CHALLENGES IN HUMAN-RATING THE CREW EXPLORATION VEHICLE TO MARS
OR
WHY HUMAN SPACEFLIGHT IS SO DAMNED EXPENSIVE

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ABSTRACT

The Orbital Space Plane (OSP) project was conceptualized to be a safe, reliable, robust, responsive, and low cost means to provide crew rescue, crew transport, and small cargo delivery from Earth to the International Space Station (ISS) for 20 years. Although the mission needs may have changed, there was value in undertaking that initiative since a crewed space transport vehicle had not been designed in over 25 years and there was danger that valuable technological and intellectual expertise was being lost by attrition. Human spaceflight is not a task to be left to the penny-pincher, tinkerer, experimenter, or inexperienced newcomer regardless of his or her sincerity. To keep established processes, frameworks, and procedures fresh and applicable to modern needs, as well as maintaining and invigorating the intellectual capital base, such a project is invaluable. This is especially true in the area of flight safety. A number of important design analyses and trade studies required to assure the safety and mission effectiveness of astronauts in the complex OSP flight system had been started (and were making considerable progress) when the program was terminated at the end of February. This work was required, in NASA parlance, to human-rate the space flight system if the system is to accommodate astronauts. High-level human-rating requirements have been provided by NASA (for general spaceflight as well as for the OSP) but decomposition of these requirements into lower level design specifications is the responsibility of the industrial design contractors. Many of these requirements were directly applicable to the Crew Rescue Vehicle (CRV) and Crew Transfer Vehicle (CTV) missions to support the ISS but many other requirements are applicable to human spaceflight in general.

Acronyms

AST	Advanced Space Technology
CAIB	Columbia Accident Investigation Board
CEV	Crew Exploration Vehicle
CRV	Crew Rescue Vehicle
CTV	Crew Transfer Vehicle
DDMS	Department of Defense Manned Space Flight Support
DOD	Department of Defense
EVA	Extravehicular Activity
ISS	International Space Station
IV&V	Independent Verification & Validation
JSC	Johnson Space Center

LOC	Loss of Crew
NASA	National Aeronautics & Space Administration
ORU	Orbital Replacement Unit
OSP	Orbital Space Plane
TM	Technology Maturation

I. INTRODUCTION

The 2004 Vision for Space Exploration encompasses a broad range of missions and activities, including journeys to the Moon, Mars, and destinations beyond. The fundamental goal of the Vision is to advance U.S. scientific, security, and economic interests through a robust space exploration program.[1] To support this goal, the U.S. will endeavor to do the following:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration

The keyword in these three endeavors is "human". The Vision seeks to achieve the goal by an approach that is centered on human exploration, as opposed to scientific investigation, security and defense, or economic industrialization. Specific human-related activities that have been identified that will bring the Vision to reality include:

- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinationsDevelop and demonstrate power generation, propulsion, life support, and other key capabilities required to support more distant, more capable and/or longer duration human and robotic exploration of Mars and other destinations
- Conduct human expeditions to Mars after adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon

To achieve these goals, requirements must be developed such that design activities can proceed in an organized and cost-effective manner. NASA has created the high level requirements that support the goals and the Vision.[2] These requirements will lead to design concepts, and then to design formulation, fabrication, assembly, test, deployment, and eventually to operations. Requirements specific to the human element are as follows:

Level 0

- Implement a safe, sustained, and affordable robotic and human program to explore and extend the human presence across the solar system and beyond
- Develop the innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic exploration
- Conduct human lunar expeditions to further science, and to develop and test new exploration approaches, technologies, and systems; including the use of lunar and other

space resources to support sustained human space exploration to Mars and other destinations
- Conduct human expeditions to Mars to extend the search for life and to expand the frontiers of human exploration after successfully demonstrating human exploration mission to the moon
- Develop an exploration transportation system to support delivery of crew and cargo from the surface of the Earth to exploration destinations and to return the crew safely to Earth

<u>Level 1 Objectives</u>
- Develop and demonstrate power generation, propulsion, life support, and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations
- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020, in preparation for human exploration of Mars and other destinations
- Develop a crew exploration vehicle and associated systems before the end of this decade in order to provide an operational capability to support human exploration missions no later than 2014
- Conduct initial flight test of a Crew Exploration Vehicle before the end of this decade

Development programs are needed to evolve, mature, and refine the design concepts. Four major elements have been identified as necessary to advance the development:
- Project Constellation – development of a Crew Exploration Vehicle
- Project Prometheus – the nuclear systems program
- Advanced Space Technology – developing and validating novel concepts and high-leverage technologies
- Technology Maturation – maturing and applying novel concepts and high-leverage technologies

II. HUMAN-RATING THE CREW EXPLORATION VEHICLE

The centerpiece of development is Project Constellation, the effort to develop a space vehicle (dubbed the Crew Exploration Vehicle or CEV) that will carry astronauts to the Moon and Mars. Since the CEV will carry human beings, it will require human-rating certification by NASA. Technologies developed in the TM and AST program elements can be used to help achieve human-rating in a more cost-effective manner than was achieved with the Space Shuttle or International Space Station (which is not as good a model for CEV as Shuttle), but achieving human-rating certification is still a significant effort. By NASA definition, human-rating is "The certification that the system has been developed and is capable of being operated in a manner appropriate for use by human crews at minimal risk". Human-rated certification includes Human Safety, Human Performance, and Human Health Management. The guiding document for design is NASA NPG 8705.2.[3]

A. Design for Human Space Flight

The industry view, as opposed to the government view, is somewhat broader because of all the design disciplines involved in creating a system that can accommodate humans. In this view, there are four aspects:
- Life Enabling (assuring human life)

- Life Maintaining & Accommodating of Uniquely Human Needs
  (assuring continued human involvement in the mission)
- Life Protecting (assuring continued human safety)
- Mission Enabling (assuring effective human involvement in the mission)

"Life Enabling" involves aspects of accommodation that, if absent, would prevent life from continuing or quickly snuff it out. Examples are:

- Food
- Water
- Environmental Control & Life Support
- Airlocks
- Radiation Protection
- Crew Altitude Protection
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This is not a trivial expense; witness the Environmental Control & Life Support System (ECLSS) on Shuttle. This is a very complicated high maintenance system consisting of cabin pressurization, cabin air revitalization, water coolant loops, active thermal control (air conditioning), potable water recycling, waste water management, solid waste collection, and smoke detection / fire suppression.[4] For the CEV, all of these systems will require almost total redesign.

"Life Maintaining and Monitoring" involves aspects of accommodation that are necessary for maintaining a sense of civility and comfort, as well as first aid and medical facilities. Examples are:

- Lighting
- Audio Communications
- Minor First Aid & Medical Facilities
- Crew Equipment
  * Dining Facilities
  * Bioinstrumentation
  * Apparel
  * Sleeping Provisions
  * Personal Hygiene Equipment
  * Restraints & Mobility Aids
  * Workplace Equipment
  * Exercise Equipment
  * Housekeeping & Equipment Stowage
  *

Although, for the most part, these expenses are somewhat predictable, the medical related expenses for longer CEV missions are still very uncertain.

"Life Protecting" involves aspects of accommodation that provide insurance against the occurrence of life threatening events, or provide aids for humans to cope with life threatening events if they do occur. "Mission Enabling" involves aspects of accommodation that enable the mission to continue, or to be adjusted, by intervention of human control or decision-making. With respect to the design accommodation, the "Life Protecting" and "Mission Enabling" aspects can often be addressed by the same design implementation or design solution. Taken together, examples include:

- Caution & Warning Systems
- Manual Flight Controls
- Visual Display Systems
- Systems & Equipment Design per NPG 8705.2
    - Design for Human Space Flight
    - Aerospace Design Standards
    - Flight Test
    - System Safety & Reliability
    - Abort & Crew Escape
    - Flight Termination (Range Safety)
    - Proximity Operations
    - Analysis & Assurance of Critical Functions
    - Human-in-the-Loop Requirements
    - Systems Test & Verification

By far, the major expense is the design of systems and equipment to meet the guidelines of NPG 8705.2. In fact, the cost of "Life Protecting" (and associated "Mission Enabling"), also sometimes called the cost of assuring human safety, generally outweighs all the other costs of human-rating put together. The overall cost of human-rating is composed of three parts:

1) Cost of Enabling Human Life (Life Enabling)
2) Cost of Assuring Human Safety (Life Protecting)
    a) Design
        i) Reliability
        ii) Human-in-the-Loop
    b) Operations
        i) Mission Operations
            (1) Flight Operations
            (2) Ground Operations
        ii) Support Operations
            (1) Maintenance & Repair
            (2) Checkout & Readiness
3) Cost of Accommodating Uniquely Human Needs (Life Maintaining)
    a) Physiological
    b) Psychological

Furthermore, the cost associated with 'Design for Reliability' and 'Design for Human-in-the-Loop' usually outweighs the costs associated with Mission and Support Operations, which are well established and are already in the process of being streamlined. These design costs include the costs of assuring the integrity of life-protecting features for the non-life-support functions as well as for the life-support functions.

B. NASA Human-Rating Requirements

The document that provides the human-rating requirements is somewhat misrepresentative in that it is only a small document of about 30 pages and incorporating about 70 requirements. However, it requires adherence to a list of other documents, including NASA-STD-3000, which contains over 3100 "shall" statements, and MIL-STD-1472, which consists of about 200 pages and contains about 170 requirement paragraphs. A fairly complete list of top-level directive documents is as follows:

- NPG 8705.2 NASA Human Rating Requirements and Guidelines for Space Flight Systems
- NASA-STD-3000 Manned Systems Integration Standards
- MIL-STD-1472 DOD Design Criteria Standard – Human Engineering
- NASA/TM-2003-210785 Guidelines and Capabilities for Designing Human Missions
- JPG 8080.5 Manned Spacecraft Criteria and Standards (JSC Design and Procedural Standards)
- JSC 26882 NASA Space Flight Health Requirements
- Other tailored military and aerospace design standards
- Software directives:
    * NASA-STD-8719.13A Software Safety NASA Technical Standard
    * IEEE/EIA 12207 Information Technology, Software Life-cycle Process
    * NPD 8730.4 Software Independent Verification and Validation (IV&V) Policy

However, nested within these top-level documents are a host of secondary applicable documents, each containing their own requirements and applicable documents. It would be interesting to determine the end level of nesting and the sum total of applicable human-rating requirements. It is not known if this has ever been done, but it would be a significant task. If just identifying all the requirements is so difficult, it can be appreciated how daunting a task it is to actually create a design that adheres to all the requirements; and consequently how expensive it could be. So expensive, in fact, that unless careful and timely design tradeoffs are made in coordination with NASA, escalating costs could easily jeopardize the program.

C. Human-Rating Design Drivers

The effort to achieve human-rating covers all programmatic aspects and is not exclusive to design. Fabrication and test activities, such as manufacturing quality control processes and verification and validation testing, are included, as are sustaining operations, such as maintenance, readiness testing, and inspection processes. Also included are mission and flight operations, procedural design, and supportability. In the area of design, the drivers for human-rating are the following:

- Providing interfaces between the crew and (1) hardware, (2) software, (3) procedures, and (4) environments for the purpose of satisfying program requirements for safety, reliability, and efficiency
- Providing for crew interfaces to monitor and control subsystems within accepted levels of human workload and situational awareness in order to minimize human error
    * Information and control is provided to the crew by:
        - dedicated and multifunction display & control hardware
        - software driven graphical and textual user interfaces
        - manual, semi-automatic, and automatic means of operation

Analysis of NPG8705.2 indicates that the design for human-rating is driven by the following:

Failure Tolerance & Redundancy

- No 2 failures can result in permanent disability or loss of life
    - * Tailoring is possible if
        - testing or analysis can provide certainty that there will be very high reliability without 2 failure tolerance
        - 2-failure tolerance is impractical or negatively impacts overall reliability
- Interactions of components operating as specified do not result in permanent disability or loss of life
- Emergency systems cannot be used to satisfy failure tolerance requirements
- Dissimilar redundancy is assessed as a defense against common cause failure in the design of critical functions

Indications for Crew Awareness

Indications are required for failure of critical system/component, detected faults, isolated fault, and means to preclude catastrophic safety risk

Abort and Crew Escape

Crew and occupant survival and recovery is provided on ascent by using a combination of abort and escape

Flight Termination

Design features (such as thrust termination) are required which allow sufficient time for safe human escape prior to activation of destruct system

Human-in-the-Loop Requirements

- Flight crew and ground crew have insight into vehicle performance and capability for intervention
- Feedback required to flight crew and ground crew for all human commands
- Control of flight path and attitude during ascent provided by independently developed and redundant software systems
- Flight Crew has capability to select between two independently developed versions of flight control software during flight
- On ascent, where margins allow, manual control of vehicle flight path and attitude is required
- Human operator overriding of higher level software and automation will not adversely impact vehicle safety during transition from software/automation to manual control
- Flight Crew has capability to monitor and control the vehicle functions critical for safety of flight
- Flight Crew is able to select and initiate abort modes
- Flight Crew is able to initiate the escape sequence
- Flight Crew is able to disable/inhibit the automated initiation of the crew escape system

- Flight Crew is able to override automatic initiation sequences
- Safety of the flight crew does not depend on communication with, or real-time support from, the ground

Each of these requirements was addressed during the OSP program but design solutions for all were not finalized. In addition to OSP-specific mission-driven requirements, the tailored human-rating requirements broke down into three areas similar to the overall design aspects associated with human space systems in general:

- Safety Specific
- Human-in-the-Loop (Operations) Specific
    - * Monitoring and situational awareness
    - * Command and control
    - * Flight and mission planning
    - * Maintenance
    - * Human Factors / Workload
- Health and Environment Specific

D. Crew Survival

The overarching requirement, but not the exclusive requirement, in NPG8705.2 is the requirement for crew survival. The goal is to protect the crew when otherwise catastrophic failures occur. It encompasses all activities necessary to acquire a collective understanding of all threats to the life of a crewmember and provide for integrated crew survival solutions. These solutions are considered in terms of **flight abort**, **crew escape**, **launch-pad/landing-site egress**, **in-space safe haven**, and **land/water crew rescue** with respect to all human-involved systems and can be applied across both ground and flight segments throughout all mission phases. Comprehensive definitions for the above terms are provided in NPG8705.2. There have been significant incidents and close calls in human spaceflight that dictate these solutions. Five documented losses of life (Russian and American), two incidents resulting in major injury, six close calls, and at least eleven other significant failure events bring the issue of crew survival to the forefront.[5] Design solutions that could possibly have prevented these incidents are possible but they are technically complicated and very expensive. In fact, crew escape by itself is so expensive that the relevant Space Shuttle design was marginal and never completed in production vehicles.[6]

On the OSP program, because of the necessity of launching atop a commercial expendable booster (Delta 4 or Atlas 5) not designed for human-rating, crew escape and/or intact abort were mandated as controls to be provided by the OSP for booster hazards that result in loss of the booster. With regard to the Space Shuttle Columbia tragedy, one of the Columbia Accident Investigation Board (CAIB) observations (O10.2-1)[7] was that "future crewed vehicle requirements should incorporate the knowledge gained from the Challenger and Columbia accidents in assessing the feasibility of vehicles that could ensure crew survival even if the vehicle is destroyed". This implies some form of crew escape. **It is unlikely that a Shuttle-like design philosophy, where features such as fault tolerance, redundancy, and high reliability are employed to prevent the occurrence of a catastrophic fault, as opposed to an Apollo-like design philosophy, where features such as crew escape or crew transfer are employed to remove the crew from a vehicle facing imminent life-threatening conditions, will be**

entertained for future human space systems. Of course, Apollo did not follow this philosophy completely. There was no crew escape for the lunar landing phase in the Lunar Excursion Module. There are always practical tradeoffs to be made. But it is likely that the CEV in the Exploration program will require a robust design for crew survival that is applicable across all mission and flight phases. And the vehicle will necessarily have to have a lower failure probability than Shuttle (OSP Spec for risk of loss of crew was < 1/400)[8] and a higher reliability for the crew escape system than Apollo (not specified and only tested in contrived conditions). But how much lower or higher? NASA's projected risk of loss of crew requirement for a future 2nd Generation Reusable Launch Vehicle is < 1/10000 [9]and projected reliability for the crew escape system is > 90%. This is probably not achievable in the near term. It all comes down to how much you can afford and how much risk you are willing to take. The design challenge will be to obtain the most bang for the buck. Whether that is sufficient to satisfy Congress and the American public is the big question.

There is an additional factor to consider. Meeting the crew escape requirements (and incurring the related design and development costs) cannot be used as credit for meeting all the other requirements of NPG8705.2, specifically the failure tolerance and redundancy requirements. That is because a crew escape system is considered to be an emergency system and emergency system design cannot be considered when verifying that the overall design meets failure tolerance and redundancy requirements. The design must be 2-fault-tolerant in addition to featuring a reliable crew escape system. This will be another cost driver. Again it comes down to how much you can afford and how much risk you are willing to take. Tradeoffs are possible between fault tolerance coverage and crew escape reliability or flight regime coverage, but engineering trades require studies and analyses. The design challenge is significant and could make-or-break the program. The "paralysis by analysis" syndrome is a real concern for a robust human space flight program. Because of the programmatic and technical complexities involved, design cleverness alone, within a single domain, is not sufficient. A fully integrated design solution is required, and that is driven by funding. And as everyone knows, NASA funding hinges on the political winds of the moment.

E. Applicability of OSP Requirements to CEV

The CEV Operational Concept will be different than that of OSP and this will drive different design solutions. For OSP, Level 1 and Level 2 requirements were developed by NASA,[10] while Level 3 requirements/system-specifications were developed by the industrial contractors. The Level 1 requirements defined the system performance characteristics and top-level interfaces that were necessary to satisfy the mission needs and the program goals and objectives. The Level 2 requirements provided details and clarification for the required functional capabilities and constraints derived from functional analyses, performance analyses, and operational analyses (in other words, it defined what must be done, how well it must be done, and under what constraints it must operate). The Level 3 requirements/system-specifications defined the industrial contractor's top-level solutions to the Level 1 and Level 2 requirements.

Of the Level 1 requirements, all are specific to the Crew Rescue Vehicle (CRV)/ Crew Transfer Vehicle (CTV)/ International Space Station (ISS). Their applicability to CEV depends upon whether the CEV yet-to-be-developed Operational Concept will include CRV or CTV type operations.

Of the Level 2 requirements, about 1/3 are CRV/CTV/ISS specific but the remaining 2/3 are not and may have applicability to the CEV. However, each will need to be analyzed in more detail after the CEV Operational Concept is released. Many of these requirements trace directly to the Level 1 requirements and therefore may have a CRV/CTV/ISS orientation. However, they may be readily evolvable to CEV requirements. As an example, consider the requirement to provide a per mission probability for loss of crew of < 1/400. This is tailored to the OSP crew transfer mission. Since the CEV mission could be considerably longer and involve more complex operations, this number requires re-evaluation. This is not a straightforward task. Longer but fewer missions may be involved; and shorter but more diverse operations may be expected. Determining a number is important because it drives almost all further engineering design work. Consequently, it is of prime interest to the industrial contractors. But the number needs to be well thought out and considered, and it is hoped that this is happening at NASA at this very minute. The ramifications of too large or too small a number are enormous.

Requirements involving proximity operations, docking, and undocking, may have direct applicability to the CEV. An example is the requirement to provide a manual capability to monitor and conduct proximity operations, docking, and undocking. In addition, requirements involving human-in-the-loop operations will almost certainly be applicable to CEV, if not expanded. An example is the requirement that the system have the capability to assess and identify degradations that require an action to correct. With OSP, this requirement could be met with mostly manual crew intervening operations. However, with CEV, much more emphasis will be placed on automatic operations and the requirements will reflect that accordingly.

Once the Level 1 requirements and Operational Concept are in a state of agreement, NASA will need to scrub the entire list of previously generated OSP Level 2 requirements in detail to determine their degree of applicability to CEV. Preliminary analysis indicates that the following Level 2 requirements, that are oriented toward human-rating, are not CRV/CTV/ISS specific and may be applicable to CEV (parameters that could be tailored for CEV are in italics):

Acceleration Environment

The maximum rotary accelerations imposed on crewmembers by the System during all mission phases shall comply with human performance and tolerance limitations for de-conditioned and ill or injured individuals.

Health and Status

- The System shall not require crew interaction for routine monitoring of the spacecraft during nominal operation.
- The System shall annunciate status alerts.
- The System shall have the capability to use the health and status data to reconfigure systems to recover functionality.

Communications

The System shall provide full-duplex voice communication between the supporting control center(s) and the spacecraft crew.

Crew Environment

- The System shall provide a habitable environment to support crew performance.
- The System shall provide life support and a *safe post-landing environment for the crew through crew recovery*.

Reliability

For crew transfer, the System shall provide a per mission *probability of loss of crew (LOC) of 1/400 or less* with 50% confidence, with an objective of 1/400 or less with 80% confidence.

Maintainability

- The System spacecraft shall require no scheduled maintenance during unmated flight operations.
- The System shall provide for on-orbit maintenance of internal ORUs *compatible with ISS on-orbit tools*.

General Safety

- No single System failure (excluding items that are designed for minimum risk) or single human error shall result in a critical hazard or catastrophic hazard.
- Subsystems or components of the System performing safety critical functions shall be physically separated, isolated, or protected such that any credible event does not result in the loss of more than one hazard control.
- The System software/firmware performing, controlling, or supporting safety critical functions shall be isolated or protected such that any failure of non-critical software/firmware does not affect the performance of the critical software/firmware.
- The System shall meet the requirements of, Human Rating Requirements and Guidelines for Space Flight Systems, NPG 8705.2, *as tailored for the OSP Program and documented in the OSP Human Rating Plan*.
- The System shall be designed to eliminate or control catastrophic and critical hazards by employing the Hazard Reduction Protocol

Crewed Vehicle Safety

The System Spacecraft shall successfully complete its mission without requiring an EVA.

External Interface Requirements

The System shall have an interface to Department of Defense Manned Space Flight Support (DDMS) (gov't-to-gov't interface) to support *OSP search and rescue contingencies*.

Human Engineering/Human Performance

- The System shall provide work and habitable space, access, stowage and physical accommodation in the defined use environments and for the defined tasks.
- The System shall require a crew awake period less than 18 hours for the first flight day.
- The System shall accommodate *Launch and Entry Suited* and non-suited crewmembers.

An 'Applicable Document', that formed part of the set of Level 2 requirements, was the OSP Program Human Rating Plan.[11] This document, written in the requirements format, was tailored from NPG8705.2 requirements to meet the specific needs of the OSP program. It is very likely that a similar CEV Program Human Rating Plan will be required for the CEV in Project Constellation. In a fashion similar to the above, the requirements in the OSP Program Human Rating Plan will need to be scrubbed in detail to determine their degree of applicability to the CEV. This is the next exercise that NASA must perform. Here again, NASA is faced with the challenge of trading off design, manufacturing, quality, and operations costs with the need for human accommodation. Crew safety, crew survival, and crew accommodation all act together to force significant costs as compared to a robotic mission. The ramifications of too great a cost or too great a risk to human safety are enormous. **The future of government sponsored human spaceflight may well hinge on the perceived acceptability of this risk/cost tradeoff! The driving factors in determining the risk/cost tradeoff are the requirement for probability for loss of crew per mission and the set of tailored requirements for human-rating.**

III. Conclusion

A preliminary analysis of the NASA human-rating requirements has been performed to determine their applicability and relative contribution to project cost for the proposed Crew Exploration Vehicle (CEV) and a piloted mission to Mars. A summary of existing and projected driving requirements and associated challenges for human-rating the design of the CEV has been presented. Although the CEV mission has not yet been completely defined, it can be seen that many design challenges lie ahead in order to achieve human-rated capability without breaking the bank. It also serves to illustrate the reasons why human spaceflight is so expensive and drawn out over time. This is a serious challenge that goes beyond just technical cleverness. If the costs and risks associated with putting humans in space is perceived to be too great by the general population, then any space based initiative, whether it be science driven exploration, economics driven construction/manufacturing/mining, or human desire driven settlement and colonization, will be effectively roadblocked for many years. It is of utmost importance that we make the best tradeoffs possible between safety/risk and cost such that the general population does not become overly risk averse and remains supportive of the human spaceflight program. Advocacy alone, without sound analysis and projections of risk vs. cost, may not be enough to convince the American voter.

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