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Habot Lunar Crew Size, Skill Mix, and Time Model

Marilyn Dudley-Rowley and Thomas Gangale
OPS-Alaska

Lawrence Lemke and Marc M. Cohen
NASA-Ames Research Center

ABSTRACT

This study presents a projected crew task timeline and skill mix for the exploration of the lunar surface in the Habot mobile lunar habitat. It takes the approach of defining crew task sets for crews of 8, 6, and 4, crewmembers to carry out proportionate amounts of work, corresponding to how many crewmembers are on the mission. It provides for the division of responsibilities between crewmembers who perform EVA and IVA tasks, and between those who go on an excursion away from the base and those who remain at the base.

A particular feature of the model is that the amount of time devoted to science is set as a constant -- an inviolable amount of crew time that normal maintenance and operations work cannot erode. The importance of this capability arises from the International Space Station experience in which sometimes only 100 crew-minutes per day, or even less, has been available for science. The way the model handles this constant is that the amount of time available for maintenance, housekeeping and routine tasks must become flexible to accommodate the science requirements. The most important output of the model is that it suggests the degree to which it will be necessary to design routine tasks for automation and robotics, to free up and protect crew time to perform those high level scientific functions that only the human can perform.

INTRODUCTION: THE HABOT CONCEPT

“Habot” is a contraction of Habitat and Robot. It constitutes an innovative approach to combine human and robotic exploration capabilities. John Mankins introduced the Habitat Robot (Habot) concept in 2000 (Mankins, 2000; Mankins, 2001). The Advanced Concepts Office began funding Habot research in FY2003 at Ames Research Center. This research began by analyzing Habot in the tradition of mobile base concepts dating from 1971 (Cohen, 2003; Cohen, February, July, November 2004).

The Habot concept consists of a self-mobile habitat that lands autonomously at a specific landing zone on the Moon. It moves under its own power to a lunar base site. More Habots follow, touching down at the LZ and then moving to the base site. The Habots cluster together to form a base-habitat complex. They dock together, form pressure seals, and pressurize the complete living environment. After verifying that the Habot base is ready, the crew arrives on the Moon to occupy the base. After carrying out their mission, the crew returns to Earth. The Habots disconnect the base and migrate across the lunar surface to the next mobile lunar base site. There they cluster together again, reconnect to form the base, and verify readiness. A new Habot logistics module may land at the second base site to resupply consumables and bring new equipment. The second crew arrives to carry out the next mission. The parameters of the Habot mission are as follows. The Habots launch to the Moon over a period of one to two years. After verification of the first Habot mobile base, the first crew arrives. The nominal mission timeline is 100 Earth-Days, allocated to a primary mission of two lunar day/night cycles (59.06 Earth-Days).[1]

There are 8 Earth-Days planned margin for lift-off from the Moon and 36 Earth-Days’ reserve capability. The minimal planned crew size is four astronauts. The baseline number of crew missions is 10, for a total planned crew time of 560 Earth-Days, with a total capability for 1000 crew days on the Moon during those 10 missions.

THE CONCERN FOR PRELIMINARY MASS BUDGET

A fundamental driver behind the Habot concept is that -- aside from the conventional methods of reducing launch mass and mission scope -- the only certain way that NASA or other space agencies know to control or

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[1] Used herein for modeling and conceptualization purposes only. A more applicable- scenario would be 90 or 120 Earth-Days (3 or 4 lunations) – for optimum sun angle for landings of potential rescue missions.

reduce costs as a large percentage of a mission or program is mass production.

Despite various tools to chip away at costs such as value-engineering, earned value management, and life-cycle cost analysis, there is no liberating miracle waiting in the shadows to reduce launch costs or development costs by half or more. The only way to reduce fabrication and operating costs over the long term is to make a vehicle that is simple and reliably produced in significant numbers to achieve an economy of scale. That is the open secret of the Russian Soyuz production line at RKK Energia. The goal for mass to Low Earth Orbit is to launch the Habots on the new generation of conventional commercial launchers such as the Delta IV or the Atlas V. One possible alternative is to develop a new launch vehicle to support the Crew Exploration Vehicle/Project Constellation and the Habot.

To make this goal possible, the mass of each Habot, including lander and mobility system should be limited to an upper figure not to exceed 10 mTons, and preferably less. A preliminary mass budget appears in Table 1.The original concept for the Habot aimed for a mass budget per unit of 3 to 5 mTons. This mass limit would be convenient for launch by existing conventional expendable rockets. However, as a preliminary analysis the 5 mTon mass budget per unit has small margin and overall is extremely tight for a nominal 100-day mission by the crew of 4 (Cohen, November 2004).

A more realistic Habot mass budget baseline may be closer to 10 mTon (10,000 kg), separate from the descent engine unit. Table 1 presents a preliminary mass budget for this Habot unit, working with the range of masses that Mankins envisioned. These bounding values appear in the top line for the pressurized habitat and its contents, including outfitting. However, these mass values are simply too small to provide the complete system for one Habot with a crew of 4 over 100 days. The lines below the pressurized habitat indicate the additional elements that would be needed. As stated above, this mass budget is uncomfortably tight, and an important outcome of the Habot Project will be to find ways to meet it and to come in below it, if possible.

This analysis leads the way to collateral questions of mass and capacity. How many crew members can this Habot system support and sustain on a lunar mission? Because of the modularity of the Habot system it leads to a different formulation of the question: How many Habots will be necessary to support the required crew? The next question is: What is the optimal distribution of equipment, supplies, and mass among these several Habot units? The answer to this second question will demand a very detailed exercise in design optimization. The "correct" answers to any of these questions are, alas, beyond the scope of this report. However, consideration of them does point to directions to follow in our modeling attempts. To begin to pave the way for answers that address concerns about preliminary mass budget, a more in-depth discussion of the lunar Habot mission and different crew size, skill mix, and time parameters is required.

BROAD OUTLINE OF THE HABOT LUNAR MISSION CONCEPT

The issue that the Habot addresses as a human/robotic architecture is how best to use the cost and effort of very expensive crew time on the lunar or planetary surface. Gordon Woodcock of Boeing led a notable study on the use of lunar surface robotics that took into consideration what were the best uses for humans and for robots (Woodcock *et al.,* 1990). Race, Criswell and Rummel posed the question this way: "Can a habitat be deployed or built robotically on the surface and its operational readiness be fully verified prior to sending humans there (2003, p. 7)?

After the crew completes their Habot mission on the Moon, they return to the Earth, in a separate, dedicated vehicle. In the following weeks or months, the Habots separate from one another, and move across the lunar surface to a new location of scientific interest, and a second crew arrives. It is also possible for the crew to travel with the Habots. The crewmembers will also use individual Habot units as pressurized rovers to explore the lunar environment. In Figure 1, the articulated legs carry manipulator devices that can pick up rocks. A hexagonal cluster of Habots appears in the middle ground at the right.

Within the baseline 100 Earth-Days, the nominal Habot mission would call for a crew of astronauts to spend 2 complete lunar day/night cycles (lunations) – 59 Earth-Days – on the lunar surface, with a planned 8-day margin for a total planned mission duration range of 67 Earth-Days.

The 33 additional days[2] would constitute a reserve capacity. In Mankins' construct, the Habot infrastructure should serve a baseline of 10 crews rotating through the Habot base, each time in a different location on the lunar surface, for a total of 1000 Earth-Days of occupancy, which approaches the overall time necessary for a human Mars mission.[3] So, this baseline implies a total productive occupancy of 590 Earth-Days with a total planned margin of 80 Earth-Days.

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[2] In this modeling scenario, a Moon-stranded crew, holding on through these reserve days, could still be retrieved by a rescue vehicle, but its pilot would be coming in with the sun in her eyes (assuming the stranded crew had landed on Day One in lunar morning.)

[3] A point supportive of "the Moon as Mars rehearsal" profile.

TABLE 1. Preliminary Habot Mass Budget

Component	Min Mass, mTon	Max Mass, mTon	Remarks
Pressurized Habitat Pressure Vessel Structure, Life Support & Thermal Control, Habitability Accommodations, Operational Systems	3.0	5.0	Habitat is fully pre-integrated before launch.
Exterior Protection Radiation Shielding, Thermal Protection, Micrometeoroid Protection	2.0	2.8	Exterior protection is a multifunction system.
Mobility System Habot "Unibody" consisting of Base frame, 6 legs, motors and mechanisms.	8.0	1.0	Mobility system requires much further study.
Energy Systems Solar Cells, batteries, SSP/"Powerbot" Microwave Antenna, Possible RTG	0.5	0.8	Energy system requires a system and optimization study.
Margin	1.0	0.4	
Limits (not totals)	7.3	10.0	

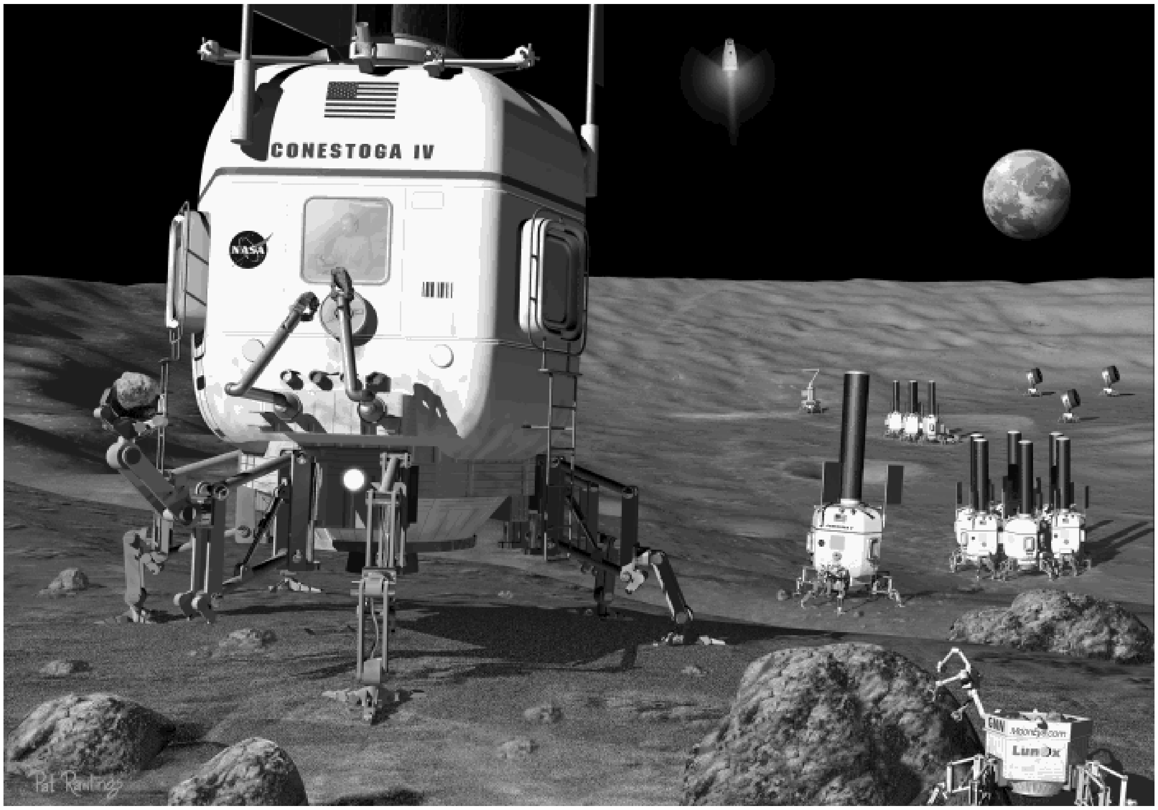

Figure 1. Artist's rendering of the Habot Mobile Lunar Base concept. Pat Rawlings, artist. Courtesy of Neville Marzwell, NASA-JPL and John Mankins, NASA HQ.

Total reserve would be 330 Earth-Days. Of course, in the event that the crew had a problem lifting off from the Moon, and no rescue mission was sent, it would be possible to resupply the crew from the Earth, almost anywhere on the Moon.

MISSON ACTIVITIES

During the lunar sunlight period, the crew will conduct the exploration portion of the mission. During the lunar day, the Habot units will make maximum use of their walking capability. Thus, the Habot units will move separately across the lunar terrain, meeting and docking as necessary for various crew operations and procedures. As the lunar day approaches its end, the Habots will cluster together and dock, creating a continuous pressurized habitable environment. During the lunar night, the crew will stay primarily in this united lunar base, and pursue work that they can perform in the laboratories with minimal need for EVA or rover excursions. They will conduct scientific work in the laboratory unit and prepare scientific and technical publications.

EXCLUSION

The Habot is not intended to serve as a crewed spacecraft in LEO, in cislunar space or in lunar orbit. It is intended for crew use only on the lunar surface. The crew will travel to the moon in a separate vehicle that is optimized to serve as a crew descent/ascent and Earth Return (ERV) vehicle. However, this vehicle or set of vehicles could derive from the Apollo architecture, but make common use of the Habot six- legged lander for the lunar descent stage. This crewed lunar transportation vehicle is not part of the Habot study.

MISSION PROFILE

The Habot mission profile incorporates several key features that support the goals of the “Early Human Return to the Moon” initiative. This profile encompasses strategies for launch, transportation to the moon, landing, the mass budget, energy system, mobility system, and the Habot module types.

LAUNCH OPPORTUNITIES

The Habot mission will be able to launch to the Moon, land and deploy at almost any time in the lunar cycle. The preferred landing opportunity is the beginning of the lunar day, as with the Apollo program. During the lunar dawn, the environment is making a thermal transition from the profound cold of the lunar night and starting to warm up into a briefly benign temperature range, before heating up to the full impact of the lunar day.

CISLUNAR TRANSPORTATION

In the initial concept for the Habot, the mission launches to Low Earth Orbit on a conventional launcher in the size range of the Delta 4, Atlas V or Ariane V, or their extended variants, with payload in the 20 to 40 mTon range. The trans-lunar injection stage launches on a second vehicle, then rendezvous with the Habot in LEO. The first, Habot launch package includes its own lunar descent and landing stage. The hope behind this approach is to eliminate the need for a large new heavy lift vehicle in the 100 + mTon payload range.

LANDING

After trans-lunar injection (TLI), the Habot stack may go into lunar orbit or land by a direct descent à la the Surveyor program. The TLI vehicle (TLIV) separates from the Habot, which begins descent under its own power, and lands on six articulated legs. After landing, it squats close to the surface, detaches and drops the descent engine unit. Then, it stands up and walks away from the landing zone.

ENERGY SYSTEM

The energy system incorporates several elements. In Figure 1 showing the Habot, a cylindrical tower atop the module carries photovoltaic cells to provide constant “lifeline” power during the lunar day. Atop this tower sits a parabolic dish antenna to receive beamed microwave or laser power. A possible back-up option for “lifeline” power would be to install a radio-thermal generator (RTG) at the base of the tower. Safe disposal of spent nuclear fuel will be required to make this concept viable. However, providing sufficient and reliable energy throughout the lunar day/night cycle remains one of the technological “tall poles” to make any mobile base concept succeed, and will demand much more research and development. In addition to the Habot approaches to energy systems are two possible alternatives using beamed energy, proposed by Williams, *et al.*, (Figure 2) and by Cataldo (Figure 3).

Williams *et al.* (1993) proposed such a scheme to power a lunar rover by beaming laser power from a solar power satellite to a parabolic receiver on a pressurized rover. The primary source of this power will be a space solar power satellite in a lunar-synchronous orbit that would keep the satellite above the rover at all times which would provide power in the 100 to 300 KW range. However, it is not clear how it would supply power when in darkness on the Moon. Such a concept might be more viable in combination with solar power satellites at the lunar L1 or L2 point or both, The Williams concept appears in Figure 2. The large laser beam antenna is mounted in the center of the cylindrical portion and the small antenna to the front is for communications. A second power alternative would be a nuclear reactor (Figure 3) mounted on a Habot, Rover, or Mobitat chassis.

Figure 3 shows Robert Cataldo’s mobile Lunar Reactor concept, following and powering a pressurized rover. This “Powerbot” would follow the Habots from a distance of several kilometers away, and beam power in the 100 to 150 KW range by microwave to the same antenna that would serve for solar satellite power.

MOBILITY SYSTEM

Although the initial artist’s concept in Figure 1 for the Habot presents the walking “Conestoga” idea, this Habot study is not presupposing any specific mobility system. Only after analyzing all of the necessary functions and components of the Habot habitat and base configurations, will it be reasonable to develop requirements for the mobility system. Nevertheless,

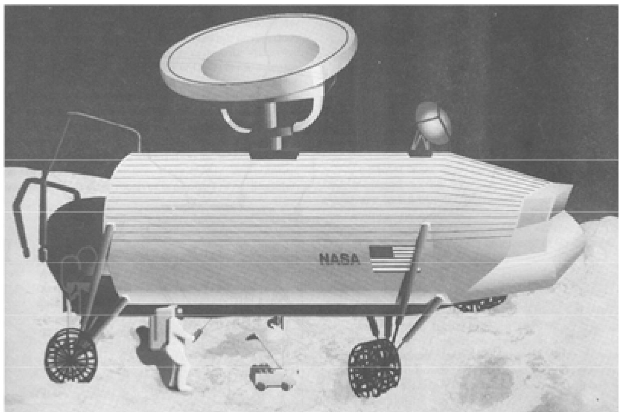

Figure 2. Williams *et al.'s* concept for a lunar rover powered by space solar power satellite via laser beam to the dish antenna on top. Courtesy of NASA-Langley Research Center.

Figure 3. Robert Cataldo's concept for a "follower" nuclear reactor rover. Courtesy of Robert Cataldo, NASA-Glenn Research Center.

since the Habot is closely associated with the walking model, it is appropriate to describe the walking aspect. The Habot will have a very modest walking speed, that need not exceed 5 km/hr. There is no advantage in designing it to move "fast" if that translates into a huge energy burden that will be used for only short periods of time. The baseline is a maximum of 2 km/hr with a crew driver over smooth, level terrain. On rough terrain, the speed will be reduced to whatever is safe, perhaps as slow as .5 km/hr on slopes or rough terrain. The baseline speed without a crew on board is 0.5 km/hr.

All Habots will land uncrewed. They will walk or roll themselves about 10 km away from the LZ to a base deployment site. There, the Habots will dock together and await the arrival of the crew. When the crew lands in the descent/ascent vehicle, they travel on the same walking system to the base deployment site. There, the crew transfers via a docking tunnel in a shirtsleeve environment to the united base. As a contingency, the descent/ascent vehicle will carry EVA suits the crew can use to make the transfer. Additional contingencies if the descent/ascent vehicle is unable to walk, a Habot from the base will come to the LZ and pick up the crew. The final fall-back mode is that the crew can walk the 10 km EVA to the base.

THE IMPORTANCE OF CREW SIZE, SKILL MIX AND TIME

It is important to establish why this paper addresses crew size, skill mix and time as founding factors for creating a model for lunar exploration. As we have described, a Habot lunar mission has a level of complexity and productivity that surpasses that of what has been demonstrated heretofore by space station missions. And, this complexity and productivity must be considered at the outset of mission planning because of its impact on mass budget. Along with prior space station experience, the lesson of the International Space Station is quite dramatic: with 3 crew members on board, they spend almost all their time just maintaining and operating the station, with very little time – minutes per day, really – to perform science. However, Habot lunar missions will be launched to the Moon to make exploration and to perform scientific work, not to re-invent the wheel of staying alive in extraterrestrial environments. A rough mathematical principle is suggested from the empirical evidence from space station missions. Crew productivity will be inversely proportional to the amount of time crews must spend on just staying alive: performing maintenance, repairs, cleaning, and other housekeeping tasks.

DISCUSSION AND CONCLUSION

This initial modeling effort of the Habot study is considering crew sizes from 4 up to 8 crewmembers for the purpose of assessing the relationship between crew size and productivity. The crewmembers would occupy and utilize several Habot modules. Just how many has yet to be determined.

The authors examined two modalities of sizes of missions numbering 4-, 6-, and 8-person crews. Those modalities were 1) IVA Habot missions that did not require extensive EVA operations with substantial rover excursions, and 2) missions that *did* make extensive use of EVA operations and rover excursions (EVA). Tables 2-7 give mock-up breakouts of essential Habot mission chores and types and numbers of crewmembers. All profiles of missions have the same type of basic chore requirements for operations in or near Habot facilities. These are reflected in sections B, C, D, and F.

Section B involves sleeping, hygiene, and changing clothes, food preparation, eating, and clean-up, as well as daily personal time. Section C exhibits a plethora of necessary maintenance chores and inspection details unique to living and working aboard spacecraft. These are as follow:

- Structural integrity and airlocks
- Life support systems and issues
- Power plant
- ISRU equipment
- Mobility equipment
- Stores and stocks
- Communications and related equipment
- Food preparation equipment
- Hygiene and waste disposal equipment
- Bioisolation and antibacterial systems
- Contingency maintenance
- Spacesuits and EVA equipment
- Health maintenance systems
- Recreation and leisure systems
- Sleeping quarters maintenance
- Power distribution
- Laboratory maintenance

Sections D and F treat chores unique to performing the exploration and scientific mission. These contain the types of chores requiring 6-8 or even more hours of crew time that must be more or less constant (K) and non-erodable. Exploration and science constants occur in terms of laboratory experiments, data recording and archiving, near-Habot and excursion sample collection, handling, and photography and imagery. In “mocking up” these different profiles to give exploration and science precedence on these Habot lunar scenarios, a second area of inviolability emerged and that is a crewmember’s personal time (Sections B and E). This category of activity has been identified as a hot-button issue over and over again in the space station experience. When “just staying alive” was a minute-by-minute concern, even sleep was expendable and its forfeiture came at a premium in terms of conflicts, accidents, and mental strain. Astronauts truly are subsystems of the mission and must be regarded in some respects as any delicate piece of life-maintaining equipment that must be preserved.

Extensive EVA and rover operations (Tables 5-7) make the Habot lunar mission scenario even more complex. Added complexity calls for more equipment and systems and poses a greater necessity for larger crew sizes. Both types of additions raise the mass budget of the Habot mission. Complexity will increase when, in preliminary mission planning, planners will attempt to abide by a set of founding assumptions and ground rules developed from prior space experience (see Appendix). From the outset, in constructing these tables, the authors attempted to toe the line on EVA monitoring by IVA personnel and in relation to EVA crews (so that no crewmember would ever go on an EVA excursion alone). Every new layer of concern changed how crewmembers could be tasked with chores, for how long, in what combinations of crew, and in what setting. The more this type of complexity emerged, the greater the need for larger crews. In considering the matter of rover deployment, for example, when two rovers are deployed simultaneously for mutual backup, at least three crewmembers are required on deployment – assuming that one person can operate one of the rovers by himself or herself. However, it would be far better to have a backup driver/navigator in each rover: to ensure proper operation of the airlock, to ensure communications if one of the rovers should have trouble, a power outage, or the like. If, according to the founding assumptions and “ground rules” in the Appendix, the main Habot base-cluster is *never* left untended, then at least three persons are required there to support an EVA activity. A fourth crewmember at the main base can easily be justified for better balance in work and sleep shifts, should any monitoring need to be done on a semi-continuous basis. When emergencies and contingencies are considered (*i.e.,* the possible injury or illness of one or more crew persons), the need for more than a minimal crew is evident.

The Habot lunar mission concept is still very much a work in progress. However, the authors’ exercise to date in modeling over different crew sizes, skill mixes, and IVA and EVA modalities point up an important consideration, and that is: we must do better than just staying alive in extraterrestrial environments. Our driving purpose for venturing on increasingly longer duration missions is exploration and science.

One strategy we have considered to facilitate an expanded model can best be described in four steps:

1. DESIGN: Space agencies must design the vehicles and habitats to be highly reliable and safe, requiring minimal maintenance. However, all aspects of the systems that are at more than *de minimus* probabilities to fail must be as completely maintainable as possible. Ideally, it will be possible to perform maintenance and repair by automation or robotics instead of by crew labor. However, nearly all repairable systems must have a manual override/crew repairable option.

2. INTEGRATION: For this design concept to work, it will be essential to install sensors in virtually all structural, mechanical, environmental, electrical, and operational components and systems of the vehicles and habitats that could fail. This system

is sometimes described as Real-time Automated Diagnostics (RAD) or Integrated Vehicle Health Maintenance System (IVHM). This system will include filters, multiplexers, relays, *etc.* to sort and deliver the data to the Central Automation Operating System for the entire vehicle or habitat.

3. ALERT AND DISPLAY: This system must present the analysis of data to the crew and mission control in a concise and rapid fashion. The data presented to the crew in this real-time situation, which may be a life safety crisis, must be accurate, precise, and sufficiently complete for them to quickly appreciate and evaluate the situation. The Alert and Display System must offer or prescribe the appropriate course and effect corrective action to the crew.

4. CORRECTIVE ACTION: The crew must have the capability to take corrective action. They must have the knowledge, tools, instruments, equipment, supplies, parts, and materials to do maintenance or make repairs. The knowledge, instructions, and guidance must come from the Alert and Display capability in Step 3. However, the crew will need some way to maintain their skills (*e.g.,* surgery or integrated circuit testing and repair), while perhaps not using them for, say, two years. There are other contingency factors such as gaining access to a damaged compartment or rescuing a disabled rover.

This four-step strategy opens additional vistas on modeling or simulating a design-integration-alert/display-corrective action scenario. It would begin with perhaps just one or two failure modes, and run them through the four steps. The goal would be to find a way to define the point at which automation and robotics might try to solve the problem and then the point when the crew becomes involved. These more in-depth modeling exercises are beyond the scope of the current report. However, their consideration points the way for our next steps in the Habot lunar mission concept.

TABLE 2. 8 Crew Members, All IVA

A.	CrewPos	Pilot/ Engr 1	Pilot/ Engr 2	Physic/ Sci 1	Physic/ Sci 2	Sci/ Physic 1	Sci/ Physic 2	Engr/ Pilot 1	Engr/ Pilot 2	CrHr
	BASE FUNCTIONS									
B.	Personal Time at Base									116.0
B.1.	SlDrHy	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	72.0
B.2	FoodEatCl	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	20.0
B.3.	Leisure	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	24.0
C.	Inspect and Maintain									10.8
C.1.	StruxAir	0.3	0.3							0.6
C.2.	ECLSAtTh	0.3	0.3							0.6
C.3.	PowerSys	0.3	0.3							0.6
C.4.	ISRUSys	0.3	0.3							0.6
C.5.	MobSys	0.3	0.3							0.6
C.6.	StoresStk	0.3	0.3							0.6
C.7.	CommoDat	0.3	0.3							0.6
C.8.	FoodSys	0.3	0.3							0.6
C.9.	Hyg/Waste	0.3	0.3							0.6
C.10.	Bioiso/Bac	0.3	0.3							0.6
C.11.	ContMaint	0.3	0.3							0.6
C.12.	SuitsEVA	0.3	0.3							0.6
C.13.	HealthSys	0.3	0.3							0.6
C.14.	RecSys	0.3	0.3							0.6
C.15.	SleepQtr	0.3	0.3							0.6
C.16.	PowerDist	0.3	0.3							0.6
C.17.	LabMaint	0.3	0.3							0.6
D.	Perform Mission									21.3
D.1.	PlanOrg	1.0								1.0
D.2.	**LabSciK**			1.6	1.6	1.6	1.6	1.6	1.6	9.6
D.3.	DonDoffPre									0.0
D.4.	EVA									0.0
D.5.	**ArchivK**			1.6	1.6	1.6	1.6	1.6	1.6	9.6
D.6.	ReportPrep	1.1								1.1
F.	Operations									43.9
F.1.	Drive	2.0	3.0						1.0	6.0
F.2.	NavComm			1.5	0.5	1.0	0.5	1.5		5.0
F.3.	**SampleK**			1.6	1.6	1.6	1.6	1.6	1.6	9.6
F.4.	**HandlingK**			1.6	1.6	1.6	1.6	1.6	1.6	9.6
F.5.	**PhotoK**			1.6	1.6	1.6	1.6	1.6	1.6	9.6
F.6.	DonDoffPre									0.0
F.7.	EVA									0.0
F.8.	Other		1.1		1.0	0.5	1.0		0.5	4.1
INDIV SUBTOTALS		24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	192.0

Based on 192 crew-hours over a 24-hour period

TABLE 3. 6 Crew Members, All IVA

A.	CrewPos	Pilot/ Engr 1	Physic/ Sci 1	Sci/ Physic 1	Sci/ Physic 2	Engr/ Pilot 1	Engr/ Pilot 2	CrHr
	BASE FUNCTIONS							
B.	Personal Time at Base							86.0
B.1.	SlDrHy	9.0	9.0	9.0	9.0	9.0	9.0	54.0
B.2	FoodEatCl	2.5	2.5	2.0	2.5	2.0	2.5	14.0
B.3.	Leisure	3.0	3.0	3.0	3.0	3.0	3.0	18.0
C.	Inspect and Maintain							6.0
C.1.	StruxAir	0.4						0.4
C.2.	ECLSAtTh	0.4						0.4
C.3.	PowerSys	0.4						0.4
C.4.	ISRUSys	0.4						0.4
C.5.	MobSys	0.4						0.4
C.6.	StoresStk	0.4						0.4
C.7.	CommoDat	0.4						0.4
C.8.	FoodSys	0.4						0.4
C.9.	Hyg/Waste	0.4						0.4
C.10.	Bioiso/Bac	0.4						0.4
C.11.	ContMaint	0.4						0.4
C.12.	SuitsEVA	0.4						0.4
C.13.	HealthSys	0.4						0.4
C.14.	RecSys	0.4						0.4
C.15.	SleepQtr	0.4						0.4
C.16.	PowerDist	0.4						0.4
C.17.	LabMaint	0.4						0.4
D.	Perform Mission							16.0
D.1.	PlanOrg	0.5				0.5		1.0
D.2.	**LabSciK**		1.4	1.4	1.4	1.4	1.4	7.0
D.3.	DonDoffPre							0.0
D.4.	EVA							0.0
D.5.	**ArchivK**		1.4	1.4	1.4	1.4	1.4	7.0
D.6.	ReportPrep			0.5		0.5		1.0
F.	Operations							36.0
F.1.	Drive	2.5				2.0	1.5	6.0
F.2.	NavComm			1.5	2.5		1.0	5.0
F.3.	**SampleK**		1.4	1.4	1.4	1.4	1.4	7.0
F.4.	**HandlingK**		1.4	1.4	1.4	1.4	1.4	7.0
F.5.	**PhotoK**		1.4	1.4	1.4	1.4	1.4	7.0
F.6.	DonDoffPre							0.0
F.7.	EVA							0.0
F.8.	Other	0.5	2.5	1.0				4.0
INDIV SUBTOTALS		24.0	24.0	24.0	24.0	24.0	24.0	144.0

Based on 144 crew-hours over a 24-hour period.

TABLE 4. 4 Crew Members, All IVA

A.	CrewPos	Pilot/ Engr 1	Engr/ Pilot 1	Physic/ Sci 1	Sci/ Physic 1	CrHr
BASE FUNCTIONS						
B.		Personal Time at Base				58.0
B.1.	SlDrHy	9.0	9.0	9.0	9.0	36.0
B.2	FoodEatCl	2.5	2.5	2.5	2.5	10.0
B.3.	Leisure	3.0	3.0	3.0	3.0	12.0
C.	Inspect and Maintain					4.9
C.1.	StruxAir	0.3				0.3
C.2.	ECLSAtTh	0.3				0.3
C.3.	PowerSys	0.3				0.3
C.4.	ISRUSys	0.3				0.3
C.5.	MobSys	0.3				0.3
C.6.	StoresStk	0.3				0.3
C.7.	CommoDat	0.3				0.3
C.8.	FoodSys	0.3				0.3
C.9.	Hyg/Waste	0.3				0.3
C.10.	Bioiso/Bac	0.3				0.3
C.11.	ContMaint	0.3				0.3
C.12.	SuitsEVA	0.3				0.3
C.13.	HealthSys	0.3				0.3
C.14.	RecSys	0.3				0.3
C.15.	SleepQtr	0.3				0.3
C.16.	PowerDist	0.3				0.3
C.17.	LabMaint	0.3				0.3
D.	Perform Mission					14.1
D.1.	PlanOrg	1.1				1.1
D.2.	**LabSciK**		2.0	2.0	2.0	6.0
D.3.	DonDoffPre					0.0
D.4.	EVA					0.0
D.5.	**ArchivK**		2.0	2.0	2.0	6.0
D.6.	ReportPrep	1.0				1.0
F.	Operations					19.0
F.1.	Drive	0.5				0.5
F.2.	NavComm				0.5	0.5
F.3.	**SampleK**		2.0	2.0	2.0	6.0
F.4.	**HandlingK**		2.0	2.0	2.0	6.0
F.5.	**PhotoK**	2.0	1.5	1.5	1.0	6.0
F.6.	DonDoffPre					0.0
F.7.	EVA					0.0
F.8.	Other					0.0
INDIV SUBTOTALS		24.0	24.0	24.0	24.0	96.0

Based on 96 crew-hours over a 24-hour period.

TABLE 5. 8 Crew Members, 4 EVA

A.	CrewPos	Pilot/ Engr 1	Pilot/ Engr 2	Physic/ Sci 1	Physic/ Sci 2	Sci/ Physic 1	Sci/ Physic 2	Engr/ Pilot 1	Engr/ Pilot 2	CrHr
	AT HABOT BASE									
B.	Personal Time at Base									56.0
B.1.	SlDrHy	9.0		9.0		9.0		9.0		36.0
B.2	FoodEatCl	2.0		2.0		2.0		2.0		8.0
B.3.	Leisure	3.0		3.0		3.0		3.0		12.0
C.	Inspect and Maintain									15.5
C.1.	StruxAir	0.5								0.5
C.2.	ECLSAtTh			2.0						2.0
C.3.	PowerSys	0.5								0.5
C.4.	ISRUSys			0.5						0.5
C.5.	MobSys	1.5								1.5
C.6.	StoresStk			0.5						0.5
C.7.	CommDat	0.5								0.5
C.8.	FoodSys					0.5				0.5
C.9.	Hyg/Waste					0.5				0.5
C.10.	Bioiso/Bac			0.5						0.5
C.11.	ContMaint	0.5						2.0		2.5
C.12.	SuitsEVA	0.5						1.0		1.5
C.13.	HealthSys			0.5						0.5
C.14.	RecSys			0.5						0.5
C.15.	SleepQtr	0.5		0.5		0.5		0.5		2.0
C.16.	PowerDist							0.5		0.5
C.17.	LabMaint					0.5				0.5
D.	Perform Mission									24.5
D.1.	PlanOrg	1.0		0.5		0.5		0.5		2.5
D.2.	**LabSciK**			3.5		5.5				9.0
D.3.	DonDoffPre									0.0
D.4.	EVA									0.0
D.5.	**ArchivK**			1.0		1.0				2.0
D.6.	ReportPrep					1.0		1.0		2.0
D.7.	MonEVA	4.5						4.5		9.0
BASE SUBTOTALS		24.0		24.0		24.0		24.0		96.0
	ON EVA EXCURSION									
E.	Personal Time: Excursion									48.0
E.1.	SlDrHy		9.0		9.0		9.0		9.0	36.0
E.2	FoodEatCl		2.0		2.0		2.0		2.0	8.0
E.3	Leisure		1.0		1.0		1.0		1.0	4.0
F.	Operations									48.0
F.1.	PlanOrg									0.0
F.2.	Drive		3.5		3.5					7.0
F.3.	NavComm		3.5		3.5					7.0
F.5.	**SampleK**						4.0			4.0
F.6.	**HandlingK**						2.0		2.0	4.0
F.7.	**PhotoK**								4.0	4.0
F.8.	DonDoffPre		2.0		2.0		2.0		2.0	8.0
F.9.	EVA Trav						1.0		1.0	2.0
F.10	EVA Tasks						1.0		1.0	2.0
F.11	InspMaint		3.0		3.0					6.0
F.12	Other						2.0		2.0	4.0
EVA SUBTOTALS			24.0		24.0		24.0		24.0	96.0

Based on 192 crew-hours over a 24-hour period.

TABLE 6. 6 Crew Members, 3 EVA

A.	CrewPos	Pilot/ Engr 1	Physic/ Sci 1	Sci/ Physic 1	Sci/ Physic 2	Engr/ Pilot 1	Engr/ Pilot 2	CrHr
	AT HABOT BASE							
B.	Personal Time at Base							56.0
B.1.	SlDrHy	9.0	9.0	9.0		9.0		36.0
B.2	FoodEatCl	2.0	2.0	2.0		2.0		8.0
B.3.	Leisure	3.0	3.0	3.0		3.0		12.0
C.	Inspect and Maintain							12.5
C.1.	StruxAir	0.5						0.5
C.2.	ECLSAtTh					2.0		2.0
C.3.	PowerSys	0.5						0.5
C.4.	ISRUSys	0.5						0.5
C.5.	MobSys	1.5						1.5
C.6.	StoresStk			0.5				0.5
C.7.	CommDat	0.5						0.5
C.8.	FoodSys			0.5				0.5
C.9.	Hyg/Waste			0.5				0.5
C.10.	Bioiso/Bac			0.5				0.5
C.11.	ContMaint							0.0
C.12.	SuitsEVA	1.0				0.5		1.5
C.13.	HealthSys					0.5		0.5
C.14.	RecSys					0.5		0.5
C.15.	SleepQtr	0.5		0.5		0.5		1.5
C.16.	PowerDist					0.5		0.5
C.17.	LabMaint			0.5				0.5
D.	Perform Mission							17.5
D.1.	PlanOrg	0.5		0.5		0.5		1.5
D.2.	**LabSciK**			5.0				5.0
D.3.	DonDoffPre							0.0
D.4.	EVA							0.0
D.5.	**ArchivK**			1.0				1.0
D.6.	ReportPrep			0.5		0.5		1.0
D.7.	MonEVA	4.5				4.5		9.0
BASE SUBTOTALS		24.0		24.0		24.0		72.0
	ON EVA EXCURSION							
E.	Personal Time: Excursion							36.0
E.1.	SlDrHy		9.0		9.0		9.0	27.0
E.2	FoodEatCl		2.0		2.0		2.0	6.0
E.3	Leisure		1.0		1.0		1.0	3.0
F.	Operations							36.0
F.1.	PlanOrg							0.0
F.2.	Drive		3.5					3.5
F.3.	NavComm		3.5					3.5
F.5.	**SampleK**				4.0			4.0
F.6.	**HandlingK**				2.0		2.0	4.0
F.7.	**PhotoK**						4.0	4.0
F.8.	DonDoffPre		2.0		2.0		2.0	6.0
F.9.	EVA Trav				1.0		1.0	2.0
F.10	EVA Tasks				1.0		1.0	2.0
F.11	InspMaint		3.0					3.0
F.12	Other				2.0		2.0	4.0
EVA SUBTOTALS			24.0		24.0		24.0	72.0

Based on 144 crew-hours over a 24-hour period.

TABLE 7. 4 Crew Members, 4 EVA

A.	CrewPos	Pilot/ Engr 1	Engr/ Pilot 1	Physic/ Sci 1	Sci/ Physic 1	CrHr
	AT HABOT BASE					
B.	Personal Time at Base					28.0
B.1.	SlDrHy	9.0		9.0		18.0
B.2	FoodEatCl	2.0		2.0		4.0
B.3.	Leisure	3.0		3.0		6.0
C.	Inspect and Maintain					5.5
C.1.	StruxAir	1.0				1.0
C.2.	ECLSAtTh					0.0
C.3.	PowerSys					0.0
C.4.	ISRUSys					0.0
C.5.	MobSys					0.0
C.6.	StoresStk					0.0
C.7.	CommDat					0.0
C.8.	FoodSys					0.0
C.9.	Hyg/Waste					0.0
C.10.	Bioiso/Bac					0.0
C.11.	ContMaint	2.5				2.5
C.12.	SuitsEVA	1.0				1.0
C.13.	HealthSys					0.0
C.14.	RecSys					0.0
C.15.	SleepQtr	0.5		0.5		1.0
C.16.	PowerDist					0.0
C.17.	LabMaint					0.0
D.	Perform Mission					14.5
D.1.	PlanOrg	0.5		0.5		1.0
D.2.	**LabSciK**			3.5		3.5
D.3.	DonDoffPre					0.0
D.4.	EVA					0.0
D.5.	**ArchivK**			0.5		0.5
D.6.	ReportPrep			0.5		0.5
D.7.	MonEVA	4.5		4.5		9.0
BASE SUBTOTALS		24.0		24.0		48.0
	ON EVA EXCURSION					
E.	Personal Time: Excursion					24.0
E.1.	SlDrHy		9.0		9.0	18.0
E.2	FoodEatCl		2.0		2.0	4.0
E.3	Leisure		1.0		1.0	2.0
F.	Operations					24.0
F.1.	PlanOrg					0.0
F.2.	Drive				3.5	3.5
F.3.	NavComm				3.5	3.5
F.5.	**SampleK**					0.0
F.6.	**HandlingK**		2.0			2.0
F.7.	**PhotoK**		4.0			4.0
F.8.	DonDoffPre		2.0		2.0	4.0
F.9.	EVA Trav		1.0			1.0
F.10	EVA Tasks		1.0			1.0
F.11	InspMaint				3.0	3.0
F.12	Other		2.0			2.0
EVA SUBTOTALS			24.0		24.0	48.0

Based on 96 crew-hours over a 24-hour period.

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CONTACT

Dr. Marilyn Dudley-Rowley
OPS-Alaska
2262 Magnolia Avenue
Petaluma, CA 94952
TEL./FAX (707) 773-1037
md-r@ops-alaska.com

Thomas Gangale
OPS-Alaska
2262 Magnolia Avenue
Petaluma, CA 94952
TEL./FAX (707) 773-1037
teg@ops-alaska.com

Lawrence Lemke
Mail Stop 244-14
NASA-Ames Research Center
Moffett Field, CA 94035-1000
TEL (650) 604-6526
Lawrence.G.Lemke@nasa.gov

Marc M. Cohen, Arch.D, Architect
Advanced Projects Branch,
Space Projects Division
Mail Stop 244-14
NASA-Ames Research Center
Moffett Field, CA 94035-1000
TEL (650) 604-0068
FAX (650) 604-0673
Marc.m.cohen@nasa.gov

APPENDIX: FOUNDING ASSUMPTIONS AND “GROUND RULES”

SAFETY RULES

For NASA, crew safety is the preeminent criteria for mission success. Safety considerations must pervade all aspects of habitat design, system architecture, and mission operations.

- No crewmember shall go on EVA (of any duration) alone except in emergency situations (*i.e.,* the "buddy system" shall apply).

- An IVA person shall monitor EVA operations at all times (a rule that may be waived in emergency situations).
- Crew skills shall include routine maintenance and repair of all mission systems.
- Crew skills shall include backup maintenance and repair for all life- and mission-critical systems.
- All mission- and life-critical systems shall be redundant or repairable by crew.
- No life-critical or mission-critical systems shall be left untended by a crew person with appropriate repair and maintenance skills.
- No systems shall remain untended or untendable by EVA within four hours.
- No person or group shall be in such a position that the loss (or incapacitation) of any one person shall jeopardize the life of any other crew person or the function of a mission-critical or life-critical system.

EXCURSIONS

The crew will make excursions from the base cluster in an Excursion Habot or "Rover."

- Any excursion greater than four hours' walking distance from the main base shall include two vehicles (pressurized or unpressurized), each capable of returning to the base with all deployed crew.
- Any excursion beyond four hours' walking distance from the main base shall include (at least) two pressurized rovers.
- It may not be necessary to have active monitoring of deployed rovers at all times, but it shall always be possible to communicate between deployed rovers and the main base.

HABITATION

The entire crew shall not inhabit a single pressurized habitat (or module) at one time without 15-second access to another pressurized (and sealable) module by all crew.

- Any crew person shall have, at all times, access to a another pressurized container or habitat or spacesuit within 15 seconds.
- A radiation storm shelter shall be available to all crewmembers at all times except when on remote EVAs.
- No crewmember will be left alone (in a pressurized module or otherwise) for no more than a percentage of the total mission time yet to be determined.

MEDICAL SUPPORT

- An MD (or suitably qualified person) shall have access to all crewmembers while they are in the pressurized base.
- An MD (or suitably qualified person) shall have access to EVA crew as quickly as possible (realistic limits may be one or two hours, depending of spacesuits and airlocks).
- A medical support system shall be available for the treatment of bone fractures, lacerations, and medicine treatable illnesses and infections.
- All crewmembers will be trained in emergency medical treatment.
- All crewmembers will be cross-trained in at least two maintenance and repair disciplines.
- Every crewmember shall allow at least one hour per week for medical examination and routine medical maintenance.

COMMUNICATIONS AND MONITORING

- No crew person shall be unreachable at any time by communications systems (There may be some necessary gaps during landing or departure).
- No crew person shall be without the ability to communicate with at least one other crewmember at any time (with the obvious exception of a malfunction of the individual's communication device, which shall be repairable or replaceable within 24 hours).
- It may not be necessary to have active monitoring of deployed rovers at all times, but it shall always be possible to communicate between deployed rovers and the main base.
- Life-critical and mission-critical system status shall be continuously monitored. This may not require that any of the crew be awake at all times, but it does require that critical situations be announced to awake or sleeping crew.
- Any situation requiring active crew monitoring will be done by at least two persons (If part of the crew is required to be awake, then at least two crewmembers must be awake).

HUMAN FACTORS

- Crew size considerations shall include psychological health, group dynamics and other human factors issues, as well as physical safety.
- Each crew person shall be allowed ten hours of every 24-hour day for sleep, sleep preparation, and hygiene.
- Each person shall be allowed two hours per day for food preparation, eating, and clean-up.
- Each person shall be allowed one day in seven for relaxation and/or personal activities.
- Crewmembers shall have the opportunity to eat in groups for most meals.
- At least one hour per day shall be allowed for each person for exercise.
- Food shall be nutritious, attractive, and appetizing.
- A room shall be available to support full crew meetings.
- The crew shall hold full crew coordination meetings at least once every seven days.
- The understanding of the roles and responsibilities of each crewmember will be part of the pre-mission training regimen.
- The crew will practice all mission activities thoroughly in simulations.

- No crewmember will be responsible for "cleaning up" after another.
- All crewmembers will understand and accept the chain-of-command.
- Authority of Earth-based personnel will be understood and accepted.
- All crewmembers will be screened psychologically for the mission.
- All crewmembers will be educated and trained in small group dynamics.
- All crewmembers will be trained to recognize and deal with psychological disorders.
- All crewmembers will accept procedures for handling a psychologically disturbed crewmember.

SCIENCE RULES AND ASSUMPTIONS

- At least one scientist shall be available to do laboratory analysis and documentation for at least five hours per day, five days out of seven.
- In a mission of 59 days' duration, there shall be a nominal schedule of 5 local science excursions (of 8 hours' duration) and a nominal schedule of 2 extended excursions (of up to 5 days' duration).
- At least one appropriately science-trained person shall participate in each excursion.
- Excursion and science mission planning shall be sufficiently flexible to allow crew members to follow up on serendipitous discoveries.

SCENARIOS AND SITUATIONS

Mission periods or modes that will determine precise crew size and skill mix include:

- Launch and assembly in Earth orbit (if any)
- Transit to Moon
- Moon orbit operations
- Habot Moon landing, setup, and checkout
- Nominal base operations
- Operations with deployed rovers
- Habot system close-up and departure
- Transit to Earth
- Earth orbital operations
- Return to Earth
- Crew requirements analysis will embrace plausible emergency and contingency situations, including:
  - Illness and injury
  - Psychological disorders
  - Meteoroid puncture
  - Mechanical failure
  - System wear and tear
  - Solar flare and radiation anomaly
  - Crash or collision
- Emergency situations shall include:
  - Loss of power
  - Loss of pressure
  - Loss of personnel
  - Loss of communications
  - Loss of thermal control
  - Loss of food cache or other critical supplies
  - Airlock failure
  - Breach of quarantine or bioisolation