Human System Drivers for Exploration Missions

Craig E. Kundrot, Ph.D.
Human Research Program
NASA Johnson Space Center
Houston, Texas 77058 USA

Susan Steinberg, Ph.D.
Wyle, Integrated Science and Engineering
Houston, Texas 77058

John B. Charles, Ph.D.
Human Research Program
NASA Johnson Space Center
Houston, Texas 77058 USA

November 2010

Table of Contents

I. Purpose

Long-duration, deep space missions represent a set of unique challenges to the human system that need to be taken into account in the course of planning and developing Design Reference Mission (DRM4)-like mission architectures under the Human Exploration Framework Team (HEFT) activity. This white paper addresses the most significant human system challenges from a mission architecture point of view by classifying each of these challenges into one of three areas:

1. **Mission Duration Limiting**
2. **Major Drivers of Mission Resources (Mass, Power, Volume)**
3. **Minor Drivers of Mission Resources (Mass, Power, Volume)**

We hope that this white paper allows the HEFT missions planners to readily identify and take into account the most significant human system challenges during mission architectures development. Since many of the human system challenges are the focus of ongoing research activities, we also hope that this white paper will facilitate a structured discussion on the need to reduce or mitigate human system risks and challenges to better enable long-duration, deep space missions.

II. Introduction

Evaluation of DRM4 in terms of the human system includes the ability to meet NASA standards, the inclusion of the human system in the design trade space, preparation for future missions and consideration of a robotic precursor mission. Ensuring both the safety and the performance capability of the human system depends upon satisfying NASA Space Flight Human System Standards.[1] These standards in turn drive the development of program-specific requirements for Near-earth Object (NEO) missions.

In evaluating DRM4 in terms of these human system standards, the currently existing risk models, technologies and biological countermeasures were used. A summary of this evaluation is provided below in a structure that supports a mission architecture planning activities.

1. Unacceptable Level of Risk

The duration of the DRM4 mission leads to an unacceptable level of risk for two aspects of human system health:

A. The permissible exposure limit for space flight radiation exposure (a human system standard) would be exceeded by DRM4.

B. The risk of visual alterations and abnormally high intracranial pressure would be too high.

[1] NASA Standard 3001, Volume I, Crew Health, which sets standards for fitness for duty, space flight permissible exposure limits (PEL), permissible outcome limits (POL), levels of medical care, medical diagnosis, intervention, treatment and care, and countermeasures; and Volume II , Human Factors, Habitability, and Environmental Health, focuses on human physical and cognitive capabilities and limitations and defines standards for spacecraft (including orbiters, habitats, and suits), internal environments, facilities, payloads, and related equipment, hardware, and software systems with which the crew interfaces during space operations.

2. Significant Effect on Resources

Several human system requirements have a significant effect on DRM4 resources such as the mass, volume, and power requirements of vehicular subsystems:

A. Behavioral health requirements drive the habitable volume.
B. Exercise equipment is necessary to address bone, muscle, and cardiovascular risks associated with long-duration missions in the microgravity environment of space. Current ISS exercise equipment is too large and heavy to be used on a DRM4 mission.
C. Food packing technology affects the mass and volume of food storage, the amount of trash generated, and the variety of foods available.
D. The medical system must monitor and treat crewmembers during the mission. The requirements for this medical system are impacted by the following: age and gender of the crew; crew medical expertise (an experienced field physician would greatly reduce the requirements); and requirements to conduct in situ analysis and return biological samples to assess human system response to the mission in order to efficiently mitigate risks in future missions.
E. Inclusion of an Extra Vehicular Activity (EVA) suit port in DRM4 drastically reduces the risk of habitat contamination by dust or volatiles, but geological sample handling and storage in the inhabited volumes raise that risk. The Environmental Control and Life Support System (ECLSS) and its consumables must be sized to treat the expected amount of dust or volatiles.
F. Availability of abort options and their transit time back to Earth affects the supplies needed to sustain ill or injured crew. The abort options also affect psychological aspects of the mission.

3. Secondary Effect on Resources

Several human system requirements are critical for the safe and effective execution of a DRM4 type mission, but have only secondary effects on DRM4 resources such as the mass, volume, and power requirements of vehicular subsystems:

A. The need for long shelf life for food, pharmaceuticals, environmental monitoring expendables, etc. can require special storage conditions.
B. Several health and performance risks are affected by the crew composition, e.g., the age and gender. The radiation carcinogenesis risk (and, therefore, mission duration) depends strongly on age and, in the current version, gender. The size of the medical system will be influenced by gender makeup of the crew.
C. The risk of decompression sickness and the operational time lost to pre-breathe protocols are driven in large part by the design of the EVA glove or its equivalent.
D. The size and capability of autonomous systems aboard the vehicle will be driven by the manner in which the functions needed for high level mission tasks are assigned to some combination of the flight crew, ground crew, and autonomous systems.
E. Many other secondary drivers of DRM duration and resources result from the quantification and mitigation of the human system risks addressed by the Human Research Program (HRP). A list of the exploration risks that the HRP is addressing is provided to provide a sense of the diversity of drivers.

III. Mission Duration Limiting

1. Radiation

NASA's radiation exposure standards permit a 3% risk of Radiation Exposure-Induced Death (REID). This standard limits mission durations at solar minimum to 5-6 months for males and approximately 3 months for females. At solar maximum, the recommended limits become 154 days for 35-year old females to 300 days for 55-year old males.

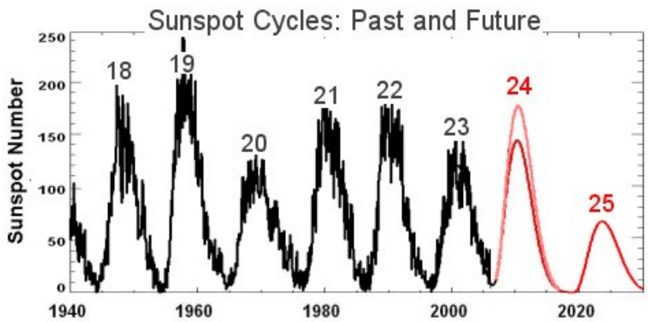
The NEO mission may occur during solar maximum, which may be relatively weak.

Maximum Mission Lengths with 95% CI in Deep Space
Solar Minimum for 20 g/cm² (7.4 inch thick) Aluminum Shield

	Current NASA Model*	NAS-BEIRVII**	Recommended NASA update
Age, yr		Males	
35	158	159	140
45	207	161	150
55	302	174	169
Age, yr		Females	
35	129	109	88
45	173	111	97
55	259	122	113

*Based on NCRP 132 Report (2000)
**NASA update based largely on UNSCEAR report. Larger difference for Females occur due to Lung transfer model from Japanese to US assumptions in BEIR vs NCRP model

HEFT Human Exploration Framework Team 8



Maximum Mission Lengths with 95% CI in Deep Space
Solar Max with SPE for 20 g/cm² (7.4 inch thick) Aluminum Shield

	Current NASA Model*	NAS-BEIRVII**	Recommended NASA update
Age, yr		Males	
35	228	248	247
45	303	256	268
55	443	273	300
Age, yr		Females	
35	187	169	154
45	252	176	171
55	379	194	196

*Based on NCRP 132 Report (2000).
** NAS Biological Effects of Ionizing Radiation (BEIR) VII Report.
NASA update based largely on United Nations (UNSCEAR) report. Larger difference for Females occur due to Lung transfer model from Japanese to US assumptions in BEIR vs NCRP model

HEFT Human Exploration Framework Team 9

Comparison of Safe Days at Higher Acceptable Risk Levels
Solar Min for 20 g/cm² (7.4 inch thick) Aluminum Shield

Number of Days in Deep Space At Solar minimum with a 95% Confidence Level to be below 3% or 6% Risk of Cancer Death*

	3% Risk (REID)	6% Risk (REID)
Age, y	Males	
35	140	290
45	150	311
55	169	349
Age, y	Females	
35	88	187
45	97	206
55	113	234

* Results are marginally non-linear with increasing Risk levels because competing causes of death compress higher risk samples

HEFT Human Exploration Framework Team 11

Longer allowed mission durations would result from less conservative assumptions in the radiation carcinogenesis model. For example, REID would be reduced by accounting for the more comprehensive cancer surveillance program available to the astronaut corps, and by projecting an increase in survivability as medical knowledge and technology advances. Longer allowed mission durations might also result as further research decreases in the uncertainties of the risk estimates.

2. Microgravity-Induced Visual Alterations/Intracranial Pressure

A JSC Space Life Sciences Directorate top programmatic risk, On-Orbit Intracranial Hypertension (risk #6169), would limit NEO missions to six months or less. 20% of long duration Internal Space Station (ISS) crewmembers have experienced clinical symptoms. Observed physical findings in long-duration crewmembers include papilledema, choroidal folds, increased optic nerve sheath diameter, and a posterior flattened globe; some of these changes were temporary and others permanent. There is a high probability that all astronauts have idiopathic intracranial hypertension to some degree, and that those susceptible (via eye architecture, anatomy, narrow disc) have a high likelihood of developing either choroidal folds or papilledema, and that the degree of that edema will determine long-term or permanent vision loss, sequelae, or impairment. This risk is under active investigation.

IV. Major Drivers of DRM Resources (Mass, Power, Volume)

3. Behavioral Health⇒ Habitable Volume

The habitable volume must be large enough and sufficiently designed to execute the necessary tasks and to provide a psychologically acceptable space for the long period of confinement. This risk of adverse behavioral health events is significant: based on estimates made for the Mission Architecture Working Group, the probability of an adverse behavioral health event is 2% and 5% for 3 month and 6 month missions, respectively. A separate whitepaper is being prepared to address the issues associated with the habitable volume.

4. Muscle Atrophy, Cardiovascular Atrophy, Bone Loss⇒ Exercise Equipment

Exercise equipment alleviates muscle atrophy, cardiovascular atrophy, and bone loss. The latest equipment deployed on ISS (Treadmill 2, Cycle Ergometer with Vibration Isolation and Stabilization, Advanced Resistive Exercise Device) occupies 3 International Standard Payload Racks. Early results suggest that the suite of equipment is effective.

5. Food⇒ Food Storage and Trash Generation

Using current food packaging technology, the amount of food one crew member needs for one year is 670 kg occupying 1.7 m^3 (the volume of about three household refrigerators). HRP is currently aiming for 30% and 34% reductions in volume and mass, respectively. If such reductions are achievable, supplies for one crew member for one year are 440 kg and 1.2 m^3. Packaging materials must also be disposed.

6. Medical Care⇒ Medical Equipment and Supplies

The HRP Integrated Medical Model (IMM) simulates medical events during space flight missions and estimates the impact of these events on crew health and mission success. A three-crew, 386 day, asteroid mission simulation with 28, 2-crew EVAs suggests an optimized medical kit having a mass of 62 kilograms and a volume of 0.15 m^3. (These figures do not include all of the medical equipment needed for diagnosis). IMM is best used to make relative comparison between different missions or sets of resources, but the estimated probability of evacuation for this scenario is 9.8% and the probability of loss of crew is 2.8%. Risks on this order of magnitude warrant active mitigation.

7. EVA Airlock or Suitport⇒ ECLSS

Permissible exposure limits mitigate the health risks associated with exposure to asteroid dust and volatiles. The scale of the equipment and consumables used for environmental treatment and monitoring depend strongly on the architecture. An EVA suitport greatly reduces the risk of contaminating the principal habitable volume compared to the use of an EVA airlock.

8. Asteroid Characteristics: Dust or Volatiles⇒ ECLSS

Permissible exposure limits mitigate the health risks associated with exposure to asteroid dust and volatiles. An asteroid with surface dust or volatile compounds poses a greater environmental risk to the habitable volume. The possibility of such contaminants will necessitate more robust sample handling; sample containment; and environmental treatment and monitoring equipment.

9. Physician Crew Member⇒ Medical Equipment and Supplies

The presence of a physician crew member may have dramatic impact on the resources required to recognize and treat an ill or injured crew member. If the crew has substantial medical expertise (e.g., military field physician and medic, and training/certification in clinical psychology, behavioral medicine or psychiatry), then there will be less need for just-in-time training, on board telemedicine equipment, and expert assistance from the ground.

10. Abort Options⇒ Medical Equipment and Supplies

The ability to abort during the mission and the time required to return to Earth has affects the supplies needed to sustain ill or injured crew. A study of the 1999 AO10 NEO launch opportunity in September 2025 showed that the mission could be aborted at almost any time, but would require about a 30 day return trip to Earth. The availability of abort options and their transit time back to Earth also has impacts on the psychological aspect of the mission.

V. Secondary Drivers of DRM Resources (Mass, Power, Volume)

1. Extended Shelf-Life for Food and Other Perishables

Food stability and variety are challenges for long duration missions. Shelf life must be calculated from the time the food has been prepared and packaged. The time it takes to ship to the launch site, prepare for launch, spiral out to L1 (or other staging area), and await crew arrival needs to be added to what is normally considered mission duration (for the crew) when considering the adequacy of the nutrition stability and acceptability of the food. Because different foods have different shelf lives, less variety in food is possible in the latter phases of the mission. The same shelf life issues apply to pharmaceuticals, environmental monitoring expendables, etc.

2. Crew Composition

Several health and performance risks are affected by the age and gender of the crew. The radiation carcinogenesis risk (driving mission duration) depends strongly on age and, in the current version, gender. The size of medical system will be influenced by gender makeup of the crew.

3. EVA Glove/End Effector

The risk of decompression sickness and the operational time lost to pre-breathe protocols are driven in large part by the design of the EVA glove. The glove drives the pressure of the EVA suit, affects what tools are required, and what tasks can be performed. A glove that can be used at high suit pressures, a mechanical assist within the glove, or the replacement of the hand-in-glove by an internal hand operated end effector would allow higher suit pressures that reduce the risk of Decompression Sickness (DCS) and minimize the length of pre-breathe protocols.

4. Crew Autonomy

High level mission tasks must be performed by some combination of the flight crew, ground crew, and autonomous systems aboard the vehicle. The communication delays and possible intermittency between the Earth and the flight crew will require new techniques to promote the asynchronous interactions between ground support and the flight crew and a redesign of tasks to be performed without real time support from the ground.

The division of functions between the flight crew and autonomous systems on the vehicle will drive equipment needs on the vehicle.

5. Other

Many other secondary drivers of DRM mission duration and resources result from the quantification and mitigation of the human system risks addressed by the HRP. Some drivers result from the need to quantify the level of risk (e.g., estimating the likelihood of decompression sickness from EVAs) while others result from risk mitigation approaches (e.g., monitoring of environmental contaminants).

Table 1 below organizes the HRP risks according to the aspect of an exploration mission that they affect the most. HRP characterizes the risks in terms of a Criticality Rating: Unacceptable (HRP would recommend against conducting the mission), Acceptable (HRP would recommend conducting the mission while continuing to reduce the level of risk), or Controlled (HRP would recommend conducting the mission without further efforts to reduce the level of risk). The Criticality Ratings of the lunar outpost mission and the Mars mission have been formally adopted by HRP; the NEO ratings shown are notional only.

TABLE 1. HRP RISKS	Lunar	NEO (Notional)			Mars
		6	12	18	
NEO-dependent: NEO-specific properties (i.e., geology, chemistry, angular rotation, g-level and lighting impact task design, regolith handling and sensorimotor issues).					
RISK OF ADVERSE HEALTH EFFECTS FROM LUNAR DUST EXPOSURE	A	A	A	A	n/a
RISK OF ERRORS DUE TO POOR TASK DESIGN	C	A	A	A	A
RISK OF IMPAIRED CONTROL OF SPACECRAFT, ASSOCIATED SYSTEMS AND IMMEDIATE VEHICLE EGRESS DUE TO VESTIBULAR/SENSORIMOTOR ALTERATIONS ASSOCIATED WITH SPACE FLIGHT	C	A	A	A	A
Mission Duration: Conditions continue to worsen with time of exposure to the flight environment (e.g., microgravity, radiation, confined living).					
RISK OF RADIATION CARCINOGENESIS RISK OF DEGENERATIVE TISSUE OR OTHER HEALTH EFFECTS FROM RADIATION EXPOSURE	A	U	U	U	U
RISK OF MICROGRAVITY-INDUCED VISUAL ALTERATIONS/INTRA-CRANIAL PRESSURE	U	U	U	U	U
RISK OF ACUTE & LATE CENTRAL NERVOUS SYSTEM EFFECTS FROM RADIATION EXPOSURE RISK OF ACUTE RADIATION SYNDROMES DUE TO SOLAR PARTICLE EVENTS	A	A	A	A	A
RISK OF ADVERSE BEHAVIORAL CONDITIONS AND PSYCHIATRIC DISORDERS	C	A	A	U	U
RISK OF IMPAIRED PERFORMANCE DUE TO REDUCED MUSCLE MASS, STRENGTH & ENDURANCE RISK OF REDUCED PHYSICAL PERFORMANCE DUE TO REDUCED AEROBIC CAPACITY	A	A	U	U	U
RISK OF CREW ADVERSE HEALTH EVENT DUE TO ALTERED IMMUNE RESPONSE	C	C	A	A	A
RISK OF EARLY ONSET OSTEOPOROSIS DUE TO SPACEFLIGHT	C	A	A	A	A
Distance: Distance impacts communication and evacuation.					
RISK OF INABILITY TO ADEQUATELY RECOGNIZE AND TREAT AN ILL OR INJURED CREW MEMBER	A	A	A	U	U
RISK OF PERFORMANCE DECREMENTS DUE TO INADEQUATE COOPERATION, COORDINATION, COMMUNICATION, PSYCHOSOCIAL ADAPTION WITHIN A TEAM	C	A	A	A	A
Vehicle/System Design: Risk related to vehicle or subsystem design; medical issues not related to mission duration.					
RISK OF COMPROMISED EVA CREW HEALTH AND PERFORMANCE DUE TO INADEQUATE EVA SUIT SYSTEMS	A	A	A	A	A
RISK OF INADEQUATE NUTRITION RISK OF PERFORMANCE DECREMENT AND CREW ILLNESS DUE TO AN INADEQUATE FOOD SYSTEM	C	C	A	A	U
RISK OF ERROR DUE TO INADEQUATE INFORMATION RISK OF REDUCED SAFETY AND EFFICIENCY DUE TO AN INADEQUATELY DESIGNED VEHICLE, ENVIRONMENT, TOOLS OR EQUIPMENT	C	C	A	A	A
RISK OF THERAPEUTIC FAILURE DUE TO INEFFECTIVENESS OF MEDICATION	C	C	C	A	A
RISK OF CARDIAC RHYTHM PROBLEMS RISK OF ORTHOSTATIC INTOLERANCE DURING RE-EXPOSURE TO MICROGRAVITY & RISK OF INTERVERTEBRAL DISC DAMAGE	C	A	A	A	A
RISK OF RENAL STONE FORMATION RISK OF BONE FRACTURE RISK OF PERFORMANCE ERRORS DUE TO FATIGUE RESULTING FROM SLEEP LOSS, CIRCADIAN DESYNCHRONIZATION, EXTENDED WAKEFULNESS, AND WORK OVERLOAD	C	C	C	C	C
RISK OF ADVERSE HEALTH EFFECTS DUE TO ALTERNATIONS IN HOST-MICROORGANISM INTERACTIONS	C	A	A	A	A

VI. Acronyms

Design Reference Mission (DRM)
Environmental Control and Life Support System (ECLSS)
Extra Vehicular Activity (EVA)
Human Exploration Framework Team (HEFT)
Human Research Program (HRP)
Integrated Medical Model (IMM)
Internal Space Station (ISS)
Near-earth Object (NEO)
Radiation Exposure-Induced Death (REID)

VII. References

HEFT Report
Mars DRM4 Report