BEGIN HIGH FIDELITY MARS SIMULATIONS NOW!

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ABSTRACT

While analog environments (e.g., Antarctica) and mission experiments (e.g., FMARS, MDRS) are useful, a long term, logically sequenced series of experiments and evaluations in faithfully simulated Mars (outdoor) and Mars habitat (indoor) environments is an absolute prerequisite for manned missions to Mars.

Mars suit pressure should be minimized in order to simplify suit design, and habitat pressure should also be minimized, to eliminate "EVA" prebreathing and to reduce structural stress. But we need to experimentally establish the long-term health implications of living in such an atmosphere before we make irrevocable design decisions. This will require a habitat simulation facility that operates continuously for years. Coupling the habitat simulation with a Martian surface simulation (Martian atmospheric pressure and composition, temperature, lighting, wind, dust, and analog-regolith) will support the long term evolutionary development cycle of all types of systems and processes: equipment reliability testing, development of techniques and procedures (e.g., repair, emergency survival), mission plan development and validation, and then later crew training and mission rehearsal. Finally, after launch, the facility will be used to "shadow" actual mission operations.

For these purposes we need high fidelity simulation facilities, not just rough analogs. Apart from reduced gravity and radiation, we can provide very high fidelity right here on earth, at costs much lower than in space or on the moon. The time to start is <u>now</u>!

INTRODUCTION

Sending humans to Mars is the capstone specific goal identified for the “Vision for Space Exploration” promulgated by President Bush [1]. Sending humans back to the moon is planned as the penultimate step, first in Apollo-scale missions, then for longer duration missions.

Following the demise of the earlier President Bush’s Space Exploration Initiative [2] in 1990, several innovative mission concepts that were proposed by Zubrin [3] as “Mars Direct” have been incorporated into NASA and other Design Reference Missions [4]: (1) a conjunction mission comprised of a 6+ month transit to Mars, approximately 18 months on the surface of Mars, and a 6+ month return; (2) pre-emplacement of unmanned assets, possibly including an Earth Return Vehicle (ERV); and (3) in-situ resource utilization (ISRU) to generate fuel (methane) and oxidizer (LOX) from Martian atmospheric carbon dioxide and hydrogen (possibly from Martian water). While the exact partitioning of functions into specific vehicles may differ among the various proposals, this nominally 30+ month “consensus” mission profile obviously presents a number of novel challenges for NASA or any other organization planning to execute it.

In addition to the "consensus" mission profile , this paper makes two explicit assumptions regarding the development of a manned Mars mission. The first is that we are not going to re-engineer the first humans we send to Mars; they are likely in elementary or high school today! We have to engineer our systems to keep our crewmembers alive, healthy, productive, and comfortable. The second assumption is that the initial Mars exploration program will consist of more than just one or two crew launches – that it will in fact reflect an extended commitment to the exploration of Mars, analogous to our efforts in Antarctica. The baseline goal should be to explore Mars thoroughly enough to convince all but the most diehard true believers that the planet has in fact never hosted life – or, of course, to actually find it! The importance of this second assumption is twofold: (1) our up-front investment will be amortized over a significant number of missions, and (2) our explorers will learn in the first mission or two exactly which things work and which will have to be modified for later missions. These are both reasons for us to spend the resources to do things right the first time.

Doing things right the first time means making as many of our inevitable mistakes as possible here on earth, years in advance of sending people to Mars – or, indeed, back to the moon. Many existing environments and activities represent analogs of various aspects of Martian exploration, and we can and should learn from them. Polar exploration (including the South Pole Station and the Antarctic dry valleys), high altitude mountain climbing, ocean sailing (a small group of people confined in a small vessel for an extended period of time), and SCUBA diving (dressing and equipping for survival) all come to mind. The Mars Society's Flashline Mars Arctic Research Station (FMARS) and Mars Desert Research Station (MDRS) [5], and NASA-supported activities at Devon Island and elsewhere provide dress rehearsals of some aspects of mission activities and constraints. One of the principal reasons articulated for returning to the moon is to learn how to do long-duration missions beyond LEO in preparation for the trip to Mars; the space station can arguably also play a role in this learning process.

This paper argues that, while we can learn much from these analogs, it is necessary that we construct faithful physical simulations on earth of some critical aspects of the Martian exploration environment and operate them over extended periods of time. Perhaps the most critical aspect we must investigate is the atmosphere our Martians will actually breathe – the atmosphere(s) inside their habitats, their pressurized vehicles, and their space suits.

ATMOSPHERES FOR HABITAT AND SUIT

Selecting atmospheric pressure and composition for space vehicles involves balancing a number of important considerations, and NASA has made different decisions for different flight systems. Mercury, Gemini, and Apollo used 100% oxygen in the 4-6 psi range. Skylab used 70% oxygen at 5 psi. The space shuttle and space station use standard earth sea-level air – 14.7 psi, 21% oxygen. NASA's space suits (Extravehicular Maneuvering Units, or EMUs in NASA-speak) have all used 100% oxygen, at 3-6 psi.

Beyond the baseline requirements of having enough (but not too much) oxygen, getting rid of carbon dioxide, and managing humidity, the key factors for selecting the atmosphere are these:

- The risk of decompression sickness (DCS) at the start of an EVA increases with increasing ratio of nitrogen partial pressure in the habitat to the total suit pressure.

- Increasing oxygen percentage increases flammability, complicating both prevention and suppression of fire; a concentration of oxygen > 30% disqualifies the use of many materials for flammability reasons.

- Reducing suit pressure increases flexibility and comfort by reducing the work required for motion.

- Reducing suit pressure decreases suit weight, complexity, and cost.

- Reducing habitat pressure reduces required habitat pressure strength and atmospheric leakage to space.

Decompression Sickness (DCS)

Decompression sickness is what divers call the "bends" or "chokes" – pain in joints or lungs due to nitrogen dissolved in body tissues forming bubbles when atmospheric pressure is reduced – we are specifically concerned with moving from a habitat or spacecraft to a spacesuit as we begin an EVA. Serious cases of DCS can have very serious consequences involving the nervous system and/or bones. The commonly used statistical measure of the risk of DCS for a decompression event in oxygen/nitrogen atmospheres is

R = (initial partial pressure of nitrogen) / (final total pressure)

R values experienced at the start of EVAs to date have varied from 1.0 to 1.9. Problems have occurred in flight, but fewer than structured ground tests would suggest. R = 1.2 is deemed to be "low risk", and is the usually stated design target.

If a decompression event consists of removing all the nitrogen from an initial mix of oxygen and nitrogen, so that the final atmosphere is pure oxygen, then

R = 100 / (initial % oxygen) – 1.0

and this is independent of the absolute pressures involved. Doing the math, we find that if we start with 50% oxygen, R=1.0; with 45% oxygen, R = 1.22; with 40% oxygen, R=1.5; and with 35%, R = 1.86. All other things being equal, then, 45% oxygen in the habitat atmosphere would allow EVA with minimal risk of DCS, without requiring any special prebreathing regimen.

EVAs and EMUs for Shuttle/Station, the Moon, and Mars

Let's calculate R for an astronaut moving from the shuttle interior's 14.7 psi 21% oxygen into a spacesuit (EMU) with 100% oxygen at 4.0 psi: (1.0 - .21) * 14.7 / 4.0 = 2.90. That doesn't sound healthy! And, in fact, it wouldn't be. EVAs from the shuttle or station are all planned in advance, and the preparatory routine is (1) breathe pure oxygen for 4 hours, (2) reduce the shuttle cabin to 30% oxygen at 10.2 psi for 17 hours, (3) breathe pure oxygen at 14.7 psi for another hour. This ugly regimen was devised in response to physiological data gathered after shuttle system design decisions were already made, but even the original plan called for several hours of prebreathing pure oxygen [6].

Our initial Mars exploration site will not be a "colony", or even a "homestead", but it will be a "compound" including a habitat, an Earth Return (or other ascent) Vehicle, a nuclear reactor (shielded by the lip of a nearby crater), likely a cryogenic storage facility, perhaps a garage for vehicle repairs, possibly a small experimental greenhouse, and almost certainly a distributed array of small networked infrastructure elements supporting local navigation, communication, and various scientific functions. There is no option for an EVA prebreathing regimen here. When something "outside" goes "thump" in the night, astronauts will have to be able to go check it out now. Not in twenty hours, not in four hours, not in one hour, but now. Their lives may well depend on it, and they will accept nothing less. (Yes, spacesuits must be quick-donning!)

Mars' gravity, at 38.5% of earth's, represents a new domain for the EMU designer. While a 125 pound astronaut wearing a suit that weighs 200 pounds on earth would still weigh only 125 pounds total on Mars (and a 200 pound astronaut with suit would only weigh 154 pounds), the inertial forces encountered in moving about would be much greater. Just as on the moon, astronauts will have to learn new ways to move about effectively and efficiently, and the EMU design will have to facilitate this. The more flexible and lightweight a suit is, the better.

Since we will be processing many tons of Martian atmosphere for the carbon dioxide needed to manufacture fuel and oxygen, we can also extract nitrogen to use as an atmospheric buffer gas. Argon is the other major constituent of the Martian atmosphere, and it would certainly be convenient to use the natural 60-40 nitrogen-argon mix of carbon dioxide-depleted Martian air in our habitat atmosphere [7]. Unfortunately, Argon is twice as soluble as nitrogen in both water and fat [8]. Neon would be a suitable buffer gas, but it is present in the Martian atmosphere as only 2.5 parts per million.

Recommendation for Habitat Atmosphere: 6.0 psi, 40% Oxygen

Since, as argued above, Martians must be able to perform an EVA ("go outside") without any prebreathing, we use the R = 1.2 criterion. And because future Martians will thank us if we decide now to minimize both habitat and suit pressures (thus reducing pressure strength requirements for structures, and permitting cheaper and more flexible suits), we recommend a habitat atmosphere of 40% oxygen at 6.0 psi, and a suit atmosphere of pure oxygen at 3.0 psi. The partial pressure of oxygen in the habitat will be 2.4 psi, which is equivalent to that at an altitude of about 6,500 feet on earth. Bumping up the suit pressure gives us R=1.2 at 40% habitat oxygen instead of 45%.

The mainstream of NASA's thinking, however, seems to run along very different lines. Perhaps because of the Apollo I launchpad fire, flammability concerns have dominated. Apart from Skylab in the 1970s, NASA has used 30% as the acceptable upper limit for oxygen, except in suits and prebreathing. Thus, the approach to dealing with DCS has been to develop higher pressure suits, and this is what NASA means when they use the phrase "advanced suit". It is not clear, however, that 30% has been adopted as a formal limit. Nor is the documentation for NASA's decision-making compelling or complete. It appears that they have assumed away the low pressure approach – in some cases charts have been truncated so that neither a 3.0 psi suit nor a 6.0 psi habitat even appear [9]. And arguing that "acceptable materials… are reduced by 85%" [10] in an atmosphere of greater than 30% oxygen is actually equivalent to saying that "materials must be chosen very carefully." NASA has recently identified 8.0-10.2 psi as the LSAM cabin pressure for the first lunar sorties [11].

Figure 1 places human experience on earth and in past and planned space missions on the "map" of atmospheric pressure and oxygen concentration. Note the lack of experience with atmospheres similar to those planned for planetary habitats.

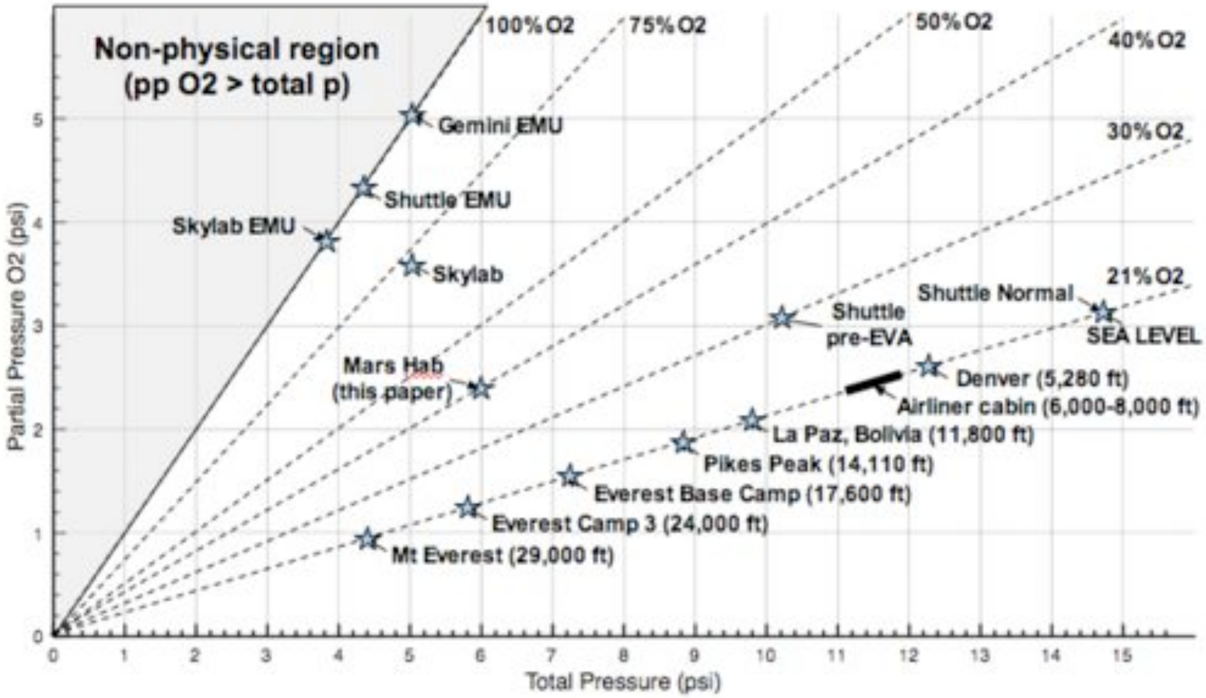

Figure 1. Human experience with atmospheric pressures and oxygen partial pressures.

Targeting a low suit pressure of 3.0 psi is consistent with an interesting alternative approach to spacesuits: the Mechanical Counter Pressure (MCP) suit. Instead of a full-body "gas bag", an MCP uses elastic fabric (e.g., spandex) to provide the required compressive counterpressure, while the skin itself acts as the vapor barrier. MCP suits have been investigated since the 1960s [12], and work is currently being done by Dava Newman at MIT [13, 14]. If this approach comes to full fruition, cheap, lightweight MCP space suits could someday completely displace higher pressure "gas bag" suits just as SCUBA displaced old hardhat diving rigs.

EARLY HIGH-FIDELITY PHYSICAL HABITAT SIMULATION TO VALIDATE ATMOSPHERIC PRESSURE AND COMPOSITION

It is clear that, whether or not NASA eventually adopts a habitat pressure as low as 6.0 psi, the atmosphere in a Mars habitat is going to be low pressure and oxygen enriched compared to sea level earth. Martian humans will be living in an atmosphere for which we have as yet no experience base. It is critical that we discover any issues involved with people actually living in this atmosphere for at least 2.5 years, and validate that it works for people, before we commit two or three decades worth of spacecraft development and missions to it. The right place to do this is on earth, where costs are minimal, the facility can be scaled up as necessary, and the simulation can be faithful in all respects except gravity, radiation, and geology. And if the moon is to play its advertised role as a way station to Mars, then the habitat atmosphere chosen for Mars should also be used on the moon. We need to build a simulated Martian habitat here on earth in order to learn how to live like Martians, and we need to initiate this right away.

What is envisioned and proposed here is an earth-based facility that continuously maintains a Martian/moon habitat atmosphere and provides accommodations and resources to support tens of people for an indefinite period of time. The life support function is completely transparent in this facility – the inhabitants are simply living "indoors" on Mars or the moon. What we intend to accomplish includes:

- Learning how best to operate this type of long-term continuously-operating large-scale "pressure chamber". This includes both "life support" and other systems, and operating procedures, including normal airlock/decompression staging and dealing with exceptional events from the trivial to the critical emergency.

- Development, validation, and documentation of tools and procedures for fire prevention and suppression, and fire risk assessment.

- Systematic study of human physiology, adaptation and acclimatization to the habitat environment, including mission-length longitudinal studies (can people live in this atmosphere without long-term negative effects?), shorter-term population studies (can we identify which people will do better or worse in this environment?), and detailed studies of the effects on intestinal and other human microflora [15].

- Development and validation of tools and procedures for small-population long-term medical care, including components of auto-medicine (crew self-monitoring and diagnosis), para-medicine (crew providing medical treatment for each other, as necessary), and tele-medicine (making use of earth-based medical professionals).

- Practicing the activities of daily living, including cooking (the boiling point of water is greatly reduced), cleaning, laundry, hygiene, etc.

- Studies of plants and animals living in the habitat environment, relevant to food, pets, and vermin (e.g., will a high percentage of atmospheric oxygen create a race of super-cockroaches?).

- Experimentation with operating a compact geological laboratory.

- Experimentation with state-of-the-art IT and communications tools and practices.

Beyond such fairly obvious potential problems as leaky pens, overheating electronics, undercooked pasta, and chronic diarrhea, this period of experimentation will be deliberately open to encountering the completely unanticipated.

The second stage of the habitat simulation is a long-term simulation of suit and pressurized vehicle atmosphere, likely between 2.4 and 4.0 psi pure (or very high percentage) oxygen. Here we will perform the same investigations to validate that this specific environment will work for humans performing EVAs and pressurized vehicle sorties on the 10-20 day timescale.

HIGH-FIDELITY PHYSICAL SIMULATIONS TO SUPPORT SYSTEM DEVELOPMENT AND MISSION EXECUTION

The previous section described a physical simulation program to validate the environmental parameters chosen for human habitation on Mars and the moon, in advance of the full Mars exploration development. This effort should be initiated immediately and pursued aggressively if we are to meet NASA's schedule for returning humans to the moon in December 2019, using approaches which can be confidently applied to the Mars exploration program a decade or so later. In this section we consider the critical roles that physical simulations will play later, during the development and execution of the Mars program itself.

One of the most important aspects of the human mission to Mars is the fact that our life support systems must work continuously for over 2.5 years. This is unlike robotic missions, most of whose systems simply "sleep" on their way to Mars. On the other hand, astronauts can serve as "onsite technicians" to make repairs. Systems must be highly reliable, yes, but even more important, they must be designed to be repairable in flight and on the surface of Mars.

Endurance testing of systems for a 2.5 year mission presents huge challenges – the duration of a single test will be of the same order as the time taken to produce the system, and longer than the commercial product cycle in such relevant technologies as computers and sensors. NASA will have to learn/invent new ways of doing development, and physical simulation facilities will play a critical role in the development process.

Starting with the habitat and surface vehicle/suit environmental simulations discussed above, we move on to simulating the surface environments of the moon and Mars ("outdoors"). It may well be the case that we add both moon and Mars environments to the basic habitat/vehicle/suit simulation facility. "Exit the left door for the moon, the right door for Mars." In each case, it may make sense to proceed in several distinct sequential steps:

- Start with the appropriate atmospheric pressure and composition (vacuum for the moon, 95% carbon dioxide at 5-10 mbar for Mars), but without the challenges of temperature extremes or dust. This will support suit testing in a benign environment.

- Add the temperature ranges that would be experienced on the moon and on Mars, but without dust. This will support the development and evaluation of thermal suit "layers" for MCP suits, and validate the thermal performance of conventional suits.

- Then add dust and (for Mars) “weather”, to support the evaluation of the effects of dust on suit bearings, seals, etc., and of abrasion of suit material due to dust and rocks. This facility will also serve as an invaluable public relations resource to impress sponsors and indoctrinate developer personnel.

- Later, implement an “outdoor” simulation that can handle large fluxes of gas, heat, etc., to support experiments with various modes of interaction of gases and liquids with the Mars (or moon) environment, both intended and unintended (leaks, decompression accidents, etc). Support the development and evaluation of all sorts of equipment, including cryogenic storage and handling systems, methane-oxygen powerplants, vehicles, and ISRU systems.

The final step in the physical simulation program is to implement the “really big outdoors” (“Superdome”?) facility, able to contain and support the evaluation of (test articles of) the actual habitats, ascent vehicles, rovers, greenhouses, etc, that will be deployed to Mars (or the moon). This facility will serve a number of purposes:

- Support for the development, evaluation (feasibility, utility, usability, maintainability), and endurance testing, initially of subsystems, and ultimately of full-up systems, including complete habitat and ERV. Specific systems and technologies that will have to be developed and then validated in the Martian environment include:
    - surface nuclear power plant (electrical, thermal)
    - cryogenic storage and handling tools
    - thermal control systems (including insulation)
    - construction technologies and equipment (including automated drilling tools)
    - methane-oxygen power sources (electrical, thermal, motive; very small to very large)
    - vehicles (manned/unmanned, ground/air, pressurized and un-, all sizes)
    - communications and navigation systems
      (intra-base, off-base, and off-planet; linking systems, vehicles, and people)
    - ultra-reliable IT support (redundant, rad-hard; wearables, etc)
    - medical strategies and tools: auto-, para-, and tele-.

- Development of operational techniques and procedures, including repair and emergency survival

- Training of actual crews (long endurance)

- Mission rehearsal

- “Shadowing” of actual missions in progress, working to anticipate and resolve issues

Since these functions are keyed to the system development process and to actual mission execution, it is possible to place them on a timeline referenced to the first manned mission launch. As the strawman data presented in Figure 2 indicates, this process will need to begin about a decade prior to this planned first launch date.

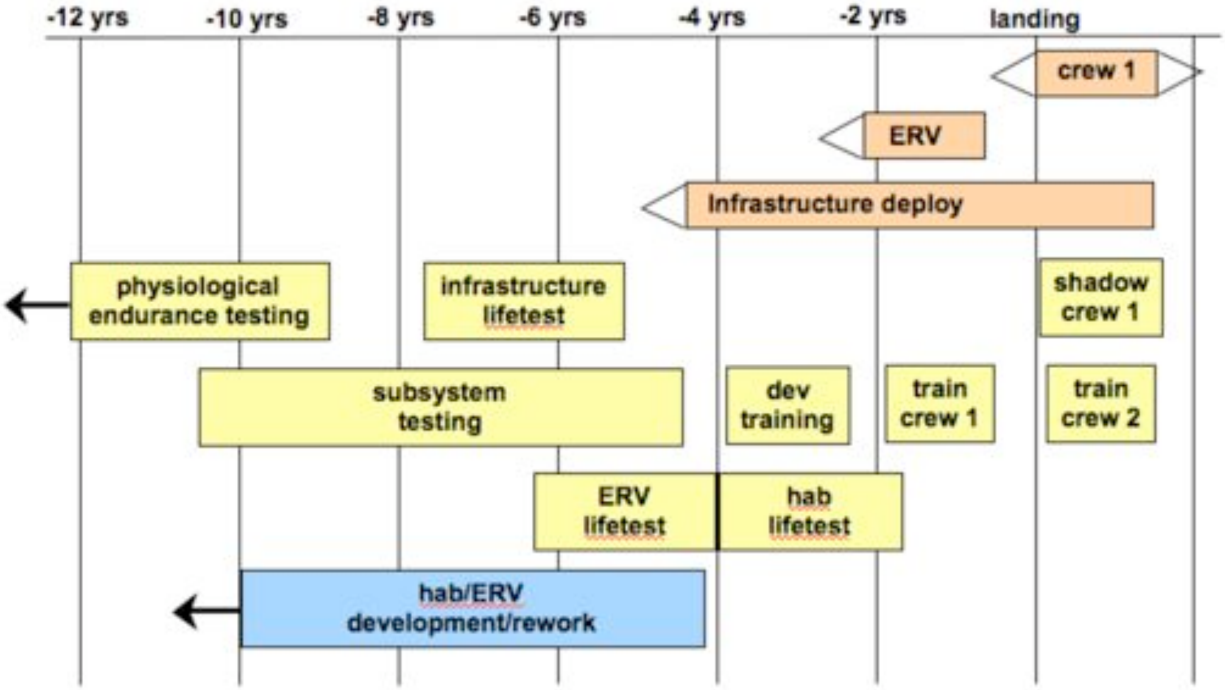

Figure 2. Roles of physical simulation in preparation for first manned Mars mission

CONCLUSIONS

High fidelity physical simulations will play multiple roles in the development and execution of human flights to Mars. Large, expensive simulation facilities will be needed for about a decade prior to the planned first launch, and these will be included as an integral part of Mars Program planning and costing.

This paper has argued that we also need an additional, earlier physical simulation effort to verify that humans can survive and thrive in the prospective Martian habitat atmosphere for multiple year missions. And, if NASA's return to the moon is to effectively support the Mars program, we should pursue this verification before we start to develop the systems we will use for extended stays on the moon – now is not too soon to start.

But NASA's exploration strategy is clear: first, return the shuttle to flight; second, complete construction of the space station and retire the shuttle; third, develop the CEV and CLV; fourth, return to the moon; and finally, proceed to Mars. This is the focus trajectory for both funding and management attention. At this point, Mars isn't on the front burner; it's hardly even on the stove.

But the initial physical simulation proposed in this paper addresses only habitat and suit, not "outdoors" on either moon or Mars. The initial costs should be in the (low?) tens of millions of dollars per year, not the billions of the full scale development effort to be pursued in the 2020s. Funding at this modest scale might be available from many sources: (1) NASA discretionary funding, perhaps as a Centennial Prize; (2) aerospace industry IRAD, perhaps through an industry consortium; (3) commercial funding for product placement, as a tourist attraction, or even as a movie set; (4) philanthropic funding; or, finally, (5) funding by an international consortium that might include ESA, JAXA, Roskosmos, CNSA, and/or NASA.

Our arguments for a 6.0 psi habitat atmosphere notwithstanding, it is worth noting that an 8.7 psi habitat facility could be constructed at the summit of 14,110 foot Pikes Peak without requiring a pressure vessel, just a seal to maintain an enhanced oxygen content. There is a road to the summit of Pikes Peak, the cog railway now runs year around, and a gift shop and food facilities are in place. A habitat simulator here could become a viable research/educational/tourist attraction, since hundreds of thousand of visitors visit the summit each year.

The long history of terrestrial exploration has demonstrated that some approaches are more appropriate and successful than others. Amundsen, for example, successfully used sled dogs and skis to go to the South Pole and return, while Scott died while using ponies and man-hauled sledges. What actually works in practice and what doesn't is not always obvious without deep experience ("gear, craft, and lore"). Amundsen succeeded by aggressively leveraging Inuit and Nordic technologies and practices. Unfortunately, we have no Martians to learn from. One way of thinking about the proposed physical simulation program is that we should create Martians here on Earth, support them in developing appropriate "gear, craft, and lore", and then leverage this on Mars itself. Every mistake we can make in simulation on Earth can save a life on Mars later.

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