Haughton-Mars Project at 20: Challenges and Designs for Future Exploration

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ABSTRACT

In 2016, NASA-affiliated researchers completed the 20th consecutive field season at Haughton Crater in Canada's High Arctic. The Haughton-Mars Project (HMP) has established a base camp to provide essential services during summer field seasons. The crater and surrounding areas provide a high-fidelity terrestrial analog for planetary exploration, with similarities in geology, weather conditions and complex logistics. This paper provides a systematic review of HMP infrastructure, design research and future development priorities. Status of camp buildings, mechanical systems, energy inputs, and site impacts are discussed, as are opportunities for integration of systems to conserve resources and reduce future operational costs. Techniques for rapid site assessment are compared. Recommendations include further design and program development for modernization of camp facilities, alongside restoration of relationships with service providers to re-engage local community members. This will ensure availability of a well-established, high quality proving ground for technologies and operational concepts for NASA's future planetary surface exploration missions.

INTRODUCTION

Since 1997, NASA has funded a variety of research activities at Haughton Crater on Devon Island. The impact crater, subsurface ice, and surrounding areas provide a high-fidelity terrestrial analog site for Mars exploration. In addition to the pristine polar desert environment, the remoteness of the location reflects the difficulties of logistics and communications for planetary exploration. The crater is situated approximately 100 km northeast of Resolute, Nunavut in the Canadian Arctic. The Haughton-Mars Project Research Station, on the western rim of Haughton Crater, is operated by the Mars Institute.

This study captures and summarizes observations made during 2016 season preparations and summer field deployment. It discusses recommendations for further design and prototyping for modernization of facilities at HMP to be undertaken during the 2017 through 2020 field seasons, with full installation and renovations in subsequent years.

BACKGROUND & HISTORY

Location. The Haughton Mars-Project Base Camp is located at 75°25'59"N 89°51'47"W, on the southwest rim of Haughton Crater on Devon Island in the Canadian Arctic (Figure 1). The site was established through agreement with the Nunavut territorial government (Lee et al, 2007) and is accessed via charter flight from Resolute, Nunavut. Annual average temperature is –16 °C (Lee &

Osinski, 2005), with nighttime temperatures ranging between –5°C and 5°C and daytime temperatures ranging between –2 °C and 16 °C during the 2016 field season.

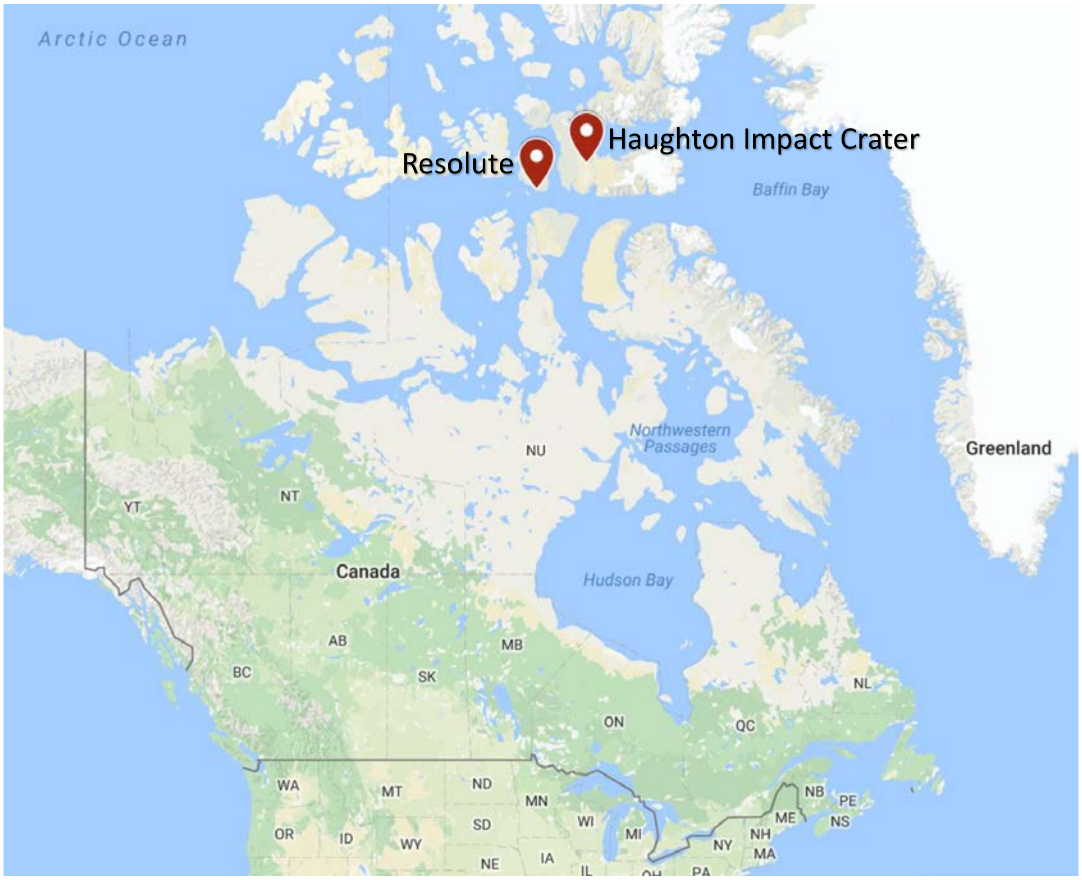

Figure 1. Location of Haughton Crater (Map Data: *Google Maps*, 2017).

Past Use. Prior expeditions studying the impact crater in the 1980s and 1990s, and the first three seasons of the Haughton-Mars Project (1997-1999) were based inside the crater itself, adjacent to the Haughton River (Lee & Osinski 2005). This smaller site however was not suitable for groups of more than ten people, nor for storing materials over-winter. In 2000 a consortium of stakeholders led by the Mars Institute and NASA began development of the current HMP Base Camp on the western edge of the crater.

The current facility was initially designed as a support facility for the Mars Society's Flashline Mars Arctic Research Station (located 1km NE) but the two Arctic facilities have been operated independently since 2002. Since that time HMP has been a leading terrestrial Mars-analog site used in developing surface science and exploration concepts, training of students, field testing of rovers, spacesuit concepts, robotic drills and instrument prototypes (Olson et al. 2011, Lee & Osinski 2005, Glass 2006, Lee et al. 2007, Giroux et al. 2006). HMP's Arthur Clarke Greenhouse was the primary test site of the Canadian Space Agency's remote greenhouse development program from 2002-2012 (Bamsey 2014, Giroux et al. 2006).

Design Concepts. Studies conducted during HMP's first decade recommended integration of systems for data collection, automation of operations and quantification of material and resource flows via circular design principles (Clancey 1999, Clancey 2003; DeWeck & Simchi-Levi 2006). Ethnographic studies of field science at HMP recommended closing feedback loops for information gathering and development of priorities (Clancey 1999, 2002, 2003). Current analyses for sustainable pioneering of Mars recommend in-situ resource utilization (ISRU) and closed-loop systems for production of essential goods (Mueller et al. 2015, Toups & Hoffman 2015). These concepts are supported by current methods for circular design (Ellen MacArthur Foundation & IDEO 2016).

REMOTE SITE ASSESSMENT

Remote Assessment Sources. Deployment planning and participant preparation is currently hindered by a lack of readily-available, concise information regarding infrastructure, equipment and consumable materials currently stored at HMP Base Camp. Details of the site facilities and past deployments were gathered from a multitude of sources through review of past reports, permit documents, government websites, web image searches, satellite maps, personal photo collections, and interviews with past participants. The layout of HMP Base Camp during the period of its peak utilization (late 2000s) is shown in Figure 2.

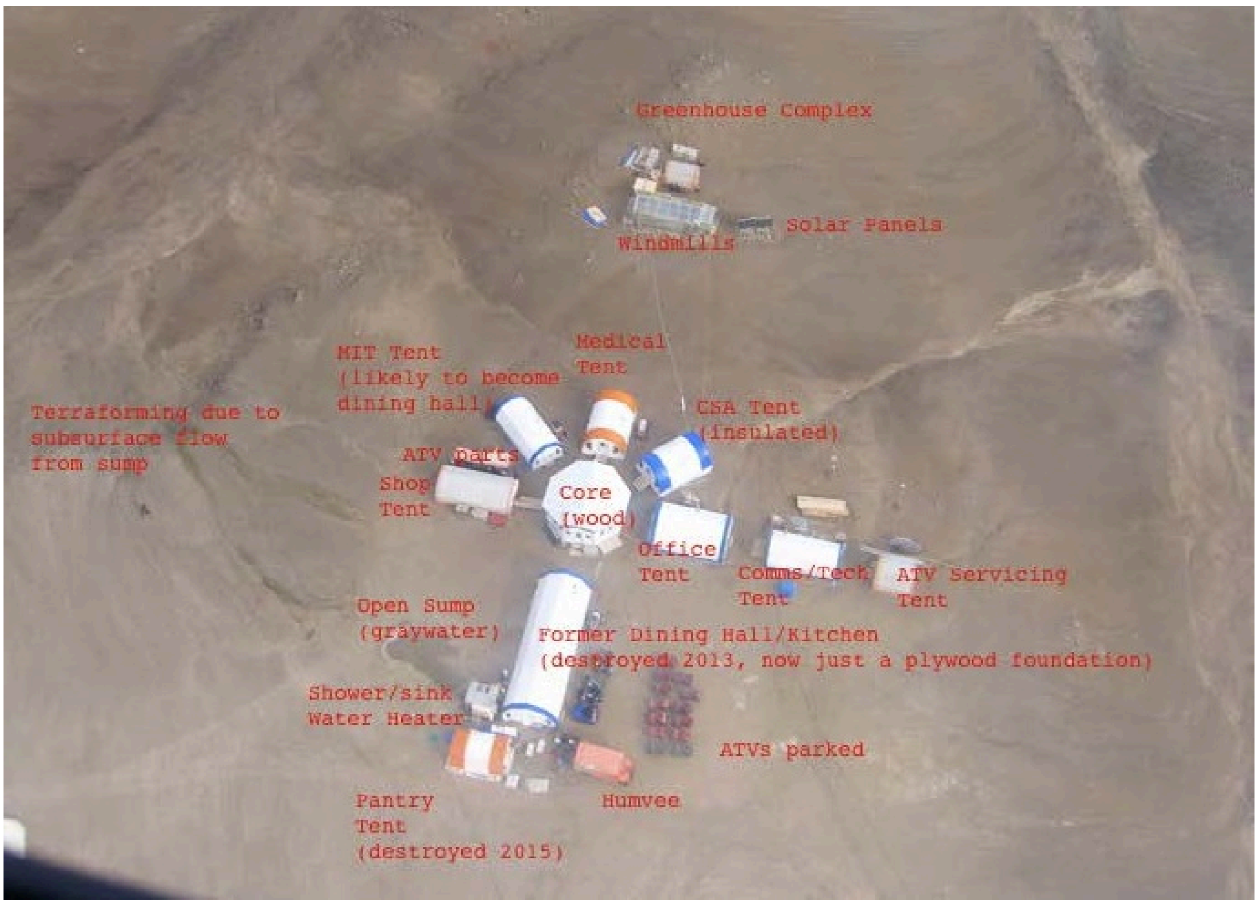

Figure 2. Layout of Haughton Mars Project Base Camp.

Technologies. Prior to and during deployment, a suite of public tools and consumer technologies were used to gather additional information and to document site layout and conditions (Table 1). Preliminary investigations of reality capture hardware were undertaken during 2016 deployment. All images are being merged to a central repository, with images containing noteworthy site details provided (Figures 3-5).

Table 1. Mapping and Imaging Tools

Type	Source or Device	2016 Season	Future Testing & Improvement Options
Satellite Maps	Google Maps	Crater displayed in detail while HMP facilities appear in lower resolution.	Planet Labs, Descartes Labs
Drones	DJI Matrice	Drone images captured via manual flight. Images to be processed for orthomosaic map (Spire Aerobotics).	DJI Mavic Pro or Phantom 4 Pro, DroneDeploy or DJI Go
Photos	Smartphone or DSLR	Used Google Nexus 5	Create digital repository with tags
2D	Web Sources, Reports & Personal Collections	Captured hundreds of images of HMP Base Camp & surrounding area	Submit to digital repository, select tools for categorization & digital inventory
Webcam	Previously used by CSA in Greenhouse	Not used	Re-establish year-round connectivity for sensor feedback and image relay.
Aerial	Smartphone or DSLR	No aerial photos taken during flyover, landing or departure.	Request flyover 6-8 weeks prior to deployment.
360 View	Ricoh Theta	Captured hundreds of images of HMP Base Camp and vicinity.	Use smartphone app for geolocation. Test higher-resolution devices.
Reality Capture	StereoLabs ZED	Tested during Feb2016 deployment to Chile. Requires additional drivers & post-processing support.	ZED with post-processing support, Matterport, Google Tango devices & apps

FIELD SEASON OBSERVATIONS

Access & Logistics. Access is currently provided via Twin Otter flight from Resolute, landing on a 320m dirt runway adjacent to HMP Base Camp. Logistics for further site development are presently limited by aircraft dimensions and cargo capacity, as well shipping costs. Logistics options for travel and shipping are shown in Table 2. Arrival for the 2016 field season was delayed for several days, due to crosswinds and poor visibility at the HMP airstrip. Options for alternate runways were studied during the 2016 season. A total of ten persons participated in 2016 with transport by two sets of put-in and takeout flights.

Communications & Safety. Communication with charter airline and emergency services is provided via Iridium satellite phone. Internet access is provided by satellite ground station using Ka-band access and 802.11a antenna for local Wi-Fi, powered by diesel generator. Local communication with traverse teams is maintained via VHF radio handsets, supervised by licensed radio operators. All field deployments to HMP are accompanied by a qualified nurse or paramedic. Additional operational requirements are established via safety plans drafted at NASA-Ames Research Center prior to each field season (since 2010).

Table 2. Cargo Shipping and Modes of Transportation

Mode	Provider	Route	Capacity & Restrictions
Local Humvees	HMP Stakeholders	HMP Base Camp to Haughton Crater & Surrounding areas of Devon Island	3-6 persons plus cargo
Local ATV	HMP Stakeholders	HMP Base Camp to Haughton Crater & Surrounding areas of Devon Island	1-2 persons plus 2 bags, bins or pelican cases
Put-In Flight	Kenn Borek Air	Resolute - Devon Island	5 passengers + 2800lbs cargo
Air Drop (C-130)	United States Air Force	Moffett Field - Thule or other US Base – Resolute - HMP Base Camp	5 pallets
Passenger Air/Combi	First Air	Ottawa-Iqaluit-Resolute	Flexible capacity, limited by cargo door dimensions for ATR-42 in use.
Air Freight	Charter Flight	Ottawa-Iqaluit-Resolute, Edmonton-Yellowknife-Resolute	Per aircraft capacity, maximum currently in service is 737-200 combi
Cargo for Deployments	FedEx	San Francisco - Ottawa, San Francisco-Yellowknife	Palletized action packers, duffels, equipment cases, cargo crates.
Sealift	Multiple	Montreal to Resolute or Grise Fiord	Unknown
Boat Ferry	None known	None known	None known
Over Sea Ice	Mars Institute	San Francisco-Cambridge Bay, Resolute-HMP Base Camp	Single mission in 2009 and 2011 to move Humvee to HMP Base Camp.

Management & Partnerships. Following the cancellation of NASA's Constellation program in 2009, reduced interest in R&D for planetary surface exploration led to fewer tests and participants at terrestrial analog sites. On-site support activities by Mars Institute have similarly been reduced in recent years to basic operation of camp facilities and provision of kitchen, medical and maintenance staff. Budget issues and lapsed prior agreements and relationships with Arctic service providers, such as the Canadian government's Polar Continental Shelf Program, local Inuit communities and service providers, Canadian Space Agency, and Kenn Borek Aviation have resulted in the availability of fewer subsidized flights, logistics and support services, leading to some service delays and higher per-person costs.

Physical Layout. The Haughton-Mars Project Base Camp was originally built following concepts for a modular Mars habitat, with an octagonal hub surrounded by spokes in a radial layout. Buildings were to be connected via greenhouse-style breezeway chambers, providing some air heating for adjacent spaces. An autonomous greenhouse was constructed by the Canadian Space Agency and university research partners in 2002 (Bamsey 2014, Giroux et al 2006).

The landing strip (right side of Figure 3) is approximately 400m east of Base Camp, and is the designated storage location for any local hazmat, primarily fuel drums (including a cache maintained by Polar Shelf for emergency flight diversions). ATV or Humvee refueling occurs nearby on rubber containment barriers adjacent to the runway zone (Fig. 5(d)).

Personal tents used for sleeping are maintained on a plateau 250m west of Base Camp, for safety reasons (separation from both the hazmat area as well as the polar bear-attracting kitchen area in Base Camp). Lacking a dormitory facility, the ongoing seasonal use of tents for sleeping quarters produces a recurring cost and time expenditure for shipping and setup of personal camping gear, while contributing to the metabolic shift experienced by visiting staff and researchers due to extended exposure to cold temperatures and continuous daylight.

Figure 3. View of Haughton-Mars Project Base Camp from communications tent.

Buildings and Materials. The wood-framed core building serves as the kitchen and meeting space, and is surrounded by seven vinyl barrel tents with separate entrances. The south tent used as the original kitchen and mess hall collapsed in 2011, and requires repair to the frame for reassembly. Two smaller tents used as pantry and latrine spaces have been removed from service due to UV degradation of their covers and have not been reconstructed. An additional tent in passable condition is used to house satellite and radio equipment where antennas are installed on a hill 400m SE above camp. Of the remaining buildings, the greenhouse is in the best condition, showing limited signs of wear while maintaining comfortable temperatures via passive heating. Three of the vinyl tents are showing signs of weather and leakage due to UV degradation and extreme cold, while the remaining four tents are expected to have 5-7 years of service life remaining. Plywood end walls, floors and furnishings show signs of mildew on untreated surfaces.

Figure 4. Condition of Buildings: (a) Greenhouse, (b) Aging vinyl frame tent.

Systems. Electricity is currently supplied via generators, while motor gasoline and diesel are used for local transportation via ATVs and Humvees. Warming of workspaces is provided by diesel heaters. As of August 2016, an inventory of approximately three barrels of each fuel remains in the (non-Polar-Shelf) fuel caches and refilling stations adjacent to the airstrip, in addition to six 100-lb remaining propane cylinders used for the kitchen and on-demand water heater. Additional 200L fuel barrels are available to be flown from Resolute at a cost of approximately $250-400 per barrel. Two wind turbines and a small array of solar panels were left in place but disconnected following the withdrawal of Canadian Space Agency-sponsored greenhouse research in 2012.

Water is currently collected from a seasonal creek located approximately 450m from Base Camp. A pump previously used to convey running water to core facilities requires parts for repair, and can be connected to a storage bladder procured during the 2016 season. Water heating was previously provided by an on-demand propane water heater. Plumbing and drainage lines are presently disconnected in core facilities, and water is heated in kettles. Since the collapse of the kitchen/dining tent in 2011, most kitchen appliances are presently in dry storage and require reassembly of the kitchen tent to provide sufficient space and reconnect to site infrastructure. Food is currently transported (as air cargo) and stored in coolers used for shipping each field season’s food provisions from Ottawa to HMP, with dry and nonperishable goods stored overwinter in coolers left behind from past years.

Greywater is presently disposed of in an open sump with a raised perimeter. Visible moss rings have formed where water and nutrients flow or seep downslope at the permafrost layer (Fig. 5(c)) Urine is captured from commodes and smaller receptacles into empty fuel drums (Fig. 5(b)), to be removed on takeout flights, however, there is currently a surplus of five full 200L barrels that have overwintered at HMP Base Camp awaiting transport. Solid toilet waste is placed in baggies lining commodes. These are collected and stored after each use, flown back to Resolute and landfilled along with kitchen and other waste at the end of the field season. An incinerator (Fig. 5(a)) was previously used to dispose of all waste produced on site. It required significant power and fuel input, and was at that time non-compliant with Nunavut environmental regulations. The town of Resolute currently imposes a fee of $500 per pallet for landfill disposal of trash, an amount which has increased with the increased demand from visiting cruise ships in the Northwest Passage.

Figure 5. Site Impacts: (a) Decommissioned Incinerator, (b) Liquid waste barrels, (c) Moss ring downslope of greywater sump, (d) Vehicle fueling station.

Table 3. 2016 Status of HMP Research Station Facility Systems

System Type	Current System	Past Systems
Water Collection	Coolers filled at creek. Pump requires repair. Water bladder in Resolute.	Water pumped from creek through filtration system to kitchen taps.
Greywater	Open Sump, plumbing disconnected	Open Sump, connected to kitchen & shower plumbing
Water Heating	Propane Cooking Stove	On-demand Propane Water Heater
Air Heating	Diesel Heater in Tents & Core Hub, Passive Solar in Greenhouse	Diesel Heater in Tents, Passive Solar in Greenhouse
Power Generation	4 Generators (2 diesel)	6 generators, solar/wind power & battery storage for greenhouse.
Shelter	Vinyl Platform Tents, Steel-Roof Wood-Frame Outbuildings, Non-Operational Greenhouse, Personal Tents for sleeping	Latrine Tents, Additional Vinyl Platform Tents, Steel-Roof Wood-Frame Outbuildings, Non-Operational Greenhouse, Personal Tents for sleeping
Food	Food shipped in coolers & action packers from Ottawa, Improvised kitchen.	Greenhouse Experiments, Refrigerator & Freezer Storage, Full Kitchen
Waste Disposal & Toilet Facilities	Via Cargo on Takeout. Urine in fuel drums, Toilet uses lined commodes & disposal with trash.	Incinerator, Urine in fuel drums.
Local Transportation & Cargo Shipment	8 ATVs, 1 Humvee working, 1 Humvee minor repairs, 2 utility vehicles, 2 ATV trailers	21 ATVs, 1 Humvee, 2 utility vehicles, 2 utility trailers

A series of modifications or gradual improvements over the current HMP baseline are given in Table 4. In waste management, building repair and maintenance, environmental monitoring and logistics there are paths towards both recommissioning/repair of prior assets (as with solar panels, water pump or a new airstrip weather station), relatively simple improvements to current facilities (coating bare wood surfaces in tents to control mildew) as well as more ambitious upgrades that would likely be necessary if future summer staffing were to approach 2000s levels (new kitchen facility, compliant incinerator, new water heater and shower unit, agreements for reduced-price logistics and charter flights).

Table 4. Proposed Systems Integration & Upgrade.

System Type	Proposed Options & Integration
Water Collection	Repair & reconnect systems, install water storage, add sensors and switching systems.
Greywater	Add filters to greywater drainage to minimize particulate and nutrient through-flow. Assess flora and microbiology of sump footprint. Test closed systems for water recycling & nutrient recovery.
Water Heating	Install solar water heating in line with on-demand water heater to serve kitchen, restroom & showers.
Air Heating	Prototype Greenhouse-Integrated workspaces, Integrate heat recovery loop with Incinerator, Add Passive Solar Breezeways and Thermal Mass to existing work tents
Power Generation	Recommission solar and wind energy systems. Reduce power requirement through solar heating, heat recovery & daylighting. Install modular, cold-tolerant smart battery systems.
Shelter	Send damaged parts on deadhead flights for replacement/repair for following season. Investigate new tent costs, and fitted covers. Continue testing program for stabilized masonry materials. Test warm/dark shelter prototypes. Install environmental monitoring on key structures.
Food	Reassemble permanent kitchen, dining and cleanup spaces. Move freezer, coolers and refrigerator to north exposure and shaded buildings to minimize heat gain and power consumption.
Waste Disposal & Toilet Facilities	Evaporate Urine, Test Composting Toilets, Separate Recycling, Bag hazmat & trash, Test low-energy incinerators and/or composting systems for paper and food waste.
Local Transportation & Cargo Shipment	Digital inventory & operations manual. Make better use of deadhead flight capacity for haulout of cargo, positioned at runway in advance.

Testing Of Materials. Samples of local soils were collected during the 2016 field season. Tests conducted in collaboration with Queen's University are currently evaluating the use of local soils for building materials. Table 5 describes coatings and materials being left in exposure at the HMP site for evaluation of future uses in renovations and construction. Some of these are shown in Figure 6. Field evaluation of bluetooth-enabled environmental sensors and small-scale modular urine evaporators took place by the authors in Chile during a related project's field deployment. Future testing is recommended for composting toilets, urine evaporators, building systems using local soils, and passive solar heating components (as in today's greenhouse). Given very long supply lines, as in other remote missions, continued food production research and evaluation of 3D printing for habitat research have been deemed worthy of further evaluation.

Table 5. Materials Testing

Material Application	Type/Description/Variations	Notes/Application
Current at HMP:	5-year exposure tests, with samples for comparison to be installed at NASA-Ames.	
Vinyl Repair	Adhesive Flashing Membrane	Interior and exterior of Tents. Replacing liquid adhesive for vinyl repair (difficult to transport).
Coatings on Plywood & Metal	Allback Linseed Oil Paint	Linseed
	Pine Tar	2 coats over linseed oil coat.
Coatings on Plywood	Boiled Linseed Oil	2 coats on plywood only.
	Bare	As control sample
Sheathed Insulation	Ecovative MycoFoam Panel sheathed with Tyvek wrap	Installed on building face, and inside tent, to evaluate moisture intrusion & degradation.
Current at Queen's University:		
Site Soils for Masonry Structures	Site soils stabilized with ball clay or Type S lime	50mm cubes crushed according to ASTM C109
Future		
Limewash	On interior plywood surfaces	To prevent mildew due to condensation.
Greenhouse glazing & lightweight, flat-pack structures	Lexan and twin-wall polycarbonate with 6063 aluminum channel	To re-clad platform tent frames, construct passively heated breezeways and workspaces.
3D printing of masonry materials	Delta printers and models used for proposed Mars habitat designs.	Simulate use of printers with Haughton soils in cold, isolated environment.

Figure 6. Material samples installed for weathering tests on end wall of technology tent. Left, from top: Plywood coated with (a) linseed oil paint, (b) bare, (c) pine tar. Right, from top: (d) MycoFoam insulation panel wrapped in Tyvek sheathing, (e) Plywood coated with linseed oil, Galvanized steel tubing coated with (f) linseed oil paint, (g) bare.

RECOMMENDATIONS

The recommendations listed below are offered for ongoing use, improvement and possible upgrades of the Haughton-Mars Project, as a fully-equipped, modern base for operations research, development and training supporting NASA's future human exploration missions to planetary surfaces:

1. Consider the implementation of renovation plans based on closed-loop, circular process design principles. Integrate site systems and built infrastructure by closing loops for heat, water, nutrient and material recovery from existing inputs and waste flows. Make use of energy and material resources available on site. Select materials and systems that break down into useful components and the end of their service life. Develop plans for refurbishment of HMP site with consideration for utility in testing the principles of In-Situ Resource Utilization in future NASA missions.
2. Continue to prioritize maintaining the Haughton Crater region as a pristine site, for research in life detection, planetary protection and stewardship of the natural environment.
3. Restore or renew relationships with Polar Continental Shelf Program and Canadian research organizations, to reduce costs and scheduling contingencies for flights and contracted services.
4. Re-engage prior relationships with local Inuit communities, and re-engage local youth and elders for provision of site services at HMP if demand increases. Coordinate with existing Canadian and Nunavut government programs for employment subsidies, job training and local engagement. Consider preparation of Impact Benefit Agreements for larger-scale future development. Consider also how the low-impact and closed-loop solutions to be tested at HMP may be replicated in ways that are useful to local communities.

5. Engage selected NASA/CSA R&D projects and participants – potential future customers -- to take an active role in specifying the operating conditions to be maintained on site, and designing future improvements. Establish a process and framework for researchers to design, deploy and monitor the systems to be used to maintain the Haughton Crater site and infrastructure, as well as their own experiments (as was done in the past for the greenhouse).
6. Provide a comprehensive and accessible public-access online repository of documents and site imagery to assist researchers with planning and preparations for future field seasons. Prepare a master list of vendors, key equipment, and contacts for ease of reference during field preparations. Compile a knowledge base including processes, inventory, and past documentation.
7. Emphasize that all HMP projects and participants are empowered to communicate needs and procure information. Ensure that all researchers are enabled to maintain and make use of facilities and equipment funded through their collaboration at HMP. Encourage field season participants to fix minor problems as they arise and propose future improvements.
8. Improve accessibility of basic comforts and daily essentials at Base Camp, so that time is used effectively during field deployments. Consider providing warmer and darkened spaces for sleeping, work and personal care to reduce effects of metabolic shift and 24-hour daylight.
9. Develop a year-to-year, accessible HMP Site Plan to facilitate collaborations, development of research proposals, the progression of testing and implementation of site modifications. Develop and maintain an updated site operations manual and knowledge base.

CONCLUSIONS

The Haughton Crater area and HMP Base camp provide an invaluable, high-fidelity terrestrial analog for planetary exploration. A survey of HMP during the 2016 season demonstrates that there are several noteworthy opportunities for integration of systems to conserve resources and reduce the future operational costs. Design and program development for the renovation or modernization of camp facilities, alongside restoration of prior relationships with Arctic service providers and local community members, will ensure the future availability of this well-established, high quality terrestrial analog side. Broadly, the development of future partnership and collaborations should aim to: (a) Engage NASA/CSA stakeholders in articulation of guiding principles and integrated systems concepts for future development at HMP Base Camp, (b) Map the required flows of resources for different future projected levels of participation and site occupancy, (c) Model integration of site systems and project development over next 5 years of field deployments, and, (d) Develop a program for technological integration, and select future HMP partners for technology review and field testing.

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