Suit Simulators for Analog Sites: Lessons Learned from HI-SEAS Testing

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Abstract

As the U.S. space program turns to focus on planetary surface exploration, there will be an increasingly important role for extended simulations at analog field sites. Field testing and training date back to the Apollo program, and have been pursued with increasing scope and concerns of fidelity during the past decade. These recent tests have included considerations of exploration for minor bodies, but in the whole have been more applicable to lunar and Mars missions. In simulating extravehicular activities (EVAs), a variety of pressure suit analogs have been adopted in the past, ranging from a full pressure suit to no special garments at all.

Simulating an EVA on Mars or, more challenging, the moon realistically in the field on Earth is an effectively impossible task. The "gold standard" would be a pressurized suit, but even without life support equipment, the suited subject weighs substantially more than they would on a mission, massively increasing physiological workload and incurring increased physical risks to the subject. To attempt to improve Earth-based fidelity while supporting field testing, the University of Maryland has developed three successive series of suit simulators using garment design and interstitial padding to represent the bulk and joint limits of a pressure suit without pressurization. This allows the use of a lighter-weight suit, more representative of the on-back weight for a suit system for the moon or Mars, without incurring the training and safety monitoring requirements of a pressurized system. Helmets of these suits are totally enclosed with ventilation fans to provide fresh air to the wearer, simulating the aural environment of a pressurized suit with vent air noise in the helmet. Since the suit garment very effectively insulates the subject, these systems also had to be designed to incorporate a liquid cooling garment and ice reservoir in the backpack assembly. These suits were used in a series of field tests in Arizona in collaboration with Arizona State University, where professional geologists performed field research while in the suits in simulation of lunar or Mars scientific exploration.

In the last two years, the UMd suit simulators have become an integral part of operations at the HI-SEAS field site in Hawaii. These tests are isolation studies, requiring the six-person crews to operate without any physical or visual interactions outside of the simulation, and requiring environmental isolation whenever an EVA simulation takes place. To date, two MX-C suit simulators have accumulated over six months of operational use in support of three successive missions. During the HI-SEAS tests, EVA operations are conducted in either MX-C suit simulators or in off-the-shelf hazardous material handling (HAZMAT) suits. The HAZMAT suits are lighter in weight, not overly restrictive of limb motion, and allow unrealistic capabilities such as pulling the arms inside and using a tablet inside the suit.

The paper focuses on the lessons learned from EVA simulations performed in the second and third HI-SEAS missions using the MX-C suit simulators. Critical issues with the MX-C suits, including the need for assistance in doffing and donning the suits, and inability for self-rescue in the event of overheating or trauma. Desirable design revisions for the next generation suit simulators based on lessons learned are presented and prioritized.

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I. Background

There has been a great deal of interest in performing simulations of planetary surface exploration at field sites on Earth. Such simulations provide valuable information on tools and procedures, capabilities and limitations, and offer realistic crew training prior to flight. However, this type of simulation is strongly impacted by the difference between gravitational acceleration levels on Earth as compared to the Moon or Mars. An 80-kg astronaut wearing a 100-kg pressure garment and portable life support system (PLSS) would have an apparent weight of 68 kg on Mars and 29 kg on the Moon; in a field simulation on Earth, the astronaut would have to support a total weight of 180 kg. This has been done, quite effectively, for short periods of time and for specific simulation objectives. However, the use of a full pressure suit clearly compromises the fidelity of the simulation for much of the activity to be performed in Earth-based field testing.

This paper addresses the potential methods of simulating EVA operations on Earth, reviewing past approaches and developing a taxonomy for what level of fidelity is important and desirable for certain types of field testing. Of particular interest is the development of suit simulators: systems which attempt at some level to replicate one or more of the critical aspects of pressure suits, without the overhead of pressurization in the field. Use of these systems allows closer compliance with flight conditions in terms of carried weight, but introduces some potential safety considerations in remote field applications.

II. The Role of Fidelity in EVA Field Simulations

The only perfect simulation of a pressure suit is a pressurized suit. While this is unquestionably true, there are many field activities on Earth that seek to understand how astronauts in space suits will establish habitats, perform routine maintenance, and undertake geological exploration of the moon or Mars in the future. From Apollo training activities to the present day, these tests have needed some of the aspect of spacesuits, without routinely incurring the complication and expense of actual pressurized suits. In every case, the simulation designers have to consider: how much fidelity is required? And at what expense, in terms of cost, complexity, and potential safety implications? The following sections discuss a range of simulated suit fidelity, ranging from no attempt at all to simulate the suit to the use of flight-type pressure suits in field activities.

A. Unsuited Analog Activities

The simplest approach to planetary surface EVA simulation is to not attempt to model the pressure suit at all. It could be said that field geology training for the Apollo astronauts, performed in normal field clothing, allowed them to experience the challenge of performing the recognition, inspection, and sample collection tasks without the encumbrance of a pressure suit. Frequently these sessions would introduce the use of the EVA tools planned for lunar surface activities, in parallel with traditional geology tools and planned support equipment such as cameras (Figure 1), providing initial training and assessment of the flight tools. This type of testing is useful and most appropriate in some limited cases; it does not, however, illuminate issues of required suit fidelity for more general applications considered in this study.

B. Limited Interfaces

Given the detrimental effects of transporting the weight and bulk of a pressure suit (or simulator) in Earth gravity, one approach which has been used extensively involves the selective use of limited interfaces. For example, in mission-specific geological training in Apollo, the crew would wear EVA gloves, radio microphones and headsets, and simulated (lightweight) PLSS mockups with sample collection bags mounted on the sides and a chest unit with mounts for a Hasselblad camera like those used on the mission (Figure 2). This allowed the crew to get the "feel" of working the tools with suit gloves, interacting via radio, and developing approaches to exploration staying close enough together to allow stowing samples on each other's backpacks. In more recent field tests, the 2010 and 2011 Desert RATS tests had the Space Exploration Vehicle (SEV) crews performing simulated EVAs via suit ports, but the only suit-type hardware they wore were backpacks which incorporated high-resolution cameras and communications systems for interactions with Mission Control, along with electronic wrist cuff checklists (Figure 3). This approach to simulation focuses on communications interfaces and reduced manual dexterity and tactile feedback, as

This category would also include the use of hazardous material ("hazmat") suits at the HI-SEAS field site in Hawaii. The hazmat suits prevent the wearer from having the sensations from the outdoor environment, helping to enforce the isolation which is the focus of these long-term studies. Other than this function, the hazmat suits do

Figure 1. Jim Lovell and Fred Haise in geological field training for Apollo 13

Figure 2. Apollo geological training with backpacks, chest packs, and tools

Figure 3. Desert RATS field testing with backpacks alone

not represent pressure suits in any meaningful detail. They are designed primarily to isolate the wearer from the environment, but to the extent possible within that overriding requirement they are designed to be simple to don and doff, and as unrestrictive of motion as possible. The HI-SEAS hazmat suits are equipped with ventilation fans, but do not provide cooling other than by air ventilation.

C. Representational Simulations

There are times when the objective is to have a garment which resembles a pressure suit visually, but without a requirement to more fully model the characteristics of motion or operations to the wearer. Probably the most common version of this are the “public affairs” suits worn at visitor centers and science museums, which are a simple outer garment with a passively ventilated helmet.

There are more advanced versions of the representational suit which has been used effectively in field simulations. As the NASA Desert RATS transitioned from a suit-oriented activity to a surface system-oriented activity, the role of pressurized suits was reduced and eventually eliminated. For tests involving the suit ports in the Lunar Electric Rover (LER)/Space Exploration Vehicle (SEV), an outer garment representing the suit and integrated to a suitport-compatible backpack was developed for testing purposed. This suit did provide the test subjects with the experience of donning and doffing suits via the suit port, but was not intended to restrict the wearer’s motion. The helmet was made with a half-height visor, allowing natural ventilation and conversation for the wearer (Figure 4).

D. Unpressurized Full-Spectrum Simulation

At some point in a simulation, there may come a time when there is a desire to increase the fidelity of the suit as much as possible without going to the mass, safety, and support implications of a full pressurized suit. Effects to be modeled may include not only bulk and physical restriction, but also isolation, helmet and body vent flows, and active body cooling. Such as system would provide a “full-spectrum” space suit simulation without pressurization, which should allow for reduction of suit mass and resultant workload on the wearer. In comparison to the simpler representational suit of Figure 4, the suits in Figure 5 are realistic simulations of the JSC Mk.III suit, including multi-roll joints in the hips and a hard upper torso. The helmet visors are complete, and force ventilation is presumably required to support the wearer. In this photo the suit simulators were designed to mount to the rover suit port but were unable to be used for ingress and egress simulations;[1] later versions of these suits allowed full simulations of suit port operations including ingress and egress.

Figure 4. Representational suit used with Lunar Electric Rover

Figure 5. Unpressurized full-spectrum suit used with Chariot unpressurized rover

E. Pressurized Suits

As was noted in the introduction, full-fidelity pressurized suits have been worn in field testing in some limited applications. Final crew EVA training for Apollo was conducted on small surface simulations, either inside or outside at NASA centers, shortly before flight using training suits. Since the sublimator used for cooling in the flight PLSS would not work in Earth’s atmosphere, these tests were generally conducted using off-board life support systems for both oxygen and cooling water, supplied via umbilicals not used in flight. Tending these umbilicals was typically performed by ground personnel, who also filled roles such as suit technicians, medical monitors, safety monitors, tool “gophers”, and similar support tasks. The primary benefit of these tests was to give the crew experience in working in pressurized suits, as well as end-to-end simulation of some limited sections of their lunar surface timelines. In recent months, Final Frontier Designs has supported some of the Mars Desert Research Station crews with the use of an experimental pressure suit for EVA simulations. Like the Apollo system, this suit used a transportable external life support system supplying power and pressurized air ventilation.

The early Desert Research Activities in Technology and Science (RATS) tests were focused on suit testing and assessment for surface capabilities, and needed the ability to have self-contained life support for pressurization and suit subject cooling. NASA Johnson Space Center and contractors developed a liquid air backpack for this purpose. A dewar of liquified air (oxygen and nitrogen at ambient ratios) supplied breathing air; the heat of vaporizing the breathing fluid was used to cool the water circulating in the subject's liquid cooling garment for thermal control. This system was used extensively over a number of years, providing approximately one hour of test time, which could be extended by refilling the liquid air dewar during the simulation. Since the subject had to transport their own body weight, as well as the Earth weight of the pressure garment assembly and liquid air backpack, these tests were extremely fatiguing on the test subjects.

III. Development of MX-Series Analogue Suit Simulators

In 2010 the University of Maryland, teamed with Arizona State University, was awarded a multiyear grant under the NASA LASER program to investigate EVA/robotic interactions to facilitate planetary surface geological exploration. The goal of the field testing under this grant was to create a system which provided a realistic suit-type environment for test subjects who were trained field geologists, but a full pressurized suit was infeasible due to both cost and complexity of operating a pressurized suit with a test subject pool was was generally not experienced with or trained in pressurized operations, such as scuba diving. To alleviate this problem, the UMd Space Systems Laboratory undertook the development of a suit simulation which replicated the restricted environment of the suit helmet, along with the bulk and restriction of a pressure suit, without requiring extraordinary training of the test subject populations.

The suit simulator was designated MX-A, to differentiate it from the series of experimental pressure suits in the SSL which are designated with successive numbers (e.g., "MX-2"). The "MX" prefix refers to "Maryland eXperimental" suit, in deference to past suit series such as RX, AX, and so forth. The MX-A used multiple fabric layers to crudely replicate the forces and restrictions of a pressure suit, with an inner comfort layer, padding to increase stiffness and increase joint torques, and an outer layer representing a thermal/micrometeoroid garment (TMG) made of rip-stop ballistic nylon for durability. The MX-A was a multi piece suit, with upper and lower torso assemblies attached by a zipper for a waist-level body seal closure. The backpack was separate from the upper torso, and mounted an interface ring for the hemispherical bubble helmet, which was supported by the backpack straps rather than the wearer's shoulders. A rolled foam-filled ring filled in the gap between the neck area of the suit and the helmet ring.

The MX-A worked well in initial tests, but a number of critical assessments were made of the design and operations. The multipart garment assembly was complicated to don and doff, and another person was required to assist in the donning and to operate the waist entry zipper. The weight of the backpack, helmet ring, and helmet itself were fully bourne via the shoulder straps into the wear's shoulders. The helmet was prone to coming off when the test subject bent over. The first generation version of the MX-A did not incorporate a liquid cooling system. It was first used at a one-day demonstration at the NASA Desert RATS tests in 2010.

As the University of Maryland and Arizona State University started their dedicated field tests to assess the potential for robots to assist crew in planetary geological exploration, there was a need for a second suit to allow two subjects to work together in conjunction with the robotic systems. The MX-B next-generation suit simulator was based on the MX-A, but incorporated a number of improvements. The simulated pressure garment is a one-piece assembly, with dual zippers originating in the center of the back and continuing around the waist and then up to the neckline of the suit. The MX-B incorporated better ventilation, and a commercial liquid cooling vest with an icy water bath and circulation pump in the backpack. This added to suit weight, but relieved significant issues in thermal control of the test subject. The helmet was not attached directly to the backpack, but was instead worn over the head and attached to the suit neck with short straps and snap fasteners. The MX-B became the primary suit for the UMd/ASU field tests, which became know as the Desert Field Lessons in Engineering And Science, or Desert FLEAS (with apologies to the NASA Desert RATS program).

In 2013, the University of Hawaii researchers conducting HI-SEAS were referred to the University of Maryland by the suit developers at NASA Johnson Space Center. As part of the first of four extended isolation missions at the HI-SEAS habitat, the crew was supplied with hazardous material (hazmat) suits to be used to represent pressure suits for simulated EVA operations. The crew rebelled against the lack of fidelity in the hazmat suits as compared to real space suits, and requested the test conductors locate a more realistic space suit analogue. Halfway through the first four-month HI-SEAS mission, UMd sent them the MX-B suit, and then following some servicing, also sent the MX-A.

The first HI-SEAS crew responded enthusiastically, but had a number of constructive criticisms and requests for improvement. Chief among these was the weight of the suit and backpack, which was entirely taken via shoulder straps directly onto the wearer's shoulders. There was also still problems with securing the helmets, and providing enhanced visibility for common tasks such as walking in uncertain terrains. The result was the MX-C suit simulator design, based around a commercial backpack frame internal to the suit to allow the wearer to adjust the straps to take the weight primarily on the hips via a waist strap. The backpack structure was changed to make it lighter, and it was permanently mounted to the backpack frame and the suit torso. A circular frame for the helmet flange was fabricated and mounted directly to the backpack frame to secure the helmet ring, and a hemispherical bubble helmet was attached to the ring frame with continuous velcro to ensure a reliable connection. In place of the MX-A and MX-B, two MX-C suit simulators were supplied to the second HI-SEAS crew at the beginning of their four-month mission.

Several unique circumstances should be noted at the outset of this discussion. The MX-C suits were created in direct response to the feedback from the first HI-SEAS crew. Since there were only a few months between the end of the first HI-SEAS mission and the start of the second, development of the suit garment was rushed, and only basic acceptance testing was performed at the University of Maryland before shipping the suits to Hawaii for the second mission. The LiFePO4 battery chosen to power the backpack was not easily air-shippable, and the HI-SEAS organizers had to procure a similar battery and integrate it to pre-configured adapters supplied by UMd.

IV. HI-SEAS Test Report for MX-C Suit Simulators

The HI-SEAS habitat is situated at an elevation of 8,000 feet on the slopes of Mauna Loa volcano in Hawaii. The local environment presents several challenges for designing an analog suit that is both safe and realistic for Extra-Vehicular Activities (EVAs). EVAs occur in extreme conditions and the crew often must navigate unstable surfaces with rubble, sharp planes, 200 feet elevation change, and varied weather conditions. Crew members can travel up to 1-2 miles on an average exploration EVA and encounter skylights, pit craters, a'a', and pahoehoe features (Figures 6-9). The basaltic lava rock of these features is extremely sharp and unforgiving on most materials.

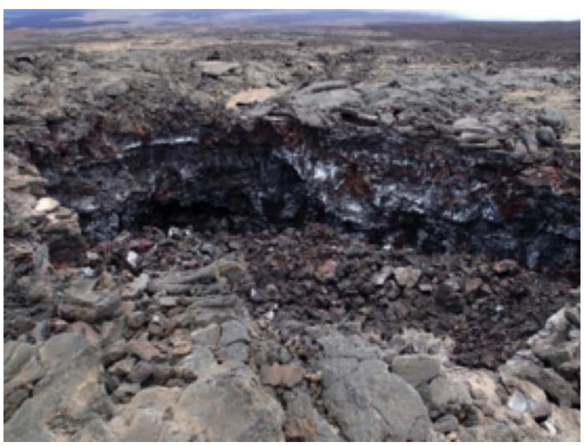

Figure 6. Skylight opening into lava tube

Figure 7. Old crumbling pahoehoe lava

The HI-SEAS program is focused on long-term studies of crew interaction and psychosocial behavior during extended isolation. Communications with "Mission Control" are via computer messaging with 20-minute delays introduced in each direction. Missions vary from four months to a year, and crews of six people are isolated in the habitat, going outside only via simulated EVAs, without any local test personnel or other observers in the area. Under the original test protocol, the only requirement was that the crew be physically isolated from the local environment; hazard materials handling ("hazmat") suits were felt to be entirely adequate for that task. The first (four-month) mission crew took the initiative to request higher-fidelity suit simulators, which led to the use of MX-series suits throughout subsequent missions.

It should be emphasized, however, that unlike other analog programs such as the NASA Desert RATS tests, the focus of HI-SEAS has never been on the EVA operations other than as another mechanism to provide tasks to the crew, including necessary (and flight-unrealistic) maintenance tasks around the habitat. Missions may or may not have a geologist as part of the crew; geology tasks are assigned primarily to control the stress of a particular EVA experience. Attempting to increase the EVA fidelity has been almost entirely driven by the initiative of individual HI-SEAS test

Figure 8. Smooth material is pahoehoe; rough is a'a'

Figure 9. Dual-suit EVA with subjects carrying sampling tool and FTIR in the lava field

subjects, as well as the participants from the University of Maryland developing and supplying the MX-series suits. The UMd personnel are not, however, considered to be part of the HI-SEAS formal investigator team, and have not been funded beyond HI-SEAS paying to ship suits back and forth. For the second and third HI-SEAS missions, the University of Maryland supplied two MX-C suit simulators. They were visually differentiated by red or blue stripes on the arms, legs, and helmet cover; as a result, the suits were individually referred to as the "red" or "blue" suit.

During HI-SEAS EVAs, crew members traverse lava fields carrying scientific instrumentation and tools with weights varying between 10 and 25 pounds. The most common equipment taken on EVAs are cameras, miniature video cameras, hiking poles, rope, ladders, medical equipment, GPS, and radio equipment. Maintenance of balance and stability are important factors when transporting some of the more sensitive equipment. EVAs can range in length from 15 minutes to check systems around the habitat, to longer exploration EVAs that last between 2 and 3 hours. The external conditions on the volcano vary from day to day with thermal ranges of 40F to 78F, and an average temperature in the 60-70F range. The winds, cloud cover, and fog all vary from day to day, with the potential to change rapidly during an EVA; affecting overall EVA performance.

EVAs within this environment fall into five categories:

- system maintenance/monitoring
- exploration
- science
- public relations
- assigned tasks

Each EVA category involves unique tasks, and requires the participant to perform different tasks, and requires specific and varied equipment.

Exploration and assigned EVA tasks have similar requirements, with EVA teams traversing lava fields to survey specific areas, collect samples, photograph features of interest, and collect data (geologic or safety related) about a particular area. These types of EVAs take the teams up to 4 km away from the habitat, and commonly require movement over a'a' and pahoehoe terrain of varying elevation. Public relations and system maintenance/monitoring EVAs keep the EVA team within 200 meters of the habitat on rubbly surfaces and on the hill/ridge behind the habitat. These EVAs tend to be about 30 minutes in length, and can be performed in any weather type, especially if an emergency repair is needed. Equipment for PR and systems maintenance can differ greatly; maintenance EVAs require the use of multiple tools. For example the HI-SEAS crew 2 used equipment ranging from, but not limited to: soldering tools, ladders, screw drivers, and measuring tapes. The last type of EVA mentioned above is the scientific EVA; this often varies greatly depending on the type of study being performed. Testing of prototype equipment may require EVA teams to traverse up to 5 km, while other studies require the team to install components outside or run testing near by the habitat. The tools in this section varied ranging from use of an FTIR to installation of a communications antenna. Data collection devices, writing, and basics tools can be used during a science EVA, requiring a high level of suit versatility.

While performing a series of simulated EVAs, the HI-SEAS crew 2 was able to develop an operational understanding of the MX-C suit simulators, focusing on the suits' capabilities, limitations, and safety. Over the 120 day mission, the crew used the MX-C suits on 29 EVAs of all five EVA types, and over various terrains featuring volcanic geology. Basic MX-C suit capabilities were compared to the modified Hazmat suits to better understand which suits should be assigned for particular EVAs, and what type of performance could be expected from each suit. Additionally, several benefits and issues were noted during suit use that could help in future designs or alterations to the MX-C.

A. MX-C Suit Fit

The MX-C is made of both adjustable and non-adjustable components and can fit a variety of people from 5'4 to 5'10 between weights of 115 pounds to 170 pounds. As mentioned before, the suit's weight is distributed over an internal backpack harness system that allows the user to adjust shoulder and waist straps to the most comfortable fit, distributing the full weight of the suit over the shoulders and waist. When fully loaded with the LCG tank and battery the suit weighs approximately 50 pounds with most of the weight low in the backpack section. The backpack harness system distributes weight evenly, allowing the user to maneuver the suit on the extreme terrain surrounding the habitat. Early on, the shoulder and waist straps caused some minor bruising and pain, but the users acclimated to the weight of the suits and the slightly shifted shoulder strap placement. This shifted placement was found to cause the straps to lie farther away from the torso distributing the weight over the shoulders in a slightly different configuration than a normal backpack. The internal harness has a metal bar on the back section that for taller users crosses the scapula (shoulder blades), leading to some discomfort over longer more strenuous EVAs.

The extremities of the suit are fitted with padding to simulate pressurization and decrease mobility as would be expected in a pressurized planetary exploration suit. A noticeable side effect from the padding was a decrease in blood circulation to extremities. This was more prevalent in the larger users who would have loss of color in their hands, tingling, and eventually complete loss feeling in their hands. Decreased circulation was noted in several users to varying degrees with smaller users experiencing less severe effects with mostly a loss of color, but not necessarily loss of sensation in hands. The lower extremities, legs, did not seem to have the same issue.

The faceplate is held on with a ring of Velcro around the circumference of the opening for the head. This has the benefit of being quick and easy to remove in the field by a teammate and although slightly more difficult it is even possible for the user to remove the faceplate of the helmet themselves. The faceplate provided a wide field of view and was preferred when performing tasks requiring clear visualization, such as photography or maintenance of more complex exterior systems. The red MX-C's fit caused the head of the user to be flush with the top of the helmet and face plate; on several occasions this contact would produce enough force to cause the helmet to detach, especially for taller users. The red suit's internal harness system did not seem to be able to lift the suit up high enough over the user's head to stop the contact between the top of the suit and the user's head; over time the force from this contact can causes the helmet to detach from the Velcro ring mounting the helmet to the suit torso and backpack.

The suit gloves are bulky, unpadded, and were not made for various sized users. The gloves were found to be large on the smaller users. They allowed the user to manipulate tools and, as seen during suit testing, decreased the amount of time a user needed during some of the gross motor control such as setting up a tripod or using a screw driver. The gloves appeared to work better for users with larger hands and fit awkwardly on smaller users, with excess material often hindering performance.

The external material of the MX-C proved to be resilient against the local basalt terrain with little damage noted to the material. The red colored terrain around the habitat did stain the white coloring of the legs, but overall this was the only noted issue with the external suit material.

B. EVA Preparations/Donning and Doffing/Post-EVA Care

Prior to any EVA with the MX-C the crew would perform a pre-EVA check and inspection of the suit and suit systems. This consisted of inspecting the exterior of the suit, ensuring the backpack section was securely attached, and inspection of the internal harnessing, ventilation hoses, ventilation fans, and all electrical connections. After the cursory inspection the crew would then attach the battery and test the ventilation system to ensure it was functioning properly with air flowing to the helmet and all extremity hoses. The LCG system was then attached and the power turned back on to ensure that the water pump was working and that water was reaching the LCG vest.

Once all systems were checked and tested the suit user would don the suit with the assistance of 1-2 other crew members. First, the user puts on the lower torso of the suit, then bending 90 degrees at the waist dives into the torso of the suit. The user needs to be sure to get their arms through the internal shoulder straps in this step, or it will have to be repeated. Once the arms are through, the user can push their head through the neck ring at the top. Pushing the head through the top can sometimes be difficult and can cause some minor scratching to the users face due to the metal ring that is under the Velcro on the head/neck of the suit.

Once the user's head is through the ring, assistance is needed to lift the user from the 90 degree bend to a standing position. Although most users could do this without aid, it was determined that assistance should be provided due to the high level of strain caused on the lower back by this maneuver. (In general, this donning procedure is very similar to that used for the A7L-B pressure suits of Apollo and Skylab.)

After the user is standing, the shoulder straps and waist strap are adjusted to ensure proper fit. The user rests the backpack portion on a table lifted to the desired height while another person adjusts the straps. Once the straps have been adjusted and secured,the assistants can zip the suit closed. Zipping up the suit is difficult due to the zipper placement; the suit has two zippers that come together at the back of the suit under the backpack. The amount of tension and stress in this area is high causing severe stress and strain on the zippers while used in EVA operations, and when initially being closed. The zippers close from the back and wrap around the sides of the suit up to the front torso. Once the zippers are closed, the assistants turn on the power to the suit and put on the user's shoes, gloves, radio, and faceplate, as it is not possible to put on or take of your shoes once inside of the suit and much easier to receive help with the other equipment to ensure proper donning.

After the EVA the user needs at least one assistant to doff the suit. The assistant turns off the suit power, removes the LCG tank, battery, shoes, unzips the suit, and is needed to hold the arms and torso while the user removes themselves. This is partly due to the sweaty condition in which the user returns causing the arms to stick in the suit due to the limited air flow in the upper extremities. Once the torso is out the user can normally remove the legs themselves, but occasionally the padding and increased moisture from sweat caused some difficulty and required the assistant to hold the leg of the suit while the user removes their leg. After doffing, the suit is briefly inspected for any obvious damage focusing on any areas that had issues during the EVA. The interior of the suit is wiped down with an antimicrobial cloth and stored open until the next use to allow the interior to dry out. The water from the LCG is removed and some of it frozen for next use and the batteries are immediately placed onto a charger to prepare for the next EVA. Any suit issues are documented and mentioned in EVA logs and reports with any serious issues immediately reported to mission support via the basecamp platform and email.

C. MX-C Ventilation

The suit is equipped with two ventilation fans; one is dedicated to providing air circulation through the helmet and the other uses 4 hoses, one for each extremity, to provide air circulation to the arms and legs. During the first few EVAs it was noted that the faceplate would fog during activity requiring higher exertion, such as climbing the 10 meter hill behind the habitat. To mitigate this issue, the ventilation hose for the helmet was repositioned from pushing air straight up and over the user's head into a position facing forward towards the faceplate. This pushed air directly across the faceplate, and decreased the fogging issues for both suits. In the blue MX-C suit the helmet ventilation would occasionally stop during an EVA; this proved to be a loose connection issue and is believed to have originated from an incident in which the suit's backpack completely detached during EVA, ripping out most of the electrical connections, damaging the Anderson Power pole connectors, and damaging some wires.

The second ventilation fan provides air to the extremities through long clear plastic tubing that can be placed into the extremities prior to donning the suit. This system provides cool air and increases air circulation in the extremities for cooling, however, due to the padding in the suit the air only cools a small portion of the extremity mainly around the hoses opening. Areas of the extremity not directly adjacent to the end of the hose do not get any airflow, and increased heating and sweating was noted by all crew members. The loose nature of the hose allowed for hose movement during EVAs, causing inadvertent repositioning of the hoses. The hose movement had another effect, in that airflow can be cut off to an extremity if the movement leads to the development of a kink in the hose. Improvements were discussed by the crew, focusing on securing the hoses in each extremity and providing small holes along the length of the hose to stop the kinking issue and increase the amount of airflow along the limb. The ideal solution would be to use a similar oval-section ventilation hose as is used in the EMU liquid cooling and ventilation garments (LCVGs); unfortunately, this appears not to be commercially available.

D. MX-C Liquid Cooling System

The MX-C has a commercially-procured liquid cooling system made up of an insulated water tank and a liquid cooling garment to assist in cooling the user's torso. The system works well half filled with water and half filled with ice; the system would stay colder longer with more ice, but is limited by the amount of ice that can be produced in an analog simulation with reduced resources. The crew would freeze water in plastic Ziploc bags or in plastic Tupperware containers so that larger quantities of ice could be made. The crew reused the water inside the LCG water tanks; the water was removed from the water tank and stored separately between EVAs. The cooling was beneficial during EVAs; without it; many of the longer EVAs could not have been accomplished. During an early EVA (EVA #11) the crew members went out to examine a large pit crater south of the habitat. The water tank had been filled and 2 trays of ice added. The EVA lasted 107 minutes; approximately 80 minutes into this EVA, the crew member in the red MX-C became overheated. It was determined later that this was due decreased cooling by the LCG after the ice in the tank melted. After this incident the crew began to freeze water into large blocks using plastic food storage containers and Ziploc bags to continually reuse the water needed for ice.

The LCG system worked 87% of the time, with the most common issue being electrical connection difficulties. The LCG connector in the blue MX-C was damaged when the backpack disconnected from the suit. Without electrical repair equipment the crew needed to tape the LCG wires to the wires supplying power until additional connectors could be obtained to replace the damaged connectors. This would occasionally lead to a bad connection and loss of power to the LCG water pump while on EVA. On one occasion the LCG lost function, and it is believed that this was due to the constriction between the suited occupant and the suit causing water to not cycle through the LCG garment. On this occasion the water pump worked, was fully powered, and worked when the occupant was out of the suit. When the occupant was suited water flowed from the tank to the garment connection point, but water would not circulate into the LCG vest.

The LCG water tank is a hard plastic container with a locking lid and internal rubber seal, housed in a flexible material cooler similar to commercial hot/cold coolers. This successfully kept water cold for about two hours before the ice would melt and the water would heat to the ambient temperature. The length of time water remained cold is a limiting factor for the amount of time EVAs can be performed. The water tank sits on top of the battery in the backpack of the MX-C and is a tight fit often pressing directly against the fan that provides air circulation to the extremities. When the suit is in a bent position small amounts of water from the LCG water tank can leak and this is a concern for the nearby electrical systems. The crew wrapped the batteries in plastic to prevent water from contacting the battery and potentially shorting the system. Originally the crew attempted to make the LCG tank more water tight with duct tape used around the internal tank and the zipper surrounding the external cover. This was attempted early on for the first few EVAs, but was found to have little effect on the amount of water leaking. The exact quantity of water leaking from the tank was not determined; only dampness in the suit material surrounding the LCG tank indicated that the water had leaked, and only occurred if the suit was not in an upright orientation during the entire EVA.

E. MX-C Electrical

The electrical systems provide both power and control over the LCG and ventilation systems. These systems are powered by a 12V/25Ah LiFePO4 rechargeable battery. The battery sits in the bottom of the backpack section with the LCG water tank on top. The electrical control panel is protected from the LCG tank by a piece of particle board that also serves as a mount for the electrical control box. The manual control for the ventilation and LCG systems are wired through this electrical control box and allow users to change the air flow rate and turn the LCG system on/off. The two ventilation fans are connected to the box with electrical wires and Anderson Power Pole connectors. The main battery connects via the same setup.

The LCG power originally used a different connector for both suits. However, both suits had difficulties with these connectors becoming damaged and disconnecting during use. The crew first attempted to reestablish working connection using electrical tape on the connectors and wires. This proved to be unreliable for the blue MX-C and was eventually replaced with one of the extra Anderson Power Pole connectors, which was labeled as the LCG connector and checked to ensure that it could be seen for setting up the suits.

While donning the blue MX-C for EVA #55 the suit was prepped, checked, and inspected as described above. Once the user was in the suit, the power was connected and turned on. Almost instantly the control box began to produce a white smoke with a strong burning plastic smell. The assisting crew first turned the power off, then disconnected the battery. At this point the suit appeared to still be producing smoke, and one crew member began removing the user's shoes while another crew member helped to hold the suit's arms while the user extracted themselves from the torso. From the time the issue was noted until the person was fully removed from the suit is estimated to be approximately 3-4 minutes to complete. Upon closer inspection inside the control box it was noted that the wiring for the LCG had gotten hot enough to melt the wire and insulation and scorch the circuit board. The LCG wires appear to have caused some additional minor melting and damage to surrounding wires. The crew's analysis was that the battery was connected directly into the LCG power line leading to this line shorting and catching on fire. This was clearly the most serious case of electrical failure during the missions to date. Due to the incident and subsequent damage, this backpack was not used again until the end of the mission, when it was returned to UMd for replacement and check-out.

The connectors for the fans, LCG, and battery in both suits were a point of suit failure, and would often have connection issues, damage, or be ripped off during more strenuous EVA activity. Most of the ventilation and LCG issues can be linked to poor connections and electrical issues. The electrical control box proved to be a point of failure in both suits, once due to structural issues in the red MX-C when the control box became detached from the mounting plate, ripping out the wiring from some of the connectors; the other incident was the previously mentioned short circuit in the Blue MX-C's control box. A possible mitigation would be to secure the wires, control box, and connectors to handle the effects of rigorous EVAs. As an unfunded project, the original connectors in the MX-C backpack were low-cost commercial connectors, which did not incorporate strain relief or high-strength latching interfaces. Although the original intent was to have unique connectors for each system, with time and limited logistics spares in the simulation habitat all of the connectors eventually became similar, increasing the risk of incorrect connections. The problem of minimal spares and limited electrical repair equipment has the potential to be a serious concern in an actual planetary mission as well.

F. HI-SEAS Crew 2 Suggestions

The crew sat down at the end of the mission to discuss the MX-C suits, how these suits can be improved in the future, and the most dominant concerns.

One of the biggest concerns is the inability to don/doff the suits alone. Being in an isolated environment with hazardous terrain, the ability to get out of the suit in the event of an emergency is an important safety factor and one that should be considered in future designs. When on EVA we always made sure that the MX-C suits were accompanied by a Hazmat suit to ensure that a person could be assisted out of the MX-C in the event of an emergency. However, even this scenario had concerns. What if the person in the Hazmat became injured or was the one in need of assistance? The person in the MX-C would be extremely limited in their abilities to assist while in the suit and would need to wait for additional crew members to provide assistance.

Additional padding or covering the metal around the collar of the suit might assist in preventing any scratching or injuries to the donning crew member. The zippers are at a point of high stress making closing these difficult and increasing the amount of zipper damage. The zippers often became disengaged, and towards the end of the mission none of the zippers would stay closed throughout an EVA. More heavy duty zippers, moving the zipper location, or adding additional support to the zippers may mitigate some of the difficulties with the zippers. It should also be noted that when the zippers disengage this causes the suits to hinder leg movement and changes how the suit's weight is distributed over the user's torso, increasing the level of exertion required to perform activities and walk in the suit.

The ventilation tubing for the extremities often moves during EVAs and makes donning the suit slightly more difficult. Securing the tubing within each extremity could mitigate tube movement during EVAs. Another suggestion for the tubing was to add holes along the length of tube in each extremity to increase airflow in hopes of increasing cooling and decreasing the amount of sweat. Different tubing for the extremities is also suggested, since this tubing tends to kink easily when on EVA, ultimately blocking airflow to that extremity. The helmet ventilation was sufficient, although to better prevent fogging, the crew thought the addition of ventilation specifically for the faceplate would be beneficial.

The internal harness was generally liked and the crew found it beneficial. The bar hitting people across the shoulder blades and the sizing of the suits were the most common fit issues. The sizing made it difficult for larger (510", 170 pounds) users to maneuver comfortably in the suit due to the padding cutting of circulation to the upper extremities. Having padding that could be adjusted based on the user would be beneficial in maintaining suit pressurization analog while allowing users to adjust suits to individual body types promoting performance and safety.

An interesting thought was brought up during suit debrief about a passive mode of operation in the event of a suit failure; for example, if active ventilation is lost, the only current option is to remove the helmet to gain access to outside air. However, if vents that could be manually opened or closed were incorporated into the helmet, this would allow the user to open these vents following a ventilation failure and increase the potential to remain in simulation while doing an emergency return to base.

The LCG system works well when the power connection remains intact, which could be solved with more sophisticated electrical connectors. The only real issue is the minor one of water leaking from the LCG tank.

The electrical components were biggest point of failure for the MX-Cs, and were problematic during operations in this extreme environment. The connectors would often break, disconnect, or have the wires ripped out during normal-to-strenuous EVA activities. The crew would perform repairs, but due to the limited electrical supplies and tools, the repairs had a limited life span and required constant monitoring and maintenance. The electrical control box was well protected from exposure to water, but had some difficulty in remaining mounted to the backpack structure. Better methods for securing connectors and the control box might mitigate many of the electrical issues. Hard wiring the fans directly into the control box or using different connectors for each fan would decrease the risk of human connection errors. The test crews are not from the same organization designing and fabricating the MX-C suit simulators; in the absence of extensive prior experience, some significant effort in supplying suit-specific tools, spare parts, and a comprehensive maintenance and repair guide would be highly beneficial.

V. HI-SEAS Crew 3 Interim Reports

The third HI-SEAS crew is currently seven months into a planned eight-month simulation at the time of writing. Via e-mail and other communications, all of which implement 20-minute delays in each direction to simulate Mars connectivity, they have also provided valuable insight into the use of suit simulators in field activities.

The third HI-SEAS mission began with only a short interval from the completion of the second mission. The MX-C suits were returned to the University of Maryland following the end of the second mission, and were examined and refurbished. Many of the findings and suggestions of the second mission were incorporated in the suits: larger ventilation tubes were placed down the suit limbs, and a specialized flow diffuser specifically designed for the MX-C helmet was 3D printed and incorporated into the ventilation system. Suit zippers were replaced with the heaviest-duty zippers commercially available to solve the problem with tooth disengagement under load. The backpack frames were checked and adjusted, and additional use and servicing videos were prepared and delivered to the third crew.

One suit was returned to Hawaii at the beginning of the third mission, but its use was delayed by a pump failure in the commercially-procured water cooling unit. The second suit required more extensive refurbishment, including the complete replacement of the electrical system due to the short-circuit described previously. Following repair and upgrades, the second suit was retained at the University of Maryland for some local tests, and was shipped to Hawaii in time for the last two months of mission 3.

VI. EVA Planning and Safety in Field Applications

Each of the HI-SEAS crews have evolved their own approaches to EVAs, and to some extent set their own limitations to what they do and do not feel comfortable doing during EVAs. For example, the second crew was highly concerned with the ability of a EVA crew to react given a medical emergency, whether trauma from shifting terrain or thermal distress in the suits. The crews have all felt a strong obligation not to “break simulation” unless in the most dire emergencies; to that end, the second crew decided that the MX-C suits would not be used for an EVA in the nearby lava tubes because of the difficulty in footing, and concerns over the ability of the other crew to extract a subject in the MX-C (or remove them from the MX-C) in the restricted volumes of the navigable lava tubes. The third crew, however, embraced the higher fidelity of the MX-C, and wore them during lava tube explorations. They did, independently from the second crew, however, come to the conclusion that crew members EVA in Hazmat suits would partner with teammates wearing the MX-C, taking on the role of safety observer and general assistant which personnel external to the simulation fulfilled in other analog tests such as Desert RATS.

This raises the issue of safety in field isolation studies such as HI-SEAS or MDRS, where everyone in the vicinity is “in simulation”. Since the MX-series of suits is designed to be as representative of a pressure suit as feasible, they are heavier, bulkier, and more difficult to put on and take off than an alternative such as a hazmat suit. Certainly, on a real planetary mission everyone on an EVA would be wearing a pressure suit, and all equally would be likely to be an accident victim or a rescuer. It is not at all clear, however, that test subjects in Earth-based simulations will (or should) accept conditions which put them at risk if there are acceptable alternatives. For the NASA Desert RATS tests, for example, the crews of the rover were accompanied by a significant number of support personnel in close proximity; the test crew was directed to “ignore them”. This would seem to be reasonable for an engineering development test such as Desert RATS; it would not be acceptable to the psychosocial test protocols of an isolation study such as HI-SEAS.

The Mars Society’s Mars Desert Research Station (MDRS) does not have this problem to the same degree, as their suit simulators are more representational, and are not intended to substantially restrict motion. They are also much easier to don and doff than the MX-series suits. The compromise adopted at HI-SEAS (having a hazmat-suited crew accompany each MX-C suited crew as a safety person) itself compromises the test protocol (as a two-person EVA becomes four-person with two subjects in hazmat suits), which they have resolved by treating the two different types of suits as interchangeable. Subjects may choose (based on size or personal preference) to wear either the MX-C or hazmat suit, and either is considered equally meaningful in terms of accomplishments during the EVA. This compromises the engineering or human factors data in favor of maximizing fidelity to the psychosocial aspects of the test, which are admittedly the predominate motivation for the test series. (It could also be pointed out that HI-SEAS differs from the UMd/ASU LASER field tests in that the test crew are generally not trained field geologists, as opposed to the smaller, shorter-duration tests where only field geologists were test subjects, and EVA test objectives were always focused on geological data collection.)

There are some alternative approaches to EVA operations fidelity, even for an isolation study like HI-SEAS. Given sufficient numbers of MX-series suits, all EVA crew could wear more realistic simulations of pressure suits. One potential solution to ensuring safety would be to have an emergency "rapid response" team in a vehicle out of sight of the HI-SEAS crew, but monitoring over the suit radios and ready to respond upon need. For a simulated mission of many months with dozens of EVAs, this response team would have to be nearly full-time, significantly raising the cost and complexity of the overall mission simulation. This approach is roughly analogous to the support crew accompanying the rovers on Desert RATS tests, albeit at greater distance.

The other key issue to be considered is the relative importance of maintaining "sim" in the face of contingencies or injuries of varying complexity and urgency. If the suits were easier to doff, particularly by the wearer without aid, the uninjured person could quickly remove the encumbrance of the suit to assist the injured teammate. This would, however, break the isolation protocol of the greater experiment. The current MX-C suit design allows the wearer to quickly and easily remove their helmet at any time; however, in one instance of cooling failure and significant overheating, the affected crew elected not to remove their helmet in the field for fresh, cool air, but did forego the nominal 10-minute wait representing depressurization once they were in the "airlock" section of the habitat.

VII. Future Suit Simulator Development and Testing

Based on the extensive feedback from three HI-SEAS crews to date, the University of Maryland is engaged in the design and initial fabrication of the prototype for the next-generation full-spectrum suit simulation: the MX-D. This unit, as currently planned, will continue some of the advances of the MX-C series, including the hemispherical helmet, interior backpack frame, and integral backpack frame. Of necessity, the suit will also incorporate water cooling for the wearer and active ventilation for both breathing air in the helmet and ventilation air in the extremities.

Much of the current redesign activity focuses on refinement of existing design features, such as larger and better-secured ventilation tubes in the arms and legs, a more efficient flow diffuser to direct breathing air over the interior surface of the helmet for better anti-fogging properties, and making it easier to adjust the internal backpack frame and simulated pressure garment to more closely fit a wider range of wearer's sizes. The padding used in the MX-C suits to replicate suit bulk and restrict joint motion has a tendency to compress and shift towards the distal end of the extremities; current plans are to incorporate an interior "padding garment" which has both inner and outer layers quilted to the padding to prevent migration of the padding under extended use.

Of potentially greater importance, however, is looking for innovative approaches to increase options for safety in field testing without unsuited (or differently suited) support personnel in the area, and without breaking "sim" for minor problems. Some of the potential approaches include the use of "buddy hoses" as in Apollo to allow the sharing of suit power, communications, helmet ventilation air, or cooling water between suits as a contingency measure. To date the most significant medical contingencies have been associated with overheating; it is hoped that having the ability to share with a teammate whose suit cooling is compromised would prevent the overheating from reaching an acute stage before returning to the habitat.

There is less that can be done strictly on the suit side for traumatic injuries, such as a sprained ankle or broken leg. This problem would be much less likely on a real mission, as the combination of lower gravity and stiffness of a pressurized suit would tend to protect the limbs from such injuries in the first place. One concept currently under consideration would be to add an exoskeletal structure to the lower legs to support the shins and ankles from such traumatic injuries.

Cooling is perhaps the most difficult challenge for longer-duration suit simulators. The current cooling reservoirs when full of water and ice weigh approximately 10 kg, which is (depending on workload) adequate for 2-3 hours of cooling. The third HI-SEAS crew has performed EVAs in MX-C suits up to five hours, although this consisted on an extended period quiescent in a lava tube for a simulated solar particle event, with the cooling water only used for the walk between the tube and the habitat. All other factors being equal, doubling active duration with cooling would more than double the cooling system weight, as the additional backpack weight would increase physiological workload just from its presence.

The NASA Desert RATS pressure suit tests used a liquid air backpack, with the cryogenic air mixture used for both breathing and suit cooling. This system was only adequate for an hour or so, and the test personnel developed a method to recharge the liquid air dewer without reducing pressure in the suit, although the subject had to be still during the recharge process. One potential approach would be to develop a system to replenish the reservoir with ice water during otherwise normal operations.

Lacking the supporting technicians of the Desert RATS tests, one approach that UMd is interested in pursuing would be a crew transport rover for HI-SEAS. Beyond extending range and reducing physiological workload by relieving the crew from the need to walk to the EVA sites, a rover could conceivably extend the duration of the EVA by having the ability to simply hook the suit backpacks into a larger icy water bath on the rover to cool multiple EVA crew during the traverse, and potentially to allow full replenishment of the backpack ice bath containers, which currently limits EVAs to durations of 2-3 hours, depending on workload. A rover could be equipped with robotic manipulators to allow it to safely collect an incapacitated crew in a suit simulator and stow them on the rover to allow a quick return to the habitat, or to meet external emergency responders in the event of major trauma or illness. Since the MX-C suits are being supplied to HI-SEAS without exchange of funds, there would have to be an external funding source to allow the design, fabrication, and operations of such a support rover, or any sort of in-test suit recharge system, in future HI-SEAS missions or similar test series.

VIII. Conclusions

Given the difficulty in getting humans back to the Moon, or to the surface of Mars, field testing is one of the most rewarding method currently feasible and affordable to better understand how best to design surface architectures and mission planning. There are now permanent field sites all over the world, set up by government agencies and enthusiastic space supporters, each with their own approaches to EVA and their own responses to the challenge of simulating pressure suits safely and economically.

The use of MX-series simulators at HI-SEAS started as a "target of opportunity" to expand the experience base on this type of suit simulator. The MX-A and MX-B suits were well tested in-house and in more traditional analog testing, where the imdividuals responsible for development were present on-site while analog EVA sorties were performed in the suit. Results from the first tests with MX-A and MX-B at HI-SEAS primarily confirmed results from prior experience.

The desire to continue to support the HI-SEAS testing, and to respond in 3-4 months to the feedback from Mission 1 in what turned out to require an entirely new simulator system, led to many of the incidents documented in this paper. The MX-series of suit simulators are *not* pressure suits, but are instead garments tailored to somewhat suggest the bulk and restrictions of pressure suits. In any contingency, there is always the recourse to simply and immediately open the helmet. One of the major "lessons learned" was that there is an entirely different dynamic when performing prolonged testing without the ability to get access to the suits, and the requirement to diagnose problems and detail solutions to subjects in the simulation with great skills but no prior knowledge of suit design and systems. As problems occur and are remedied based on available parts, the configuration of the system changes with time, and the remote developers become less and less aware of the current configuration and potential problems from improper connections or simple wear on the system.

The one UMd subject with extensive experience wearing A7L-B and EMU pressure suits in neutral buoyancy estimates (entirely subjectively) that an MX-C garment is "about 25% of the way from shirtsleeves to a space suit". The development team feels that (a) this is significantly closer to space suits than any other suit simulator developed and used to date, and (b) there is some benefit in pushing the technology to improve the realism of the experience for analog test subjects. In that process, ongoing activities at HI-SEAS have identified the shortcomings of a higher-fidelity suit simulator, in that a closer representation to the true restrictions of a pressurized suit produce not only limitations in what the wearer can do in nominal circumstances, but also what they can do in the event of an emergency, whether their own or a teammate's. The crews of HI-SEAS have shown that higher-fidelity suit simulators can be used on an everyday basis safely and effectively, but self-limit their use to ensure that personnel in suits with fewer encumbrances will be available in the event of an emergency. The challenge to designers of suit simulators seeking higher levels of fidelity to actual pressure suits is to increase the constraints of the suit simulator, while at the same time seek out solutions to increase the ability of the wearer to rescue their teammates or themselves.

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