Framework for a Crew Productivity Figure of Merit for Human Exploration

Marc M. Cohen[1] and Paul C. Houk[2]
Northrop Grumman Corporation, El Segundo, CA 90245

A critical element of mission cost effectiveness and ways of ensuring mission success will be to establish, implement, and support metrics for Crew Productivity. Northrop Grumman has been developing a new approach to defining and substantiating Crew Productivity as a top level Figure of Merit on an equal standing with Crew Safety, Cost, Mission Success, and Mass. This Crew Productivity FOM is based upon a careful reading of the NASA Human Systems Integration Requirements (NASA CxP-70024C, 9 MAR 2009), and the formulation of Crew Productivity metrics that supplement the HSIR for the Lunar Lander program. The structure is based upon an extrapolation of the psychologist Abraham Maslow's Hierarchy of Human Needs. [3]

Nomenclature

AL	Airlock
Altair	NASA's crewed lunar lander under the Constellation Program
AM	Ascent Module
CP	Crew Productivity
CARD	Constellation Architecture Requirements Document, NASA CxP-70000
DM	Descent Module
EDS	Earth Departure Stage
EVA	Extravehicular Activity
FOM	Figure of Merit
FP:	Front Porch
HSIR	Human Systems Integration Requirements, NASA CxP-70024.
IPT	Integrated Product Team as part of the trade and analysis team
IVA	Intravehicular Activity
LM	Apollo Lunar Module
MDO	Multidisciplinary Optimization
PLOC	Probability of Loss of Crew (inverse translates to crew safety)
PLOM	of Loss of Mission (inverse translates to mission success)
VERT	Vertical access connection for the lander

I. Introduction

The purpose of this paper is to present a conceptual framework to describe the role and characteristics of a figure of merit (FOM) based on crew productivity for the analysis, design, and trade studies of human spacecraft. Northrop Grumman Space Exploration Systems seeks more systematic and effective ways to carry out the complex process of designing large crew carrying space vehicles. Standard aerospace systems design processes rely on defined Figures of Merit (FOMs) as a means to rationally compare design approaches during trade studies and design cycle updates. Typical FOMs include payload mass, life cycle cost, safety, and probability of mission success. However, there are no well-established FOMs that address crew productivity and accommodations. This

[1] Lead Human Systems Integration Engineer, Advanced Programs and Technology Division, One Hornet Way Mail Stop 9QS4/W5, El Segundo, CA 90245. AIAA Associate Fellow.
[2] System Engineer, Advanced Programs and Technology Division, One Hornet Way Mail Stop 9N18/ES-1/W9, El Segundo, CA 90245.
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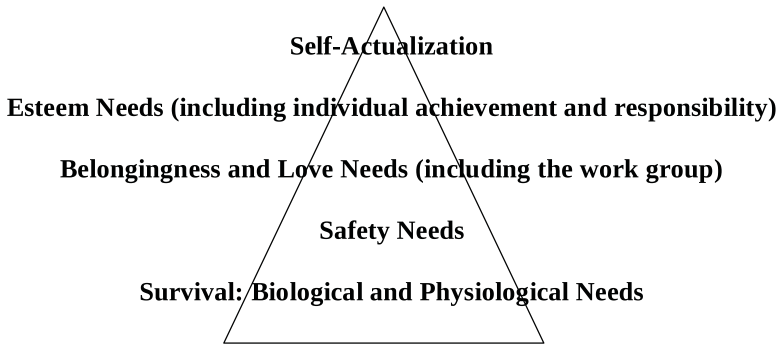
paper considers the broad area of human systems effectiveness with the ultimate objective of determining useful Crew Productivity Figures of Merit (CP FOMs).

In seeking a conceptual model to represent the CP FOM, Maslow's hierarchy of needs (Maslow, 1962) proved relevant and useful. Adapting Maslow's hierarchy of needs to Crew Productivity enabled the Crew Productivity trade and analysis team[4] to identify the sets of needs and corresponding metrics for the crew and to distinguish among those needs, particularly in terms of causality and prioritization. Maslow's hierarchy consisted originally of five levels, arranged in his iconic pyramid:



In Maslow's scheme, the lowest level of the hierarchy is the most fundamental; all the levels above depend upon meeting the need at that level. Moving up the pyramid, the need levels above depend upon meeting those below before they can fulfill their own needs.

For this analysis, the team found it valuable and necessary to identify two additional levels of crew needs, for seven levels. This adaptation consists of two changes:

1. Splitting the survival level Biological and Physiological Needs into two levels to create the separate Physiological Needs in Dynamic Spaceflight, and
2. Adding the Quality of Life and Health need to represent habitability as an intermediary between Safety and Belongingness, which here is called Crew as a Team. Quality of life and health become increasingly important with the increase in mission duration.

These resulting seven levels shown in FIGURE 1 correspond to the needs that the crew encounters on a space mission. In attempting to delineate the metrics that can measure CP, it became necessary to resolve a contradiction with the closely related topic of crew safety. For example, if the crew is fearful for their safety, their productivity will be impaired perhaps dramatically. In order to resolve the contradiction, it became essential to identify the demarcation between these two topics, which is one purpose of the approach in FIGURE 1. What is subtler and persistently confounding here are the ways in which human spacecraft and their systems simultaneously support crew safety and productivity and how effectively the crew can do their jobs.

Another purpose of the application of Maslow's Hierarchy is to identify those Crew Safety and CP concerns *as metrics* that may interact with the design of spacecraft configuration. The interaction may work this way: The configuration affects the ability of the system or a subsystem to provide or ensure or performance on certain verification requirements. Conversely, if a FOM metric or verification requirement emerges as sufficiently important, it may be necessary to rework the spacecraft configuration to ensure better performance on that metric. The paper presents examples of CP FOM metrics at each of the seven levels of the hierarchy. These metrics apply to any human spacecraft or lunar/planetary habitat.

The specific objectives of the Crew Productivity trade and analysis team[4] were:

- To utilize Lunar Lander Program and Altair system data as the starting point to define the CP Figure of Merit (CP FOM): based on how well the Altair system supports the crew
- To track key NASA <u>HSIR</u> verification requirements and identify the perceived gaps as to minimize interaction and overlap of identified CP metrics,

[4] Northrop Grumman trade and analysis team members who contributed to the Crew Productivity effort include: Jim Berry, Ken Cameron, Shyama Chakroborty, Marc Cohen, Paul Houk, Warren James, Gary Lantz, Ron Pirich, Ken Rourke, Don Sandersfeld, and Tad Theno.

- To identify what aspects of the lunar lander living and working environment that the HSIR verification requirements and the CP metrics affect, and
- To develop a guideline that allows the team to distinguish between the roles of the CP and Crew Safety (PLOC) FOMs.

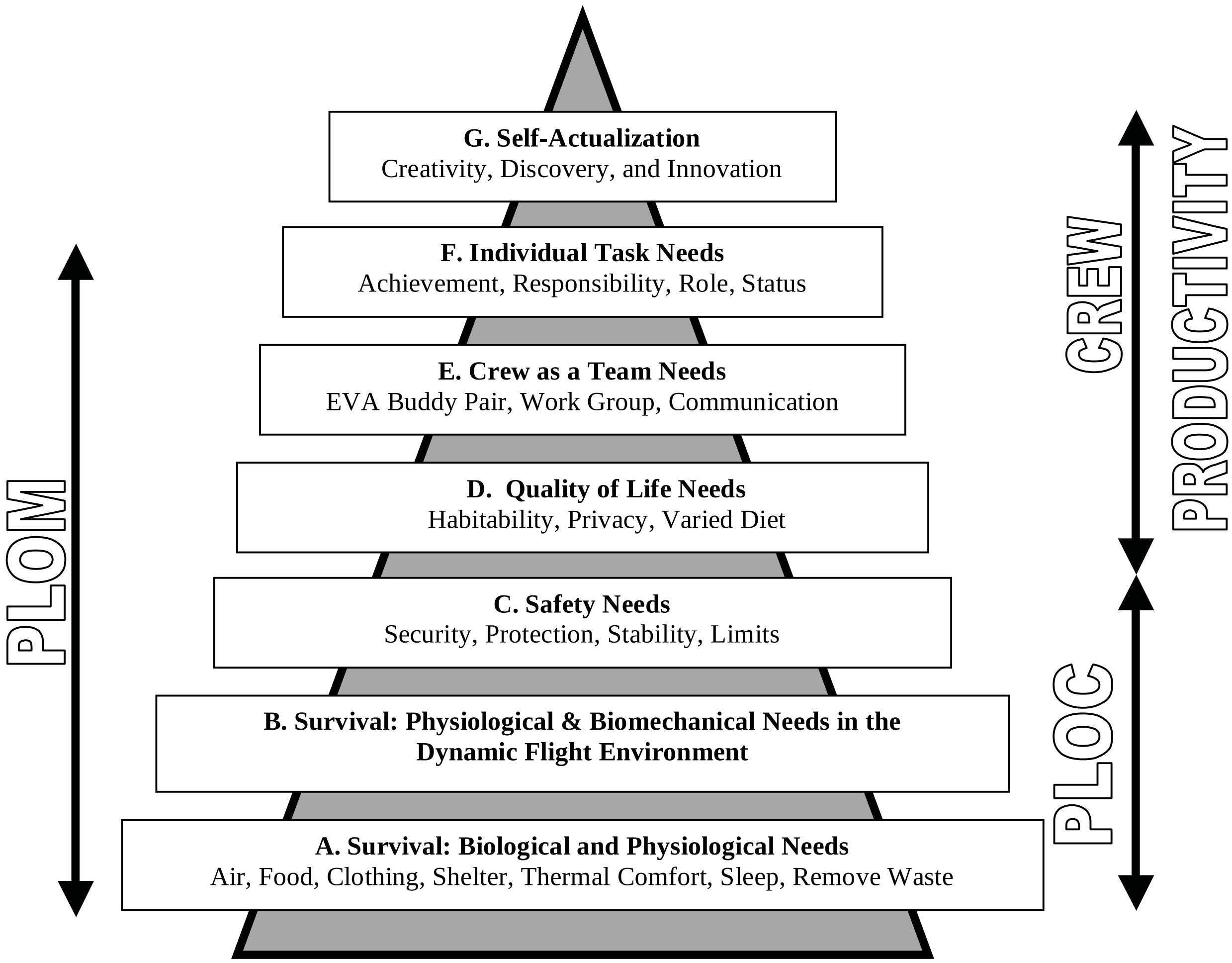


FIGURE 1. Maslow's hierarchy of human needs (1962, 1968, 1999) from Toward a Psychology of Being, adapted to the Altair crew as seven levels.

For the Lunar Lander program, the team defined the Crew Productivity FOM to mean ***how well the spacecraft system supports the crew:***

- *To be effective in carrying out the mission accurately and successfully,*
- *To be efficient in performing tasks in a timely manner with reasonable use of available resources, and*
- *To optimize the human suitability of the operational environment.*

Using the CP FOM framework the team proceeded to define a preliminary set of supporting measurement metrics. An immediate discovery from this effort was that the most immediate metric for CP is the availability and efficient use of crew time in space -- the most precious commodity in human spaceflight. However, the vehicle design, operations, and human performance capabilities raise complex issues that require more extensive and specific metrics to characterize CP over the course of an Altair mission. Therefore, the paper focuses on the trade and analysis study team's initial work on the metrics definitions.

The detailed definitions of these metrics and their NASA counterparts appear in APPENDIX I. The outline of the complete range of metrics appears in APPENDIX II. The goal is to minimize the duplication of PLOC and CP, but some overlap is unavoidable. The key contribution to spacecraft design is to understand the relationship between crew safety and productivity, with all the inherent contradictions and complexity. In this context, it is important to understand that FOM metrics do not equal requirements. The purpose of the FOM metrics and the NASA HSIR verification requirements is to measure how well the design, technology, and system integration achieves the mission, program, or vehicle-level requirements.

In addition to identifying these metrics, it became important to offer guidelines to distinguish the trade and analysis team's new CP FOM from the well-established Probability of Loss of Crew (PLOC) FOM for Crew Safety. Certainly, there is overlap between Maslow's two levels of Survival and Safety on one hand and the aerospace notion of PLOC on the other. The application of Maslow's hierarchy enables this analysis to describe the relationship between the two sets of precepts. Indeed, in analyzing the NASA Human Systems Integration Requirements (HSIR), the team found that HSIR's coverage of survival and safety (constituting the first three levels in FIGURE 1) was complete and sufficient. This recognition allowed the team to focus most of their efforts on the upper four levels: Quality of Life, Crew as a Team, Individual Needs to Perform Tasks, and Self-Actualization.

II. Approach: "DIRECT"

In formulating the approach to defining the CP FOM, the team's challenge was to find a way to explicate its broad dimensions and aspects within a framework suitable for measuring the crew vehicles and their missions. The team met this challenge by applying an iterative methodology that enabled them:

- To review the HSIR systematically within the analytical framework,
- To correlate the HSIR verification requirements to the modified Maslow hierarchy of needs,
- To identify potential gaps within the HSIR verification requirements,
- To recommend CP FOM metrics to fill those gaps, and
- To refine the FOM metrics for further team investigation, and
- To translate the metrics into tools for multidisciplinary optimization.

FIGURE 2 presents the methodology used by the team to bound the FOM framework of recommended metrics. The application of this iterative approach to assess CP FOM metrics showed that, it was often necessary to work through the sequence (shown in FIGURE 2) by moving individual metrics to other levels and then work through the process again for each relocated metric.

A. Distinguish between Crew Productivity Metrics and Safety Metrics.

At the outset of this analysis, it was far from apparent how to draw a line between Crew *Productivity* and Crew *Safety*. The most intense discussion within the team concerned this question: whether to track and organize the metrics by a) the initial threat condition to the crew or to their productivity or b) by the most severe consequence that could result for the crew. The initial approach that seemed self-evident was to take the *a fortiori* approach of Aristotelian logic: to argue from a more extreme or stronger case to a less extreme or weaker case (Aristotle, Circa 350 BCE, II:23-4), starting with the most extreme possibility of risk.

However, *a fortiori* yielded two unexpected results. First, total failure on almost any one these metrics can threaten safety and survival for the crew or mission, therefore *a fortiori* pushed almost everything down Maslow's pyramid (FIGURE 1) toward the bottom, into the domain of *Safety* instead of *Productivity*. Second, it could create absurd warnings, for example for lunar dust, "It can kill you,[5] and it can also make you sneeze[6]. After lengthy debate, the team agreed to track the metrics by the highest level of the pyramid that they may affect, wherever the effects begin. To continue with the lunar dust example, this switch means "Lunar dust can irritate your sinuses, skin, eyes, and lungs, and if it is not controlled effectively can become a potentially lethal threat."

[5] Survival: Biological Needs
[6] Quality of Life and Health

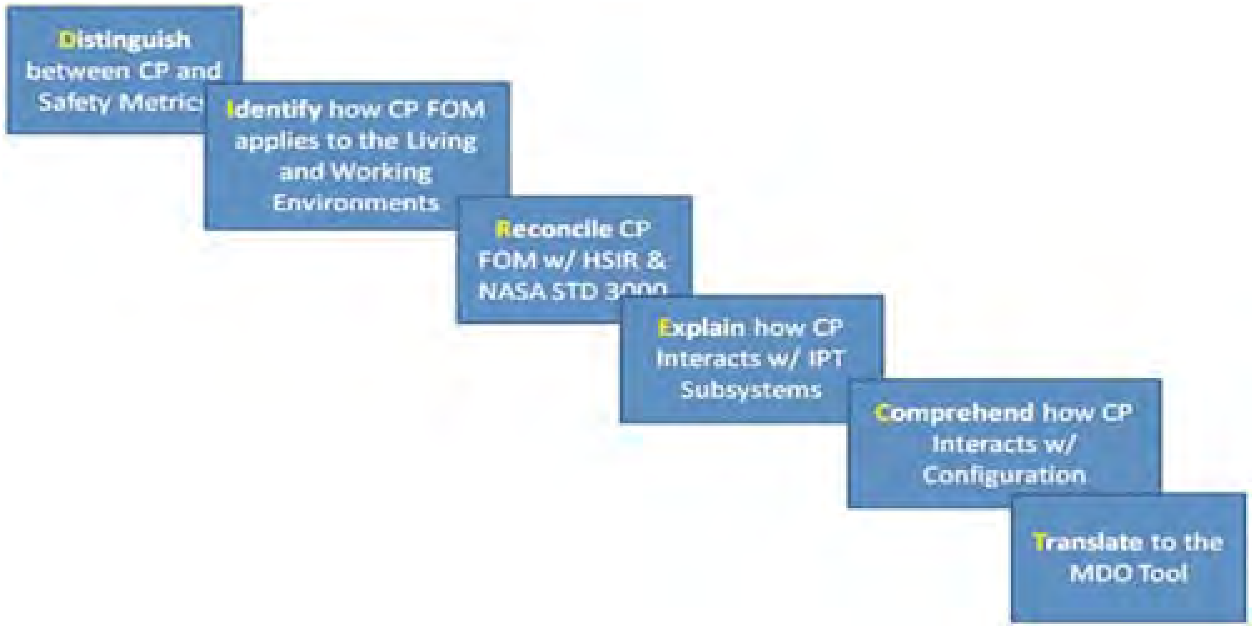


FIGURE 2. "DIRECT" Approach to the Crew Productivity Figure of Merit.

B. Identify how Crew Productivity applies to the mission

This step identified the aspects of the crew living and working environment that affect CP, including operations throughout the mission phases. The adaptation of Maslow's Hierarchy of Needs to correspond to the lunar lander showed that the seven levels of the pyramid were necessary to capture the full living and working environment. The team built a lunar mission *timeline*, looking particularly at what the crew were doing in each mission phase and operation, including sleep, eating, and personal time. This timeline identifies many of the key activities for the crewmembers. A small part of this timeline appears in TABLE 1. The timeline is important to this CP exercise because it shows how the crew moves around the lander configuration to perform operations and mission tasks.

C. Reconcile how the Crew Productivity FOM relates to the NASA HSIR

This step attempts to reconcile and integrate the team's CP FOM Metrics with the NASA Human System Integration Requirements (HSIR), CxP-70024 and the Human System Integration Standard, NASA Standard 3000. The method was to first assign all the HSIR verification requirements to the Maslow levels, while keeping their original NASA identifier numbers. Next, the team performed a ***gap analysis*** to identify metrics that could be important but that do not appear in the HSIR.

The team found that the HSIR provided sufficient information to perform the gap analysis. The gap assessment indicated that the HSIR provisions are comprehensive at the two survival levels: *a) Biological*, and *b) Physiological*. The gaps arose from levels C Safety though G Self-Actualization shown in FIGURE 1. The only level without an HSIR Verification Requirement was G Self-Actualization.

D. Explain the ways that the CP FOM interacts with the Subsystems

This step places the CP FOM in the context of the subsystems on the spacecraft. This step compiled all the verification requirements and metrics using subjective ranking to sort out which metrics brought the greatest impact for the subsystems. Conversely, the team asked how the subsystems affect CP; it became possible to identify potential interactions. TABLE 2 presents the subjective ranking results for the "Top Ten" metrics that effect subsystems in alphabetical order. It was not feasible to make meaningful rankings among these results. However, nine of the ten – all except for crew autonomy – also interact with the lunar lander configuration.

E. Comprehend how the CP FOM interacts with the Lunar Lander Configuration.

This step was part of a larger effort to develop Lunar Lander designs for NASA that included the Habitat Module Configuration Study (Cohen, July 2009; Cohen, July 2010). A key product of this research was a trade and analysis study that identified the following considerations for habitable module configurations in FIGURE 3:

TABLE 1. Example of the Crew Time Model for Altair Sortie Mission																			
Mission Phase	**1**	**2**	**3.1**	**3.2**	**3.3**	**3.4**	**4.0.1**	**4.0.2**	**4.0.3**	**4.0.4**	**4.1.1**	**4.1.2**	**4.1.3**	**5.1**	**5.2**	**5.3**	**6.1.0**	**6.2.1**	**6.2.2**
Mission Event Timeline	Launch Prep	Earth Ascent	LEO Operations				TLI Burn			TLI	TCM 1: REPEAT AS NEEDED			Lunar Orbit Insertion (LOI)			LLO	Undock	
			Check-out	Pre-Dock	RV & Dock	Crew Check	TLI burn prep	TLI Burn	TLI Post Burn	Coast	Burn Prep	RCS Burn	Post Burn	LOI Prep	LOI Burn	Post Burn	Loiter	Undock Prep	Undock
Maximum Time, Hours	4	0.2	8	360	30	4	3	0.09	0.5	21	3	0.05	1	6		1	144	4	0.01
Minimum Time, Hours	3	0.2	6	330	24	4	3	0.09	0.5	21	3	0.05	1	6	0.083	1	19	4	0.01
CREW TIME IN MODULE (Hours)	**0**	**0**	**0**	**0**	**0**	**16**	**6**	**0.36**	**0.2**	**42**	**6**	**0.1**	**2**	**12**	**0.166**	**2**	**38**	**16**	**0.4**
Orion							6	0.36	0.2	42	6	0.1	2	12	0.166	2			
Ascent Module						8											38	16	0.4
Airlock						4													
Habitat Module						4													
Descent Module																			
Lunar Surface																			
CREW TIME BY ROLES (Hours)						8	6	0.18	0.1	42	6	0.1	2	12	0.166	2	38	8	0.2
Pilot/Engineer					Orion	4	3	0.09	0.05	10.5	3	0.05	1	6	0.083	1	9.5	4	0.1
Engineer/Co-Pilot					Orion	4	3	0.09	0.05	10.5	3	0.05	1	6	0.083	1	9.5	4	0.1
Scientist/Doctor					Orion			0	0	10.5							9.5	0	
Doctor/Scientist					Orion			0	0	10.5							9.5	0	
Crew Actions																			
Orion					Crew		Pilots	Crew	Pilots	Sleep	Pilots	Crew	Pilots	Pilots	Crew	Pilots		Comm	Comm
Ascent Module Control	KSC	JSC	JSC	JSC	Orion	Crew	Crew			Crew							Sleep	Pilots	Crew
LIDS Hatch	Closed	Closed	Closed	Closed	Closed	Open	Close	Closed	Closed	Open	Opened	Opened	Opened	Close	Closed	Closed	Open	Close	Closed
AM/Hab Hatch	Closed	Closed	Closed	Closed	Closed	Open	Close	Closed	Closed	Open	Opened	Opened	Opened	Close	Closed	Cloesed	Closed	Closed	Closed
Descent Module Control	KSC	JSC	JSC	JSC	JSC	Crew	Crew	Crew	Crew	Crew	Crew	Crew	Crew						
Airlock	KSC					Check	Off												
Habitat Module	KSC					Check	S			Sleep							Sleep		
EDS Control	KSC	JSC	JSC	JSC	JSC	Crew	Crew	Burn	Dispose										
CREW LOCATION																			
Pilot/Engineer						AM/	Orion	Orion	Orion	AHO	Orion	Orion	Orion	Orion	Orion	Orion	AM	AM	AM
Engineer/Co-Pilot						AM/	Orion	Orion	Orion	AHO	Orion	Orion	Orion	Orion	Orion	Orion	AM	AM	AM
Scientist/Doctor						Hab/ AL	AM/ Hab	Orion	AM/ Hab	AHO	AM/ Hab	Orion	AM/ Hab	AM/ Hab	Orion	AM/ Hab	Hab/ Or	Hab	AM
Doctor/Scientist						Hab/ AL	AM/ Hab	Orion	AM/ Hab	AHO	AM/ Hab	Orion	AM/ Hab	AM/ Hab	Orion	AM/ Hab	Hab/ Orion	Hab	AM

TABLE 2. The Top Ten Metrics Affecting Crew Productivity on the Lunar Lander						
FOM Metric	**Affect Config?**	**Affected Subsystems**	**Need Level**	**How Measured**	**Verification Requirements**	**Range of Values**
1. Crew Autonomy	No	Comm, Data, Automation	7. Self-Actualization	Multiple Metrics	Simulation, Analysis	TBD
2. Dust Mitigation – Reject, remove, and dispose of dust, control dust density in the air.	Yes	ECLSS, Hab, Configuration, materials,	4.Quality of Life, Safety	Vertical distance aids gravity settling; Density of dust particles per unit volume of air.	Inspection, Test, and Analysis	0.05m to 7, 0.1 to 10 micron particles: <0.05 mg/m^3
3. Field of View, landing, rendezvous, dock	Yes	Windows, Structure, Config, Controls/Displays	6.IndividualTask	Window size, shape, direction, proximity to front, View angle to surface	Analysis, Demonstration	Closer to leading edge of DM is better.
4. Uninterrupted IVA Circulation	Yes	Configuration, Hatches	5. Crew as Team	Continuous circulation, not interrupted by AL Depress	Analysis, Demonstration	90 to 100% time Uninterrupted
5. Noise Control (Crew Awake)	Yes	Structure, Config, ECLSS, Hab	4.Quality of Life	Vibration, resonance, acoustics, machine noise.	Analysis, Test	See HSIR verification reqts
6. Radiation Protection	Yes	Structure, Config, Materials	4. Quality of Life, Safety	Effective body-integrated dose	Analysis, HSIR HS3085V	Exposure < the design SPE
7. Safe Access to the Surface	Yes	Config, Ladder, Landing Gear, Propulsion.	5. Crew as team	Airlock hatch proximity to surface. Closer is better.	Inspection, Demonstration	1 m to 7 m
8. Sleep Assurance (Noise Control)	Yes	Structure, Config, ECLSS, Hab,	4. Quality of Life	Temperature, humidity, vibration, acoustics,	Analysis, Test	Multiple Ranges
9. Workload Management	Yes	Automation, Config, Hab/Lab, Controls/Displays	5. Team, 7. Self-Actualization	Crew Time Model, Mission Timeline, Work Stations, availability of workspace	Analysis, Simulation	Time available; prevent error; workspace use.
10. Workstation Human Factors	Yes	Windows, C&DH, Controls/Displays, Hab	6. Individual Task	Coordination of Windows & Flight Deck Controls & Displays	Analysis, Inspection, Simulation, Test	Multiple Ranges

TABLE 3. Crew Productivity and Safety Metrics that Interact with Configuration (Cohen, July 2010)							
CP FOM Metric	**Tracking Number**	**Statement of Metric**	**Type of Variable**	**Units of Measure**	**Allowable Range**	**Rule**	**Comments**
C. Safety Needs	NG3005V	Ascent Module Launch on Abort During Descent / Launch from Surface	Logical	True / False	True	Descent Module and other Structure of Descent Module and other pressurized modules may not obstruct AM departure trajectory	Folding the configuration for compact descent then unfolding for launch may be too complex.
C. Safety Needs	NG3006V	Ensure the ability to abort: Minimize separation complexity and risk of *failing to cut or disconnect the tunnel* when separating the AM from the lander.	Integer	Whole number	0, 1	AM pressurized parting planes may not exceed one to reduce the risk of a separation failure.	Range may expand with more reliable disconnect technology
E. Crew as a Team Needs	NG5009V	Maximize the availability and use of crew time to perform the mission.	Logical	True / False	True	Crew may not be required to perform EVA routinely to pass from one pressurized volume to another.	Crew time is the most precious commodity in the Constellation Program
E. Crew as a Team Needs	NG5010V	Provide minimally interrupted IVA access among the pressurized modules	Real	Day, given as a percent of time pressurized	Initially, 100%, 95 to 90% may be acceptable.	IVA circulation may not be excessively interrupted by a depressurized Airlock.	A scenario might be possible where rapid, “routine” EVA allows the Airlock to be repressurized between egress & ingress.
E. Crew as a Team **Needs**	NG3001V, NG3002V	Provide safe access from the Ascent Module to the lunar surface and back.	Probability	Percentage	TBD	The surface ConOps may not expose the crew to the danger of falling from the Airlock or vertical circulation system.	Altair must support safe surface operations.

- IVA circulation,
- Ease of EVA egress and ingress from the airlock,
- Safe vertical access to the lunar surface,
- Safe and reliable separation of the Ascent Module from the Descent Module, and
- Lunar dust control and mitigation.

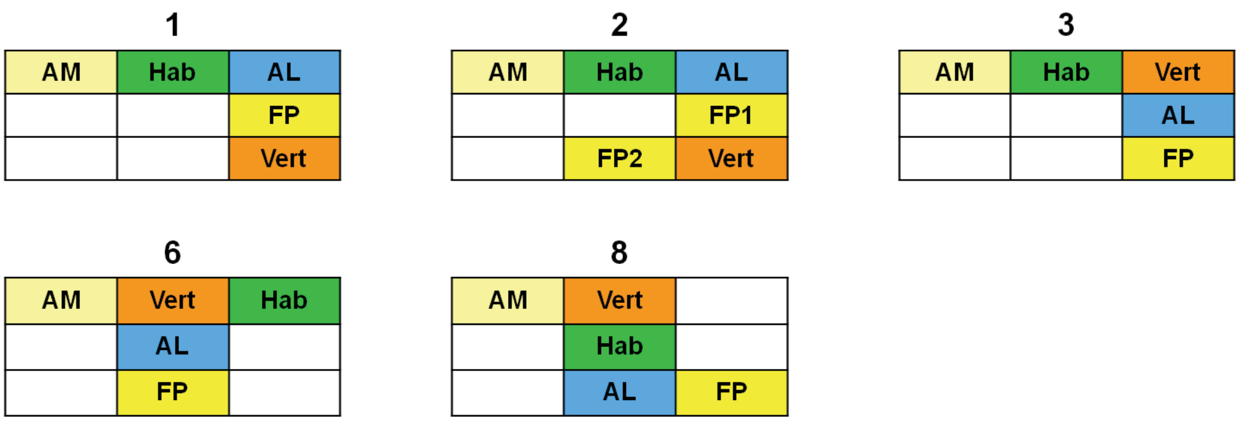


FIGURE 3. Final Configuration Topologies for the Lunar Lander (Cohen, July 2010, p. 19).

Example of Topology 1 **Example of Topology 3**

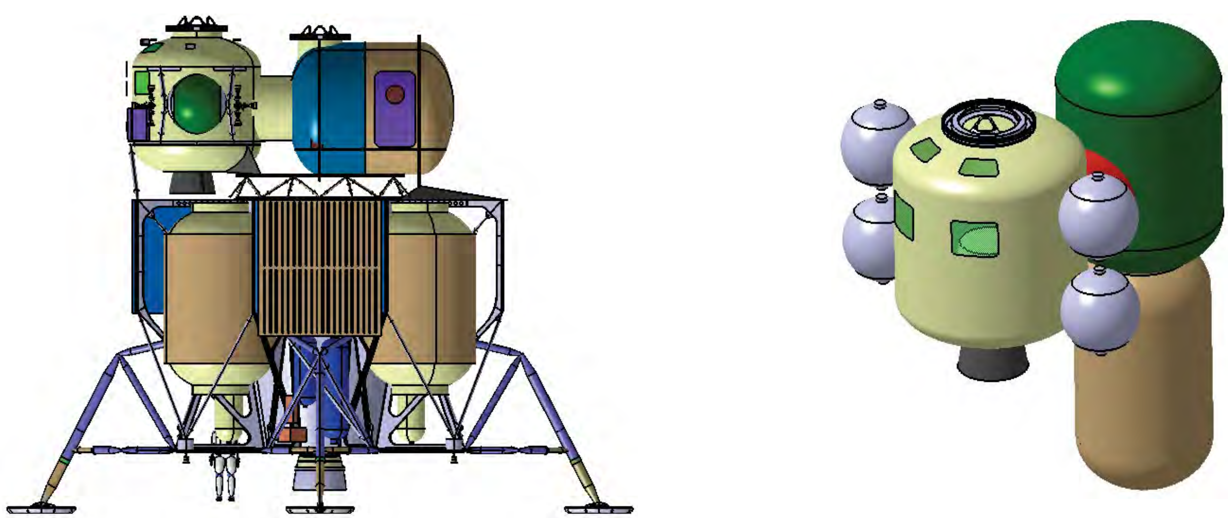


FIGURE 4. Examples of Two of the Final Five Topologies that Met the Crew Productivity and Safety Metrics (Cohen, July 2010, pp 14 and 23).

FIGURES 3 and 4 illustrate the "final five" configurations from the Habitable Modules Configuration Study (Cohen, July 2010). TABLE 3 summarizes the CP FOM metrics that interact with the lunar lander configuration and so came to play a role in the trade and analysis study.

F. Translate to the Multidisciplinary Optimization Tool (MDO) Tool.

A long-term goal of the lunar lander research was to create a multidisciplinary optimization tool (MDO) that could track and quantify all the interactions among the subsystems and between the subsystems and the vehicle. The team made a preliminary assessment of various MDO applications. One example that stood out from the assessment dealt with options for the location of the Airlock relative to the Ascent Module:

> *A design where the airlock is located on the descent module such that it can be accessed from the ascent module provides significant advantage over any design solution that would locate the airlock on the ascent module. Another option would be to locate it on the ascent module and detach it before the ascent flight. In order to assess the impact of location of the airlock, the lander weight was assessed without any airlock in either the ascent module or the descent module. This is the reference point with zero growth in the lander weight . . . . Then three other cases were run with a 250-ft³ airlock in the ascent module, a 250-ft³ airlock in the descent module and finally, a 250-ft³ airlock each in the ascent module and descent module. The growth in the lander weight was more than doubled when the airlock was added to the ascent module as compared to the descent module* (Chakroborty, Berry, Meade, 2007, p. 8).

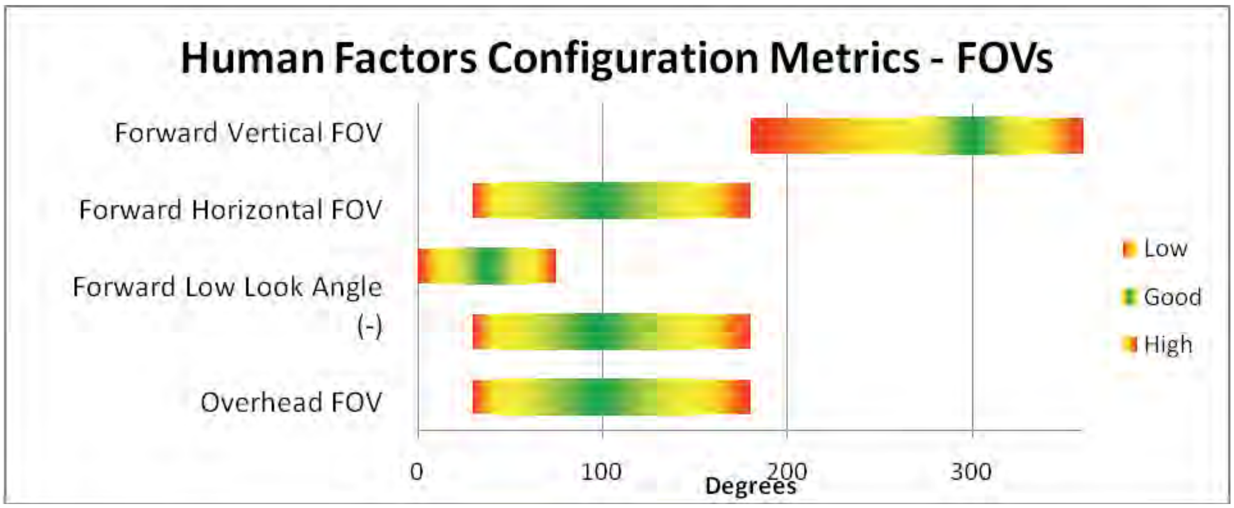


CHART 1. Multidisciplinary Optimization Tool result for a Piloting Window Concept on a Lunar Lander Design, courtesy of Tad Theno, multi-disciplinary optimization engineer.

Following this general approach, the team began building an MDO Tool in Model Center software. The tool grew as a series of small models to represent discrete interactions. These models pass input values as quantitative and logical variables and receive values back to create a complete simulation of what CP means for the totality of the Lunar Lander. CHART 1 shows an example of the analysis for piloting windows, to understand how best to arrange the windows for the maximum field of view (FOV). The highlight *Forward Low Look Angle* because it shows that the requirement for down vision during surface landing needs to be as close to the front as possible.

III. NASA HSIR Verification Requirements

The CP trade and analysis team conducted a review of the NASA HSIR to understand the myriad of requirements for verification. The HSIR designates four methods of verification: *analysis, demonstration, inspection, and test.* The team's analysis of the four HSIR verification methods revealed that two additional verification methods needed to be added to enable the CP FOM metrics: *simulation* and *survey,* to augment NASA verification methods and as an aid to address potential gaps:

Simulation: to provide a representation of the Altair functionality, operations, structure, or other attributes that enables us to verify that the system or subsystems are working the way they should and as a way of identifying potential problems at the interfaces between systems.

Survey: there is a special case of analysis or inspection that affords the use of statistical testing to the verification process, based upon the principles of a scientific quasi-experiment.

IV. Framework of Trade and Analysis

The framework of this trade and analysis identifies human factors that support the definition of a FOM for Crew Productivity. The Altair living and working environment factors correlate with remarkable accuracy to the Maslow model offering a useful representation of what the Altair system must do to support crew productivity. The focus was to find the elements of all the subsystems that interact with the Figures of Merit: mass, cost, PLOM, PLOC, and CP. The nature of the interaction takes the form of a *trade*: any improvement in performing on a metric results in a change to the other FOMs and the spacecraft configuration.

a. Survival: Biological Needs

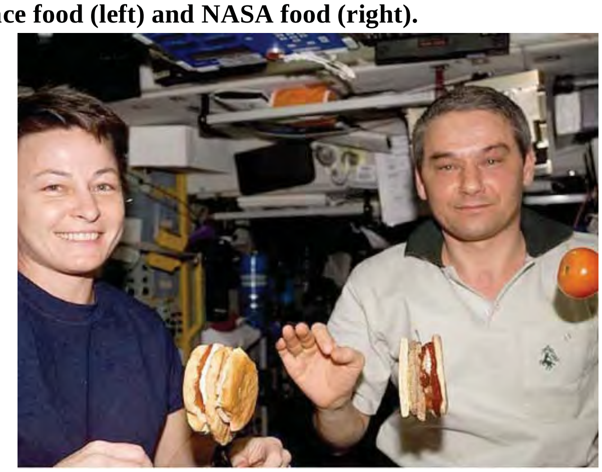
The ***biological needs*** correspond to the crew's needs for life support, habitability, and health, to meet minimal needs at the survival level. Key biological survival needs include: Food, Clothing, Shelter, Air, Thermal Stability, and power to operate the life support, command, control, and communication systems. The team found that the HSIR verification requirements were sufficient to address the survival/biological needs. An example of Biological Needs/Survival is Food for the crewmembers.

Russian Borsht in a tube, courtesy of the National Air and Space Museum, Washington DC.

NASA Space Food on a Tray, NASA photo

FIGURE 5a. Examples of Russian space food (left) and NASA food (right).

Andre Kuipers on ISS, Zvezda Module with food stowage boxes. 2004, NASA photo



Peggy Whitson & Valery Korzun on ISS with hamburgers and fruit, 2002.NASA photo.

FIGURE 5b. ISS Crew with Examples of Food in Space Meeting the Survival – Biological Need

FIGURE 5 shows examples of astronaut and cosmonaut food, and crewmembers with food in space. Like food, Biological survival is not subject to a ***TRADE***. Although there may be some options that present preferences over other options, ***biological survival is the baseline*** for human spaceflight.

TABLE 4 shows an example of how Survival Biological Needs can interact with the lunar lander configuration. NASA Verification Requirements from the HSIR to protect crew sleep from disruption by vibration show that structural isolation of vibration is an important consideration in spacecraft design.

TABLE 4. Summary of NASA HSIR Verification Requirements for Biological Needs that Interact with Configuration

Verification Requirement	Title	Metric / Tool	Description
HS3106V	Vibration Levels During Crew Sleep	0.01 g frequency-weighted rms acceleration in each of the X, Y, and Z axes between 1.0 and 80 Hz	Vibration levels on the support surfaces of the rest areas are less than 0.01 g

b. Survival – Physiological Needs in the Dynamic Flight Regime

Specialized ***physiological needs*** appear at the second level in the Maslow hierarchy, focusing on biomechanical protections for the crew to pilot and fly the propulsive vehicle through high accelerations and angular rates of change. This protection is important because severe vibration in the Ascent Module during descent, on launch from the surface, abort, or contingency maneuvers could harm the crew or interfere with their ability to read displays and operate controls. The team found that the HSIR verification requirements were sufficient to address the survival/physiological needs. TABLE 5 presents the verification requirement for vibration in dynamic flight that **interacts with configuration**.

TABLE 5. NASA HSIR Verification Requirement for the Dynamic Flight Environment that Interacts with Configuration

Verification Requirement	Title	Metric / Tool	Description
HS3105V	Limits for Vibration During Dynamic Phases of Flight	Vectorial sum of the X, Y, and Z frequency-weighted accelerations between 0.5 and 80 Hz does not exceed the levels and exposure durations	Vibration levels at crew seat or restraint during landing/touchdown. Ascent launch?

Apollo Lunar Module Spacecraft on the Lunar Surface **Apollo LM Ascent Module lifts off.**

FIGURE 6a. Dynamic Flight Maneuvers for the Apollo Lunar Module: Ascent from the Surface.

NASA Altair Lunar Lander: Shroud Separation before Trans-Lunar Injection

NASA Altair Lunar Lander after separation from the Orion CEV during terminal descent and landing.

FIGURE 6b. Dynamic flight maneuvers for the Altair Lunar Lander (NASA images).

FIGURE 6 shows dynamic flight for the Apollo LM and the Altair concept for a Lunar Lander. In Figure 6a images, the LM Ascent Module stands by on the Descent Module, then launches from the lunar surface. FIGURE 6b shows the Altair going through two maneuvers: separating its shroud before trans-lunar injection and beginning its descent to the lunar surface. Vibration Control **interacts with configuration,** propulsion, cryo storage, structures, and the hatches. Propulsion generates the vibration, which the cryo storage can help to damp. The tank and truss structures translate the vibration to the modules and the crew stations. ***THE TRADE IS: Investing in better isolation for the engines, stiffer structures to change the mode, more effective cryo damping against crew safety and performance.***

C. Safety Needs

The ***safety needs (Maslow Level C, FIGURE 1)*** correspond to the environmental factors that affect crew safety beyond the basic survival needs. The safety needs include hazards such as failure of radiation protection or loss of structural integrity that can arise from failures within the spacecraft during operations. The HSIR verification requirement for radiation that interacts with configuration appears in TABLE 6. Given the tremendous effort that NASA is putting into radiation protection, this single verification requirement is elegantly stated. The "design SPE" refers to radiation exposure values that NASA published separately in the Design Specification for Natural Environments (DSNE). The team found that although the HSIR verification requirements covered safety well, there were some aspects of interaction with configuration that still need to be developed.

FIGURE 7 suggests a point of departure to solve certain aspects of the radiation protection challenge. Ionizing Radiation from a solar particle event is an acute threat to crew health and safety; some solar flares can give a lethal dose. All parts of the spacecraft, and all materials and structures in the spacecraft can help increase radiation shielding. The principal subsystems that can provide radiation shielding include module primary structure, micrometeoroid protection, thermal/body-mounted radiators, and cryogenic storage tanks. The **interaction with configuration** derives from placing modules to shield the safest zone in Altair can help increase radiation protection. ***THE TRADE IS: Arranging the modules and materials through multifunctional construction to maximize shielding versus adding mass to provide shielding.***

TABLE 6. NASA HSIR Verification Requirements for Safety that Interact with Configuration

Verification Requirement	Title	Metric / Tool	Description
HS3085V	Radiation Design Requirements	Effective (Integrated Body) Dose, Table 3.2.7.1.1-1, TBD-007-001	Maximum effective dose incurred by any crewmember within the vehicle does not exceed the value given for the design SPE.[7]

[7] NASA, CxP 70023, DSNE, Section 3.3.4.

FIGURE 7. Alternate Lunar Lander Configuration. This arrangement of Ascent Module and "wing tanks" above the Habitat can increase radiation shielding on the surface, drawing credit: Rush Wofford.

TABLE 7. Crew Productivity Metrics for Safety Needs that Interact with Configuration

CP FOM Metric	Title	Metric / Tool	Description
NG3001V	Egress from the Airlock	Demonstration Inspection, Test	The crew needs the ability to step out of the EVA airlock onto a safe area.
NG3002V	Ingress to the Airlock	Demonstration Inspection, Test	The crew needs the ability to step up off the ladder onto a safe area.
NG3003V	Descent of the Ladder to the Surface	Demonstration Inspection, Test	The crew's ability to descend the ladder from the AL to the surface.
NG3004V	Ascent of the Ladder from the Surface	Demonstration, Inspection, Test	The crew's ability to ascend the ladder from the Surface to the AL
NG3005V	Ascent Module Launch on Abort During Descent	Simulation and Inspection	The DM and other structure may not obstruct the AM departure trajectory.
NG3006V	Ascent Module Parting Planes	Simulation, Inspection, Test	The number of AM parting planes shall not exceed one.

TABLE 7 presents the level C Safety Needs that interact with the configuration. The gap analysis found that HSIR did not address these issues: EVA and Ascent Module (AM) launch. The EVA concerns include egress from the Airlock and ingress back to it, plus access down to the lunar surface and back up to the Airlock. The CP metrics for AM launch cover both launch from the surface and abort upon descent. The concern for launch upon descent is that no part of the lander should obstruct the AM's propulsive departure. An additional concern is that the AM tunnel should not have too many parting planes where its IVA circulation tunnel connects to the Habitat Module or the Airlock. Therefore, this safety metric allows no more than one parting plane.

D. Quality of Life and Health Needs

The *quality of life and health needs* criteria take the crew from the assurance of safety to being able to perform their jobs well over a sustained period of time. There are some important distinctions between the Biological Needs and the Health and Quality of Life need levels. For food, the standard Shuttle seven-day diet (which includes sufficient nutrition but not a great deal of variety or interest) would satisfy the biological survival level. The quality of life enhancement would introduce more varied and interesting foods, ideally including fresh food grown in space for long duration missions. Privacy is another distinction; for example simply providing the waste management facility (toilet) and hygiene facility (sink) meets the biological need. However, adding a privacy curtain or better still, a completely enclosed compartment meets a quality of life need.

The team found that all the HSIR verification requirements that applied to Quality of Life and Health were appropriate, but none interacted with the configuration. The *gap analysis* identified CP metrics for dust mitigation and spatial cognition that interact with configuration. TABLE 98 presents these Quality of Life and Health metrics.

TABLE 8. Crew Productivity Metrics for Quality of Life that Interact with Configuration.

CP FOM Metric	Title	Metric / Tool	Description
NG1002V	Dust Removal	Ultra fine particles of 0.1 - 5 micrometer; >99.99% removal from the crew cabin	Neutralize and decompose captured dust particulates into harmless, non-toxic by-products
NG1003V	Dust Disposal	>99.9% collection and compaction	Collect and compact particulates; separate and dispose back to the lunar surface
NG4003V	Perceived Spaciousness	Modeling, Analysis by Isovists, Depth-mapping.	Habitable module interior shall provide perceived spaciousness.
NG4004V	Spatial Cognition Locomotion	Space Syntax & spatial models analysis	Habitable module interior shall accommodate the *locomotion* spatial cognition response to enable smooth movement and translation.
NG4005V	Spatial Cognition: Way-finding	Space Syntax and other tools	Habitable module interior shall accommodate the way-finding spatial cognition response.

Lunar dust protection is perhaps the thorniest issue to classify to a single level, because it has ramifications for the biological need to breathe, safety from toxicity, and the assurance of health and quality of life. It does not appear likely that lunar dust would cause the *Loss of Vehicle* or *Loss of Crew* during the lunar mission, but may cause extremely uncomfortable, inconvenient, and unhealthy effects for the crew once they start operating on the surface, and the health effects may persist after return to earth. For this reason, the lunar dust problem appears here as an issue for health and quality of life. The HSIR addresses lunar dust in one verification requirement:

> ***Lunar Dust Contamination***
> ***[HS3006DV]*** *The limit of lunar dust in the internal atmosphere shall be verified by analysis. The analysis shall include a review of the vehicle design and testing of the Atmosphere Revitalization System (ARS). The verification shall be considered successful when the analysis and tests show the particulate contamination of less than 10 micron and equal to or greater than 0.1 micron size (TBR-006-004) within vehicle can remain below 0.05 mg/m^3.*

HS3006DV provides an example of where NASA states a verification requirement, but the trade and analysis team's assessment found the specification needed more specificity to become fully actionable. The team realizes this is an evolutionary document, but also recognizes that a key issue in this instance is that the human spaceflight community does not yet know enough about lunar dust within a life support system and spacecraft ventilation to perform such an analysis in the absence of empirical testing. Therefore, the team created a more extensive set of metrics to posit testing that specifies what to test and to what level of result. TABLE 9 indicates CP metrics for both lunar dust and spatial cognition.

The team responded to this finding by formulating its own metrics for lunar dust mitigation as part of the Quality of Life Need Needs: Lunar Dust Mitigation [NG1002V]. The countermeasures against dust may extend to all parts of the habitable modules. Dust mitigation **interacts with configuration,** life support ventilation, power, thermal, and configuration. Moving air through filters will be the primary means of removing dust from the environment. If the airlock is below the level of the Habitat/Ascent Module, it enables the use of lunar gravity to help downward ventilation to control the dust.

THE TRADE IS: locating the Airlock below, the habitat changes the configuration but can save on pump size, power consumption, and cooling. FIGURE 8 shows an example of a lunar lander configuration with the airlock below the Ascent Module and Habitat Module, making it possible to separate the dust collection and removal area from the crew living areas. The ventilation air will flow down to the dust removal filters. The height of the tunnel combined with gravity and forced ventilation help to mitigate the threat of lunar dust.

FIGURE 9 illustrates another *Quality of Life Need for habitable volume and the spatial cognition* that goes with it. In addition to lunar dust, TABLE 8 addresses spatial cognition and visual perception needs for Quality of Life.

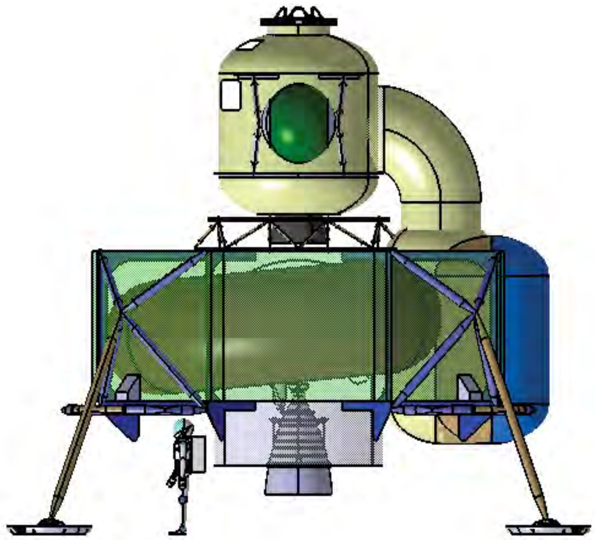


FIGURE 8. Vertical tunnel acts as a ventilation & gravity flow duct to collect dust particles for this option derived from the 2008 Northrop Grumman Lunar Development Study.

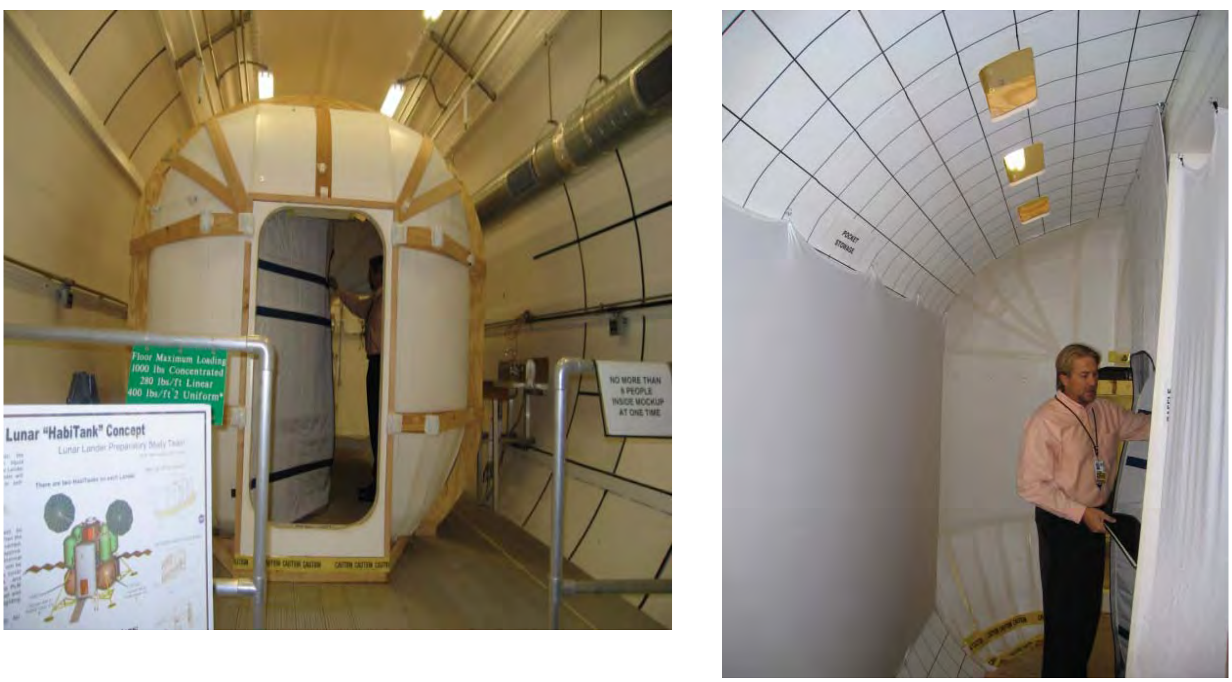


FIGURE. 9. Kriss Kennedy's (JSC) 2007 Habitank Concept Mockup as an Example of the Quality of Life Need for Spatial Cognition, author photo.

Example of Quality of Life Needs: Spatial Cognition [NG4003V] -- The size, shape, outfitting, and arrangement of the modules can affect how the crew perceive, use, and move in the living and working environment (Dara-

Abrams, 2009, pp. 24:1-24:8). Spatial Cognition interacts with Configuration because the crewmembers move through it. Perceived spaciousness affects how much living space the crew feels that they have (Turner, Doxa, Maria; O'Sullivan, Penn, 2001, pp. 103-121). Spatial Cognitive Locomotion interacts with how the crewmembers move through the space. Spatial Cognitive Way-finding affects how the crew understands where they are and how to go somewhere. Spatial Intelligibility affects how well the crew can read the environment (Parke 2009, pp. 86:1-86:14). ***THE TRADE IS: Sizing, shaping, and arranging the modules can contribute to crew quality of life on a variety of metrics, which may increase mass and structural complexity.***

E. Crew as a Team Needs

The ***crew as team's needs in the Working Environment*** provides the basic capability to perform the mission. These needs apply to CP in a collective sense. They include crew relations with other elements such as the Mission Operations Directorate and the various Payload Operations Centers support science and engineering payloads on Altair.

TABLE 9. Summary of NASA HSIR Verification Requirements for the Crew as a Team that Interact with Configuration

Verification Requirement	Title	Metric / Tool	Description
HS5004V	Suited Ingress, Egress, and Escape Translation Paths	Analysis using high fidelity CAD and demonstration using high fidelity mockup.	Identify suited operation scenarios for crew ingress, egress, and escape from one vehicle or transfer between two.
HS5005V	Unsuited Internal Translation Paths	Analysis using high fidelity CAD and demonstration using high fidelity mockup.	Models include the vehicle, unsuited crewmembers, and unsuited crewmembers' movement through the translation paths.
HS5006V	Crew Ingress/ Egress Translation Paths in Space	Analysis and demonstration using high fidelity mockup or flight vehicle.	Assisted in-space ingress and egress of an incapacitated pressurized-suited crewmember.
HS4022V	Emergency Equipment Access	Access the EE within the time required.	Identify all EE and location in Altair.

The crew as a team needs include communications, group living and working spaces, cross training, buddy pairing, and decision-making. The team identified four HSIR verification requirements that interact with configuration, which appear in TABLE 9: suited EVA Egress from pressurized volume to vacuum and ingress from vacuum back into the pressurized volume. TABLE 9 also addresses IVA circulation within pressurized modules, including access to emergency equipment. The *gap analysis* showed the need for CP metrics to address IVA circulation in terms of not being interrupted by an unpressurized airlock or other unpressurized conditions. These metrics derive from the "lesson of Skylab," where the EVA airlock when depressurized interrupted circulation between the Apollo Command and Service Module and the Multiple Docking Adapter on one side and the Saturn Workshop habitat on the other side. TABLE 10 shows the CP metrics for crew circulation within pressurized volumes.

TABLE 10. Summary of Crew Productivity FOM Metrics for Crew as a Team.

CP FOM Metric	Title	Metric / Tool	Description
NG5009V	Continuity of IVA Circulation between Pressurized Modules	Inspection, Analysis	Crew may not be required to perform EVA routinely to pass from one pressurized volume to another.
NG5010V	Continuity of IVA Circulation during Airlock Depressurization	Inspection, Demonstration, Analysis	A depressurized Airlock may not interrupt IVA circulation more than TBD % of the time.

Example of Crew as a Team Need: Rapid and Reliable EVA Ingress/Egress and Safe Access to the Surface: EVA is eminently a **team need** because of the *Buddy System* protocol, which dictates that for every EVA there must be at least two space-suited crew members involved. Even when only one astronaut egressed the vehicle (first Gemini EVAs and then Apollo trans-Earth injection retrieval of the external camera), the other EVA buddy or buddies were suited-up and ready to help if their EVA colleague had a problem. FIGURE 10 shows two views of the Apollo 11 landing. The one on the left shows the view from a video camera mounted on a lander leg. The one on the right shows a mockup of the landing at the Cradle of Aviation Museum. The ladder height is about 3m.

"One small step for a man," Neil Armstrong steps off the Apollo 11 "Eagle" ladder to the lunar surface. Courtesy of NASA.

A mannequin of an astronaut climbs the leg-mounted ladder of a LM, Cradle of Aviation Museum. (First author photo).

FIGURE 10. Two views of Apollo Lunar Landings.

FIGURE 11. The LDAC-1 Lunar Lander Concept on the Lunar Surface, 2007. NASA Image.

The EVA Airlock system should afford simple, rapid, and reliable Don/Doff and Egress/Ingress procedures. Placing the EVA Airlock as close to the surface as possible will minimize the descent and ascent on the ladder. Part of ensuring safe and reliable access is providing a Front Porch for the airlock at the top of the ladder and a bottom platform (or a second Front Porch) at the foot. ***THE TRADE IS: Arrange the modules and propellant tanks to provide IVA circulation to the Airlock positioned close to the surface***

The initial NASA Lunar Development and Analysis Cycle One (LDAC-1) concept for Altair was problematic in terms of EVA crew access to the lunar surface. FIGURE 11 illustrates the NASA LDAC-1 (Cohen, July 2009, pp. 11-13). Note the height of the deck about 7m above the surface. The EVA crew ladder is visible behind and towards the right under the propellant tanks. To channel Neil Armstrong's famous phrase, "That's one big fall down for a man . . ." In addition to the problematic ladder height, the LDAC-1, 2, and 3 configurations did not address the issue of piloting windows illustrated in CHART 1 and discussed below as a CP FOM example.

Example of Crew as a Team Need: Access to Emergency Equipment [NASA HSIR-VR HS4022V]. The key to the crew functioning as a team is the ability to gain access to emergency equipment to assist other crewmembers in need or to make urgent repairs. FIGURE 12 shows two examples of crew access to emergency equipment.

Fyodor Yurichikhin in the Zvezda Module on ISS, 2007. Note the Fire Extinguisher on the wall.

Sunita Williams in the Destiny Lab on ISS, floating above the first aid kit, 2007, NASA photo.

FIGURE 12. Crew Access to emergency equipment on ISS, NASA photos.

The question of what constitutes emergency equipment or repair equipment and the imperative to give priority access it touches upon every subsystem. The obstruction of emergency equipment by subsystem hardware, cargo payloads, science payloads, or general clutter can pose an unacceptable threat to crew safety and emergency response. The problem of access to emergency equipment arises when a subsystem design and engineering team is unaware of the safety response requirements for that area or volume where the will be installed. Access to Emergency Equipment **interacts with configuration** if a crewmember is cut off in one module but the equipment is in another. ***THE TRADE IS: Putting the requirement on all the subsystems to preserve access to emergency equipment and to provide redundancy if configuration is an issue.*** The clutter in the US Destiny Lab illustrates how the proliferation of paraphernalia could create an obstruction to access to the emergency equipment, such as the fire extinguisher on the left or the medical kit on the right.

F. Individual Task Needs

The individual task needs address the design, procedures, and operational protocols that enable individuals to perform their jobs reliably, safely, and successfully. These accommodations include anthropometrics, ergonomics, controls and displays, situational awareness, workload management, fatigue monitoring, and countermeasures against degraded performance and error. The HSIR verification requirements identified several aspects of windows in the spacecraft in their role for individual tasks that interact with configuration. TABLE 11 presents these aspects.

TABLE 11 also identifies unsuited internal translation paths, which is included here as an aspect of individual needs to perform tasks. The *gap analysis* showed that the two HSIR verification requirements for windows were not sufficient to address all the necessary dimensions of the piloting windows. Table 12 presents two additional CP metrics that complete the characterization of the piloting windows. The metrics in TABLE 12 provide the connection to the relationship between the windows and the configuration, whereas TABLE 11 focuses more on the cognitive-perceptual aspects of the window-workstation ensemble. The interaction with configuration arises in relation to the placement of the windows in relation to the larger spacecraft geometry.

Example of the Individual Crew Member's Need to Perform a Task: Window Viewing for Pilot According to *NASA HSIR HS5201V and the trade and analysis team-derived requirement NG6010V (described in tables below)* ensuring that the crew can perform their tasks effectively and reliably requires excellent human factors design and integration. Piloting is the most critical task for which to design windows for the Ascent Module. Window viewing for the Pilot involves: the position and design of the flight crew station, the position and design of the window, and he view angle to the surface where the pilot wants to land. The Pilot Window **interacts with configuration** and Mass Properties because it must be located far enough forward to gain a full view of the surface for landing. Window design interacts with the position of the Ascent Module on the Descent Module and can affect the shape and orientation of the Ascent Module itself. ***THE TRADE IS: Placing the Ascent Module and its Pilot Windows as far forward as possible versus changes in mass properties off the thrust axis.***

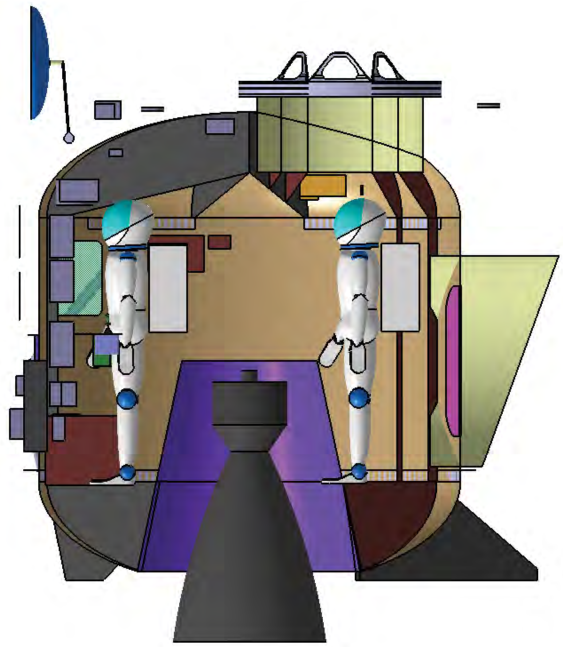
TABLE 11. Summary of NASA HSIR Verification Requirements for Individual Crewmembers Needs to Perform Tasks.

Verification Requirement	Title	Metric / Tool	Description
HS5021V	Window Viewing for Piloting Tasks	Analysis using CAD and demonstration using high fidelity mockup and simulator.	Fields of view through the (2) piloting windows are adequate to support all NASA approved piloting tasks.
HS5022V	Unsuited Internal Translation Paths	Analysis using CAD and demonstration using high fidelity mockup and simulator.	Models include the vehicle, unsuited crewmembers, and unsuited crewmembers' movement through the translation paths.
HS5055V	Window for Motion Imagery and Photography	Analysis and demonstration.	The optical performance of the window that supports motion imagery and photography with lens apertures up to 100 mm in diameter.

FIGURE 13 illustrates two aspects of the piloting windows. On the left is a drawing that shows the essential relationship between the pilot, flight deck, controls and displays, and the out-the-window view. The design of all three elements must proceed in close coordination. On the right appears a view of an Ascent Module with the pilot station facing left out the window. This image demonstrates the need to place the piloting window in a leading-edge position that the two examples in FIGURE 14 exemplify. In both these configurations, the Ascent Module sits off-center from the vertical (Z) axis of the lander.

TABLE 12. Crew Productivity Metrics for Individual Crewmembers Needs to Perform Tasks.

CP FOM Metric	Title	Metric / Tool	Description
NG6010V	Piloting Window View Angles	Analysis, Modeling, Inspection, Simulation	Unobstructed view angles for Descent, TDL, rendezvous, and docking.
NG6011V	Alignment of Flight Crew Station with Piloting Window	Analysis, Modeling, Inspection, Simulation	Layout of window and workstation shall fall with the operator's cone of vision.



Human-in-the-loop pilot flight deck concept, courtesy of Jeff Wilbert.

Ascent Module configuration concept with piloting window on the left, courtesy of Abid Ali-Khan

FIGURE 13. Flight Crew Station and Piloting Window Concepts.

FIGURE 14 suggests another aspect of windows for crew operations. The figure shows a photo of two shuttle astronauts, one IVA at the Aft Flight Deck that looks out on the cargo bay and the other from which the crewmembers operate the robotic arm. Looking in through the aft window is an EVA astronaut. FIGURE 14 provides both an example and a counter-example, the example being of a crewmember potentially using the window to monitor the EVA activities of fellow crew.

FIGURE 14. Megan McArthur at Shuttle aft flight deck on Atlantis with a crewmate in an EMU Spacesuit looking through the window, NASA photo.

The counter-example is that unlike Shuttle EVAs to the Cargo Bay, most lunar surface EVAs will occur well outside and beyond the range of visibility that any lander window provides. The crew therefore will need to rely on means other than direct visual sighting for of observation, monitoring, and communications**.**

F. Self-Actualization

When the team first started trying to interpret the notion of *self-actualization*, the term seemed too "New Age" even though it dates from 1962, well before "counter-culture" emerged. However, it was the best term the team could find so they kept it. At the apex of the Maslow pyramid, ***self-actualization*** represents more of a goal state than a specified need, but it plays an important role in the highest-level crew functions for carrying out mission objectives. The CP metrics for self-actualization appear in TABLE 15.

Self-actualization is essential to crew motivation and morale. Specifying key self-actualization attributes of thoughts and behaviors such as scientific discovery, serendipity, and creative innovation during a mission proved difficult but not insurmountable. TABLE 15 shows a set of self-actualization metrics and provides suggestions for how to begin trying to measure the system performance for them. More than any of the other Maslow levels, self-actualization shows the need for more work.

Example of Self-Actualization: Coordinate Schedules with Available Workspace -- The crew needs to perform three types of IVA Activities: Living and Habitation Activities, Spacecraft Working Activities, and Science and Payload Working Activities according to team-derived self-actualization requirement *NG7005SA in TABLE 13*. Since most space on Altair will be multi-use, the crew will often have the three activities going on, plus EVA prep. The workspace must be sufficient to accommodate all multi-use functions simultaneously. Available Workspace **interacts with configuration**, module size, interior subsystems, and outfitting. Planning the Altair crew time model engages the available workspace. ***THE TRADE IS: Designing the habitable modules to afford sufficient workspace (volume) for the necessary tasks versus the increase in mass, size, power, thermal, etc.***

FIGURE 15 shows the Spacelab 1 Mission on STS-9. This mission encountered intense crew activity within a small area of the Spacelab module in the Shuttle cargo bay. The mission was constrained insofar as the crew did not have alternate places to do their tasks or to organize their time.

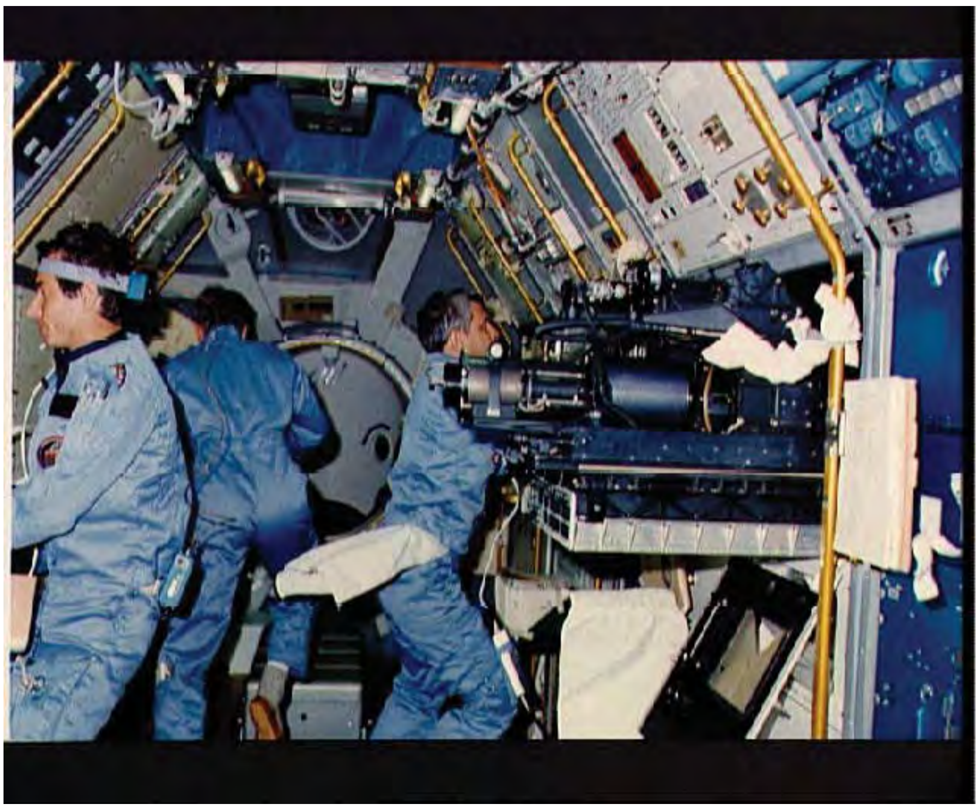


FIGURE 15. STS-9 Crew Members during the Spacelab-1 flight. NASA photo.

In the 1985 Space Station Crews Safety Alternatives Study, authors Rockoff, Raasch, and Peercy of Rockwell observed:

> *It has been noted on the Shuttle/Spacelab flights that workspace within a module is at a premium. The allocation of work tasks should be incorporated into the timeline to ensure that people will not be working on top of each other. On one of the Russian flights, a personnel problem occurred when one of the cosmonauts proceeded to do the other's work (Rockoff, Raasch and Peercy, 1985, p. 41).*

This observation makes an important link between physical space, territoriality, and individual or team division of work responsibilities. It shows that good design of the workspace can help support both the crew as a team and individuals to perform operations and other tasks. Accomplishing and sustaining this team and individual performance is an important support for self-actualization.

TABLE 15. Summary of Crew Productivity Metrics for Self-Actualization					
Affect Config	**CP FOM Metric**	**Title**	**Metric / Tool**	**Description**	**Reference**
No	NGC7001SA	Contain the Workload	TBD	"Let's ease off on the work load. Let's let the astronomers have some time to just sit there and look through telescopes."	Douglas, 1986, p. 41.
No	NG7002SA	Workload and Realistic Schedules; Minimize Busy Work	TBD	"Consequences for work underload, work overload, unrealistic schedules, and 'make work.'"	Vander Ark, Curtis, Holland, Flynn, 1997, p. 5.
No	NG7003SA	Serendipity and Contingency Timelines	TBD	"Provide a system component - *a person - who is able to respond to the unexpected scientific event."*	Sieber, et al, 1979. p. 7.
No	NG7004SAV	Protect Off-Duty Time	During a full mission simulation in a high fidelity simulator, the crew works no more than TBD % overtime.	The crew falls behind in their work schedules, making up their assignments by "working overtime" during their "off-duty" hours.	
Yes	NG7005SAV	Coordinate Work Schedules with Available Workspace	Modeling to show that multiple crew members use the same workstation or workspace no more than TBD % of the time	The allocation of work tasks should be incorporated into the timeline to ensure that people will not be working on top of each other.	Rockoff, Raasch, Peercy, 1985. p. 41.
No	NG7006SA	Meaningful Work	TBD	The crewmembers need the opportunity to be intellectually involved in their work.	Helmreich, Wilhelm, Foushee, 1988, p. 5.
No	NG7006SA	Intellectually Valid Tasks	TBD	Use the person in the higher level control of experiments rather than to control a specific parameter	Lichtenberg, 1988, pp. 2-3.

One of the most provocative statements in the space crew literature came in an anonymous interview with an Apollo astronaut conducted by Bill Douglas (*1986, p. 41)*, flight surgeon for the original Mercury 7 astronauts.

> *Let's ease off on the workload. Let's let the astronomers have some time to just sit there and look through telescopes. What's wrong with that? That's where all the great astronomers got all their great ideas anyway.*

This comment may refer to the Apollo Skylab Solar Telescope and the fact that the Skylab 4 Astronauts on the third and final mission of 84 days staged a one-day "strike" because they felt overscheduled, overworked, and harassed

(Rockoff, Raasch & Peercy, 1985, pp. 9, 44). FIGURE 16 shows the Skylab 3 crew in front of the Apollo Telescope Mount for the solar telescope.

FIGURE 16. Skylab 3 crew (Owen Garriott, Jack Lousma, Alan Bean) in the Multiple Docking Adapter mockup-simulator, in front of the Apollo Telescope Mount control panel, NASA Photo.

The Astronaut Byron K. Lichtenberg {1988, pp. 2-3), who flew on the Shuttle and Spacelab linked the precepts of meaningful work and automation, and stated a philosophy with far-reaching implications for the design of space laboratory systems:

> *The workstations of the future should support automation and possibly artificial intelligence. The crew should have the benefit of working on intellectually valid tasks, not simply controlling a parameter like DC offset or gains. The philosophy should be to use the person in the higher-level control of experiments rather than closing the loop to control a specific parameter . . .. Research concepts that need to be explored include the degree to which automated systems control experiments.*

V. Findings

The Findings of the Northrop Grumman study and analysis team were:

A. Adding Levels to Maslow's Hierarchy of Human Needs

In adapting Maslow's Hierarchy of Human Needs to the lunar lander crew, it became necessary to add two levels to the original five: Physiological Needs for Survival and Quality of Life and Health.

B. Defining the Framework for the Crew Productivity FOM

It was feasible to define the framework for the CP FOM in a meaningful way based upon adaptation of the Maslow Hierarchy for identifying the metrics, leading the team to interpret the NASA HSIR verification requirements as a kind of template for the CP FOM metrics. This approach led to the first clause in the definition of CP, which is: *how well the system supports the crew to perform the mission.*

C. Distinguishing between the CP and the PLOC FOMS

Making the distinction about how to draw the boundary between CP and PLOC was the most critical decision in the process of developing this exercise. It required a close examination of the logic and rationale for each of the many decisions in the chain of reasoning.

D. Correlation with the NASA HSIR

At the two survival levels – biological and physiological – the HSIR was complete, and the team reserved adding any metrics to the framework CP FOM. At the Safety level, the team identified several gaps and proposed CP metrics to compensate. Similar results were found for Quality of Life, Crew as a Team, and Individual Needs metrics. There were no HSIR verification requirements for Self-Actualization, so the team recommended those metrics.

E. Adding Verification Methods

NASA provided four verification methods in the HSIR: *analysis, demonstration, inspection, and test*. The team found shortcomings in the lack of definitions for these verification methods. As a result, the team added two methods: *simulation* and *survey*, with definitions in order to complete their analysis.

F. Full Lunar Flight Regime

Developing the complete Lunar Sortie Mission timeline was a useful tool to assess the CP FOM across the full flight regime, both *in space* in microgravity and on the lunar surface in 1/6-G.

G. Lunar Dust

There was one NASA HSIR verification requirement that the team found inadequate, *Lunar Dust Contamination [HS3006DV]*, **because it specifies only "analysis" as the sole method of verification**. The team felt strongly that empirical testing is both necessary and feasible, and so wrote metrics for dust exclusion, rejection, removal, and disposal.

H. Configuration-specific Trades

For many of the CP FOM metrics and for all of the examples shown in this paper, it was possible to articulate a trade that interacts with the configuration. Generally, modifying the configuration to support the CP and safety will drive up mass and structural complexity. Conversely, always optimizing solely for the "big two" FOMs of mass and cost will inhibit crew effectiveness and put their health and lives at risk.

III. Conclusion

The adaptation of Maslow's Hierarchy of Needs to Crew Productivity and Crew Safety served as a worthwhile exercise to better understand the NASA HSIR, particularly the section that explicates the verification requirements. This exercise enabled the Northrop Grumman trade and analysis team to identify new CP metrics to complement the HSIR verification requirements. Applying the CP FOM metrics proved an effective way to identify and evaluate configuration trade issues for the Altair pressurized modules. This effort is a first step toward an overarching CP model that encompasses the full range of challenges and activities for space mission crews. Northrop Grumman is leveraging this internally funded work for application to other new spacecraft during the conceptual design phase and later during detailed design.

The long-term goal that emerged from this study is to develop a Human Systems-*optimized* habitable module configuration. This goal means moving in both a micro and a macro direction for configuration solutions satisfying CP requirements. The *micro* direction means building a suite of tools that can apply this framework to any human spacecraft. It entails developing a quantitative/logic approach to expressing the CP Interaction with the Subsystems and Configuration for the MDO Tool. It also means creating much more precise quantitative metrics and predictive methods for how the spacecraft design will interact with crew performance. The *macro* direction means developing a program management and organizational discipline that ensures the CP and Safety considerations can stand on their own. Under this system, all design and operations elements and changes will need to be evaluated for their impact upon the crew and their needs. The tools that derive from this CP FOM effort will serve to measure these interactions between crew needs and spacecraft design and operations.

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References

Aristotle (Circa 350 BCE). Rhetoric, Translated by W. Rhys Roberts, Compiled online by Lee Honeycutt, Ames Iowa: Iowa State University. http://www2.iastate.edu/~honeyl/Rhetoric/rhet2-23.html retrieved 7 Jan 2010.

Chakroborty, Shyama; Berry, James; Meade, Carl (2007). A Systematic Approach for the End-to-End Configuration Optimization of Manned Systems to the Moon, IAC-07-D3.3.05, *58th International Astronautical Congress*, Hyderabad India, September 24-28, 2007.

Cohen, Marc M. (2010 July). Trade and Analysis Study for the Altair Habitable Module Configuration, *AIAA 40th International Conference on Environmental Systems (ICES)*, AIAA-2010-6134, Barcelona Spain, 11-15 July 2009. Warrendale, Pennsylvania, USA: Society of Automotive Engineers.

Cohen, Marc M. (2009 July). Comparative Configurations for Lunar Lander Habitation Volumes: 2005-2008 (SAE 2009-01-2366). *39th International Conference on Environmental Systems (ICES*), Savannah, Georgia, USA, 12-16 July 2009. Warrendale, Pennsylvania, USA: Society of Automotive Engineers.

Dara-Abrams, Drew (2009). Extracting Cognitively Relevant Measures from Environmental Models, *Proceedings of the 7th International Space Syntax Symposium*, Stockholm, pp. 24:1-24:8. London: University College.

Douglas, William K., (1986). Human Performance Issues Arising from Manned Space Station Missions, NASA CR–3942 (NASA Scientific and Technical Information Branch, Washington, DC) 1986.

Helmreich, Robert L.; Wilhelm, John A.; & Foushee, H. Clayton (1988). Astronaut and Aquanaut Performance and Adjustment Behavioral Issues in Analogous Environments, SAE 881004, *18th ICES*, San Francisco, CA, July 11-13, 1988, Warrendale, PA: Society of Automotive Engineers.

Lichtenberg, Byron K. (1988). Concepts for Crew Experiment Interaction—Future Space Flights: Workstation Design and Requirements, SAE 881025, *18th ICES*, July 11-13, 1988, San Francisco, CA.

Maslow, Abraham (1962, 1968, 1999*). Toward a Psychology of Being*, 3rd Edition, New York: John Wiley and Sons.

NASA (2008, November 7). Constellation Program Design Specification for Natural Environments (DSNE), CxP-70023A, Change 001. Houston TX: Johnson Space Center.

NASA (2009, March 5). Constellation Architecture Requirements Document (CARD), NASA CxP-70000C, Houston TX: Johnson Space Center.

NASA (2009, March 6). Constellation Program Human System Integration Requirements, NASA CxP-70024C. Houston TX: Johnson Space Center.

Park, Hoon-Tae (2009). Boundary Effects on the Intelligibility and Predictability of Spatial Systems, *Proceedings of the 7th International Space Syntax Symposium*, Stockholm, pp. 86:1-86:14. London: University College.

Rockoff, L. A.; Raasch, R. F.; Peercy, R. L., Jr. (1985, June). *Space Station Crew Safety Alternatives Study—Final Report:* Volume III—Safety Impact of Human Factors, NASA CR-3856, Rockwell International, Washington DC: NASA Scientific and Technical Information Branch.

Turner, Alasdair; Doxa, Maria; O'Sullivan, David; Penn, Alan (2001). From Isovists to visibility graphs: a methodology for the analysis of architectural space, *Environment and Planning B: Planning and Design*, Vol. 28, pp. 103-121.

APPENDIX I – Definitions of PLOC and PLOM

A. Probabilistic Risk Assessment

The Probability of the Loss of Crew (PLOC) or the Probability of the Loss of Mission (PLOM) is the analytical calculation that either of these events occurs and should include a component failure except in the case of DFMR components. However, when calculating probability, the LOC and LOM are treated as mutually exclusive.

NASA CxP-70087 Constellation Program Reliability, Availability, and Maintainability Plan (Section 7) states:

> *The CxP 70000 document (CARD) has top-level LOC/LOM risk requirements defined for the different Design Reference Missions (DRMs) as well as Launch Probability requirements. The LOC/LOM requirement metrics include risk contributions from all sources including software failures, Micrometeoroid and Orbital Debris (MMOD), human errors, and catastrophic environmental events not associated with inherent hardware design reliability (p. 56).*

With respect to the definition of "significant/primary mission objectives" those are defined in the design reference missions (DRMs). The DRMs define the capabilities necessary to define "significant/primary mission objectives".

NASA goes one step further and includes a LOV (Loss of Vehicle) metric but in the Probabilistic calculations, if crew is on board, then LOV = LOC if it's empty (e.g. Altair sitting in LEO before an Ares I launch) then LOV = LOM.

1. *Probability of Loss of Crew (PLOC) FOM (Crew Safety)*

CxP-70000C, the Constellation Architecture Requirements Document (CARD) states:

a. **[Ex-0011-05]**
The Constellation Architecture shall limit the risk of Loss of Crew (LOC) for a Lunar Sortie mission to no greater than 1 in 100 (p. 45).

Applicable Design Reference Missions: Lunar Sortie Crew

Rationale: The 1 in 100 means a .01 (or 1%) probability of LOC during any Lunar Sortie mission. The baseline numbers were derived from a preliminary PRA within NASA-TM-2005-214062, NASA's Exploration Systems Architecture Study.

b. **[Ex-0011-07]**
The Constellation Architecture shall limit the risk of Loss of Crew (LOC) for a Lunar Outpost Crew mission to no greater than 1 in (TBD-EARD-018).

Applicable Design Reference Missions: Lunar Outpost Crew

Rationale: The 1 in (TBD-EARD-018) means a (TBD-EARD-018) (or (TBD-EARD-018) %) probability of LOC during any Lunar Outpost Crew mission (pp. 45-46).

NASA's statement of the purpose of the Human System Integration Requirements, NASA CxP-70024, puts crew safety in the context of human-rating the spacecraft:

> *The Constellation Program must meet NASA's Agency-level human rating requirements, which are intended to ensure crew survival without permanent disability (p. 12).*

The understanding of Loss of Crew (LOC) is death of one or more crew members or permanently debilitating injury to them

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2. *Probability of Loss of Mission (PLOM) FOM (Mission Success)*

CxP-70000C, the Constellation Architecture Requirements Document (CARD) states:

a. [Ex-0011-04] The Constellation Architecture shall limit the risk of Loss of Mission (LOM) for a Lunar Sortie mission to no greater than 1 in 20.

Applicable Design Reference Missions: Lunar Sortie Crew

Rationale: The 1 in 20 means a .05 (or 5%) probability of LOM during any Lunar Sortie mission. The baseline numbers were derived from a preliminary Probabilistic Risk Assessment (PRA) within NASA-TM-2005-214062, NASA's Exploration Systems Architecture Study (ESAS).

b. [Ex-0011-06] The Constellation Architecture shall limit the risk of Loss of Mission (LOM) for a Lunar Outpost Crew mission to no greater than 1 in (TBD-EARD-016).

Applicable Design Reference Missions: Lunar Outpost Crew

Rationale: The 1 in (TBD-EARD-016) means a (TBD-EARD-016) (or (TBD-EARD- 016) %) probability of LOM during any Lunar Outpost Crew mission (pp. 41-42).

The understanding of Loss of Mission (LOM) is Loss of ability or inability to complete significant/primary mission objectives, including LOC.

APPENDIX II – Crew Productivity Outline/Table of Contents

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