Future Mars Exploration Operational Simulation: Research Outcomes and Educational Benefit

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1 Introduction

The pursuit of sustained and successful human presence throughout the solar system will require a global effort consisting of contributions from governments, industry, and private interests. For such a goal to be achieved, it is important that space exploration activities build on top of the wealth of experience and wisdom gained from 60 years of spaceflight. The exchange of such knowledge can be a

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challenge though, especially for organizations such as NASA, which has a large nearing-retirement generation and a recently recruited younger generation, but not as many employees in between these age groups to facilitate the flow of knowledge [1–3]. This challenge is not just within organizations, but across them, to transfer knowledge from a body such as NASA to the governments, companies, and private entities that have recently entered into the human spaceflight exploration enterprise. To address these knowledge transfer challenges and to build towards the dream of a human future throughout the solar system, a human spaceflight operations course was designed that helps young professionals and those newly entering into the human spaceflight field to take a step forward from where they would normally start their careers. This course helps them acquire some of the knowledge from those with substantial experience (particularly related to lessons learned that cannot necessarily be well documented).

As a capstone to this human spaceflight operations course, a Mars Operational Simulation Exercise was run to investigate how a hypothetical future Mars exploration campaign might be operated. The class split into four Tiger Teams[1] organized in a way that blends the current NASA structures of Mission Operations (how the system is operated) and Mission Engineering (the evolving design of the system). The exercise was designed with dual aims of:

1. Educating students on how human spaceflight operations are currently done.
2. Studying how operations might evolve in the future with new technology and new operational scenarios.

Current plans for future Mars human spaceflight operations tend to be an extension of Moon mission operations [5, 6], yet operations on Mars present many more challenging features, such as the up to 20 min communication delay [7–10], and the difficulty of returning to Earth. These challenges present a substantially different scenario to any space mission that has been performed before; hence there is a strong need to perform investigations specifically into how Mars human spaceflight operations should be performed.

There have been a number of physical, in-person Mars analog simulations, such as the MARS2013 analog [10], the Mars Desert Research Station [11], the NASA Haughton Mars Project [8, 12], and the Desert RATS (Research And Technology Studies) analog [8], that have been able to provide many valuable insights into important aspects of Mars operations. Some key operational aspects that the analogs have investigated include: dealing with substantial communication delay [8–10], operating with greater crew autonomy [11, 13], telerobotic integration [8, 14, 15], telemedicine [8], In-Situ Resource Utilization (ISRU) [8], and dealing with an "Us vs Them" mentality between Mars and Earth [10]. The Mars Operational Simulation Exercise presented in this chapter simulated purely the operational aspects

[1] A team of diverse technical specialists assigned together to troubleshoot and track down every possible source of failure in a system. Inspired by NASA's Tiger Teams, as coined by J.R. Dempsey et al. [4].

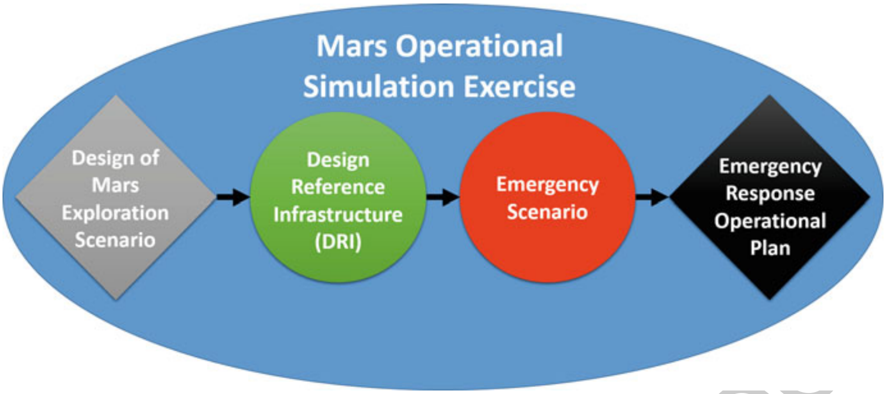

Fig. 1 Outline of the components of the Mars Operational Simulation Exercise

without any physical analogs, and as such enabled expansion from the concepts in past analogs to investigate a more complex and complete Mars Exploration Scenario and the associated unique challenges. These types of simulations can be powerful tools to explore technical, integration, and mission architecture requirements that were previously not visible, which then provides input to drive current efforts in mission and system design for Mars exploration.

In the first step of the Mars Operation Simulation Exercise, a Design Reference Infrastructure was created, then an emergency response operational scenario based on that design was addressed (see Fig. 1).

This chapter presents an overview of the Mars Operational Simulation Exercise, including: the goals, details on the novel aspects of the hypothetical Mars Exploration Scenario, and a description of the emergency scenario.[2] Highlights of the proposed solutions will be briefly described, followed by analysis of the key lessons learned about Mars human spaceflight operations. The experiences in the first iteration of the exercise were used in an updated second exercise. The changes made to the exercise will be described and the additional findings then analyzed. The strong benefit of these types of simulation exercises in providing input to drive Mars mission design efforts will then be discussed. Finally, the educational value of the exercise will be assessed and future plans outlined.

[2]For brevity, full details on the exercise are not included here, but can be found in the textbook associated with the course: "Human Spaceflight Operations: Lessons Learned from 60 years in Space" by Chamitoff and Vadali [16], to be published in 2017. Alternatively, contact the first author at benjamin.morrell@sydney.edu.au for further details.

2 Goals of the Mars Operational Simulation Exercise

The Mars Operational Simulation Exercise had dual goals of providing an enriching educational experience for the students and investigating considerations of how future human Mars operations might be carried out.

The students were to implement techniques and tools learned throughout their Human Spaceflight Operations class. Some of these include: merging of engineering design and operations to arrive at a beneficial compromise in system capabilities; failure point assessment and recognition of next-worst failure networks [17] to address these issues as early as possible in the design process. With the traditional way of teaching engineering to college students there is little, if any, exposure to the later stages of the engineering product lifecycle, when the product is in continued use. Education institutions tend to emphasize the theoretical and design aspects of engineering. The integration of these aspects with the system behavior, operations, and broader implications are not taught and many times not even mentioned. This exercise aimed to produce and instill an operations oriented mindset to the students involved and to consider the impact this mindset can have on engineering design.

The dual goal of the exercise was the actual research outcomes produced. Having dozens of fresh-minded students tackle an open-ended scenario where they could implement a myriad of ideas provided an ideal situation to come up with novel solutions, and indeed that was the case. The thoroughness of research put into the operational aspects of the scenario enabled the students to stress test aspects of proposed Mars mission architectures and operations, uncover new important requirements for a Mars exploration mission, highlight several roadblocks in the difficult Mars environment, and devise previously unforeseen work-arounds to equipment malfunctions and system constraints.

3 Overview of the Mars Operational Simulation Exercise

In the Mars Operational Simulation Exercise, a working infrastructure was designed that included elements of both engineering design and operational requirements. The exercise started with preliminary specifications of a Mars Exploration Scenario that included several unique and challenging aspects, such as:

- Multiple government, private and colonial interdependent contributors.
- Distributed and limited resources.
- Limited assistance from Earth.
- Blurring of the role of mission operations and mission engineering.

A class of 60 students were split into four Tiger Teams, which included a number of focused Technical groups, a Planning group, a Technical Integration group, and a Mission Integration group to lead each team (see Fig. 2).

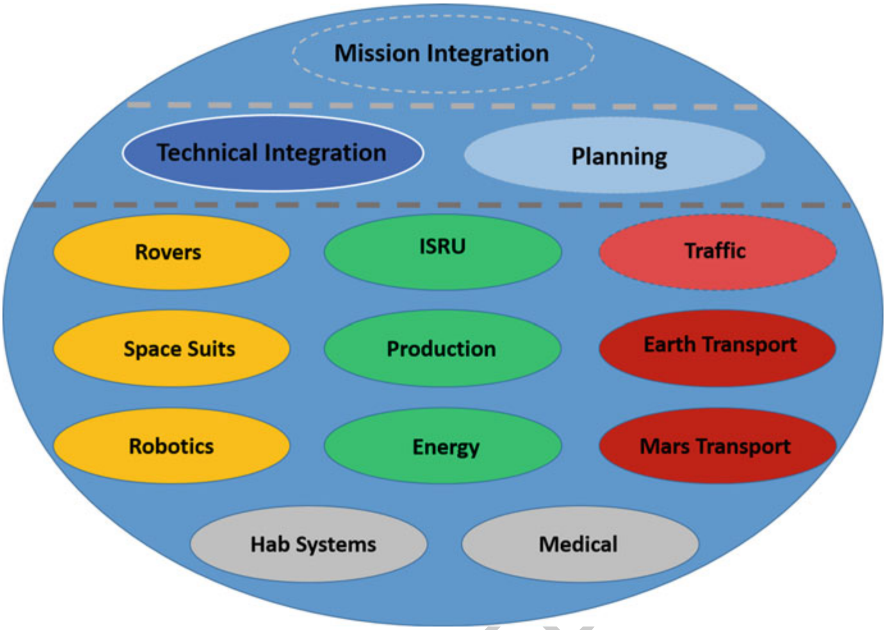

Fig. 2 Organization of Tiger Teams into discipline groups. All groups coordinate with each other. Mission Integration group oversees all groups. Activities of Technical Integration and Planning groups involve all technical groups below the *dark gray dashed line*. Traffic has coordination roles for the two transport groups

The roles of each of the groups are outlined in Table 1, where Mission Engineering and Mission Operations responsibilities are present in each group.

Referring to Fig. 1, the Mission Engineering component of the exercise required the teams to design the technical aspects of the Mars Exploration Scenario[3] to produce a Design Reference Infrastructure. The Design Reference Infrastructure was then tested in an emergency operations simulation, requiring Mission Operations approaches in the teams.[4] Through designing the infrastructure and then developing operational plans to address the emergency scenario, the teams achieved a number of goals from an educational and research perspective.

[3]The overview of the Mars Exploration Scenario was initially defined by the last two authors, with details to be created by the teams.

[4]The emergency scenario was defined by the last two authors based on the Design Reference Infrastructures developed by the class.

Table 1 Outline of group roles in each Operational Tiger Team

Group	Role	
Mission integration	Coordinate the team and align with mission goals.	t179.2
Technical integration	Ensure technical compatibility between groups. Also manages the Surface Colony.	t179.3
Planning	Operational planning and timelines. Also manages the Phobos Station.	t179.4
Traffic	Flight planning of all spacecraft. Also manages the Deimos Station.	t179.5
Rovers	Manage technical and operational details related to all surface rovers.	t179.6
Space suits	Manage technical and operational details related to all space suits and Extra Vehicular Activities (EVAs).	t179.7
Robotics	Manage technical and operational details related to all robotic assets.	t179.8
ISRU	Manage technology used for In-Situ Resource Utilization assets and operational considerations. Resources include: water, fuel, and raw materials.	t179.9
Production	Manage technical and operational details related to production of food and manufactured materials.	t179.10
Energy	Manage technical and operational details related to energy production from solar, wind, and nuclear on all celestial bodies.	t179.11
Earth transport	Responsible for technology and operations related to transport between Martian system and Earth.	t179.12
Mars transport	Responsible for technology and operations related to transport between Mars surface and moons.	t179.13
Habitation systems	Manage technical and operational details related to habitation systems and life support.	t179.14
Medical	Responsible for medical technology and considerations related to microgravity and radiation countermeasures.	t179.15

4 Architecture and Scenario Description

While there have been a number of studies that have investigated specific aspects of a sustainable Martian mission [18, 19], many of the past Mars operation studies consider short-term missions [8, 10, 12]. This study investigated an established Martian operation, in a state of development similar to where the International Space Station is today. The scenario examined considers a possible future where medium-term Martian missions are being undertaken by multiple government coalitions and a commercial consortium. Additionally, a small group of colonists have settled at a base that they are seeking to establish as the first permanent human colony on Mars. The Mars planetary system is physically connected to Earth by a group of cycler spacecraft, similar to the proposed Aldrin Cycler [20]. Together, we term all the architecture associated with the colony, moon bases, and the transport between them as the *Mars System*.

4.1 Design Reference Infrastructure

Building from initial specifications of the Mars Exploration Scenario, the teams added details to create the Design Reference Infrastructure. The interesting and key details in the Design Reference Infrastructure are described here.

There is a colony of settlers on the surface of Mars; they provide services, maintenance, and resources to governmental missions that come to the surface for scientific purposes. Phobos and Deimos are operated by both government entities and a consortium of private corporations that aid in the transport to and from the Mars System, as well as peripheral activities within the Mars System.

On the surface of Mars, a variety of advanced technology equipment is available including long range Excursion Rovers with science equipment. Additionally, there are Utility Rovers without science equipment that carry maintenance equipment and have the capability to haul trailers. Pressurized space suits are provided by the government entities and mechanical counter pressure suits are provided by the colony. There are also humanoid robots on the surface, Phobos and Deimos that are extensions of the NASA Valkyrie [21] and Robonaut 2 [22]. These humanoid robots can be configured with legs, or with a wheeled base (similar to NASA's Centaur [23]) and can perform a variety of tasks that human crew can also complete.

The method of transport between the surface and the moons of Mars is very flexible and adaptable. The Mars Lander and Cargo Lander vehicles are modular reusable transport craft that enable traffic flexibility between the surface and Phobos/Deimos. The Mars Lander can land on both the surface of Mars and the moons while carrying three crew members. In order for the Mars Lander to launch from the surface and reach orbit or one of the moons, it needs to be paired up with three Cargo Landers. The three Cargo Landers act as a booster stage to get enough energy for orbital insertion.

The Mars Landers also provide transport between moon bases. Most importantly, four Mars Landers are required to launch all the transient personnel from Deimos to rendezvous with the cycler spacecraft that provides the transport between Earth and Mars. The system is also supplied with cargo directly from Earth with infrequent launches.

A key aspect of the above-mentioned rover, robotic, and transport technologies is that they are teleoperable. This is important because these technologies are all dynamic, they move and/or transport other equipment; therefore the ability to teleoperate any of them greatly enhances crew time and operational flexibility.

At the surface, ISRU stations are located around the colony of settlers (see Fig. 3). These stations include: regolith mining, atmospheric extraction, ice mining, and support services for them. Some of these stations carry minimal surplus equipment for emergencies. There are various methods of power generation at the surface. The main supply is through a nuclear reactor, with additional supplies coming from a solar array farm and a wind generator. The colony has a substantial greenhouse for food production. Other services are also distributed around the system, with a doctor and advanced medical equipment based on Phobos.

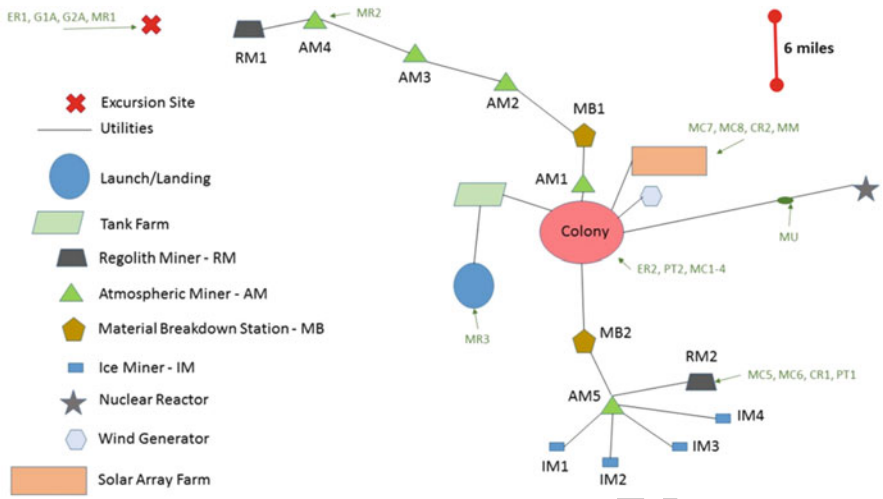

Fig. 3 Layout of the Mars Colony Site

There is a mix of asset ownership in the system, and mixed services that the entities carry out. The commercial consortium provides some of the power and ISRU as services to the colony and government organizations. The government entities own the Excursion Rovers and many of the robots. The colony owns the solar arrays, Utility Rovers, and the greenhouse.

When the architecture described and shown in Fig. 3 is working as expected (that is, there are no system failures or emergencies), the state of the simulation is referred to as the nominal scenario. Working with the initial overview of the Mars Exploration Scenario, the students in the class defined each of the components of the system and how they would operate in a nominal scenario, thus creating the Design Reference Infrastructure. These included defining ISRU capabilities, excursion procedures, medical practices, and standard operating procedures. Once the nominal scenario was planned by each Tiger Team, an emergency rescue scenario was presented as the final assignment for the class.

4.1.1 New Technology Solutions

Through defining the components of the Design Reference Infrastructure with an operational emergency scenario in mind, the Tiger Teams came up with a number of novel technology solutions. Of particular interest are the two different options for emergency medical response were that were created.

The first is a Mobile Emergency Life Support tent (MELS tent). The MELS tent is a combination of a trailer home and a small clinic. Inspired by military solutions to battlefield emergencies, the MELS can be hitched to the Utility Rovers and moved around to have a truly portable solution to moderate clinical emergencies. The MELS are designed to be distributed around the Mars colony to greatly enhance the safety and mitigate risk for any kind of operations.

The second solution to assist medical emergency responses is the concept of the Patient Emergency Transport/Restraint Apparatus (PETRA), a novel apparatus created to address the challenges during a medical emergency whilst on an expedition. The PETRA can be viewed conceptually as a combination of a sleeping bag and a stretcher. It's main feature is a rigid pressurized bag that can stabilize a human in an unhealthy condition. For more details, please see Appendix.

4.2 Emergency Scenario

Each Tiger Team was to formulate a solution and present a coherent plan to respond to an emergency scenario. One of the main objectives of this exercise was to encourage collaboration amongst all the different technical groups, while the Technical Integration group was expected to ensure cohesive operational procedures that met all the technical requirements of the teams. The Mission Integration group served as the leaders of the Tiger Teams and directed the interface with the instructors.

4.2.1 Initial Operational State

The emergency scenario started with a detailed state of operations within which an incident occurred, requiring an immediate operational response. Although the state of operations is large in scope and has great detail, several key issues require particular attention during this simulation, including the following:

1. Two scientists in an excursion vehicle just found evidence of existing life on Mars and are currently 2 days' travel time from the colony site to return with the critical samples.
2. Following a failed harvest, a critical harvest is currently underway at the Mars Colony.
3. One of the colonists is three months away from delivering the first baby to be born on Mars and cannot perform the manual tasks necessary to support the colony.
4. The surface nuclear reactor is currently offline due to a failure in the power line to the reactor, therefore:
   - Fuel production is not possible due to high power requirements
   - The power to all ISRU stations has been switched off as a precaution.

- A replacement section of power line could be manufactured in a week using materials available at the Southern Regolith Mining Station.

5. Due to a dust storm, the solar arrays are obscured and must be cleaned in order to restart the wind turbine and recharge the Colonial Rovers (it will take the rest of the day).
6. Four Mars Landers are needed on Deimos to be prepared for launch at Earth Departure Time (EDT) in 23 days, to transport the government and commercial crew to the cycler:

   - Mission rules require one Mars Lander to be left at each site by EDT: surface colony, Phobos, Deimos (there are seven in total in the system).
   - Mission rules also require a fueled Mars Lander and a fueled Cargo Lander (ten total in system) to be grounded and staged on Deimos at EDT as backup.
   - In an emergency, these backup Landers may be used.

7. Three Cargo Landers are on Deimos with extra fuel for the launch to the cycler:

   - All fuel supplies on Deimos are planned for Earth departure or are the required backup.

4.2.2 Emergency

The operational simulation was complicated by a minor explosion inside the cabin of the Excursion Rover, with two scientists inside. In addition, this rover contains the evidence of existing life. One of the scientists was injured in the blast and lost consciousness due to decompression and trauma injuries before the second scientist managed to slow (but not stop) the leak in the cabin. Though the injured scientist is stabilized after being placed in the PETRA device, they require immediate hyperbaric treatment and likely surgery at the Phobos Station infirmary within 48 hours.

Each Tiger Team is assigned as Earth Mission Support, to work the issues related to the evolving situation. Five issues are specified as top priority:

1. Get the injured crew member to safety and medical care.
2. Get the required four Mars Landers and the eight non-colonists crew to Deimos by EDT (or as many crew as is possible).
3. Assure the colonists' survival (as well as any remaining crew that cannot get off-surface).
4. Deliver the critical scientific samples to Deimos for EDT.
5. Protect all critical equipment.

Each of the four Tiger Teams was responsible for developing both a primary operations plan (assuming the injured scientist can tolerate a launch by EDT) and backup operations plan (assuming the injured scientist cannot tolerate a launch by EDT). Each Tiger Team reported on the overall plan for these two scenarios, in addition to creating detailed reports from each of the individual Technical Groups, Technical Integration Groups, and Mission Integration Groups that addressed topics including:

- The technical area's contributions to both plans.
- Any assumptions that have not been provided as input or stated in a technical group's specifications sheet.
- Details on which groups need to be integrated to successfully complete each step of the plan.
- Assessment of risk associated with the five top priority issues.
- A critique of the team's response, the exercise itself, and suggested improvements.

5 Solution Highlights

While the four Tiger Teams came up with varying solutions, some common trends emerged from the four operational plans. Two teams chose to use one of the centaur robots in order to transfer either the injured crew member, the critical samples, or both. Substantial use of teleoperation was mentioned in three of the teams' final reports, specifically for rover/robot operations, crop labor, and EDT cycler preparations, suggesting the importance of the technology.

All teams decided it was important to get as many of the eight transient crew as possible to Deimos by EDT in parallel with addressing the other concerns. A different paradigm of allowing some crew to remain on Mars might be beneficial to consider in future exercises. Two of the groups decided that the rovers must move at maximum speed in order to achieve the necessary goals and travel the distance to the colony in 2 hours or less. In contrast, one of the teams highlighted the operational limit on the rover and robot speeds during teleoperation due to potential delays in communications and reaction times to avoid hazards, and adjusted their plans accordingly.

One Tiger Team decided that instead of spare space suits (flight or EVA), at least one MELS Tent should be located at each ISRU station for emergency responses. In contrast, another team relied heavily on the use of the PETRA device for patient transport.

Many of the team's solutions included key decision points where the condition of the patient was assessed at the colony. It is at this point that the flexibility of the system was utilized, with plans employing either: (a) telemedicine capabilities to enable the doctor to stay on Phobos while treating the patient, (b) flying the doctor to the surface to treat the patient, or (c) flying the patient to the fully equipped medical facilities on Phobos.

Another common element between the different plans was an assumption of a high degree of collaboration and support between entities. All plans included colonists assisting the government scientists to treat the injured crew and retrieve the scientific samples, and close cooperation between all transient crew. Nonetheless, there was consideration for the colonists' priorities, with plans aiming to minimize the impact on their critical activities, while maintaining social and contractual obligations. Despite this, there could have been more investigation into how different interests may have affected operational possibilities.

6 Lessons Learned for Future Space Operations

From the experiences and solutions in the Mars Operational Simulation Exercise, there were a number of key lessons learned about changes that are required for successful future Mars operations. Some of these lessons suggest there is a need for a paradigm shift in the way human spaceflight operations are done to cope with the physical and temporal remoteness of Mars.

6.1 Relation Between Operations and Technology Development

The first fundamental lesson learned was that there is a strong need for substantial input of operational knowledge into the design and development of technology and larger scale systems. Current NASA spaceflight operations utilize the Plan-Train-Fly doctrine [24, 25] which has been tested and proven for past spaceflight operations, but may be unreliable in future operations as it can require extensive testing and procedure planning [26]. It was seen in the Mars Operational Simulation Exercise that the operations/technology relation needs to be circular: advanced technology enables operational advances, while operational requirements drive the needs of technology development (see Fig. 4). This is a similar conclusion to one arrived at by Kurt [27].

The PETRA medical evacuation space suit is one example where the operational need drove a technological idea: the planning of emergency medical operations identified a need to transport an injured person, leading to the PETRA suit. These findings suggest that it would be beneficial to involve operations experts in the early stage development of technology, and for those developing technology to have an appreciation of how it might be included in the operational environment, perhaps by carrying out an exercise similar to the one described in this paper. The exercise required a mix of design and operational thinking, giving the students a unique insight into how important the connection between the two is.

6.2 Self-Reliant Operations

Another salient lesson learned from the exercise was the need for Mars operations to be self-reliant, not just in resource utilization but also in operational planning. For example, in contrast with the current practice of meticulously planned EVAs, it was

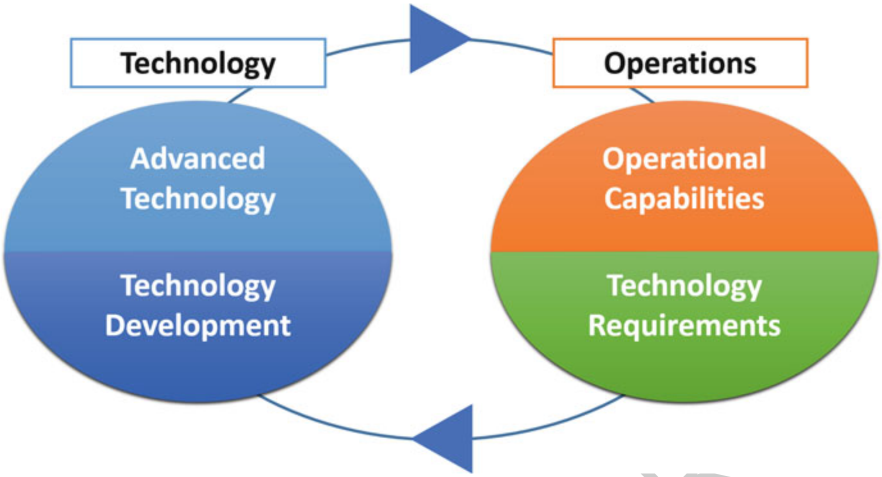

Fig. 4 The circular link between operations and technology

found that the Mars colony needs to have the ability to rapidly and independently plan and initiate an EVA without any input from Earth, and potentially with minimal interaction with other crew in the Mars System (who would likely be busy with their priorities). This finding draws some parallels with previous Mars analogs, such as in the MARS2013 and Haughton Mars Project analogs, where the challenges of a lack of autonomy were identified [10, 12], and in the Mars Desert Research Station, where greater autonomy in EVA planning was found to be beneficial in achieving scientific goals [11]. What does the need for self reliance mean for operational planning? Perhaps there needs to be some simple procedures or guidelines that an individual or group on Mars can quickly enact, but can also mold and adapt to the necessities at the time.

6.3 Self-Reliant Resources

The use of ISRU was found to be an important aspect to enabling self-reliant operations, not only for the practicality of accessing resources, but also for the locally planned operations to have control over their resources and be able to adapt to different scenarios. For instance, if an emergency operation requires the use of a large amount of a particular resource (e.g., fuel for the Mars Landers), then the Mars colony can adapt their production and consumption straight away and start to ameliorate the situation. These actions are in contrast to having to wait for planning an action from Earth, or even materials from Earth.

6.4 Operational Flexibility

The flexibility of the Mars System in an operational context was found to be extremely important in a successful Mars System. Flexibility in ISRU tasking, crew tasks and location, transport vehicle tasking, and scheduling were found to be critical factors in the operational plans developed. Taking the Mars Landers as an example, their multi-use, reusable nature for Mars ascent, moon to moon transport, and moon to cycler transport, in combination with their large number and distributed locations meant that their use could be readily adapted to different operations and contingency scenarios. This adaptability was evident in the numerous emergency scenario plans that were possible. The flexibility grants the ability to carry out the operations that best fit the scenario, and in some cases enables an operation that might otherwise not be possible. This finding echoes the experiences reported in the Haughton Mars Project in the benefit of flexibility in their ATV (All Terrain Vehicle) operations during excursions [12].

6.5 Telerobotics

Perhaps the most enabling technology was advanced telerobotics. The ability for crew on Phobos to control surface robots, and for the doctor on Phobos to be able to perform tele-surgery on the Mars surface, drastically opened up the operational possibilities in the exercise. The technology enables a crew member to quickly and easily transition between tasks in completely different locations, giving the ability to effectively be in multiple locations at the same time. Examples in the exercise included the doctor being able to perform remote surgery, and for crew on the moons to assist in the remote operation of the ground robots and rovers for transporting the patient, while still having all the moon based crew ready to leave the Mars System, and to support the preparations to launch to the cycler. The major role telerobotics played in three of the four operational approaches produced by the Tiger Teams showed just how beneficial the technology is.

Telerobotics is an aspect that has been widely studied in Mars operations, in particular with various Mars Rovers [14, 28, 29]. Yet these robots are controlled from Earth. The use of telerobotics by those on Mars does have some initial studies in assisting expeditions, such as a quadrotor at the Mars Research Station [11] and in the Haughton Mars Project, where robots were used to follow-up scientific surveys by humans, controlled in a fashion that could translate to Mars based teleoperation [15]. The plans by the Tiger Teams identified that further work on advanced teleoperation capability throughout a Mars exploration campaign would be highly beneficial.

6.6 Collaboration

An important lesson learned was how crucial it is to have cooperative interaction between different entities. With the possibility for representatives from multiple nations, commercial entities, and colonists, there are a range of differing goals and priorities that may be competing at times, yet they all need to work cohesively to enable an effective, integrated, self-reliant Mars exploration campaign, especially with shared and distributed resources. The exercise identified the merit of well thought-out agreements between the different entities, detailing the obligations that each has to the other. This was highlighted in the emergency scenarios where the colonists' priority for long-term presence had to be balanced with their efforts to assist the government agencies, who would have an all-out approach to save and evacuate their personnel. These dynamics are one of the components that could be explored in greater depth in future exercises.

7 Second Iteration of the Mars Operational Simulation Exercise

The human spaceflight operations course was run again in the first half of 2016, and again included a Mars Operational Simulation Exercise as a capstone project. The experience and feedback from the first exercise were used to update how the second exercise was structured. In the first exercise, the class was given two large documents to outline the two main tasks of the exercise; defining the Design Reference Infrastructure and developing plans for the Emergency Scenario. The complexity and detail in these documents that gave the initial definition of the Mars Exploration Scenario, and the timing of the exercise towards the end of the semester, led to information overload for some students. As a result, the second exercise was organized with smaller assignments throughout the semester. This updated format of the exercise allowed the students more time to design and problem solve, and also made the exercise more closely resemble a professional work environment, where there are typically longer timespans for design.

With the extended project time, a preliminary phase was added to the project: the design of the overall architecture of the Mars Exploration Scenario by the students within broad constraining guidelines, rather than being predetermined by the course coordinators (i.e., the students designed the first diamond in Fig. 1). By starting the project on the initial design of the Mars Operational Scenario, students were able to gain even more insights into the links between technology design and operations.

The division of disciplines into expert groups was also modified from the first exercise, to consolidate areas of similar responsibility and better spread workloads, much like specialties have combined and morphed over time at NASA's Johnson Space Center Mission Control [25]. Table 2 presents the updated expert groups.

Table 2 Outline of the responsibilities for each expert group in the Tiger Team for the second iteration of the exercise

Group	Responsibilities
Mission management	Priorities, goals, design choices, rationale, mission plan.
Technical integration	Capabilities, system interactions, resources, utilization of assets, contingencies.
Exploration integration	Science, resources, surveying.
Surface ops	Suits, rovers, robots, external equipment, and their teleoperations.
ISRU	Energy, fuel, materials, gases, water.
Life support	Gases, water, waste, atmosphere, food.
Space transportation	Earth to/from Mars, Mars to/from moons, traffic model.
Infrastructure	Surface, moon, and orbital facilities.
Habitat	Living space, working space, greenhouse, facilities, internal equipment.
Human factors	Medicine, psychology, living conditions, hygiene, radiation, gravity, dust, safety.

Note that some responsibilities are shared

The students also met with their individual Tiger Teams from the start of the exercise, with limited discussion between each Tiger Team in the initial design phase, to encourage a greater diversity of solutions. Collaboration between the Tiger Teams then increased, with the expert groups forming together to develop a common Design Reference Infrastructure before splitting again into individual Tiger Teams to plan the emergency scenario operational responses.

Another key change was the context of the exploration scenario and the emergency event. These changes were intended to present a new challenge to test different ideas and stress different operational aspects in comparison to the first exercise. The key details of the new Mars Exploration Scenario are described below, followed by a summary of design highlights and a discussion of the additional insight that came out of the second iteration of the exercise.

7.1 Key Details of the New Mars Operational Simulation Scenario

The students were tasked to design the specific details for a Mars Exploration Scenario in the context of a mission establishing the first permanent Mars Colony. The design space was shaped by a number of key aspects:

- There is a 500 Metric Ton limit to what can be sent to Mars
- A cycler provides resupply connection to Earth.
- Teams need to decide where to place the bases on the planet; balancing scientific goals with long-term survival goals.
- Robotic driven construction can be used to establish the bases before humans arrive.

- There is an existing permanent base on Phobos.

The teams were tasked with developing the operational plans to establish a surface based colony. Their designs were then tested in the Emergency Scenario: a loss of all communications with Earth.

7.2 Exploration Scenario Highlights

The open nature of the exercise led to a number of interesting architectures and technologies being devised and tested by the teams.

The selection of surface base locations was diversified by many teams, with 3 to 4 different base locations to provide robustness and flexibility to the evolving colony, as well as having assets located near to different resources and areas of scientific interest. These bases would be developed by robotic assets before humans arrived, with assistance from "Mission Control Mars" based on the permanent Phobos base. The bases themselves took on a variety of interesting designs, employing temporary inflatable technologies for easy repair, taking inspiration from the Mars Base 10 design [30, 31], and integrating a combined hydroponics/fish-farm structure for long-term sustainable food sources.

Autonomy and adaptability of rovers and robots on the surface were widely utilized; in the building of the bases, in transport of people and supplies between base locations, and in the production of resources to support the colony. Autonomous factories, manned by robots and autonomously controlled rovers, were developed at one base to mine and process minerals, and then transport them to other bases. In addition to using rovers for transport between bases, a network of heavy lift *Hoppers* was developed: suborbital launch vehicles to make *hops* between base locations, with the capability of carrying habitat modules, resources, and colonists. To provide sustainable power to the bases one group made heavy use of a network of solar power generation satellites, with the capacity to beam energy to collector stations on the ground (similar to the JAXA Space Solar Power Systems concepts [32, 33]).

By integrating these somewhat futuristic concepts into an operational architecture, then testing them in an Earth-independent situation in the emergency scenario, the teams were able to test the viability and utility of the concepts for future Mars exploration and colonization operations.

7.3 Key Findings and Lessons Learned

As with the first simulation exercise, there were some key lessons learned from review of the solutions developed by the different teams. In many ways these reinforced the original findings, but also provided some extra insights.

7.3.1 Relation Between Operations and Technology Development

Through designing the complete Mars Exploration Scenario and iterating on the specifications, students were able to more deeply appreciate the technology design/operational requirements loop outlined in Fig. 4. Numerous adaptations were made to the initial design of the technology to provide additional capabilities based on operational needs. For instance it was identified that there was a strong need to have autonomous capability on the rovers to transport supplies between bases, because operationally it enabled crew to focus on more challenging tasks critical to colony survival at specific bases, while also allowing bases to be distributed to best access local resources.

7.3.2 Self-Reliant Operations

The architecture and technology for self-reliant Mars operations were specifically tested with the emergency scenario where Earth communications was lost. One critical component of the architecture that assisted the Earth-independent operations was the Phobos base, which acted as a "Mission Control Mars" to coordinate and oversee all operations in the Mars system in a similar fashion to the way mission control currently operates for the International Space Station. Yet in addition to the Phobos base, the teams identified that for extended operations (as with a colony) there was also a strong need for the crew on the surface to be able to plan and execute operations independently.

A salient outcome from the emergency scenario responses was that, for a majority of teams, the loss of communications with Earth actually had minimal impact on the Mars System. This is because in creating the Design Reference Infrastructure, the teams took on a mindset of "*thinking like a colonist*" and identified a clear need to design self-reliance from the outset. The fact that many of the teams had designed essentially Earth-independent systems before knowing about the emergency scenario gives strong support to the findings from the first exercise; that in the Mars context, self-reliant operations are a key consideration.

7.3.3 Self-Reliant Resources

A significant finding in the second exercise that wasn't as apparent in the first was that *resources are key*. Many of the challenges in designing the architecture and technology were related to how resources could be attained and transported to the appropriate locations: base locations were selected to have close access to specific areas for mining, autonomous factories were designed to have continuous processing of resources, autonomous rovers or Hoppers were used to transport materials between bases and have greater flexibility in where to store resources, and advanced sustainable food production technologies were utilized (hydroponics and fish farm concepts).

All of these solutions were to manage the production, distribution, and storage of *in-system* resources and to provide the infrastructure to adapt these activities to suit the current situation. With a limited mass of transport available from Earth, and a long-term colonist's mindset, the solutions developed provided exactly the capability called for from the first exercise, strengthening the argument of the need for self-reliant resource capability in a long duration Mars mission scenario.

7.3.4 Operational Flexibility

The solutions developed by the teams in the second exercise strongly supported the need for operational flexibility in a Mars context, but in subtly different ways to the first exercise. One driver for a high degree of flexibility was the limit to the amount of mass that could be sent to Mars for the colony. This limit led to a strong desire to maximize the utility of everything that was sent: for a technology to be flexible to be used for different tasks. A salient example is the extensive use of the rover, which through a range of attachments was able to carry out tasks including: construction, mining, maintenance, agriculture, supply transport and to serve as an emergency lifeboat. The technology gave the operational flexibility to use the rover for the most important task at the time, while also granting the ability to maximize the use of the asset.

It was also identified that the architecture can grant operational flexibility to a Mars operation, such as the choice of having multiple bases on the surface. The diversification of base locations means that operations in the long term could adapt to focus on the most suitable base to further develop the colony, rather than being stuck with one location that may evolve to be unsuitable.

7.3.5 Telerobotics and Automation

Going beyond telerobotics, it was automation that was identified as a critical technology to effectively operate in the Mars colonization context. The automation of ISRU and transportation of materials between bases gave similar benefits of teleoperation: to completely free the crew from a number of mundane tasks so they can focus on difficult, high skill tasks and managing the overall operations on Mars. Autonomous technology also allows the crew to simultaneously manage multiple assets to effectively be in many places at one time, rather than focusing on one asset, as in teleoperation. The importance placed by the teams on autonomous technologies suggests that further developments in this field would be highly valuable to, if not essential for, future Mars operations.

7.3.6 Collaboration vs Independence

In contrast to the first exercise, the second exercise did not include the element of multiple collaborating entities and instead focused on colonists. The mission was designed to have a staged transition from Earth led operations, to Earth led strategic goals and scientific directions. This structure enabled a deeper investigation into what the evolving mindset of a colonist might be, and the impact that may have on operations. The result was a strongly independent system from the outset that was robust to losing connection with Earth.

In the situation where colonists are gradually becoming independent from Earth, the social and psychological considerations are equally, if not more important than the technical considerations. One example is in the decision on whether to prepare the cycler for evacuation of all personnel to earth or to salvage parts from the cycler to support the colony and sever the last connection with Earth. The finding is that planning for and managing the relation with Earth would be important for any future long duration Mars missions.

8 Benefit of Operational Simulations for Driving Mission Design

A significant realization that resulted from the Mars Operational Simulation Exercises was how beneficial such exercises can be for exploring aspects of technical, integration, and mission architecture requirements that were not previously visible. Many of the lessons learned, discussed above, show examples of what an in-depth simulation exercise can uncover about changes required to the design of both the mission architecture and the systems that make it up. The creation of the PETRA device is an example where new technical requirements were unveiled. Other medical considerations also identified new integration requirements, including how space suits, rovers, habitation systems, and space transport systems interface with each other in the case that a medical patient requires transportation, as well as how the medical supplies should be distributed to support such a patient transportation operation.

The need for flexibility in operations is an example where the simulation gave insights on new requirements for the mission architecture. For longer term Mars missions, the architecture needs to have the capability to adapt to evolving scenarios so that changes, such as modifying a habitation module to be a greenhouse, can be supported by the mission architecture, instead of having to be hacked by the colony (as in the recent book and movie, *The Martian*). The simulation also revealed areas of technology-mission misalignment, where the choice of technical capabilities did not match the mission requirements in an operational context. These misalignments became clear in cases where the requirements of some technologies changed when they were considered in the context of how operations would be conducted. Some examples of this is the redesign of the Exploration and Utility Rover capabilities in the Design Reference Infrastructure, where their operational envelopes were expanded to support the nominal operations, and in the second exercise where autonomous capabilities were introduced to the rovers to aid efficient transportation of resources.

Through review of the Mars Operational Simulation Exercises, it became clear that in-depth operational simulations can be powerful tools to drive the mission and systems design for Mars exploration, and provide valuable input to shape current planning decisions.

9 Educational Benefit

The Mars Operational Simulation Exercise demonstrated the importance of communication and integration of several different technical systems together into one cohesive design with corresponding operational plans. It is designed to replicate a real-world application that combines engineering and operations, where the operational aspect is considered from the beginning of the design process rather than evolving only after the design is finalized (as if often the case). Some of the graduating students accepted jobs at the mission control center at NASA's Johnson Space Center, helping to give the new workforce a systems level, operational understanding. In addition, it gave all the students in the class an appreciation for current operational approaches. Since the assignment was somewhat futuristic, it pushed the limits on what is possible or may become possible for near-future state-of-the-art Mars operations.

10 Other Considerations for Future Studies

Due to the open-ended and broad nature of the project, there were many more unsolved situations than the ones the students actually worked through. Particularly during the emergency scenarios, there were inevitable shortcomings of the proposed plans.

One of the major factors is the psychological aspect of having colonists and transient explorers from Earth. In the very early days of a potential colonization effort, there may not be a separation between colonists and transient explorers. But as colonists increase their time on the surface, a unique identity is eventually going to develop. Assuming a limit in the amount of resources, transportation, and time available to the colonists, a set of priorities will define what gets taken care of first when a colonial mindset is taken, as was evident in the second exercise.

An off-nominal situation may pit the colonists and the transient explorers against each other. Cooperation is most important in this situation, but inevitably hard to achieve. Transient explorers, fearing the unknown, may want to secure as many resources as possible to ensure safe transportation to Earth. The colonists may want to do the same, because they have nowhere to go. The mindset of the transient explorers was reflected in the Tiger Team plans in the first exercise, all of which aimed to get all transient crew ready to launch to the cycler in time. The second exercise, in contrast, was exceedingly Earth independent. Future exercises could have a greater consideration of the impact of the interaction between these mindsets and the possible conflicts between them.

Feedback from the exercise identified that the emergency scenarios could be tailored to be of more benefit for researching Mars mission designs. A number of different scenarios could be given to the teams that stress different components of the Design Reference Infrastructure. By having situations that specifically stress different components, the exercise would more directly give an opportunity to test the effectiveness of the technologies and system architectures involved, and to uncover limitations that call for new developments in technology or operations. The goal would be to encourage outcomes such as the PETRA device, and the highlighted need for more thought on patient transport, that came from stressing the medical evacuation component in the emergency scenario.

11 Conclusion

The Mars Operational Simulation Exercise provided an open-ended task that enables a group of students to learn in depth about human spaceflight operations, while also investigating how a future Mars operation might be performed. Through designing components of a novel future Mars system, including a surface colony, moon bases, multiple entities, and flexible space transport systems, and then planning the operations for an emergency scenario, the students were able to gain a deep understanding of the operations mindset and unique insight into the links with technology design. Application of the students' creativity to future challenges led to a number of novel design ideas, such as the Patient Emergence Transport/Restraint Apparatus (PETRA), a non-conformal space suit for medical emergencies.

The exercise led to a number of findings on requirements and constraints for future Mars operations. It was found that there needs to be a paradigm shift in how human spaceflight operations are carried out, to change from an Earth-reliant, Earth-controlled way of operating to a Mars self-reliant and flexible operational structure. Another key finding was the importance of having a tight feedback loop between technology development and operations. To achieve this, it was identified that there needs to be more frequent input of operational expertise into the early stages of technological development. Of the technologies involved in the exercise, teleoperation and automation of robotics, rovers and space transport craft played a critical role in the operational plans developed, highlighting the importance of the capability in future Mars operations.

The operational simulation proved to be a powerful tool for testing and exploring new aspects of technical, integration, and mission architecture requirements. It was found that the lessons learned from these types of operational simulations can provide valuable input to drive current mission and systems design for Mars exploration.

Lessons learned from participants were used to improve the educational and research value of the Mars Operational Simulation Exercise, refining the approach to run in a second iteration. The exercise will be further developed to better impart knowledge of how human spaceflight operations are done to the new space exploration workforce. The development of the exercise is building towards providing a tool to bridge the knowledge gap between those with vast experience, and the young professionals, governments, companies, and private entities now entering into the space exploration enterprise.

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Appendix: Patient Emergency Transport and Restraint Apparatus (PETRA)

The PETRA device was designed by the students as part of the Design Reference Infrastructure. It is intended to be primarily used as an emergency method of transport for a patient who is incapable of wearing a space suit. It will also provide radiation protection should it be necessary to transport the patient in an unenclosed rover. An initial sketch of the device is shown in Fig. 5, and the specifications are as follows:

- Provides pressurized environment and breathable air.
- Pressure level is 4.7 psi of pure oxygen.
- Has ventilation system for air and to collect blood if blood starts to free float in a zero-g environment.
- Contains external ports for an IV bag, and an internal IV drip line (a pump will be used for zero-g).
- Straps will help restrain patient in zero-g and for launches.
- Transparent material allows patients to see out (for psychological purposes) and personnel to see in (for medical purposes).

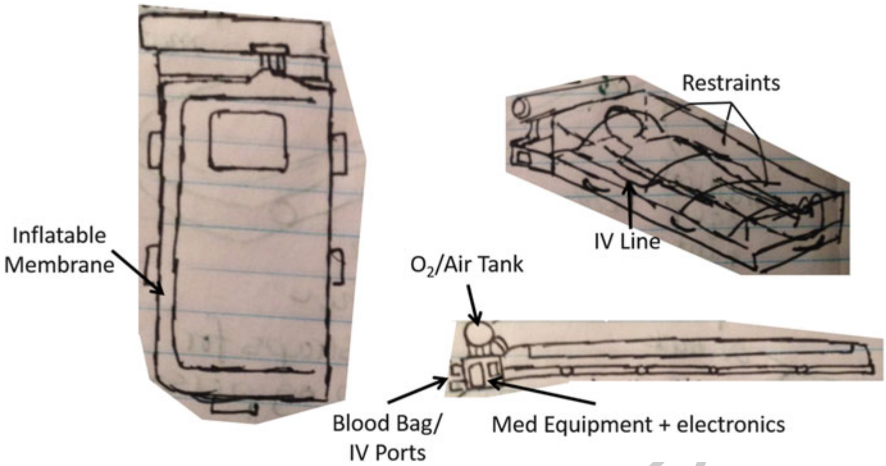

Fig. 5 Preliminary Sketches of the PETRA device

- Electrocardiogram (EKG) and other miscellaneous medical devices monitor health/vital signs of patient; these are displayed on removable palm device.
- Provides automatic chest compressions with a pneumatic device should the patient's heart stop beating. (Manual chest compressions would be difficult due to the pressurized bag).
- Expected to sustain patient for time to travel to Phobos medical facility, approx. 10+ hours.
- Carried by larger excursion rovers.

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AQ1. Please check if the edits made in the sentence “A Mars Operational Simulation Exercise was performed...” in the online abstract are fine.