THE IMPORTANCE OF ANALOG PLANETARY RESEARCH FOR SUCCESS AND SAFETY OF HUMAN AND ROBOTIC SPACE MISSIONS

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ABSTRACT

Testing of hardware and training of astronauts in space analog environments have been performed since the beginning of the space age. In the frame of planetary exploration, the so called Analog Planetary Research (APR) can be defined as the study of flight hardware, operational constraints, procedures and planning strategies on Earth in an environment that resembles (partly or fully) the conditions of the targeted planetary body. The findings and lessons learned from APR missions can be analyzed regarding mission concept, risks and constraints and the overall mission efficiency prior to launching a real space mission.

Here we want to demonstrate that APR is not only crucial for the scientific mission success or the reduction of mission costs, but also represents a key factor for the safety of robotic or crewed planetary surface exploration missions.

1. INTRODUCTION

Testing and training in space analog environments have been performed since the beginning of the space age in preparation of the crewed space missions. Analog Planetary Research (APR) is of importance to test the overall mission concept, identifying risks and ways for improvements at an early stage of development. Software and hardware bugs can be detected and corrected, operational constraints and procedures can be adapted with the outputs of simulations and the planning strategies can be refined under controlled conditions on Earth before the launch of the mission. This will not only validate the mission design, but is also much more cost-effective than testing hardware and operational concepts in real space environments.

1.1 Definition of Analog Planetary Research

Analog Planetary Research (APR) is the development and testing of strategies including scientific, technical, operational, social and medical aspects in simulated space or planetary environments for the application of crewed and robotic space exploration missions.

1.2 Description of Analog Planetary Research

The aims and goals of APR are to serve as a low-cost, low risk basis to prepare all kinds of thinkable parts and aspects for future planetary missions. APR uses the well-known conditions and properties of analog environments on Earth or in Earth orbit to provide stable test conditions as they are to be expected on the planetary body of choice. These environments can be of either artificial, such as laboratories or the International Space Station, or natural origin, such as deserts, mining areas or cave systems to resemble the geologic structures of the outer space destination [1].

Analog Planetary Research includes robotic analog missions where the activities and simulations are carried out without the presence of human beings. An example for a later application would be a sample return mission. Also APR is done for rovers such as the

NASA JPL Mars Science Laboratory, where a prototype is used to test certain mission aspects in analog environment.

APR does also include all human factor studies under simulated mission environments for both astronauts and mission control crew. It aims to replicate the effects of long-term exposure of non-Earth environments and all included difficulties on astronaut crews, their behavior and efficiency, as well as physiological effects. Here, analog environments do not necessarily need to resemble similar geologic structures as expected on the target bodies, but can be confined and/or isolated locations on Earth or in Earth orbit.

2. ANALOG STUDIES IN PAST AND PRESENT PRACTICE

APR has been conducted since the beginning of the space age. So far, APR could be distinguished into two different fields of study; astronaut training and hardware testing.

2.1 Astronaut Training

APR was used to physically and mentally prepare astronauts and cosmonauts to the challenges of the Vostok and the Apollo Programs, acquiring abilities for spaceflights, extravehicular activities, interaction with rovers and geophysics [2].

2.1.1 Spacecraft Flight Simulator Training

Spacecraft flight simulators have been used since the beginning of the crewed programs to train the abilities of the astronauts flying and operating the spacecraft, preparing them for every possible contingency. By extensively practicing the flight procedures, both in nominal and failure scenarios, astronauts were prepared for almost any situation that they could face, especially during mission critical operations [3]. This was to ensure success and safety of a mission and is still standard practice today.

One famous and crucial simulator program was the Lunar Landing Research Vehicle (LLRV) by NASA Flight Research Center. As safety measure, the LLRV had a zero altitude and zero airspeed, to allow the safe ejection of the pilot even on ground [4]. It was designed to simulate the behavior of the Lunar Module under the attraction of the reduced lunar gravity, and enable the development of piloting techniques to improve the Apollo Lunar Module design while training the Apollo astronauts to fly it [4]. The first crash of a LLRV occurred while Neil Armstrong was practicing his lunar descent, and thanks to the safety systems he was able to safely land far away on a parachute, while the LLRV crashed and burned [4].

As a follow-up on the success of the LLRV, NASA created the Lunar Lander Training Vehicle (LLTV), which allowed Armstrong to practice pretty accurately the real lunar landing of July, 1969 [5]. After the Apollo 11 landing, Armstrong recognized that without appropriate training and simulations with the LLRVs/LLTVs he couldn’t have achieved it successfully [5].

2.1.2 Geological Training for Lunar Missions

To develop and train the astronauts’ abilities to take geological samples of scientific value on the target planetary body, geological field trainings have been performed, such as for the Apollo missions [6]. With the assistance of the United States Geological Survey (USGS) and NASA, the Apollo astronauts conducted analog field geology in order to prepare for geological experiments on the Moon. Essentially, these astronauts were being trained in scientific observation and geology in various places such as Arizona and New Mexico [7]. Dr. Eugene Shoemaker and Dr. Farouk El Baz, along with NASAs first geologist in space Harrison Schmitt, went out into the Moon-like geography of the U.S. in what would be considered field geology missions consisting of lessons on surveying landscape and identifying geological objects [7]. Added to this was also the aerial plane surveying, preparing the Command Module Pilots for surveying the Moon’s large structures and geological make-up from above. For example, because of these geological field trainings, once the astronauts got to the Moon they then had a better idea as to what geological samples should be collected and which ones were not of interest for the scientific collection [8].

2.1.3 Traverse Planning Training

During the later Apollo missions, the exploration of the Lunar surface was limited to a maximum of 3 days using a Lunar rover. Although the exploration areas were restricted to be close to the landing site, only few kilometers apart, several hours of training and simulations for each of the Lunar Extra Vehicular Activities (EVAs) were performed, in order to ensure maximum scientific return [9]. The analog simulations were aiming to perform the mission goals of the respective Lunar mission and used pictures and topographic Lunar maps to locate the best routes and calculate the estimated travel times [9].

2.1.4 Underwater Training

Neutral buoyancy chambers were used during space training so that astronauts could experience a microgravity similar as during spacecraft operations. The fidelity of the neutral buoyancy simulations is compromised due to the fact that, as everything is suspended in a dense liquid medium, there is a small percentage of friction in every movement [10]. Currently neutral buoyancy is the best EVA training for astronauts, and it has been used to train and prepare astronauts and cosmonauts for the Gemini [11] and Salyut [12] EVAs.

An example for when this APR technique saved a space mission was Skylab. When the Skylab module was launched, one of its solar radiation protection panels was lost and the inside temperature increased to such high levels that it wasn't possible to occupy the station and the hardware went under high thermal stress. Thanks to the Neutral Buoyancy Space Simulator and the station mock-up, it was possible to identify through simulations on Earth how to repair the damage and return Skylab to operational status [13].

More recently the NASA Extreme Environment Mission Operations (NEEMO) has been used by astronauts, scientists and engineers to conduct APR underwater. This research facility allowed astronauts to train in an environment similar to the one in the space station module, using real crew procedures, mission rules, time lines and diet plans [14].

2.2 Hardware Tests

Just as every household machine needs to get tested before it is sold on the market, also every hardware part that goes to space needs to be tested. Since space missions bear great risks, the testing needs to be more intense and under conditions that simulate specific mission periods and environments.

2.2.1 Equipment for Astronauts

The space suit is the most important equipment for astronauts in space. A space suit can be compared with a small spacecraft, it holds all life support systems to protect the astronaut from the lethal space or planetary environments. It has to be 100% airtight, insulated against the cold of space, protect against radiation and particles, and – in case of surface exploration suits – it has to withstand abrasion from reactive or sharp sand and dust. Each mission had its own requirements for the space suits, so they evolve in parallel to the astronauts' activities [15]. For example, during the Apollo program, space suits came back to Earth both abraded and penetrated by Lunar dust after just 2 to 3 EVAs [16]. Therefore, all the operating services that a spacesuit is designed to provide, have to be thoroughly examined since they are immediately connected to the astronaut's safety.

This was done with APR missions not only by NASA who performed abrasion testing in 2009 to provide a preliminary evaluation of existing outer layer fabrics for their use on Planetary EVA suits [16], but also during the Mars 500 mission.

In 2011, during the simulation of Mars 500, two of the six crew members simulated a Mars landing and a complete EVA on the Martian surface. During the EVA, they simulated going through a sandstorm with drained batteries. This kind of simulation provides more details on how to improve and design the real missions [17].

On Mars, astronauts would eventually need to deal with the danger of possible sandstorms, and as proved for the Apollo astronauts, the spacesuits can suffer abrasion while doing EVAs [18].

2.2.2 Partial or Entire Spacecraft Testing

In order to ensure the functionality and success of a mission, as well as to guarantee the safety of the involved crew members in case of crewed missions, all hardware components must undergo extensive tests in order to be qualified as suitable for a space flight. At the beginning of each mission, the survivability requirements have to be established, based on the mission's characteristics, such as length, orbit, launch date, launch vehicle etc. After these have been identified, margins are applied (temperature ranges, vibration extremes, radiation tolerances, particle impact limits etc.) and a new set of conditions is generalized for design requirements [19].

The hardware components have to be therefore validated in the corresponding operational conditions and in the spacecraft's launch environment. Spaceflight hardware is being evaluated in the testing facilities of the large space agencies such as NASA, ESA, JAXA, RKO, ISRO as well as by private firms around the globe. By providing an analog simulation environment, the testing facilities are used to test and optimize hardware, and to qualify it for crewed spaceflight. The main environmental conditions simulated there include vibration, temperature, shock, acceleration, radiation, electromagnetic compatibility, particle impact, vacuum, humidity, atomic oxygen and pressure. Each of these can occur during different stages of the mission.

Already during the Apollo era the Apollo Spacecraft Certification Test Program was designed to ensure extensive testing of the flight hardware by providing ground and flight tests [20].

Since then the wide-ranging capabilities of modern testing facilities have been extensively used to test launch vehicle payload fairings, orbital hardware including International Space Station systems, the Rosetta spacecraft and planetary landing systems like the Mars Pathfinder and the Mars Exploration Rovers' airbag systems [21] [22] [23] [24] [25].

3. IMPROVING SPACE SAFETY VIA ANALOG PLANETARY RESEARCH

The history of spaceflight shows that the first missions did not comply with the modern safety standards as we consider them today, therefore, APR has been – and still is – an integral part of preparing and operating said missions. As the future of space exploration surpasses the Earth's orbit and the Moon, APR becomes an even more important field for studying hardware, strategies, procedures, and human factors for these missions. This is based on the need for higher efficiency and the ever increasing need for safety standards, policies and laws.

3.1 Hardware Testing

A crucial requirement for a safer space mission is reliable hardware. Therefore, spacecraft, space suits, rovers, tools, and other critical equipment must be reliable and allow options in the case of breakdown, either by redundancy, multiple use, and/or ease of repair [26].

In many hardware systems, most of the initial design errors can be removed through testing in analog environments either in a laboratory or during an APR mission, so the problems remaining after the development primarily stem from wear out and other types of component failure. All of these issues are compounded by the fact that the current widely used safety and reliability engineering analysis techniques, such as Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA), were designed to identify component failure accidents [27]. Starting with high-level safety constraints at the beginning of spacecraft design, a new form of hazard analysis technique based on the System Theoretic Accident Model and Processes (STAMP) can be used to refine the safety constraints and spacecraft design decisions in parallel in a process called safety-driven design [28]. Here, APR serves to find the weaknesses of the hardware. This knowledge is then used for the safety-driven design, improving the hardware towards being more reliable, therefore adding up to the overall safety of the mission.

3.2 Planning Strategy Testing

One of the crucial things to consider when sending missions to outer space bodies, such as Moon or Mars or even further, are the planning strategies. One critical issue to deal with will be the delay in communications caused by large distances between the planetary bodies [29]. For the Moon this delay will only be in the range of 1.5 seconds, therefore still allowing real-time operations directed by Mission Control on Earth [29], but for further places when a more significant delay occurs in the range of minutes e.g. for Mars with 2 to 21 minutes one-way or in the range of even hours for missions to the outer Solar system, real-time operations will be impossible. Hettrich et al. [30] therefore suggest planning and scheduling strategies that require a certain autonomy and training of the astronauts and the ability to take quick decisions on their own without waiting for Earth to answer. The proposed 3-days-in-advance and 1-day-in-advance strategies not only aim for the highest possible scientific efficiency that way that the mission and EVA time is used efficiently regarding time and resources, but also aims to provide safe contingency plans, to continue operations without exceeding viable resources. Furthermore these planning strategies are set up as conservative as possible with margins built in to ensure the highest amount of safety for crew and equipment [29].

These planning strategies have been applied for past Mars analog missions, such as Mars2013 [31], and are still under development to implement the lessons learned and to improve efficiency and safety of future human space missions.

3.3 Procedure Testing

Simple activities under Earth surface conditions become challenging in space. Operating tools and equipment from within a space suit is more challenging than performing the same tasks without [29]. Additionally a different environment such as reduced or non-existent gravity, extreme temperatures, or extreme pressures might also increase the difficulties of EVA operations and therefore also the risks in accidents. APR therefore not only aims in testing and improving the usability of tools and hardware, but also to train the astronauts in their usage and to adapt the procedures where necessary. These procedures need to provide both high efficiency for performing the planned tasks and meet the highest safety standards. At the same time, future missions will require a higher autonomy of astronauts to make changes during EVAs if necessary and take decisions on their own. This needs to also be considered when setting up and improving every experimental and operational procedure, if the mission aims for maximum safety.

3.4 Human Factors

Studying human factors is crucial for future space missions that involve astronauts. Since humans evolved to survive in Earth's environments, unprotected exposure to non-terrestrial conditions is lethal. Although living on board of a spacecraft or inside the International Space Station becomes more and more convenient it still causes stress responses on cellular, physiological and psychological levels. The human body experiences cellular and physiological adaptations and factors like living in permanent danger, restricted space, no privacy, interactions with other crew members, boredom or homesickness thus causing psychological stress responses.

Fast physiological transformations occur in cardiovascular, urinary and nervous systems. In the cardiovascular system microgravity results in the loss of the blood pressure gradient between cerebral and peripheral circulations in the upright posture and shifts the mean arterial pressure from 70mmHg on Earth to 100mmHg [32]. Body fluid shifts (from the lower extremities to the thorax) cause difficulties in breathing and congestion of mucous membranes in the sinuses and nose. Hence, astronauts suffer from chronic rhinitis and decreased perception of smell and taste. Kidneys reduce the rate of blood filtration, the volume of blood vessels decreases 20% causing a lower number of erythrocytes. The nerve system adjusts to microgravity conditions in about three days (personal communications with Roberta Bondar, first neurologist in space). During this time gravity receptors in vestibular, somatosensory and visual systems stop to distinguish up-down directions causing several orientation illusions, nausea and malaise. Additionally dysregulated circadian clock induces headaches and sleep disorders [33]. Fast physiological responses cause intensive psychosomatic discomfort but the stress shock is relatively short. Far more complex in analysis and important for long-term missions are long-term physiological adaptations to living in non-terrestrial environments. They concern morphological and functional changes of the body by reduction of number of cells in the blood and immune system [34], in muscles [35], in bones and in organs. Studies on Earth help to solve physiological problems like osteoporosis and muscle atrophy during long-termed spaceflight missions [35][36]. Yet other long-term physiological effects need to still be studied in more detail.

Psychological aspects during long duration spaceflight missions also wait to be dissected and analyzed. Regarding complexity of human behaviors, APR missions are particularly important in this issue. The crucial advantages of such approach are: (1) increased number of tested humans, (2) elimination of undefined stressors occurring in space (like electronic noise, electromagnetic pollution, artificial light, irradiation, hormonal problems etc.), (3) higher control over the experiment and (4) comparable control samples.

Understanding the influence of environmental and physiological stress factors on crew members is crucial to eliminate or decrease negative stimuli during the mission, to predict and help in difficult psychological

Table 1. Stress conditions causing stress responses of astronauts during spaceflight missions.

Stress factor	**Stress category**	**Stress response**	**Effects**
Microgravity	Immediate physiological changes	Loss of the blood pressure gradient	Nausea, malaise
	Immediate and long-term physiological changes	Body fluid shifts	Chronic rhinitis, difficulties in breathing and congestion, decreased perception of smell and taste
		Decreased rate of blood filtration in kidneys	Decreased number of erythrocytes
	Long-term physiological changes	Reduction of number of cells in the blood, immune system, bones, muscles and organs	Anemia, decreased immune-resistance, osteoporosis, muscle atrophy
Lack of 24 hour day-night cycles	Long-term physiological changes	Desynchronization of the biological clock, decreased levels of serotonin	Headaches, sleep disorders, depression, behavioral changes
Permanent danger, Unexpected situations	Long-term and immediate psychological responses	Increased levels of adrenaline and cortisol, not described	Aggression, neurohormonal disorders, behavioral changes
Restricted space, No privacy	Long-term and immediate psychological responses	Increased levels of adrenaline and cortisol, not described	Aggression, depression, neurohormonal disorders, behavioral changes
Interactions with a crew members	Long-term and immediate psychological responses	Not described	Aggression, depression, neurohormonal disorders, behavioral changes
Boredom, Homesickness	Long-term and immediate psychological responses	Not described	Depression, behavioral changes

states of astronauts (ex. aggression and depression), and finally to analyze astronauts' behavior and overall success of the mission. The main stress factors with stress responses and effects on humans are summarized in Tab. 1. Medical and psychological treatments to reduce the effects of stress caused by living in a non-terrestrial environments still need to be tested and applied.

3.5 Ethical and Political Perspective

Ethically speaking it is considered rational behavior to test hardware before its use. This is especially important when sending technology and humans into the harsh environment of space. Analog Planetary Research takes this quality assurance – safety – further. Considering how costly space exploration is to operate for a space-faring nation or agency (ex. NASA, ESA, JAXA, RKA, etc), or to even produce hardware, it is in the best interest of the space-faring nations to pursue simulated tests not only for cost effective benefits, but also for the element of safety. As space-faring nations make decisions that try to secure the safety of their citizens, they too must make decisions that should try to secure the safety of their astronauts and the space environment. Ethically, space-faring nations have a duty to their crews, investors and the environment to try to create the most safe situations for space exploration. Accidents and problematic events can still occur, however, APR can help to try to alleviate these issues from arising.

At this time, most standards of safety for the space industry are conducted at the national level. The lack of international standards is what makes safety "different" from one program to another, from one agency to another or one country to another and this is also a slight ethical dilemma. It would be in the best interest of all space-faring nations if international standards of space safety could be created and upheld. That is why the IAASS [37] was created and it is the only association dedicated to space safety. One of their goals is to propose standards to be considered by the space agencies, and so far, they are working on the standardization for various topics including the general laws and regulations of space safety.

4. CONCLUSION

Since the beginning of space exploration, the presence of human beings in space has been increasing until the point where we currently have a space station with a permanent crew of six astronauts aboard, and solid plans for future crewed Mars missions, e.g. the NASA Design Reference Architecture [38]. Before embarking on another human space exploration endeavor, we need to have a clear understanding of the risks and effects on human psychology and physiology as the risks of long-duration space missions are high and many. Analog Planetary Research is the best tool to minimize risks as much as possible and increase safety with high fidelity simulations.

APR is essential for the mission efficiency, mission success, readiness, reliability, design of habitats, crew operations, trainings and hardware as well as playing an important role in understanding the effects of long term space environment on humans both physically and psychologically. It ensures safety of hardware, operators, crews and missions.

Currently, we have not yet solved the radiation issue in order to send humans to Mars and we still need to work in a safer way to take a future crew on Mars back to Earth. Current APR addresses and covers very well the robotic part, the habitats, and to a certain extent, the isolation effect as well. However more in-depth studies will be necessary especially on the effects of long duration spaceflight on humans, the environment (for growing food), long distance and delayed communications, and the life-time and reliability of life support systems. In the case of having humans living for long durations on other celestial bodies, we should have safer procedures to avoid accidents derived from natural and artificial causes.

History has shown that the final performance during a real space mission is directly linked to the training and preparation made prior to it, therefore conducting and intensifying APR will greatly increase space safety.

5. OUTLOOK

In the future, it will be necessary to see space safety standards aligned both vertically (international and national down to small non-governmental organizations) and horizontally (between space-faring nations). For space safety is not just for one mission but for the benefit of all space-faring nations and all missions. This is very much aligned with the Outer Space Treaty, Article I, which calls for the notion that

> "The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind." [39]

Space safety and "for the benefit of all countries" should work in a harmonious partnership. This partnership can only be strengthened by transparency building measures to promote and assist in safety measures between states. Lessons learned in a transparent capacity would allow for further problems and accidents to potentially be diminished. Hand-in-hand with this transparency between space-faring nations is the notion of transparency between APR projects within organizations. The more we know before we go to space, deep space, or Mars (as a planetary example) and the more transparent we are with our findings, the stronger our space safety measures and capabilities will be worldwide.

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