A SIMULATION-BASED STUDY OF OPERATIONAL VULNERABILITIES AND CONTINGENCY PLANNING FOR SMART EXTRATERRESTRIAL HABITATS

by

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To my parents for their unconditional support, my brother for keeping me in check, and the rest of my friends and family for always lifting me up to new heights

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ABSTRACT

Although decades of experience in human spaceflight have produced and refined a wealth of operational knowledge, the unique challenges posed to long-term extraterrestrial surface habitats will require new approaches to mission design. The key objectives of this thesis are to develop an understanding of 1) how to use simulation to study these habitats and 2) how to make contingency plans for these habitats under complex, changing conditions. In order to accurately represent the challenges posed, we identify the common qualities of mission architectures that are likely to be present in near-future habitats. These qualities are used to formulate sample crew schedules that contribute to developing realistic models for meaningful research. We discuss the development of such models and demonstrate the suitability of simulation to enable the design and study of resilient space habitats. Simulation can be used as a tool to understand the challenges and consequences associated with decision making, as well as the importance of resilient design choices in a hazard-prone environment. We then identify aspects of vulnerability in space habitat mission operations, the subfactors that influence changes in habitat vulnerability, and the effects of each identified category of vulnerability. These 'vulnerability factors' are subsystem availability, environmental conditions, safety control options, and recent events. Each vulnerability factor has several subfactors that influence its change during a mission.

The set of vulnerability factors is significant because each captures some category of behavior in surface habitats that changes over time and impacts the likelihood or consequences of risks to the habitat. We use these vulnerability factors to formulate six research questions which can be addressed via simulation-based research. A simulation set plan is developed to highlight the significant concepts at play in each research question. Finally, we conduct trials and analyses of these questions via simulation by injecting faults into a modular coupled virtual testbed for space habitats. The results of the simulations are used to develop lists of key implications for each vulnerability factor in practice. In addition, the lessons learned over the course of simulation set design and the usage of the simulation tool are discussed to support future simulation-based research efforts. We conclude by summarizing the major findings and potential for future work in the area.

1. INTRODUCTION

Current efforts in human spaceflight push nearer toward sustained habitats on the Moon, with Mars looming over the horizon. While years of experience in human spaceflight will inform and bolster this effort, numerous conditions existing uniquely in missions of this kind will separate planetary habitats from past successes. Among these conditions new to long-term space habitation are the effects of low gravity (as compared to 'zero-g'), new thermal considerations, farther-than-ever distances to Earth, and surface interactions such as moonquakes and dust (Dyke et al., 2021). Radiation exposure, near-vacuum pressure, and inhospitable temperature ranges round out the list of hazards. New technologies and design frameworks are being developed to address these hazards and enable indefinite surface habitation efforts in the interest of science and exploration.

The exact appearance of an extended lunar surface mission concept of operations is not yet solidified by NASA. With over 50 years having passed since the last time humans set foot on the Moon, in situ testing and field trials with modern technology are a necessary future step. Shortcomings must be identified where the need for new technologies exists to make these missions possible. Detailed mission architectures will be informed by the implementation and evolution of early Artemis missions (*Moon-to-Mars Architecture Definition Document*, 2023). NASA states that the greatly increased distances and communication delays on the lunar surface versus those of low Earth orbit (LEO) missions "significantly complicate or eliminate crew rescue options that may be available in LEO" (*Moon-to-Mars Architecture Definition Document*, 2023). This distance motivates independently resilient habitat design.

The time is critical for the development of tools to supplement the 'hard' lessons learnt by mission implementation with low-cost, no-risk, easily modifiable simulations early in the design process. The central objectives of this thesis are twofold. First, we aim to develop effective usage practices to use computer simulation tools for meaningful research into extraterrestrial surface habitats. Secondly, this thesis is interested specifically in deepening the current understanding of the vulnerabilities and necessary contingency planning considerations for these habitats. To enable study of contingency planning, we start from generalized mission operation definitions based on current expectations for future lunar habitation missions.

1.1 Resilient Extra Terrestrial Habitats Institute

The Resilient Extra Terrestrial Habitats Institute, or RETHi, is a NASA-funded space technology research institute headquartered at Purdue University (Dyke et al., 2021). RETHi is divided into three thrusts. The Resilience Thrust is focused on developing system architecture design capabilities to prevent the habitat from entering hazardous or accident states or restoring it to nominal conditions when it does enter those states. The Awareness Thrust deals with autonomous state estimation, fault diagnosis, and predictive capabilities. The Robotics Thrust is concerned with the autonomous robotic agents that will manage habitats in the absence of crew and assist crew with certain actions.

RETHi is developing three testbeds to enable research in these areas. The modular coupled virtual testbed (MCVT) is a low- to moderate-fidelity model of a space habitat into which users can inject various disruption scenarios and study habitats at a relatively low level. The MCVT is the sole tool for simulations performed in this thesis, and more details will be provided ahead of those simulations. The MCVT is complemented by the cyber-physical testbed (CPT), a real-time hybrid simulation tool which provides a physical component to the MCVT model that can validate behaviors in the MCVT. The third testbed is the control-oriented dynamic computational modeling framework (CDCM), a more compact model of the habitat intended for higher-level simulation to perform large trade studies and answer additional research questions.

1.2 Smart Space Habitats (SmartHabs) and the Notional Real Habitat (NRH)

RETHi operates with the vision to “establish the know-how to design and develop resilient and autonomous SmartHabs” (Dyke et al., 2021). Future extraterrestrial habitats will require autonomous capabilities to enable long-term habitation. Both human and robotic agents will work together to accomplish a variety of maintenance and science utilization tasks, ultimately keeping the habitat useful and functional. The term ‘SmartHab’ describes a semi-autonomous surface habitat, and the term is used throughout this thesis to refer concisely and specifically to the range of habitats with the qualities discussed herein.

The Notional Real Habitat (NRH) is a functional and spatial design concept for the RETHi lunar SmartHab (Igarashi & Barket, 2022). The SmartHab models implemented in the MCVT and other simulation tools are based on design choices in the NRH, meant to represent a realistic possibility for lunar habitat architectural design based on current developments in that field.

1.3 SmartHab Resilience

Rapid technological change, new kinds of accidents and hazards, complex and coupled systems, increasing standards of safety, and human-automation relationships are all modernly relevant contributing factors to a need for change in how we approach safety engineering (Leveson, 2012). In SmartHabs, these factors are not only relevant, but represent core characteristics of habitation missions. In addition to the known hazards considered throughout the design process, unknown risks may arise throughout the length of SmartHab missions.

Two traditional schools of thought on systems-oriented risk management can be applied to SmartHabs to understand how to respond to these unknown risks. The first, Normal Accident Theory, suggests that accidents are an inevitable result of systems that are complex and tightly coupled (Perrow, 1999). SmartHabs exhibit complex interactions because the subsystems are highly interconnected and their effects on each other are not necessarily intuitive or easily predictable. SmartHabs exhibit tight coupling because damage to one component can cause cascading effects that impact others, and a hazard such as a fire or hole in the structure can cause worsening effects the longer it is left unfixed. Perrow additionally asserts that efforts to mitigate the kinds of risks caused by these factors may add more complexity to the system and thus increase its risk potential.

The second school of thought, High Reliability Organization Theory, suggests that at a system level, certain principles can be adopted to significantly mitigate risks (Roberts & Rousseau, 1989). This sentiment is a much more optimistic viewpoint than that of Normal Accident Theory, but it is not necessarily contradictory. The concepts of both schools can be taken into account to acknowledge the risks inherent to SmartHabs and also formulate practices that help mitigate those risks.

In this thesis, we frequently refer to habitat design and contingency plans in terms of resilience. Resilient system design is one answer to approach unforeseen or rare disturbances with which we have little experience (Uday & Marais, 2015). A resilient SmartHab is one that can both survive and recover from the hazards that threaten it. The goal of identifying SmartHab vulnerabilities in this thesis and how they influence contingency planning is to contribute to resilient SmartHab design and operation.

1.4 Space Habitat Decision-Making

The content of this section and 1.5: Simulation-Based Design has been published by Vaccino et al. (2023). The propagation of disruption scenarios in a SmartHab and ultimately the success or failure of a mission depend on the decisions made by the humans and/or autonomous systems responsible for maintaining critical systems. The decision-making involved in maintenance or repair courses of action is critical enough to heavily influence subsystem design. As identified by Dyke et al. (2021), proactively designing a resilient system architecture is one central approach to mitigating the long-term impacts of disruptions, alongside effective situational awareness and robotic intervention capabilities. While the ISS and other missions have provided years of experience in in-flight repair, longer missions beyond Earth’s orbit will stray farther from the helping hand of mission control, requiring more independence in maintenance capabilities (Rohrig et al., 2019). This direction will necessitate new standards, procedures, and design considerations to keep systems working as intended. Modular systems with common subcomponents that lend themselves to repairability are one approach, but may increase the risk of common cause failures, exacerbated by the high ‘infant mortality’ failure rates of new component designs (Jones, 2016). Few assumptions about system reliability can be carried from past missions into the realm of long-term planetary SmartHabs.

Deciding how to respond after a disruption that puts a SmartHab into a hazardous state is no simpler than designing for resilience proactively. There are tradeoffs to any course of action, and a certain course may not always be identifiable as strictly better or safer than another. The MCVT contains its own user-defined priorities for how to address failures if multiple occur at the same time. Nakane & Miyajima (2022) describe and discuss the importance of prioritizing for maintenance, repair, or expansion of an advanced life support system. To minimize risk to the habitat and any people inside it, system downtime must be held to the absolute shortest time possible. If multiple types of damage occur simultaneously, the order of repair must be selected appropriately to maximize safety. Even after decisions are made, the repair of complex, damaged subsystems is not an exact science. Important aspects of the damage may go unidentified, repairs may fail, and new types of damage may develop during the course of the response (Jones, 2019). This complexity calls for an approach that is flexible and conscious of vulnerability throughout the repair process. Choosing one subsystem over another may allow some health metric to persist in an unsafe range for a greater amount of time. In extreme cases, there must be a choice made between the survivability of the habitat and the risk of death or injury to the crew, leading to evacuation and mission abort (Trujillo & de Weck, 2018). Catastrophic disruptions are far from being outside the range of possibility, and changing mission objectives are an important part of the equation.

1.5 Simulation-Based Design

Given the lack of practical experience in constructing and operating extraterrestrial habitats and the infeasibility of in-situ testing to assess design choices, a different approach is needed to gather the necessary knowledge. The ISS provides a testbed and educational example for many of the components surface habitats will incorporate, but testing in space is resource intensive, and in some cases will not be a suitable analog for planetary environments (West et al., 2017). Space analog missions, such as those conducted by NASA Extreme Environment Mission Operations (NEEMO) are a more accessible alternative to study the practices and challenges involved with new kinds of space, but are still highly resource intensive (Li et al., 2017). The lessons learned from such analog habitats are an important piece of the puzzle, but still a faster and cheaper testbed is needed.

By utilizing simulation-based design (SBD), designers and modelers can address difficulties related to modeling faults and repairs. SBD addresses a range of challenges, including reducing simulation time, managing complex models, exploring various system architectures, and modeling a wide range of components. Additionally, the ability to inject various faults enables researchers to analyze how systems respond to failures.

Other efforts before the MCVT have made contributions to the field of space habitat design with simulation tools. As illustrated by Li et al. (2017), even practical, crew-in-the-loop testbeds such as analog habitats benefit from computational simulation tools. The study described in the referenced paper involves the use of physics-based simulations for ECLSS and thermal control which can be easily manipulated and computationally controlled. Virtual reality (VR) based simulations, such as those developed by Cecil et al. (2018), strike a compromise between the human involvement of physical analogs and the accessibility of virtual testbeds. They allow users to study design choices in 3D pseudo-physical environments. The tool developed by Simon & Wilhite (2013) tackles the evaluation of habitat interior layout evaluation, a task one might also approach with VR. By quantifying various aspects of interior layout and accounting for mission constraints, the evaluation tool can cover a large quantity of layouts of without the need for manual CAD processing or human evaluators. As another example, Lagarde & Lipiński (2022) introduce a similar tool to be used for the design of habitats and other structures in extreme environments. This capability, applied to mission characteristics beyond the interior layout and structure of the habitat, enables engineers to make early design eliminations, rapidly adapt to changing conditions, make decisions with objective reasoning, and ultimately save on time and cost.

SBD is clearly not a new idea to space habitat design or systems engineering in general, but it does not come without persisting limitations. Goswami (1994) identifies some of the challenges involved with and advantages of SBD for fault-injected, repairable models. These models require rigorous validation and qualifications of their results to mitigate concerns with generalizability and accuracy. Jones (2017) further identifies limitations applicable to life support system models as well as some of the benefits of constructing a model for a specific research goal. The process itself of developing a system model is an effective tool in familiarizing new investigators with the intricacies and research needs of the systems they model. On the other hand, models and SBD are generally not universally applicable -- a model developed with a certain goal in mind may lack too much detail in certain areas to be informative outside of a specific domain. Computational models are at risk of software errors leading to unreliable results. To address these limitations, RETHi complements the MCVT with the aforementioned CPT and CDCM. The work discussed herein focuses only on the MCVT, but future studies might exploit the complementary nature of these tools.

1.6 The Modular Coupled Virtual Testbed (MCVT)

Free from the limitations of physical testbeds, the MCVT can be used to address a wide range of research questions and scenarios while properly representing the complexities of a SmartHab. Users have the ability to study SmartHabs at both subsystem and system levels. The MCVT and tools like it can help researchers evaluate potential designs of SmartHabs under the intense demands and strict constraints of planetary surface environments.

The complexity of the MCVT and its subsystem interactions is consistent with that of a notional real SmartHab. Because it was designed with the intent to capture emergent behavior, all interactions between subsystems are modelled. In this section, we outline the major functions and architectural features of the MCVT that will be used in this thesis.

1.6.1 MCVT Habitat Architecture

The MCVT model is divided into subsystems representing the major functions of the NRH. Modeled subsystems include the structure (ST), structural protective layer (SPL), interior environment (IE), environmental control and life support systems (ECLSS), power subsystem (PW), and an agent (AG) which acts on the orders of an automated health management system. The ECLSS includes pressure and thermal control in the IE. The PW system includes a nuclear generator, a solar array, battery storage, and power distribution systems. The user can select from a suite of disruptive events consistent with those which might occur on the Moon or Mars, including micrometeorite impacts, moonquakes, fires, and coolant leakage. The specific details of these disruption scenarios are discussed in 1.6.2: Disruption Scenarios.

The disruptions are propagated through the relevant subsystems according to the parameters determined by the user, such as the intensity level of the disruption, the initial conditions, the start time of the event, and certain habitat design choices. Specific user inputs are discussed in 1.6.3: User-Controlled Inputs. Damage to components is detected via synthetic fault detection and diagnosis (FDD) and repaired according to the agent's pre-defined priorities.

Figure 1 graphically depicts the interconnected relationships among the subsystems in the MCVT. The complex nature of these interconnections and the propagation of disruptions (originating from the disturbance block labelled DB) is illustrated by the various types of interactions between each subsystem. The cyber components at the bottom of the figure consist of C2, the autonomous command and control block, DRDS, the data repository and data service system, HCI, the human-computer interface, and the communications network, CN, which serves as the bridge to the physically connected components.

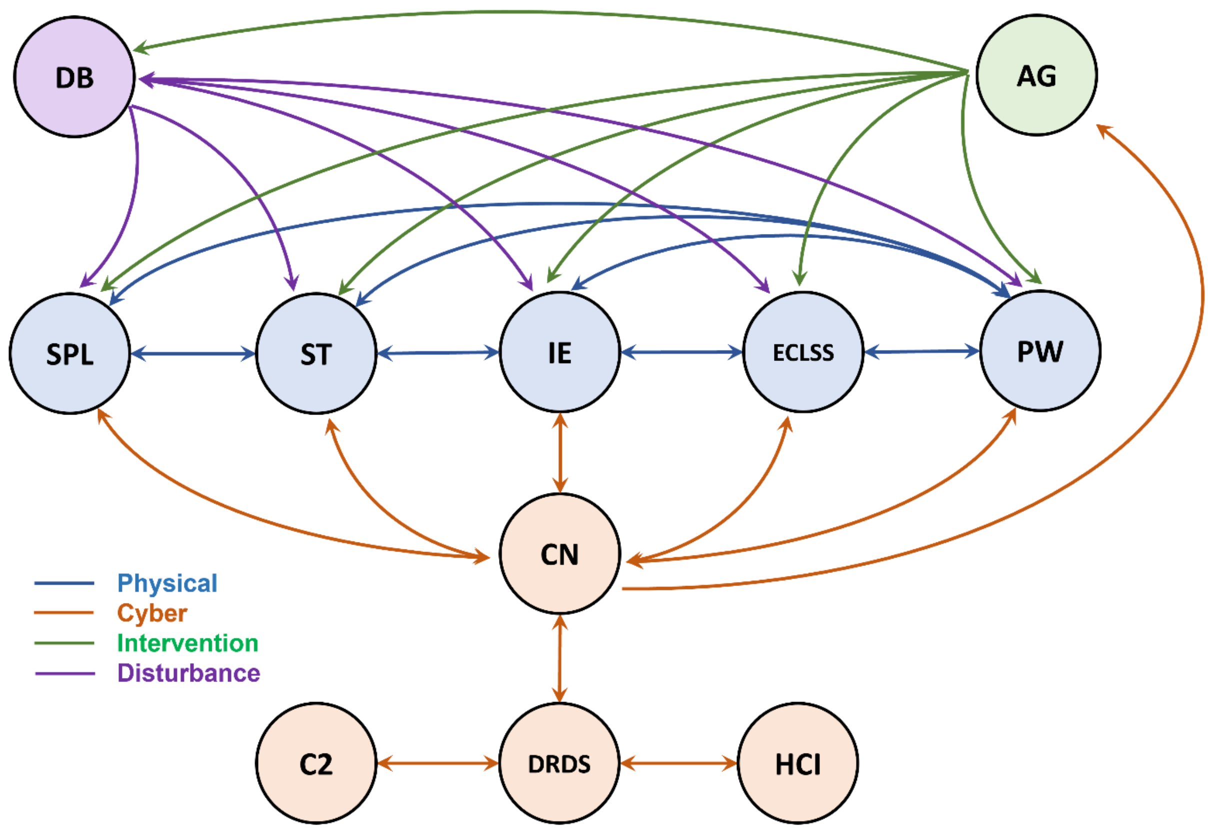

Figure 1. MCVT Subsystem Architecture
(*Modular Coupled Virtual Testbed (Version 6.3)*, 2023)

While the MCVT habitat model is meant to be representative of the NRH, it does not contain the full multi-dome layout. The habitat that is modeled consists of a single dome divided into two zones. Figure 2 shows the dimensions of the scaled, modified NRH layout used for the MCVT. The scaling is selected to match that of the CPT and enable smooth interfacing between the two tools. In the figure, PD is power distribution, ES is energy storage,. Between the two zones is a pocket door that can close as a safety control to isolate the two zones from each other.

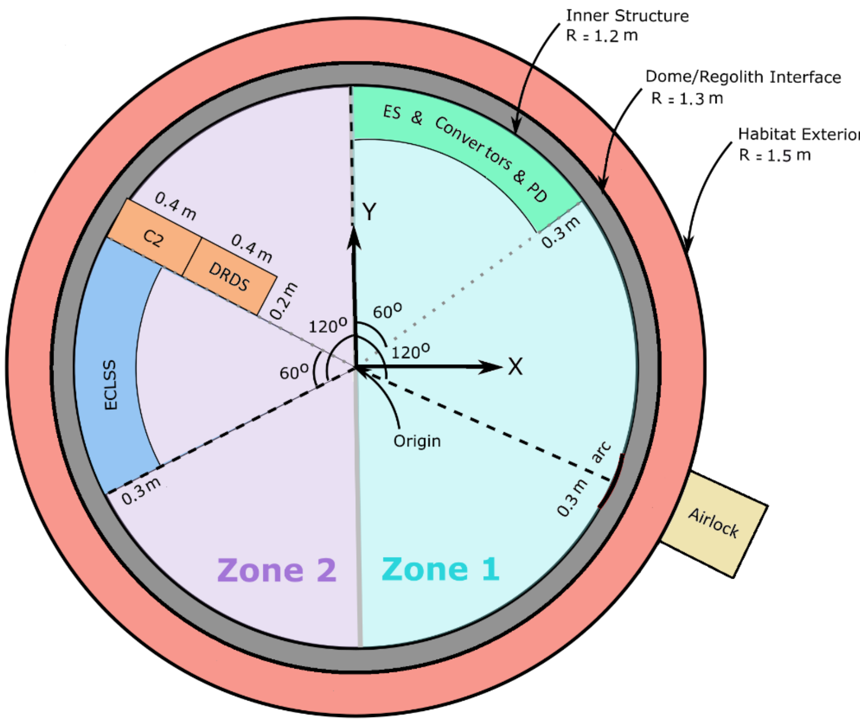

Figure 2. Dimensions of the MCVT Scaled Habitat
(*Modular Coupled Virtual Testbed (Version 6.3)*, 2023)

Figure 3 shows the layout of components external to the habitat dome. The locations of these components are relevant to the simulations in Chapter 4.

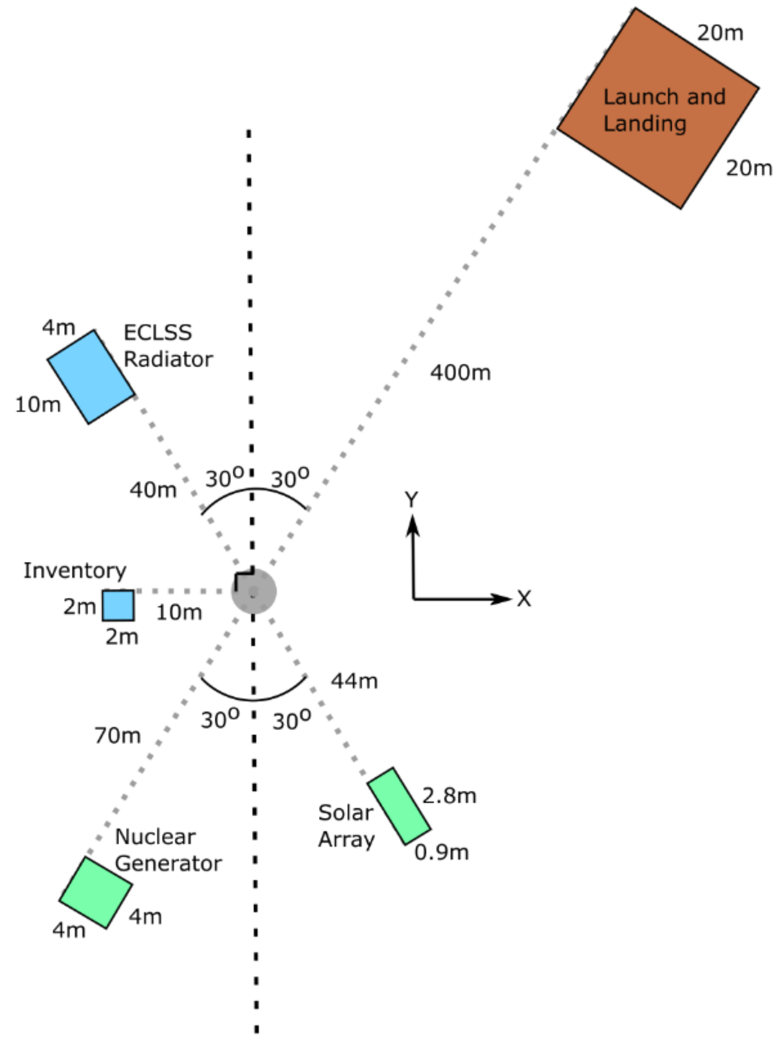

Figure 3. Scaled MCVT Habitat Exterior
(*Modular Coupled Virtual Testbed (Version 6.3)*, 2023)

1.6.2 Disruption Scenarios

The MCVT allows the user to input settings for several disruption scenarios, including sensor failure, airlock failure, moonquake, and nuclear coolant leakage. Primarily in this thesis, we are interested in the disruption scenarios of meteorite impact and fire because these scenarios offer the most versatility in user-controlled damage propagation.

Meteorite impacts in the MCVT are simulated with varying size and location. The size of the meteorite or micrometeorite determines the extent of the damage that will occur, while the location of the impact determines which subsystems will be affected. When a micrometeorite directly impacts a subsystem component, FDD will detect the disruption, and the agent will act to repair the damage. This damage can cause reduced or lost functionality of critical systems and is entirely user-defined. When a micrometeorite impacts the surface outside of the habitat, it can cause dust accumulation on exterior surfaces, potentially reducing the efficiency of certain components. When a micrometeorite impacts the dome of the habitat, it may create a hole in the structure, causing a leak of atmosphere. Pressure and temperature decrease somewhat rapidly until the hole is repaired by the agent. The size of the hole is also user defined.

Similarly, fires in the MCVT are simulated with varying size and location, with the added component of spread rate. Fires are modelled phenomenologically as circles with linearly increasing radii. If a fire originates on top of one of the components shown in Figure 2 or spreads to reach that component, the subsystem will incur damage defined by the user. While the fire propagates, it releases a heating load to the IE that drives up temperature and pressure. When FDD detects the fire, the agent moves to extinguish it at a user-defined rate, and the thermal and pressure control systems return the IE to a nominal state.

1.6.3 User-Controlled Inputs

The MCVT allows for user control of disruption scenario settings, initial conditions, habitat design settings, and agent behavior. The disruption scenario settings have already been discussed. The most impactful initial conditions include temperatures and pressures in each zone of the habitat, the initial solar angle, and the ES state of charge. Habitat design features can be modified to user specifications of power system sizing and pressure and temperature setpoints for ECLSS. Due to the modular nature of the MCVT, users can further modify subsystem architectures beyond input values within the Simulink file.

The agent itself and its capabilities are completely user-defined – it can be modified to account for a variety of assumptions. The amount of time it takes to repair damaged components, travel between locations, and its repair priorities are determined in the input variables. It is often used to represent a robot but may be altered to simulate a human crew member.

1.7 Thesis Overview

In Chapter 2, we expand on terms and practices relevant to SmartHabs, providing an extensive, practical description of how an extraterrestrial habitat mission might operate. Day-in-the-life schedules describe a notional crew's hourly activities to provide context for the rest of the thesis. We also take time to discuss SmartHab transitional states, an important design consideration for these missions. The place of this chapter in the thesis is to establish generalized reference operations to enable the following steps in the research.

Chapter 3 concentrates the information in Chapter 2 down to a list of operational vulnerability factors and the subfactors that influence those vulnerabilities. We discuss the significance of these challenges to SmartHab operations and use them to identify research questions for further investigation. The consequences of each factor should be well understood to facilitate smooth and resilient SmartHab missions.

In Chapter 4, we use the MCVT to demonstrate and test our qualitative understandings. Simulation plans are developed in line with each research question from Chapter 3, and the relevant data are plotted. We discuss whether the simulation results align with intuitive expectations. Interesting behaviors are identified and lead to conclusions to improve our understanding of the vulnerability factors.

Finally, in Chapter 5, we draw conclusions from our investigations and the lessons learned throughout. A table is included summarizing learnings about each vulnerability factor. Future work is suggested to build upon our findings, and suggestions are made for how the MCVT (and tools like it) can be best improved and utilized in the future.

2. LUNAR SMARTHAB MISSION OPERATIONS AND CREW DAY-IN-THE-LIFE

The content of this chapter has been submitted for publication by Pritchard et al. (2023). Toward the goal of developing realistic models and conducting useful trade studies, researchers, including those in RETHi, depend on a shared notional understanding of how a SmartHab might look and operate. Models must originate from a baseline reference architecture for all mission characteristics. This chapter qualifies some general assumptions made about the daily activities and objectives of a SmartHab's crew. It provides crew schedules to represent agent actions and availability through a day-in-the-life (DITL) but refrains from defining a concrete mission architecture that might infringe on simulation flexibility. Researchers and designers can use these DITL schedules and the content of this chapter as a contextual reference point to inform future projects. The generalized nature of the definitions in this chapter will follow to the identified vulnerability factors in Chapter 3.

2.1 Motivation

The purpose of this chapter is to describe notional crew activities onboard a SmartHab, articulating and generalizing RETHi's assumptions for practical use. The information within is presented to help inform decisions regarding agent representation, simulation parameters, trade study topics, and more. This goal is accomplished through review of existing literature covering space habitation and, where appropriate, extrapolation of this literature to the lunar surface environment. The final product is a set of sample Day-In-The-Life (DITL) schedules for habitat crew members, covering several potential operational modes of the habitat. These schedules are not intended to propose the best or most effective scheduling methods; they serve as a reference architecture and common ground specific to long-term space habitats and intend to support current and future research efforts. It is also important to note that the SmartHab missions described are not intended to propose schedules for the upcoming Artemis missions nor to describe existing plans for Artemis. Where differences exist between the assumptions described in this chapter and literature regarding the Artemis missions, they can be attributed to the differences in relevant mission architecture, technology, and duration. Primarily, a modeler would be expected to reference the DITL schedules to see where crew members would be and what they might be doing at a given time of day during a given phase of the operation. In this thesis, the schedules are used as a reference point to develop an understanding of SmartHab vulnerability factors.

2.2 Lunar SmartHab Overview

Rather than being defined by a concrete concept of operations or mission architecture, the habitat is described by characteristics that are likely common to many in the range of interest of RETHi and other researchers, providing flexibility to modelers. SmartHab details highlight inclusion of RETHi's three main research thrusts: resilience, awareness, and robotics (Dyke et al., 2021). This SmartHab is assumed to be well established, with all major setup/construction tasks completed. Any missions being performed are for long-term upkeep and operation of the habitat, and the missions are focused on research. These missions involve long duration (months- or years-long) crew cycles, and the components being modelled may be at various points of age and degradation, requiring attention to repair and maintenance capabilities. When a crew departs the SmartHab, autonomous and remotely controlled systems keep it in an operational condition via sensors and robotics. Information on the specific technologies and developing capabilities that will eventually facilitate SmartHab operation can be found in Abercromby et al. (2022), Broyan et al. (2022), or literature covering the progression of the Artemis missions toward longer durations. Here we will discuss primarily the mission implications of future technology requirements without going into details beyond the scope of the topic.

2.2.1 Notional Real Habitat and High-Level Mission Objectives

As the NRH aims to provide physical context for simulation tools, the DITL schedules aim to provide temporal context for crew activities. The scheduling process shares design considerations and assumptions made in the development and implementation of the NRH.

Some of the most important design considerations to inform this development are the mission objectives of inhabiting the lunar surface. Specifically of concern are the research goals posed by RETHi to advance the knowledge and technology necessary to establish extraterrestrial habitats. The major objectives of the notional SmartHab mission include crewing the NRH for extended periods of time, performing realistically relevant science and engineering activities, observing safe and reliable equipment selection and maintenance, and evaluating effective mission practices for future long-term habitation missions in harsh environments (e.g., Mars).

2.2.2 Comparisons to Orbital Research Stations

Over the years of human spaceflight mission planning for both long and short duration missions, certain standard requirements and practices have been established. To keep RETHi's DITL schedules as realistic as possible, scheduling practices established for orbital research stations like the International Space Station (ISS) and planned for the Lunar Gateway can be applied to the NRH and adjusted appropriately to reflect environmental conditions on the lunar surface and support the objectives of the SmartHab. Then it is necessary to describe differences between a lunar surface SmartHab and an orbital research station.

One of the most obvious qualities of a surface habitat is the presence of gravity. The presence of gravity affects the structural design of the habitat, how both humans and robots move around and use equipment, physiological effects of long-term habitation, and more. One effect may be that less resistive exercise is necessary to maintain crew members' musculoskeletal health (*Human Integration Design Handbook (HIDH)*, 2014).

Another important difference is the potential for geological interactions. Dust from the surface can accumulate on exterior surfaces like solar panels, requiring intervention lest it damage or inhibit external systems. Dust may also find its way into the habitat with crew ingress, requiring a regular cleaning system. In situ resources can be repurposed and utilized, as regolith might be used to insulate the habitat. Perhaps one of the most significant effects is that the potential for research into the Lunar surface features is high. This focus may drive an increase in extravehicular activities (EVAs) and time spent outside the habitat, which would also drive changes in mission constraints due to the unique radiation and thermal profile on the lunar surface.

Autonomy is what puts the 'Smart' in SmartHab research. It is another important feature to consider for DITL schedules which support research into autonomous capabilities. To reflect this focus, the scheduling process should accommodate robotic agents for various roles and also consider dormant periods of the mission where the habitat is uncrewed by human agents.

2.3 Habitat Activities

The daily activities of crew members will follow a generally consistent schedule for steady-state mission operations (i.e., days not including arrival/departure or contingency operations). The crew members accomplish necessary tasks and, with what time is available, utilize science equipment. This section follows closely the guidance provided for ISS operations in NASA's Baseline Values and Assumptions Document (BVAD) (Anderson et al., 2018).

2.3.1 Crew Requirements and Habitat Maintenance

The amount of time available to be devoted to desired, mission-related tasks is limited by the amount of time required for crew member wellness and habitat maintenance tasks. This limitation makes defining the "invariably scheduled time," as the BVAD refers to it, a good starting point for scheduling (Anderson et al., 2018; Chamitoff & Vadali, 2021).

Each day, human crew members must sleep, eat, maintain personal hygiene, exercise, and enjoy some personal time for mental wellness. For ISS schedules, the BVAD indicates that crew members are given 8.5 hours for sleep (Anderson et al., 2018). Before and after sleep, there is 1 hour of "pre-sleep" and 0.5 hours of "post-sleep" time. This activity is personal time during which crew members can set routines according to preference. Exercise and hygiene are scheduled for 2.5 hours per day – 1 hour to complete a routine of aerobic training, and 1.5 hours for anaerobic resistance training, including some overhead for personal hygiene (Anderson et al., 2018; *Human Integration Design Handbook (HIDH)*, 2014). It is suggested that the duration of resistance training could be reduced in the presence of gravity. Compared to in the zero-g environment, crew members in a lunar habitat experience greater stress on muscles when moving around or lifting equipment. For the notional lunar SmartHab, exercise is reduced to 2 hours per day. In 2.4: Day-In-The-Life Scheduling, it is shown that exercise is reduced further to 1 hour for crew members who perform EVA the same day. This allocation is based on assumption and should be adjusted depending on the content and duration of the EVA. Three daily meals, taking 1 hour each (including preparation and cleanup), incur 3 hours per day total. Lastly, crew members are given 6 hours of recreation time on each weekend day. This time is prone to interruptions due to unexpected issues or experiments that require daily tending, but lost time is generally compensated for (Anderson et al., 2018). Time requirements for invariably scheduled time are shown in the darkened cells of Table 1. Times shown are measured in crew member hours per crew member day (CM-h/CM-d). The terminology and types of activities represented in the table are largely identical to those provided in the BVAD, aside from the differences explicitly mentioned here.

Regular maintenance and planning operations are also required to keep the mission running smoothly. This category is broken down into scheduled/unscheduled repairs of equipment, planning conferences with mission control, time reserved for individual preparation and planning, and necessary housekeeping tasks. The BVAD refers to it as "Variably Scheduled Time" (Anderson et al., 2018).

Daily planning conferences (DPC) typically take the form of 15-minute meetings at the beginning and end of each weekday. This routine is followed by 1 hour of plan review/report preparation at the end of the day. Crew members also have about 30 minutes to prepare for the day's work appropriately. All this planning leaves 7 hours of time for maintenance and research/mission objectives. While the original table combined these activities into a single category, they are separate here because trade studies may be interested in how much more time can be devoted to mission objectives, versus undesired but necessary maintenance. On the weekends, crew members perform housekeeping and may launder their clothes to keep the habitat tidy and comfortable. While laundry in the traditional sense is not possible with such limited water supply, it may be performed in some adapted form in future surface habitats, such as via in-situ resource utilization. The duration of the housekeeping activity was increased from 2 to 2.5 hours to represent the increased space and comforts of living expected/necessary for long-duration missions. The longer the crew cycle of a mission, the more the mental health of the crew depends on the typical comforts they experience on Earth (Chamitoff & Vadali, 2021). There may also be scheduled time devoted to research on experiments that require attention on weekend days.

Table 1. Time Allocations for Crew Schedule
(Adapted from Anderson et al. (2018))

Type	Activity	Weekday (CM-h/CM-d)	Weekend (CM-h/CM-d)
Variably Scheduled Time	Daily Planning Conferences	0.5	0.0
	Daily Plan Review / Report Preparation	1.0	0.0
	Work Preparation	0.5	0.0
	Systems Maintenance	? / 7.0	0
	Research and Mission Objectives	? / 7.0	0.5
	Housekeeping and Laundry	0.0	2.5
Invariably Scheduled Time	Meals	3.0	3.0
	Exercise, Hygiene, Setup/Stow	2.0	2.0
	Pre-Sleep	1.0	1.0
	Sleep	8.5	8.5
	Post-Sleep	0.5	0.5
	Recreation	0.0	6.0
	Total	**24.00**	**24.00**

2.3.2 Science and Technology

As with most space exploration missions, a central interest of sustaining a lunar habitat is the advancement of science. NASA's Exploration EVA System Concept of Operations describes objectives for lunar missions defined by the scientific community (Coan, 2020). To paraphrase some of these objectives, they include studying the impact history of the inner Solar System, the evolution of the Moon as a planetary body, the history of solar radiation visible in lunar soil, volcanic and seismic processes, in-situ utilization of regolith and other resources, the lunar water cycle, and more. In itself, the practice of operating a lunar surface habitat would provide experience and knowledge for later missions on the Moon or Mars.

These high-level science objectives can be used to derive corresponding science requirements, and subsequently determine how a crew's time should be spent. According to Coan (2020), these requirements include mobility to reach regions of interest, EVA regularity to obtain samples and establish new procedures, the deployment of delicate instruments, setting up equipment to characterize the local environment, and more. In addition to the listed requirements, crew members would need to participate in health studies to better understand the effects of long-term living in hypogravity. Further, RETHi is particularly interested in the topic of autonomy, which will be discussed in 2.3.4: Autonomy.

2.3.3 Extra-Vehicular Activities

EVAs are a key part of both science and habitat maintenance. It can be expected that crew members living in a lunar habitat would perform EVAs regularly. The BVAD indicates that a lunar habitat crew may nominally perform 10 sorties per week, totaling up to 80 crew member hours (Anderson et al., 2018). This allocation is equivalent to 2 crew members performing an 8-hour EVA, 5 days per week. These EVAs may be shorter in length, and may be divided into multiple separate EVAs on a given day, but the general time spent matches with what is defined in the Exploration EVA System Concept of Operations, and is similar to plans for future Artemis missions (Coan, 2020). EVA sortie frequency may vary from Artemis mission plans because sustained SmartHabs are not as concerned about a short-term surface stay (< 2 weeks), and EVA protocol should be refined by the time of sustained surface habitation.

There are many factors which cause difficulty in performing EVA and take time away from other mission objectives. For one, EVA suits operate at low pressures and high oxygen content to facilitate mobility and prevent hypoxia. Human crew members must perform a prebreathe phase to purge nitrogen from their tissues and prevent decompression sickness. The exact length of a prebreathe depends heavily on suit pressure and habitat atmosphere, but it may be as short as 15 minutes, given the 8.2 psia (6.5 kPa), high-oxygen habitat atmosphere proposed by NASA to accelerate EVA procedures (Abercromby et al., 2015). A conservative upper bound of this duration in higher pressure atmospheres is 1 hour (Anderson et al., 2018). Another challenge is the radiation exposure concerns for astronauts, leading to bulkier and less maneuverable suits. The Exploration EVA System Concept of Operations describes areas of interest and potential future solutions for current limitations (Coan, 2020). Because the RETHi habitat exists in a notional future habitat, some of these issues are assumed to have been improved upon, allowing for regular and efficient EVA sorties.

2.3.4 Autonomy

One of the central pillars of RETHi is the Robotics Thrust, investigating potential applications of autonomous or human-operated robotic agents in future habitats. In addition to human crew, it is then important to look at the scheduling and operations of these robotic agents.

Robotic agents in concept have both advantages and disadvantages over crew members. For the advantages, they require no sleep, no food, no personal time, exercise, or hygiene, and they can be designed to operate outside the habitat with no suit or gradual entry/exit requirements. They require only charging and maintenance and could perform specialized tasks like heavy lifting or precise measurements. They can assist human crew with various tasks or even eliminate the need for a human to attend to a certain task. Robots like the Astrobee[*] system on the ISS are already contributing to the operation of space habitats. The trade-off of robotic crew is that they are not as versatile as people. The tools they are equipped with cannot perform universal tasks, and often they are only designed for a narrow, focused purpose. This limitation could present difficulties for portions of a habitat's lifecycle where it is uncrewed – an important design consideration for robotic agents.

Another major piece of the puzzle is the variety of autonomous systems that provide awareness and intelligence to the SmartHab. Sensors, fault diagnosis systems, and autonomous activity planners work in tandem to keep systems operational with minimal or no input from humans, especially during uncrewed periods (Badger, 2018). The work done by autonomous systems not only frees up astronauts from certain tasks, but also it supplements the tasks they do engage with and allows them to make more informed decisions. The implementation of autonomous planning and execution systems is an open area of research, and the precise functions of these systems are uncertain, as is the level of involvement during crewed periods. For the lunar SmartHabs described here, autonomous systems are assumed to be capable of operating the necessary functions to keep

[*] https://www.nasa.gov/astrobee

the habitat operational with no crew present and restore it to a livable state when humans return (see 2.4.4: Dormant State).

2.4 Day-In-The-Life Scheduling

The culmination of this review is the schedules shown in Figures 4-7, 9, and 11. The schedules are divided into 15-minute increments and include all invariably scheduled and variably scheduled activities for a crew of 4. As in Gateway (Richey et al., 2018), the notional crew is made up of a commander (CDR), an engineer (ENG), a doctor (DR), and a scientist (SCI). The format of the schedules is adapted from Richey et al. (2018).

Figure 4 shows a nominal template with all invariably scheduled activities – it can then be filled in with the relevant activities of the day.

GMT	**00**	.25	.50	.75	**01**	.25	.50	.75	**02**	.25	.50	.75	**03**	.25	.50	.75	**04**	.25	.50	.75	**05**	.25	.50	.75
HAB CDR												SLEEP												
HAB ENG												SLEEP												
HAB DR												SLEEP												
HAB SCI												SLEEP												

GMT	**06**	.25	.50	.75	**07**	.25	.50	.75	**08**	.25	.50	.75	**09**	.25	.50	.75	**10**	.25	.50	.75	**11**	.25	.50	.75
HAB CDR	POST SLEEP			BREAKFAST			MORN PREP					EXERCISE												
HAB ENG	POST SLEEP			BREAKFAST			MORN PREP													EXERCISE				
HAB DR	POST SLEEP			BREAKFAST			MORN PREP																	
HAB SCI	POST SLEEP			BREAKFAST			MORN PREP																	

GMT	**12**	.25	.50	.75	**13**	.25	.50	.75	**14**	.25	.50	.75	**15**	.25	.50	.75	**16**	.25	.50	.75	**17**	.25	.50	.75
HAB CDR		LUNCH																						
HAB ENG		LUNCH																						
HAB DR		LUNCH						EXERCISE																
HAB SCI		LUNCH														EXERCISE								

GMT	**18**	.25	.50	.75	**19**	.25	.50	.75	**20**	.25	.50	.75	**21**	.25	.50	.75	**22**	.25	.50	.75	**23**	.25	.50	.75
HAB CDR	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB ENG	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB DR	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB SCI	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				

Figure 4. DITL Schedule Skeleton

2.4.1 Operational States

The lifecycle of the notional habitat can be broken into several operational states. Brief summaries of these states can be found in Table 2. Of note are the low tempo and transition states. Due to the high-workload nature of frequent EVA, nominal mission phases are expected to be broken up by shorter intravehicular-focused periods. During these low tempo periods, crew members focus on tasks within the habitat. Regularly used pieces of equipment, especially vehicles, are also attended to during this phase. The transition state occurs when a crew is either preparing the habitat for dormancy as they leave (decommissioning) or recovering the habitat as they return (commissioning). This phase is an especially complex time, during which many characteristics of the habitat are in flux.

Table 2. SmartHab Operational States

Nominal Crewed State	**Low Tempo Crewed State**	**Transitional State**	**Dormant State**
Standard crewed operations of the habitat; frequent EVAs and science utilization tasks	Periodic low tempo 'rest' period; focus placed on maintenance and minimal EVA	State between crewed and dormant; habitat is altered for ensuing state (crewed or dormant)	Uncrewed operations; autonomous or remote utilization and upkeep

2.4.2 Nominal Crewed State

As discussed, a typical day in a SmartHab is likely to include EVA for 2+ crew members. Figure 5 shows the schedule of a sample EVA while the habitat is in a nominal operational state. After breakfast and planning, the 2 astronauts will perform EVA preparations, checking out their suits and performing a prebreathe. They will then don the suits and egress from the airlock. The entire window between EVA preparation and egress is heavily system dependent. Factors that can affect the duration required for these tasks include airlock design, EVA suit design, and the amount of crew on the EVA. 2 hours total for preparation and egress tasks is a conservative assumption that includes the NASA-defined 1 hour upper bound on prebreathe time as well as suit checkout, donning, and safe egress protocol (Anderson et al., 2018). The EVA is performed with at least 1 crew member in the habitat on standby at all times in case something goes wrong. The crew members on EVA will eat and drink supplies while in their suits, rather than returning to the habitat and having to perform ingress/egress procedures multiple times. Exercise is reduced to 1 hour for the crew members that performed EVA.

GMT	00	.25	.50	.75	01	.25	.50	.75	02	.25	.50	.75	03	.25	.50	.75	04	.25	.50	.75	05	.25	.50	.75
HAB CDR												SLEEP												
HAB ENG												SLEEP												
HAB DR												SLEEP												
HAB SCI												SLEEP												

GMT	06	.25	.50	.75	07	.25	.50	.75	08	.25	.50	.75	09	.25	.50	.75	10	.25	.50	.75	11	.25	.50	.75
HAB CDR	POST SLEEP			BREAKFAST			MORN PRI		EVA PREP/CHECKOUT					DON & EGRESS						EVA				
HAB ENG	POST SLEEP			BREAKFAST			MORN PRI		EVA PREP/CHECKOUT					DON & EGRESS						EVA				
HAB DR	POST SLEEP			BREAKFAST			MORN PREP					EXERCISE							STANDBY EVA SUPPORT					
HAB SCI	POST SLEEP			BREAKFAST			MORN PREP			SCIENCE			STANDBY EVA SUPPORT						EXERCISE				

GMT	12	.25	.50	.75	13	.25	.50	.75	14	.25	.50	.75	15	.25	.50	.75	16	.25	.50	.75	17	.25	.50	.75
HAB CDR					EVA								CLEAN UP & INGRESS					EXERCISE				EQUIP CHECKO		
HAB ENG					EVA								CLEAN UP & INGRESS					EQUIP CHECKOUT			EXERCISE			
HAB DR						LUNCH										SCIENCE								
HAB SCI		LUNCH					STANDBY EVA SUPPORT													SCIENCE				

GMT	18	.25	.50	.75	19	.25	.50	.75	20	.25	.50	.75	21	.25	.50	.75	22	.25	.50	.75	23	.25	.50	.75
HAB CDR	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB ENG	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB DR	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB SCI	EVE REVIEW/REPOR				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				

Figure 5. Nominal Crewed DITL Schedule with EVA

Long-duration missions require sufficient rest and recovery time to maintain the crew's health. Even during nominal operations, 1-2 days per week will be scheduled as 'off-duty'. The schedule shown in Figure 6 matches up with the weekend column of Table 1. Off-duty days will contain all of the typical invariably scheduled activities, alongside housekeeping/laundry, required daily science tasks, and time for recreation.

GMT	00	.25	.50	.75	01	.25	.50	.75	02	.25	.50	.75	03	.25	.50	.75	04	.25	.50	.75	05	.25	.50	.75
HAB CDR												SLEEP												
HAB ENG												SLEEP												
HAB DR												SLEEP												
HAB SCI												SLEEP												

GMT	06	.25	.50	.75	07	.25	.50	.75	08	.25	.50	.75	09	.25	.50	.75	10	.25	.50	.75	11	.25	.50	.75
HAB CDR	POST SLEEP			BREAKFAST						EXERCISE							HOUSEKEEPING & LAUNDRY							
HAB ENG	POST SLEEP			BREAKFAST					HOUSEKEEPING & LAUNDRY										EXERCISE				
HAB DR	POST SLEEP			BREAKFAST										RECREATION										
HAB SCI	POST SLEEP			BREAKFAST										RECREATION										

GMT	12	.25	.50	.75	13	.25	.50	.75	14	.25	.50	.75	15	.25	.50	.75	16	.25	.50	.75	17	.25	.50	.75
HAB CDR		LUNCH			SCI/MAINT									RECREATION										
HAB ENG		LUNCH			SCI/MAINT									RECREATION										
HAB DR		LUNCH			SCI/MAINT					EXERCISE							HOUSEKEEPING & LAUNDRY							
HAB SCI		LUNCH			SCI/MAINT				HOUSEKEEPING & LAUNDRY										EXERCISE				

GMT	18	.25	.50	.75	19	.25	.50	.75	20	.25	.50	.75	21	.25	.50	.75	22	.25	.50	.75	23	.25	.50	.75
HAB CDR								SUPPER			PRE-SLEEP TIME									SLEEP				
HAB ENG								SUPPER			PRE-SLEEP TIME									SLEEP				
HAB DR								SUPPER			PRE-SLEEP TIME									SLEEP				
HAB SCI								SUPPER			PRE-SLEEP TIME									SLEEP				

Figure 6. Nominal Weekend/Off-Duty DITL Schedule

2.4.3 Low-Tempo Crewed State

Figure 7 shows a schedule for a day during the low tempo phase of a mission. This day is similar to the nominal DITL, and it still involves plenty of work, but it is more focused on work that can be done inside the habitat (IVA), without performing EVA. Maintenance tasks are performed on regularly used equipment. Crew members receive a human factors and behavioral performance assessment to keep tabs on mental health.

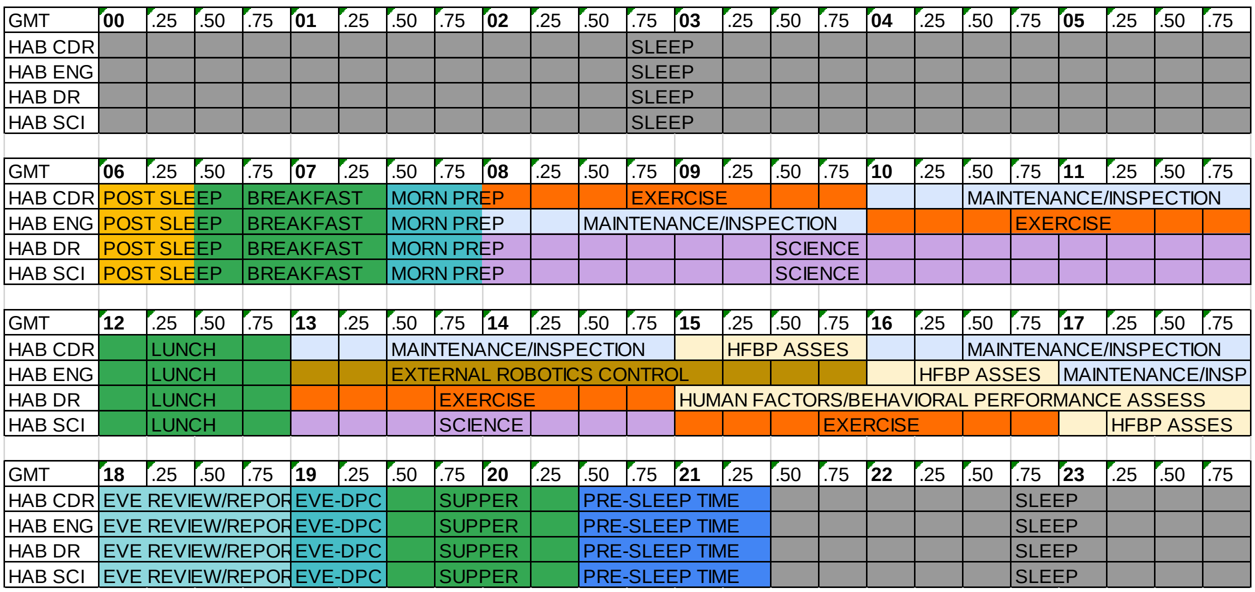

Figure 7. Low-Tempo DITL Schedule

2.4.4 Dormant State

While the habitat is dormant, no crew members are present, and so no daily human schedule is constructed here. Despite the absence of humans, dormancy is still an extremely important phase of the mission to consider as a design driver and significant portion of a SmartHab's lifetime. Extensive details on operations of each subsystem have been compiled by Badger (2018). Several considerations must be made for dormant operations. Environmental control and life support systems (ECLSS) undergo the most drastic changes as functionality can be reduced without the necessity of keeping humans alive. Many of these changes, as well as the order in which they occur, have been explained by Sargusingh & Perry (2017). In dormancy, pressure is maintained with nitrogen, rather than oxygen, to decrease fire risk. Temperature control is loosened to only what is necessary to preserve electronics and other delicate systems. Subsystems that involve water must be carefully managed to avoid microbial growth or freezing. Due to the reduction in ECLSS functionality, power draw is decreased, and power generating components may require adjustments (Badger, 2018).

The role of robotic agents in SmartHab upkeep is increased significantly during dormancy. Specialized robots must be present to perform necessary maintenance tasks, autonomously or by remote operation. Contingency response during dormancy is also different than with crew present: rather than preserving the life of the crew, the main goal becomes to preserve the integrity of the habitat. It must be kept in a safe and operable state for the arrival of the next crew. Certain considerations, such as maintaining safe evacuation routes for crew members, are no longer relevant (Badger, 2018). No hourly schedules are included here for uncrewed operations, although the robots and autonomous systems may still be busy tending to science experiments and cycling through various priorities in habitat upkeep. A modeler can instead use the crewed schedules and information provided here as context for the specific autonomous systems in their model and define the schedules as appropriate to their notional SmartHab and simulation granularity.

2.4.5 Transitional State

The transition from crewed to dormant (decommissioning), and vice versa (commissioning), entails a complex string of actions in a specific order. Especially for ECLSS, the order of actions is important to avoid unwanted disruption-prone states. Certain actions during transition will be performed by crew members, while others will be performed by software or autonomous systems and robots.

Figure 8, developed based on information from Badger (2018) and Sargusingh & Perry (2017), contains a flowchart of operations during the transition from a crewed state to dormancy, decommissioning. Those activities that can happen before the humans depart are performed by humans when possible. Humans are able to respond to faults more flexibly than robots and can decide whether to fix the problem or abort the transition. The last actions before egress are to set up any dormancy-specific robots and autonomous systems and reconfigure life support systems as described in 2.4.4: Dormant State. In Figure 9, this flowchart is mapped onto the established DITL Schedule format over two days. During transition operations, normal exercise duration may not fit in the schedule. After the crew has egressed, autonomous systems wrap up any leftover tasks, or tasks that could not be performed with humans present (ECLSS functionality reduction).

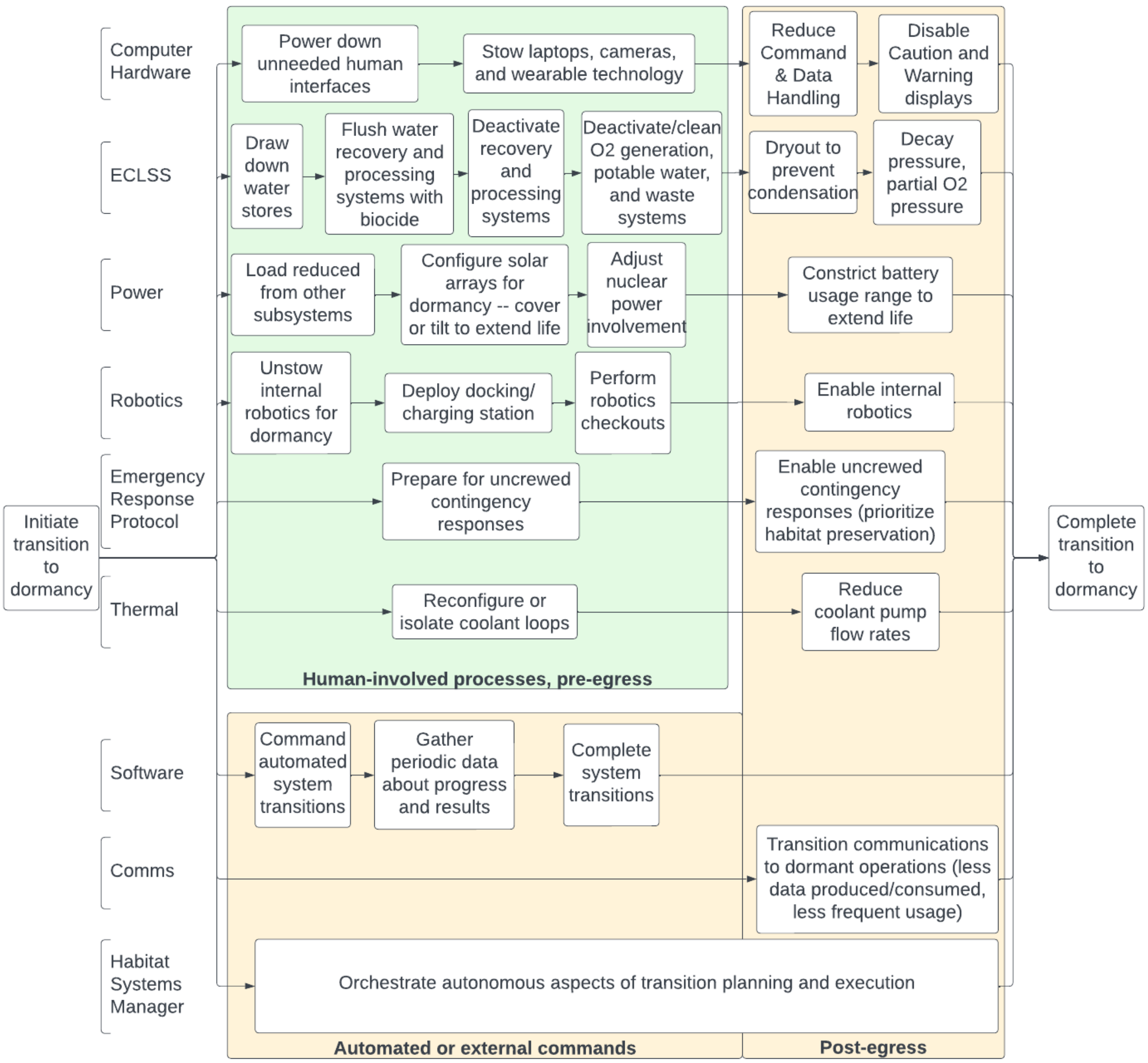

Figure 8. Decommissioning Flowchart

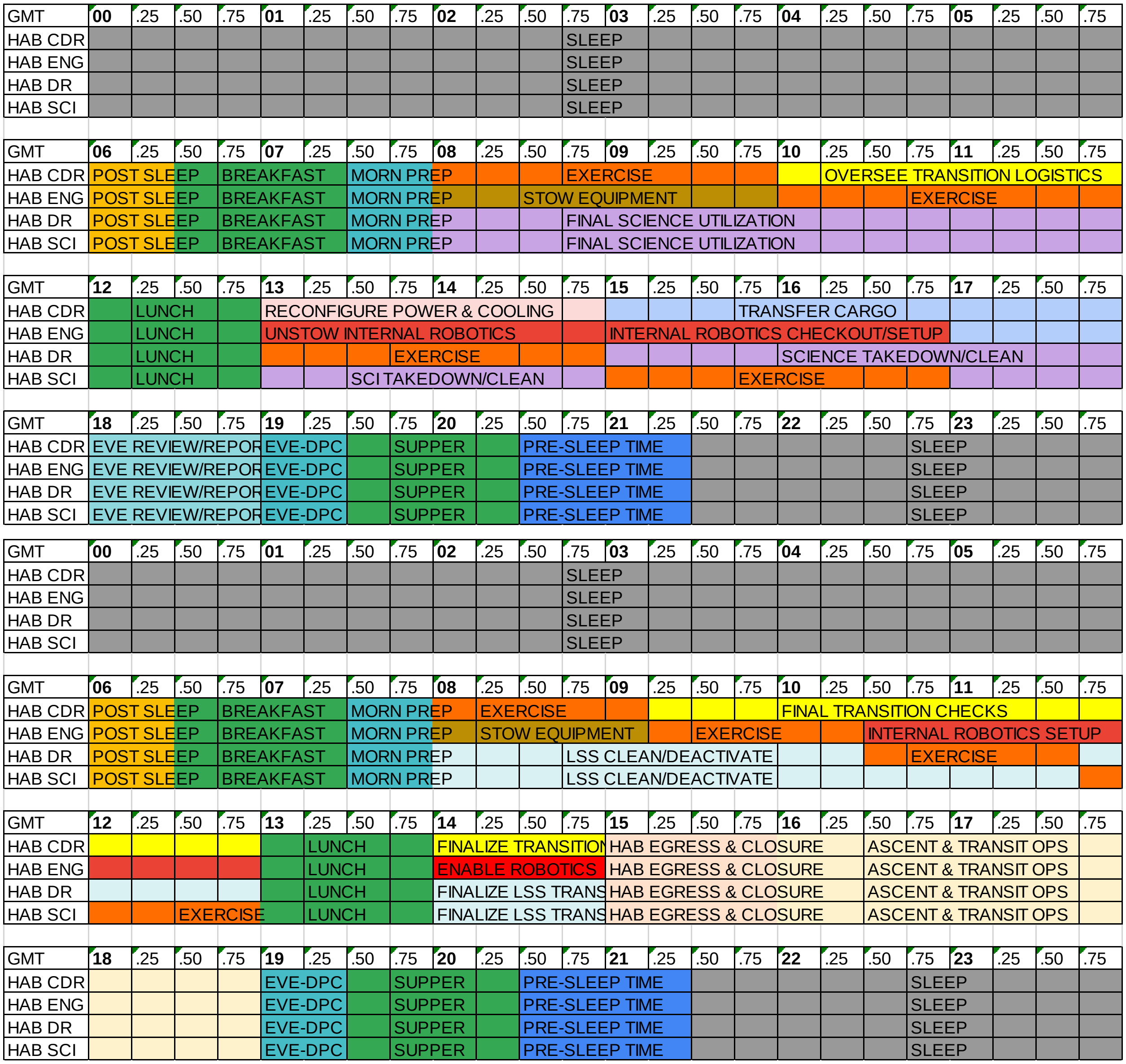

Figure 9. Decommissioning DITL Schedules

For transitioning the habitat back out of dormancy, commissioning, a different route is taken. Most activities happen before the crew returns so that faults can be diagnosed, understood, and the habitat is known to be safe to enter. For example, if an ECLSS function were malfunctioning, the proper procedure to follow to repair it upon arrival could be devised ahead of time along with potential contingency plans. It is important to establish and verify a livable atmosphere for the crew as early as possible. Figure 10 and Figure 11 contain the commissioning flowchart and mapping to the DITL schedule format, respectively.

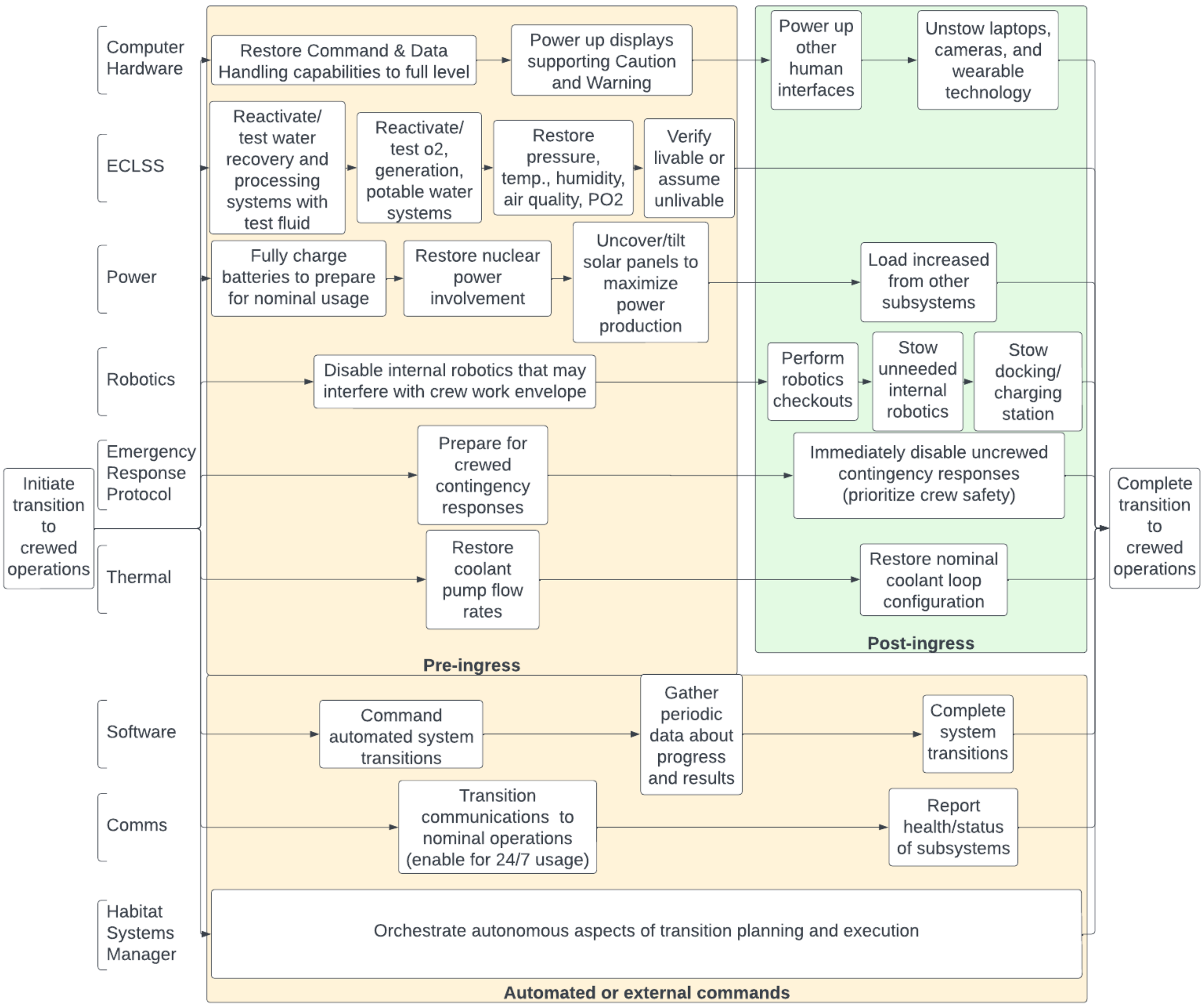

Figure 10. Commissioning Flowchart

GMT	00	.25	.50	.75	01	.25	.50	.75	02	.25	.50	.75	03	.25	.50	.75	04	.25	.50	.75	05	.25	.50	.75
HAB CDR												SLEEP												
HAB ENG												SLEEP												
HAB DR												SLEEP												
HAB SCI												SLEEP												

GMT	06	.25	.50	.75	07	.25	.50	.75	08	.25	.50	.75	09	.25	.50	.75	10	.25	.50	.75	11	.25	.50	.75
HAB CDR	POST SLEEP			BREAKFAST			MORN PREP			DESCENT & INGRESS PREP											HAB INGRESS			
HAB ENG	POST SLEEP			BREAKFAST			MORN PREP			DESCENT & INGRESS PREP											HAB INGRESS			
HAB DR	POST SLEEP			BREAKFAST			MORN PREP			DESCENT & INGRESS PREP											HAB INGRESS			
HAB SCI	POST SLEEP			BREAKFAST			MORN PREP			DESCENT & INGRESS PREP											HAB INGRESS			

GMT	12	.25	.50	.75	13	.25	.50	.75	14	.25	.50	.75	15	.25	.50	.75	16	.25	.50	.75	17	.25	.50	.75
HAB CDR	INITIAL CHECKOUTS					LUNCH				EXERCISE				RECONFIGRE POWER & COOLING										
HAB ENG	INITIAL CHECKOUTS					LUNCH			ROBOTICS CHECKO				SHUTDOWN/STOW ROBOTICS							EXERCISE				
HAB DR	INITIAL CHECKOUTS					LUNCH			LSS CHECKOUT/FINALIZE					TRANS		EXERCISE			EQUIPMENT UNSTOW/SETUP					
HAB SCI	INITIAL CHECKOUTS					LUNCH			LSS CHECKOUT/FINALIZE TRANSITION															

GMT	18	.25	.50	.75	19	.25	.50	.75	20	.25	.50	.75	21	.25	.50	.75	22	.25	.50	.75	23	.25	.50	.75
HAB CDR	EQUIPMENT UNSTOV				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB ENG	EQUIPMENT UNSTOV				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB DR	EQUIPMENT UNSTOV				EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				
HAB SCI		EXERCISE			EVE-DPC			SUPPER			PRE-SLEEP TIME									SLEEP				

Figure 11. Commissioning DITL Schedule

2.5 Significance

The pursuit of research on resilient and autonomous lunar SmartHabs is an important step towards future planetary habitation efforts on Mars and beyond. In order to create meaningful models and perform informative simulations, it is critical to understand qualitatively and quantitatively how these SmartHabs will operate. While no exact long-term SmartHab mission architectures have yet been realized, the descriptions in this chapter are an informed realization of what they will look like. For RETHi researchers and others, DITL timelines contribute to the realism and relevance of simulation-based SmartHab studies. The lessons learned in the development of these definitions and schedules are used to extrapolate SmartHab vulnerability factors in Chapter 3.

3. IDENTIFICATION OF RESEARCH QUESTIONS AND SIMULATION METHODOLOGY

In this chapter, we form the methodology of the thesis by identifying several of the necessary operational challenges to overcome in SmartHab design and consequently the research questions we will address.

3.1 Vulnerability

Beyond the well-defined and potentially unknown hazards that threaten extraterrestrial habitats, there are a number of non-constant conditions that complicate their operation. In order to adequately plan for contingencies and form a resilient mission design, certain details must be recognized and accounted for. In this thesis, we use the term ‘vulnerability’ to refer specifically to some condition in or around a SmartHab that worsens the otherwise constant classification of a given risk.

NASA typically classifies risks in terms of likelihood and consequences (Dezfuli et al., 2011). We consider vulnerability to be a condition that *changes* the likelihood or consequences of a risk. A SmartHab in a vulnerable state may be more likely to experience the impact of a risk because latent conditions that lead to the risk occurring are more plentiful. The consequences of that risk can change because the robustness or resilience of the SmartHab to the risk are somehow weakened in a temporary or permanent manner. Because the study in this thesis is based in simulations with predefined disruptions, we focus more on the changing consequences, as likelihood is not an active parameter in the simulation.

3.2 Identification of Operational Vulnerabilities

To better understand the conditions that can impact the consequences of a disruption, we look to our generalized definition of SmartHab mission operations and seek to derive a digestible set of ‘vulnerability factors’ which can be more precisely studied. The first step is to lay out the identified challenges, especially those unique to SmartHabs versus other space habitation efforts, and attempt to capture their implications succinctly.

The first obvious, defined quality of a SmartHab is the inherent focus on autonomy. Given the distance from Earth, the communication delays underline the importance of independence, and the added difficulty of evacuation (abort-to-orbit versus abort-to-Earth) amplify the dangers of unchecked disruptions. During both crewed and dormant periods, sensors and autonomous planners will play a central role. It is critical to identify disruption scenarios at the earliest possible point in time, before the damage has a chance to spread and propagate through coupled subsystems. In the DITL timelines in Chapter 2, it is demonstrated that crew frequently move between activities and likely locations in the habitat. Sometimes several crew members are asleep, and other times several are on EVA away from the habitat entirely. Paired with a dependence on sensor reliability, that can cause the SmartHab's awareness to fluctuate over the length of a mission. We identify **awareness** as the first vulnerability factor. The expectation is that the ability or inability of a SmartHab to diagnose a problem and 'nip it in the bud' will have major implications on the consequences of the disruption.

Another quality evident is the interdependent nature of SmartHab subsystems that support each other's functions. The power subsystem supplies energy to the ECLSS, which maintains an interior environment within the safe operable ranges for water-circulating or electronic components. The structure and structural protective layers contain the atmosphere and protect internal components from high velocity impacts. Damaged components are repaired by human agents that are kept alive by a livable interior environment or robotic agents that are charged by the power subsystem. Many components are dependent on consumable resources that may or may not be restorable without external intervention (i.e. arrival of supply shipments from Earth). Reduction in any single functionality for reasons of damage, resource supply strain, or maintenance can cause effects that ripple throughout other subsystems and potentially come back to affect other components in the original subsystem experiencing reduced function. To capture this interdependency, we introduce **subsystem availability** as the second vulnerability factor. As the availability of critical functions changes, so does the overall ability of the SmartHab to respond resiliently to disruptions.

One of the first unique qualities we identified of surface SmartHabs relative to orbital habitats like the ISS is the unfamiliar planetary surface environment. SmartHabs are subject to geologic surface interactions including dust, moonquakes, and the thermal influence of the ground. A SmartHabs location relative to the poles can impact the directness of solar rays and external temperature ranges. On the Moon, the near month-long day/night cycle is incompatible with Earth days. Inside, the thermal impact of sunlight (or lack thereof) inflicts varying power demand from the thermal control system. Air quality, air composition, and the state of temperature and pressure relative to the boundaries of the established safe ranges affect crew and equipment safety. The corresponding vulnerability factor, **environmental conditions**, is intended to encompass the effects of changing ambient circumstances. The impact of a disruption scenario may be worsened by the absence of solar power and other internal or external thermal/pressure states.

In the event of any disruption, there is a certain set of safety controls designed into the SmartHab mission that are intended to mitigate the effects of the disruption. We know from the discussion of SmartHab states in Chapter 2 that safety priorities and agent repair capabilities change throughout a mission. Changing priorities, such as the focus on human safety during the crewed state, can disqualify certain controls inconsistent with those priorities, which shrinks the set of options and has implications on the consequences of the disruption. Additionally, some safety controls may depend on the availability of limited repair-oriented supplies such as spare components. To include the effects of these phenomena on SmartHabs, we recognize **safety control options** as a vulnerability factor. This definition is not to say that more safety control options are a cause of additional vulnerability – it is rather the variation in which control options are employable that make the options a factor of disruption consequences and thus vulnerability. This factor is separate from subsystem availability because there are safety control options that may be restricted or available regardless of subsystem availability, and there are resource availability concerns which are unaffected by the subfactors that influence safety control options.

Lastly, the recent onset of effects from a disruption scenario does not preclude the risk for an additional disruption to occur – in some cases, it may increase the likelihood of that risk. The habitat is likely in its most vulnerable, weakened state when components or entire subsystems are experiencing reduced functionality. Reduced functionality may stem from more than just external disruptions. In the discussion for the identification of subsystem availability as a factor, we noted that scheduled system maintenance can involve disabling critical capabilities. In addition, the commissioning and decommissioning flowcharts in Chapter 2 indicate that transitions to and from dormancy involve various moving parts during a time period with comparatively little operational experience. The SmartHab may undergo unfamiliar states during transition where the usual contingency plan is unavailable for a scenario that would typically only be experienced while that plan is active. For example, human crew are likely to always be present when certain life support systems, such as air quality control and potable water delivery, are in operation (because those systems would be inactive during dormancy). During the commissioning ECLSS ramp-up in preparation for crew arrival, a failure in one of these systems would require a new strategy. To capture the vulnerable state a habitat is placed in when conditions are already off-nominal, we identify the vulnerability factor of **recent events**.

3.3 Operational Vulnerability Factors

Table 3 catalogs the identified vulnerability factors and the more specific subfactors that influence them. With the goal of better grasping these complications via simulation, they will form the basis of the research questions to follow. Table 12 (in Chapter 5) is the counterpart of this table and includes the lessons learned through simulation.

These factors are not necessarily independent from each other – in fact, their causes and effects are largely overlapping, giving significance to a simulation-based approach to clarify their distinctions and supporting the intent to capture as many relevant behaviors as possible within the entire set. While each represents a unique major concept, the research questions developed may apply to several vulnerability factors. For simulation set design, we aim for the most illustrative and interesting scenario. The sets are written with regard to lunar habitats specifically because the MCVT was designed to that environment.

Table 3. Operational Vulnerability Factors and Subfactors

Factor	Subfactors of Influence
Awareness	• Crewing status • Crew preoccupation • Location of disruption • Detectability of disruption • Sensor functionality
Subsystem availability	• Energy storage • Solar power strength • Systems disabled for maintenance

Environmental conditions	• Interior environment
	  ○ Temperature setting
	  ○ Pressure setting
	  ○ Air composition/quality
	• Exterior environment
	  ○ Surface temperature
	  ○ Solar angle
	  ○ Location

Safety control options	• Crewing status • Crew preoccupation • Agent capabilities • Disruption location • Resource concerns
Recent events	• Lingering effects from prior disruptions • In-progress transition to/from dormancy • Airlock usage

3.3.1 Awareness

Awareness is influenced by a number of independent subfactors. As touched upon in Table 3, one of the main factors affecting awareness is the presence or absence of a crew, and the crew's activities at a given point in time when present. As shown in Chapter 2, each astronaut could be performing one of several tasks in various locations. A portion of the crew may be outside the habitat, asleep, or busy with some project that consumes their attention. If they happen to already be in the location where a disruption begins, they will of course detect it more quickly. During uncrewed portions of the missions, sensors and diagnosis systems will provide the habitat's awareness. These sensors will be subject to nonzero failure rates and will be designed for the detection of specific disruptions. Unknown risks may go undetected, and even expected risks may be difficult to identify or pinpoint.

Awareness becomes especially critical during dormant phases of the habitat, which is why it exists as its own distinct research topic in RETHi. Its inclusion in this table is not to say that we will attempt to fully tackle the concept in this thesis, but rather that the amount of time that passes before a disruption is diagnosed, as well as the accuracy of that diagnosis, will affect the system's resilience to that disruption. Awareness is then an important factor of habitat vulnerability. In order to understand the effects of these conditions, we introduce Research Question 1 (R1).

R1: How does the level of awareness affect the propagation of disruptions?

To approach this question with the user-modifiable inputs in the MCVT, we can control the amount of time before FDD recognizes a disruption has occurred and triggers the agent to make repairs. We choose a fire as the disruption scenario because its effects will naturally worsen as it is allowed to grow and spread. The fire starts near, but not directly on, a power distribution hub. In this simulation set, shown in Table 4, the amount of time between the onset of the fire and its detection will represent the level of awareness. The reasons for a certain level of awareness are not defined – it could be due to any of the subfactors already discussed. We will observe the temperature and pressure in the habitat in each simulation.

Table 4. Simulation Set R1

Disruption Scenario	Location	Time Until Detected (s)	Plots
Fire	Near power distribution	1s	Fire radius, Temperature, Pressure
		31s	
		61s	
		91s	
		121s	
		151s	

3.3.2 Subsystem Availability

Subsystem availability is a broad category spread out across the entire habitat. Throughout the regular course of usage, maintenance, and internal failures, the availability of resources within a subsystem can fluctuate. For one example, energy storage may deplete in the absence of solar power. Solar power itself can be thought of as another subsystem resource that is not always available. Other components, such as ECLSS fans, may be temporarily disabled to allow for repair or replace procedures.

While a subsystem or the capability that it provides is unavailable, the habitat lacks the design-intended benefits of that capability. This limitation may affect the habitat's ability to maintain a safe interior environment. In the case of a disruption, it can exacerbate damage or prevent adequate response. Predictive capabilities in autonomous planning systems could help influence response decisions based on estimates of resource drain, for example, by determining how much time remains before batteries are depleted or the IE passes outside of the safe range. With resources and options constrained, prioritization must occur to reflect which capabilities are the most mission critical.

R2: How do we select which damage to address first when multiple systems or components are affected by a disruption?

The primary interest in planning a simulation set for this question is to affect several damageable components in order to create more potential permutations of repair orders. To this end, we select a meteorite that pierces the dome of the habitat and impacts the internal power systems, cutting off contributions from solar and nuclear generators outside the habitat. At the same time, perhaps due to a secondary impact on the outside of the habitat, dust accumulates on the nuclear radiators panel, reducing their ability to cool and overall nuclear power generation. In each simulation shown in Table 5, the repair order is written sequentially. Simulations where the hole is the final repair are not considered.

Table 5. Simulation Set R2

Disruption Scenario	**Location**	**Repair Order**	**Plots**
Meteorite impact	Through dome onto power distribution; surface outside habitat	Hole - Power Distribution - Dust	Temperature, pressure, power supplied, hole size
		Hole - Dust - Power Distribution	
		Power Distribution - Hole - Dust	
		Dust – Hole – Power Distribution	

3.3.3 Environmental conditions

Environmental conditions on both sides of the habitat hull are a constant concern for the safety of crew and equipment. Externally, the day/night cycle inflicts wide variations in surface temperature dependent on the location of the habitat, whether polar or nearer to the equator. Internally, specific settings or ranges for temperature and pressure are chosen to be maintained by the ECLSS. These settings may be selected for crew comfort, to support EVAs, or to preserve delicate equipment or experiments. The air composition depends on mission design and phase: partial pressure oxygen being maintained higher during the crewed phase to avoid hypoxia, and fully decreased during uncrewed phases to prevent fire. Small dust particles or smoke can affect air quality.

Changing surface temperatures naturally propagate to affect structural wall temperatures inside the habitat and must be compensated for by thermal control. In the absence of sunlight, solar power will be negligible, and overall power generation will decrease. Different temperature and pressure settings make the habitat vulnerable to different threats. For example, a habitat maintained at a lower pressure will have less time to respond to a hull breach before criticality. A habitat maintained at a higher temperature will have less time to respond to a fire. Poor air quality impacts crew health and can potentially damage ECLSS if recirculated.

R3: How does the lunar day and night cycle affect the propagation of disruptions?

One of the most major changes between day and night is the availability of solar power. To highlight this variable, we choose a scenario that will affect the other power sources – a fire originating from the batteries. Upon diagnosis, the agent will extinguish the fire then begin repairing the affected power converters. The power system will prioritize critical loads if there is not enough power supplied to cover everything. Solar angles of 0°, 45°, and 90° represent pre-dawn, early morning, and lunar noon, respectively. While a solar angle of 0° is not exactly night, the sun is still on the horizon, and solar generation is effectively zero. Table 6 shows the full simulation plan.

Table 6. Simulation Set R3

Disruption Scenario	**Location**	**Solar Angle (°)**	**Plots**
Fire	Power (energy storage and distribution)	0	Power loads supplied, solar generation, temperature
		45	
		90	

3.3.4 Safety control options

Once again, the presence or absence of the crew has the most bearing on the involvement of this variable. Human astronauts will have access to different tools and capabilities than robotic agents. Humans can move, interpret, and approach problems in different ways. Robots may carry other advantages, such as strength, precision, or durability to hazards that might threaten a human's health. This distinction can shift the effective list of what is possible in the face of a disruption. The location of the disruption, and especially whether it is inside or outside the habitat dome, may lend itself to a robotic approach. Since crew members have busy schedules and a mission priority is to optimize the amount of time spent on scientific tasks, they may be unavailable to perform repairs at a given time, or it may simply be more efficient for robots to share the workload. While the crew can expand the list of safety controls thanks to human versatility, they can also cause limitations. Crew safety is paramount, meaning any safety controls that would endanger the crew are effectively off-limits while they are present. For some examples, oxygen cannot be cut off from the habitat to starve a fire, unless the crew also dons EVA suits. Habitat areas affected by fires or hull breaches cannot be sealed off from the rest of the habitat if the sealing-off would trap crew members or inhibit evacuation. Some other safety controls may depend on a limited resource, such as component replacements, that may deplete over the length of a mission.

Any time a disruption occurs, one of the first steps to choosing a response is to recognize the active set of what safety controls are available. Once the options are laid out, they can be ranked against each other based on their requirements and expected consequences. Combining multiple safety controls means selecting the order in which they occur, which may depend on minute details of the disruption, as addressed by R4. The selected safety control(s) must reflect the 'best' expected outcome based on mission priorities and risk assessment. R5 explores the impact of changing priorities and changing control options.

R4: How do we change our response to disruptions of varying severity?

Meteorite impact is a disruption scenario in which one of the major impacts, the size of the hole in the structure, can be finely tuned to achieve varying results. This simulation set, shown in Table 7, puts five different hole sizes to the test for two potential responses: fixing the pressure and thermal controls first, or sealing the structural hole. The goal is to assess whether the outcome of one response becomes more favorable as the hole size (severity) increases.

Table 7. Simulation Set R4

Disruption Scenario	Location	Repair Order	Hole Size (m)	Plots
Meteorite Impact	Through dome onto ECLSS	Damaged ECLSS - Structural Hole	0.0025	Temperature, pressure
			0.005	
			0.0075	
			0.01	
		Structural Hole - Damaged ECLSS	0.0025	
			0.005	
			0.0075	
			0.01	

R5: How should differing safety priorities between dormant and crewed states be reflected in disruption response actions?

One safety control available for disruption scenarios that affect the interior environment of the habitat is to close the pocket door, dividing the habitat into two isolated halves. While crew are in the habitat however, this control must be used carefully to avoid trapping astronauts in the same zone as the hazard or otherwise impeding their path to safety. For simulation set R5, outlined in Table 8, a structure-breaching meteorite impact and fire are tested separately against a dormant-representative habitat, with the pocket door ready to be employed, and a crewed habitat containing astronauts in both zones. The dormant and crewed habitats each have different safe ranges for pressure and temperature, as defined in Table 10. The pressure and thermal control systems are given commands to maintain pressure at least 2000 Pascals from the lower safe boundary and temperature at least 2 Kelvin from both ends of the safe range.

Table 8. Simulation Set R5

Disruption Scenario	**Location**	**IE Safe Ranges**	**Pocket door (1 indicates active)**	**Plots**
Meteorite Impact	Through dome, zone 1	Dormant	1	Pressure
		Crewed	0	
Fire	Zone 1	Dormant	1	Temperature
		Crewed	0	

3.3.5 Recent events

Certain events can create off-nominal conditions in the habitat that make it more vulnerable. Disruptions will generally leave lingering effects for some amount of time. A second disruption event is unlikely (not impossible) to occur independently, but one could absolutely occur as a result of the first, or from a common cause. Intentional actions such as periodic maintenance or repair can involve disabled subsystem components. Airlock usage for EVA exposes the interior environment of the habitat to one fewer layer of protection. Transitions between crewed and dormant states are perhaps the most major example in the category of recent events causing vulnerability. The definition of 'nominal' is actively changing during a transition, complicating the expected interactions between subsystems.

When a disruption occurs amidst already off-nominal conditions, special care must be taken to respond optimally. The disruption could worsen the existing vulnerability or create new damage that spreads resources more thinly. Off-nominal conditions can compound with several other vulnerability factors, narrowing the window of safe response. The effects of one disruption could even make it more difficult to properly diagnose another. R6 assesses response considerations in the unfortunate-yet-possible case of multiple disruptions occurring in rapid succession.

R6: How does the potential for a second disruption affect the outlook of the first?

There are myriad possibilities of combinations for when a second disruption scenario occurs before the effects of the first have fully dissipated. Both disruptions might affect the same components, regions of the habitat, or resources, or they may have no overlap in their effects.

Both of these scenarios are represented in the simulation set for R6, shown in Table 9. In this simulation set, a meteorite hits the nuclear generator panels outside the habitat, causing damage and dust accumulation. The scenario where *only* the meteorite impact occurs serves as a control for simulations containing the other two disruption scenarios: a fire affecting power storage and distribution, and a fire affecting the thermal control system.

Table 9. Simulation Set R6

First Disruption Scenario	Location	Second Disruption Scenario	Plots
Meteorite	Nuclear generator	None	Temperature, energy storage
		Fire (PW)	
		Fire (ECLSS)	

3.4 Simulation Qualifications and Assumptions

These simulation sets can be seen as case studies of the MCVT's applications for the study of SmartHabs early in the design process. The answers to research questions developed in Chapters 4 and 5 are not comprehensive and represent only the information gleaned in the process of developing generalized definitions of SmartHab mission operations and vulnerabilities.

3.4.1 Disruption Scenario Selection

The disruption scenarios in these simulation sets are selected to best highlight the behaviors and characteristics related to each research question. These disruption scenarios are generally biased toward the scenarios with the most options for customization and observation within the MCVT architecture. Further research into each research question could be performed with differently selected disruption scenarios, initial conditions, and habitat designs.

Fire

Fire inside the habitat is a legitimate risk and one that is relatively fleshed out within the MCVT, having the capacity to vary the size, location, spread rate, and exact damage caused by a fire. In space habitats, the amount of oxygen maintained in the interior environment is balanced between the risk for fire and the potential to cause hypoxia in human inhabitants. As discussed in Chapter 2, a SmartHab nominal pressure setpoint could be as low as 8.2 psia (57kPa), a value closer to the pressure of EVA suits, in order to facilitate rapid egress with minimal prebreathe time; it also necessitates a higher oxygen content of 34% to prevent hypoxia. Versus the current ISS setpoint of 21% oxygen, the increased oxygen concentration contributes to enabling changing mission objectives at the cost of increasing fire risk (Anderson et al., 2018). The increased risk of fire merits additional study into the consequences of fire propagation on the interior environment and subsystems at risk of damage.

During dormant periods, hypoxia is not a concern, and the pressure in the habitat will be maintained with nitrogen specifically to reduce the risk of fire (Badger, 2018). Despite this mitigation, the shift from high oxygen content is not instantaneous – pressure inside the habitat is allowed to naturally decay to dormant values during the decommissioning state transition. In addition, before the crews return to recommission a dormant habitat, life support values are restored to nominal crewed values to ensure system functionality. These two periods, the time after a crew's departure yet before oxygen content reaches minimum, and the time before a crew's arrival when oxygen is restored to crewed nominal, represent two significant durations during the transition/dormant phases where the heightened fire risk still exists. Fire is a disruption scenario with relevance to all SmartHab states, necessitating study into both human and robotic agent responses.

Fire represents a complex hazard that worsens in impact the longer it propagates. While it spreads and drives up the interior temperature, the component damage it causes provides the opportunity to study *compound* repair strategies that differ in more than just the kind of safety control selected.

Meteorite Impact

The lunar surface is frequently impacted by meteorites and micrometeorites in a wide range of sizes and velocities, with impacts becoming less frequent as we observe objects of larger diameter. Micrometeorites with a mass on the order of a milligram may strike SmartHab-sized structures about once per year (Heiken et al., 1991). Larger micrometeorites, on the order of grams, can be expected to cause functional damage to habitat systems and are a necessary consideration for structures intended to persist for several years and potentially grow in footprint.

Meteorite impacts are a useful disruption for research because, similar to fire scenarios, they are thoroughly implemented in the MCVT and highly customizable. As a complement to the advantages of simulating fire-based disruption scenarios, meteorites can also impact SmartHab components outside of the dome. In addition, a pressure leak caused by meteorite impact to the dome will not grow in size in the way a fire does, representing a different source of damage with the same potential for studying complex repair strategies. To address the leak alone, responses vary among repair, employing pressure control to 'feed the leak', having crew don EVA suits to survive the unsafe pressure and temperature incurred, isolating the affected zone, and a full abort/evacuation of the SmartHab (Trujillo & de Weck, 2018). These responses can be combined with the additional responses to other component damage to create interesting scenarios for research.

Other Disruptions

Other disruption scenarios within the MCVT have potential for research in a similar capacity but, at this time in version 6.3, are generally less thoroughly implemented or less versatile, limiting what parameters can be varied across a single-disruption simulation set. Airlock failures, having the effect of a gradual decrease in interior pressure, are addressed in the MCVT by simple repair and compensation by pressure control. The nuclear coolant leak scenario affects only the nuclear power generation and other subsystems minimally over long periods of simulation. Moonquakes of extreme magnitude can shake the structure and cause damage to both ECLSS components and energy storage, but the realistic impact of this scenario is not as pronounced or well-defined as for fire or meteorite impact. Lastly, sensor failure in the MCVT represents an important case of isolated component failure (in the absence of external disruption), but limitations lie in the effects of the failures as implemented (the scenario can inflict NaN sensor readings but not zero-values or sensor drift, and thermal/pressure control only depend on the readings if the user modifies the Simulink architecture).

To achieve the same results as meteorite impact or fire scenarios with the use of the other currently available disruptions, a user would need to carefully combine multiple types of disruptions. This additional complexity is seen as a potential hindrance to the clarity and verifiability of simulation results. The explanation of how different scenarios accumulate could be more difficult to follow and distract from the significance of the results. Finally, the minute likelihood of several MCVT disruption scenarios occurring to a real SmartHab simultaneously justifies first studying more realistic results from fewer disruption scenarios that still afford the same complexity.

3.4.2 Scaling

All simulations in the MCVT pertain to a lunar habitat, but could be conceivably extrapolated to a Martian habitat, with qualifications, in certain cases. The size of the habitat is scaled, affecting distances, surface areas, and the volume of the air in the habitat, which can affect the speed of certain dynamics. User-input details such as fire radius and hole radius are also appropriately scaled to the size of the habitat.

The repair and agent travel times are also tuned to make the desired dynamics visible within the bounds of each simulation. The selected values are notional, and all quantification is unique to the MCVT model of the RETHi NRH. As such, the simulation results should not be viewed as realistic demonstrations of time scales within Lunar habitat disruption scenarios.

3.4.3 IE Safe Ranges

Simulation discussions in Chapter 4 refer to safe ranges for pressure and temperature. These numbers are based on current ISS safe ranges and were obtained from a discussion with M. Sargusingh (*Nasa Johnson Space Center, Houston, TX 77058*) in September 2021. The ranges are outlined in Table 10. The safe ranges for the crewed state are primarily limited for the safety of humans in the habitat. The ranges for the dormant state are determined by the tolerable ranges for habitat equipment, such as ECLSS components that contain water.

Table 10. Safe Temperature and Pressure Ranges

Habitat State	**Temperature (K)**	**Pressure (Pa)**
Crewed	291.5 – 299.8	70,326 – 101,353
Dormant	274.8 – 309.8	65,500 – 101,353

4. SIMULATION RESULTS AND DISCUSSION

In observing the course of a SmartHab DITL, we naturally encountered some of the challenges that the design of the SmartHab and mission architecture must address. In this chapter, we address the challenges and vulnerabilities framed as questions to be answered via simulations run using the MCVT. Because we're concerned with the resilience of a SmartHab, we put the system through disruptions and attempt to identify the main factors involved in survival and recovery.

In the case of a disruption scenario with a severe effect on the health state of the habitat, factors with design implications have been found to fall into five general areas, already explained in Chapter 3. To reiterate, the vulnerability factors are awareness, subsystem availability, environmental conditions, safety control options, and recent events. These factors change throughout the mission on varying timescales. The MCVT user inputs and architecture are manipulated to best highlight the factors of interest across multiple simulations for each research question.

For each question, we have formed a plan for answering the question with the MCVT. In this chapter, we follow up with a presentation of simulation results and their analysis.

4.1 How does the level of awareness affect the propagation of disruptions? (R1)

The first plot for this set of simulations, Figure 12, is an illustrative reference to show the extent to which the fire grows in each simulation. The fire starts with a given radius at t=50s. As it is allowed to propagate, the radius increases at a linear rate. When the agent begins to extinguish the fire, the radius decreases according to a predefined rate. The time between the onset of the fire and when the agent moves to manage it is determined by the 'awareness' delay and is indicated by the labels in the legend. The fire originates at a point in the habitat approximately 0.09 meters away from a power distribution hub. In simulations where the fire radius surpasses this value (detection delays greater than 60s), power supply is cut off to the thermal control system. Reference Table 4 for the simulation set outline.

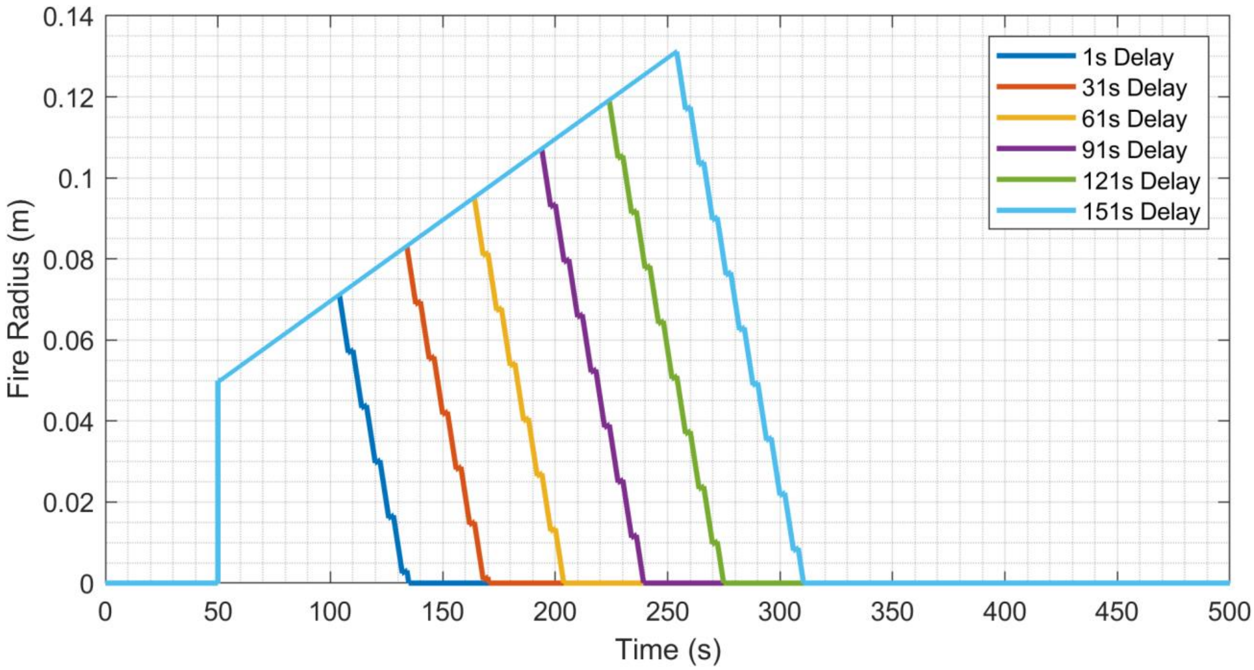

Figure 12. Fire Radius for Simulation Set R1

Figure 13 and Figure 14 show the temperature and pressure for each simulation in this set. Both exhibit similar dynamics – as the fire is allowed to spread in the delayed-response simulations, the increased heat drives the pressure higher in the habitat. Thermal control attempts to compensate by injecting cooled air, further increasing pressure away from the set point.

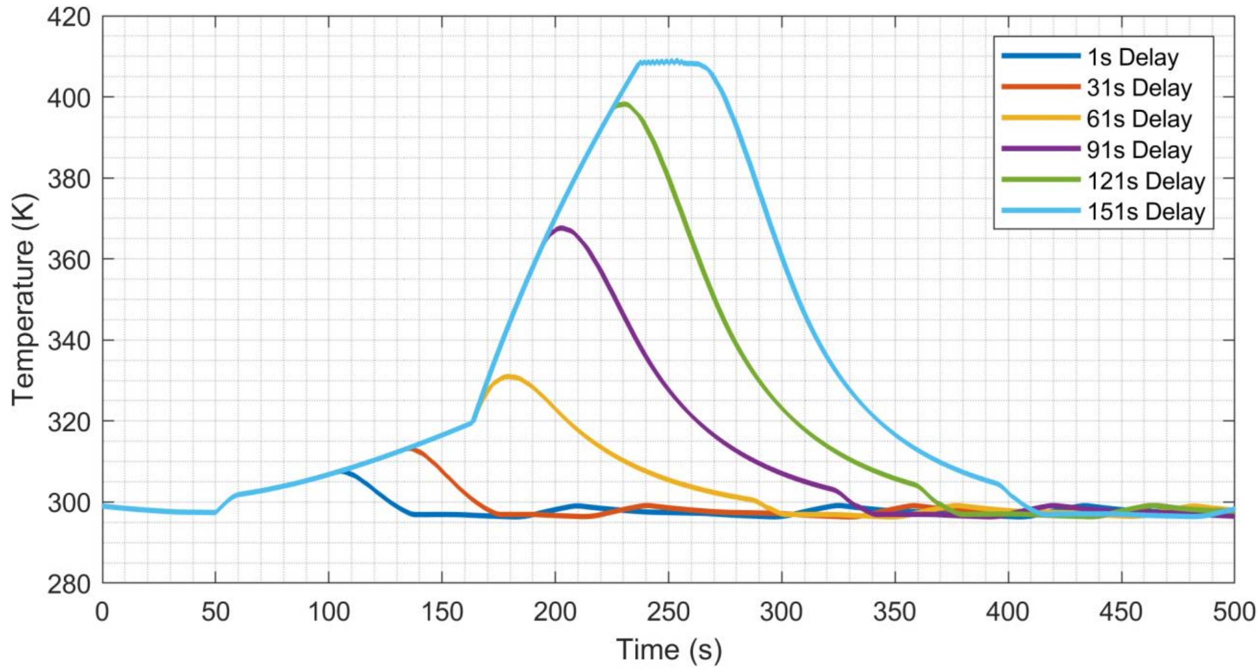

Figure 13. Temperature for Simulation Set R1

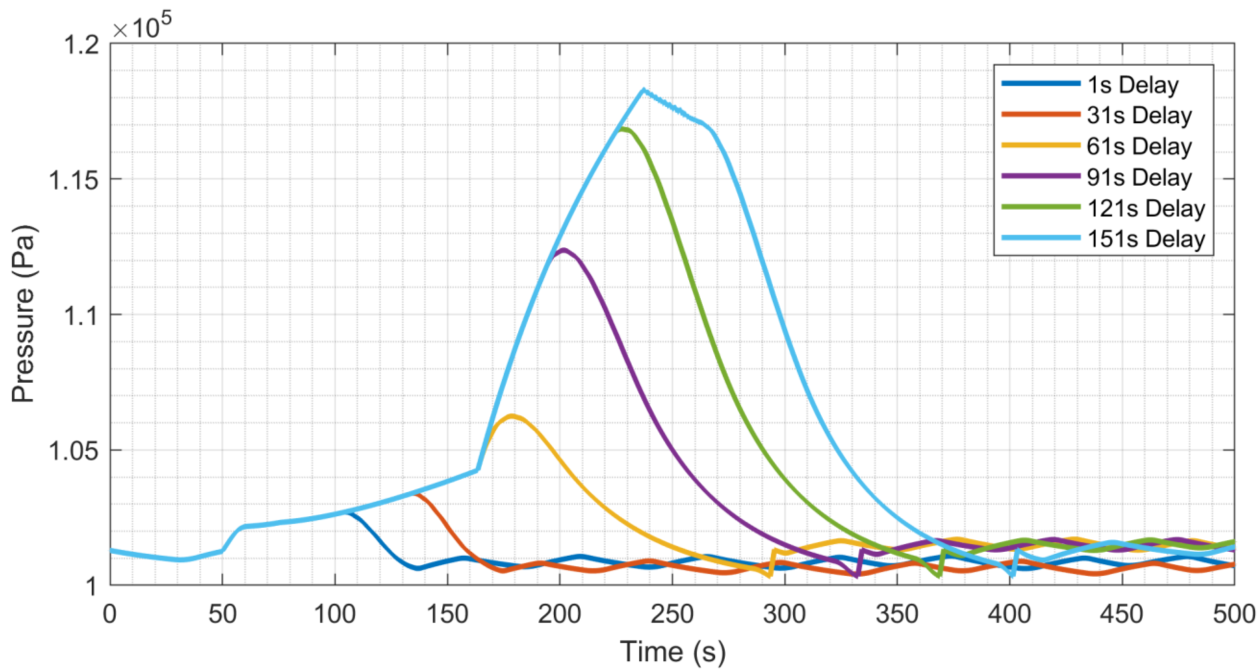

Figure 14. Pressure for Simulation Set R1

At about t=165s, in the simulations in which the fire is untouched by the agent (the latter four), the fire reaches the aforementioned critical radius that damages power distribution. With the thermal control system receiving an inadequate amount of power, the habitat's ability to cool the interior environment is reduced. This phenomenon is visible as a pitch upwards in the slopes of the temperature and pressure curves, which have already exceeded the upper limit of the safe ranges for both crewed and dormant habitats. Extended periods of time in this unsafe territory can affect the habitat as well as the agent's ability to complete repairs itself.

Significance: The habitat's failure to recognize the disruption earlier complicates the damage and response. Not only must the agent spend more time extinguishing larger fires, but the agent must also make additional repairs to newly damaged subsystem components. This additional repair duration prolongs the amount of time the habitat spends in a hazardous state. Other risks not modelled in the MCVT, such as smoke from the fire invading air circulation systems, can add additional damage. Based on the radius of the fire when it is detected, a rapid determination must be made as to whether repair is possible, or evacuation is the safer option. Prior knowledge of such trends contributes to more informed, more optimal response decisions.

4.2 How do we select which damage to address first when multiple systems or components are affected by a disruption? (R2)

In this set of simulations, a meteorite pierces the habitat structure and damages power converters while an uptick in dust accumulation outside the habitat reduces the efficiency of the nuclear generator. Table 5 contains the simulation plans for this set. There are three major components to the damage: the hole in the structure, dust on the nuclear panels, and restricted power distribution. A response must be carefully selected to account for the functionality of each damaged component. For visibility, the repair order details have been reproduced in Table 11.

Table 11. Repair Orders for Simulation Set R2

Index	Repair Order
1	Hole - Power Distribution - Dust
2	Hole - Dust - Power Distribution
3	Power Distribution - Hole - Dust
4	Dust – Hole – Power Distribution

Figure 15 tracks perhaps the most critical damage, the structural hole. While the hole remains unsealed, air leaks out of the habitat, decreasing pressure and temperature. Pressure and thermal control systems attempt to compensate using what power they are supplied. As the hole is a major source of continuing IE degradation, it is likely the most important damage to address first. Repair orders 1 and 2 take this approach while repair orders 3 and 4 take time to prioritize the power availability.

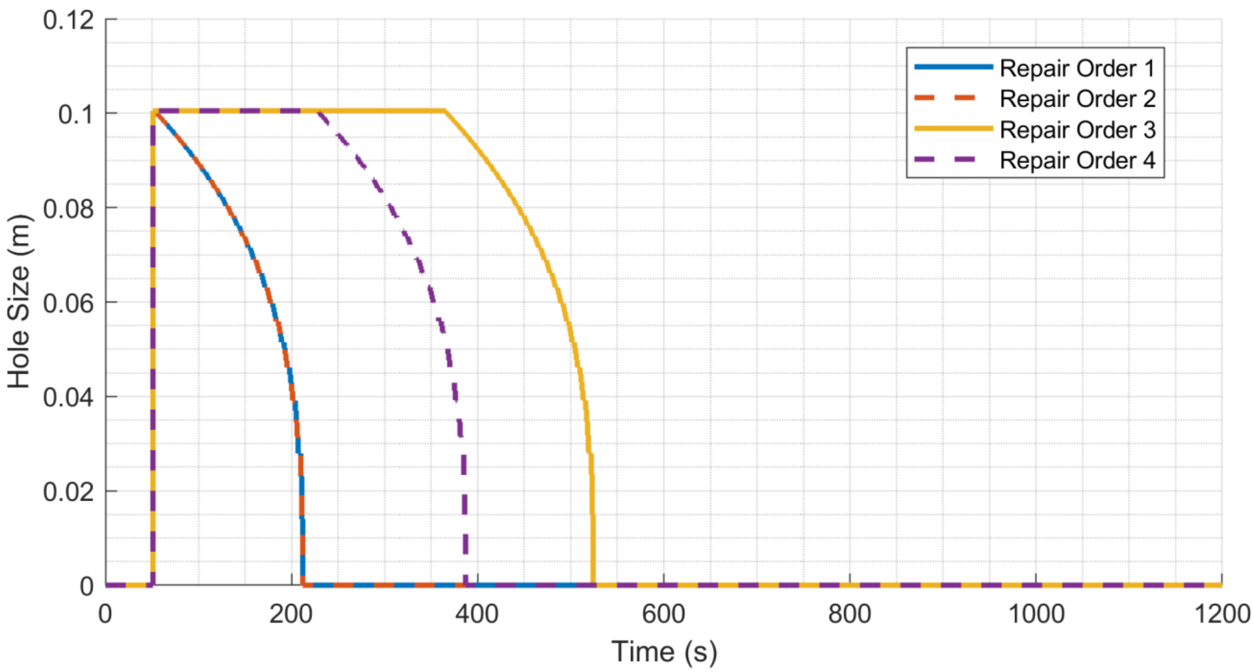

Figure 15. Hole Size for Simulation Set R2

Figure 16 highlights the consequences of the power distribution system damage. The power system in the NRH prioritizes the set of critical loads with whatever supply is available – these are primarily ECLSS and the autonomous command systems. When power is not supplied to these systems, the habitat is at great risk.

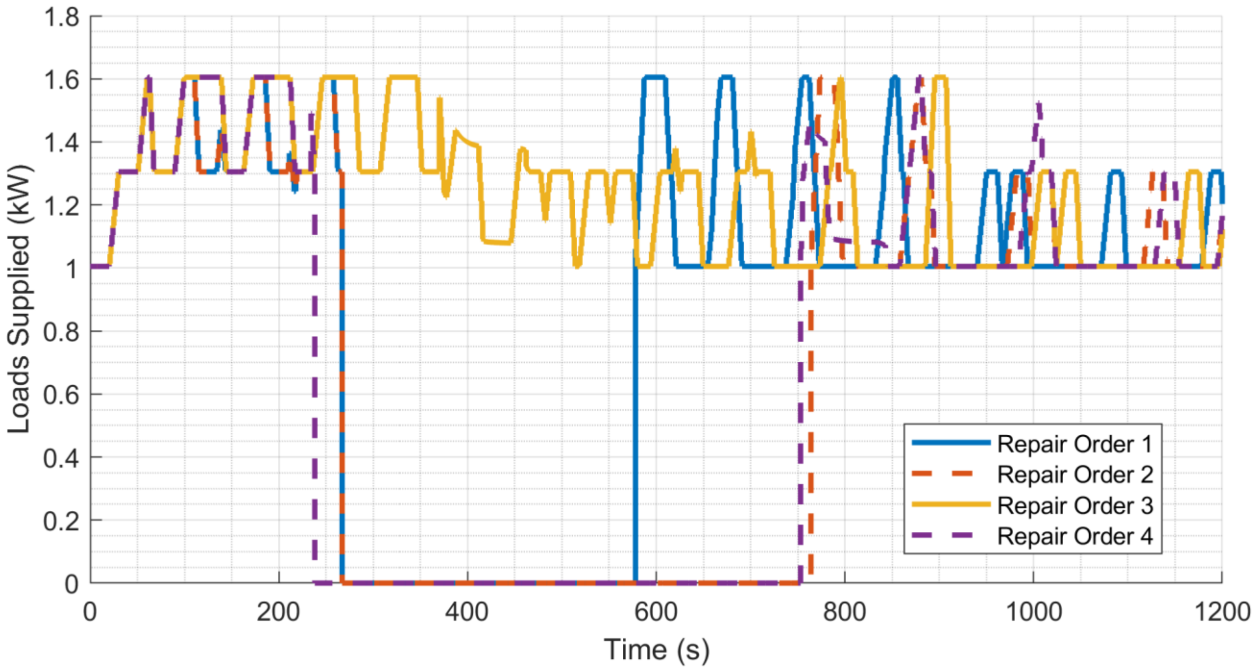

Figure 16. Critical Power Load Availability for Simulation Set R2

Repair orders 1, 2, and 4 all undergo a period of time where the critical system power loads are not being supplied with power. This lack of supply indicates in addition that the rest of the power loads, lighting, monitoring, and other, are also unpowered. Repair order 1, despite first addressing the structural hole, is the first of the three to restore sufficient power supply by immediately moving to fix power distribution. Repair order 4 just barely edges out repair order 2 on this front because the route the agent takes is slightly more optimal in terms of travel time

Figure 17 and Figure 18 show pressure and temperature, respectively, in the zone of the habitat where the meteorite impacted. Having fixed the hole early, repair orders 1 and 2 are able to recover to a nominal IE state before the atmosphere has had a chance to reach equilibrium between the leak and ECLSS compensation. Repair order 3 returns the habitat to a nominal state of pressure before repair order 4, while repair order 4 returns to a nominal state of temperature first. This behavior is likely due to the coupling between temperature and pressure: when the pressure in the habitat is extremely low, the thermal control system is able to influence the temperature more easily. While repair order 3 has fully recovered the pressure, repair order 4 sits at a slightly-above-minimum pressure value while the hole is sealed but repairs on power distribution are still being completed. In this time, the temperature is returned to nominal.

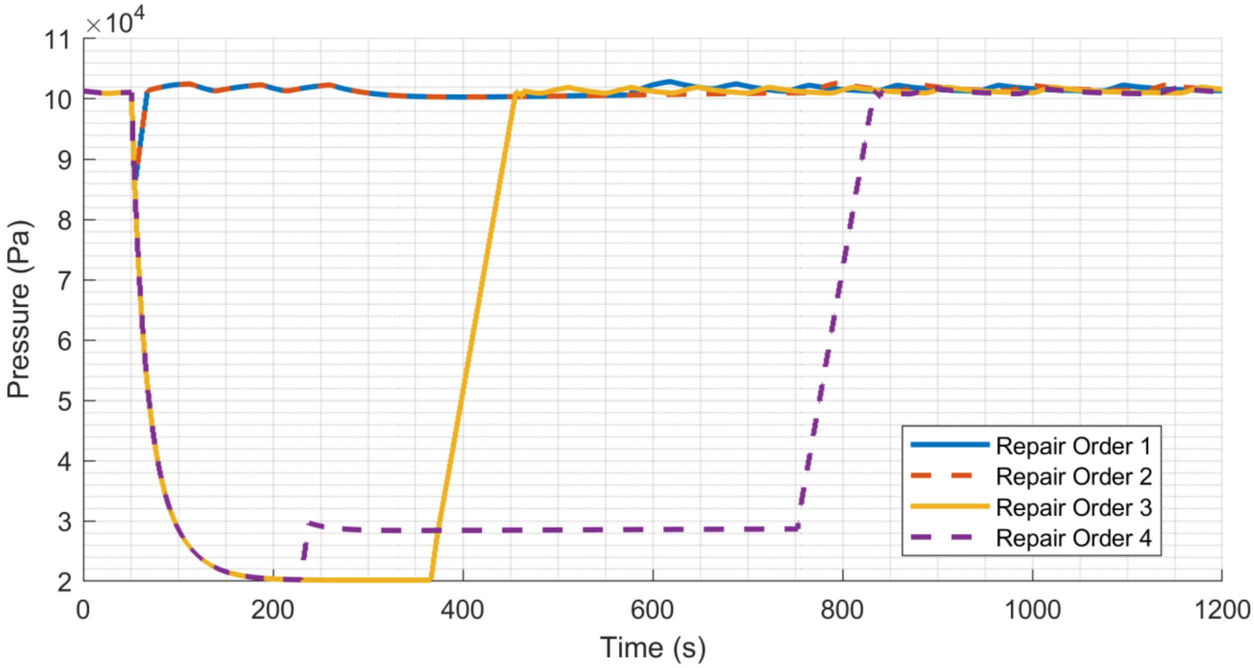

Figure 17. Pressure for Simulation Set R2

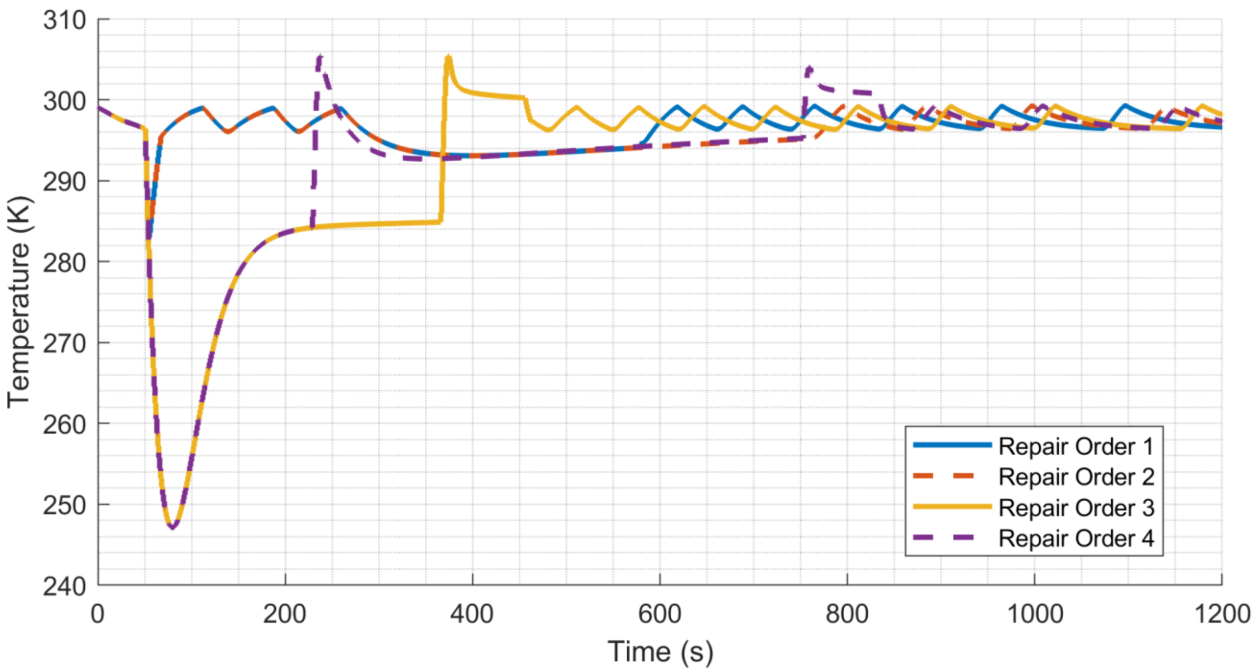

Figure 18. Temperature for Simulation Set R2

In most cases, repair order 1 probably leads to the best result. It first fixes the hole, the source of lost atmosphere in the IE. It then moves to power distribution – although the nuclear power generation is not at full capacity due to the dust, there is still some power being moved into critical systems. Repair order 4 could be considered the worst of the four, as it is the last to achieve a nominal IE, and still the second-to-last to restore power. In the case where the loss of power is considered the most critical issue, repair order 3 could be selected over repair order 1. This decision may be relevant in a situation where the atmosphere leak can be isolated to one zone of the habitat, and power is paramount to maintain safety in the other zone or keep some critical function online.

Significance: The question of which repair order is most appropriate comes down to mission priorities and the specific impacts of each metric remaining in an unsafe range. The parameters involved in making this decision must be well defined ahead of time to facilitate a swift arrival at a suitable plan. While it is clearly important to respond to a disruption quickly, it is also crucial to evaluate all options and make an informed choice, as demonstrated by the varied outcomes of the repair strategies in this set.

4.3 How does the lunar day and night cycle affect the propagation of disruptions? (R3)

For simulation set R3, we run three simulations with different values for the initial condition of the solar angle. Figure 19 provides a reference for the effects of the solar angle on the capacity of the solar panels to generate power. At 90°, the sun is directly overhead, and the panels provide maximum power. At 0°, the sun is just on the horizon, and the solar power generated is negligible. 45° solar angle is an intermediate scenario where the solar panels are productive but are not strong enough to power the entire habitat in the absence of other sources. The power generation gradually changes over the course of the lunar day, but these changes are negligible within the length of these shorter simulations. The apparent decrease in generation during the 45° solar angle simulation is due to negligible error within the numerical solver – if left to run for longer, a gradual increase could be observed.

In this simulation set, the solar panel becomes solely responsible for powering the habitat due to a fire on the power systems that damages energy storage and the converters that distribute power from the nuclear generator. Reference Table 6 for the simulation set outline.

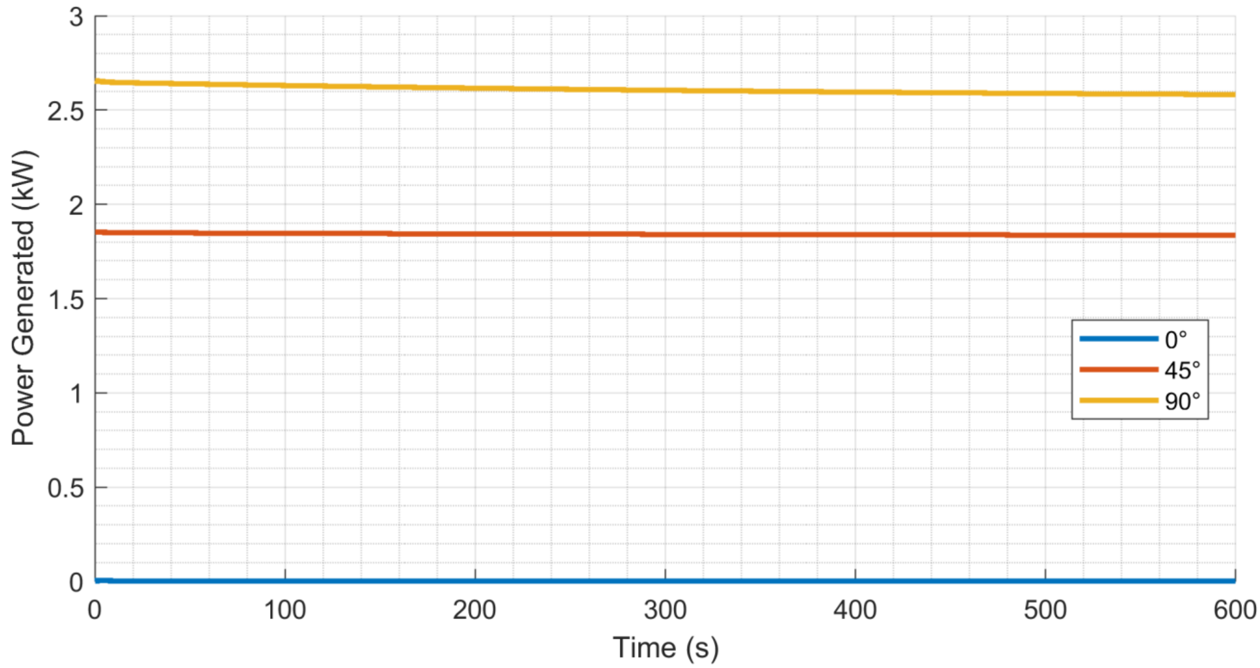

Figure 19. Solar Power Generation for Simulation Set R3

The effects of reduced solar power can be observed in Figure 20, which shows the power supplied to each of the three load classifications: critical, monitoring, and other. To reiterate, critical loads include ECLSS functionality and autonomous planning systems. Monitoring loads are the second level priority for the power system; this classification includes sensors and lighting. 'Other loads' is the catch-all classification for non-essential functions such as housekeeping and science experiments. While monitoring and other loads are mostly constant, the critical loads fluctuate with ECLSS power demand.

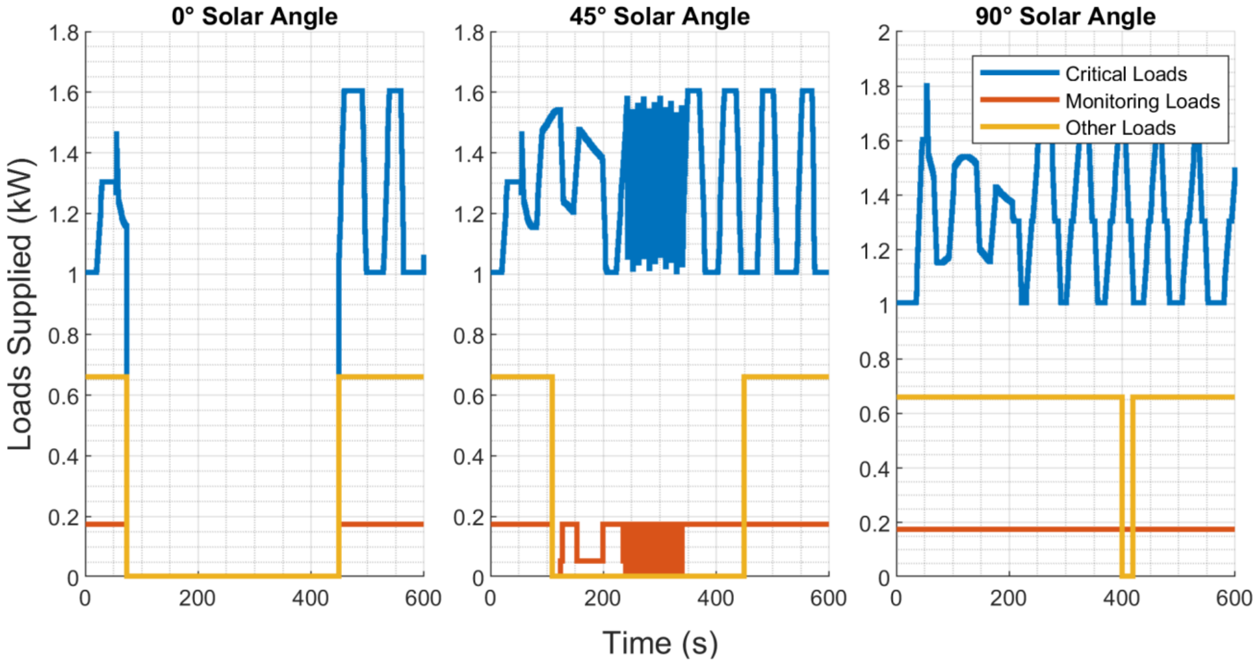

Figure 20. Power Load Supply for Simulation Set R3

The effects of the fire on the power systems appear as reductions in supply to these systems. In the simulation at 90° solar angle, the power system functions mostly nominally, with only a slight dip in the third-priority loads around t=400s. At 45° solar angle, the critical loads remain powered, while the other loads suffer a longer draught, and the monitoring loads fluctuate with availability. The 0° solar angle simulation, where solar power is negligible, sees all power supply cut off for the length of the disruption scenario.

Following from the supply to critical loads, the IE of the habitat responds in accordance with the thermal control system's ability to offset the heating load of the fire. Figure 21 visualizes these consequences in the temperature of the affected zone. The 45° and 90° solar angle simulations have nearly the same temperature curve because the critical load supply is mostly unaffected. The 0° solar angle simulation has a temperature that surges much higher. Because the power supply is nonexistent to thermal control, the heating load of the fire is uncontested.

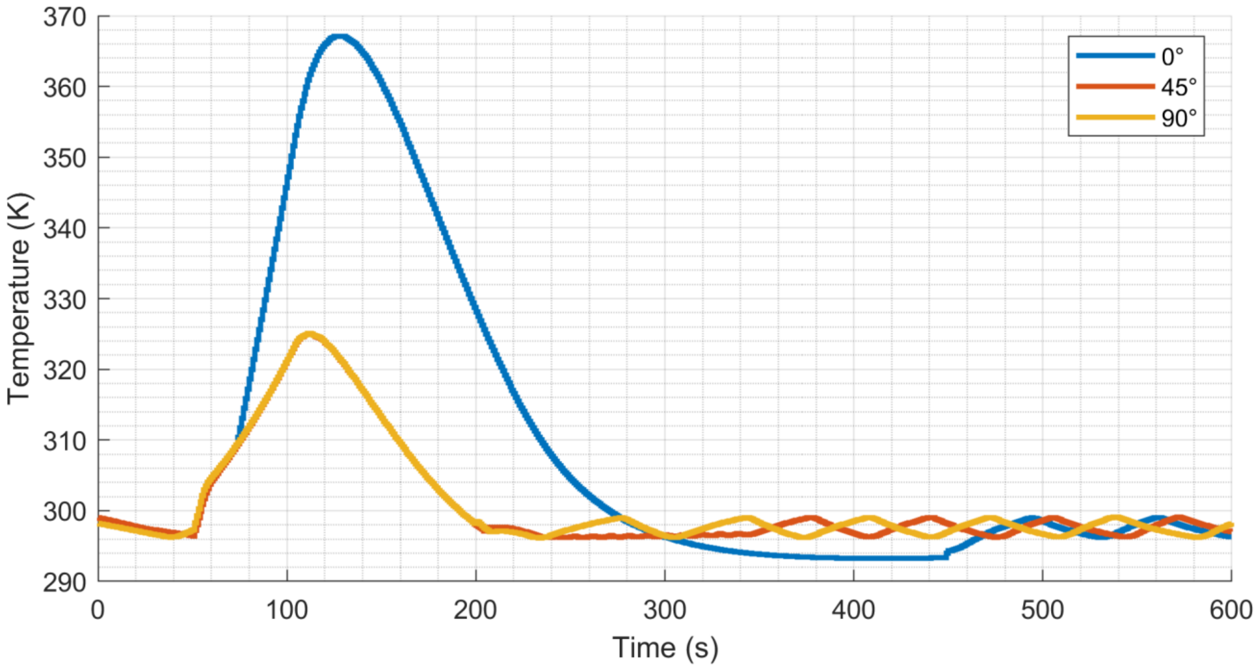

Figure 21. Temperature for Simulation Set R3

It is clear that, in the case of this disruption scenario, the habitat is more vulnerable during the lunar night. One additional consequence which is not apparent in this simulation set is the added thermal considerations of this cycle – cooling of the surface during the lunar night and heating during the day cause thermal control loads to fluctuate dependently. Despite this fluctuation, the NRH is well insulated, so the thermal effects of solar radiation or its absence are not as immediately significant as the effect on power generation. It would take an extended period of weak or no thermal control for the effects of solar radiation to be obvious in the interior environment.

Significance: The lunar day/night cycle is much longer than what we typically design for on Earth, meaning there are unfamiliar risks to consider. If it is true in practice that a SmartHab is generally more vulnerable during the lunar night, and especially near the end of the lunar night when power stores might be depleted, then certain subsystems must be sized accordingly. Understanding how SmartHab vulnerability fluctuates as a function of time throughout missions can improve preparation for disruptions that arise and help mitigate the negative consequences of that vulnerability from being fully realized.

4.4 How do we change our response to disruptions of varying severity? (R4)

Threats to SmartHab survival can come in different sizes and cause varying levels of damage to critical systems. Meteorites, for example, may be so small that they simply bounce off the outside of the dome, or so large that they penetrate the structural protective layer, the structure, and cause damage to a component within the habitat. In this simulation set, we attempt to understand how different repair strategies are suited to different levels of disruption intensity level. The structure of the set is to vary the size of a meteorite-induced structural hole and compare different repair strategies: whether to first address the damaged pressure and thermal control systems, or the hole itself. Reference Table 7 for details on the simulation plan.

Figure 22 depicts the temperature curves for each hole radius, shown on the legend, and each repair strategy, separated between the plots. The results are consistent with the repair strategy prioritizations. On the left plot, when the thermal and pressure control systems are repaired first, the temperature begins to recover. Due to the low pressure in the habitat, the thermal dynamics are rapid. The near-zero pressure of the 0.01m hole radius simulation is the cause for the strange-looking fluctuations around t=150s. As pressure increases to a new equilibrium point between the effects of pressure control and the still unsealed hole, the thermal control system struggles to maintain the temperature setpoint. The issue is resolved once the hole is repaired.

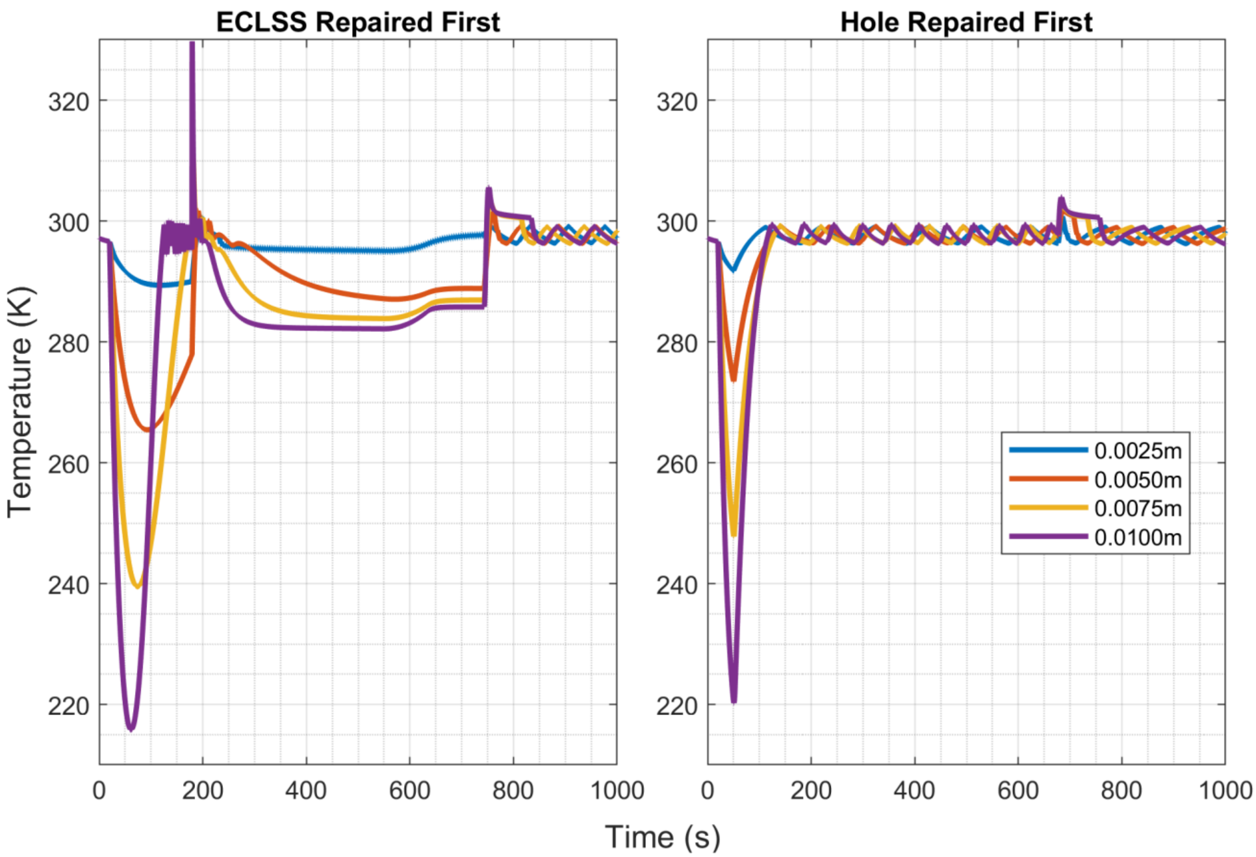

Figure 22. Temperature for Simulation Set R4

On the right plot, the hole is repaired immediately, and temperature does not fall quite as low for all hole radius cases. Despite damage to the thermal controller, the habitat is still able to restore a nominal temperature range due to the low-pressure environment. The spike in temperature seen at about t=700s is due to the pressure controller supplying air to restore a fully nominal IE.

Figure 23 similarly displays the results for pressure in all simulations. On the left, the rapid repair of the pressure controller allows the ECLSS to feed the atmosphere leak and reach a balance between air being supplied and air being lost through the hole. For larger hole radii, this equilibrium point is lower because the rate of airflow out is greater. Pressure is returned to nominal when the hole is repaired.

On the right, early repair of the hole prevents pressure from dropping as low as it does in the corresponding simulations of the other repair order. The damaged pressure control system, however, is still too weak to restore nominal conditions. The pressure hovers around an equilibrium point, again slightly higher than in the corresponding simulations on the left, until the control system is fully repaired.

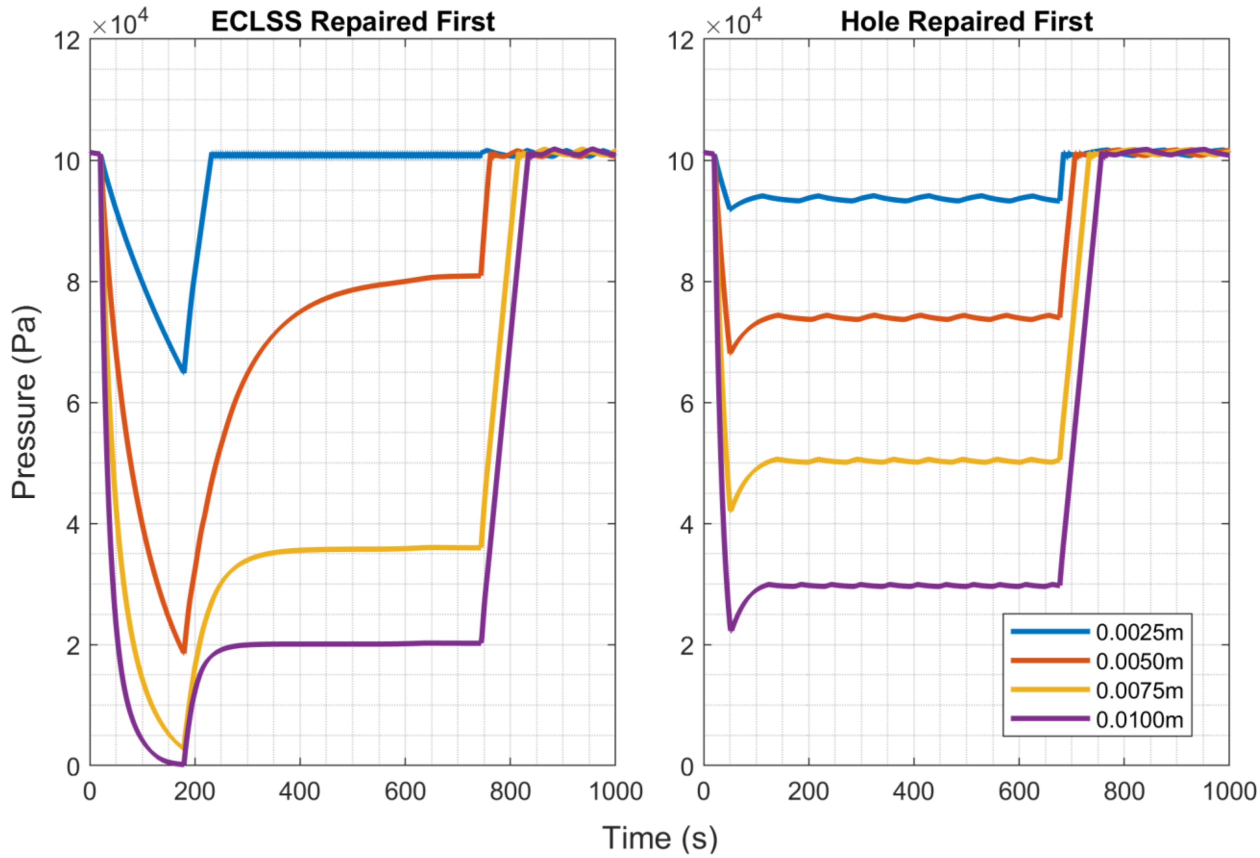

Figure 23. Pressure for Simulation Set R4

While temperature is restored more quickly when the hole is prioritized, both repair strategies achieve nominal pressure at about the same time. Interestingly, the two simulations with the smaller of the hole radii show comparable results between both repair strategies. In the cases where ECLSS receives first repair, the equilibrium point for pressure is well within the safe ranges for both crewed and dormant habitats. Temperature ranges are also within the dormant safe range for most of the simulation. Most significantly, the pressure in the smallest hole radius simulation returns to nominal more quickly when the pressure control is repaired before the hole. Although pressure drops to a lower value than in the hole-repaired-first case, it is still within the safe range for a dormant habitat. This safe pressure value indicates that repairing the pressure control and allowing it to compensate for the leak first might actually be the preferred approach for smaller radius structural leaks. The phenomenon becomes more pronounced the smaller the hole is.

Significance: The significance of these results is that the most obvious or intuitively best repair strategy is not necessarily the optimal one in practice. The question of which damage to address first is one of prioritizations and evaluation of potential cascading effects. The complex interactions and tight coupling inherent to various aspects of SmartHabs can lead to consequences outside what may be expected. Simulations like this allow habitat designers, mission control, or autonomous planners to make decisions based on rigorously obtained data, which carries weight in what is essentially a new frontier that cannot depend on experience or tacit knowledge alone.

4.5 How should differing safety priorities between dormant and crewed states be reflected in disruption response actions? (R5)

A key step in responding to a disruption scenario is identifying the available safety controls. Safety controls can be limited for a number of reasons, identified in Chapter 3. Reasons may include agent (human or robot) capabilities, resource scarcity, and controls that are incompatible with each other. In this simulation set, outlined in Table 8, we observe the case where safety controls are limited in the interest of crew safety. While there may be certain situations in which closing the pocket door can help place the habitat in a safer state for crew, this scenario assumes a situation in which isolating the zones from each other would restrict crew movement and hinder the opportunity to evacuate if necessary.

The first of the two disruption scenarios occurring in this simulation set (in separate simulations) is a meteorite impact in zone 1 of the habitat. The meteorite pierces the habitat dome, leaving a hole in the structure, but does not damage any other subsystems. Because this set is focused on investigating a single safety control and the vulnerability implications of dormancy versus transition, the agent is deactivated and will not perform any repairs. Rather than creating a traditional resilience curve, we observe the full propagation of the disruption scenario to highlight the effects of the safety control. Figure 24 depicts the effects of the meteorite impact in a dormant habitat where the pocket door is closed. The pressure in zone 1 quickly drops out of the safe range, stabilizing when it reaches the aforementioned equilibrium point between the leak and the pressure control system. The pressure in zone 2 is only slightly affected and remains at a safe value.

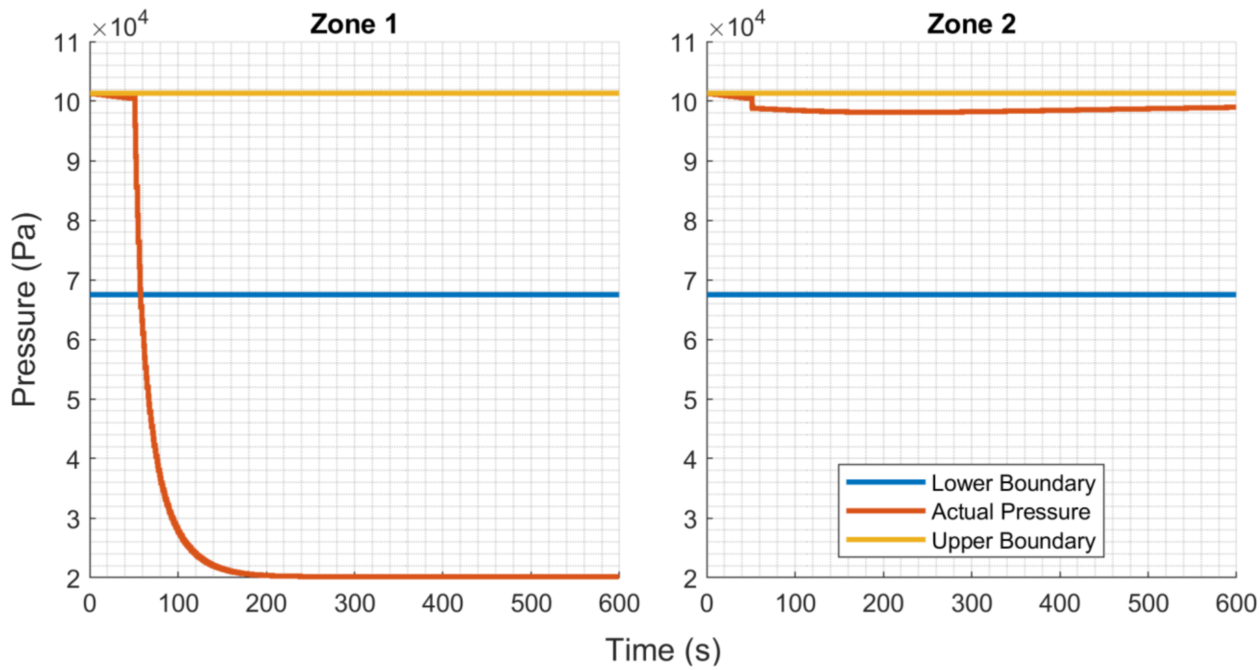

Figure 24. Pressure in Dormant Habitat, Pocket Door Active, Meteorite Impact for Simulation Set R5

The simulation in Figure 25 is the crewed counterpart of the simulation in Figure 24. When the pocket door does not close, the leak and load on pressure control is effectively shared between the two zones. The loss of atmosphere occurs at a slightly slower rate than in the previous simulation, and the equilibrium point of pressure is higher. Regardless, the extent of the pressure drop is so severe that a different safety control, such as donning of EVA suits, must be undertaken to prevent loss of the crew.

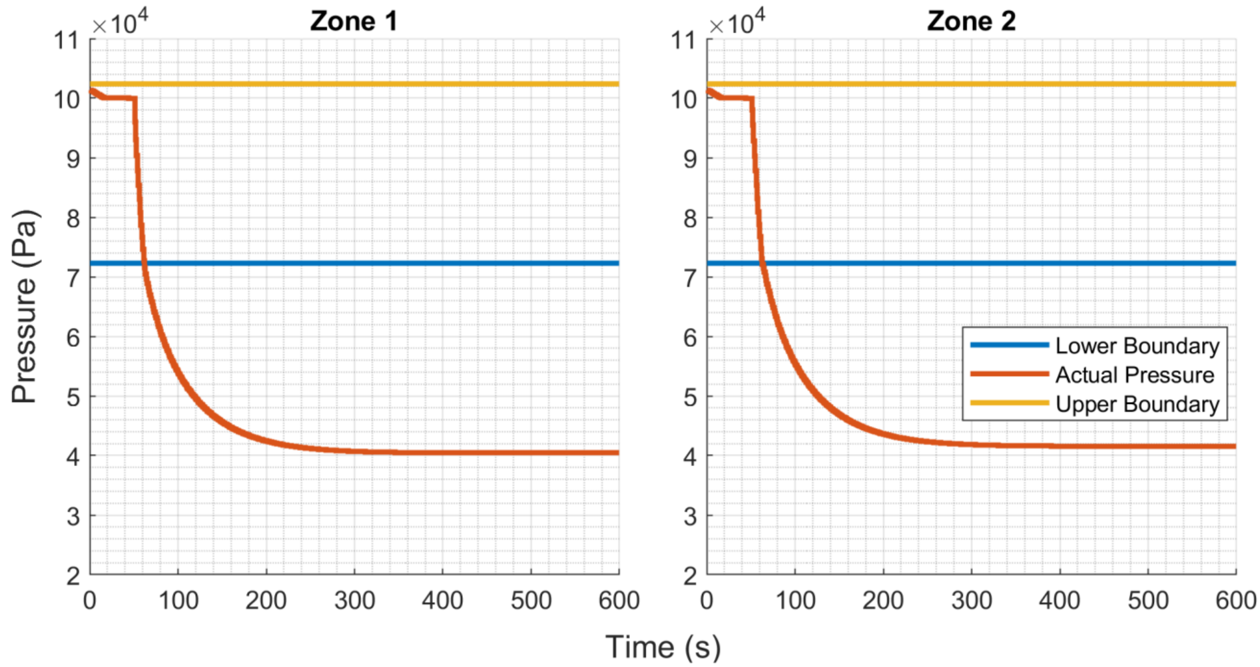

Figure 25. Pressure in Crewed Habitat, Pocket Door Inactive, Meteorite Impact for Simulation Set R5

The effects of the pocket door in the meteorite impact scenario are consistent with what one might expect. Sealing the affected zone off, in the absence of repair, sacrifices the safety of that zone in order to preserve the other. This action could be useful to protect an area of the habitat that contains delicate, critical components such as water storage. When the pocket door is not closed, the severity of the disruption is shared across the zones, leaving the affected zone in a state that can be considered safer than if the door had been closed. This load sharing is likely only desirable if that state remains within the safe ranges of the habitat.

Moving on to the second disruption scenario in this set of simulations, Figure 26 and Figure 27 display the effects of a fire in zone 1 of a dormant and crewed habitat, respectively. Similarly to the meteorite impact, the fire does not cause any damage to subsystem components – it is the sole hazardous state in the simulations. The propagation of a disruption scenario involving fire is different from one involving a meteorite impact because the fire grows and spreads while the structural hole remains the same size. As the fire spreads, its effects magnify, and there is no similar equilibrium point of pressure or temperature.

In the dormant habitat, the pocket door closes as soon as the fire is detected. The thermal control system is initially able to negate the heating load of the fire, but at about t=160s, the size of the fire becomes too great for thermal control to counteract it. The temperature in zone 1 departs from the safe range and continues to rise, while the temperature in zone 2 remains stable inside the safe range.

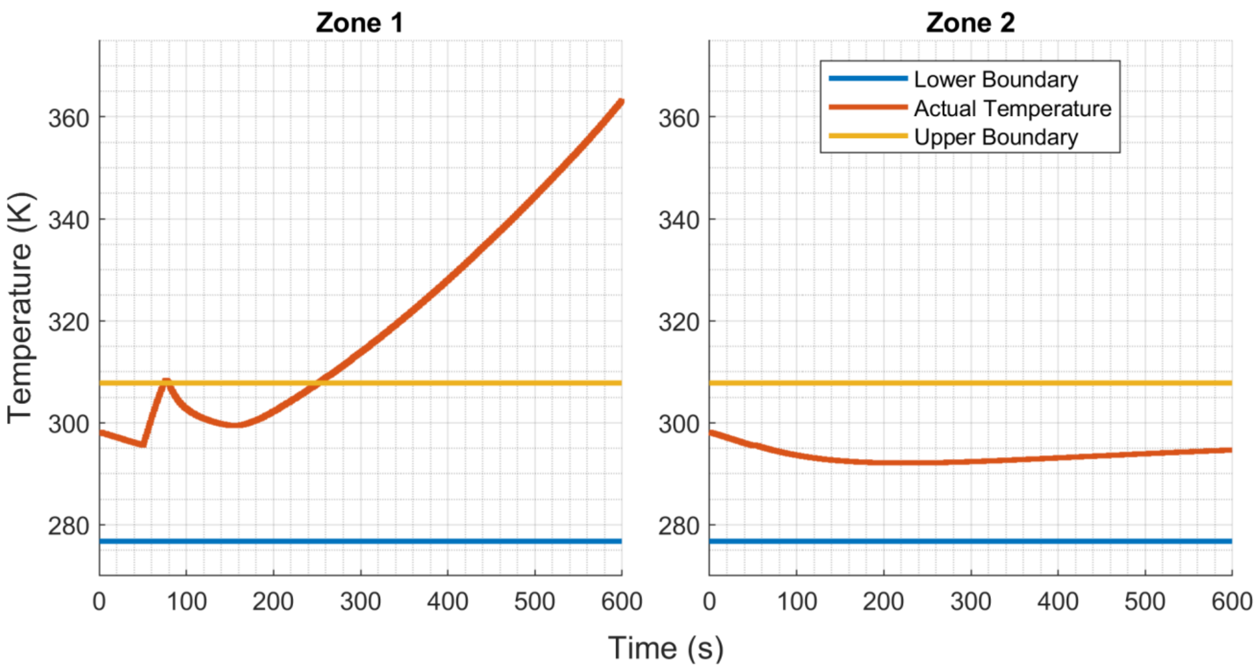

Figure 26. Temperature in Dormant Habitat, Pocket Door Active, Fire for Simulation Set R5

In the simulation in the crewed habitat, the fire causes the temperature in zone 1 to exceed the safe range much more quickly because the crewed safe range is more strict than the dormant safe range. Unlike in the meteorite impact simulations, the load sharing between zones is not as immediately evident. This difference is because the thermal dynamics in the habitat are much slower than the pressure dynamics. The additional volume of air from zone 2 barely offsets the heating effects of the fire in zone 1, and the absence of the pocket door is much less impactful. The time it takes for the fire to push temperature into extreme highs is too short for the thermal control system alone to make a difference in its propagation. Increasing air circulation to better spread the heating load between both zones may have unintended effects, such as fanning the flames and causing the fire to grow, or sending more smoke into ECLSS and damaging components.

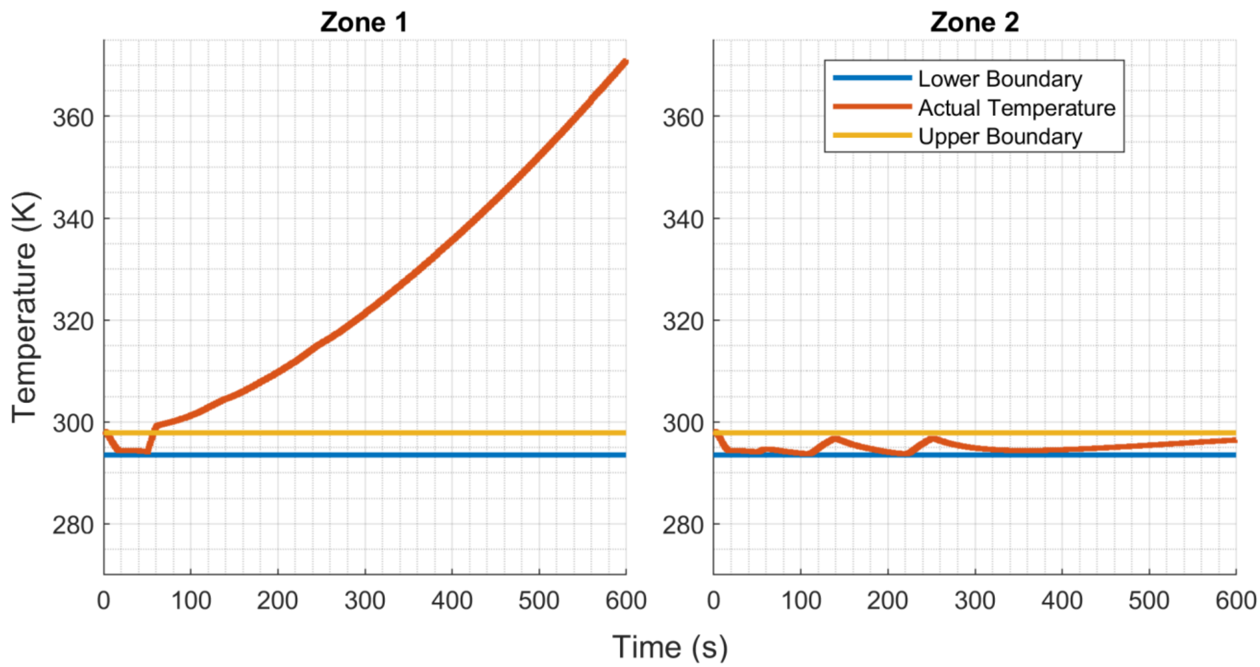

Figure 27. Temperature in Crewed Habitat, Pocket Door Inactive, Fire for Simulation Set R5

Significance: Like many other safety controls, the use of the pocket door to isolate unsafe zones of the habitat can have a variety of consequences, desired or not. The effectiveness of its usage to achieve a safer interior environment depends not only on the crewing state, but also the details of the disruption scenario occurring. The implementation of more safety control options provides potential for backup plans in the face of control limitations and contributes to the versatility and, ultimately, resilience of a SmartHab.

4.6 How does the potential for a second disruption affect the outlook of the first? (R6)

SmartHab design must take into account all hazards that can negatively impact the safety of the crew and equipment. Although designing robustly for every worst-case scenario is too costly to be realistic, the implications of unlikely but extremely severe disruption scenarios should still be considered from a resilience standpoint. In this simulation set, we observe the additional effects of two disruption scenarios occurring in sequence. The first disruption is a meteorite that impacts the nuclear generator outside the habitat. Because the simulation takes place during the lunar night, solar power is unavailable, and nuclear is the sole source of generation. We test two possibilities for the second scenario: a fire on the energy storage and power distribution systems in zone 1, which have already been affected by the meteorite, and a fire on the thermal control systems in zone 2, which were previously in a nominal state. The simulation plans can be found in Table 9.

Figure 28 illustrates the disruption effects on the power subsystem with the total energy storage of the habitat. With only the meteorite impact outside the habitat, batteries become the primary power source. They continue to drain until the nuclear panels have been fully repaired, at which point nuclear again becomes the primary source of power and energy storage is restored to full capacity. The results for energy storage are similar when the fire occurs on thermal control because the power system is otherwise unaffected.

When a fire starts on the batteries following the impact of the meteorite, many are destroyed, and the habitat suffers a major loss of energy storage capacity. At this point, t=250s, the habitat is fully reliant on battery power. The damage compounds with the existing damage to nuclear, pushing energy storage much closer to zero and closely approaching a total loss of power supply in the habitat. The battery drains more due to a damaged converter, and the agent must abandon repairs of the nuclear systems to address the fire before it spreads further. When all repairs have been made, the energy storage recharges much more slowly due to a full load on ECLSS.

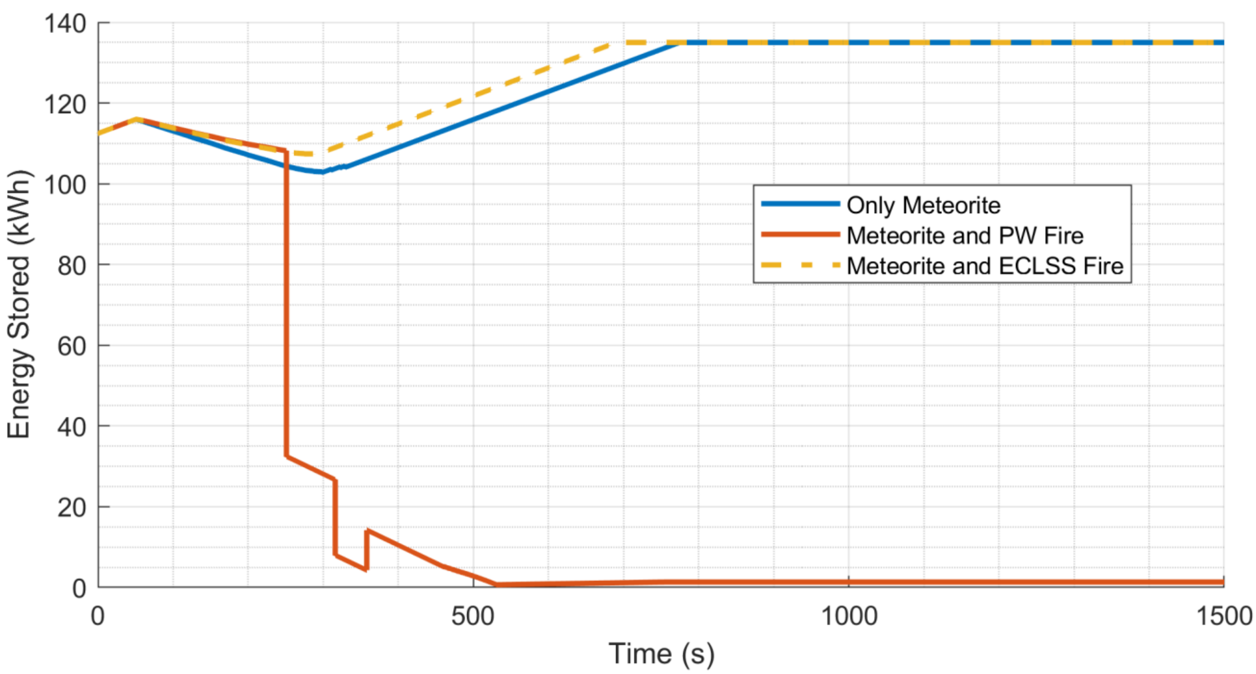

Figure 28. Energy Storage for Simulation Set R6

We observe the effects of the disruptions on the interior temperature in Figure 29. Because the secondary disruption scenarios occur on separate zones, the individual temperature of each zone is shown. From the meteorite impact alone, the temperature in either zone is unaffected – there is no shortage of battery power or damage to thermal control to prevent the habitat from maintaining nominal temperature conditions. With the fire in zone 1 on the power systems, supply to ECLSS is restricted, and the heating load of the fire is initially left unchecked. The temperature in zone 1 spikes outside the safe range, while temperature in zone 2 begins to drop due to a loss of thermal control. When power supply is fully repaired, the temperature is returned to the nominal range.

In the simulation with the fire on thermal control, the temperature in zone 2 is affected. Although thermal control is weakened by the damage from the fire, it still counteracts the heating load to a degree. As in the previous simulation, the agent moves immediately to extinguish the fire. With the batteries still carrying a near-full charge, the damage to nuclear generation is not as critical in this simulation. The habitat is returned to a fully nominal IE in a short time and the repairs are finished in the absence of further hazards.

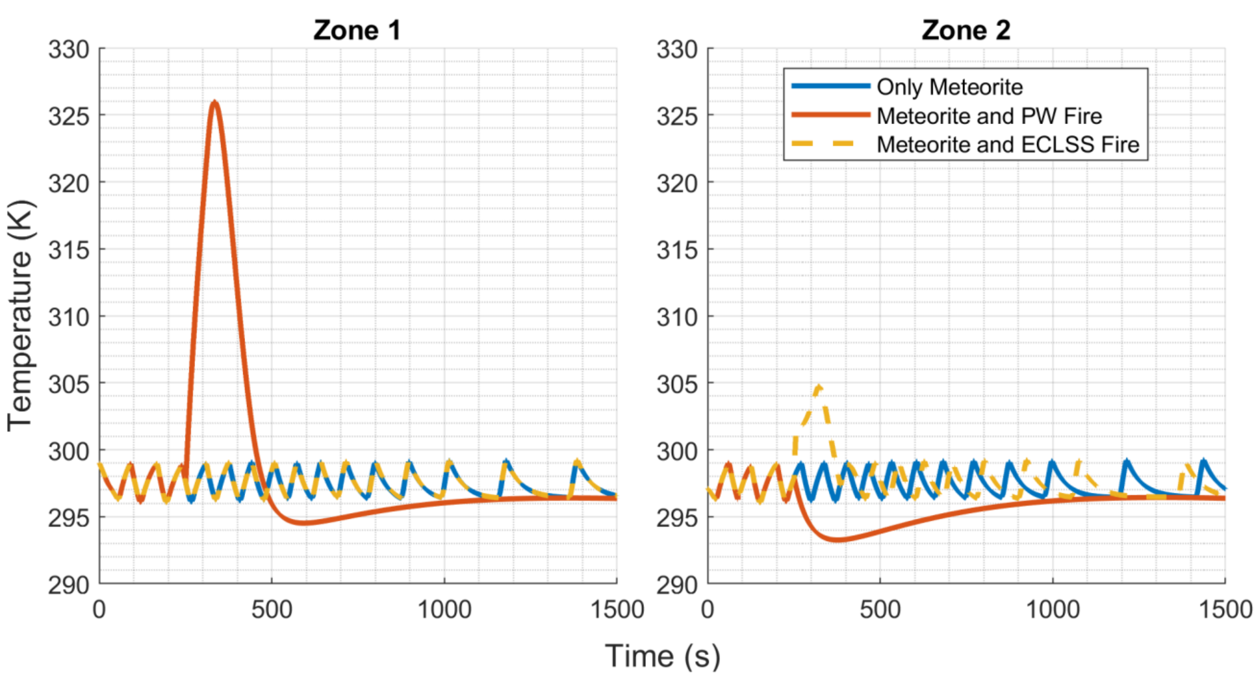

Figure 29. Temperature for Simulation Set R6

Significance: While it would be erroneous to make a direct quantitative comparison between two disruption scenarios of different natures, the two disruptions with compounding effects appear to pose more of a threat to habitat survival than two disruptions with more varied effects in this case. The results are potentially counterintuitive. Logically, the fire on thermal control should be more impactful on the IE temperature because these systems have a very direct relationship. The results show this is not necessarily the case – the combined damage to power due to the fire on energy storage place the entire power subsystem in such a depleted state that other habitat functions are affected. This behavior demonstrates the tight coupling of SmartHab subsystems, many of which have both causal and resultant relationships. The risk of multiple disruptions in sequence adds to system complexity and warrants holistic, context-based investigation.

5. CONCLUSIONS

Reiterating the objectives stated in Chapter 1, we sought to explore the causes and effects of SmartHab vulnerabilities and to demonstrate effective usage practices for the MCVT as a simulation-based research tool. In this chapter, we summarize our conclusions about each objective, provide suggestions for MCVT improvement, and propose future related work.

5.1 Vulnerability Factors

Having now explored the research questions inspired by Table 3, Table 12 resolves the study with the impacts of each vulnerability factor and the corresponding design considerations arrived at through the research questions.

Table 12. Operational Vulnerability Factors and their Impacts

Factor	Impacts/Considerations
Awareness	• The severity of system damage can increase the longer a disruption scenario propagates unchecked • Repair times and cascading effects grow as more damage occurs to crucial subsystem functions
Subsystem availability	• Damage to a given subsystem often comes with direct impacts on the functions of other subsystems • Repairs must be sequenced according to safety priorities and potential cascading effects
Environmental conditions	• Lunar SmartHabs are more vulnerable to certain disruptions at night due to the absence of solar power generation • Power loads change with environmental thermal and pressure variables, demonstrating coupling between subsystems
Safety control options	• Disruption scenarios can warrant different response strategies based on the severity of their impacts • Certain safety controls can inflict unwanted consequences that make their outcome unsafe in a new way
Recent events	• The potential for multiple disruption scenarios (common-cause failures or successive but unrelated) adds to system and response complexity • Disruptions that worsen already off-nominal functionalities can cause severe effects in coupled subsystems

The simulation sets run were generally able to demonstrate the desired phenomena for each vulnerability factor. The results are consistent with the expectation that tight coupling and complexity in SmartHab systems promotes emergent behaviors that result from the interactions between subsystems. The potential for various response activities adds another layer of complexity on top of these interactions that is rich with research areas. Studies such as this can contribute to the body of knowledge and understanding for SmartHab design.

5.1.1 Significance of Simulations

Some of the behaviors explored in Chapter 4 were fairly intuitive, and the general trends could have been predicted without the use of a virtual model. Value lies in the unintuitive results and cases in which consequences varied depending on the specifics of the scenario at hand.

Quantification

One major capability of the MCVT is the potential for quantification of disruption scenario impacts and response consequences. While the simulations in this thesis were run with notional habitat design, a model could be updated accordingly to capture actual feature details as SmartHab design matures. These numbers can be not only used for design, but also programmed into autonomous control systems in SmartHab. As demonstrated, the ability to rapidly diagnose a disruption and plan a response is key to survivability. A planning tool with accurate predictive capabilities helps to mitigate uncertainty in hazardous conditions.

Context

Versus isolated mathematical equations that capture singular behaviors, a comprehensive modelling tool like MCVT provides a holistic approach to studying SmartHabs. The value of this context is difficult to understate in such a complex and tightly coupled system. Cascading effects and consequences that are not captured by narrow mathematical approaches are at least as important to understand as the more obvious behaviors.

Informed Design

Simulation-based design allows SmartHab designers and system engineers to assess practical operations early in the design process at a low resource cost. This functionality contributes to a more comprehensive evaluation in the field of design choices. In conjunction with the aforementioned advantages of simulation, virtual models are a powerful tool, especially on a frontier that lacks operational experience.

5.2 Lessons Learned for MCVT Simulation-Based Studies

The MCVT is a tool that has only recently moved from development to full implementation for research. While the knowledge that can be gained from its use is already extensive, it must be well understood to be used effectively, and there are still areas of its functionality that could be improved for further research. We identified various best practices in MCVT usage to design meaningful simulation sets and maximize the ratio of results to effort.

5.2.1 Simulation Set Design

Design and analysis can be thought of in terms of several phases. Before beginning simulation, the researcher must establish the research question or specific SmartHab behavior they set out to investigate. The question can be refined later in the process, but as with any research, it is important to set a target to form a basis for the simulations.

The first phase in running any simulation of this kind is to start with shorter, faster, highly time-scaled simulations to identify the general effects of selected disruption scenarios. These simulations help to draw out which relevant outputs should be observed and dispel inaccurate or preconceived notions early in the process. In the current version of the MCVT, leaving all agent input values and disruption scenarios at their default values will achieve very fast simulations. Most disruption scenarios simulated in this way will fully resolve within simulations shorter than 300 seconds, but the results will be far from usable for meaningful analysis. At this phase, the user should plot the outputs of every subsystem with the available "plot_all" script included in the MCVT folder download. By plotting all available metrics after each simulation, a user can catch otherwise invisible behaviors in all subsystems, perhaps helping to explain an unintuitive result. It is a relatively quick process to eliminate disruption scenarios that do not align with the research objective and to discover which disruption scenarios will be useful.

As the user hones in on how to represent their target scenario, they should move to the next phase where they gradually decrease the rate of agent repairs to make the effects of damage more substantial and observable. These inputs generally take liberal modifications to the default repair rates, often on the order of multiplying or dividing the default value by 10 or 100, to achieve the desired results. For components with binary health states (either damaged or not damaged), changing the repair duration will have a similar effect. In our experience simulations must be at least 600 seconds to 1,200 seconds to show meaningful dynamics. The user should exercise judgement as they perform this tuning to avoid running unrealistic simulations, for example a simulation where repairs are still being made inside a habitat of extreme temperature values. The simulation time should be selected with a cushion for systems to return to nominal or otherwise stabilize at the end of the simulation to capture all behaviors.

The third phase of simulation set design is to begin varying some selected input (or multiple inputs across matrices) to begin answering the relevant A user should be conservative in choosing which variables to change throughout a simulation set. Often, modifying a single initial condition or design factor is enough to cause meaningful change in simulation results. Tracking these changes one step at a time ensures that the results will not be misunderstood or misrepresented in analysis. When choosing which metrics to plot for the larger simulation set, they might be selected in terms of illustrative utility (metrics like pressure and temperature are easy to understand), relevance to the question at hand, and causal relationships. By plotting metrics whose effects naturally flow to each other, the resulting analysis will be more comprehensive and understandable.

The final phase in simulation is to settle on final results and perform analysis. The simulation set can be considered finalized when the results provide an answer to the research question, and all relevant behaviors have been confirmed to be realistic in quality and magnitude. It may be necessary to circle backward to an earlier phase in the cycle to achieve a good result. When analyzing, it is important to draw out the significance of the results and what they represent in the context of the scenario and mission.

5.2.2 Errors and Unexpected Behavior

There were several times in the development of this thesis that unexpected metrics illustrated behavior relevant to the research question being investigated. At some points, these behaviors were discovered to be errors within the MCVT. Suspected modelling errors must be reported constructively as early in the process as possible. By saving all simulation outputs and inputs, modelers can see exactly what conditions led to the error’s discovery.

Sometimes, suspected errors were not errors at all, but strange behavior resulting from complex interactions under the surface. Discussions with individual subsystem modelers can help explain these behaviors, but it is also useful for users to acquire a strong grasp on the way subsystems and their interactions are designed within the MCVT architecture. Very few, if any, behaviors within the MCVT occur in a vacuum. A user must take the time to learn to recognize the interconnected structures and the way effects can cascade throughout the SmartHab to properly explain their results.

5.2.3 Simulation Architecture Customization

The modular nature of the MCVT makes it possible to manually insert behaviors or capabilities that are not natively supported or accessible. While it is difficult and potentially unwise to modify the behaviors of subsystems themselves without in-depth knowledge of the model, we can conservatively modify the inputs or outputs of those subsystems to achieve the desired results. An example of this is sensor fusion. In the current version of the MCVT, artificial sensors meant to represent the inputs to thermal control are simply the physical temperature signals with noise added. The user can split the air temperature inputs immediately before they enter the thermal control system block and artificially represent multiple sensors that experience more complex noise or sensor drift and are fused by some user-determined method. Changes like this can create disruption scenarios not in the native MCVT input file.

The agent's behavior is one of the most important aspects to control in the MCVT. There are a few capabilities that all users should understand. First, as mentioned, repair rates and durations must be tuned to illuminate dynamics resulting from damage. Repair order can also be modified by changing the "T2F" (time to failure) values in the agent settings to represent and test different repair priorities. This change is important to make even if the topic of a simulation set is unrelated to repair order, as the default values are entirely arbitrary, and may lead to unrealistic results. Second, users can delete the T2F value for a given damage index to prevent the agent from making the repair at all. This capability can be useful for understanding the time to failure (in the absence of repairs) in a given scenario.

The stochastic input options in the MCVT should be used with care. Setting some damage to occur in 10% of simulations and then noting how many simulations out of 100 exhibited that damage is not a meaningful result nor the intention of including those input options. One useful way to include stochastic inputs in simulation set design is to *combine several* stochastic inputs and use the results over a large set of simulations as a sort of sensitivity study on *later cascading consequences* of the inputs. This way, the user can develop an organic story to answer their target research question.

5.2.4 Information Sources

The first place to find information about the model is the latest version of the MCVT documentation or user guide (*Modular Coupled Virtual Testbed (Version 6.3)*, 2023). Although MCVT models have presumably been constructed to reasonably represent SmartHab specifications, and those specifications have been properly verified, it is still useful to seek information from external sources to avoid misrepresenting results or modifying subsystems in a way that detracts from meaningful simulations. Two highly informative sources for this are the NASA Life Support Baseline Values and Assumptions Document (BVAD) and Human Integration Design Handbook (HIDH), both already mentioned in Chapter 2 (Anderson et al., 2018; *Human Integration Design Handbook (HIDH)*, 2014). By reading up on genuine NASA descriptions of subsystems and SmartHab-related definitions, users can maintain their simulations within realistic context.

5.3 Potential Improvements for the MCVT

In general, more control over minute details of simulation is beneficial to obtaining useful results. As more research is performed and the available topics to study within the MCVT are gradually exhausted, the addition of new controls over disruption scenarios and habitat design can deepen the extent of available information. To stay current with developments in SmartHab design and actual mission architectures as they become available, the MCVT must evolve over time. The nature of a moderate-fidelity, high-sampling-frequency simulation tool leaves room to grow toward more and more specific habitat design inputs. This growth would maintain the MCVT in a position where the quantities extracted are accurate and meaningful.

One area in which the current MCVT version lacks is the potential to study more simple component level failures, not caused by habitat-threatening disruption scenarios, within the bounds of user input files. While worst-case scenarios are important to study for subsystem sizing and qualitative disruption investigation, reliability-oriented independent failures are an important component of SmartHab vulnerability. Users can already delve into the Simulink model itself to achieve desired results in this area, but moving this functionality to input files promotes accessibility and decreases the knowledge needed to perform new analysis.

As the MCVT currently stands, there is only one agent. The agent can be modified to represent different kinds of repair capabilities among humans and robots, but it can not currently be used to represent multiple repairers simultaneously. In a real SmartHab, a crew of four to six or multiple robotic agents with different design could work on separate damaged components at the same time and potentially change considerations related to repair order. Adding the capability to simulate multiple agents in the MCVT would contribute to more possible research.

5.4 Future Work

In terms of the SmartHab mission operation definitions in this thesis, future work can expand on the accuracy and scope of the DITL schedules by keeping up with current developments in SmartHab design and including a wider variety of DITL schedules. Certain DITL schedules can be applied to simulation tools to observe the effects of disruptions on a given day. The content of Chapter 2 can also be used as a complement to other research efforts into higher-level mission architecture overviews.

Any one of the research questions introduced in this thesis could be studied more to obtain a deeper answer and better understand the implications on SmartHab vulnerability factors. Specifically, the study of dormancy and transition is a relatively unexplored concept and is one of the main features of future habitats that has lacked from previous space exploration efforts. The MCVT has the capacity to simulate dormancy and transition scenarios and contains a well of potential information for future research in this area.

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