Methodologies in Assessing and Repairing Space Analog Research Stations

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Earth-based research stations are used to practice techniques and develop technology that will be used in space. Insight into how humans will use in-situ resources on the moon and Mars to inspect and maintain their habitat can be studied by focusing on these terrestrial stations. This paper reviews the 15th expedition to the Mars Society's Mars Arctic Research Station in the high Arctic. Emphasizing the importance of inspecting systems for safe habitation during simulated Mars missions, the study draws parallels with repair practices on existing and future space missions. Inspection techniques adapted from commercial aviation practices are discussed. The expedition used a hierarchical decision-making approach, prioritizing critical inspection tasks for safety and mission success. The Mars Arctic Research Station underwent a comprehensive assessment after being uncrewed for nearly six years due to mission scheduling and the COVID-19 pandemic. Outlined herein are the task planning process, inspection results, recommendations for future analog astronauts, and the need for inspection programs to improve habitat conditions and longevity. The inspection revealed satisfactory conditions for safe habitation and operation of the Mars Arctic Research Station during the 2023 Arctic Mars analog mission season.

I. Introduction

HUMAN missions to Mars such as Mars Direct and NASA's Mars Reference Mission may use a method of deploying equipment to the surface of Mars using both crewed and uncrewed spacecraft. In these two example mission plans, a crew will land on the surface of Mars in the vicinity of a previously deployed supply vehicle or return vehicle

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[1, 2]. These vehicles may be sitting dormant for many months or years before a crew will be able to assess their status. Preliminary mission planning is made easier if one assumes the equipment will either operate nominally, or the crew will have what they need when they arrive to bring the equipment to a safe working condition. Mature mission planning should include the lessons gained throughout the decades of human spaceflight. The primary goal of analog research on Earth is to add to this experience by working in environments that most closely match those that might be encountered on the moon, Mars, and beyond.

Space habitats such as Skylab and the International Space Station (ISS) undergo repairs frequently, with support from NASA Mission Control Center (MCC), using time, tools, and equipment in situ to perform unscheduled repairs [3]. These repairs can include rework or replacement of systems and their components and may be necessary for safety and mission success, making them a priority over scientific research. The time delay in communication between MCC and the ISS is not as limiting a factor as the time delay between Earth and Mars, which can range from ~5 to ~20 minutes depending on planetary position. The astronauts tasked with repairs on Mars would use a different approach than those in Low Earth Orbit due, at least, to these communication constraints. It should not be assumed that MCC would play the same support role on a Mars mission as they do today. The astronauts are rarely, if ever, the same people who designed or built the item they may be inspecting and repairing, and it is not difficult to imagine a time in humanity's future when a crew might be deployed to an existing facility on Mars without a complete beforehand knowledge of its condition. This hypothetical crew may find success if they have an established procedure for assessing a facility, vehicle, or piece of equipment, possess or have access to the knowledge of how to repair it, and have the skills and tools needed to carry out the tasks. These skills, tools, and procedures can be established by practicing them on Earth with the luxury of resources and reduced cost. Variables such as time delay, tool design, and repair procedures can be altered and tested well ahead of a mission to space.

Research in analog locations on Earth that closely resemble conditions on the Moon and Mars have been in use for many decades [4-6]. Locations such as remote islands, the Arctic/Antarctic, and deserts of the southwest United States offer such conditions. In 2023, a rare opportunity to practice approaching and assessing the systems and structures of a previously deployed space analog research station presented itself. The Flashline[1] Mars Arctic Research Station owned by the Mars Society and located in the far north of Canada had been uncrewed for over 5 years due to

[1] The author notes that the naming rights for this Mars analog facility have expired, therefore this paper will use Mars Arctic Research Station (MARS) or the Arctic Station to refer to the formerly named Flashline Mars Arctic Research Station.

mission scheduling and the COVID-19 pandemic. Starting in mid-2022, planning efforts for the 15th expedition to the Flashline Mars Arctic Research Station, dubbed FMARS-15, were initiated. The primary goals of the FMARS-15 expedition were to perform a systems and structural assessment of the primary habitat (hab), perform necessary repairs if able, and carry out a science mission while under simulated Mars mission procedures. In addition to gathering data for several scientific research studies, the results of this expedition would inform recommendations for the 2024 expedition season.

II. The Mars Arctic Research Station

The Arctic Station is located on the rim of the Haughton Impact Crater on Devon Island in Nunavut, Canada. The Haughton Crater has long been established as a feature of interest for scientists and researchers for its similarity to Mars [7]. The facility consists of a 2-level cylindrical structure with crew rooms, a galley, engineering and laboratory spaces, and EVA hatches [Fig 1]. The primary habitat is approximately 8.2 m (27 ft) in diameter and 8.2 m (27 ft) tall. It is constructed of 15 cm (6 in) thick fiberglass composite walls and a domed fiberglass composite roof. The floors and internal secondary walls are of standard North American wood housing design. The habitat sits 1 m (3 ft) above the ground supported by 6 steel legs and outriggers. MARS has been in use since it was deployed as the first permanent Mars analog research facility in 2000 until the late summer of 2017. A total of 14 Mars analog missions have been conducted between its deployment and 2017 during which research was conducted including space suit testing, telerobotics, and human factors in long-duration analog missions [4, 8].

An assessment of the facility and its ability to provide a safe habitable space in which to perform the research and simulated mission was necessary due to the unknown condition of the hab and surrounding area. The COVID-19 pandemic interrupted the scheduling activities of the Mars Society at the Arctic Station which prevented the hab from being crewed between the end of the 2017 season and the arrival of the 15th expedition crew in 2023. Without a consistent crew presence to use and maintain the facility and equipment, the condition of the station was unknown outside of one remote scientist visit in the summer of 2022 when photos were taken and provided to the FMARS-15 crew. A large portion of crew planning time was spent determining priorities for the tasks and tools that were necessary not only to provide a full inspection and repair report, but to also position the crew to safely achieve their research goals for their analog Mars mission.

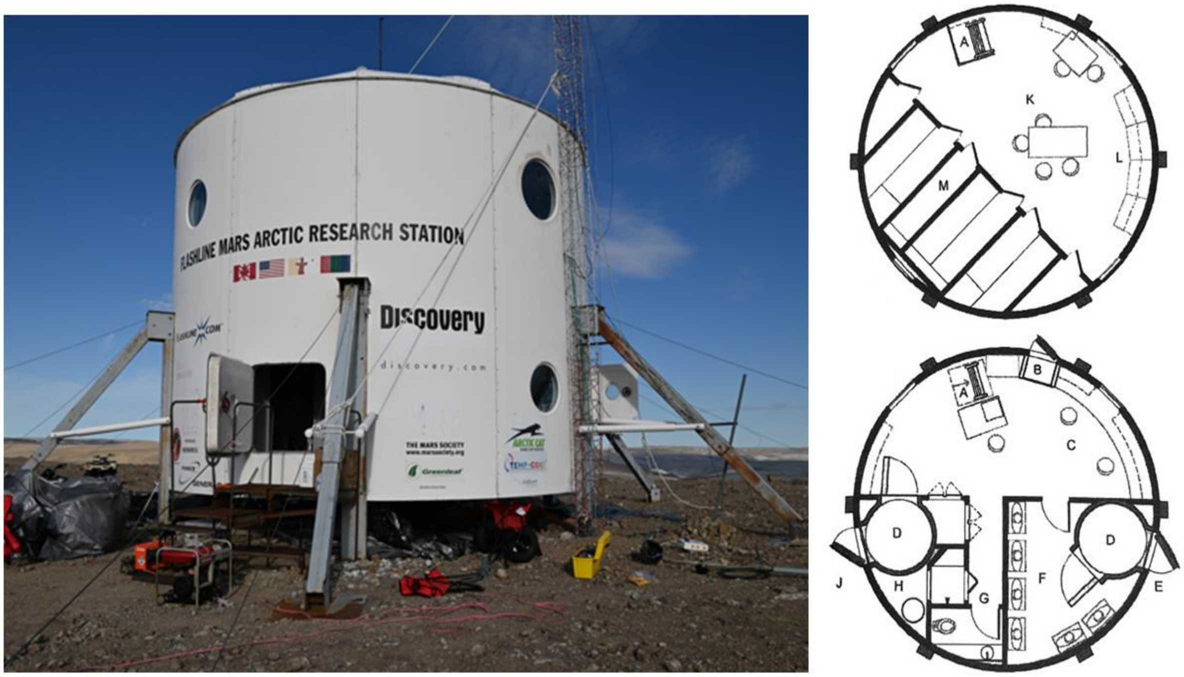

Fig. 1 MARS Habitat in the summer of 2023, Main Hatch side shown (left). Layout of the hab interior with correct orientation of both levels relative to one another (right) [4]: (A) Stairway, (B) Sample Hatch, (C) Laboratory, (D Right) Main Airlock, (D Left) Engineering Airlock, (E) Main Hatch, (F) EVA Preparation Room, (G) Hallway and Shower, (H) Toilet, (J) Engineering Hatch, (K) Wardroom, (L) Galley, (M) Crew Quarters.[2]

III. Task Planning

An expedition duration of 4 weeks was originally planned for the summer of 2023, but delays in permitting reduced that time to approximately 3 weeks. Early mission planning that maintained a small number of clear goals ensured the schedule was flexible enough to handle these types of changes. Limitations on travel through commercial airlines and charter flights influenced the expedition weight and materials limits.

The mission was planned out by the crew and Mission Support Team over teleconference at least weekly at the beginning of the year, moving to more frequent meetings in the latter 2 months leading up to the expedition. A review of the latest photographs, videos, mission reports, crew journals, inventory lists, and prior crew interviews made up the primary sources of crew training and information about the facility. It was clearly established at the beginning of the mission that the hab analysis and repairs would take priority over the science objectives since certain systems, and

[2] The space between the Hallway (G) and Engineering Airlock (D Left) is a storage area for tools and equipment often referred to as the Engineering Room.

the hab itself, would need to be safe and operational for any science to be performed. The balance of science and engineering[3] tasks (and time dedicated to those tasks) was largely driven by the resources needed to complete them in their necessary sequence. The task resources include the number of crewmembers needed for a given task, equipment, materials, and time. Crew Engineers planned a script of tasks that needed to be completed in sequence from the moment the crew would land on the island. The script included the equipment and materials needed to complete the tasks and thus made up the bill of materials (BOM) and mass required for the mission. Time spent talking through the elements of the script among the crew allowed for logic and efficiency to be built into the task scheduling. (For example: external structural assessment preceded entering the hab for mold testing and cleaning, and removing mold that could pose a risk to the crew had to be completed before pushing further into the hab to test systems and equipment. Generators would need to be started early and the source of water secured before the hab could be inspected, repaired, and deemed fit for occupancy.) The final assessment preceding occupation and the analog mission would be done by the crew with the help of Mission Support.

The lack of information regarding on-site materials and equipment status was a major driver of increased mission planning time and mass. The available information in the form of a master inventory list with images and equipment status was established in 2009 with many updates applied in later years by other analog astronauts. The dates recorded for equipment status were noted but might not have made any difference given that the facility had not been crewed, and thus equipment was left unused for over 5 years when mission planning began. Conservative assumptions were made about the status of certain tools and materials such as hand tools, power drills, and weather sealant, and were backed up by previous crew interviews, inventory, and photographs of the engineering room. Tasks and their BOM that were critical to allow the expedition to proceed safely were identified, and some tools and materials were brought up with the crew regardless of whether they were recorded as already at the hab. Issues that were identified as a high risk to mission safety were given priority in the schedule. Tools and equipment needed to help solve these issues were given priority in the mass budget if it was uncertain whether the tools or materials would be on site and usable. The unknown condition of these items led to duplicates in the on-site inventory but helped ensure a successful expedition and simulated Mars mission overall.

Broader logistical requirements placed pressure on the expedition that drove certain task, timing, and mass decisions. Limits imposed on materials, weight, and the number of carry-on and checked items for international flights

[3] The term “engineering” here envelopes inspection, test, maintenance, and repair design.

drove the timing and delivery requirements (re: financial cost) of certain items into Canada. At least 4 major legs and as many different aircraft would deliver the crew and equipment from their individual cities to the Houghton Crater. Of these aircraft, the DeHavilland Twin Otter's payload weight was most critical. Thus, limiting total mission weight to less than 2,000 kg was financially beneficial. However, it was determined that the total expedition weight would require at least two flights in the Twin Otter from Resolute to deliver all the needed items and crew members to the hab on Devon Island. Knowing this as early as possible in the planning stage was important to securing expedition funding. Once the task list and BOM were created, weight and volume were determined and compared to these logistical limitations. Splitting the put-in flights into two demanded a determination of which items were to be placed on the first put-in flight, with all critical tools and safety equipment on the first load.

The first minutes and hours after delivering the first crew members and half the payload would be the most critical. It was determined that the Engineering team would be on the first put-in flight to begin working through the tasks [Ref. Table 1]. There were ~1.5 hours between the departure of the first plane leaving the crater rim and the departure of the second plane leaving Resolute to bring the rest of the crew. During this time, several decisions needed to be made before the rest of the crew would be cleared to depart for the hab on the 2^{nd} put-in flight. The decisions included surveying the water from the nearby stream, inspecting and starting the generators, and performing the exterior inspection of the hab and surrounding area to determine if it was safe to stay. If these elements were not satisfactory, the mission could pivot or abort before the 2nd flight departed from Resolute.

Table 1 Engineering Task List

Task	Description
Landing and Traverse to Habitat	The crew will land within a few kilometers of the hab. Unload the airplane of equipment and supplies. Carry equipment using ATVs and on foot from the landing site to the hab.
Grounds Inspection	Inspect the area around the hab for hazards, damaged equipment, or debris.
Hab Inspection - Exterior	Perform a walkaround inspection of the outer surfaces and structural supports of the hab.
Generator and Incinerator	Set up the generator to provide power to the site and to the incinerator.
Structural Assessment 1st Level	Visual structural inspection of the interior of the first level.
Mold Test 1st Level	Test any mold that is identified for the presence of black mold (Stachybotrys chartarum).
Address Contaminated Items 1st Level	Remove or clean items suspect of mold contamination.
Structural Assessment 2nd Level	Similar to 1st Level
Mold Test 2nd Level	Similar to 1st Level
Address Contaminated Items 2nd Level	Similar to 1st Level
Clean 1st and 2nd Level	Complete cleaning operations, perform a final assessment to determine the habitability status of the facility by the crew.
Load In/Power On/Set Up Comms	Move items inside the hab, apply power to the power panel, establish internet connection and communication with mission support.
Power System Inspection	Inspect the power receptacles, lights, and equipment on the 1st and 2nd levels.
Water System Inspection	Fill reservoir and run water through the plumbed water lines and fixtures. Test the water at each outlet for contamination. Check for leaks throughout the system.

IV. Methods of Analysis

Inspection focused on the systems and structure of the habitat. For the purpose of organizing this information, the structure of the hab is treated as a system. Inspection methods were adopted from commercial aviation practices as described in Advisory Circular AC 43.13-1B [9]. This AC guidance is provided by the Federal Aviation Administration in the absence of a manufacturer-recommended inspection program, as is the case with MARS. Visual inspection was used most as it is the most common method for commercial aircraft inspection, encompassing approximately 80% of all Non-Destructive Inspection procedures [9]. It is worth noting that crewed missions to Mars will benefit from robust maintainability and inspection practices defined early in the program design requirements and facilitated by the contracted manufacturers responsible for designing the equipment, systems, and structure in accordance with established NASA standards.

Types of inspection performed:

Visual - looking over component and material surfaces aided by mirrors and light source to detect a wide variety of discontinuities such as cracks, corrosion, contamination, surface finish, weld joints, solder connections, and adhesive disbonds.

Operational - energizing or using a device or system as it is designed to be used to determine if desired functionality is present. Sophisticated devices or systems may have built-in test equipment which can aid in inspection and troubleshooting.

Tap test - tapping on the surface of a bonded part such as the hab walls with a coin or other tool will produce varying acoustic responses that can be used to detect the presence of delamination or disbond when compared to a known acceptable area.

Leak check - a combination of Visual and Operational inspection such as filling a system with working fluid or fluid for transport and inspecting the system for leaks.

The facility is split into its major systems for inspection, and those systems are further segmented into physical areas of the hab, or into their constituent assemblies or components where it made sense to do so. Further segmenting down to the detail part level could add lengthy and unnecessary work. By separating the systems into large segments, failures can be identified and isolated to those segments. Closer troubleshooting and inspection would follow only as needed. Another way that system segments were identified to be inspected was by how critical the elements were to mission success. For example: while the equipment of the water system allowed for configuring for water-use monitoring and data collection, this is not needed for safe water consumption by the crew while outside of the simulated mission or while water use monitoring is not a mission requirement. Therefore, the Engineering tasks for this system would be those needed to provide safe drinking water at the least, and noting additional tasks that could be performed if time permitted.

Since the plumbing and wire diagrams were not up to date with ongoing hab maintenance, broad inspection areas were defined rather than individual system components or circuits. This allowed some freedom to choose how to inspect and test a system while on site. Generally, the flow of inspection was dictated by the system. For example, the water system was tested from the starting point by loading a minimal amount of water into the hopper on the 1st Level and then inspections proceeded through the plumbing system in the direction of water flow. Similarly, the electrical circuits were individually tested within broad areas like the 1st Level regardless of whether the circuit energized components in other areas, and then those other areas were tested starting at the Electrical Power Panel proceeding outward.

Safety considerations would also drive task order. Electrical power was needed to run exhaust fans prior to cleaning with detergents. Mold cleaning would commence only after mold test results were reviewed. Structural inspection had to precede all tasks. Contingency conditions or issues that would likely require mission support to aid in determining how to proceed were noted during the planning phase. A major structural problem, for example, would preclude any use of the hab and would require mission support help with quick planning and the logistics of getting more equipment and materials on site if needed. The expedition could then shift to a recovery and repair operation to ensure the MARS could be brought to a safe operating state for future use.

The following list shows how the systems were segmented and ordered for inspection.

- Structure
    - Exterior
        - Support legs and guy wires
        - Hatch stairs
        - Outer walls
        - Underside
        - Radio tower
        - Roof
    - Interior
        - 1st Level
            - Floor
            - Interior walls
            - Secondary walls
            - Ceiling
        - 2nd Level
            - Floor
            - Interior walls
            - Secondary walls
            - Ceiling
- Water
    - Hopper and pump
    - Pipes, valves, and fittings
    - Header tank and pump
    - Water heater
    - Laboratory faucet and sink
    - Galley faucet and sink
    - Shower, bathroom faucet, and sink
    - Toilet

- Power
  - Fuel Barrels
  - Generators 1-5
  - Electric Power Panel
  - 1st Level
    - Receptacles
    - Lights
  - 2nd Level
    - Receptacles
    - Lights
  - Electrical Power Storage
  - Wind Turbine Generator

The levels of this list highlight how the system can dictate the best method for incremental inspection, whether split into physical zones like the structure and power, or by system operation as with the water system.

A brief note on an aspect of the MARS design is useful at this point. The remote location of the Haughton Crater underscores the necessity of strategic decision-making regarding the hab's materials, components, and equipment [7]. Opting for commercially available off-the-shelf (COTS) items is paramount in this context. Utilizing COTS items not only ensures access to well-documented repair and maintenance procedures but also helps guarantee the availability of familiar and easily procurable replacement parts and materials. Furthermore, it provides a valuable source of customer support. Apart from the primary structure and some experimental equipment, most components of the Arctic Station, including its systems and support equipment, are sourced from COTS products.

V. Observations

Structure

The MARS primary structure is a combination of fiberglass composite, wood floors, and steel support legs. The bulk of the weight of the structure is in the composite elements [Ref. Table 2]. Wall panels and ceiling sections are made of a composite layup of glass fiber face sheets with a glass fiber corrugated channel core [Ref. Fig 2, 3].

The major structural members were inspected for obvious signs of damage from an initial walk around at a distance of 2-5 m (6-16 ft) to ensure no major structural issues were present, a more detailed inspection followed once it was deemed safe to do so [Ref. Appendix Table 3].

Water

The water that supplies the hab is usually sourced from a stream ~1 km (0.6 mi) to the Northwest. Eight 26.5 L (7 gal) water cans are filled and hauled back to the hab using the ATV and trailer. The water is loaded into a plastic hopper on the lower level in the EVA room. From there, it is pumped to the attic header tank via PEX pipes and a potable water pump. The header tank provides pressure along with a smaller water pump to the water heater, shower, and faucets in the galley and bathroom. Grey water is drained through plumbing to a plastic evaporation pool [Ref. Appendix Table 4].

Power

Power is provided by any one of four generators, two run on diesel fuel and the other two on gasoline. A 5th diesel generator was not operational and can be used for spare parts. All liquid fueled generators advertise an output of 5000W. The generators are stored either under the hab or in a shed ~30 m (98 ft) from the hab to the north and are located outside of the shed when in use. An electrical lead runs from the generator to the hab power panel providing 120V/240V AC power. The hab wiring consists of mostly Metal Clad (MC) cable with some Romex located within the secondary walls. A wind turbine generator was brought on this expedition, installed, and operated for the duration of the expedition. With the given winds, it provided minimal power useful only to charge 12V batteries used for power storage and EVA suits. Power storage was also brought with this expedition in the form of an Anker Powerhouse 757. Both the wind turbine generator and power storage were stored in the hab at the close of the expedition [Ref. Appendix Table 5].

Ventilation and air quality

Ventilation was not identified as a system to be inspected during mission planning beyond operating the exhaust fan as needed. An air quality meter was brought by the science team for unrelated measurements but was used casually in the hab to monitor carbon dioxide (CO_2), volatiles, and particulates. The AQI meter was deployed inside the hab at several locations on the 1st and 2nd levels. These observations were not scientifically rigorous. The measurements showed elevated levels of CO_2 above atmospheric baseline measurements made outside the hab, plus an increase in particulates during cooking. Both conditions were expected and mitigated with active air circulation using exhaust fans. Elevated levels of Benzene and other volatiles were recorded on several occasions and similarly mitigated with the use of exhaust fans.

Table 2 Weight of structural components of the hab

Component	Material	Quantity	Weight[4]	Total Weight
Wall Section	Fiberglass composite	12	363 kg (800 lb)	4356 kg (9600 lb)
Roof Section	Fiberglass composite	12	160 kg (350 lb)	1920 kg (4233 lb)
Primary Legs	Steel	6	181 kg (400 lb)	1086 kg (2394 lb)
Floor[4]	Wood	2	1120 kg (2468 lb)	2240 kg (4936 lb)
MARS Hab		1		9602 kg (21163 lb)

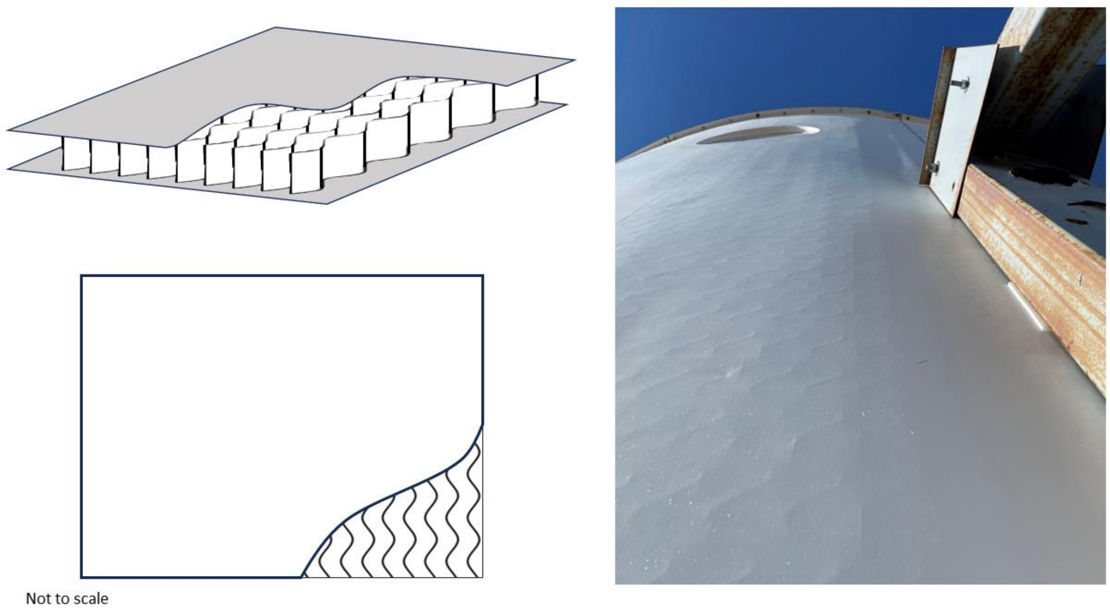

Fig. 2 Illustration showing composite layup and core shape and orientation typical of the wall and roof panels (Left). A view at a low sun angle shows the corrugations through the exterior face sheet (Right).

[4]The floors are made of wooden joists with plywood faces. Assumptions were made on the spacing of joists where direct measurements were impractical. Average weights for wooden structure were used in the calculation.

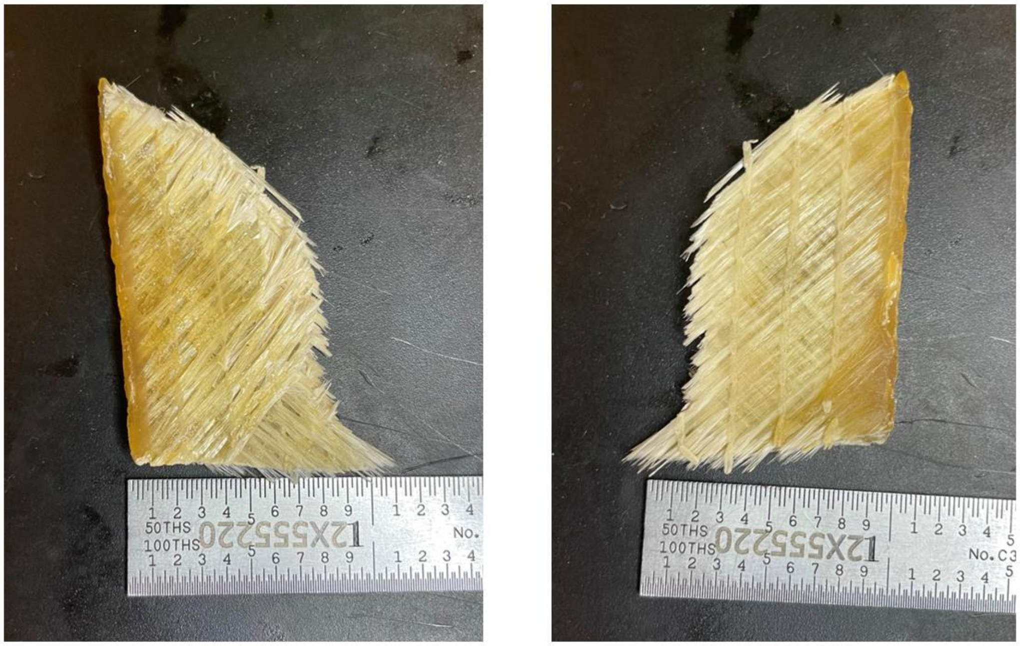

Fig. 3 A sample of the composite from the core section of the wall panel ventilation hole near the Engineering Hatch.

VI. Conclusion and Recommendations

Implementation of an inspection program is paramount to the continued success of the MARS habitat. The program should include a well-organized plan for inspection and reporting criteria on the systems listed in this paper. A foundational training should be provided to future Analog Astronauts that plan to use the MARS facility. This training should include standard instructions for carrying out the inspection program.

Regardless of planned analog missions, the unneeded fuel barrels must be removed from the site as soon as possible to avoid the risk of contamination of the hab and crater environment.

The water that was removed from the wall panels shows that it was being retained within the walls. This could be a possible source of the mold problems of this and previous missions. Mold levels should be monitored, suspect locations recorded, and any mold addressed on each expedition.

Convene a design group to create an installation plan for ventilation of the 2nd level that includes passive ventilation in the off season and active ventilation when the habitat is crewed. This active ventilation design should take into consideration noise levels so as not to disturb crew sleep.

It is recommended that future Analog Astronaut crew selection include personnel that have a maintenance background regardless of education or occupation. Engineering time should be focused on hab inspection and maintenance in accordance with an established inspection and maintenance program.

A comprehensive equipment and materials inventory for any remote station is critical to its longevity. By knowing the status of equipment ahead of an expedition, weight can be saved by carrying only equipment that is needed. This also helps keep expedition expenses affordable. The available master inventory was used extensively and updated for future expedition use. The inventory list should continue to be used as a reference for an inspection and maintenance planned for the Arctic Station.

Overall, the FMARS-15 crew determined the habitat to be in a satisfactory condition for safe habitation and completed a successful Mars Analog mission during the 2023 expedition season.

Appendix

Table 3 Structural inspection, results, and disposition

System Element	Inspection Method	Inspection Results	Recommended Disposition
Support legs	Visual	There are six support legs, each with an outrigger-like landing leg reminiscent of a Mars or Lunar Lander. Extendable PVC tubes are installed between the support leg and the outriggers. These tubes are decorative and were not inspected. All support legs and outriggers are missing finish on approximately 50% of the surface, along with cracking and blistering finish in some areas. Exposed steel shows evidence of corrosion with mild pitting. Fasteners are tight when tested by hand. Signs of cracking through the part thickness or deformation of the material was not present.	Consultation with structural corrosion experts is recommended for further action. Implement an inspection program for the Support Legs.
Guy Wires	Visual	Each of the six legs has two guy wires. All guy wires were slack and carrying no load. Turnbuckles at the lower end of the guy wires showed no evidence of lubrication. Mild corrosion was present common to the cable clamps. Anchors for the 12 guy wires showed some evidence of being pulled through the soil in the load direction but were sturdy when a load was applied by hand.	Remove and replace rusted components. Verify anchors are adequately secured. Adjust and tighten Guy Wires. Implement an inspection program for the Guy Wires and components.
Main Hatch Steps	Visual	The hatch steps are steel anti-slip grating design constructed using steel pipes and U-bolts. Four steps lead up to a platform on the same level as the 1st level. The lower two steps show evidence of some missing finish, corrosion is widespread where the finish is missing. The upper 2 hatch steps and platforms show widespread corrosion and minor pitting. Evidence of large reduction in material cross section was not present. Fasteners were tight when tested by hand. The steps are split with one steel railing installed on the left side and one down the center. The steps on the right side are incomplete with only 2 steps below the platform with 1 step significantly off level. The right-side steps are not acceptable for safe use. One step segment was located inside the main airlock. Cargo can safely be hauled to the platform level using access on the right side of the main hatch steps when standing at ground level.	Install a permanent railing or method to block human access to the right side of the steps until parts can be supplied to restore the steps to their original design, as reflected on the left side. Implement an inspection program for the Main Hatch Steps.
Engineering Hatch Steps	Visual	The Engineering Hatch Steps are similar in construction to the Main Hatch Steps except they have 3 steps up to a platform and are half as wide. The top two hatch steps are not level, tilted toward the crater, the platform is not level and tilting away from the crater. The hatch steps show widespread corrosion and minor pitting. Evidence of large reduction in material cross section was not present. Fasteners were tight when tested by hand. Railings are installed on both sides.	Loosen or remove the U-bolts common to the step segments and platform. Level each step and the platform. Tighten or reinstall the U-bolts. Implement an inspection program for the Engineering Hatch Steps.
Wall External	Visual, Tap test	All 12 wall panels were inspected from the ground and found to have evidence of weathering. Evidence of cracking of the outer finish was negligible and therefore not	Implement an inspection program that: Records finish crack location and

		rigorously recorded. Where cracking was present, the finish was brittle and flaked off with some manual effort in small pieces less than 1cm square. The exposed fiberglass beneath the finish was continuous. Tap testing resulted in solid and minimally varied acoustic response common to surfaces within arm's reach, approximately 2m above the ground. Common crack length did not exceed 10cm. Evidence of large cracks or areas of delamination was not present. The surface finish is a matte white. Many thin fibers were present on all inspected surfaces uniformly spaced and randomly oriented. These fibers are much thinner than the structural glass fibers and are only visible at a distance of ~10cm from the surface. It is suspected these fibers are a component of the surface finish and are evidence of the finish undergoing erosion or some kind of deterioration. Drain holes in the wall panels were found to have been plugged with silicon caulk. These holes were opened and allowed to drain water that had been trapped within the wall panels. Additional holes were drilled into the same surface as the existing drain holes. These new hole locations are marked with an arrow in black permanent marker on the lower part of the wall panels. At least 3 holes per wall panel were drilled or opened. One wall panel with windows facing the crater [Ref. Fig. 1, point A] released water from a 5/16th inch drilled hole for approximately 30 minutes, suggesting 10's of liters of water was being retained within the wall. Discoloration common to the outer surface near the bottom was present on some of the wall panels. Evidence of cracking and gapped disbonding of the bottom surface from the wall panel was present at several locations. Two ~15cm holes previously drilled through the wall structure for use as an incineration toilet vent and air vent allowed for inspection of the interior of the wall at that area. The holes are located ~50cm above the lower surface of the wall adjacent to the Engineering Hatch Steps, counterclockwise when viewed from above. The holes are 1m apart. The holes showed the internal core structure and the fiberglass insulation that is common throughout the hab walls. A structural composite sample was removed from the hole for ply schedule analysis [Ref. Fig. 3]. The incinerating toilet vent hole was then completely sealed with expanding foam insulation as it was no longer in use. Evidence of discoloring, delamination, and disbond was present around and below both holes. Tap testing supported this observation with a dull and varied acoustic response when compared to a known good area. The discrepant areas are each approximately 24cm by 50cm around and below the holes.	dimensions, identifies crack dimension criticality criteria, and establishes a review panel after the mission season to review crack inspection results and explore repair options. Inspect drain holes to ensure they are open and free of fod or debris at least once per year. Apply Non-destructive Inspection (NDI) using ultrasonic inspection to determine the extent of the delamination around the 15cm holes, external wall bottoms, and other identified locations. Review the results and determine repair options. Trim foam and weather-seal the incinerating toilet exhaust hole.
Hab Bottom External	Visual	The bottom of the hab sits approximately 1m above the ground. As a precaution, this space was not entered by the crew and only visual inspection was performed. The material of the bottom of the hab is plywood secured to wood joists that make up the 1st level floor. Evidence of fiberglass insulation can be seen in gaps around the perimeter. There is a square wooden beam that spans most of the diameter of the Hab Bottom and supports the floor structure in an approximately East-West orientation. The beam is supported from the	Jack and shore the support beam as needed to achieve no sag. Implement an inspection program for the Hab Bottom External that includes mapping water staining, tracking the sag of the support beam, and fastener inspection.

		ground at 6 locations using vertical square wooden beams. There appears to be a slight sag to the support beam when viewed down its length. Full deflection of the beam does not appear to be more than the thickness of the beam. The Hab Bottom External material is unfinished (not painted) and shows evidence of water staining on less than 25% of the surface area. Evidence of fastener damage such as shear and pull-through were not present in those fasteners within sight. Evidence of damage or sagging of panels relative to one another was not present. Wall panel bottom surfaces - see Wall External.	
Radio Tower	Visual	The radio tower stands on the ground next to the hab and is secured to the Support Leg to the right of the Main Hatch counterclockwise when viewed from above. The tower extends another ~4m above the roof. Its construction is steel self-supporting with a square cross section. A ~2m tall antenna attached to the tower was found to be damaged and folded in half. Several loose coaxial cables for 2 antennas and a weather station were hanging from the tower. The unused coaxial cables were removed from the equipment and tower. The finish on the tower is orange and is missing from most areas. Where the substrate material is exposed, it appears to be galvanized steel. Evidence of corrosion is not present. Rope of 30mm diameter is secured to the top of the radio tower and is tied off to the lower part of the tower. The rope is in fair condition. The tower was used to gain access to the roof using fall protection equipment.	Implement an inspection program for the Radio Tower. Remove or replace the rope if it is to be used. Any climbing using the radio tower should be performed only by trained personnel with appropriate fall protection equipment. Consider installing a flagpole pulley to the tower to reduce crew exposure to fall risk.
Roof External	Visual, Tap test	The roof is made of 12 dome sections with a middle crown piece. They are all of a similar construction and thickness to the walls. The curved upper surfaces exhibit evidence of pitting and cracking at a higher rate than that of the walls, yet at a low rate of occurrence as to have an insignificant effect on structural integrity. Some cracks are over areas of delamination of the finish from the fiberglass beneath. Exposed fiberglass shows signs of weathering as exposed dry fiber bundles. Despite this, individual exposed fibers did not show separation or discontinuity. Evidence of fastener pull-up at the roof dome flanges is present. This evidence appears as a gap in the flanges between fastener locations with a pinching of the flanges at the fastener locations. Fasteners are tight when tested by hand. Evidence of cracking at fastener locations along the roof flange is present. Caulk from prior missions has been applied to these cracks. Gaps along each roof flange allow water and snow to enter the 2^{nd} level of the hab. Roof repair caulk was applied to all roof flange joints and fasteners. Roof sealing tape was applied to 6 flanges on the south-facing side of the roof. A steel pole approximately 1.5m tall extends from the center of the crown piece. This pole was secure in the axial direction but moved a small amount radially with little force. When the Mars flag was attached to this pole, the wind vibrated the pole which caused noise inside the hab. The top of the pole was then anchored to the radio tower to help mitigate vibration. The steel pole exhibits widespread corrosion and minor pitting. The base of the	Cracks and holes are areas of water ingress and can rapidly expand and drive delamination and disbond throughout the roof structure. Implement an inspection program that: Records finish crack location and dimensions, identifies crack dimension criticality criteria, and establishes a review panel after the mission season to review crack inspection results and explore repair options. Install roof repair tape to the 6 roof flanges that do not already have this installed. Bring extra roof repair tape to leave in the hab for future use, record the expiration date if any applies to the product.

		pole showed evidence of dried and flaking silicon caulk. Roof repair caulk was applied to the area as a means of weather sealing.	
1st Level Floor	Visual	The 1st level floor is constructed of plywood with a thin carpet covering 50% and no apparent finish applied. The carpet is stapled to the floor and is present in the engineering area, the hallway to the bathroom, and in the shower room. Carpet is not present in the toilet, Main Hatch, EVA room, Laboratory, and Engineering Hatch. Stains are present on the carpet in the engineering area. There is a soft area of the floor ~1m in diameter near the window facing the crater. The floor sags slightly toward the middle in the same manner as the support beam below the Hab Bottom. Evidence of major structural issues was not present.	Implement an inspection program for the 1st Level Floor. Remove all the carpet and staples from the first floor. Remove any damage to the floor and repair as needed. Apply a weather proofing finish to the floor.
1st Level Wall Interior	Visual, Tap test	The interior wall surface is the internal face sheet of the hab composite wall. It is used to support lightweight shelves, cabinets, water system components, and power system components. Wood screws are used to fasten components to the internal wall. Minor delamination and discoloration are present at fastener locations. The internal wall surface shows evidence of surface staining and some discoloration. Wall joints show streaks of staining coming from the 2nd Level Floor joist joints. The latter may be evidence of water and rust entering the interior at these locations.	Implement an inspection program for the 1st Level Wall Interior. Develop a fastener installation plan using procedures to drill, seal, and install drywall fasteners or similar clamping fasteners that do not rely on thread engagement with the composite face sheet – this will increase the longevity of the internal wall.
1st Level Ceiling	Visual, borescope	The first level ceiling is drywall affixed to the 2nd level floor joists similar to North American housing construction. The finish is a light grey paint. A continuous crack of approximately 4m is present running from the west corner of the stairs opening toward the center hallway. The crack is in the finish and is along the tape joint of the sheets. The cracking may be evidence of relative movement between the sheets due to deformation (sagging) of the 2nd level floor and/or weathering of the tape and mud at the sheet joints. A gap exists around the circumference of the ceiling between the ceiling material and the interior walls varying from zero to a few cm. This gap serves to allow air to move between the two levels. Evidence of mold is present above the ceiling near the stairs inspected by borescope. Evidence of fastener damage such as shear or pull-through was not present.	Implement an inspection program for the first level ceiling. Determine if removing and replacing the ceiling is needed.
1st Level Secondary Walls	Visual	The Secondary Walls on the 1st level are a stick frame based on standard North American homebuilding standards with 2x4 lumber studs and drywall. The secondary wall does not have insulation where inspections could be made to the interior of the wall. It is a structural component of the 1st and 2nd level flooring, transferring load from one to the other. The secondary walls create a separate space for the Main and Engineering Hatches, EVA Room, Laboratory and Engineering area, hallway, toilet, and bathroom. Evidence of stress and deformation is present in the form of cracked drywall near the hallway. These cracks are present around the hall doorway and form at the corner of the hall doorway and extend	Implement an inspection program for the 1st Level Secondary Walls that includes recording of existing cracking before and after support beam leveling. Record areas in need of replacement and put into place a plan to rework those areas.

		up to the ceiling. This is consistent with findings on the 1st Level Ceiling, 1st Level floor, and floor beam.	
2nd Level Floor	Visual, borescope	Similar construction to the first level floor. The carpet was removed due to excessive mold growth. The plywood floor is finished with a grey paint. There is evidence of water staining near the galley sink. Extreme mold growth was present on the MDF cabinets near the sink. Borescope inspection showed evidence of mold growth within the floor structure. Mold was cleaned and damaged materials removed. A gap similar to the first level ceiling is present around the perimeter of the floor which allows air to move between the levels.	Implement an inspection program for the 2nd Level Floor. Remove all cabinetry and replace with cabinetry of a material that does not foster mold growth.
2nd Level Wall Interior	Visual, Tap test	Similar to the 1st level wall interior. There is a waviness or wrinkle to the upper wall surface which may be found in composite parts manufactured without a caul plate, although this has not been confirmed for the MARS. The waviness can be seen using a light source at a low angle and can be felt by hand. It does not appear to cause any structural issues. Water staining is present at the wall joints near the ceiling. There is an area of impact damage through the interior face sheet. Broken fibers, delamination, and disbond are present in an area 30cm in the vertical direction and 12cm horizontal located 1m above the 2nd level floor at the top of the stairs adjacent to the window that faces the crater. Tap testing suggests delamination extending from this area not more than 6cm in any direction. This is the only area of such damage throughout the entire inspected composite structure and appears to be due to an impact to the wall.	Implement an inspection program for the 2nd Level Wall Interior that includes NDI for disbond and delamination. Apply a temporary barrier to the damaged area to prevent injury and glass fibers from entering the hab. Determine if a repair of the face sheet is needed.
2nd Level Secondary Walls	Visual	The secondary wall encloses the crew quarters and creates an attic space. Unlike the 1st level secondary wall, it is independent of the hab structure and is a load on the 2nd level floor. Contrary to several publications, the crew quarters wall is not coplanar to the 1st level secondary wall. This contributed to disorientation when determining cardinal direction between the first or second level [Fig. 1]. Water staining is present beneath the header tank in the attic. Evidence of fastener damage such as shear and pull through were not present.	Implement an inspection program for the 2nd Level Secondary Walls. Apply cardinal directions to the 1st and 2nd level interior walls near the ceiling to aid in orientation.
2nd Level Ceiling	Visual, Tap test	The 2nd Level Ceiling is the lower surface of the roof which is made of 12 dome sections and a crown piece. The roof is of similar composite construction to the hab walls. Access to the ceiling is limited to visual only for the southerly portion that is not accessible via the attic space above the crew quarters. There is a waviness or wrinkle to the ceiling surface which may be found in composite parts manufactured without a caul plate, although this has not been confirmed for the MARS. The waviness can be seen using a light source at a low angle and can be felt by hand. It does not appear to cause any structural issues. Some of the white finish is peeling in small areas. This peeling finish is unique to the ceiling and does not expose the substrate glass fibers. There is evidence of pull-up at the roof dome flanges. This evidence appears as a gap between fastener locations with a pinching of the flange at the fastener locations. Fasteners are tight when tested by hand.	Implement an inspection program for the 2nd Level Ceiling that includes NDI for disbond and delamination and monitoring of the flanges for cracks due to pull up forces. Remove peeling finish. Verify fasteners are properly torqued.

Table 4 Water system inspection, results, and disposition

System Element	Inspection	Results	Disposition
Hopper	Visual, leak check	The Hopper is a large plastic basin located in the EVA room. Evidence of leaks and damage was not present.	Implement an inspection program for the Hopper.
Hopper Pump	Visual, operational, leak check	The Hopper Pump appears to be a Johnson Pump WPS 5.2 similar to part number 10-13406-107. The pump is powered by a 12V deep cycle battery located on an equipment shelf in the EVA room. A component of the pump assembly was damaged during pump operation. The component was secured in a temporary working state with a hose clamp. No other leaks or damage was present.	Implement an inspection program for the Hopper Pump. Replace the pump assembly with one that has an overpressure relief mechanism to protect pump components. Retain the existing pump on site as a backup.
Pipes, valves, and fittings	Visual, leak check	Pipes, valves, and fittings throughout the water system use the PEX brand system and were operational and did not show evidence of leaks.	Implement an inspection program for the water system pipes, valves, and fittings.
Header Tank	Visual, leak check	The Header Tank is a large plastic basin located in the attic. Water is pumped from the Hopper to the Header Tank using the Hopper pump and plumbing. A leak was present due to a crack near the forward left side of the tank. Maintaining ¼ full level prevented this leaking.	Implement an inspection program for the Header Tank. Replace the Header Tank.
Header Tank Pump	Visual, operational, leak check	The Header Tank Pump was operational. A slow leak was present at the drip loop for the water hose that feeds the pump. A small container captured leaking water and was drained twice daily.	Implement an inspection program for the Header Tank Pump. Replace the hose and fittings between the Header Tank and the Header Tank Pump.
Water Heater	Visual, operational, leak check	The Water Heater was operational, taking ~2 hours to heat water. No leaks were present.	Implement an inspection program for the Water Heater.
Laboratory Faucet	Visual, operational, leak check	The Laboratory Faucet is a standard household faucet and is installed in the Laboratory Table but not connected to the water system.	Determine if connecting the Laboratory Faucet to the water system is necessary.
Laboratory Sink	Visual, leak check	The Laboratory Sink is a standard household sink and is installed in the Laboratory Table but not connected to the water system.	Determine if connecting the Laboratory Sink to the water system is necessary.
Galley Faucet	Visual, operational, leak check	The Galley Faucet is a standard household faucet and showed signs of leaking when primed with water and in use. The faucet was replaced, which eliminated the leak.	Implement an inspection program for the Galley Faucet.

Galley Sink	Visual, leak check	The Galley Sink is a standard household sink and was operational and did not show signs of leaking.	Implement an inspection program for the Galley Sink
Shower	Visual, operational, leak check	The Shower is a prefabricated plastic stall which includes the shower head and a drain through the 1st Level Floor to a collection basin. The Shower is operational with no signs of leaks.	Implement an inspection program for the Shower.
Bathroom Faucet	Visual, operational, leak check	The Bathroom Faucet lacks appropriate water pressure to be useful.	Implement an inspection program for the Bathroom Faucet. Inspect the line to determine the cause of the low water pressure.
Bathroom Sink	Visual, leak check	The Bathroom Sink is a standard household sink and was operational and did not show signs of leaking.	Implement an inspection program for the Bathroom Sink
Toilet	Visual, operational, leak check	The toilet is the frame of an incinerating toilet used as a camp toilet by placing a toilet bag within the bowl for solid waste. Liquid waste is collected with a urinal funnel that is drained into a steel 55-gallon barrel beneath the hab through plastic pipes through the floor. The toilet was operational, as was the male urinal funnel. The female urinal funnel requires an adapter for sanitary use, crewmembers must maintain their own adapters as needed.	Implement an inspection program for the toilet. Remove the existing urinal system and replace it with a new design that satisfies sanitary requirements.

Table 5 Power system inspection, results, and disposition

System Element	Inspection	Results	Disposition
Fuel Barrels	Visual	Fuel barrels are stored in 2 separate spill containment beds. 28 barrels contain various levels of diesel and gasoline.	Remove all fuel barrels from the site as soon as possible. Remove and dispose of the 2 spill containment beds. Install a new spill containment bed and have a backup spill kit. Establish a strict limitation on fuel delivered to the island and a requirement to remove all fuel barrels that are brought with each expedition.
Generator 1 (Diesel)	Visual, Operational	Generator 1 is a Yanmar 5500 and is operational and outputs 120/240V. The fuel line is not OEM and cracked 3 times during operation.	Implement an inspection program for the Generators. Repair or replace Generator 1 with a quieter unit.
Generator 2 (Diesel)	Visual, Operational	Generator 2 is a Yanmar 5500 and was producing power until the last day when the starter puller was damaged. Output is 120/240V. Electric start can be used on this and other generators.	Implement an inspection program for the Generators. Repair or replace Generator 2 with a quieter unit.
Generator 3 (Diesel)	Visual, Operational	Generator 3 is a Yanmar 5500 and was not able to be tested due to a missing fuel tank. Output is 120/240V.	Implement an inspection program for the Generators. Determine if repairing or replacing Generator 3 is necessary. This unit may be used for parts for the other 2 diesel units
Generator 4 (Gasoline)	Visual, Operational	Generator 4 is operational, but output is limited to 120V.	Implement an inspection program for the Generators.
Generator 5 (Gasoline)	Visual, Operational	Fuel line leak prevented operational check.	Implement an inspection program for the Generators. Replace this fuel line or replace this generator with a quieter unit.
Electric Power Panel	Visual, Operational	The Electric Power Panel is located in the Engineering tool room and is in good condition. Evidence of damage is not present.	Implement an inspection program for the Electric Power Panel. Document the schematics of the electrical system.
1st Level Receptacles	Visual, Operational	The 1st level receptacles use MC Cables and metal electrical boxes for receptacles. The wiring and receptacles are in good condition and are operational. Some wiring appears to be installed incomplete. Exposed wires were tested, capped, and stowed in place.	Implement an inspection program for the 1st Level Receptacles. Monitor fastener holes in accordance with fastener inspection for the 1st Level Wall Interior.
1st Level Lights	Visual, Operational	The 1st level u 6-inch recessed lighting with compact fluorescent bulbs. Malfunctioning bulbs were replaced with bulbs that were on site. The	Implement an inspection program for the 1st Level Lights.

		wiring and fixtures were in good condition where they were able to be viewed and inspected.	
2nd Level Receptacles	Visual, Operational	The 2nd Level Receptacles use MC Cables and metal electrical boxes for receptacles. The receptacles are in good condition and are operational in the wardroom. Fasteners attaching the wiring and boxes to the wall show signs of rusting, resulting in staining on the walls. Some fasteners are loose.	Implement an inspection program for the 2nd Level Receptacles. Determine if replacing the fasteners with drywall/clamp-style fasteners is necessary. Clean stains from the walls and monitor fastener condition. Troubleshoot and repair the wiring for the staterooms.
2nd Level Lights	Visual, Operational	The 2nd Level Lights consist of 3 fluorescent tube fixtures in the wardroom and individual light fixtures in the staterooms. The fluorescent fixtures were not plugged into receptacles and there were no receptacles within range of the fixture plugs. The bulbs were removed and stored in the 1st level for disposal. 6 flat LED lamps were attached to the existing fluorescent fixtures and wired down the ceiling and wall to 2 switches in the wardroom using MC cable. Stateroom lighting was not operational.	Implement an inspection program for the 2nd Level Lights. Troubleshoot and repair stateroom lighting. Stateroom lighting was facilitated with battery-operated lights.
Wind Turbine Generator	Visual, Operational	Unit was installed during this expedition. The turbine produced power as designed, but low winds limited output to several orders below the legacy-fueled generators. Plastic hub was damaged and discarded.	Implement an inspection program for the Wind Turbine Generator. Determine if the unit is to remain on site or removed.
Electrical Power Storage	Visual, Operational	Electrical Power Storage was supplied using an Anker Powerhouse 757 that was brough with the crew and stored in the hab for future use. Electrical Power Storage was operational.	Implement an inspection program for the Electrical Power Storage.

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