EVA and Surface Mobility Operations for Mars Exploration: Analog Field Tests of Tethered Balloon Systems at the NASA Haughton-Mars Project Site, Devon Island, High Arctic

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Tethered balloons have been proposed as promising airborne systems for Mars science and exploration operations, both in the context of future robotic and human missions. Tethered balloons may carry instrument payloads such as cameras for real-time aerial imaging, mapping, navigating, and scouting; meteorology packages for atmospheric surface boundary layer investigations and weather monitoring; communications systems to serve as relays for remote field communications, in particular in topographically complex, labyrinthine terrain; and many other types of payloads. We report here on field tests of the deployment and operation of experimental tethered balloon systems during crewed vehicular excursions, including in spacesuited EVA mode, at the NASA Haughton-Mars Project analog field site on Devon Island, High Arctic. Lessons learned are analyzed, and implications for the design of future tethered balloon systems for Mars are presented. We propose in particular the use of a deployable vertical boom for balloon inflation and stowage, to ensure that a tethered balloon's deployed components (e.g., envelope, tether line) never come in inadvertent contact with the terrain, other anchor platform hardware, or spacesuited crew members.

Nomenclature

EVA	=	Extra-Vehicular Activity
F	=	Force
HMP	=	Haughton-Mars Project
m	=	Mass
P	=	Pressure
ρ	=	Density
ρ_A	=	Aera density
$R_{specific}$	=	Specific gas constant
r	=	radius
SETI	=	Seach for Extra-Terrestrial Intelligence
T	=	Temperature
TBS	=	Tethered Balloon System
W	=	Weight

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I. Introduction

TETHERED balloons have been proposed as promising airborne systems for Mars science and exploration operations, both in the context of future robotic and human missions[1,2,3]. *Helikites®*, which combine a helium aerostat and a kite, have also been investigated for Mars[4]. At a fixed base on Mars, or during crewed or uncrewed rover excursions, tethered balloons may carry instrument payloads such as cameras for real-time aerial imaging, mapping, surveying, navigating, and scouting; meteorology packages for atmospheric surface boundary layer investigations and weather monitoring; communications systems to serve as relays for remote field communications, in particular in topographically complex, labyrinthine terrain; and many other types of payloads **(Fig. 1 left).**

In spite of their promise, however, concepts of tethered balloon systems for Mars have undergone only very limited testing. In 1988, a fixed anchor tethered balloon imaging experiment was conducted at Dumont d'Urville Station, Adélie Land, Antarctica, simulating the use of a tethered balloon imager to monitor natural change and human activity at a Mars base over time[1] **(Fig. 1 center)**. The experiment produced the first aerial photo of the French base in winter[1]. In 2000, the NASA Haughton-Mars Project (HMP) on Devon Island, High Arctic, conducted an initial series of field tests during which a tethered balloon carrying an aerial TV (television) camera was deployed from an ATV (all-terrain vehicle), allowing the ATV's human operator to drive the vehicle with the benefit of real-time remote-sensing imaging **(Fig.1 right)**. The tethered balloon imaging concept for ATV traverse imaging was successfully proven. However, the coarse spatial and spectral (panchromatic only) resolution of the imaging system were limiting, and vehicle traverses remained within the immediate vicinity (≤ 1 km range) of the HMP Base Camp[1].

Figure 1. Concepts of Operation and Early Fieldwork on Tethered Balloons for Mars Science and Exploration. ***Left:*** *Mars tethered balloon science and exploration concepts of operations at a fixed base and on mobile platforms[1];* ***Center:*** *Mars analog fixed base tethered balloon imaging experiment in 1988 at Dumont d'Urville Station, Antarctica[1];* ***Right:*** *Mosaic of HMP-2000 Mars analog ATV-tethered balloon imaging experiment[1]. Note the TV display mounted on the ATV console, with an oatmeal carton serving as makeshift sunshade (HMP-2000/P.Lee).*

We report here on new field tests of the deployment and operation of experimental tethered balloons as Mars analog science and exploration systems during the 2022 summer field campaign of the NASA Haughton-Mars Project (HMP) on Devon Island, High Arctic (HMP-2022). With technological progress and the ready availability now of commercial off-the-shelf (COTS), robust, lightweight, high-resolution imaging systems, tethered balloon field tests at HMP can be productively expanded beyond the immediate vicinity (> 1 km) of base camp and to extended range vehicular excursions. The following two experiments were carried out: The "HMP-2022 Tethered Balloon Traverse Experiment" and the "HMP-2022 Tethered Balloon and EVA Spacesuit Experiment".

The "HMP-2022 Tethered Balloon Traverse Experiment" was conducted first during a long-distance, ~50 km open ATV (all-terrain vehicle) traverse out to a range of ~17 km from camp, and back, then during an additional shorter, 25 km traverse to test out a possible technical solution to the problem of the balloon coming in contact with the ground, the mobile platform hardware, or the vehicle operator.

The "HMP-2022 Tethered Balloon and EVA Spacesuit Experiment" was the first field test to examine the operation of a tethered balloon system with the crewed vehicle operator wearing a Mars analog concept spacesuit (provided by Collins Aerospace), in extra-vehicular activity (EVA) mode operating an unpressurized rover. This second experiment evaluated the deployment and operation of a tethered balloon during a short-range open ATV traverse within ~1 km range from HMP Base Camp.

In Section II, we describe the HMP Mars analog field site, the Mars analog balloon and EVA systems, and the concepts of operations used in our HMP-2022 study.

In Section III, we describe the objectives and implementation, and analyze the results, of our "HMP-2022 Tethered Balloon Traverse Experiment".

In Section IV, we describe the objectives and implementation, and analyze the results, of our "HMP-2022 Tethered Balloon and EVA Spacesuit Experiment".

In Section V, we apply lessons learned to date to propose basic designs and concepts of operations for tethered balloon systems for future science and exploration operations on Mars, on either robotic or crewed vehicular platforms. We propose in both cases the use of a deployable vertical boom for on-board balloon inflation and stowage, to ensure that the deployed components of an inflated tethered balloon never come in inadvertent contact with the terrain, other hardware on the anchor platform, or spacesuited crew members.

II. NASA Haughton-Mars Project (HMP)

The Haughton-Mars Project (HMP) is an international multidisciplinary field research project dedicated to advancing planetary science and exploration. The HMP was established in 1997 and is centered on the scientific study of the Haughton meteorite impact crater and surrounding terrain on Devon Island, High Arctic, viewed as a planetary analog, in particular for the Moon and Mars. Devon Island is the largest uninhabited island on Earth. The environment on Devon is extreme by terrestrial standards and is best described as a polar desert (not tundra), *i.e.*, cold (-40°C < T < +10°C), dry (precipitation < 13 mm/yr), and sparsely vegetated to unvegetated. The island presents the single largest continuous area of barren rocky polar desert on Earth. Devon Island is home to Haughton Crater, a 20 km-diameter meteorite impact crater formed 23 million years ago, during the Miocene epoch. The HMP site has been used extensively by NASA as a uniquely relevant Moon and Mars science and exploration analog. The site is commonly referred to as "Mars On Earth". Research at HMP is divided into two programs: Science and Exploration. The HMP Science program seeks to learn about the site's geology and biology in order to gain insights into the nature and evolution of the Moon, Mars, and other planetary bodies via comparative studies. In the process, the HMP Science program also contributes new knowledge about Devon Island, the Arctic, and the evolution of the Earth through time. The HMP Exploration program seeks to use the site, and the opportunity of real planetary exploration-relevant field science being conducted, to develop, test, and validate new exploration technologies and strategies for planning the future human and robotic exploration of the Moon and Mars. Exploration systems studied include habitats, spacesuits, ground vehicles, aircraft - drones and other unmanned aerial vehicles (UAVs) -, robotic rovers, drills, instruments, tools, life support systems, plant growth systems, and communications and other information systems. Human factors and crew resource management (CRM) studies are also carried out. Research at HMP is supported by NASA and other research partners in government, academia, non-profits, and industry.

The Haughton-Mars Project Research Station (HMPRS), the HMP's permanent base camp on Devon Island, is located at 75° 26' N, 89° 52' W, in the northwestern rim area of Haughton Crater **(Fig. 2)**. The HMPRS is currently the largest privately operated polar research station on Earth, and the only one dedicated to planetary analog science and exploration studies. The NASA HMP is headquartered at NASA Ames Research Center (ARC) at Moffett Field, California. For more information: www.marsonearth.org

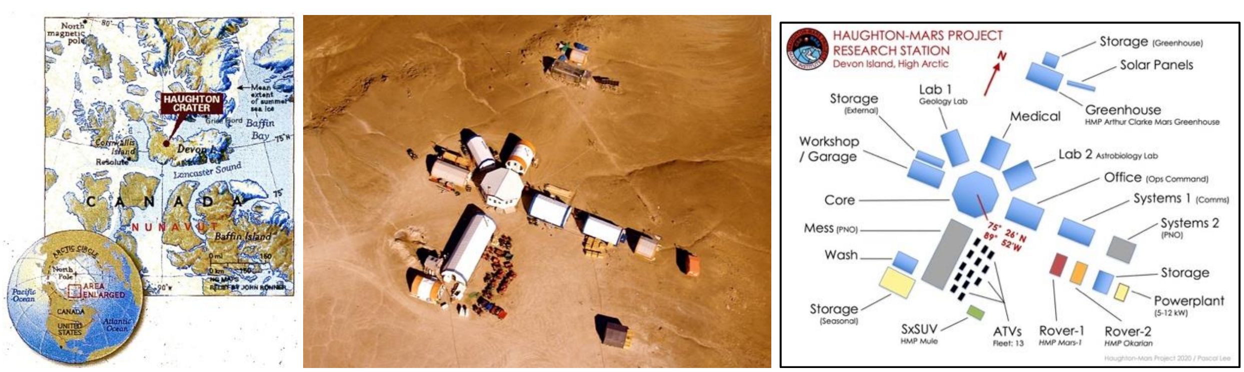

Figure 2. Haughton-Mars Project Research Station. ***Left:*** *Location map.* ***Center & Right:*** *Base camp. (HMP).*

III. HMP-2022 Tethered Balloon Experiments: Objectives and Systems

The HMP-2022 Tethered Balloon Experiment had two main objectives:

Objective O-1: *Identify challenges and solutions to conducting tethered balloon operations during terrestrial crewed traverses in open all-terrain vehicles (ATVs) across a range of Mars analog terrain.*

Objective O-1 was achieved by accomplishing three tasks:

Task O-1-1: Deploy and operate a tethered balloon system during a long range (≥ 10 km) ATV traverse across Mars analog terrain at and around Haughton Crater;

Task O-1-2: Record and analyze incidents with the tethered balloon during the traverse;

Task O-1-3: Formulate and test potential solutions to prevent similar incidents.

Objective O-2: *Define basic requirements, concepts of operations (CONOPS), and preliminary designs for Mars tethered balloon systems in three cases: a) fixed base; b) robotic rover; c) crewed rover.*

Using lessons from *Objective O-1*, *Objective O*-2 was achieved by accomplishing four tasks:

Task O-2-1: Estimate size and mass requirements for tethered balloon systems on Mars.

Task O-2-2: Define CONOPS and preliminary design for a Mars balloon tethered to a fixed base.

Task O-2-3: Define CONOPS and preliminary design for a tethered balloon on a Mars robotic rover.

Task O-2-4: Define CONOPS and preliminary design for a tethered balloon on a Mars crewed rover.

Objective O-1 was addressed by an "HMP-2022 Tethered Balloon Traverse Experiment". Objective O-2 was addressed via the combination of two experiments: the same "HMP-2022 Tethered Balloon Traverse Experiment" and an additional "HMP-2022 Tethered Balloon and EVA Spacesuit Experiment". Three hardware systems were key to carrying out all objectives: a) All-Terrain Vehicle (ATV); b) tethered balloon system; c) concept Mars spacesuit. We briefly describe these systems below.

All-Terrain Vehicle (ATV). The HMP operates a fleet of Kawasaki Bayou 220 and 250 ATVs (quad bikes). ATVs are critical to conducting HMP field science, exploration, and logistics operations, and have been proposed as an optimal conceptual solution to mobility needs for future human Moon and Mars surface operations[5]. For the HMP-2022 Tethered Balloon Experiment, ATVs served as analog open surface mobility platforms, allowing us to examine both robotic rover tethered balloon operations (even if the ATV was not actually robotic but had to be ridden by a human operator) and unpressurized crewed rover tethered balloon operations. HMP ATVs have both front and rear equipment racks allowing balloon tether line reels to be anchored. Tethered balloon operations in the case of a fixed base were also supported using an anchoring ATV parked in specific locations.

Tethered Balloon System (TBS). Two balloons in total were used in the experiment, both 5.5 ft (1.67 m)-diameter "Cloudbuster" chloroprene balloons from *Bargain Balloons*. The helium (He), in a pressurized tank containing $75 m^3$ of He at 1 atm, was procured in Yellowknife, NWT, airfreighted to Resolute Bay, NU, and flown on to the HMPRS. The tether lines, made of polyester and acquired from *Emma Kites*, were ~305 m (1000 ft) long, but deployed only out to a maximum of 100 m during the HMP-2022 field tests reported here. The lines were outfitted with swivel pins rated at ~90 kg (200 lbs). The loop reels were 9 inches in diameter. The camera was a GoPro Hero 4 or equivalent.

Concept Mars Spacesuit. The HMP has an ongoing field research collaboration with Collins Aerospace on future EVA spacesuit systems and operations. The HMP Tethered Balloon Experiment borrowed a Collins Aerospace concept spacesuit for Mars exploration – internally designated "Dave" - to provide the shape and volumetric constraints associated with a spacesuit for the EVA operations portion of the HMP-2022 field investigation.

IV. HMP-2022 Tethered Balloon Long-Range Traverse Experiment

We report here on *Tasks O-1-1 through O-1-3*, which required that we plan, deploy, and operate a tethered balloon system during a long range (≥ 10 km) ATV traverse across Mars analog terrain at and around Haughton Crater, record any incidents in balloon operations during the traverse, analyze their cause, and formulate and test potential solutions.

On 14 August 2022, a day with moderate 5 kts winds gusting to 10 kts, we conducted a multi-vehicular ATV traverse from the HMPRS base to a remote vehicular outpost, the HMP's *Mars-1 Humvee* rover parked at a range of 17 km south-southwest of HMPRS, outside the southwest sector of Haughton Crater, and back. The range of the traverse, and more importantly the distance traversed, 49 km, far exceeded the experiment baseline minimum range of 10 km, providing substantial opportunity to test and evaluate the behavior of tethered balloons on a traverse. The return route was also in part different from the outbound route, and included extremely rough, blocky terrain in

Ingenuity Valley, a 2 km-long, < 20 m wide valley never visited before but scouted by drone a few days prior (and given its provisional name in honor of the first Mars rotorcraft scout). Two identical balloons were simultaneously deployed at the start of the traverse, an orange one on the lead ATV, and a yellow one on the second ATV, to ensure the balloons would be easily distinguished in photos and videos documenting the traverse. Both balloons were initially kept on relatively short, ≤ 4 m-long tether lines, to help prevent the balloon envelopes from striking the ground or narrow valley walls, in particular in *Pete Conrad Valley*, the first valley entered upon departure from camp **(Fig.3)**.

Figure 3. HMP-2022 Tethered Balloon Long-Range Traverse Experiment: ***Left:*** *ATV with balloon in free tether configuration, i.e., with the tether line rising freely from the ATV-anchored reel. Note also the small black camera payload suspended from near the top of the balloon tether line.* ***Center and Right:*** *ATVs on traverse***,** *two equipped with tethered balloons in free tether, entering Pete Conrad Valley shortly after departing HMP base (HMP).*

Due to winds that day and the dynamic pressure from the relative wind associated with the ATVs moving at groundspeeds of 5-15 km/hr, balloon height and direction were unstable and displayed oscillation tendencies, even when the ATVs came to a stop. Near the end of *Pete Conrad Valley*, an attempt was made to extend the lead orange balloon's tether line length out to 10 meters in hopes of finding more stable air higher above ground. However, the balloon continued to experience oscillations of growing amplitude and, in spite of efforts to reel it back in rapidly, it eventually contacted the rocky valley floor behind the ATV and burst, catastrophically terminating its mission within the first 0.5 hour of the 8.25-hour excursion. The yellow balloon, while also experiencing oscillations, was kept reeled in at ≤ 4 m length and eventually survived the entire long-range traverse.

Thus, the only tethered balloon operation incident during the long-range traverse was the loss of the orange balloon in *Pete Conrad Valley*. Upon this balloon bursting, local winds were measured using a *Proster MS6252A* handheld digital anemometer and found to be 5 kts gusting to 10 kts (2.6 to 5.2 m/s, or 6 to12 mph), with significant turbulence in proximity (within meters) of the valley walls. However, as Earth's atmospheric density is 100 times higher than Mars', the dynamic pressure, which scales as ρSv^2, is significantly higher for winds on Earth than for similar wind speeds on Mars. On Mars, winds would have no significant effect, either drag, dynamic lift, or sustained oscillations, and so no quickly-undampened oscillation of the tether line would be expected, even while ground vehicles are in motion. Relative wind speeds would have to be 10 times faster on Mars than what we experienced during our field test on Earth to produce the same amount of drag, dynamic lift, and sustained oscillations, which would be an extremely rare if even possible occurrence on Mars. Winds on Mars typically average 2 to 8 kts (1.1 to 4.2 m/s, or 2.5 to 9.3 mph). The fastest surface winds recorded in the strongest storms on Mars peaked at ~58 kts (30 m/s, or 67 mph).

In the terrestrial context of Devon Island, the orange balloon crashing to the ground could have been avoided if the balloon had been reeled in or out more quickly. Being able to secure the balloon at a specific location on the ATV once reeled in would provide added safety to the balloon system. We observed that, given the winds on the traverse day, both balloons were at risk of striking the ground for tether line lengths < 10 m.

The tether line oscillation and balloon ground strike problem was solved the next day, once back at camp, by creating a way to prevent the balloon envelope from ever contacting the ground, rover platform hardware, or the ATV operator, even with zero tether line length, *i.e.*, even once the balloon system is fully retracted. The solution found was to run the tether line through and along a rigid hollow vertical boom, providing an elevated anchor point for the balloon **(Figs. 4 and 5)**. The solution was successfully tested on 16 August 2022 during a 6-hour, 25 km ATV science traverse to *Planet of the Apes Valley*, and back. While atmospheric drag and dynamic lift on a balloon, and sustained oscillations of the tether line, are not expected to be issues on Mars, the solution found will still help stow a balloon, inflated or deflated, to prevent it from contacting the vehicle, its operator, or the ground.

Figure 4. Iterating on the ATV Tethered Balloon System Anchor Interface: ***Left:*** *ATV equipped with front-mounted blue vertical flexible PVC tube to anchor the balloon well clear of the ground when the tether line is reeled in. The flexible boom, however, interfered adversely with vehicle operation. The problem was solved by rigidifying the boom.* ***Center:*** *To increase boom rigidity, the blue PVC tube was inserted through a rigid steel tube to reinforce it.* ***Right:*** *ATV equipped with front-mounted rigid vertical boom serving as an elevated fixed anchor. (HMP).*

Figure 5. ATV Tethered Balloon System Interface. *Close-up of ATV tethered balloon boom attachment. (HMP).*

V. Size and Mass Requirements for Mars Tethered Balloon Systems

In this section, we report the results of Task O-2-1. We estimate the size and mass requirements for Mars tethered balloon systems, considering the Martian atmosphere's low atmospheric density and pressure compared to Earth's, Mars' atmospheric composition, and a range of potential payload masses.

Earth's atmosphere at the surface is assumed to be at a pressure of 101.32 kPa and a temperature of 0 °C (273 K), with the specific gas constant of air being 287.05 $J.kg^{-1}.K^{-1}$. Mars' atmosphere at the surface is assumed to be 100% CO_2 at a pressure of 610 Pa and a temperature of -63 °C (210 K), with a specific gas constant of 188.92 $J.kg^{-1}.K^{-1}$. The atmospheres are assumed to behave as ideal gasses.

The design we consider is a zero-pressure balloon, *i.e.*, the pressure inside and outside the balloon are the same. Thus, buoyancy is achieved by the lower molecular mass of the gas inside the balloon compared to that of the CO_2 of the Martian atmosphere. A 100 m long, 3 mm diameter polyester tether with a 0.005 kg/m linear mass is included in the system. This corresponds to a fixed additional mass of 0.5 kg. This tether is rated for a 500 N working load, which gives a factor of safety of 2 with a 24 kg system mass. With lighter payloads, this margin could be used to add data and/or power lines, and/or a UV radiation-resistant sheath.

The balloon's areal density[6] is 0.02 kg/m^2, with the specific gas constant of the hydrogen (H_2) fill gas being 4124.2 $J.kg^{-1}.K^{-1}$. Because the Martian atmosphere is lacking in free oxygen (O_2), balloons on Mars may be filled with H_2, the neutral gas with the lowest molecular weight, without concern for hydrogen combustion. If produced on Mars (from Martian H_2O), hydrogen would be the safest and most efficient gas to use. If hydrogen has to be flown in from Earth, then helium would be the safest and likely more cost-effective alternative given the flammability and storage challenges of hydrogen. **Figure 6-Left** shows a free body diagram of the tethered balloon system (TBS).

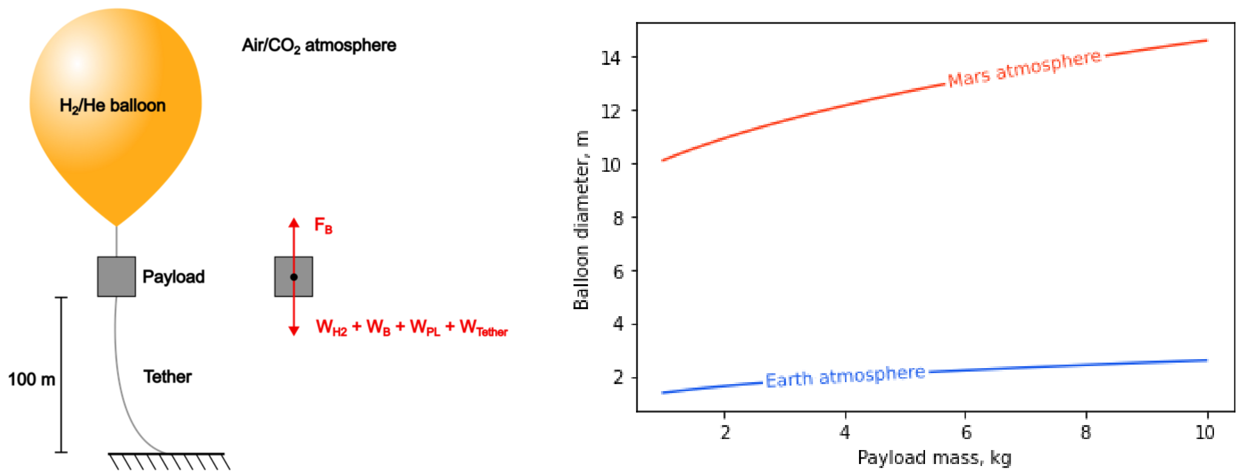

Fig 6. Tethered Balloon System on Earth vs Mars. Left: *Free-body diagram of a tethered balloon system (TBS) on Mars. F_B is the buoyant force on the balloon. Drag and dynamic lift are ignored given the low Martian atmospheric density and relative wind speeds on the TBS. W_x is the weight of component x, where x is in turn the gas in the balloon envelope (H_2 and/or He), the balloon envelope (B), the payload (PL), and the tether line (Tether).* **Right:** *Tethered hydrogen balloon minimum diameter vs payload mass on Earth and on Mars.*

The force balance is as follows, adapted from [7], and with variables defined in Fig.6:

$$F_B = W_{H2} + W_{balloon} + W_{payload} + W_{tether} \quad (1)$$

$$\rho_{atmosphere} * V_{balloon} * g = m_{H2} * g + m_{balloon} * g + m_{payload} * g + m_{tether} * g \quad (2)$$

where ρ is density (in kg/m^3), V is volume (in m^3), m is mass (in kg), and g is gravity (in m/s^2).

$$\rho_{atmosphere} * V_{balloon} = \rho_{H2} * V_{balloon} + \rho_{A,balloon} * A_{balloon} + m_{payload} + m_{tether} \quad (3)$$

The final equation depends on balloon radius:

$$4/3 * (\pi * r^3) * (\rho_{atmosphere} - \rho_{H2}) - 4 * \pi * r^2 * \rho_{A,balloon} = m_{payload} + m_{tether} \quad (4)$$

From the ideal gas law, we also have: $\rho = P / (R_{specific} * T)$, where P is gas pressure (in Pa), $R_{specific}$ is the gas constant specific to the gas (mixture) used (in J/kg/K), and T is the temperature (in K).

The minimum diameter for tethered hydrogen balloons to lift payload masses between 1 and 10 kg in Earth's and Mars' atmospheres is shown in **Figure 6-Right**. To first order, tethered balloons diameters need to be about an order of magnitude larger on Mars than one on Earth for the same payload mass.

VI. Concepts of Operations and Preliminary Design of Tethered Balloon Systems for Mars

In this section, we summarize our findings from *Tasks O-2-2* through *O-2-4*. We consider concepts of operations and preliminary designs of tethered balloon systems: i) at a fixed base on Mars; ii) on a robotic Mars rover; iii) on a crewed Mars rover.

Tethered Balloon at a Fixed Mars Base. A fixed base on Mars is generally understood to be a fixed, human-occupied habitable infrastructure established at the surface of Mars to serve as a science and exploration hub; but it can also be a temporary outpost represented by a pressurized rover parked at a remote location.

There are several important advantages to having a tethered balloon system at a fixed base on Mars, all capitalizing on the value of having the observation perspective and visibility of a low cost, stable, quasi permanent, high-elevation platform[1] **(Figs. 1-Left & 7).** Such a platform may serve as a) an observation platform from which change at a base site, natural or human-induced, may be monitored through time, b) a weather station "mast" from which changes in local environmental conditions may be monitored through time; and c) a field communications relay visible from a great distance in the region around the fixed base.

Tethered Balloon on a Robotic Mars Rover. Tethered balloon operations from a robotic rover have been considered for a long time[2,3], but for reasons perhaps of perceived complexity associated with a tethered balloon's deployment mechanism and the envelope's limited gas-tightness, tethered balloons have yet to be deployed on Mars. Tethered balloon operations from a roving platform began to be examined in a field setting during HMP-2000 summer. Our follow-up traverse tests during HMP-2022 have produced a simple, possibly simplistic, preliminary concept **(Fig.8)**.

Figure 7. Value of a Tethered Balloon for a Fixed Base on Mars from Terrestrial Analog Examples. Left: *Winter aerial view of Dumont d'Urville Station, Antarctica, acquired by author Lee via a tethered balloon anchored to a fixed point and carrying a time-delayed single-lens-reflex shuttered camera*[1]*; this image, acquired in 1988, was the first aerial picture of the French base in winter;* **Center and Right:** *Aerial views of the Haughton-Mars Project Research Station on Devon Island, High Arctic, acquired from a fixed base tethered balloon (HMP).*

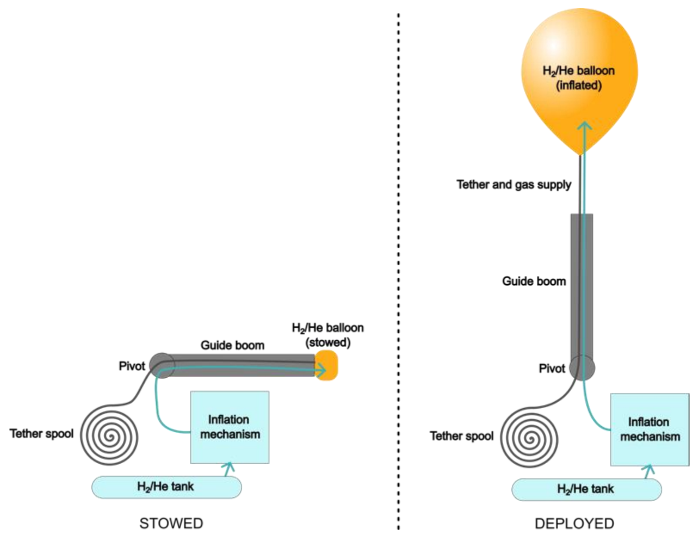

Figure 8. Tethered Balloon System Deployment Mechanism Concept for Robotic or Crewed, Fixed or Mobile Mars Exploration Platforms.

Tethered Balloon on a Crewed Mars Rover. To understand better the functional design requirements of a tethered balloon system for future unpressurized crewed rovers on Mars, we first conducted a field experiment, the "HMP-2022 Tethered Balloon and EVA Spacesuit Experiment", in which the operator of an ATV equipped with a tethered balloon system donned a Mars analog spacesuit. The experiment was opportunistic given the availability at HMP-2022 of an early generation Collins Aerospace concept spacesuit for Mars exploration and was of limited scope. It aimed mainly to serve as a preliminary opportunity to examine the accommodation of a tethered balloon system on an unpressurized crewed rover, with attention to potential interference between the suited vehicle operator and the TBS. Although it was understood from the start that the concept spacesuit used was not pressurized, and so a Mars astronaut's actual mobility, dexterity, and situational awareness limitations would not be represented with high fidelity, we nevertheless recorded and examined the challenges encountered by the suited subject in roving with, deploying, retracting, and stowing the TBS, focusing on basic TBS volumetric accommodation and spatial interference. TBS operations were evaluated during a short-range ATV traverse within 1 km range from HMP Base Camp, with the crewed ATV operator, author Dubé, wearing the concept spacesuit, and with the boom interface in place **(Fig. 9).** A Cooper-Harper[8]-inspired scale, adapted from the original to evaluate comfort and performance in Collins Aerospace concept spacesuit studies at HMP, was used to collect feedback from the suit subject during a post-experiment interview, along with external observations collected during the test.

It was observed that, in context of the specific configuration in which the crewed ATV and TBS were tested, the tether line often brushed against the suit's PLSS (Portable Life Support System). The suit subject also had difficulty remaining aware of where the balloon was in the sky given that the entire tether line was behind him. These two issues would be easily solved by implementing the proposed rigid deployment boom mechanism, and if the boom was located in front of, not behind, the ATV operator. These two findings would likely not change if the suit had been pressurized, and so are considered robust, albeit possibly obvious.

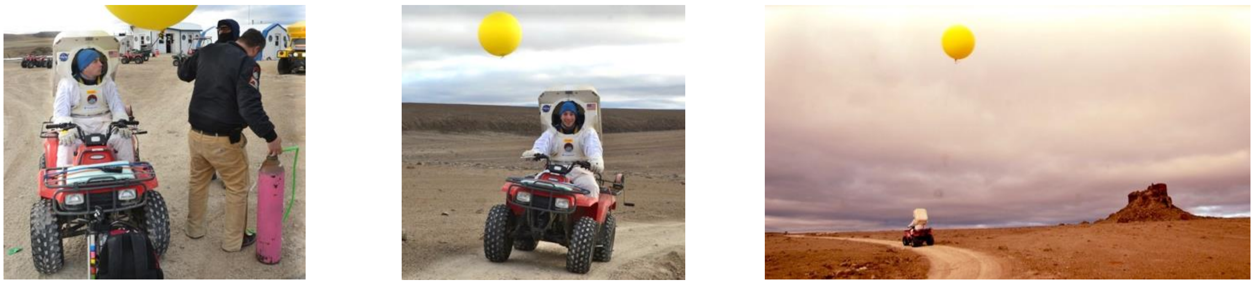

Figure 9. HMP-2022 Tethered Balloon and EVA Spacesuit Experiment. ***Left:*** *Balloon inflation at start of spacesuited field test (HMP/Rod Pyle).* ***Center:*** *Author Dubé in Collins Aerospace concept spacesuit for Mars exploration, on an ATV with balloon in free tether (HMP).* ***Right:*** *TBS deployed to >10 m during suited test. (HMP).*

VII. Conclusion

Tethered balloons are a versatile, potentially game-changing capability for Mars exploration in the context of both robotic and human missions, with or without mobility. When tethered to a fixed anchor – on a lander, at a human base, or on a parked pressurized rover serving as a temporary outpost – they provide a towering vantage point from which long-term monitoring of a site and of its assets can be conducted, and long-range communications covered. When tethered to a mobile platform – a robotic or crew operated rover – tethered balloons enable real-time remote sensing for positioning, scouting, navigation, science (including ground-truthing of orbital data), environmental monitoring, and communications relaying. The Haughton-Mars Project 2022 field study described in this paper focused on the practical operational implementation of a tethered balloon system from mobile platforms in the conduct of Mars-relevant surface science and exploration activities. The use of a rigid deployment arm to clear the balloon from the vehicle deck and operator and prevent the balloon envelope from contacting the ground promises to be a viable approach for implementing a tethered balloon system on a future Mars surface exploration platform. We recommend that a severable, instrumented tethered balloon system be further matured and included as often as possible as part of future Mars surface exploration missions. In the meantime, further investigations of this concept with more mature prototypes, higher fidelity tests, and additional interested stakeholders will be sought.

Acknowledgments

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