Risk Profile for NASA's Crew Exploration Vehicle (CEV) System

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1. Executive Summary

This paper provides the results of a three-step modified Delphi technique that was used to develop the risk profile for NASA's Crew Exploration Vehicle (CEV) system, which is now being developed to have the capability to travel to International Space Station (ISS), Moon, Mars and beyond. The authors used an Electronic Meeting System (EMS) at DAU, Ft. Belvoir, VA to achieve the final round of consensus among space technology experts, internal and external to NASA. This paper exemplifies how one can identify risks up front on a complex, multi-discipline, multi-year, and multi-Billion dollar program that is heavily dependent on System of Systems (SoS).

2. Background

2.1 Vision for Space Exploration: On January 14, 2004, the President of the United States of America announced at the NASA headquarters a new vision for the civil space program based upon exploration of Moon, Mars, and beyond (Figure 1). The vision for space exploration (VSE) is simply:

- *Extend humanity's presence across the solar system, starting with a return to the moon by the year 2020, followed by journeys to Mars and beyond.*

This bold vision can be translated to the following specific goals, as stated by the President (Ref 1):

- "Our first goal is to complete the International Space Station by 2010"…
- "Our second goal is to develop and test a new spacecraft, the Crew Exploration Vehicle, by 2008"…
- "Our third goal is to return to the Moon by 2020"…
- "With the experience and knowledge gained on the moon, we will then be ready to take the next steps of space exploration: human missions to Mars and to the worlds beyond"

The President further added, "We will invite other nations to share the challenges and opportunities of this new era of discovery. The vision….. is a journey, not a race, and I call on other nations to join us on this journey, in a spirit of cooperation and friendship". One should note that this vision is in sharp contrast to the first moon mission of the 60's, which was more of a race for establishing superiority in space exploration.

Figure 1: President George W. Bush greets shuttle astronauts from right, Peggy Whitson, Stephanie Wilson, and John Grunsfeld, and Ellen Ochoa at NASA headquarters in Washington, D.C., Wednesday, Jan. 14, 2004. White House photo by Eric Draper

2.2 Commission's Report: Following the President's announcement, the President's Commission on Implementation of US Space Exploration Policy, headed by Pete Aldridge (former Secretary of the US Air Force), released a report, *A Journey to Inspire, Innovate, and Discover*, on June 4, 2004 (Ref 2). The Commission developed several findings and recommendations for a sustainable, affordable and credible space exploration program. Specifically, it recommended:

- The space exploration vision must be managed as a significant national priority, a shared commitment of the President, Congress, and the American people.
- The successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedule and affordable costs.
- International talents and technologies will be of significant value in successfully implementing the vision for space exploration, and tapping into the global marketplace is consistent with our core value of using private sector resources to meet mission goals.

Figure 2: Artist's Concept of Mars Exploration
(source: NASA web site, Ref 4)

2.3 NASA Initiative: With the new direction for space exploration, NASA has started developing concepts for a challenging and most complex "System of System" that would support the President's vision for space exploration. This "System of System", sometimes called a "Super System" or "Exploration System" by NASA, would have multiple complex systems, including:

a) Crew Launch Vehicle (CLV or Ares I)
b) Cargo Launch Vehicle (CaLV or Ares V)
c) Crew Exploration Vehicle (CEV)
d) Service Module (SM)
e) Cargo Delivery Vehicle (CDV)
f) International Space Station (ISS)
g) Lunar Surface Access Module (LSAM)
h) Earth Departure Stage (EDS)
i) Mars Transfer Vehicle (MTV)
j) Nuclear Thermal Propulsion (NTP)
k) Lunar Outpost
l) Mars Surface Habitat

Based on a newly released Exploration System Architecture Study by NASA (ESAS, Ref 3), three distinct cycles of development and operation are illustrated in Figure 3a through 3c below, with journey to ISS, followed by Moon and Mars. In these three Reference Design Missions (RDM), the CEV, its safety issues and meticulous planning for each mission appear prominently. The CEV essentially takes the center stage in all these missions.

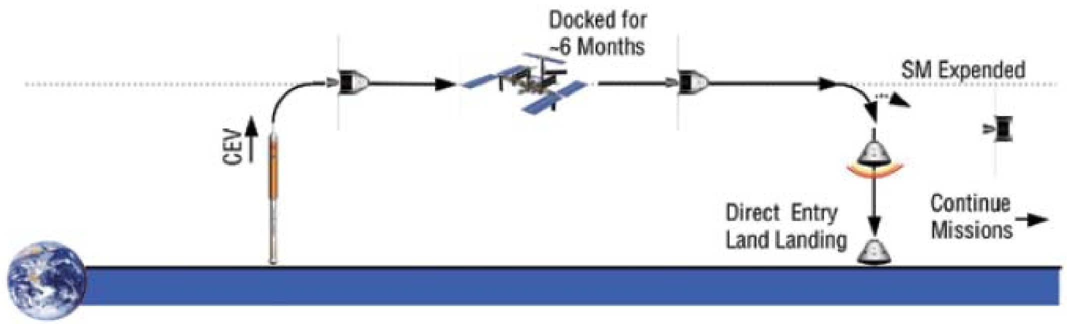


Figure 3a: Exploration System Architecture Study– CEV to ISS and Return
(Source: NASA's ESAS, Ref 3, Part 1)

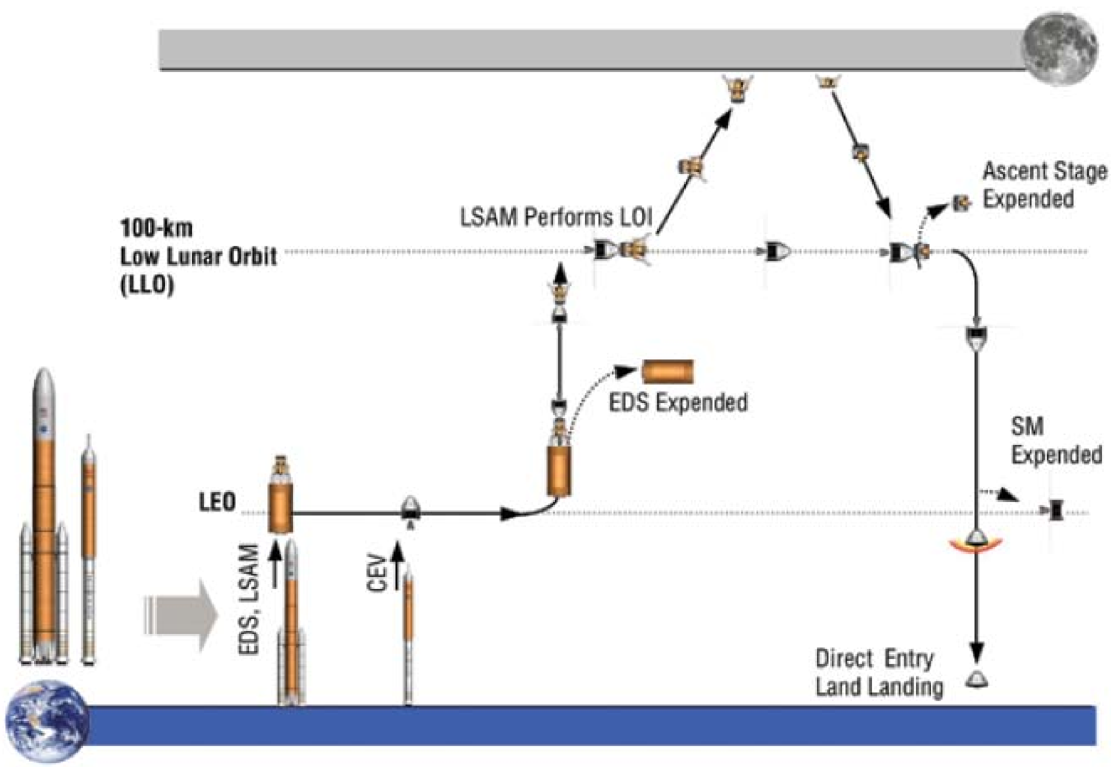


Figure 3b: Exploration System Architecture Study– CEV to Moon and Return
(Source: NASA's ESAS, Ref 3, Part 1)

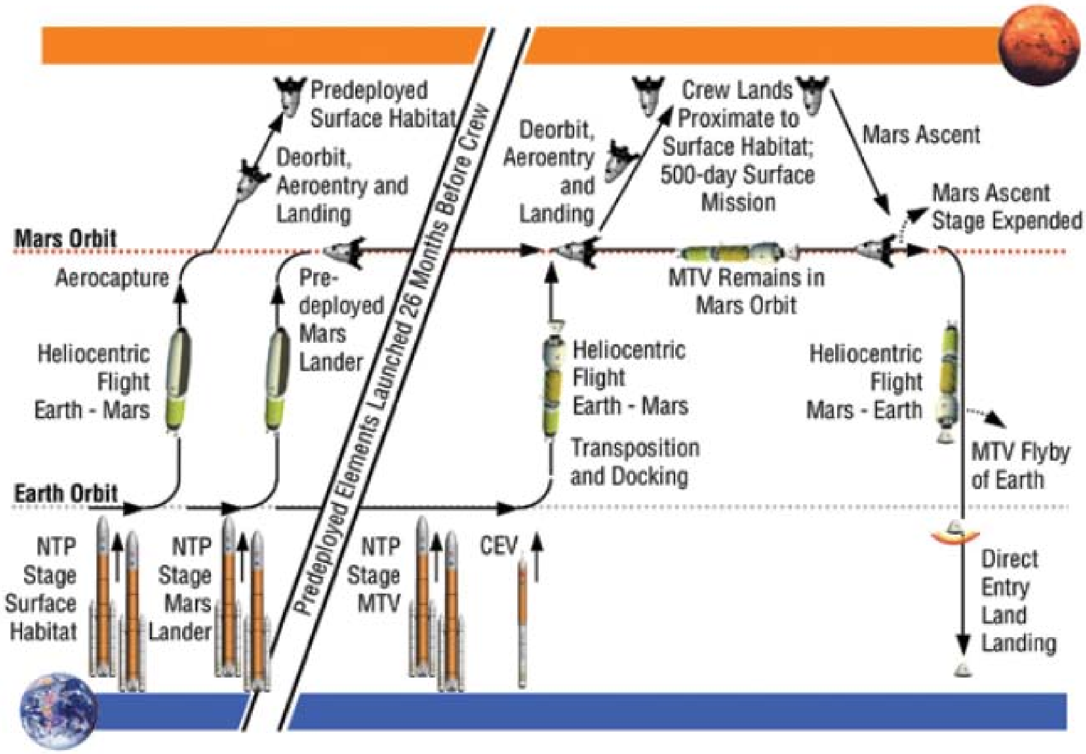
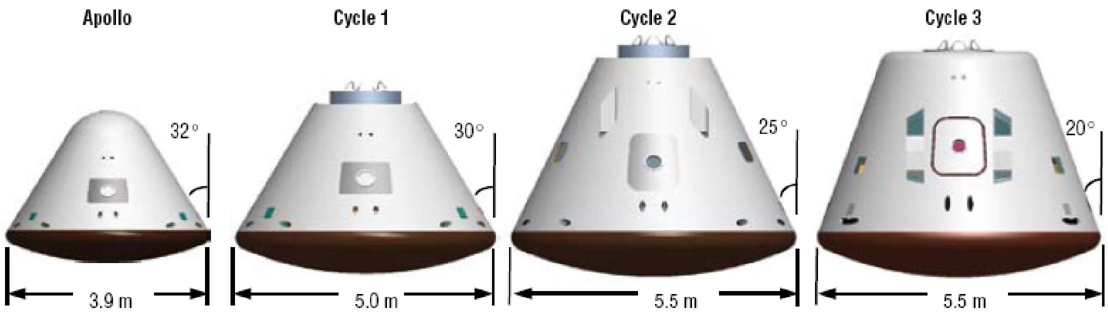


Figure 3c: Exploration System Architecture Study - (CEV to Mars and Return)
(Source: NASA's ESAS, Ref 3, Part 1)

In order to formulate a development strategy for CEV, the most critical system and which would ferry humans from earth to ISS, Moon, Mars and beyond, the Office of Chief Engineer at NASA (specifically, the Academy of Program and Project Leadership) sponsored an initiative to identify and analyze the risks associated with the CEV system, prior to the acquisition process in March 2005. The authors worked as a team to take this challenge in close cooperation with NASA. There was a great urgency and relatively short time to accomplish this task. This initiative got a jump start in November 2004, with the naming of Bobbie Jenkins as NASA project manager

This paper provides the details of the process used for developing the risk profile, and finally the results for the Crew Exploration Vehicle (CEV), NASA's replacement for the Space Shuttle with capability to travel beyond low-Earth orbit (LEO) and the Moon. The CEV is much like the Apollo space capsule that sat on top of the launch rocket during the first lunar programs. In the present case, the CEV is also shown on top of the new Crew Launch Vehicle (Ares I). Earth landing is done by a parachute system.

Figure 4. CEV Shown on Top during Launch Configuration, Using ARES I Launch Vehicle
(Source: NASA's ESAS, Ref 3, Part 1)



Configuration	Diameter (m)	Sidewall Angle (deg)	OML Volume (m³)	Pressurized Volume (m³)
Apollo	3.9	32.5	15.8	10.4
Cycle 1 (EIRA)	5.0	30.0	36.5	22.3
Cycle 2	5.5	25.0	56.7	39.0
Cycle 3	5.5	20.0	63.6	39.5
Cycle 4	5.5	32.5	45.9	30.6

Figure 5. Concept of NASA's Crew Exploration Vehicle – Progression Compared to Apollo Capsule. Shown here is an Evolutionary Development: Cycle 1 for ISS, Cycle 2 for Moon, Cycle 3 for Mars (source: NASA's ESAS, Ref 3, Part 1)

Figure 5 illustrates the evolutionary development of the CEV. It is much like the Apollo capsule on the left. However, the size is much bigger and the CEV can carry 6 to 8 Astronauts. Cycle 1 refers to the first generation CEV, meant for the crew transport to the International Space Station (ISS). Cycle 2 refers to the second generation CEV, which can travel to Moon and back. Lastly, the Cycle 4 design is for journey to Mars and back. The risks involved in all three phases of the development and operation (2005 through 2020) were identified and analyzed by the authors as part of this task.

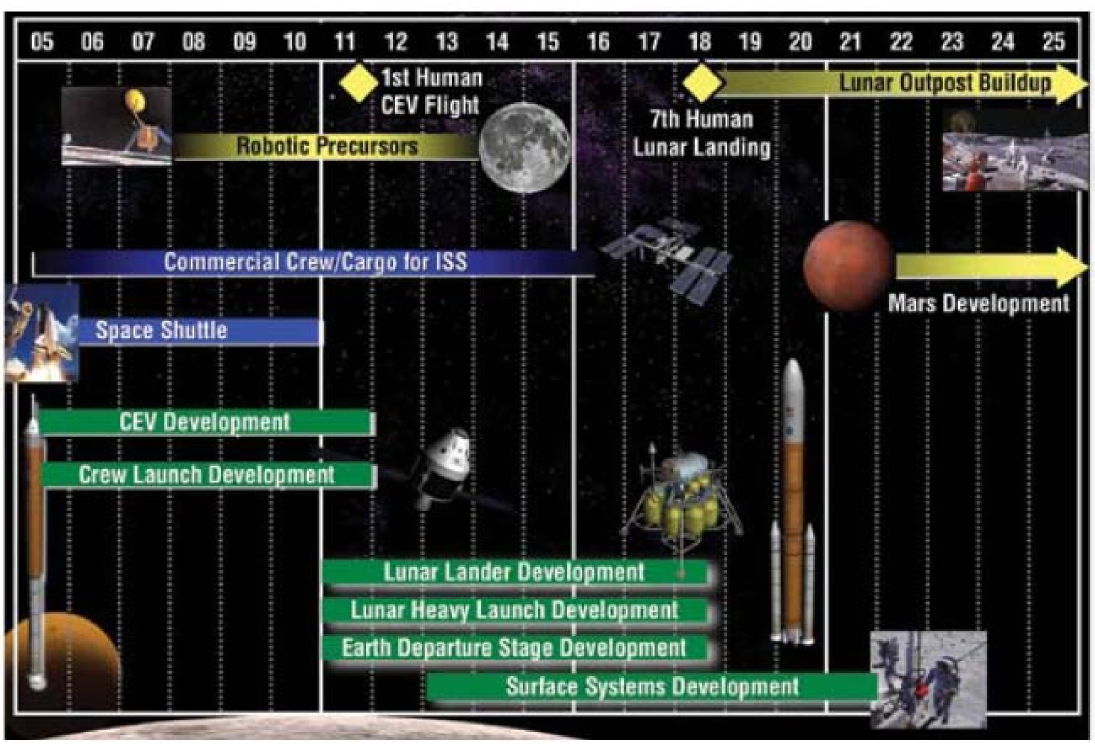


Figure 5. Integrated Master Schedule of CEV and other Systems
(Source: NASA's ESAS, Ref. 3, Part 11)

A development schedule (major milestones) of CEV and other systems is provided above for reference purpose (Figure 5). First generation CEV development (cycle 1) is planned between 2005 and 2011.

From budget perspectives, a comparison of the Apollo program with new Exploration Vision (with and without ISS servicing by CEV) is provided in Figure 6. The cost estimates are from NASA's Architecture Study (Ref 3, Part 12). Briefly, Exploration Vision costs ($83B) are roughly half of the Apollo costs, when compared in constant CY2005 dollars. When ISS servicing is added, CEV operation adds another $16B to the costs. One can therefore conclude that early CEV operation and development (Cycle 1) cost is roughly 16% of the full Exploration Vision budget. Therefore, CEV is a significant part of the Exploration Vision, called System of Systems:

Apollo costs:	$165B (in CY05 dollars)
Exploration Vision costs:	$ 83B (in CY05 dollars)
Exploration Vision costs:	$ 99B (in CY05 dollars)
(with ISS service by CEV)	

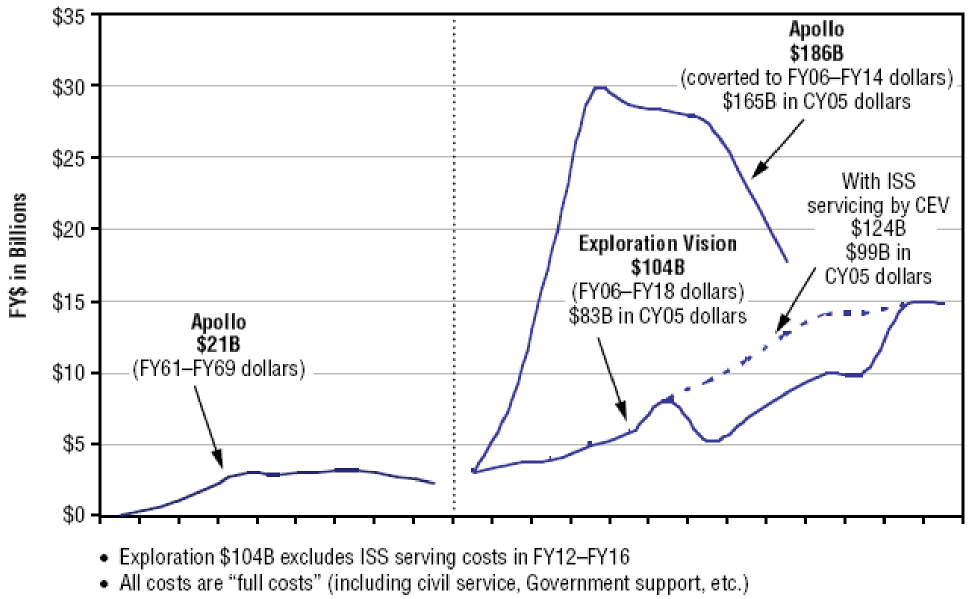


Figure 6. Budget for Exploration Vision & CEV
(Source: NASA's Exploration Systems Architecture Study, Ref. 3, Part 12)

3. What was Accomplished on this Task?

3.1 Selection of Risk Experts: The authors worked in November 2004 through January 2005 with senior scientists, engineers and managers (internal and external to NASA, having expertise in manned and un-manned missions), to develop a risk profile for the CEV. A list of the experts in risk and risk management is provided in Appendix A. Their roles were to provide expert opinion on risks faced by the CEV and its crew. They represented a cross-section of experts from government agencies, industry, and academia. The non-NASA representatives were from well know organizations, including Lockheed Martin, SAIC, Perot Services, Kistler Private Launch Program, MIT, UCAL(Berkley), and CPMR Science Council (USRA). These experts were selected in coordination with the Office of Chief Engineer and major NASA Centers.

The authors, in close coordination with NASA project manager, set out to develop a risk profile for the CEV. Specific accomplishments included:

- Identification of risks
- Risk categories

This task of identification of risks for CEV benefited NASA, its Exploration Vision program, NASA's Procurement Office (regarding issue of an RFP), and the bidders of the CEV system. The risk profile of the CEV was used by NASA in preparation for the acquisition process. In March 2005, an RFP was finally issued for the development of the CEV. NASA wanted to make sure that the most critical risk items were considered by the bidders in proposing a system. The safety issues, cost, schedule and performance are closely tied to the risks of the complex CEV system for space exploration. The authors recognized fully the value of this information to the bidders. They also understand that it is very difficult for the bidders to go through a risk analysis in a short time in preparation for the proposal. Therefore, the NASA-provided risk profile gave a good starting point for the all bidders of the CEV program. NASA was quite satisfied with the risk identification task, carried out by the authors with the help of a dozen experts.

4. How was it Done?

4.1 Delphi Technique: The authors applied the Delphi technique to identify the risks of the CEV system. This technique refers to the ancient Greek oracle at Delphi that was believed to make accurate predictions about the future. Forecasts and advices from gods were sought through intermediaries at this oracle.

The modern-day Delphi technique, developed by RAND Corporation in the 1940s through early 1950s, was employed to assist with the decision-making required to reach consensus among the participants. One of the very first applications of the Delphi method carried out at the RAND Corporation is illustrated in the publication by Gordon and Helmer. Its aim was to assess the direction of long-range trends, with special emphasis on science and technology, and their probable effects on society. The study covered six topics: scientific breakthroughs; population control; automation; space progress; war prevention; and weapon systems. The first Delphi applications were in the area of technological forecasting and aimed to forecast likely inventions, new technologies and the social and economic impact of technological advancements. In terms of technology forecasting, the objective of the Delphi method is to combine expert opinions concerning the likelihood of realizing the proposed technology as well as expert opinions concerning the expected development time into a single position. When the Delphi method was first applied to long-range forecasting, potential future events were considered one at a time as though they were to take place in isolation from one another. Later on, the notion of cross impacts was introduced to overcome the shortcomings of this simplistic approach.

The Delphi technique is an exercise in group communication among a panel of geographically dispersed experts. The technique allows experts to deal systematically with a complex problem or task. The essence of the technique is fairly straightforward. It comprises a series of questionnaires sent either by mail or via computerized systems, to a pre-selected group of experts. These questionnaires are designed to elicit and develop individual responses to the problems posed and to enable the experts to refine their views as the group's work progresses in accordance with the assigned task. The main point behind the Delphi method is to overcome the disadvantages of conventional committee action. Anonymity, controlled feedback, and statistical response characterize Delphi. The group interaction in Delphi is anonymous, in the sense that comments, forecasts, and the like are not identified as to their originator but are presented to the group in such a way as to suppress any identification.

4.2 Modified Delphi Technique: The authors opted finally to apply the Delphi technique in its modified form for the reasons given below. The modified approach differs in that the statistical analyses of responses between "rounds" of inputs from experts were eliminated because of the time constraints of this task. However, the range of inputs received from the experts was considered robust enough to apply the technique for the desired level of accuracy. It was necessary to a conduct face-to-face meeting with the respondents to resolve all the disputed items that arose during the data gathering phase. An initial Questionnaire allowed the responders to provide inputs, without knowing what the other experts were recommending. The modified –Delphi technique provided a fast response cycle through e-mails, fax and direct overnight mailings. The response provided by the experts was solely based on their experience and honest opinions. A cross-section of experts brought divergent view points at first, as expected. The group coordinator's goal was to get the opinions and views converge gradually through multiple iterations. The authors used a three-step process to develop a risk profile for the CEV system

Step 1: Send a Questionnaire

A Questionnaire on risk profile was developed and sent to the panel of experts (about a dozen individuals, internal and external to NASA). The Questionnaire was developed initially by the authors in coordination with NASA and its Project Manager (see Appendix B). The Questionnaire elicited risk information on the CEV system development

Step 2: Iterate on Responses and Categorize Risks

A summary of feedbacks and responses was distributed again to the entire panel of experts without attribution. At this stage, the experts did not know who recommended which risks. Three iterations of responses on risks were further consolidated in light of new information until the group coordinator was satisfied that some convergence on important issues had been reached using anonymous communications. The panel agreed on 9 general categories of risks, and a set of 15 probing questions; which had to be addressed to cover all the major risks faced by the CEV system. A list of this general category of risks is shown below.

- 1) Requirements
- 2) Systems Complexity
- 3) Systems Architecture
- 4) System/Subsystems Design and Development
- 5) System re-entry mode
- 6) Schedule
- 7) Integration, Verification and Validation
- 8) Programmatic/System Engineering Issues
- 9) Others

Step 3: Conduct Face-to-Face Meeting Using Electronic Meeting System (EMS)

For the final resolution of issues, a face-to-face meeting was arranged by the authors, using an Electronic Meeting System (EMS) at DAU (Ft. Belvoir, VA). The EMS provides a quick resolution of issues, when the experts provide their inputs on a network of computers which then tally the results instantly and indicate the trend toward convergence or divergence. The experts try harder each time to reach a consensus. The program coordinator acts as a facilitator for the entire session. An 8-hour session on the EMS was enough to resolve the tough remaining issues on risks of the CEV system.

5. Our Results on Risk Profile for NASA's CEV

5.1 Results from Modified-Delphi Technique: The authors prepared a final report on CEV Risk profile in January 2005, based on the three-step process described above (Ref 5). This paper draws heavily from the final report, and provides a current, real-life example of how to get started on a multi-discipline, multi-year, and multi-Billion dollar program that is heavily dependent on System of Systems. Delphi technique (or a modified version) is most appropriate for SoS and complex systems, such as NASA's CEV system. The development of CEV involves multiple disciplines, including: spacecraft design, human engineering, communications, bioengineering, life sciences, physiology, psychology, long-duration space travel, etc. The development of CEV is a long process (2005 through 2011), and its first cycle budget is roughly 16 Billion (through ISS flights). Following that there are two more cycles of development and operation leading to Moon and Mars missions. Therefore, the CEV is a major system of the Exploration Vision (system of systems).

As an example, the final result of responses by experts to Question 8 on CEV's "launch-related risks" is shown below. Note that the experts deferred their assessments on risk probabilities and impacts.

Example Question 8

What are launch-related risk issues that will affect the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk. List under each category.

1) Requirements
   - None identified
2) Systems Complexity
   - LV reliability
   - Overall reliability of the integrated LV/CEV/Crew Escape system (resulting in reduced probability of overall mission success and increased probability of loss of life)
   - Abort and crew escape capability
   - Design will not meet max probability of mission catastrophic failure requirements
3) Systems Architecture
   - None identified
4) System/Subsystems Design and Development
   - Failure to design a robust CEV/Crew Escape system
   - Implementation of "all phases" abort capability
   - CEV weight growth
   - Insufficient lift capability
   - Design not fully meeting safety requirements
   - Insufficient development and testing of propulsion components
   - IVHM System design for abort modes / scenarios
5) Re-entry Mode
6) Schedule
   - Range impacts due to multiple launch timelines required to accomplish mission objectives
7) Integration
   - Launch vehicle integration
   - Propulsion systems integration with other systems
   - Inadequate test methods
8) Programmatic/System Engineering Issues
   - Programmatic impacts associated with separate organizations within NASA and USAF-NRO
   - Compliance with NASA human rated requirements
   - Availability of domestic capabilities for testing
   - Incomplete system engineering
   - Insufficient full-scale test of realistic accident scenarios
   - Inadequate launch platform mass to orbit margin to meet total mission objective

9a) Others: Launch Failure Modes
   - Debris impact
   - Failure of hold down mechanism
   - Failure of umbilicals/arms to operate properly
   - Failure of Booster solid rockets
   - Failure firing of range safety system
   - Failure to separate
   - Loss of engine(s)
   - Loss of communications
   - Loss of RCS system
   - Loss of OMS
   - Loss of major structure
   - Loss of minor structure
   - Loss of CEV cabin pressure
   - Loss of TVC (APU/HPU)
   - Loss of Telemetry
   - Loss of partial TPS system
   - Loss of LPS automated launch processing capability
   - Leak of propulsion tanks or lines
   - Benign failure of the launch vehicle
   - Failure of the launch escape system given catastrophic failure of the launcher
   - Failure of the launch escape system given benign failure of the launcher

9b) Others: Environmental Considerations
   - Environment (wind, rain, temperature, lightning)
   - LV induced acoustic, thermal, and physical effects upon the CEV
   - Launch site weather, air quality, and range safety

Appendix C provides the final list of all the risks posed by CEV, as agreed by the experts. The risks are organized along 15 questions and roughly 9 categories (provided above). There are more than 600 risks listed in the Appendix. A short list of major risks faced by CEV and its crew is highlighted below (Question number and general Category number is provided for reference purpose). The experts were very keen on listing the unusual type risks faced by spacecrafts, based on their years of experience. Two such risks are underscored below. Obsolescence of technology is of particular concern because of 15-20 year long development program. In addition, NASA's decision making culture is still an issue in the experts' opinion.

Summary of Major Risks Identified in Appendix C

- Q1/C4: Inadequate design of thermal and radiation protection
- Q1/C4: Inadequate automated rendezvous & docking system
- Q2/C7: Improper hardware/software integration
- Q2/C8: System obsolescence and degradation of performance******
- Q4/C4: Lack of crew escape and abort system development
- Q5/C3: Lack of mission abort capabilities in all phases of mission
- Q6/C2: Insufficient CEV systems reliability and operability

- Q7/C5: On-orbit debris and on-route meteorite strike on CEV
- Q8/C5: Failure of Booster solid rockets
- Q8/C5: Loss of cabin pressure
- Q9/C4: Re-entry heating larger than expected
- Q9/C5: Failure of parachute deployment mechanism
- Q11/C9: Issues with NASA decision-making culture******
- Q15c: Unknown effects of long duration missions on astronauts

The Final Report on CEV's Risk Profile (Ref 5) provides further elaboration of the list of the all the risks identified in this task.

For any SoS, risk identification for all its systems is a "ground floor" activity. It must be done early at the concept level, and then updated regularly, following the Continuous Risk Management (CRM) principle.

6. Follow-on Results of Risk Analysis Reported in NASA's Recent Exploration System Architecture Study (ESAS):

Let us now look at some results of the follow-on risk and reliability analysis that was done as part of the Exploration System Architecture Study (ESAS) in November 2005, by another group of space technology experts. This was an extensive and thorough study. They went beyond identifying the risks, and estimated probabilities and consequences of such risks. These included probabilities of failure of major CEV subsystems and even grave consequences, such as Loss of Mission (LOM), and even Loss of Crew (LOC).

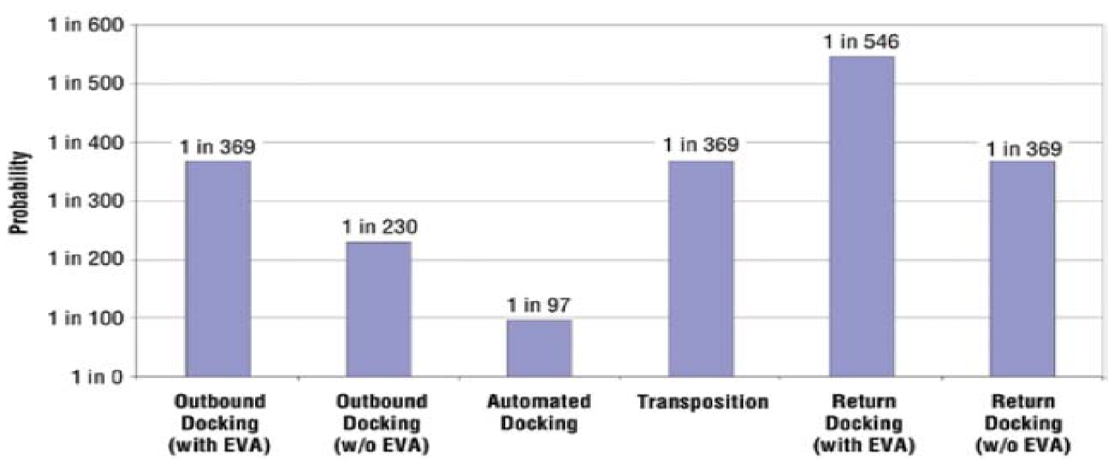


Figure 7: Docking Failure of CEV on a Lunar Mission (Source: NASA's ESAS, Part 8)

Figure 7 illustrates the probability of docking failure, especially during lunar mission (cycle 2). Return docking (with extra vehicular activity) is projected to have the highest failure rate (1 in 546), which is significantly high. This failure rate adds to other risks in the lunar mission.

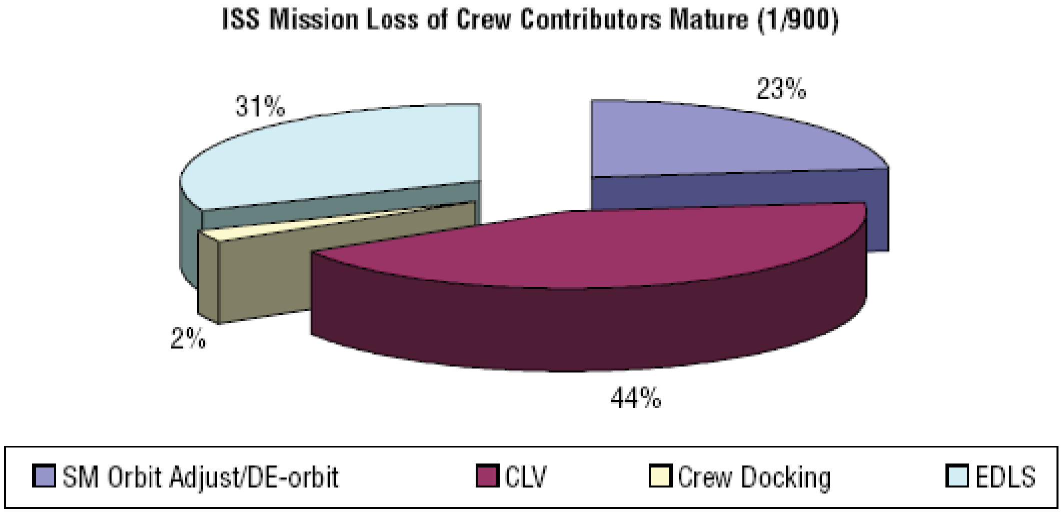


Figure 8: LOC Contributors for Mature Vehicle (CEV plus CLV) for ISS Servicing

Figure 8 provides NASA's prediction for major contributors to loss of crew, when servicing the ISS. For a mature system, the CEV & CLV (or Ares I) contribute about 44% of the probability of loss of crew. Therefore, the CEV is the most critical system for success in lunar missions. These failure rates, although worrisome, are the realities of space travel.

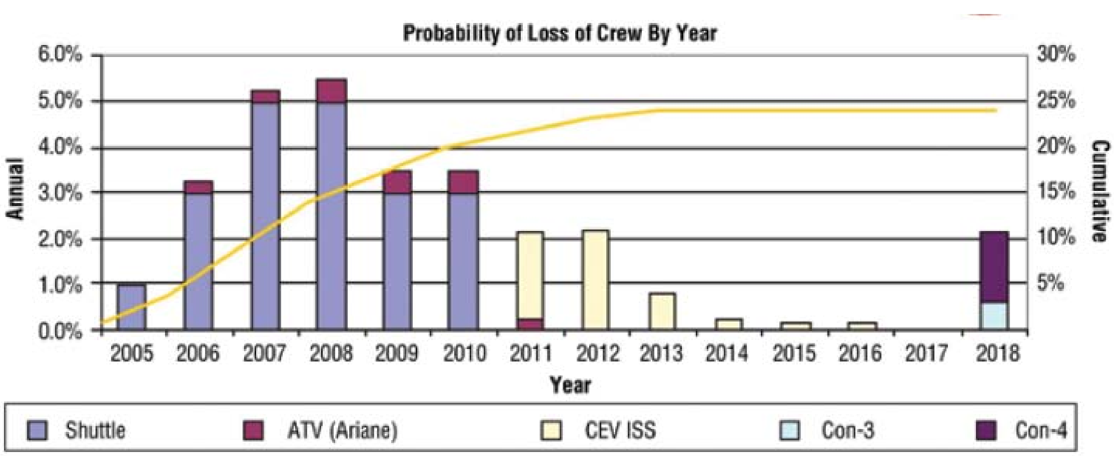


Figure 9: Probability of Loss of Crew (LOC) Estimated on Annual Basis
(Source NASA's ESAS, Part 8)

Observe in Figure 9, the CEV/ISS mission has a probability of 2% loss of crew (LOC) annually in the years 2011 and 2012, which is above the current 1% level for the case of the Space Shuttle. As maturity is gained in the CEV, this probability reduces to well below 0.2% (between 2014 and 2017). It ramps up again, as more complex lunar landings are attempted in 2018 and beyond.

7. Accomplishments and Conclusions of our CEV Task

7.1 Accomplishments:

Let us now summarize the accomplishments of our task of identifying all the risks of the CEV. This was a very special effort conducted by the authors, in close coordination with NASA officials. NASA opened up the process to non-NASA experts, in order to remove any bias by NASA experts. This approach of risk identification is especially significant since the Columbia accident. It illustrates NASA's more open approach to solving problems. The major accomplishments were:

- Modified Delphi technique helped identify about 600 risks for the CEV system.
- This task was completed in less than 90 days.
- The cost of this task was kept under $100K.

7.2 Conclusions: The conclusions of this task of identifying risks of a highly complex Crew Exploration Vehicle (CEV), as a major part of a system of systems, are the following:

- Risk identification task provided timely information to NASA, Acquisition Office, and the proposal teams that wanted to bid on the CEV development.
- We encourage the developers of similar complex systems as well as "system of systems" to conduct an up-front risk identification and assessment of risks. We found that Delphi technique was easy to apply and cost-effective at the same time.
- It is well known through NASA's data on past programs, that initial engineering analysis, like this risk identification, pays great dividends in terms of reducing overruns and achieving mission success.

Acknowledgements

This work was sponsored by: The Academy of Program and Project Leadership (APPL),
The Office of Chief Engineer, NASA HQ

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3) NASA's Exploration System Architecture Study (ESAS), November 2005.
4) NASA web site: Space Exploration System and Crew Exploration Vehicle Concept (June 2006).
5) Final Report, "Risk Profile for NASA's Crew Exploration Vehicle (CEV) System", Jan 2005.

Appendices

- **A) List of Experts**
- **B) Initial Questionnaire**
- **C) Final List of Risks and Categories**
- **D) List of Abbreviations and Acronyms**

Appendix A: List of Experts

Internal to NASA

1. NASA HQ, Code Q: Flight Safety: Bryan O'Connor
   Former Astronaut, and Deputy Associate Administrator for human space flight, as well as Program Manager for SSP. Currently AA for Code Q, responsible for flight safety, and would have important insights on this topic of risk profile, which would be factored in – up front
2. NASA Langley Research Center: Bill Cirillo
   Extensive experience in independent systems analysis, including risks for ISS, SSP, RTF and exploration planning
3. NASA Johnson Space Center: Safety Review panel member at JSC: Wayne Peterson
   A key person from this group, who evaluates flight project risks and mitigation requirements

External to NASA

1. Lockheed Martin – Space (Denver): John Karas
   Lead LM advance launch vehicle development program including the Atlas V, which may be a candidate platform for future Exploration Mission Directorate (EMD) missions
2. SAIC: Joe Fragola
   Strong credential in risk management as a discipline, in shaping programmatic decisions and technology investment strategies. Participant in Apollo, in independent assessments for SSP/ISS, RTF, and was a lead collaborator in a CPMR sponsored workshop to use the Delphi process to shape EMD Mars Human Precursor Mission study with JPL to establish the Mars Robotics Missions for Exploration
3. Perot Services Government Systems: Steve Krahn
   Risk management and systems engineer expert involved in implementation of US Navy's Safe Sub Program
4. Kistler Private Launch Vehicle Program: George Muller
   Former Program Manager during Apollo, and current CEO of Kistler
5. Independent Consultant: Dick Kuhrs
   Former SSP Program Manager during Challenger RTF program, and AA Space Station Freedom, and currently involved in private launch vehicle business
6. University Space Research Association (USRA), Center for Program Management Research (CPMR), Fellow at UCAL, Berkley: Karlene Roberts
   Strong academic credential in risk management research, and involved in the US Navy's Safe Sub Program, and Navy Carrier Landing Programs which have had remarkable success in improving safety
7. CPMR Fellow at MIT: Nancy Leveson
   Strong research credential in organizational and cultural impact on safety, and extensive involvement in NASA research in this area, including involvement in CAIB assessment report
8. CPMR Science Council: Joe Rothenberg
   Former Associate Administrator for human flight at NASA, including SSP, ISS, and also led NASA's first Hubble Servicing Mission, for which he received National recognition for excellence in program/project management

USRA Consultant: John O'Neill
CPMR Peer Review panel lead, and internal lead for Exploration Strategy for USRA. Former Director of MOD and JSC, extensive experience in Apollo, SSP, and Mission Ops.

Appendix B: Questionnaire

Crew Exploration Vehicle (CEV) Risks

Background Information:

The CEV RFP Team of NASA would like to identify risks associated with the Crew Exploration Vehicle (CEV) in response to the needs of NASA Exploration Systems Mission Directorate (ESMD).

This approach will leverage the expertise of experienced practitioners to provide a framework for addressing risks associated with the CEV. To this end, we will use the "Delphi" technique (qualitative forecasting methodology) via a panel of experts who respond individually to a single questionnaire before reaching a consensus. (Note: Delphi process is not to reach a consensus, but to determine the distribution of the responses to questions. Typical output is the high, low, average and statistical distribution of responses)

A summary of feedback is then distributed to the entire panel, and then iterations of responses are revised in light of new information until the group coordinator is satisfied that the best possible consensus has been reached.

Risk Management (RM) Questions:

The attached questions were developed to identify "risks" associated with CEV, working with a panel of internal and external NASA experts. We will present the questions, prompting responses for risk identifications and potential impacts based on expert opinion with past projects, current status, and future probabilities after the initial draft questions have been vetted with both the CEV RFP team and the performing team.

The approach to develop the framework of questions was based on composing first draft questions that correspond to the topic being examined. These initial draft questions should articulate a purpose in question form. Behind every question on a questionnaire should be an intent to capture some information that indicates something about the topic we are examining.

The draft questions have been segmented into the following four categories:

1. Continuous Risk Management (CRM)
2. Risk-based Acquisition Management (RBAM)
3. Risk Management (Mitigation) Plan
4. Crew Exploration Vehicle (CEV)

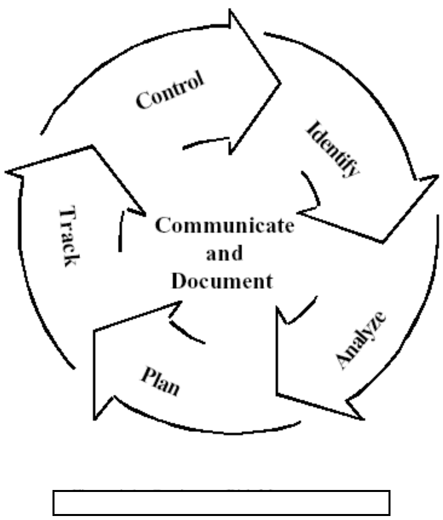
Risk Profile for NASA's Crew Exploration Vehicle (CEV) System

Topic Being Examined	Purpose	Indicators	First Draft Questions
Continuous Risk Management (CRM) Figure A-1 ——— The Risk Management Process Figure A-2	**To identify and manage risks**: • analyzes their impact and prioritizes them • develops and carries out plans for risk mitigation or acceptance • tracks risk and the implementation of mitigation plans • supports informed, timely, and effective decisions to control risks and mitigation plans • assures that risk information is communicated and documented • Determine alternatives to plan and process for mitigation	• Mission Success Criteria • Development Schedule • Budget Limits • Launch Window • Vehicle Availability • International Partner Participation • Critical Single Source Providers • Security or Environmental Concerns • Human Space Flight Safety Issues • Tools: FMEA –Failure Modes & Effects Analysis FTA –Fault Tree Analysis PRA – Probabilistic Risk Assessment	• What prior experiences have you had with the CRM process for developments similar to CEV? • What aspects of CRM can help programs/project managers identify specific CEV risks most effectively? • How rigorously is this process followed throughout the program/project life cycle in NASA missions? • What other risk management methodologies have you successfully used? • What are the pros and cons of using CRM for CEV development? • What are your general observations concerns regarding the CEV development process? • In your view, has CRM been successfully applied on the Space Shuttle programs? Is IRMA (Integrated Risk Management Analysis) tool, used by NASA on Space Shuttle programs, capable of handling the CEV development?
Risk-based Acquisition Management (RBAM)	**To refocus risk as a core acquisition concern for**: • Acquisition Planning – ensure that the acquisition is structured to address appropriately the concerns of these disciplines as they relate to the requirements • Solicitation Process – requests for any perceived safety, occupational health, security, environmental, export control, etc. • Surveillance Plans – reflect NASA's surveillance approach relative to the perceived programmatic risk	• Risk List • Risk Acceptance Records • Risk Mitigation Plan • Acquisition Strategy Meeting: o Risk Quantification (magnitude of risk) o Structure Acquisition Approach to Manage Risk o Identifies Decisions: ▪ Accept ▪ Mitigate ▪ Track ▪ Research	• What is your preferred approach to ensure mission success of NASA's CEV when using RBAM? • What are your past experiences with RBAM regarding a CEV type program/project? • Based on your expert opinion, what is the best way to use RBAM for CEV on a program/project basis? • What are your general observations on past CEV type programs/projects that have used RBAM? • What aspects would you change to NASA's RBAM to apply on the CEV development? • Is NASA's RBAM process considered "state-of-the-art". If not, why?

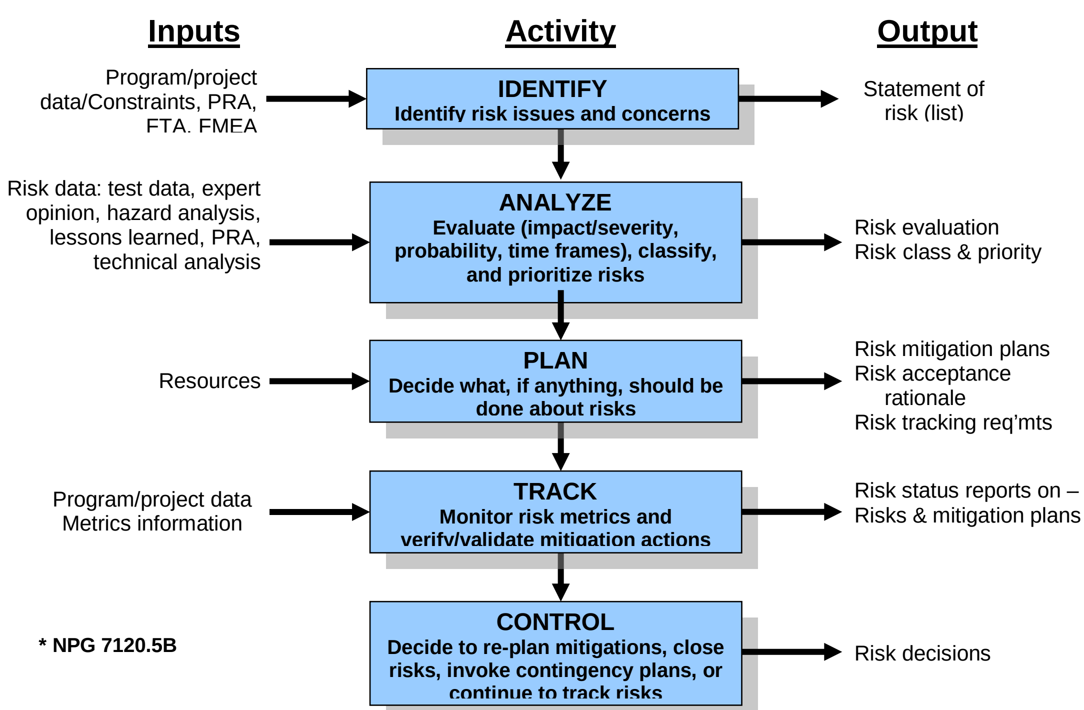
Risk Profile for NASA's Crew Exploration Vehicle (CEV) System

<table>
<tr><th>Topic Being Investigated</th><th>Purpose</th><th>Indicators</th><th>First Draft Questions</th></tr>
<tr><td>Risk Management Plan</td><td>To document a summary of basic risk management planning for the program/project via a standalone plan – Risk Management Plan:
• Configuration Controlled
• Introduction
• Overview of Risk Management Processes
• Organization
• Process Details
• Resources and Schedule of Risk Management Milestones
• Documentation of Risk Information
• Methodology Associated with Program/Project Descope</td><td>• Scope
• Assumptions
• Success Criteria
• Constraints
• Key Ground Rules
• Information Flow
• Risk Mitigation Strategies
• Responsibility Assignment Matrix
• Schedules with Milestones
• Allocation of Resources
• Resource Contingency Plan
• Program/Project Risk List
• Risk Profile
• ISS Risk Summary Card
• IRMA Risk Database</td><td>• What aspects of NASA's Risk Management Plan will help program/projects manage specific CEV risks most effectively?
• What are your general observations on past CEV type programs that have developed comprehensive Risk Management Plans?
• What other Risk Management Plan methodologies have you successfully used?
• What confidence do you have in successfully developing an effective CEV Risk Management Plan?
• Have you used or considered using the ISS Risk Summary Card for a CEV type program/project? If so, what aspects do you find most effective? Least effective?
• Based on your experience, what is your preferred methodology for developing a resource contingency plan to overcome resource and schedule risks?</td></tr>
<tr><td>Specific Risk Concerns in Crew Exploration Vehicle (CEV) Development</td><td colspan="2">The vision for Space Exploration sets a goal of developing a new CEV by 2014 that is capable of carrying astronauts beyond low Earth orbit and a goal of landing astronauts on the Moon no later than 2020.</td><td>• Develop additional generic open-ended risk management questions relating to the CEV mission
• With the 2014 date as a goal for going beyond LEO, what year do you feel the launch propulsion system will be available?
• The CEV's navigation system?
• The crew's environmental system?
• The "in-flight" propulsion system?
• What other critical support systems are needed? When do you feel they will be operational for support to the CEV?</td></tr>
</table>

NASA's Continuous Risk Management (CRM) - Figure A-1 (RE: NPG 7120.5b)



NASA's Risk Management Process - Figure A-2 (RE: NPG 7120.5b)



Hybrid Technique (Figure A-3) (RE: NPG 7120.5b)

Probability of Occurrence	
Scale	**Measure**
5	Almost Certain
4	Highly Probable
3	Probable
2	Possible
1	Improbable

Impact of Occurrence			
Scale	**Technical Measure**	**Cost Measure**	**Schedule Measure**
5	Technical goals cannot be reached	Budget increase of greater than 10%	Slip of key project milestones
4	Significant degradation in technical performance	Budget increase of 7% to 10%	Slippage on the project critical path
3	Moderate reduction of technical performance	Budget increase of 2% to 7%	Some slippage affecting several need dates
2	Small reduction in technical performance	Budget increase of less than 2%	Minor schedule slips, but no key dates affected
1	Minimal or no consequence	Minimal or no consequence	Minimal or no consequence

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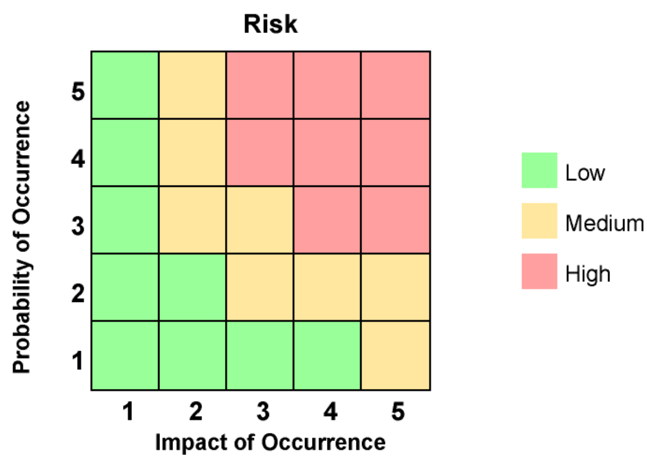

Appendix C: Final List of Risks and Categories for CEV

Question 1 Analysis
What are the major technical risks, in priority order, associated towards achieving a CEV demo by 2008? (Please answer with the understanding that the parameters for a 2008 demo are not defined, and that your responses will gauge developmental risk based on your combined knowledge and experience to be used as a baseline definition to work from). Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Concise and adequately defined initial technical requirements
- Overall system requirements definition
- Funding requirements and stability
- Design requirements
- Requirements creep

System complexity
- Interface definition and design
- Definition of overall interfaces
- Mission profile design
- Payload (lift) ratios

System Architecture
- System integration, including CEV with EELV
- System software development
- Integrated LV/CEV/Crew Escape system
- Design dependencies not fully defined

System/Subsystem Development
- Launch platform design
- Subsystems development
- Mass properties control
- Thermal protection systems
- Development of an adequate Automated Rendezvous & Docking system
- Development of Integrated Health Management System to meet NASA standards
- TPS development
- Introduction of new technologies

Schedule
- Sufficient testing plan design and schedule
- Schedule incompatibility

Integration
- Final Integration and testing for Demo

Other Issues
- Loss of another shuttle to impact overall program
- Issues with NASA culture

Others not identified on this list

Question 2
What are the major technical risks, in priority order, associated with meeting Program Evaluation Review (PER) requirements by 2008? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Requirements definitions
- Adequately defined Functional Requirements
- Requirements creep
- Lack of early requirements definitions

System Complexity
- Vehicle mold line design
- Mission profile definition and conditions
- Identification of potential single point failures
- Complexity of design

System Architecture
- Support Infrastructure development
- Vehicle weight to payload ratios

System/Subsystem Development
- Automated Rendezvous & Docking system development
- Thermal protection systems

Schedule
- Verification, validation and certification of designs time line
- Software system development
- Inadequate Integrated LV/CEV/Crew Escape System design

- Flight demo schedule

Integration
- Hardware/software integration
- Systems integration
- CEV integration with EELV

Programmatic Issues
- Adequate types and levels of resources assigned
- Adherence to CAIB recommendations
- Integrated Health Management System compliance with NASA standards
- Compliance with NPR 8705.2 (Human Requirements and Guidelines for Space Flight Systems)
- Ineffective cost controls and financial management

Other Issues
- Loss of a shuttle

Others
- Ineffective program management
- Clearly defined roles and responsibilities
- Late deliveries if components Interfaces not clearly defined or understood
- Un-negotiated (constructive) change orders
- Operating environment not understood
- Inadequate Safety design
- Baseline CEV technical and operational requirements
- Higher than estimated costs
- Selection of prime contractor
- System Design maturity demonstrating requirement compliance

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Question 3

What particular technical risks, in priority order, are associated with achieving a human-rated CEV by 2014? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- System requirements definitions
- Integrated LV/CEV/Crew escape system requirements
- EELV requirements and capabilities
- System and functional design requirements
- Lack of specificity in defining human-rated requirements
- Changing requirements
- Complete design requirements

Systems Complexity
- Maintaining systems redundancies
- Definition of crew roles and interfaces
- Mission profiles
- Vehicle health maintenance (VHM)
- System Safety plan/process
- Systems Interface designs

Systems Architecture
- Crew safety – launch, on-orbit and re-entry rescues
- Baseline technology architectures for CEV in LEO, moon orbit, moon landing, etc.
- CEV outer mold line design

System/Subsystems Development
- TPS development
- In-space propulsion system development
- Lack of LV performance requirements leading to less than optimal design
- Payload weights
- Life support systems
- Baseline technology architectures for CEV in LEO, moon orbit, moon landing, etc.
- Development of in situ propellants support technologies
- Cryogenic Fluid Management systems
- Autonomous Rendezvous and Docking technologies
- Thermal protection system
- CEV weight growth
- Software maturity
- Thermal protection technologies
- Maturity of System/Subsystem designs

Schedule
- Program Schedule

Integration
- Software systems V&V

- Hardware/software integration
- LV integration with CEV
- Systems integration

Programmatic Issues
- Adequate resources assigned
- Develop IHMS in compliance with NASA safety standards
- Availability of testing facilities
- Concurrency in program execution

Others
- Compliance with CAIB recommendations
- Lack of experience for this type of program

Others Not Identified in the List

Question 4

What technical risks, in priority order, are associated with mating the CEV to a human-rated launch platform by 2014? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Integrated LV/CEV/Crew escape system requirements
- Requirements definition of human rated LV
- Compliance with NASA human rated requirements
- Identification of proper vibra-acoustical environment
- Requirements definition
- Environmental considerations
- Overall systems requirements and specifications

Systems Complexity
- Definitions of range safety implementation
- Mission profile

Systems Architecture
- Vehicle outer mold line design

System/Subsystems Development
- Develop IHMS that will meet NASA safety standards by 2008 demo
- Crew escape and abort system development
- Development of expendable LV engines and avionics
- Decisions in selecting an existing booster vs. developing a new vehicle
- CEV weight growth
- Insufficient LV lift capability
- Detailed interface designs
- Structural interfaces compatibility
- Mass properties
- Fully understood design dependencies

Schedule
- (No Responses)

Integration
- Systems integration
- Integration of CEV with LV
- Systems integration

Programmatic Issues
- Lack of testing facilities
- Timing of LV certification
- Qualified and experienced work force
- Design will not pass PRA causing schedule slip for redesign

Others
- ELV launch pad upgrades including crew access and rapid egress
- Certification testing
- Integrating upgrades to LV for enhanced reliability and safety
- Launch facilities to accommodate LV
- Inadequate regulatory process
- Demo failures

Question 5

What technical risks will be associated with unrealistic design specifications and insufficient performance, safety, and test margins? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Unrealistic specifications for LV success probabilities
- Overly-specified safety requirements leading to growth in weight and cost
- Unrealistic design specs revealed late in development cycle
- Ability to meet orbit endurance requirements
- Concise and adequately defined initial technical requirements
- Inadequate envelope definition
- Requirements creep
- Internal CEV acoustics
- LV and main engines performance requirements and cost-effectiveness

Systems Complexity
- Lack of understanding of mission profile

Systems Architecture
- Mission abort capabilities in all phases of mission profile
- Internal and external interface specifications definitions

System/Subsystems Development
- Unreliable CEV systems
- Design compromise by requirements creep
- Failure to develop adequate Autonomous Rendezvous & Docking system with sufficient capabilities
- Failure to develop an adequate IHMS
- LV/CEV/Crew Escape System Development less than optimal output
- Lack of test margins constrains flight envelope
- Rendezvous margins not sufficiently identified
- Lack of operations considerations in design
- Mass property controls
- Mission-dictated mass constraints not met

Schedule
- Testing schedules

Integration
- Test conditions modeling do not mirror actual environmental conditions

Programmatic/System Engineering Issues
- Unable to meet system specifications
- Unable to certify for flight
- Component design specifications inconsistent with system design requirements
- Conflict of system performance requirements with system safety requirements
- Insufficient performance causing compromised system design to meet objectives
- Loss of skill sets and corporate knowledge
- Human capital loss
- Late stage of development design changes
- Availability of funding

Others
- Loss of vehicle and life
- Operations supportability

Question 6

What technical risks will be associated with parts, materials, and component selection? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Radiation hardening requirements
- Design requirements not fully articulated
- Concise and adequately defined initial technical requirements

Systems Complexity
- CEV systems reliability and operability
- Energy generation and storage systems
- Environmental impacts on materials
- Reliability under-specified

Systems Architecture

System/Subsystems Design and Development
- Improper materials selections
- Materials not meeting performance specifications
- Materials do not have required system/subsystem/component performance characteristics
- Fabrication difficulties with materials
- Immature technologies in systems/subsystems

- Cabin atmosphere effect on hardware
- Premature failures

Schedule

- Lead times not conducive to program schedules
- System design timeline impacts to component design/development

Integration

- Test plan development

Programmatic/System Engineering Issues

- System obsolescence
- Quality assurance support for design requirements
- Lack of human spaceflight qualified vendors
- Availability of EEE parts
- Materials and parts sources
- Insufficient quality control at vendors
- Parts certification process
- Longevity of parts suppliers
- Inadequate acceptance test process
- Materials and parts tolerance levels not maintained

Others Not Identified in the List

Question 7

What technical risks will be associated with in-orbit hazards (i.e. radiation, single-event effects, S/C charging, in-orbit debris)? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements

- Radiation
- Unknown requirements relative to MMOD for expected mission model for space exploration
- Availability of early solar flare warning or prediction system between Sun/Earth and far side for Mars Missions
- Inadequate definition/understanding of thermal environment (solar flux/albedo, etc)
- Launch into high debris orbital region
- Hardening for electronics
- System mass growth driven by radiation shielding and on-orbit debris rqmts

Systems Complexity

- S/C charging
- Lack of technology development for effective radiation shielding concepts
- Vehicle weight to mitigate SEU, radiation, and MMOD risks due to added equipment & protection materials will rise above ELV lift capability

Systems Architecture

System/Subsystems Design and Development

- On-orbit debris
- Meteorite Impact
- Failure to properly characterize the interactions of the radiation protection system materials with the space environment
- Failure to properly understand and plan for the possibility of failed automated rendezvous and docking
- Shielding design
- Single event upsets and similar effects to volatile and non-volatile memory
- Weight control relative to radiation hardening
- Inadequate mitigation of radiation
- Inadequate protection for SEU
- Inadequate protection for spacecraft charging
- Inadequate protection for meteoroid/debris strike
- Mass properties impact
- Insufficient collision avoidance design

Schedule

Integration

Programmatic/System Engineering Issues

- Single Event Effects
- Part selection, qualification and testing

Safety

- Fire
- Radiation physiological effects to crew
- Inadequate system safety plan/process

Others

- Human Error

Environmental regulatory process

Question 8

What are launch-related risk issues that will affect the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
Systems Complexity
- LV reliability
- Overall reliability of the integrated LV/CEV/Crew Escape system (resulting in reduced probability of overall mission success and increased probability of loss of life)
- Abort and crew escape capability
- Design will not meet max probability of mission catastrophic failure requirements

Systems Architecture
System/Subsystems Design and Development
- Failure to design a robust CEV/Crew Escape system
- Implementation of "all phases" abort capability
- CEV weight growth
- Insufficient lift capability
- Design not fully meeting safety requirements
- Insufficient development and testing of propulsion components
- IVHM System design for abort modes / scenarios

Schedule
- Range impacts due to multiple launch timelines required to accomplish mission objectives

Integration
- Launch vehicle integration
- Propulsion systems integration with other systems
- Inadequate test methods

Programmatic/System Engineering Issues
- Programmatic impacts associated with separate organizations within NASA and USAF-NRO
- Compliance with NASA human rated requirements
- Availability of domestic capabilities for testing
- Incomplete system engineering
- Insufficient full-scale test of realistic accident scenarios
- Inadequate launch platform mass to orbit margin to meet total mission objective

Launch Failure Modes
- Debris impact
- Failure of hold down mechanism
- Failure of umbilicals/arms to operate properly
- Failure of Booster solid rockets
- Failure firing of range safety system
- Failure to separate
- Loss of engine(s)
- Loss of communications
- Loss of RCS system
- Loss of OMS
- Loss of major structure
- Loss of minor structure
- Loss of cabin pressure
- Loss of TVC (APU/HPU)
- Loss of Telemetry
- Loss of partial TPS system
- Loss of LPS automated launch processing capability
- Leak of propulsion tanks or lines
- Benign failure of the launch vehicle
- Failure of the launch escape system given catastrophic failure of the launcher
- Failure of the launch escape system given benign failure of the launcher

Environmental Considerations
- Environment (wind, rain, temperature, lightning)
- LV induced acoustic, thermal, and physical effects upon the CEV
- Launch site weather, air quality, and range safety

Others Not Identified in the List

Question 9 Analysis
What are entry-related risk issues that will affect the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Requirement for passive re-entry from lunar
- L/D selection and required cross range capability
- Inadequate user documentation
- Incomplete understanding of the operating environment
- Capability to land either in water or on the land

Systems Complexity
- Definition of abort modes and changes/alterations (determine max velocity, loads, etc.)
- Developing the wrong or inadequate user interface

Systems Architecture

System/Subsystems Design and Development
- Thermal Protection System technology and design
- OML shape change during flight (TPS loss of integrity, aerodynamic/aero-heating design)
- Development of new TPS materials (weight and long exposure to space environment)
- Ability to safely withstand thermal environment
- Reentry heating larger than expected
- Ability to meet abort requirement / capabilities at any point
- Design landing system for covering contingencies where entry targets are not met
- Ability to safely meet ground impact forces
- Ground system design to include GN&C and CCC
- Lack of critical communications coverage
- Lunar communication capability
- Design not fully meeting safety requirements
- GN&C design issues

Reentry Failure Modes
- Loss of ECLSS
- Crew recovery
- Improper crew re-entry
- Loss of cabin pressure in crewed vehicle
- Loss of power
- Loss of APU
- Guidance failure
- Inadequate controllability during reentry
- Entry targeting and navigation scheme
- Loss of OMS
- Loss of RCS
- Loss of elevons
- Loss of Body Flap
- Loss of or damage to Thermal Protection System (TPS)
- Failure of the heat shield
- Loss of brakes, including Rudder Speed Brake
- Loss of Landing Gear
- Failure of the parachute recovery system
- Loss of telemetry
- Loss of major/miner structure
- Failure of the de-orbit burn maneuver

Schedule

Integration
- Inadequate test methods
- Ability of NASA to integrate its component parts

Programmatic/System Engineering Issues
- Impact to budget and mission timeline of reentry failure on first (unmanned) mission
- Contracting out launches without sufficient oversight

Others Not Identified in the List

Question 10 Analysis
What are software technical risks for the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Changing priorities
- Necessity for automation complicating FDIR for uncrewed flight
- Artificial intelligence for vehicle command and control while uncrewed
- Verification and Validation requirements and facilities

Risk Profile for NASA's Crew Exploration Vehicle (CEV) System

Systems Complexity
- Lack of clear product vision
- Uncertainty, lack of agreement, and prioritization of product requirements
- Requirements creep (changing functionality and shoring up H/W-operations deficiencies)
- Uncertain and changing technologies
- Unreasonable constraints on number of lines of code
- Closed software architecture making infusion of new technologies difficult
- Crew Interface and Human Factors
- Incomplete understanding of the operating environment

Systems Architecture
- Inadequacy and complexity of user documentation

System/Subsystems Design and Development
- Software requirements maturity
- System not robust enough to acuminate (?) changing/new requirements
- Non crew tended operation (long term operations while the crew is on the lunar surface)
- Use of fault tolerance in the software (additional complexity impact to system reliability)
- Error in the configuration presented to the code
- Ground system design to include GN&C and CCC for multiple on-orbit targets
- System redundancy driving design requirements and mass
- Incorporation of a fully independent back-up software capability
- Software systems fail to interface properly
- Developing the wrong or inadequate user interface
- Software error in the guidance code
- Software quality assurance to detect mission critical faults
- Need for independent design and coding
- Building too much intelligence and autonomy into the software
- Level of on-board autonomy and ability to validate pre-launch
- Automated functions with crew input and override intervention
- Selection of platforms/programming languages
- Aging software and computers that are difficult to upgrade
- Computing platforms /architectures for the CEV that will tolerate radiation environment
- Older technology less attractive as a professional challenge to software professionals
- Locking in on a programming language results in attraction and retention issues
- Multiple development languages for both ground and flight software
- Language selection for system, support and application software
- Increased number of layers of software between the operating system and the user
- Lower order languages vs. higher order
- Use of software that cannot be modified in-house (COTS, MOTS, etc.)
- Immaturity of autonomy technology and the host processor

Schedule
- Adequate times to develop and validate regardless of autonomy levels

Integration, Verification and Validation
- Software fails to meet system requirements
- Implementation of Integrated Health Management System and associated software
- Inadequate test methods
- Lack of regressive, automated testing techniques
- Inadequate software and system validation testing (with flight hardware)
- Inadequate failure path testing
- Implementation of late flow software patching
- Error in the adaptation of the code to a particular mission requirement
- Safing/abort software problems
- Failure to follow proper IV&V standards
- Validation of software for intended use

Programmatic/System Engineering Issues
- Ineffective requirements change management process
- Inadequate impact analysis of requirements change
- Late delivery of test/flight software
- Late discovery of software problems
- Critical skill shortages for qualified, trained personnel
- Retention of current launch control software experts
- Staff leaving the project permanently or temporarily
- Subcontractor, supplier, or vendor delivering late or late to start
- Shortfalls in externally provided software
- COTS or single-vendor developed software on-site
- Outstanding software professionals available to develop/sustain CEV through its lifetime
- Sole-sourcing software development results in creation of one-of-a-kind software system

Others
- Lack of understanding of technical operation requirements

Inadequate software support to crew situational awareness

Question 11 Analysis
What are communications, command and control technical risks associated with the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Incorporation of range, coverage and bandwidth requirements
- Vehicle health management and autonomy requirements
- Ground CCC requirements for 0 crew operations
- Requirements control to keep all CTS segments/elements to a common/compatibility set
- Uncertain, new, changing and creeping requirements

Systems Complexity
- Availability of communication architecture for lunar missions
- Level of autonomy both crew and system can provide vs. cost of comms infrastructure
- Ground and crew roles

Systems Architecture
- Lunar navigation capability-need for infrastructure on the moon

System/Subsystems Design and Development
- Inadequate antenna design to achieve required coverage
- Low signal quality
- User interface complexity could cause operator overload
- Automation and failsafe reaction capability impacts to operator overload, mission safety
- Secure controls for remote capability, software up/down loading, and data transmission
- Development of Integrated Health Management System to meet NASA safety standards
- Resolution of automated vs. crew functionality associate with abort determination Long dormancy in lunar orbit drives complex fault detection, isolation, recovery routines
- Improper knowledge of alignment of GN&C devices creating larger control errors
- Implementation of autonomous operations
- Properly defined C3 interface and integration with other C3 systems
- Launch and landing tracking capability
- Lunar orbit rendezvous
- Lack of data fusion could cause delays in critical decisions by operators/astronauts

Schedule

Integration, Verification and Validation
- Lack of end-to-end communications test
- Inadequate test methods
- Unable to define environment to establish test methods
- Code Errors/Proper Validation
- Data Reduction
- Incorrect sensor or affector polarity (installation vs. software)
- Improper software control constant settings

Programmatic/System Engineering Issues
- Life cycle cost considerations drive de-staffing ground control during dormancy periods

Others
- Failure of communication either within a CEV crew or from crew to ground
- Misalignment errors
- Issues with NASA culture, decision making, leadership, big picture, training, motivation
- Early solar flare warning or prediction system between Sun / Earth and far side for Mars Missions
- Human Error in uplinks
- Changing priorities
- Inadequate configuration control

Question 12 Analysis
What are technical risks associated with the impact of the space environment on achieving a human rating, to include on-board life support and power systems? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Protection from space environment of on-board life support and power
- Radiation environment and human rated reliability in the lunar environment
- Capability to reduce logistics/re-supply requirements relative to life support systems
- Need for Regenerative ECLS to avoid driving mass
- Definition of cabin atmosphere
- Unknown consumable requirements (need capability for 45 day 4 man crew)
- Crew clinical medical care capabilities and procedures limitation on Lunar Stay time
- Achieving countermeasures for de-conditioned crew

- Unknown MMOD requirements for expected mission model for space exploration
- New, changing and creeping requirements
- Omissions in the design requirements

Systems Complexity
- Insufficient understanding of the long-term exposure limits for the Mars spiral design
- Contamination
- Provide suitable psychological effects for crew for a small space craft, long durations
- Impacts of long term space travel on humans are as yet unknown or have no solution
- Problem of carrying sufficient supplies for some missions and getting rid of waste
- Dependencies in the design not identified or not fully defined
- Inadequate standardization among different vehicle configurations

Systems Architecture
- Power system trades-solar, fuel cells, battery etc
- Complexity of the design (CEV Architecture) not fully defined or understood
- Internal and interfaces not identified or completely defined

System/Subsystems Design and Development
- Inadequate meteoroid/FOD debris shielding design
- Integrated power and active thermal control system for longer missions
- Development and integration of adequate spares and an in-situ repair capability
- Inadequate spacecraft charging mitigation design
- Inadequate thermal protection system design
- Long term power generation capability
- Redundancy, back-ups, and alternate operational scenarios to achieve a human rating
- Weight control relative to radiation hardening
- Capability to provide adequate radiation shielding
- Inadequate radiation shielding design
- Systems design/certification to maintain the CEV unmanned in lunar orbit for 45-99 days
- SEU (Single Event Upset) of computer system
- Changing and uncertain technologies

Schedule

Integration, Verification and Validation
- Regenerative life support systems have limited demonstration in space environment

Programmatic/System Engineering Issues
- Compliance with NASA human rated requirements
- Roles and responsibilities not clearly defined
- Separate organizations responsible for integration/delivery of human rated systems

Others
- Environmental regulatory process
- Inadequate system safety plan/process

Question 13 Analysis

What are technical risks associated with quality, integration, systems management and testing of the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Inadequate requirements definition and traceability
- Lack of control of requirements growth
- New, changing and creeping requirements
- Agreement on requirements for Human Rating ELV
- Changes in mission goals drive changes in CEV Technical and operational requirements

Systems Complexity
- Complexity of the design not fully defined or understood
- Dependencies in the design not identified or not fully defined
- Omissions in the design requirements
- Level of on-board autonomy and ability to validate pre-launch
- CEV weight increase required providing Human Rating exceeding ELV lift capability
- System level aerodynamics/aero acoustic requiring extensive ELV rework and costs

Systems Architecture
- Capability to define/control interfaces for all elements
- Interface definition to prevent test and system failures, integration issues, schedule slips
- Internal and external interfaces not identified or completely defined

System/Subsystems Design and Development
- Piece part design philosophy in ESMD
- Technically sound, top-down, guided design process
- Mismatch of physical and / or functional interfaces
- Building reliability into the design is essential

Schedule
- Schedule time allotted to test real flight hardware with flight software

Integration, Verification and Validation
- Inadequate inspection fails to detect flaws/defects
- Incomplete failure modes and effects analyses fails to detect hazard
- Inadequate records kept to investigate problems/anomalies/waivers
- Changing and uncertain technologies
- Multiple procurements of system components complicating integration effort
- Integration with other space exploration elements (lander, in-space propulsion elements)
- Element to element interface verification (structure, fluids, electrical, communications)
- Inadequate verification/validation process
- Test program to account for all factors including all relevant variables in simulation
- Proper and timely definition of requirements for simulation and testing of crew interfaces Domestic capabilities for testing (wind tunnel, arc jet testing, system test facilities)
- Insufficient /inadequate integrated testing
- Integrated testing environment available for all components of system
- Build and operate a high fidelity avionics /communications simulation facility
- Validation that the simulation facility response matches that of the real flight hardware
- Test and Verification from development through Subsystem and Integrated System Test
- Thorough integrated testing should include both Hardware and Software verification
- Testing should occur with Hardware and Software emulating flight configuration
- Use of high fidelity simulators is warranted
- Inadequate integrated systems testing
- Inadequate systems testing of off-nominal scenarios and failures
- Inadequate regression of late changes
- Test parameters/end conditions incorrectly applied or assumed
- Test does not adequately evaluate system
- Test support equipment not ready in time for the tests
- Integrating component/subsystem and system test identification & audit
- Improper system engineering allowing mismatches of CEV and launch

Programmatic/System Engineering Issues
- Large number of parties involved in integration leading to role/responsibility issues
- Ability to control technical requirements across all elements
- Inadequate ICD (Interface Control Document)
- Buying the elements one at a time, and not all in an integrated fashion
- Inadequate development funding
- Reserves managed to minimize constraint on critical systems
- Roles and responsibilities not clearly defined
- Budget and schedule need to provide for Integrated Testing of Flight Systems
- Lack of testing facilities –vacuum, thermal, acoustic, radiation
- Lack of human spaceflight vendors who can meet quality requirements
- Decreasing industrial capability and knowledge base
- Industrial base of capable contractors has decreased
- Limited numbers of engineers having experience in human space flight-specific skills
- Quality resources
- Multiple vendors
- Lack of experienced staff (numbers and quality)
- Inadequate and insufficient SE&I
- Knowledgeable engineering expertise
- Training requirements
- Lack of standardization among different vehicle configurations
- Environmental regulatory process

Quality Assurance
- Inadequate QA requirements imposed on contractors
- Parts Incompatible

Others
- Lack of timely and correctly placed MIPs
- Lack of safety related engineering culture within NASA and aerospace primes
- Inadequate system safety plan/process

Question 14 Analysis
What are technical risks associated with the structural design and fabrication of the CEV? Please assign a Probability of Occurrence and Impact of Occurrence rating to each identified technical risk.

Requirements
- Launch, orbital and re-entry environments
- Lack of standardization among different vehicle configurations
- New, changing and creeping requirements

Systems Complexity
- Not all environmental conditions understood and designed in
- Dependencies in the design not identified or not fully defined

CEV weight growth when integrated with human rated launch vehicle
Complexity of the design not fully defined or understood

Systems Architecture
Element to element interfaces
Internal and external interfaces not identified or completely defined

System/Subsystems Design and Development
Material selection
Known metallic material vs. composites for primary structure
Composite cryo-tanks
Weight Margins
Light weight structure
Achieving the weight and c.g. requirements
Design loads incorrect
Misapplication of structural loads
Structural analysis error
Structural design codes not met
Integrated design process
Life cycle and mass challenges
Development of an adequate docking/berthing mechanism
Lightweight Pressure vessel design
Changing and uncertain technologies
Inadequate assessment of late design changes
Final structural design does not meet all system design requirements
Structural design does not include all important environmental considerations and loads
Inconsistent designs relative to loads and structural designs
Inadequate design for ground structural integrity inspection
Inadequate design for on-orbit structural integrity inspection
Insufficient robustness
Difficult to repair

Schedule

Integration, Verification and Validation
Problems or anomalies not adequately investigated and resolved/repaired

Programmatic/System Engineering Issues
Roles and responsibilities not clearly defined
Environmental regulatory process
Control of design environment requirements
Different structural design philosophies across numerous NASA agencies/contractors

Fabrication Issues
Validation, verification and certification of fabrication processes
Titanium Fiction Stir Welding needs further development
Structural welding of primary structure
Welding flaws and cracks
Hidden or undetected flaws

Others
Inadequate system safety plan/process

Question 15

This question will address in multiple parts the availability of technology for major systems associated with the CEV. Based on your knowledge and experience, please identify the technology and estimate the range of time it will be available for the CEV by selecting a rating.

With the 2014 date as a goal for going beyond LEO:

15.a. Identify the technologies and rate availability for the launch propulsion system.

Propulsion Technologies

- LO2/LH2 propulsion technologies are currently available and can be used on new launch systems.
- LOX/RP-1 propulsion technologies are currently available and can be used on new launch systems.
- Hypergolic propulsion technologies are currently available and can be used on new launch systems. .
- Nuclear technology.
- Booster Propulsion
- New upper-stage propulsion (if required, probably will need for later spirals)
- Highly reliable main propulsion with adequate ISP and thrust.

Launch Vehicle

- Launch vehicle capability 5
- Shuttle derived can achieve about 4 to 6 launches a year
- Heavy lift, cheaper than shuttle, expendable LV to achieve 4 to 6 launches a year.
- Launch escape system integrated into the ELV

Human Rating

- IVHM System required to support NASA Human Rating Standards
- Human ratable vehicle monitoring and control systems
- New human rated upper stage engine
- Human rating an EELV
- Assume you use a human rated EELV or Shuttle derived in-line vehicle.
- Human-rated launch vehicle capability

Abort Capability

- Engine development
  Abort system
- Launch abort systems to allow complete ascent coverage
- Abort capability and abort decision logic/identification
- CEV Abort Systems

Other

- Integrated health management
- Non-toxic propellants

15.b. Identify the technologies and rate availability for the navigation system.

GPS or GPS-Based

- GPS. Rating
- Global Positioning System applicable to lunar environment
- Star Tracker/IMU/GPS navigational technologies are currently available and can be used on new launch systems.

GN&C

- Existing Guidance Navigation &Control technologies should be adaptable to the CEV mission with minimal issues
- New GN&C technologies

Lunar Orbit Navigation

- Rendezvous Navigation
- Translunar tracking
- Descent targeting and tracking

Other Technologies

- Inertial.
- AR&D;
- Sparing / Repair, Interchangeable modules
- Solid state attitude sensors
- Non-propulsive attitude control affectors
- Position and attitude determination system (assume that GPS is out of range)
- Nav/ Landing Aids

15.c. Identify the technologies and rate availability for the crew environmental system.

ECLS

- ECLS technologies are currently available and can be used on new launch systems
- Regenerative ECLS
- Closed regenerative ECLS systems
- Closed loop ECLS

Air and Life Support

- Advanced Life Support System design to support long duration missions
- Breathing air
- Oxygen Generation System
- CO2 Reduction

Medical

- bone decalcification
- long term psychological health
- sleep dysfunctions

Other Environmental

- Temperature control
- Temp. & Humidity Control

- Water Recovery / Reclamation
- Crew exercise equipment
- Crew shower
- Crew toilet

15.d. Identify the technologies and rate availability for the in-flight propulsion system.

Hypergolic

- Hypergolic propulsion technologies are currently available and can be used on new launch systems.
- No technological development required if traditional hypergolic fuels used. Hypergols

Cryogens or Alcohol-based

- New vs. existing technologies
- New transfer system, e.g., cryo systems
- 'Clean' in space propulsion

Non-Toxic

- "Green" storable systems
- Non-toxic technology maturation challenge

Storables

- If simple storables propulsion
- Storable bipropellant existing propulsion systems

Others

- Adequate Launch Vehicle upper stage TLI;
- On-Orbit reaction control thrusters
- Electric propulsion systems
- Nuclear thermal propulsions systems
- Throttleable Descent engine
  Ascent engine- storable propellants
  LOI/TEI engines

15.e. Please identify other critical systems, their technologies, and rate their availability.

Thermal Protection System

- Shuttle TPS (tile, blanket, FIR, SOFI, MSA, MTA, SLA, Cork, etc.) technologies are currently available and can be used on new launch systems.
- Apollo honeycomb filled heat shield TPS technologies are currently available and can be used on new launch systems.
- Gemini metal shingle heat shield TPS technologies are currently available and can be used on new launch systems.

Launch Site

- Launch site processing throughput shuttle style, 4 to 8 launches a year.
- New cheaper launch site processing architecture, 4 to 8 launches a year

Docking / Berthing / Rendezvous

- Berthing/docking mechanism
- Automatic Docking/Rendezvous Capability

Power

- Long term power generation capability
- Power generation / fuel cells

Health / Medical

- Clinical Crew Medical Care to enable long duration stays
- Crew Health / Exercise systems for long duration flight

Others

- Crew Escape System;
- Active Thermal Control System for long stay missions;
- Spacesuits for launch/entry, EVA, Lunar surface compatible with crew cabin environment
- Cryo fluid management and early demonstrations
- Windows
- High bandwidth communications
- AR&D
- DoD Interface
- Radiation shielding

END

Appendix D: List of Abbreviations and Acronyms

AA	Associate Administrator of NASA
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle (Ares I)
CaLV	Cargo Launch Vehicle (Ares V)
CAIB	Columbia Accident Investigation Board
CDV	Cargo Delivery Vehicle
CPMR	Center for Program Management Research
CRM	Continuous Risk Management
DAA	Deputy Associate Administrator of NASA
DELPHI	Delphi technique named after ancient Greek oracle
EDS	Earth Departure Stage
EMD	Exploration Mission Directorate
EMS	Electronic Meeting System
ESAS	Exploration System Architecture Study
FTA	Fault Tree Analysis
FMEA	Failure Mode Effects Analysis
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LOC	Loss of Crew
LOM	Loss of Mission
LSAM	Lunar Surface Access Module
MIT	Massachusetts Institute of Technology
MOD	Mission Operations Directorate at JSC
MTV	Mars Transfer Vehicle
NASA	National Aeronautics and Space Administration
NTP	Nuclear Thermal Propulsion
RDM	Reference Design Mission
RTF	Return to Flight
SM	Service Module
SoS	System of Systems
SSP	Space Shuttle Program
UCAL	University of California
USRA	University Space Research Association
VSE	Vision for Space Exploration