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Mars Habitat Power Consumption Constraints, Prioritization, and Optimization

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Abstract

The Hawaii Space Exploration Analog and Simulation (www.hi-seas.org) is an experiment that simulates life in a Mars habitat for long duration. Power for the simulation is generated by solar energy which varies in production rates daily. During days with cloud cover, crew need to adapt their work schedule and support systems to ensure they can continue to function over the duration of low power constraints. Presented here is the method developed and implemented by the crew from Mission 5 that creates power budget profiles for low, moderate, and high-power production days. The power budget profile limit which systems and devices can be used and for what duration. The HI-SEAS power subsystem is characterized though power audits and data from daily use trends. Developing tools to enable prioritization of components for crew-member usage and compliance with restrictions are discussed. Data production and usage from all five missions are presented and compared. An optimization method is proposed to discover the most efficient schedule to match power usage profiles.This research is applicable to most manned space systems with the goal of providing the most optimal power consumption in a variety of conditions.

Keywords: Mars habitat, power, machine learning

Acronyms/Abbreviations

Hawaii Space Exploration Analog and Simulation (HI-SEAS), National Aeronautical and Space Association (NASA), Residual State of Charge (RSOC), Design of Experiments (DOE), Analytical Hierarchy Process (AHP), Multi-Criteria Decision Making (MCDM), Local Area Network (LAN), Photovoltaic (PV), Extravehicular Activity (EVA), Liquid Propane Gas (LPG)

1. Introduction

HI-SEAS is an experiment funded by NASA and operated by the University of Hawaii at Manoa. NASA has designated a number of red flag problems that must be solved prior to extending manned missions deeper into the solar system, with crew performance and cohesion being major concerns during long periods of isolation. [1]

Studies have included dealing with team risk and performance that include Team Performance Task/Price of Cooperation test, continuous monitoring of face-to-face interactions with sociometric badges, mitigation of the effects of isolation using immersive 3D virtual reality interactions with the crew's family and friends, measurement of emotional and effective states using automated analysis of multiple forms of textual communication provided by crew members to identify relevant and effective teamwork behaviors, and multiple stress and cognitive monitoring studies. [2]

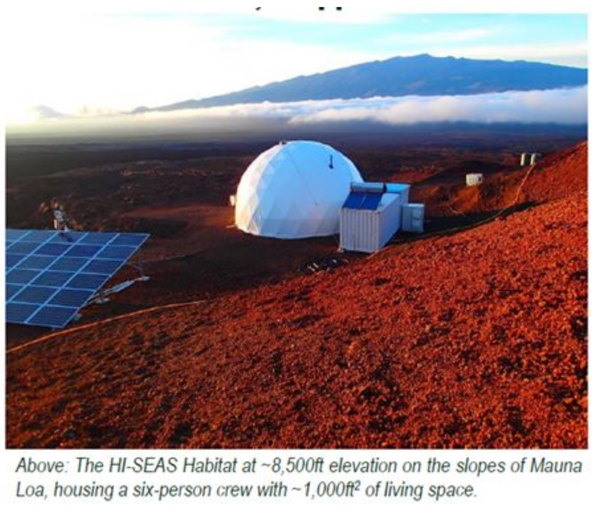


Fig 1. The HI-SEAS Habitat at ~8500ft elevation on the slopes of Mauna Loa, housing a six-person crew with ~1000 square feet of living space.

The HI-SEAS habitat is a geodesic dome providing an isolated and confined environment for six crew on the slope of Mauna Loa volcano in Hawaii. Crew are selected from an astronaut-like pool of candidates for psychological study of crew composition and cohesion during isolated long term missions. The habitat and crew schedule simulate daily life of astronauts on the Martian surface. The habitat features multi-use spaces, laboratory and private crew quarters. Due to the isolated location, the habitat life support systems rely primarily on renewable or storable resources. Life support systems at HI-SEAS include power, potable water, heating and ventilation, and communications.

Previous studies have looked at power usage and forecasting energy consumption using machine learning and the crew's overall psychological state (mood) [3], and comparisons between different missions and their resource consumption were analyzed. [4] Additionally the habitat energy requirements were broken down to personal usage for each crew member and task within various areas of the habitat. [5] The work presented here will focus on energy prioritization and the differences between days with high energy production and low.

1.1 Power Subsystem

Primary habitat power is generated by a 10kW photovoltaic array and stored in a 28.5kWh battery bank for later use. In fair weather, the PV array will fully charge the batteries by mid-morning with a realized efficiency between 0.08 and 0.135 due to hardware and environmental losses. A system diagram of the habitat power system including PV array, fuel cell and dual fuel generator is shown in Fig. 2.

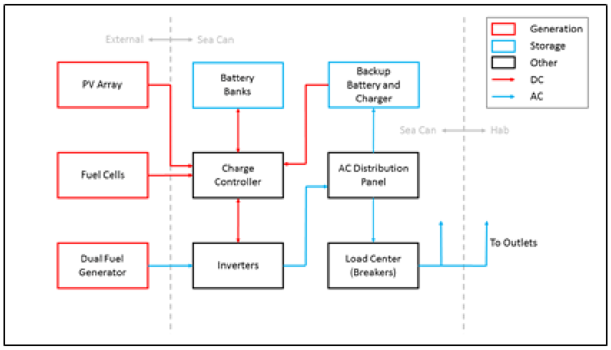


Fig. 2. *Power system diagram showing power sources, conversion from DC to AC and support of habitat power loads.*

Secondary power is provided by hydrogen fuel cell automated to run when the residual state of charge of the batteries drops below 10%. Low RSOC is most likely to occur in the early morning hours before the sun has begun to charge the batteries through the PV array and while the crew is still asleep and unable to take action to reduce power consumption. The hydrogen fuel cell provides immediate short-term backup power without crew intervention.

Long term backup power is provided by the dual fuel generator, and requires crew startup and shutdown operations outside the habitat. This can be difficult on poor weather days when extravehicular activities by the crew are difficult; however, this is also the most likely time for low solar power generation requiring backup power systems.

Fig.3: HI-SEAS 10kW solar array

1.2 Habitat Telemetry and Communications

The habitat power instrumentation provides real-time telemetry data on power generation, consumption and weather conditions affecting PV system performance. Solar power generated is compared to battery RSOC and current power consumption to determine net power gain or loss in the battery bank. Current pressure in the hydrogen tanks is also measured for the secondary hydrogen fuel cell system. LPG pressure for the generator is not instrumented and is recorded periodically by the crew while on EVA.

Telemetry data is recorded locally and accessible through the habitat LAN, providing real time and recorded past values of local irradiance, AC power generated and AC power consumed to the crew. A 20-minute communication delay is observed by all crew and support personnel to simulate the asynchronous data transfer from Martian orbit to Earth.

1.3 Crew Operations

Daily crew operations are pre-scheduled, but with greater autonomy and flexibility than ISS crews to reflect the need for independent decision making on a Martian mission. The 20-min communications delay and transient weather creates a need for crew to alter their scheduled and unscheduled time autonomously to accommodate current power conditions. One restriction for self-scheduling is that crew EVAs must be requested and pre-approved by support personnel. An EVA is required for crew to turn on the LPG generator creating a natural crew preference to manage power use by reducing consumption in the habitat before resorting to backup generation measures.

2. Material and methods

An energy audit was conducted for the habitat during Mission 5 to establish standby, average and peak power consumption of appliances, laboratory equipment and crew electronics connected to the habitat power subsystem. For appliances with variable power consumption, like heated kitchen appliances, a low, medium and high power value were recorded with water or food applied as a typical thermal load. Nominal daily use was characterized for the largest energy consumers and to baseline typical power requirements for crew research and recreation activities.

Daily PV charging trends were observed from habitat telemetry establishing time and efficiency of first morning charge, time to full battery in low, medium and high available sun conditions, storm and cloud cover characterization, and the time of last charge approximating sunset. Habitat life support usage was monitored during crew sleep hours to establish the uninhabited baseline for autonomous processes. A portion of Mission 5 was conducted with a long term plant growth experiment running during day and night hours. Overnight power consumption is assumed for a worst case baseline that includes the plant experiment running 24 hours a day.

The crew developed numerical tools to calculate power consumption trends and used them to predict hourly and daily RSOC given current conditions and expected cloud cover. The tools use current battery and PV data from the habitat telemetry to determine a power input rate and all current and future power loads in the habitat as a power debit including expected crew activities for cooking, recreation and research. Calculations were then run to project an RSOC value for the following morning assuming typical overnight power load. Highlighted in this report are daily trends split into high, moderate and low power generation conditions. These cases were turned into budgets to guide crew on appropriate limitations for power use.

A set of activities and appliances were selected for prioritization representing those with the largest effect on power projections that the crew can self-schedule. Automated processes, like the central furnace fan, were excluded as were powered telemetry equipment and safety critical computing equipment. The Mission 5 crew completed surveys to rate the importance of the activities based on four criteria: mission criticality, necessity for primary research, necessity for personal research, and importance for mental or emotional wellbeing. Relative priority weights for the four criteria were determined through a pairwise comparison by the Mission 5 engineer acting as survey administrator, shown in Table 1. Crew ranked the given appliances according to personal beliefs on a scale of 1-9 for each of the four criteria. Rankings were normalized and a weighted arithmetic mean was calculated following Saaty, 2008. A rating analysis was selected over pairwise comparison to allow a greater number of activities to be compared, but limited the methods to aggregate results for the entire crew.

Table 1. Priority weightings for AHP criteria

	Priorities	Idealized Priorities
Mission Criticality	0.461	1.000
Primary Research	0.181	0.393
Personal Research	0.047	0.102
Personal Well-being	0.311	0.675

3. Results

The Mission 5 crew typically used 50-60% of the battery RSOC from sunset to sunrise and could reduce this to a minimum of 34% on extreme low power days. This minimum supported the mission critical hardware and life support systems, but did not support activities like cooking, electronic entertainment or lighting. On moderate-low power days, the crew reduced consumption by turning off excess lighting, minimizing cooking times, only powering mission critical research devices or life support and lowering the thermostat to the limit for the composting toilets yielding approximately 45% RSOC used overnight.

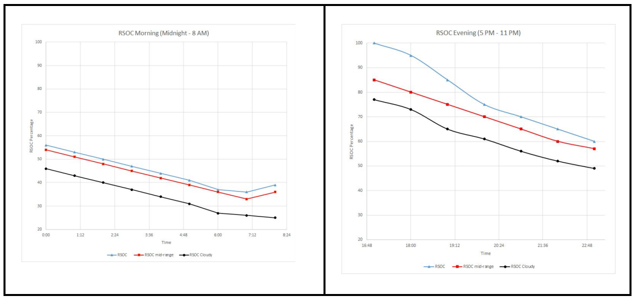
The daily crew use trends and RSOC projections were combined and refined into power budget profiles given in Table 2. For low, medium and high power conditions, minimum RSOC was established according to the time of day. Assuming solar irradiance was high, crews were allotted a more aggressive use profile than on a day with more cloud cover. All power budgets approach similar morning RSOC assuming similar sunrise and crew wake times.. Crew cooking, computing and recreational activities were organized to fall within these ranges attempting to prevent using backup power sources. The minimum successful overnight RSOC was approximately 60% at sunset using aggressive power saving techniques.

Table 2. Power budget profiles for HI-SEAS Mission 5 crew

Time of Day	RSOC Sunny	RSOC Mid-range	RSOC Cloudy
17:00	100	85	77
18:00	95	80	73
19:00	85	75	65

20:00	75	70	61
21:00	70	65	56
22:00	65	60	52
23:00	60	57	49
0:00	56	54	46
1:00	53	51	43
2:00	50	48	40
3:00	47	45	37
4:00	44	42	34
5:00	41	39	31
6:00	37	36	27
7:00	36	33	26
8:00	39	36	25

Fig. 4 a) and b) show graphs of the morning and evening periods for data displayed in Table 2. Fig 4 a) shows the RSOC from midnight until 8 AM when the habitat life support systems are running autonomously and crew is resting. Fig. 4 b) shows the RSOC from 5pm until 11 pm when crew is actively consuming power, but generation through the PV array has stopped. Critical power saving actions will be taken in the afternoon or evening hours. One can see there is a significant difference between the morning RSOC and the RSOC in the evening from the power requirements of the life support system.



(a) (b)

Fig 4: Percentage of (a) RSOC for the morning, and (b) the RSOC for the evening.

If current or projected RSOC was below threshold values in the early evening, powered activities could be reduced until the trend was met to prevent using secondary backup power measures. This necessitated a prioritization of activities which would be removed from the power plan in order of importance to achieve RSOC targets. Aggregated crew priorities are shown in Fig. 5 from the AHP activity, providing general guidance on crew preferences when cutting powered activities. Access to personal computers and laboratory freezer were highly prioritized; both were required to support scientific research tasks. Items of middle importance had more variation across crew members and few clear priorities emerged. Personal comfort items like toilet ventilation and a warmer thermostat setting were moderately important to crew members. Specialized tools and equipment had low priorities, those that were important for a single crew member. Other priorities are closely scored, showing little difference in preference. Crew were asked to rank their priorities without concern for power consumption or other crew's need. In practice, Mission 5 crew often negotiated power use for a personal projects based on expected consumption.

A portion of the power audit results are presented in Fig. 6, showing the relative mean power drawn for each appliance.

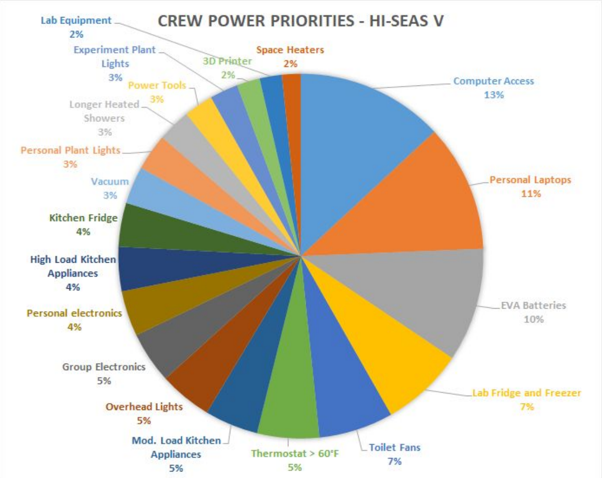


Fig. 5. *Relative power priorities chart for Mission 5 showing aggregated priorities of appliances used in self-scheduled tasks*

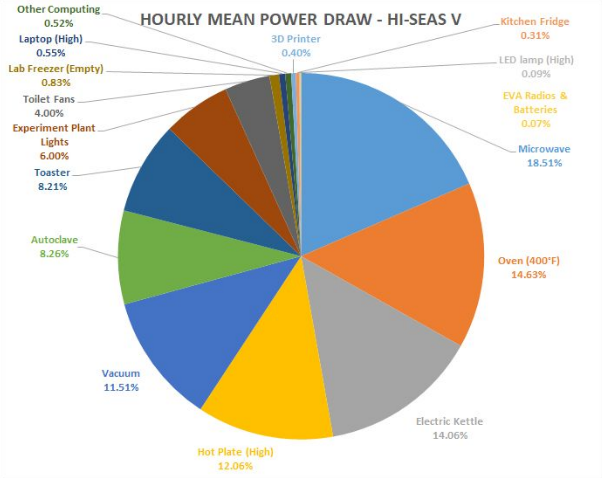


Fig. 6. *Power consumption chart for Mission 5 showing mean steady-state power drawn for one hour by common habitat appliances*

Many appliances in the habitat are run for an hour or more of time, but the microwave, electric kettle, vacuum and toaster are used for minutes at a time. They are considered to be moderate load appliances. Most non-heated appliances draw little power, and individual crew were regularly able to negotiate a power allotment for personal needs even on moderate or low power days. Over a single day, the toilet fans and experimental plant growth lights would require the greatest energy since they ran constantly and are largely responsible for the power consumed between midnight and 8am. Considering both power audit and prioritization results, Table 3 shows Mission 5's recommendations for high power activities under high, middle and low power generated conditions.

Table 3. Recommended RSOC thresholds for Mission 5

Activities	RSOC Sunny	RSOC Mid-range	RSOC Cloudy
Dinner	13%	11%	5%
Toilets	23%	23%	23%
Plant Lights	11%	11%	11%
Personal Computers	9%	9%	1%
Other Loads	7%	4%	4%
Total Battery Used	63%	58%	44%

At least eight significant low power days occurred during Mission 5 (RSOC below 77 at 17:00), with four requiring the crew to utilize one or more backup power sources. These days were heavily overcast preventing power generation through the PV array and required either the LPG generator charge the battery bank during the afternoon or the H2 fuel cell to turn on automatically in the early morning. Half of these low power days occurred within the first 45 days of Mission 5 when the crew was less adept at changing their behavior and before a powered plant growth experiment was performed overnight requiring higher power loads. The crew prioritized social interaction even if power could not be used by playing games and spending social time together on "dark" evenings. The crew also prioritized power to support research tasks, attempting to keep assignments on schedule and charge equipment like batteries and radios for EVAs scheduled the following day.

3.1 Comparing consumption constraints between HI-SEAS missions

Each of the HI-SEAS mission crews worked hard to ensure that energy would be consumed in a manner that is realistic to a Mars mission. The crew engineer would indicate a 'low power' day where the crew would need to reduce power usage, mainly due to low solar power production. The low power days are identified for each of the crew in Table 5 which shows the average total power usage on a normal day compared to a power constraint day. Fig. 6 shows the relative difference in average power savings for each of the missions in a bar chart.

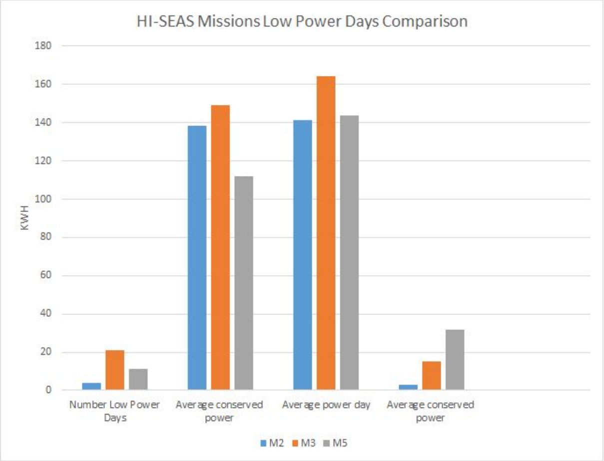


Fig. 6: HI-SEAS Low power consumption comparison between missions

Examining Fig. 6 we see that Mission 2 saved an average of 2.13% power on low power days. Mission 3 reduced consumption by 9.3%. Meanwhile, Mission 5 reduced consumption by a much greater amount of 22.2% on average.

4. Discussion and Conclusions

The data presented characterizes crew power consumption and prioritization in an isolated Martian analog. It is useful in planning for resources on long duration missions and show how allowing for changes in moral and personal preference might affect power use positively and negatively

The predictive power calculation tool, power budgets and crew priorities from Mission 5 could be leveraged to create a parametric response model of the habitat power subsystem. Daily inputs of irradiance and time of charge can be varied according to the power budget profiles. Typical crew behaviors can be varied parametrically and the resulting RSOC can be projected for minimum morning charge. Future work will implement this model into a workflow in the parametric optimization software modeFRONTIER for sensitivity and optimization studies. A simplified DOE study was already run in modeFRONTIER during Mission 5 using the predictive power calculator tool and confirmed overnight minimum charge values observed by that crew. The future optimization workflow will seek optimal threshold usage for crew powered activities while maintaining RSOC high enough to reach sunrise the next day. AHP or similar priority methods could be further developed and used in combination with the optimization model to support multi-criteria decision making from optimized results.

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