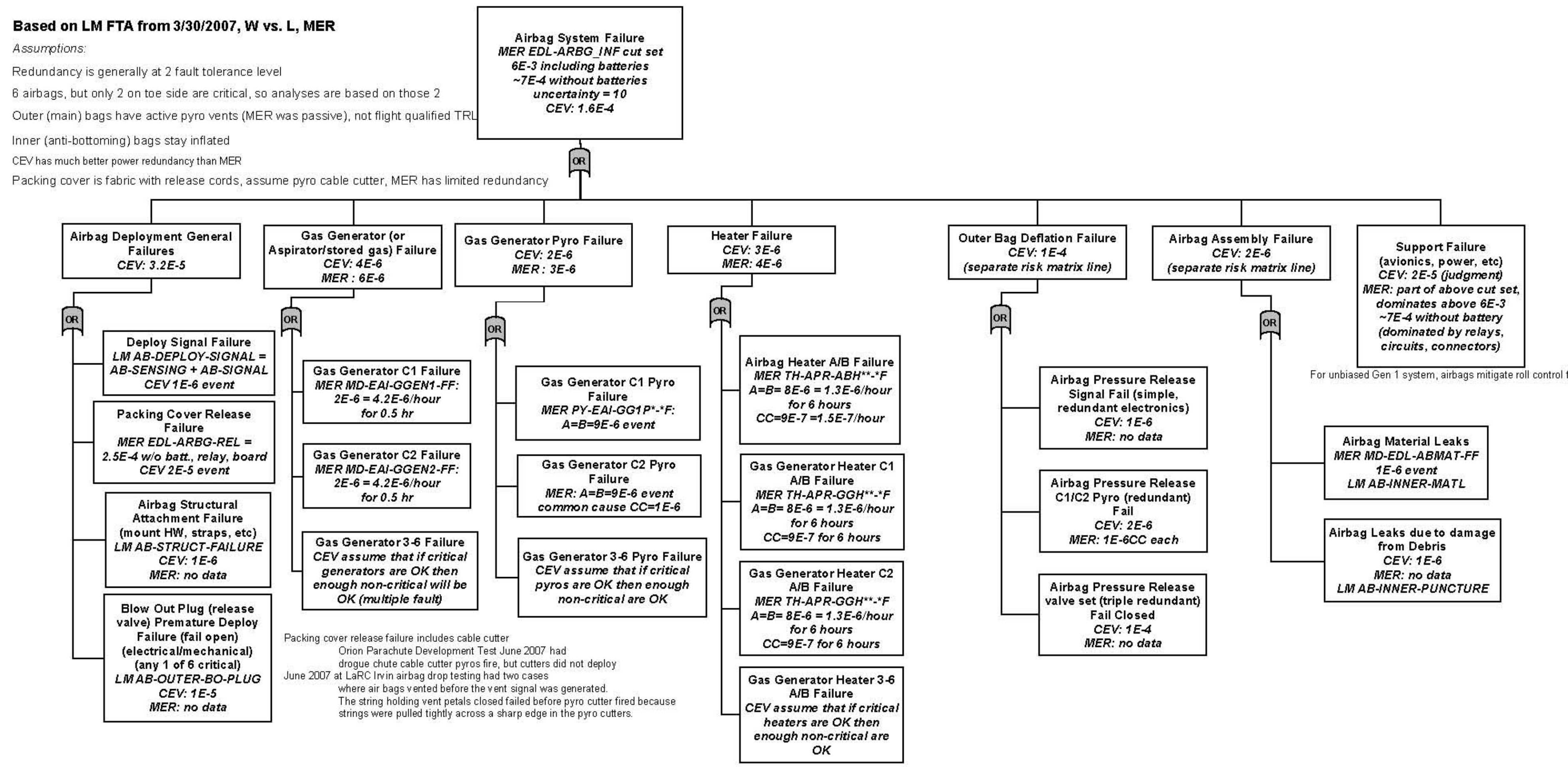


File: Landing_Assessment_Risk_Matrix_2007-10-31-(9-22-09).xlsx; Airbag FT

Printed: 9/22/2009, 2:32 PM

Based on Retro Fault Tree by Ravi Prakesh 3/22/07, W vs. L, etc.

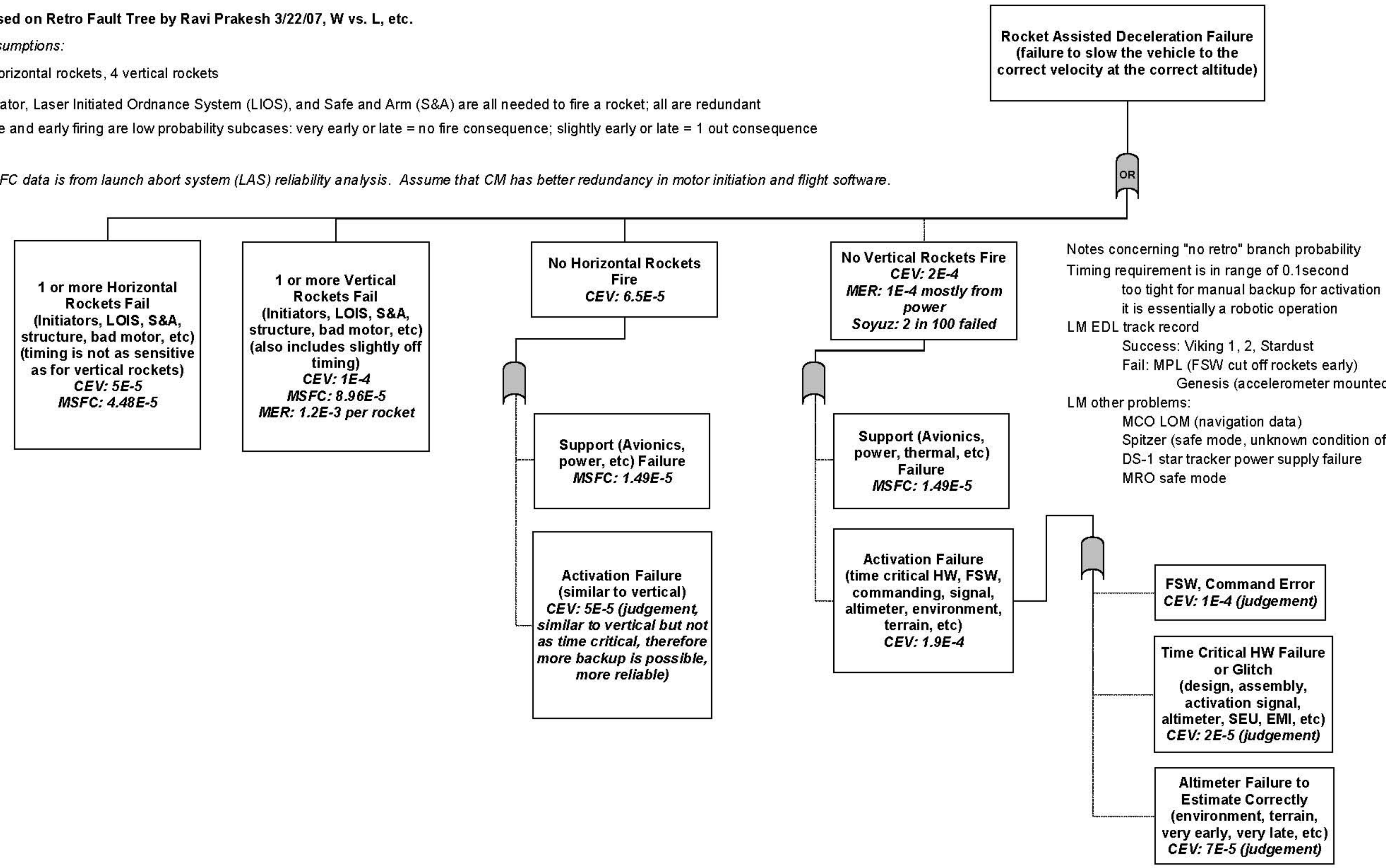
Assumptions:

4 horizontal rockets, 4 vertical rockets

Initiator, Laser Initiated Ordnance System (LIOS), and Safe and Arm (S&A) are all needed to fire a rocket; all are redundant

Late and early firing are low probability subcases: very early or late = no fire consequence; slightly early or late = 1 out consequence

MSFC data is from launch abort system (LAS) reliability analysis. Assume that CM has better redundancy in motor initiation and flight software.

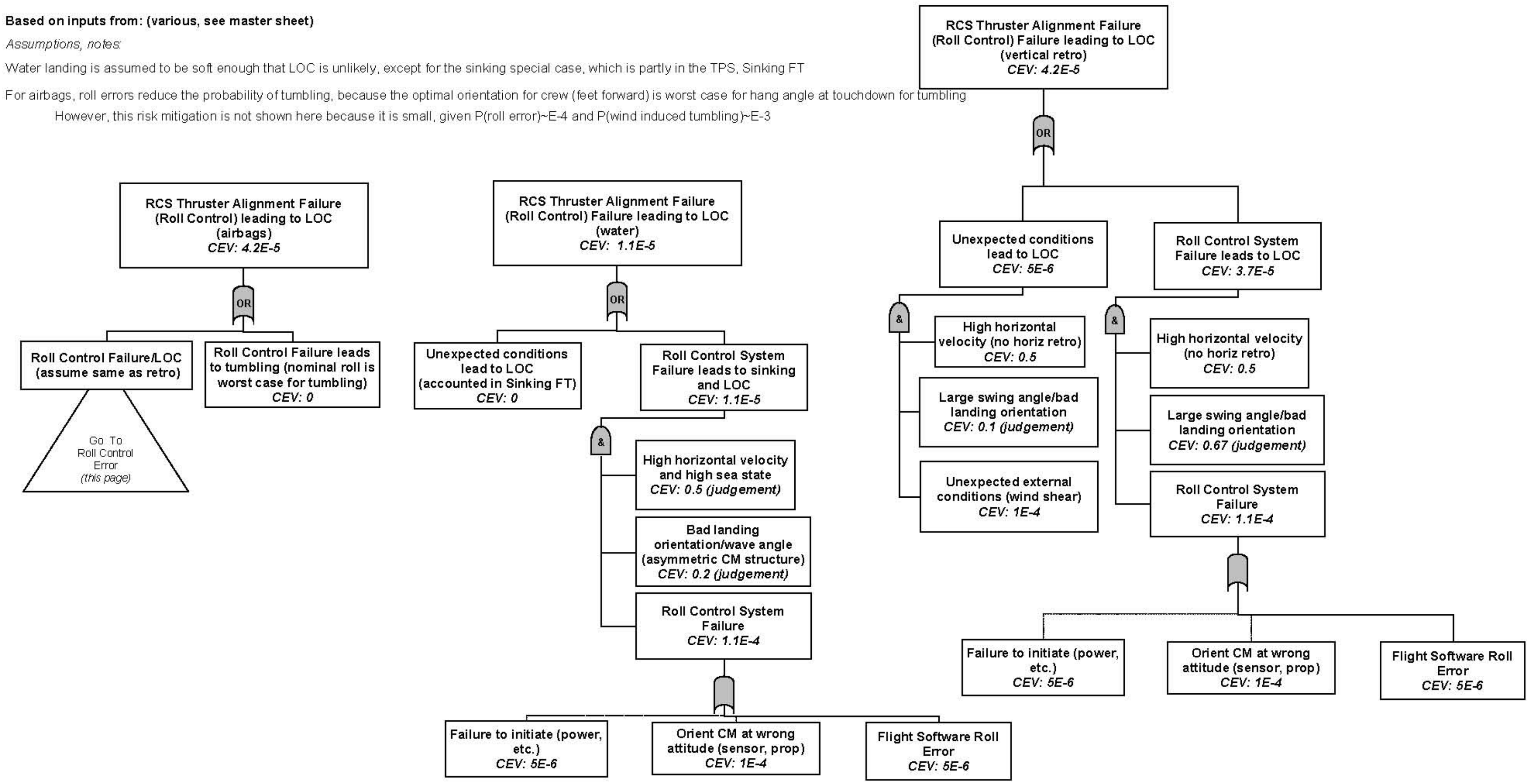


Based on inputs from: (various, see master sheet)

Assumptions, notes:

Water landing is assumed to be soft enough that LOC is unlikely, except for the sinking special case, which is partly in the TPS, Sinking FT

For airbags, roll errors reduce the probability of tumbling, because the optimal orientation for crew (feet forward) is worst case for hang angle at touchdown for tumbling
However, this risk mitigation is not shown here because it is small, given P(roll error)~E-4 and P(wind induced tumbling)~E-3



File: Landing_Assessment_Risk_Matrix_2007-10-31-(9-22-09).xlsx,Roll FT

Printed: 9/22/2009, 2:32 PM

ISS Return Terminal Descent and Landing - Retro Rocket, RCS, Baseline Seats

Assumptions: SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
15	RCS thruster alignment fault (Capsule Roll)	Failure to initiate (pwr)	0	5.00E-06	0.00E+00	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
16	RCS thruster alignment fault (Capsule Roll)	Orient CM at wrong attitude (sensor, prop)	0	1.00E-04	8/8/06 JSC meeting: Jerry noted that roll stability could be harder than it seems due to chute gimbal friction	0	1	0	0	0.5	0.67	1	1	1	1	1	3.4E-05	3.4E-05	3.4E-05		
17	RCS thruster alignment fault (Capsule Roll)	Flight S/W roll error	[501] MER: 1e-6	5.00E-06	Assume that RCS and retros have approx same prob of failure	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
18	RCS thruster alignment fault (Capsule Roll)	Unexpected external conditions (wind shear)	MER 1e-4	1.00E-04	0.00E+00	0	1	0	0	0.5	0.1	1	1	1	1	1	5.0E-06	5.0E-06	5.0E-06		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
20	Retro-rocket fault	1 or more vertical rockets out	see FT	1.00E-04	From launch abort system reliability analysis (MSFC). Assume that we have better redundancy in motor initiation, flight software redundancy better also	0	0	0	1	0	0	0.01	0	0.5	1	1	1.0E-06	0.0E+00	5.0E-05		
21	Retro-rocket fault	1 or more horizontal rockets out	see FT	5.00E-05	"". Also, P(high velocity) in col K is 1/5th the high wind value for no retros.	0	1	0	0	0.002	0	0.5	0	1	1	1	5.0E-08	0.0E+00	1.0E-07		
22	Retro-rocket fault	No vertical retros fire (power, etc)	see FT	2.00E-04	""	0	0	1	0	0	0	1	1	1	1	1	2.0E-04	2.0E-04	2.0E-04		
23	Retro-rocket fault	No horizontal retros fire (power, etc)	see FT	6.49E-05	"". Also, uses Tim Oram (NASA Meteorologist) data for wind speeds at EAFB >21 fps on landing when OK 3 hours earlier.	0	1	0	0	0.01	0	0.5	0	1	1	1	3.2E-07	0.0E+00	6.5E-07		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28	Crew attenuation system failure	Couch damping failure	0	1.00E-06	0.00E+00	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-07	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Retro Rocket, RCS, Alternate Seats

Assumption & SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
15	RCS thruster alignment fault (Capsule Roll)	Failure to initiate (pwr)	0	5.00E-06	0.00E+00	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
16	RCS thruster alignment fault (Capsule Roll)	Orient CM at wrong attitude (sensor, prop)	0	1.00E-04	8/8/06 JSC meeting: Jerry noted that roll stability could be harder than it seems due to chute gimbal friction	0	1	0	0	0.5	0.67	1	1	1	1	1	3.4E-05	3.4E-05	3.4E-05		
17	RCS thruster alignment fault (Capsule Roll)	Flight S/W roll error	[S01] MER: 1e-6	5.00E-06	Assume that RCS and retros have approx same prob of failure	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
18	RCS thruster alignment fault (Capsule Roll)	Unexpected external conditions (wind shear)	MER 1e-4	1.00E-04	0.00E+00	0	1	0	0	0.5	0.1	1	1	1	1	1	5.0E-06	5.0E-06	5.0E-06		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
20	Retro-rocket fault	1 or more vertical rockets out	see FT	1.00E-04	From launch abort system reliability analysis (MSFC). Assume that we have better redundancy in motor initiation, flight software redundancy better also	0	0	0	1	0	0	0.01	0	0.5	1	1	1.0E-06	0.0E+00	5.0E-05		
21	Retro-rocket fault	1 or more horizontal rockets out	see FT	5.00E-05	**. Also, P(high velocity) in col K is 1/5th the high wind value for no retros.	0	1	0	0	0.002	0	0.5	0	1	1	1	5.0E-08	0.0E+00	1.0E-07		
22	Retro-rocket fault	No vertical retros fire (power, etc)	see FT	2.00E-04	**	0	0	1	0	0	0	1	1	1	1	1	2.0E-04	2.0E-04	2.0E-04		
23	Retro-rocket fault	No horizontal retros fire (power, etc)	see FT	6.49E-05	**. Also, uses Tim Oram (NASA Meteorologist) data for wind speeds at EAFB >21 fps on landing when OK 3 hours earlier.	0	1	0	0	0.01	0	0.5	0	1	1	1	3.2E-07	0.0E+00	6.5E-07		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28.5	Crew attenuation system failure	Couch damping failure	0	1.00E-07	Some alternate couch system, assume 10 times better	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-08	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[S04]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Retro Rocket, no RCS, Baseline Seats

Assumption & SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for [illegible]	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
18.5	High horizontal velocity, no horiz retro, airbag, wet surface other options: airbag/retro, roll/not, horiz/not, tip/flip	Wet soil, Unexpected atmospheric conditions (wind forecast <14fps, actual > 37) catastrophic	0	4.00E-03	1 (random) site Monte-Carlo	0	1	0	0	1	1	1	1	1	1	1	4.0E-03	4.0E-03	4.0E-03		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
20	Retro-rocket fault	1 or more vertical rockets out	see FT	1.00E-04	From launch abort system reliability analysis (MSFC). Assume that we have better redundancy in motor initiation, flight software redundancy better also	0	0	0	1	0	0	0.01	0	0.5	1	1	1.0E-06	0.0E+00	5.0E-05		
22	Retro-rocket fault	No vertical retros fire (power, etc)	see FT	2.00E-04	""	0	0	1	0	0	0	1	1	1	1	1	2.0E-04	2.0E-04	2.0E-04		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28	Crew attenuation system failure	Couch damping failure	0	1.00E-06	0.00E+00	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-07	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Retro Rocket, no RCS, Alternate Seats

Assumptions: SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term): 0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Given Terminal Descent State, Probability of: - P(loss): Crew Injury	Crew Loss	CM Damage /Loss	Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss): Crew Injury	Crew Loss [001], [004]	CM Damage/Loss	Common Cause Notes	Mitigation Notes
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 00 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
18.5	High horizontal velocity, no horiz retro, airbag, wet surface other options: airbag/retro, roll/not, horiz/not, tip/flip	Wet soil, Unexpected atmospheric conditions (wind forecast <14fps, actual > 37) catastrophic	0	4.00E-03	1 (random) site Monte-Carlo	0	1	0	0	1	1	1	1	1	1	1	4.0E-03	4.0E-03	4.0E-03		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
20	Retro-rocket fault	1 or more vertical rockets out	see FT	1.00E-04	From launch abort system reliability analysis (MSFC). Assume that we have better redundancy in motor initiation, flight software redundancy better also	0	0	0	1	0	0	0.01	0	0.5	1	1	1.0E-06	0.0E+00	5.0E-05		
22	Retro-rocket fault	No vertical retros fire (power, etc)	see FT	2.00E-04	""	0	0	1	0	0	0	1	1	1	1	1	2.0E-04	2.0E-04	2.0E-04		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28.5	Crew attenuation system failure	Couch damping failure	0	1.00E-07	Some alternate couch system, assume 10 times better	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-08	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Airbag, RCS, Baseline Seats

Assumptions SWCM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E 3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
15	RCS thruster alignment fault (Capsule Roll)	Failure to initiate (pwr)	0	5.00E-06	0.00E+00	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
16	RCS thruster alignment fault (Capsule Roll)	Orient CM at wrong attitude (sensor, prop)	0	1.00E-04	8/8/06 JSC meeting: Jerry noted that roll stability could be harder than it seems due to chute gimbal friction	0	1	0	0	0.5	0.67	1	1	1	1	1	3.4E-05	3.4E-05	3.4E-05		
17	RCS thruster alignment fault (Capsule Roll)	Flight S/W roll error	[501] MER: 1e-6	5.00E-06	Assume that RCS and retros have approx same prob of failure	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
18	RCS thruster alignment fault (Capsule Roll)	Unexpected external conditions (wind shear)	MER 1e-4	1.00E-04	0.00E+00	0	1	0	0	0.5	0.1	1	1	1	1	1	5.0E-06	5.0E-06	5.0E-06		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
21	Retro-rocket fault	1 or more horizontal rockets out	see FT	5.00E-05	**. Also, P(high velocity) in col K is 1/5th the high wind value for no retros.	0	1	0	0	0.002	0	0.5	0	1	1	1	5.0E-08	0.0E+00	1.0E-07		
23	Retro-rocket fault	No horizontal retros fire (power, etc)	see FT	6.49E-05	**. Also, uses Tim Oram (NASA Meteorologist) data for wind speeds at EAFB >21 fps on landing when OK 2 hours earlier.	0	1	0	0	0.01	0	0.5	0	1	1	1	3.2E-07	0.0E+00	6.5E-07		
24	Airbag fault	Failure of one or more critical airbags to inflate	see FT	6.10E-05	0.00E+00	0	0	1	0	0	0	1	1	1	1	1	6.1E-05	6.1E-05	6.1E-05		
25	Airbag fault	Pressure release valve failure (deflation)	see FT	1.00E-04	0.00E+00	0	0	0	1	0	0	1	1	1	1	1	1.0E-04	1.0E-04	1.0E-04		
26	Airbag fault	Airbag tearing or leaking (shear, penetration, etc)	see FT	2.00E-06	0.00E+00	0	0	0	1	0	0	0.05	0	1	1	1	1.0E-07	0.0E+00	2.0E-06		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28	Crew attenuation system failure	Couch damping failure	0	1.00E-06	0.00E+00	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-07	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Airbag, RCS, Alternate Seats

Assumptions SWCM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term): 0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Given Terminal Descent State, Probability of: - P(loss): Crew Injury	Crew Loss	CM Damage /Loss	Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss): Crew Injury	Crew Loss [001], [004]	CM Damage/Loss	Common Cause Notes	Mitigation Notes
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CLV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
15	RCS thruster alignment fault (Capsule Roll)	Failure to initiate (pwr)	0	5.00E-06	0.00E+00	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
16	RCS thruster alignment fault (Capsule Roll)	Orient CM at wrong attitude (sensor, prop)	0	1.00E-04	8/8/06 JSC meeting: Jerry noted that roll stability could be harder than it seems due to chute gimbal friction	0	1	0	0	0.5	0.67	1	1	1	1	1	3.4E-05	3.4E-05	3.4E-05		
17	RCS thruster alignment fault (Capsule Roll)	Flight S/W roll error	[501] MER: 1e-6	5.00E-06	Assume that RCS and retros have approx same prob of failure	0	1	0	0	0.5	0.67	1	1	1	1	1	1.7E-06	1.7E-06	1.7E-06		
18	RCS thruster alignment fault (Capsule Roll)	Unexpected external conditions (wind shear)	MER 1e-4	1.00E-04	0.00E+00	0	1	0	0	0.5	0.1	1	1	1	1	1	5.0E-06	5.0E-06	5.0E-06		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
21	Retro-rocket fault	1 or more horizontal rockets out	see FT	5.00E-05	**. Also, P(high velocity) in col K is 1/5th the high wind value for no retros.	0	1	0	0	0.002	0	0.5	0	1	1	1	5.0E-08	0.0E+00	1.0E-07		
23	Retro-rocket fault	No horizontal retros fire (power, etc)	see FT	6.49E-05	**. Also, uses Tim Oram (NASA Meteorologist) data for wind speeds at EAFB >21 fps on landing when OK 3 hours earlier.	0	1	0	0	0.01	0	0.5	0	1	1	1	3.2E-07	0.0E+00	6.5E-07		
24	Airbag fault	Failure of one or more critical airbags to inflate	see FT	6.10E-05	0.00E+00	0	0	1	0	0	0	1	1	1	1	1	6.1E-05	6.1E-05	6.1E-05		
25	Airbag fault	Pressure release valve failure (deflation)	see FT	1.00E-04	0.00E+00	0	0	0	1	0	0	1	1	1	1	1	1.0E-04	1.0E-04	1.0E-04		
26	Airbag fault	Airbag tearing or leaking (shear, penetration, etc)	see FT	2.00E-06	0.00E+00	0	0	0	1	0	0	0.05	0	1	1	1	1.0E-07	0.0E+00	2.0E-06		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28.5	Crew attenuation system failure	Couch damping failure	0	1.00E-07	Some alternate couch system, assume 10 times better	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-08	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Airbag, no RCS, Baseline Seats

Assumptions: SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
18.5	High horizontal velocity, no horiz retro, airbag, wet surface other options: airbag/retro, roll/not, horiz/not, tip/flip	Wet soil, Unexpected atmospheric conditions (wind forecast <14fps, actual > 37) catastrophic	0	4.00E-03	1 (random) site Monte-Carlo	0	1	0	0	1	1	1	1	1	1	1	4.0E-03	4.0E-03	4.0E-03		
24	Airbag fault	Failure of one or more critical airbags to inflate	see FT	6.10E-05	0.00E+00	0	0	1	0	0	0	1	1	1	1	1	6.1E-05	6.1E-05	6.1E-05		
25	Airbag fault	Pressure release valve failure (deflation)	see FT	1.00E-04	0.00E+00	0	0	0	1	0	0	1	1	1	1	1	1.0E-04	1.0E-04	1.0E-04		
26	Airbag fault	Airbag tearing or leaking (shear, penetration, etc)	see FT	2.00E-06	0.00E+00	0	0	0	1	0	0	0.05	0	1	1	1	1.0E-07	0.0E+00	2.0E-06		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28	Crew attenuation system failure	Couch damping failure	0	1.00E-06	0.00E+00	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-07	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

ISS Return Terminal Descent and Landing - Airbag, no RCS, Alternate Seats

Assumptions: SM/CM separation

Fault No.	Fault Type	System Failure	Reference Probabilities	Probability of System Failure - P(sf)	Basis of Probability	Given System Failure, Probability of Descent Phase Terminating in: - P(term)						Given Terminal Descent State, Probability of: - P(loss)			Common Cause Factor	Risk Mitigation Factor	For Terminal Descent Failures, Overall Probability of: - P(sf)*P(term)*P(loss)			Common Cause Notes	Mitigation Notes
						0-Chute vertical velocity	3-Chute vertical velocity	2-Chute vertical velocity	1-Chute vertical velocity	High horizontal velocity (beyond SRD)	Large swing angle/ bad landing orientation	Crew Injury	Crew Loss	CM Damage /Loss			Crew Injury	Crew Loss [001], [004]	CM Damage/Loss		
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	Apollo experience	1.00E-01	Guess for chance of significant window damage	0	0.99	0	0	0	0	0	0	1.00E-04	1	1	0.0E+00	0.0E+00	9.9E-06	example: redundant pyros reduce P(f) 10x	example: drop test 10 apex covers
1	Apex cover separation (needed for parachute deploy)	apex cover recontact	0	1.00E-01	0	0	0	0.01	0	0	0	0.01	0	0	1	1	1.0E-05	0.0E+00	0.0E+00		
2	Apex cover separation (needed for parachute deploy)	no apex cover separation	0	2.00E-04	Analogy: to CEV heatshield separation	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	2.0E-04	2.0E-04		
3	Parachute fault (pilot, drogue, or main)	2 drogue chute deployment failure	5E-5 ESAS	1.00E-04	0	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-04	1.0E-04		
4	Parachute fault (pilot, drogue, or main)	single main deployment failures	0.17% USPA Civilian Data	1.70E-03	8/8/06 JSC meeting: 1:600 number from military may be pessimistic due to superior NASA technicians, possibly as good as 1E-4, but we'll stick with 1.7E-4 for now	0	0	1	0	0	0	0.01	0	0.1	1	1	1.7E-05	0.0E+00	1.7E-04		
5	Parachute fault (pilot, drogue, or main)	two main deployment failures	10x USPA statistic	1.70E-04	0	0.9	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.5E-04	1.5E-04		
5	Parachute fault (pilot, drogue, or main)	two main chute failures after inflation	0	1.70E-04	0	0	0	0	0.1	0	0	0.1	0	1	1	1	1.7E-06	0.0E+00	1.7E-05		
6	Parachute fault (pilot, drogue, or main)	all main deployment failure	4E-5 ESAS; 7E-4 MER w/o batteries	5.00E-06	Includes power and other support systems. Scott Peer thinks 5E-6 estimate is optimistic for support systems, even with manual backup.	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	5.0E-06	5.0E-06		
7	heat shield separation fault	h/s re-contact	1E-4 MER, MSL 3E-4 [302]	5.00E-06	CEV HS recontact = 5E-6 is less than MSL, MER because lower velocity, better known environment, ballistic coefficients	0	1	0	0	0	0.01	0	0	1	1	1	0.0E+00	0.0E+00	5.0E-06		
8	heat shield separation fault	no h/s separation	6E-4 MER w/o batteries ; 2E-3 MSL [301]	5.00E-05	Analogy/analysis: primarily MER PRA, see fault tree.	0	1	0	0	0	0	1	1	1	1	1	5.0E-05	5.0E-05	5.0E-05		
9	heat shield separation fault	early h/s sep	[303]	5.00E-05	Early HS sep: before entry (FSW/circuit, cmd unlikely due to multiple cmd) is LOC, during entry aero keeps in place but higher recontact risk	0	1	0	0	0	0	1	0.75	1	1	1	5.0E-05	3.8E-05	5.0E-05		
10	heat shield separation fault	late h/s sep	[304]	1.00E-06	Late HS sep: assume heat soak is not issue, assume timing has 80 second window	0	1	0	0	0	0	0	0	0	1	1	0.0E+00	0.0E+00	0.0E+00		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!		
18.5	High horizontal velocity, no horiz retro, airbag, wet surface other options: airbag/retro, roll/not, horiz/not, tip/flip	Wet soil, Unexpected atmospheric conditions (wind forecast <14fps, actual > 37) catastrophic	0	4.00E-03	1 (random) site Monte-Carlo	0	1	0	0	1	1	1	1	1	1	1	4.0E-03	4.0E-03	4.0E-03		
24	Airbag fault	Failure of one or more critical airbags to inflate	see FT	6.10E-05	0.00E+00	0	0	1	0	0	0	1	1	1	1	1	6.1E-05	6.1E-05	6.1E-05		
25	Airbag fault	Pressure release valve failure (deflation)	see FT	1.00E-04	0.00E+00	0	0	0	1	0	0	1	1	1	1	1	1.0E-04	1.0E-04	1.0E-04		
26	Airbag fault	Airbag tearing or leaking (shear, penetration, etc)	see FT	2.00E-06	0.00E+00	0	0	0	1	0	0	0.05	0	1	1	1	1.0E-07	0.0E+00	2.0E-06		
27	Main chute disconnect	Early chute disconnect	stats for operator error, incl interlocks	1.00E-05	0.00E+00	1	0	0	0	0	0	0	1	1	1	1	0.0E+00	1.0E-05	1.0E-05		
28.5	Crew attenuation system failure	Couch damping failure	0	1.00E-07	Some alternate couch system, assume 10 times better	0	1	0	0	0	0	0.2	0	0	1	1	2.0E-08	0.0E+00	0.0E+00		
29	Post touchdown	Failure to disconnect main chutes	[504]	1.00E-05	Manual parachute disconnect (automatic may be needed due to 0.5 sec timing)	0	1	0	0	0.01	0	0.2	0	1	1	1	2.0E-06	0.0E+00	1.0E-05		
					Totals SUM [P(sf) * P(term)]	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!					Totals SUM [P(sf) * P(term) * P(loss)]	#REF!	#REF!	#REF!		

Number needs review

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14. ABSTRACT
Crew Exploration Vehicle (CEV) Chief Engineer requested a risk comparison of the Integrated Landing System design developed by NASA and the design developed by Contractor- referred to as the LM 604 baseline. Based on the results of this risk comparison, the CEV Chief engineer requested that the NESC evaluate identified risks and develop strategies for their reduction or mitigation. The assessment progressed in two phases. A brief Phase I analysis was performed by the Water versus Land-Landing Team to compare the CEV Integrated Landing System proposed by the Contractor against the NASA TS-LRS001 baseline with respect to risk. A phase II effort examined the areas of critical importance to the overall landing risk, evaluating risk to the crew and to the CEV Crew Module (CM) during a nominal land-landing. The findings of the assessment are contained in this report.

15. SUBJECT TERMS
Constellation Program; Crew Exploration Vehicle; Crew Module; Loss of Crew; Impact Dummy

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