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# Space vs. chemical domains: virtual and real simulation to increase safety in extreme contexts

Irene Lia Schlacht[a,*], Salman Nazir[b], Davide Manca[c]

[a]Extreme-Design Research Group, Design Department, Politecnico di Milano, Via Durando 38-a, 20100 Milano, Italy
[b]Human Factors Research Group, Department of Maritime Technology and Innovation, Buskerud and Vestfold University College, Postboks 4, 3199 Borre, Norway
[c] PSE-Lab, CMIC Department "Giulio Natta", Politecnico di Milano – Piazza Leonardo da Vinci 32, 20133 Milano, Italy

**Abstract**

Each year, millions of people are injured in the work place. Preventing injuries and thus protecting the health of people working in extremely dangerous contexts is of paramount importance. Outer Space is the environment that presents the most life-threatening challenges for human life: Radiation, absence of pressure and oxygen, difference of gravity, confinement are some of the conditions that strongly affect safety. Knowing how these elements affect humans and how to deal with them is very important for the success of Space missions as well as for facing other extreme challenges on Earth. For these reasons, the simulation of Space missions can be used to learn how to increase safety and improve user-system interaction in other extreme contexts such as chemical industry on Earth. Applying a cross-comparison between human factors and safety procedures in those contexts, this paper aims to realize possible safety procedures implementations in all life-threatening and extreme contexts such as disasters. The case studies presented are: real simulation of a Space mission, a virtual simulation of a Mars mission, simulation of an accident scenario in a chemical plant. With these case studies we aim to improve safety in the relevant domains by analyzing the results and implementing mutually the findings. A new methodology of knowledge transfer among different cases of extreme and life-threatening environments aimed at obtaining an innovative solution is likely to emerge from this paper.


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*Keywords:* Human factors; Safety; Extreme environment; Simulation; 3D; Virtual simulation

* Corresponding author. Tel.: +39 320 3168723.
*Email address:* irene.schlacht@mail.polimi.it


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**Nomenclature**

| | |
|---|---|
| CROP | Control room operators |
| EVA | Extra Vehicular Activity |
| FOP | Field operators |
| IVA | Intra Vehicular Activity |
| MDRS | Mars Desert Research Station |
| Space | Extra-terrestrial space |
| Space analog | Environment that has extreme conditions similar to the extra-terrestrial environment (e.g., research laboratory in Antarctica, desert, MDRS, etc.) |

## 1. Introduction: Safety and simulation

"Safety first" – it is well known that safety is the most important factor that is always given top priority in every project, especially in recent decades. When we need to address particularly dangerous contexts, safety requirements need even more attention. In order to optimize safety requirements, testing them during a complete system simulation is considered the most suitable approach. In particular, the cases we are presenting here for studying safety include system simulations of two special contexts that are relevant as being particularly dangerous: the case of Space missions and the case of chemical industry. The Space scenario was selected as being characterized by the most life-threatening challenges. Indeed, this context includes the most extreme and adverse factors for human life, such as radiation, absence of pressure and oxygen, physical adaptation to microgravity, social isolation, and spatial confinement [1,2]. A very specific and small range of users also characterizes this context: astronauts. In case of chemical industry, life-threatening challenges are not rare either, but they affect a wide range of users in comparison to Space missions. For instance, the literature on accidents such as Chernobyl, Bhopal, and Deep Water Horizon highlights the catastrophic consequences that those accidents brought with them.

This paper compares three simulation scenarios to increase safety in particularly life-threatening environments:

- Space analog simulation: the case of the Mars Desert Research Station (MDRS) in Utah, where a crew of six members took part in real simulation of a Space mission, testing safety, user interfaces, procedures.
- Space virtual simulation: the Mars Society mission, where a crew of four members took part in a virtual simulation of a Mars mission, testing safety, user interfaces, procedures, as well as reduced gravity.
- Chemical plant accident virtual simulation: the experiment at the Politecnico di Milano, where a group of twenty-four people tested two methodologies to improve performance and safety during an accident.

## 2. Simulation in a Space-analog environment: the MDRS

At the Mars Desert Research Station in the Roswell desert in Utah (Fig.1a), every year a rotating crew of six members simulates a mission of the Moon-Mars scenario, testing safety as well as factors such as human interaction and procedures (Fig.1b) [3,4,5,6,7]. A factor being specifically studied on human interaction is habitability, which is defined as "the usability of the environment" [8]. During selected missions, safety and living conditions have been investigated with the help of a "habitability debriefing", a new instrument of analysis [9,10]. During the missions,

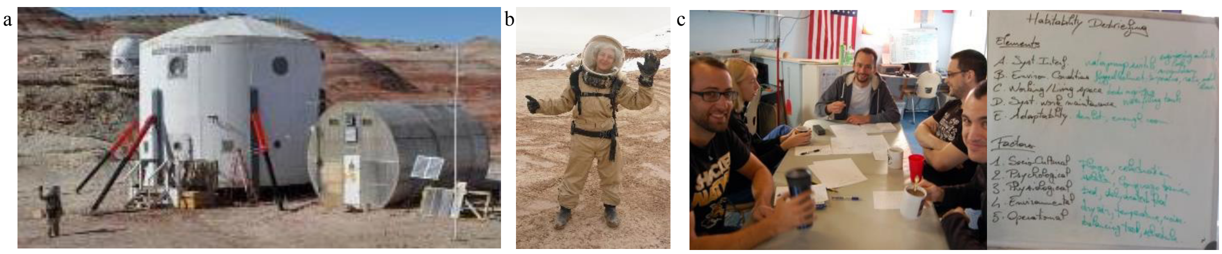


Fig. 1. (a) MDRS; (b) EVA at the MDRS; (c) The crew performing the debriefing at the MDRS (photo © Mangeot 2014).

the debriefing was performed by all crew members together (Fig.1c). In order to increase the overall system safety and performance, the methodological aim was to let the group of users collectively discuss each possible problem and problem solution covering all the different human factors aspects. To cover all the human factors aspects, the discussion was guided in particular to operational, psychological, socio-cultural, environmental, and physiological factors. A holistic approach was used (i.e. an approach that covers all the aspects together as a whole, holos=all) [1,11]. This approach is quite different from the traditional approach, where each crew member is questioned individually and each factor is studied separately. For example, operational problems are traditionally investigated after the mission, with each user facing a team of experts, while with the habitability debriefing, the investigation of operational factors is carried out jointly by all crew members during the mission; operational problems are investigated in relation to and in parallel with psychological, socio-cultural, environmental, and physiological factors. Research performed at the MDRS is optimal for testing and optimizing mission safety, in particular considering the specific desert surrounding the station, which is a perfect analog of the Mars environment such as the natural reserve of the San Rafael Swell, a red-colored desert in Utah [12]. The organization of a simulation campaign is a complex procedure related to several factors and has to take into account specific rules. The analyzed mission was characterized by the following structure:

- Crew composition: usually mixed-gender (men and women)
- Crew selection: based on motivation and profiles
- Crew structures and hierarchies: the crew has a sound structure with fixed tasks. There are six main roles that need to be covered: Commander, Executive Officer, Crew Engineer, Health and Safety Officer, journalist, crew scientists (e.g., human factors researcher, geologist, biologist)
- Extra roles outside the crew are: campaign director, mission support, project scientists
- Training: around six months before the mission, crew meetings are organized via remote conference calls, in an attempt to accommodate the different goals and instruct the members to follow the strict safety rules and ethical restrictions of the station
- Mission schedule: during the two weeks of the mission, each crewmember carries out planned tasks, including scientific research, social activities, and station maintenance in accordance with the simulation requirements.

The isolation in a Space-analog environment such as the Utah desert, the strict procedures, and the crew hierarchy are some of the constraints that make this mission simulation an optimal scenario for verifying, testing, and increasing safety in extreme contexts. The methodology used to achieve a deep understanding of safety and performance problems concern the application of the habitability debriefing. The debriefing is performed the day before the end of the mission: In complete privacy, the crew is guided for 90 min by a strict procedure regarding multidisciplinary analysis and collective discussion of the overall mission. The main mission problems and possible solutions are discussed from the perspectives of safety, performance, and comfort by the crew alone. Regarding the results during the 2014 MDRS mission, six crew members consisting of male and female members with international identity were able to spend two weeks simulating life on Mars. The Human Factors discipline was integrated and evaluated during the simulation to find problems and solutions as well as propose implementation recommendations to increase the overall system performance.

1. Find problems and solutions: Socio-cultural, psychological, operational, environmental, and physiological aspects were investigated. Operational aspects emerged as the most frequently discussed problem; in particular, “communication” was the most frequently recurring topic associated with this problem (Table 1). The main problems and solutions were referred to increase the quality of:

    - Communication associated with the operational field
    - Equipment and structure associated with operational, psychological, and environmental areas

2. Propose implementation recommendations to increase the overall system performance: The crew proposed improving the design of the equipment (EVA equipment, toilet, station structure) and the communication (manual, guideline).

In conclusion, in particular extreme and isolated contexts, safety, performance, and comfort are elements that are strongly correlated. A very uncomfortable scenario in a Mars mission will influence the performance and, as a consequence, also impact the safety of the crew.

Table 1. Problems and solutions voted as most important and discussed by the crew during the MDRS mission (November 2014).

| Problem (P) | Problem | Solution | Field | Crew vote |
|---|---|---|---|---|
| P1: EVA equipment | Spacesuit fatigue, $CO_2$ build-up, poor air circulation, helmet fogging | Better design of air distribution<br>Sensors; water cooling system; anti-fog system | Psychological - EVA<br>Operational - EVA | 6/6<br>6/6 |
| P2: Toilet smell | Toilet smell | Increase ventilation; difficulty to clean the room (new design); closable trash; more frequent flushing (recycling water) | Psychological - IVA<br>Environmental - IVA | 6/6<br>5/6 |
| P3: Mission control communication | Lack of transparency and knowledge transfer | Manual, guideline improvement | Operational - IVA | 6/6 |
| P4: Station incomplete structure | Fake tunnel "breaking " simulation | Finish the tunnel and roof over the porch of the engineering airlock | Operational - IVA | 6/6 |
| P5: Communication on maintenance | Limited flexibility to make easy fixes, unclear what maintenance requires mission approval | Manual and guidelines improvement | Operational - IVA | 6/6 |

## 3. Simulation in virtual reality for Space missions: the Mars Society mission

Another scenario used to test procedures, equipment, as well as the overall mission safety was a simulation in virtual reality. In order to effectively test such a particular extreme environment, equipment needs to be developed to properly simulate the effect of specific factors such as the different gravity or the absence of oxygen during EVA. In this case, a simulation realized by the Mars Society is presented; specifically, the December 2014 mission carried out in Italy is used as a case study. The virtual simulation is composed of a complex infrastructure and team structure. The infrastructure is mainly based on four virtual stations characterized by the following key elements:

- Immersive virtual simulations on the Blender Game Engine (BGE) with 3D virtual reality headset (Oculus Rift)
- Full body tracking via a Kinect device
- Main component: four Motivity omnidirectional treadmill (called also station), linked via dedicated multiplayer support able to synchronize the events happening at the four simulation nodes.
- The Mumble voice chat software is used to ensure the overall voice communication infrastructure.

The people involved are assigned specific roles and tasks:

- The team is composed of: Mission Director, Science Officer, Technical Support Team, Outreach Communication Team (Earth based), and the crew that is performing the mission simulation (Mars based).
- The crew is composed of: Commander, Executive Officer, Crew Engineer, Health and Safety Officer

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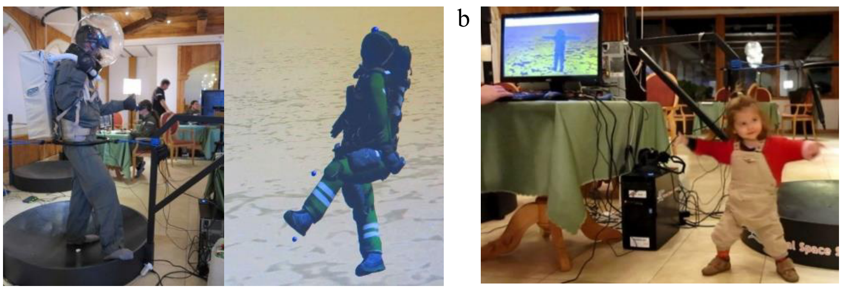

Fig. 2. (a) Simulation on the Motivity virtual dimension station; (b) Visualization of the avatar on Mars; (c) Tracking child (photo © Schlacht 2014).

The team supports the crew regarding the performance of the following experiments: habitat design and station design review, communication test, health monitoring, simulation of telemedical support session, ATV vehicle review, EVA missions review, simulating Martian reduced gravity (Motivity omnidirectional treadmill), test of the analog space suit during the simulation, human performance in teleoperation, human factors analysis. The Mission Director is responsible for the overall mission operation, coordinating all necessary actions with the team. As far as we know, this virtual mission simulation was carried out for the first time with this configuration of equipment and experiments, developed specifically to achieve the most reliable conditions to simulate the main factors related to a Mars mission, from the difference in gravity to the difficulties in performing activities during EVA.

The methodology applied was the one described above for the MDRS using the habitability debriefing as an instrument of investigation, but it was adapted to analyze both the VR context (in both VR IVA and VR EVA conditions) and the overall mission from the VR simulation (Real). The crew debriefing allowed to learn from the crew how to improve the overall safety, performance, and comfort of the mission. Regarding the results during the Mars Society mission, four crew members consisting of members with international and mixed-gender identity were tracked in virtual reality and could interact through an avatar with different field tasks on the Martian surface. The Human Factors discipline was integrated and evaluated during the simulation to find problems and solutions as well as propose implementation recommendations to increase the overall system performance, as here described.

1. Find problems and solutions: Socio-cultural, psychological, operational, environmental, and physiological aspects were investigated. Operational aspects emerged as the most frequently discussed problem; in particular, "Motivity" was the most frequently recurring word associated with "uncomfortable". The main problems and solutions referred to increasing the quality of:

   - the system (test the system before the mission and increase the number of team members);
   - the tasks (increase the margin among tasks to avoid overload, ensure free time for the crew, in particular after dinner, and physical training)
   - the equipment (increase the comfort of both Motivity (Fig.2a) and quality of the navigation)

2. Propose implementation recommendations to increase the overall system performance**:** it was proposed to implement the system for different user typologies and anthropometrics (Fig.2c tracking user with the anthropometrics of a 2-year old child, using an extremely small human size to verify the performance of the system in abnormal situations), to implement the interior design and interface with movement data from tests on Martian gravity (Fig.2b), and finally to provide the possibility of interaction among crew members in VR. Social aspects did not emerge as a problem; however, late work and short periods of free time led to dissatisfaction, which was not approached by the team. In conclusion, it was verified again (as in the MDRS mission) that safety is strictly correlated with performance and comfort.

## 4. Virtual simulation of an accident scenario in a chemical plant

During an accident scenario in a chemical plant, the training methods of industrial operators were evaluated as one of the key factors that increase the correct response of operators and decrease the consequences of possible accidents. In order to evaluate the impact of different training methods on the performance of industrial operators

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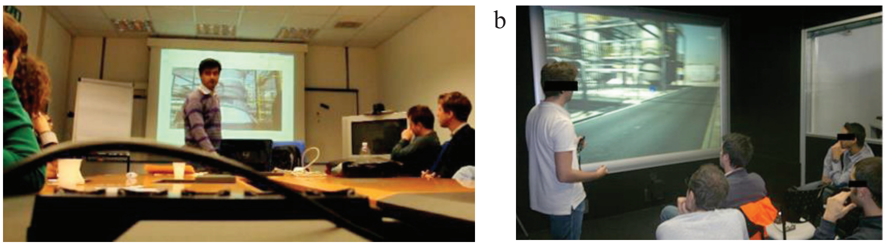

Fig. 3. (a): Training with slide presentation; (b) Training in 3D immersive environment (photo © Nazir 2015).

during an accident scenario, a detailed study was designed and implemented at Politecnico di Milano. A common section of a refinery (chemical/process industry) was simulated using UNISIM (a dynamic process simulator from Honeywell). The process simulator was later simulated in a 3D immersive environment. A detailed plan of the experiment was first devised, including process simulation, hardware used, participant details, dependent and independent variables, etc. [13]. In this paper, the aim of discussing the experiment is mainly to compare it with the other two case studies described above. The scenario started with the collision of an excavator with a pipe containing hydrocarbons (a flammable liquid). The collision resulted in the leakage of liquid butane, which formed a pool that got ignited. In this scenario, various actions were required by the operators to overcome the accident situation and minimize the damage. The occurrence of such an accident is not a rare event in the process industry. If we assume a process industry plant as a complex socio-technical system, then it is easy to identify that the main subsystems are:

- Control room: replicates the real plant and the Distributed Control System
- Field: where real processes/reactions/production take place
- Industrial operators (control room operators (CROP) and field operators (FOP))

The scenario can be represented in the form of a sequence of actions with respect to time. As can be seen in Table 2, continuous communication is necessary to mitigate the impact of abnormality, which is triggered by the collision. Two groups of operators (n = 12 each) participated in the experiment. The first was trained using a slide presentation (see Fig.3a) and the second was trained with the help of a 3D immersive environment (see Fig.3b). The experiment had been previously designed in detail [13].

Table 2. Tasks description of a specific case of accident scenario in chemical industry.

| Tasks Sequence | Events Description |
|---|---|
| t1 | The FOP is at the butane/propane separation section of the refinery |
| t2 | The excavator hits a pipe and breaks a flange, which results in a leakage |
| t3 | The FOP reports the leakage to CROP |
| t4 | The CROP suggests the FOP to close a valve (valve I) |
| t5 | The emitted liquid flowrate forms a pool on the ground |
| t6 | The pool gets ignited, and this results in a pool fire |
| t7 | The FOP communicates the fire ignition to the CROP |
| t8 | The liquid emission is cut off but the liquid level in the reboiler starts increasing and reaches the high alarm level |
| t9 | The CROP asks the FOP to open a manually operated valve (valve II) to decrease the reboiler level |
| t10 | The reboiler level decreases back to the correct value |

After the training session, each participant was placed in front of the immersive simulator, where s/he faced the accident scenario as explained in Table 2. The training was conducted as a group, whereas the performance assessment was done individually. The participant acted as FOP while an expert performed the actions of CROP in order to keep the experiment consistent. A specific methodology allowed us to measure the performance in a systematic and consistent way [13]. For instance, identification of the valve in the case of an accident situation is of vital importance and can have a direct impact on the consequences of an accident or abnormal situation. For each operator, the correct (or incorrect) identification of the valve was recorded. Moreover, the response time in evaluating the valve and the total time of the experiment were also calculated. When analyzing the data from the experiment regarding well-defined performance indicators, it was found that participants who had been trained in an immersive environment outperformed the participants trained with a slide presentation; in particular, the former were able to handle the accident situation with minimum consequences to the plant and the operator. Based on these results, it was concluded that simulations of accidents in immersive environments during the training phase could result in improved and better performance of the operators in the plant during an abnormal situation, thus leading to an increase in safety.

## 5. Comparison of the three case studies

The domains considered in this work are Space and process industries. Both domains have some similarities, for instance the increase in complexity in terms of technical details as well as operational processes. The interconnections among the agents involved in these complex systems add to the risk-proneness. The operators, respectively the astronauts, who are the social components of these socio-technical systems, play a vital role in overall safety. Thus, the right operator or astronaut must be selected for this job, and training is necessary to provide the necessary skills to ensure smooth as well as safe operation in these contexts.

Specifically within the chemical industry context, it has been verified that training in an immersive environment allows increasing the equipment and operator safety during an accident scenario. In the context of Space, it has been verified both with virtual reality and with analog environment simulations that the safety is strictly correlated to the performance and comfort involving the optimization of human factors. This is because in the Space context, the user is involved in an extremely dangerous context during a period of several months, which includes not only working time but also living time [1,14]. This is why it is important to have an environment that can simulate all the factors that may impact safety, performance, and comfort. With the holistic approach, socio-cultural, psychological, operational, environmental, and physiological aspects are investigated together by all the crew members to show the interconnections related to safety, performance, and comfort. Another relevant factor of comparison is that in the Space context, the user cannot be replaced (as during a mission in Space, an astronaut cannot easily return to Earth and be replaced), for example in case of emerging stress. In the context of the chemical industry, the interaction among those factors is also very important, but with lower individual risks, as the time involved is only the working hours and the user can be replaced, if necessary. At the same time, the overall risk involved in running chemical plants may be much higher than that related to Space missions as the consequences on the surrounding population and environment of the production site make the difference between Space and Earth facilities.

The abovementioned factors need to be predicted and recognized in time in the chemical industry, which is why it is rather important to adopt a holistic approach, in particular during measures of prevention such as operator training. Finally, in order to prevent accidents in particularly dangerous environments, simulation and training in scenarios that are as similar as possible to the real condition can be accomplished in an analog or 3D immersive virtual environment.

## 6. Conclusions and further developments

In conclusion, it can be stated that the MDRS Space-analog simulation mission, the Mars Society virtual simulation mission, and the chemical industry accident training were all performed successfully. With the application of human factors and the use of a holistic approach, the habitability debriefing motivated the group of users to develop problem solutions together to increase safety, performance, and comfort during the Space mission simulations. Within the chemical industry context, it has been verified that training in an immersive environment allows to increase the equipment and operator safety during an accident scenario. In all contexts the users played a vital role in overall safety. Indeed, in these three contexts, the most important variable was the user or better, the "unpredictable human". This is why whenever there is any human interaction, it is even more important to test the elements not only in isolation, but also holistically as an overall system simulation, to predict the possible user interactions. Especially during an extended system simulation, the variables are mutually interacting, and this leads to much more reliable results for the increase of user and system safety. In other words, as Aristotle said, "The whole is greater than the sum of its parts".

Further development could see the integration of Human Factors and the holistic approach starting from an early phase of the project development. Also, further investigation regarding the application of the immersive training system in the Space context and the habitability debriefing performed with groups of users in the chemical industry context might bring crossover benefits, increasing safety in both extreme contexts.

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## Authors

*Irene Lia Schlacht* from the extreme-design.eu group (Design department, Politecnico di Milano) is a Human Factors specialist for extreme contexts. She is the developer of the habitability debriefing carried out at the MDRS and during the Mars Society mission. (Schlacht http://www.extreme-design.eu/group.html)

*Salman Nazir and Davide Manca* from the PSE Lab (CMIC department, Politecnico di Milano) are experts in modeling and simulation applied to human factors and industry safety. They were responsible for the virtual reality simulation of an accident scenario in a chemical plant. (Nazir: http://pselab.chem.polimi.it/persona/salman-nazir/ Manca: http://pselab.chem.polimi.it/persona/davide-manca/).

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