Survey of Past, Present and Planned Human Space Mission Simulators

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ABSTRACT

In light of the renewed international interest in lunar exploration, including plans for setting up a permanent human outpost on the Moon, the need for next generation earth-based human space mission simulators has become inevitable and urgent. These simulators have been shown to be of great value for medical, physiological, psychological, biological and exobiological research, and for subsystem test and development, particularly closed-loop life support systems.

The paper presents a summary of a survey of past, present and future human space mission simulators. In 2006, the Vienna based company Liquifer Systems Group (LSG) conducted an in-depth survey, for a European Space Agency (ESA) commissioned Phase-A contract involving a Design Study for a Facility for Integrated Planetary Exploration Simulation (FIPES). The survey data served as reference material for development of the FIPES architecture and, more importantly the application of the data ensured that the Systems Requirements reviewed and amended as part of the FIPES Study fully reflected the design, experience, and lessons learned from the use of such facilities.

The paper addresses a hitherto unfulfilled need: a comprehensive, comparative survey of most, if not all, simulators to date. It is a condensed and updated version of the detailed ESA Technical Report produced for the FIPES Study. It presents a comparative analysis of simulator characteristics and consolidated summaries for each simulator classified into (1) site and purpose, (2) key technical data, (3) scientific and medical research functions, and (4) technology test and development functions. It is beyond the scope of this paper to provide details for all twenty-seven simulators surveyed. Therefore, the paper presents selected summaries of three sets of relatively recent simulation campaigns, one European, one American and the other Russian-International. The paper concludes with excerpts of lessons learned from these campaigns.

INTRODUCTION

The international space community is contemplating human missions to the Moon in the coming decade and future human missions to Mars. The cumulatively aim at further human exploration of the Moon in the 2020-2025 timeframe. The Americans, Russians, Chinese, Indians, Europeans and Japanese have all individually announced intentions to set up a human base on the Moon.

When preparing for long-duration space missions beyond the 3 to 6 month range currently used on the International Space Station (ISS), medical and psychological aspects become an issue of major importance. The isolated and confined nature of spaceflight, in particular when considering missions beyond Lower Earth Orbit (LEO) to the Moon and Mars, along with its potential hazards, poses challenges and great risks related to human performance. These risks may be influenced by boredom, crew autonomy and increased reliance on each other, crowding, duration of flight, interpersonal tensions, mechanical breakdowns, poor communications, scheduling constraints and requirements and sleep disturbances. To prepare for crewed exploratory missions to Moon and Mars; study of these aspects in a simulated ground-based environment is therefore regarded as an important step to minimizing known risks.

In this regard, human space mission simulators play an important role in developing and testing hardware and software technologies required for such missions. Simulators also provide an ideal platform to conduct research in psychology, physiology, medicine, mission operations, human factors and habitability. These research areas are critical in ensuring crew well-being and performance.

In 2006, an in-depth survey was conducted by the Vienna based Liquifer Systems Group (LSG) as part of a European Space Agency (ESA) Phase-A contract involving a Design Study for a Facility for Integrated Planetary Exploration Simulation (FIPES). This paper represents the starting point for the planning and development of the FIPES architecture. It summarizes the survey of past, present and future simulation facilities worldwide, conducted as part of the FIPES Study.

The paper addresses a hitherto unfulfilled need, a comprehensive, comparative survey of most, if not all, simulators to date. It is a condensed and updated version of the detailed ESA Technical Report produced for the FIPES Study. The simulators surveyed by LSG are listed below:

Early Simulators
1. Regenerative Life Support Study
2. Apollo Ground-based Tests
3. Skylab Medical Experiments Altitude Test (SMEAT)
4. Skylab Mobile Laboratory (SML)
5. BIOS-1 and BIOS-2
6. Ben Franklin Underwater Research Laboratory
7. Tektite-I and II Underwater Research Laboratory

Recent Simulators
1. Isolation Study of European Manned Space Infrastructure (ISEMSI-90)
2. EXperimental campaign for European Manned Space Infrastructure (EXEMSI-92)
3. Lunar Mars Life Support Test Project (LMLSTP)
4. Biosphere-2
5. Canadian Astronaut Program Space Unit Life Simulation (CAPSULS)
6. HUman Behavior in Extended Spaceflight (HUBES-94)
7. Simulation of Flight of INternational Crew on Space Station (SFINCSS-99)

Present Simulators
1. Flashline Mars Arctic Research Station (FMARS)
2. Mars Desert Research Station (MDRS)
3. Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)
4. BIOS-3
5. Aquarius and NASA Extreme Environment Mission Operations (NEEMO)
6. Concordia
7. Closed Ecology Experiment Facilities (CEEF)

Virtual Simulators
1. Interactive Mars Habitat

Planned Simulators
1. Integrated Human Exploration Mission Simulation Facility (INTEGRITY)
2. Environmental Habitat (EnviHab)
3. European Mars Analog Research Station (EuroMARS)
4. Australian Mars Analog Research Station (MARS-Oz)
5. Integrated Planetary Simulator Studies

COMPARATIVE ANALYSIS OF SIMULATORS

The LSG team carried out a comparative analysis of the various simulators that is presented via a set of four tabulations. The simulator examples cited were chosen on the basis that technical information was available for the following:

- Purpose and mode of use,
- Development and adaptation for extended use,
- an indication of cost,
- method of funding and operation,
- Public interfaces (key word: outreach)
- Crew size and length of simulated missions
- Size of facility, and
- Facility power requirements

The first table provides basic summary information about the simulators surveyed for the FIPES Study. The second table summarizes the research functions of the simulators surveyed. The third table summarizes the technological tests and developments of the simulators surveyed. The fourth table allows for further comparative analysis and synthesis of information into new architectural and environmental categories including pressurized volume, habitable volume, private volume, atmosphere, temperature, noise level, number of airlock and number of viewports, among other key technical variables identified by the LSG team as innovative and valuable factors for assessing simulator conditions.

Table 1. Summary of past, present and planned terrestrial-based space simulators

Name	Agency	Site	Purpose	Ref.
Early simulators				
Regenerative Life Support Study	NASA	Mc Donnell Douglas, Huntington Beach, stationary, surface	Manned, 60 and 90 day closed environment test of ECLS systems (4 crew: Male)	[1]
Apollo Ground-Based Tests	NASA	NASA, stationary, surface	Apollo mission flight preparation in realistic environment (3 crew: Male)	[2]
Skylab Medical Experiments Altitude Test (SMEAT)	NASA	NASA JSC, transportable/mobile, surface, seaborne	56-day, bio-medical flight preparatory tests for Skylab missions (3 crew: Male)	[3-7]
Skylab Mobile Laboratory (SML)	NASA	Mobile, transportable by Lockheed C-5A Galaxy	Facility to obtain data on Skylab crewmen 30 days before lift-off, within 1 hour after recovery, and until pre-flight physiological baselines was retained.	[8]
BIOS-1 and BIOS-2	Russia	Russia	Facility to assess the bio-regenerative abilities of algae and long-term closed-system food production mission – 365 days (BIOS-2 3 Crew)	[9]
Ben Franklin Underwater Research Laboratory	Private	Mobile (submarine)	Summer 1969 mission to monitor living in closed confined environment (6 crew)	[10]
Tektite I and II Underwater Research Laboratories	NASA, NOAA and Private	US Virgin islands Stationary, underwater	Tektite II: 14 day mission to monitor physiological and psychological aspects of living at depth in relative isolation. First all-female crew (5 crew)	[11,12]
Recent simulators				
Isolation Study for the European Manned Space Infrastructure (ISEMSI-90)	ESA	NUTEC (Norwegian Underwater Technology Centre), Norway, stationary, surface	28-day test of closed loop system to examine psycho-physiological themes, in addition to contamination and tele-operational factors. (1990) (6 crew, Male)	[13,14]
Experimental Campaign for the European Manned Space Infrastructure (EXEMSI-92)	ESA	DLR Cologne Germany, NUTEC (Norwegian Underwater Technology Centre as Project Manager/Contractor), stationary, surface	Long duration test of closed-loops system - 60-day test. Main aims were organization of the management of the "flight" and Psychological/Physiological experiments (1992) (4 crew: 3 Male-1 Female)	[14-19]
Lunar Mars Life Support Test Project (LMLSTP)	NASA	NASA JSC, stationary, surface	Long duration test of closed-loop system employing biological & physicochemical techniques (4 crew: 3 Male-1 Female)	[20-22]
Biosphere-2	Private	Arizona, USA, Stationary, surface	Very long duration ecological environment tests (8 crew: 4 Male-4 Female)	[23-27]
Canadian Astronaut Program Space Unit Life Simulation (CAPSULS)	CSA	DCIEM (Defense and Civil Institute of Environmental Medicine, Toronto, Canada, stationary, surface	Short duration (7 day) test to gain first hand experience on operational aspects of a typical space mission, with psychological objectives (6 crew, Male). (1994)	[28,29]
Human Behavior in Extended Spaceflight (HUBES)	IBMP, ESA, NUTEC, EAC	Mir simulator, IBMP, Moscow, Russia, stationary, surface	Long duration test of closed-loop systems, high-fidelity simulator. 135 day for research into human-related effects (Psycho-physiological) of manned spaceflight. (1994-95) (3 crew, Male),	[14, 30,31]

Simulation of Flight of International Crew on Space Station (SFNICSS)	IBMP, NASDA, CSA	IBMP, Moscow, Russia, stationary, surface	Long duration test of closed-loop systems to observe effects of multiple crews of mixed gender, multi-cultural, living and working in a simulated space environment for extended periods (4-week to 240 days), 1999. (Multiple crews: Male-Female: Multicultural)	[32-35]
Present simulators				
Flashline Mars Arctic Research Station (FMARS)	Mars Society	Devon Island, Canadian Arctic, stationary, surface	Long duration isolation tests & geological field work (6 crew: Male-Female)	[36,37]
Mars Desert Research Station (MDRS)	Mars Society	Hanksville, Utah, USA, stationary, surface	Long duration isolation tests & geological field work (6 crew: Male-Female)	[38-39]
Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)	NASA	NASA JSC, stationary, surface	Long duration, biological & physicochemical life support technologies testing (4-6 crew)	[40,41]
BIOS-3	Institute of Biophysics	Krasnoyarsk, Siberia, stationary, surface	Development of bio-regenerative life support systems for Moon/Mars missions (1 – 3 crew: Male)	[42-46]
Aquarius and NASA Extreme Environment Mission Operations (NEEMO)	NOAA, NASA	Stationary, underwater	Extreme environment, research habitat designed as a multi-objective mission analogue for long-duration space flight (6 crew: Male-Female)	[47-49]
Concordia	ESA, IPEV, PNRA	Antarctic, stationary, surface	Medical, physiological and psychological research for long duration space missions (16 crew: Male-Female0	[50-55]
Closed Ecology Experiment Facilities (CEEF)	Institute for Environmental Sciences	Rokkasho, Japan, stationary, surface	Ecological tests (2 crew: Male + animals)	[56-58]
Virtual simulators				
Interactive Mars Habitat	Nexterra	Interactive website	Platform for design development offering virtual walk-throughs of a highly-detailed 3D computer model of a Mars habitat, a pressurized rover and a green house (no crew)	[59]
Planned simulators				
Integrated Human Exploration Mission Simulation Facility (INTEGRITY)	NASA	NASA JSC, surface, stationary	Life support and habitat research, including simulated Moon or Mars terrain on where astronauts can evaluate extra-terrestrial surface tasks	[60-62]
Environmental Habitat (EnviHab)	DLR	DLR Cologne, stationary, surface	Space analogue for inter-disciplinary and inter-national research in medicine, psychology & environmental sciences (8 crew)	[63]
European Mars Analog Research Station (EuroMARS)	Mars Society	Iceland, stationary, surface	Geological and exobiological field work (6 crew)	[36,37]
MARS-OZ	Mars Society	Australia, transportable, surface	Geological field work (multiple crew)	[64,65]
Integrated Planetary Simulator Studies	NASA	NASA JSC, stationary, surface	Habitat development to support lunar exploration	—

Table 2. Summary of simulator scientific and medical functions (*Gray shading is meant to highlight boxes with tick marks*)

Simulator	Scientific / Medical Investigation									
	Physiological	Cardiovascular	Musculoskeletal / metabolic	Neurophysiology	**Internal** Nutrition & endocrinology	Haematology	**Environmental** Micro-biology	Exobiology	Psychology	Human factors
Early simulators										
Regenerative Life Support Study	✓	✓	✓	✓	✓		✓		✓	✓
Apollo Ground-Based Tests	✓	✓	✓			✓	✓			
Skylab Medical Experiments Altitude Test (SMEAT)			✓	✓	✓	✓		✓		
Skylab Mobile Laboratory (SML)	✓	✓	✓	✓	✓	✓	✓			✓
BIOS-1 & BIOS-2	✓		✓		✓					
Ben Franklin Underwater Research Laboratory	✓	✓	✓		✓	✓	✓		✓	✓
Tektite I and II Underwater Research Laboratories	✓	✓	✓				✓		✓	✓
Recent simulators										
Isolation Study for the European Manned Space Infrastructure (ISEMSI-90)	✓	✓	✓		✓		✓		✓	
Experimental Campaign for the European Manned Space Infrastructure (EXEMSI-92)	✓	✓	✓		✓	✓	✓		✓	
Lunar Mars Life Support Test Project (LMLSTP)	✓		✓		✓		✓		✓	✓
Biosphere-2	✓		✓		✓		✓		✓	✓
Canadian Astronaut Program Space Unit Life Simulation (CAPSULS)	✓								✓	✓
Human Behavior in Extended Spaceflight (HUBES)	✓	✓	✓		✓				✓	✓
Simulation of Flight of International Crew on Space Station (SFNICSS)	✓	✓	✓		✓	✓	✓		✓	✓
Present simulators										
Flashline Mars Arctic Research Station (FMARS)	✓								✓	✓
Mars Desert Research Station (MDRS)	✓								✓	✓
Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)	✓		✓		✓		✓			
BIOS-3	✓		✓		✓					
Aquarius and NASA Extreme Environment Mission Operations (NEEMO)	✓	✓	✓						✓	✓
Concordia	✓			✓					✓	
Closed Ecology Experiment Facilities (CEEF)	✓				✓					
Virtual simulators										
Interactive Mars Habitat										✓
Planned simulators										
Integrated Human Exploration Mission Simulation Facility (INTEGRITY)	✓		✓		✓		✓		✓	✓
Environmental Habitat (EnviHab)	✓							✓	✓	
European Mars Analog Research Station (EuroMARS)								✓		
MARS-OZ	✓	✓	✓		✓	✓	✓	✓	✓	✓
Integrated Planetary Simulator Studies									✓	✓

Table 3. Summary of simulator technology test and development function *(Dark gray shading in boxes is where there was certainty on the investigations conducted and light gray shading is where there was some uncertainty)*

Simulator	Technology, Test and Development								
	Planetary environment	Environmental control & life support	Hygiene	Waste management	Food preparation & storage	Surgery / dentistry	Extra-vehicular activity	Interior habitation architecture	Infotainment
Early simulators									
Regenerative Life Support Study		✓		✓	✓				
Apollo Ground-Based Tests		✓	✓	✓					
Skylab Medical Experiments Altitude Test (SMEAT)		✓	✓	✓	✓				(✓)
Skylab Mobile Laboratory (SML)		✓				✓			
BIOS-1 & BIOS-2		✓		✓					
Ben Franklin Underwater Research Laboratory									
Tektite I and II Underwater Research Laboratories		✓	✓	✓			(✓)		✓
Recent simulators									
Isolation Study for the European Manned Space Infrastructure (ISEMSI-90)		✓	✓	✓					
Experimental Campaign for the European Manned Space Infrastructure (EXEMSI-92)		✓	✓		✓				
Lunar Mars Life Support Test Project (LMLSTP)		✓	✓	✓	(✓)				
Biosphere-2		✓		✓	✓				✓
Canadian Astronaut Program Space Unit Life Simulation (CAPSULS)	✓					✓			
Human Behavior in Extended Spaceflight (HUBES)		✓			✓			✓	✓
Simulation of Flight of International Crew on Space Station (SFNICSS)		✓	✓	✓	✓				✓
Present simulators									
Flashline Mars Arctic Research Station (FMARS)							(✓)		✓
Mars Desert Research Station (MDRS)							(✓)		✓
Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)		✓	✓	✓	✓			✓	
BIOS-3		✓	✓	✓	✓				
Aquarius and NASA Extreme Environment Mission Operations (NEEMO)		✓					(✓)		
Concordia		✓	✓	✓					
Closed Ecology Experiment Facilities (CEEF)		✓		✓	✓				
Virtual simulators									
Interactive Mars Habitat								✓	✓
Planned simulators									
Integrated Human Exploration Mission Simulation Facility (INTEGRITY)		✓	✓	✓			✓		
Environmental Habitat (EnviHab)		✓		✓					
European Mars Analog Research Station (EuroMARS)							(✓)		
MARS-OZ							(✓)		✓
Integrated Planetary Simulator Studies							✓		

Table 4. Summary of simulator technical data (*Data in italics estimated. No technical data available for future simulators*)

Simulator	Key Technical Data															
	Simulation duration (days)	Crew Size	Gender	Dimension (meter)	Pressurized Volume (cubic meter)	Habitable Volume	Pressurized Volume per crew	Habitable volume per Crew	Area (square meter)	Area per crew member(square meter)	Internal Pressure (kPa)	External Pressure (kPa)/	Main Airlock Volume (cubic Meter)	Number of Airlocks	Number of Viewports	Costs
Early simulators																
Regenerative Life Support Study	60	4	M	ø3.66 x 12.19	116	N/A	29	N/A	*36*	9	70	100	4.5	1 + 2 small (ø46cm)	N/A	N/A
Apollo Ground-Based Tests	7.6	3	M		8.8	N/A	12 492	N/A		0	34.5	>10	N/A	1	N/A	N/A
Skylab Medical Experiments Altitude Test (SMEAT)	56	3	M	ø6.1 x 2.3 (8.4 total height)	*81*	N/A	27	N/A	35.3	11.8	34.5	100	20	1 + 1 small (ø46cm)	15	N/A
Recent simulators																
Lunar Mars Life Support Test Project (LMLSTP)	91	4	3M+1F	ø6.1 x 8.4	226.5	N/A	56.63	N/A	87.3	21.8	N/A	100	20	1	15	N/A
Biosphere-2	700	8	4M+4F	154 x 110 x 28	203880	N/A	25 485	N/A	13 000	1 625	100	100	N/A	N/A	glass front	150M USD
Present simulators																
Flashline Mars Arctic Research Station (FMARS)	40	6	M+F	ø8.2 x 7.3	352	N/A	58.67	N/A	100	16.7	100	100	*3,2*	1?	9?	680K USD
Mars Desert Research Station (MDRS)	14	6	M+F	ø8.2 x 7.3	352	N/A	58.67	N/A	100	16.7	100	100	*3,2*	2 + 1 small	6	573K USD
Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)	425 (planned)	*6*		ø4.61 x 11.38 (5 bldgs)	*900*	N/A	150	N/A	*400*	*66.7*	N/A	100	N/A	N/A	N/A	N/A
BIOS-3	180	3	M	15 x 8.4 x 2.5	315	N/A	105	N/A	126	42	N/A	100	N/A	N/A	N/A	N/A
Aquarius and NASA Extreme Environment Mission Operations (NEEMO)	10	6	M+F	ø4 x 13.7	172	11	28.67	1,833	*30*	5	250	250	N/A	1	*3*	N/A
Concordia	420	16	M+F	ø17 x 17 (2 bldgs)	6 800	N/A	425	N/A	*1 200*	75	64,5	64,5	N/A	N/A	*40*	N/A
Closed Ecology Experiment Facilities (CEEF)	120	2	M		*1 000*	N/A	*500*	N/A	*333*	167	102	100	N/A	N/A	N/A	N/A

SELECTED SIMULATOR HIGHLIGHTS

It is beyond the scope of this paper to provide summaries of all twenty-seven simulators surveyed by LSG. The authors have therefore selected a set of relatively recent (1990-2000) simulation campaigns for the purpose of conveying differences in research focus, operations and overall architecture, of the simulation campaign designs involving European, American and Russian agencies and researchers.

The first is a series of three isolation tests (ISEMSI-90, EXEMSI-92, HUBES-94) commissioned by ESA; the second is a series of isolation chamber tests (LMLSTP, 1995-1997) conducted by NASA Johnson Space Center (JSC); the third is a series of isolation studies (SFINCSS-99) managed and run by the Russian Federation State Research Center (SRC), Institute for Biomedical Problems (IBMP) of the Russian Academy of Sciences, in collaboration with partner space agencies of the International Space Station (ISS) program: National Aerospace Development Agency of Japan (NASDA), Canadian Space Agency (CSA), and the European Space Agency (ESA). The simulations are best known in the research community by their abbreviated names as listed below. The European and Russian campaigns are suffixed with the year of their respective commencements.

1. European: ISEMSI-90, EXEMSI-92, HUBES-94
2. American: LMLSTP
3. Russian, International: SFINCSS-99

ISOLATION TESTS COMMISSIONED BY ESA (SERIES OF 3 CAMPAIGNS)

The European Space Agency's (ESA) Long Term Program Office conducted three experimental campaigns called:

- ISEMSI-90 (Isolation Study of European Manned Space Infrastructure),
- EXEMSI-92 (EXperimental campaign for European Manned Space Infrastructure), and
- HUBES-94 (HUman Behavior in Extended Spaceflight).

These campaigns aimed at obtaining information on the psychological and physiological effects of long-term isolation and confinement of a small crew under conditions simulating those that may be expected to exist in a space station. An overview of the campaign duration, location, crew size, simulator type, volume and experiments is summarized in the table below.

Table 5. Comparison of ISEMSI, EXEMSI and HUBES campaigns and experimental plans

Campaign	**ISEMSI-90**	**EXEMSI-92**	**HUBES-94**
Duration (days)	28	60	135
Crew Size (number, gender)	6 (all male)	4 (3 male, 1 female)	3 (all male)
Crew make-up/Language	European/English	European/English	Russian/Russian
Habitable Volume	118 m^3	94.4 m^3	100 m^3
No. of chambers	4 main chambers for living and working	2 main chambers allowed separate living and working	1 chamber both for living and working
No. of Psychological Experiments	7	10	20
No. of Physiological Experiments	5	9	14
No. of Operational Experiments	11	12	1
Location	Norwegian Underwater Technology Center (NUTEC), Bergen, Norway	Institut für FlugMedizin (Institute for Flight Medicine), Deutsche Luft- und Raumfahrt (DLR), Cologne, Germany	Institute for Biomedical Problems (IBMP), Moscow

ISEMSI-90

During the isolation period of 4 weeks, a crew of 6 male scientists/engineers was asked to perform tasks accepted as real and meaningful and similar to those performed on a space station. The tasks were selected to require collaboration among crew members and that collaboration was observed and measured according to performance criteria. The experimental purpose of ISEMSI was based in psychological and physiological experiments, as well as operationally oriented studies in the areas of contamination and tele-operations. The contaminations studies included experiments in microbiological and chemical contamination in addition to long term evolution of the chemical composition of the chamber environment and operational calibrations of the monitoring equipment. Of notable interest within the experimental campaign, was a set of tele-operation experiments, which focused on tele-medicine, tele-training, and tele-science.

The psychological themes investigated during the experiment included:

1. Social interaction/communication
2. Autonomic nervous system
3. Crew performance
4. Cognitive demand
5. Subjective status
6. Sleep and rhythmicity

The physiological investigations included:

1. Psycho-endocrinology
2. Immunology
3. Blood volume regulation
4. Body fluid balance
5. Lower body negative pressure
6. Heart rate and heart rate variability

Although ISEMSI achieved scientific success of the simulation, several shortcomings were identified in operational management, crew selection and training, data management and storage. The next step was the EXEMSI-92 campaign.

EXEMSI-92

The reference mission scenario for EXEMSI was a space laboratory in lower earth orbit (LEO) where a visiting crew would be servicing the orbital complex and performing payload operations. Similar to astronauts in a space station, four "emsinauts" lived and worked for 60 days in this closed system simulation scenario. They had to provide for themselves and to work on several tasks provided by a team of scientists. The crew was multi-national and was made up of three men and one woman. The ground crew was made up of one man and two women.

One important aims of the investigation was the organization of the management of the "flight" as a ‘mini space mission’ and one of EXEMSI’s main achievements was that it demonstrated that a major and useful project could be planned and executed in less than a year’s time and on a moderate budget. In addition to achieving the scientific objectives (physiological and psychological), the EXEMSI simulation project provided valuable experience in the training of members of chamber crew and ground control crew for their tasks. It covered all aspects of a mission from call for experiment proposals, crew selection and training, integration and testing of the facility and its equipment, to daily monitoring and managing of the mission, and finally post-isolation data collection and evaluation.

The main part of the study was carried out in the living chamber-A, a vessel 2.2 m in diameter and 6.6 m total length for the permanent stay of 4 crew members. The complex served as the habitat, sanitary area, galley and storage area. The main lock in the front end served as entrance and as experimentation area. The test subjects reached the transfer chamber B through the sanitary part. Chamber C served as another experimentation room. All chambers could be operated independently of one another. The complex was augmented by a custom-built steel container, which served as the main laboratory facility. The life support system regulated the temperature, moisture and the percentage of O_2 in the air, thus providing the parallel to spacecraft, which also require a closed atmospheric circulation. Overall the environment was considered representative of a space station. The Campaign Control Centre was the central point for control and monitoring of the facility and experiment operations.

Figure 1. (a, b, c) Titan Hyperbaric Chamber used for the EXEMSI campaign, (d) a test subject exercising on a bike ergometer (Source: DLR)

Psychological objectives of the study were numerous and included investigations into the social behavior, interrelations, cohesion, efficiency and team formation of the crew. The objectives focused on critical comparison of a variety of test methods leading to recommendations for their applications in selection, training and support for future studies of this kind. The study consisted of three phases:

- Pre-isolation Phase: Initial individual and group assessments were made in order to understand the motivation, characteristics, and styles of the crew members, the state of the crew, and to make a prognosis for the behavior of the group and its members,
- Isolation Phase: Tests and observations are made to analyze crew behavior and group dynamics, and to detect manifestations of stress,
- Post-isolation Phase: During this phase final assessments are made and debriefings carried out.

During these three phases individual and group tests were carried out. Direct methods (e.g. questionnaires and tests) as well as indirect methods (e.g. observations of behavior) were used. These had cognitive, affective-emotional and social components; they were quantitative, qualitative or a combination.

Observations made before isolation were that the crew members expressed strong confidence in the team and in their own personal capability and furthermore, that the leadership of the Commander seemed uncontested. Noting, the relatively short period of the experiment, and the absence of real risk, there was some question as to whether the crew's behavior (isolation of affects and denial of anxiety) would be adequate in a real spaceflight situation, and was even considered dangerous. During isolation there were no clear manifestations of stress. Nevertheless, the confinement and isolation were experienced as the major stress factors. The crew members described themselves as a heterogeneous but harmonious group that was successful in their mission, with their success attributed to maintaining cohesion by opposing external authority (management and the ground crew). Again, it was questioned whether group cohesion would have persisted in a life-threatening crisis or even in a prolongation of the experiment. Further, given the mixed-gender crew, it was observed that the woman in the crew was never involved in conflicts and acted as a peacemaker.

Psychological state of the crew and their need for psychological support during prolonged isolation were observed using well-established methods employed during Soviet spaceflights. Communication between Commander and Crew Interface Coordinator (CIC) was analyzed and crew disposition was observed and analyzed for information about the process of group formation and the role of each crew member in this process. The key findings were adaptive changes in communication:

- Use of unplanned contacts and intensive contacts with a preferred ground crew member,
- Resistance to penetration into crew life (increase in aggressive statements and self-justifications, reduction of report length and claims),
- Closing communication to 'outsiders' by using a special code and decreasing discussion of problems.

Daily monitoring also included a range of physiological variables. The study team developed a food and nutritional management system that provided online analysis of all available foods (macro-nutrients, water, minerals, and vitamins) and allowed for an accurate record of daily food intake. The findings revealed that eating and nutrition during the 60-day study were not problematic, though vitamins B1 and B6 were shown to be rather low and warranted the need for supplements. Crew members rated food appreciation on a daily basis (questionnaires) and conveyed that food offered daily pleasure and social activity, which in turn was seen to potentially decrease stresses related due to confinement and isolation. Crew rated the food provided very high. Their satisfaction level was in part attributed to some operational aspects whereby the crew was directly involved in selection of the menu prior to the mission, in addition there was large menu variety, and extra supply, which allowed crew members choice in regards to food intake. The follow-up to EXEMSI-92 was HUBES-94.

HUBES-94

The HUBES mission endeavored to further findings in the area of comparison and validation of psycho-sociological methods and tools for use in crew selection, training, monitoring and in-orbit flight support. Prior relevant campaigns, including ISEMSI-90 and EXEMSI-92 were taken into account, particularly their findings in the psychology of group dynamics as well as individual performance under isolation and confinement. HUBES focused on the process of how to select those considered most appropriate for a real long-duration spaceflight (e.g. EUROMIR 95) and through the combined objectives of psychological methodology and crew selection, the mission aimed to improve knowledge about human requirements for extended space missions. EUROMIR 95 was selected as a model for the HUBES experiment and thus informed the duration, crew, schedule organization, workload, mission control, set-up for communications and data processing, and layout of the facility. The modeling of HUBES (surface) against EUROMIR 95 (space) was such that it allowed for the evaluation of the additional stress induced by microgravity, with respect to isolation and confinement.

The facility was set up like a small space station; the crew's living quarters provided limited living space and comforts. The fidelity of the experiment to a Mir mission was maximized to the greatest degree possible. The total volume of the simulator was 100 m^3, internal volume similar to Mir. For example, the organization of workstations into racks, the structure of working zones and leisure zones, and the dimensions of the various zones were the same as on Mir. Consideration was given to many aspects of habitability: traffic flow, privacy, meal structure and food preparation zone, workstations set-up, lighting, sleeping area and storage.

Operations and communication aspects were also configured to resemble a Mir mission, to the greatest degree possible. Similarly, crew selection was such that candidates were selected for the same medical, psychological, and professional qualifications as Russian and ESA astronauts. Unfortunately, due to the requirement to speak Russian, no European Union (EU) member state candidates were selected. The primary purpose of the HUBES experiment was to achieve a better understanding of human related effects of long duration manned spaceflight. A total of 31 studies were carried out in the following areas: individual performance, group behavior, medicine, immunology, chronobiology, nutrition. The experiment was preceded by a 2-part training phase; with the second component of mission training included to minimize the problems previously experienced on ISEMSI and EXEMSI with crew assignment procedures. The main study ran the complete 135-day period, as planned and was followed by a 2-week post-testing period involving a range of psychological and physiological evaluations.

GLOBEMSI-96

The three successive campaigns ISEMSI-90, EXEMSI-92 and HUBES-94 involved a wide range of experiments in three broad categories: psychology, physiology, and operations. ESA implemented an elaborate database management system to document and analyze these experiments through a well-planned system called Global Analysis of Scientific Data from the European Manned Space Infrastructure (GLOBEMSI) [66]. The measurements of psychological and physiological parameters were made via different methods which on one hand included individual questionnaires, computer tests, video recordings, audio recordings, etc. and on the other hand involved collection of blood, saliva and urine samples, echocardiography, body weight, skin temperatures, etc. These were the Dependent Variables. Other data such as experiment time, date, subject identification, and other data from operational experiments such as gas contamination, water composition, subjects' nutrition, etc. were the Independent Variables. From a scientific point of view, in order to integrate all the data and analyze the inter-relations between all the variables, it was necessary to collect and organize all of the data in GLOBEMSI-96 database, specially formatted for global multidisciplinary data analysis. The GLOBEMSI database was designed to be fully compatible with both PC and Macintosh. Running on Microsoft Excel 5.0, it was developed with Visual Basic Applications.

GLOBEMSI is an excellent example of how a series of study protocols can be developed and carried out in order to achieve multiple, multi-disciplinary investigations. As a review, the experimental protocol of ISEMSI-90, EXEMSI-92 and HUBES-94 involved confinement within closed habitats varying by architecture, crew size and duration. One of the key features of GLOBEMSI was its adoption of an ethological approach; an "approach particularly concerned with the globality of physiological and psychological systems involved in the adaptive process which require, as far as possible, to keep the characteristics of living and working conditions in its integrity (communications, crew task, volume, etc.) for spontaneous behavior."

GLOBEMSI endeavored to achieve its experimental design by varying the architecture of the simulation facilities, increasing the duration of the isolation and confinement period, and decreasing the size of the crew with cultural differences. The parameters of GLOBEMSI were considered as social or individual adaptive indexes of crew members in a space mission simulation for detection of the less evident behavioral and psycho physiological disturbances during real space missions. From an experimental design perspective, GLOBEMSI involved a complex set of methods and approaches to evaluate the range of psychological and physiological parameters. Management of the data was planned as a relational data set from the outset through the use of a conceptual data model, which allowed for navigation and management of the database. In summary, from the three campaigns the database totaled 89 experiments, of which 37 were Psychological, 28 were Physiological and 24 were on Operational aspects. 65 different Principal Investigators performed these experiments for 38 different parameter units (metric, reaction time, pressure, etc) from 31 procedures (video, computer test, monitoring, and telemedicine) and involved 120 key words for data coding (e.g. cardiovascular, interaction, nutrition, interpersonal, etc).

ISOLATION TESTS CONDUCTED BY NASA JSC (SERIES OF 4 PHASES)

The primary goal of the Lunar-Mars Life Support Test Project (LMLSTP), conducted from 1995 through 1997 at the NASA Johnson Space Center (JSC), was to test an integrated, closed-loop system that employed biological and physicochemical techniques for water recycling, waste processing, and air revitalization for human habitation. NASA evolved and upgraded the previous Skylab Medical Experiments Altitude Test (SMEAT) simulator project into the LMLSTP, which was built in the same vacuum chamber as the SMEAT facility. As an analogue environment for long-duration missions, the conditions of isolation and confinement enabled studies of human factors, medical sciences (both physiology and psychology), and crew training.

The LMLSTP was planned, designed, and operated by the Advanced Life Support Group at NASA's Johnson Space Center. It was based on the Advanced Life Support System (ALSS) concept that a human life support system, supplying food, water, and oxygen, open with respect to energy but closed with respect to mass, can operate indefinitely in space without re-supply from Earth. This meant that regenerative or recycling technologies had to be used. As part of the technology development effort, a series of tests were conducted.

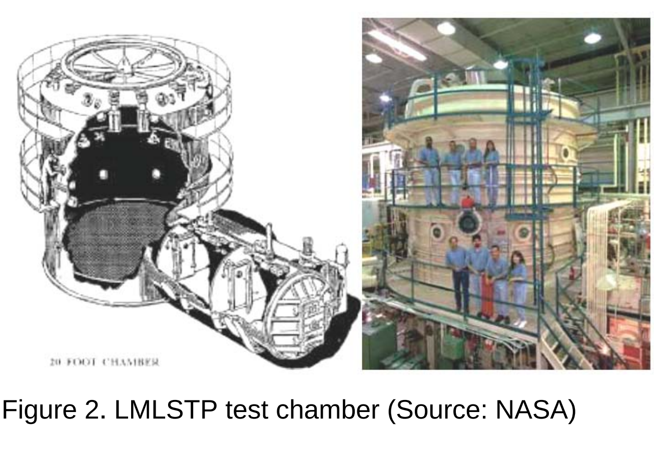

Figure 2. LMLSTP test chamber (Source: NASA)

Table 6. Comparison of the LMLSTP simulation campaigns

	Phase I	Phase II	Phase IIA	Phase III
Year	1995	1996	Early 1997	Late 1997
Duration	15 days	30 days	60 days	90 days
Crew Size	1	4	4	4
Test Focus	Air Revitalization System (ARS)	Integrated Physico-chemical ARS, Water Recovery System (WRS) and Thermal Control System (TCS)	International Space Station (ISS) Integrated Environmental Control and Life Support System (ECLSS)	Integrated Physico-chemical & Biological ARS, WRS, and TCS test
Facilities	Variable Pressure Growth Chamber (VPGC)	Life Support Systems Integration Facility (LSSIF)	Life Support Systems Integration Facility (LSSIF)	Life Support Systems Integration Facility (LSSIF) and Variable Pressure Growth Chamber (VPGC)

Phase-I: LMLSTP Phase-I Test was performed in August 1995. The purpose was to obtain engineering and scientific data to demonstrate the ability of a crop of wheat to provide air revitalization for a human test subject for a 15 day period. The test also characterized crop growth and test bed performance of wheat, from seed to harvest, in the closed, controlled atmosphere of the growth chamber section of the Variable Pressure Growth Chamber (VPGC), using hydroponics and high intensity light. The test chamber was divided into two sections, the plant growth chamber and the airlock, which was used as the human habitation chamber.

Figure 3. Montage of LMLSTP chamber tests showing crew members performing a variety of tasks (Source: NASA)

Phase-II: LMLSTP Phase-II began on 12 June 1996 and was the second human test to validate regenerative life support technologies. A ground based test bed facility, the Life Support System Integration Facility (LSSIF), was constructed using an existing 6 meter vacuum chamber and outfitting it with life support systems to perform verification testing with four test subjects in a closed environment.

Phase-IIA: LMLSTP Phase-IIA began on 13 January 1997 and was the third human test to validate regenerative life support technologies. This test used hardware representative of the International Space Station (ISS), scheduled for first launch in 1998. As in Phase-II, this was an integrated test recycling the air and water required for a crew of four. Results from this test were combined with results from NASA Marshall Space Flight Center tests for evaluation and comparison of advanced life support system technologies. The test was successfully completed on 14 March 1997.

Phase-III: LMLSTP Phase-III was a 90-day test with 4 crewmembers and two test chambers connected to each other by gaseous air exchange. The crew lived in the Integrated Life Support Systems Test Facility (ILSSTF) with oxygen augmented by oxygen produced by wheat growing in the Variable Pressure Growth Chamber (VPGC) and carbon dioxide produced by the crew being transferred from the ILSSTF to the VPGC for uptake by the wheat during growth. A unique bioreactor designed and built at JSC was the primary component of the water recycling process—it used microbes to clean-up the water. And for the first time in this series of tests, an incinerator was used in the solid waste processing system to turn crew fecal matter into ash and gaseous carbon dioxide products for reuse by the wheat.

A Product Gas Transfer System, with components between and interfacing with both chambers, was responsible for gaseous exchange between the ILSSTF and the VPGC to correctly balance the oxygen and carbon dioxide for the crew in the ILSSTF and the wheat crops in the VPGC. Included in this gaseous exchange was the use of the carbon dioxide collected in the VPGC airlock from the incinerator for use by the wheat crop, and use of oxygen generated by the wheat for the incinerator. The Phase III Test systems consisted of: plant growth systems, a solid waste incineration system, an Air Revitalization System (ARS), a product gas transfer system, a water supply and Water Recovery System (WRS), a Thermal Control System (TCS), energy balance instrumentation, food system, crew accommodations, and facility support systems.

The LMLSTP project has been documented in a book authored by the researchers involved in the study. The book is titled ‘Isolation: NASA Experiments in Closed Environment Living’.

ISOLATION TESTS MANAGED BY IBMP (SET OF 7 GROUPS)

The main purpose of SFINCSS-99 was to obtain experimental data on implications of long-term isolation and confinement in simulated International Space Station (ISS) conditions. It especially focused on the ISS assembly phase that called for a highly demanding schedule, which impacts both mental and physical health of crewmembers and, consequently, elevates the risk of health problems. Therefore, instruments used for health monitoring and prediction, work-ups, and medical care in flight must be substantially upgraded. The associated duties require more flexible scheduling of particular operations and procedures. In the Mir program, the in-flight work/rest schedule was ironclad, and this fact explained the keen scientific interest in comparison of the effect of rigid and flexible work/rest schedules on the ‘post-flight’ status of crew members in long-term isolation and confinement.

The Institute of Biomedical Problems (IBMP) in Moscow was commissioned by the Russian Space Agency to research and develop methods, tools and prototypes of biomedical equipment to enhance the existing medical care system for space crews. Integrated test verification of these methods and means during simulation of the most challenging period of the ISS program allowed a definitive conclusion regarding their potential in the context of crew mental and physical health maintenance. Prior spaceflight simulation studies led to the hypothesis that adaptation of a group of human subjects to closed controlled environments would proceed in phases. Each phase (approximately two months into isolation and confinement) would culminate in a transition period to let the body functional controls readjust their structure. The associated strain in the body functions may deteriorate professional efficiency. Testing of the hypothesis would contribute to a significant increase in spaceflight safety.

The following objectives were set for the project:

- Determination of the effects of monotony of long-term isolation and confinement on space crew performance and human body functioning
- Comparison of the psycho-physiological status of test-subjects on the fixed or flexible work/rest schedule
- Identification of regular patterns of the bodily adaptation to the artificial climate of pressurized modules
- Observation of the behavior of several crews during "rendezvous" missions when they will tend to their specific tasks while interacting with each other
- Test evaluation of robustness and efficacy of the flight control systems and research facilities and procedures proposed for utilization aboard ISS; framing of relationships among investigators.

Other important ISS aspects included collaboration and interaction of groups differing in culture, length of orbiting and adaptation to the spaceflight conditions that implement different missions in relatively isolated ISS modules. Experience of the Mir/NASA space program revealed some national, cultural, professional and other differences that served as a substrate for establishment of psychological subgroups. These types of conflicts may lead to negative consequences for the success and safety of space missions. So far, there had been no reports on simulation and investigation of these phenomena anywhere. For this reason, SFINCSS-99 investigated the psychology of interaction between several crews that were assigned independent missions tasks and interface in the process.

Sources of psychological information included: video tapes of crews, observations of relationships within and between the groups, voice communications with controls, analyses of e-mail, various checklists and questionnaires, and other computerized methods.

To determine the extent to which the monotony of isolation and confinement may impair space crew performance and physical state, the SFINCSS-99 configuration comprised monitoring of the parameters which characterize efficiency and proficiency of operators on a space mission, their high psychic functions, psycho-emotional, cardio-respiratory, biochemical, immunologic, hematological, morpho-biochemical, and metabolic status, the immunity-microflora system, etc.

The project covered the following fields of research:

- Intergroup and group behavior
- Individual and operator's psychology, behavior
- Clinical/physiological investigations
- Biochemical and immunologic assays
- Sanitary/hygiene and microbiological survey
- Biological studies
- Engineering and technological experiments (included data base verification).

Strict medical criteria were used to select members for test subjects. A total of 21 test subjects (15 Russians, 3 Japanese, 1 German, 1 Canadian and 1 French) participated in the experiment. The test subjects were divided into two kinds of groups, the long-duration *primary crews* and the short-duration *visiting crews*.

- Three Primary Crews: Group-1 (240 days), Group-2 (110 days), Group-3 (110 days)
- Four Visiting Crews: Groups 4 and 5 (7 days), Group-6 (4 days), Group-7 (28 days)

SFINCSS isolation campaign started with Group-1 on June 2, 1999 who entered EU-100 for their 240-day isolation and ended with Group-7 when they completed their 28-day confinement on April 14, 2000.

Table 7. Comparison of mission parameters for the three Primary Crews of SFINCSS-99

Primary Crews	**Days**	**Chamber**	**Number, Gender, Age**	**Nationality**	**Profession**	**Remarks**
Group-1 Mir schedule	240	EU-100 ($100\ m^3$)	4 males 37-48 years	Russian	3 physicians, 1 engineer	Group-1 performed scheduled operations during eight working hours maximum with the energy expenditure of 2400-2600 kcal. They lived on a schedule typical for space station Mir crews. Physical exercise adhered to the Mir protocol i.e. a four-day cycle.
Group-2 ISS assembly phase: Fixed work-rest schedule	110	EU-37 ($200\ m^3$) Mars Flyer module	4 males 27-45 years	1 German (Commander), 3 Russians	3 physicians, 1 engineer	Group-2 entered EU-37 on day 28 since the beginning of the experiment and remained until day 138 (total: 110 days). The crew had a *fixed* work-rest schedule and was charged with more demanding and tedious tasks that cost daily average of 3200 up to 3600 kcal. The increased energy expenditure was associated with mimicking the ISS assembly operations. This was achieved via an EVA simulator, and exercise machines. The working day was up to 12 hours.
Group-3 ISS assembly phase: Flexible work-rest schedule	110	EU-37 ($200\ m^3$) Mars Flyer module	3 males, 1 female 27-37 years	Japan, Austria, Russia and Canada	3 physicians, 1 sports expert	Group-3 began in EU-37 22 days after the return of group-2, and remained in the module for 110 days. The crew faced the same challenges and difficulties as its predecessor, but with a *flexible* work-rest schedule. The work-rest schedule was the result of two-step planning. The crew was given just a task list for a day with the emphasis on chief duties, required job quality and time-limit, thus they were free to opt for approaches to a task, setting its priorities, whether to defer it to a later hour or do at the sacrifice of leisure time or other activities.

There were four 'Visiting Crews' consisting of 3 to 4 members of different sexes and nationalities including experienced cosmonauts. Their stays ranged from 7 days to 28 days. Groups 4 and 5 (3 and 4 members respectively) came for 7-day visits to the modules. Group-5 was international and consisted of members from France, Germany, Japan and Russia.

Group-6 comprised entirely of medical professionals devoted 4 days to comprehensive medical examination of the members of Group-1 inside their module in order to evaluate their fitness to continue the experiment. Group-7 was intended to test methods of counteracting adverse effects of under-use of the musculoskeletal apparatus. It consisted of 4 male subjects, 3 physicians and one engineer. Group-7 entered EU-100 for a 28-day stay and for 5 days they interacted with members of Group-3. Figure 4 provides a visual overview of the complex experimental flow of interacting groups over the course of the complete SFINCSS-99 campaign.

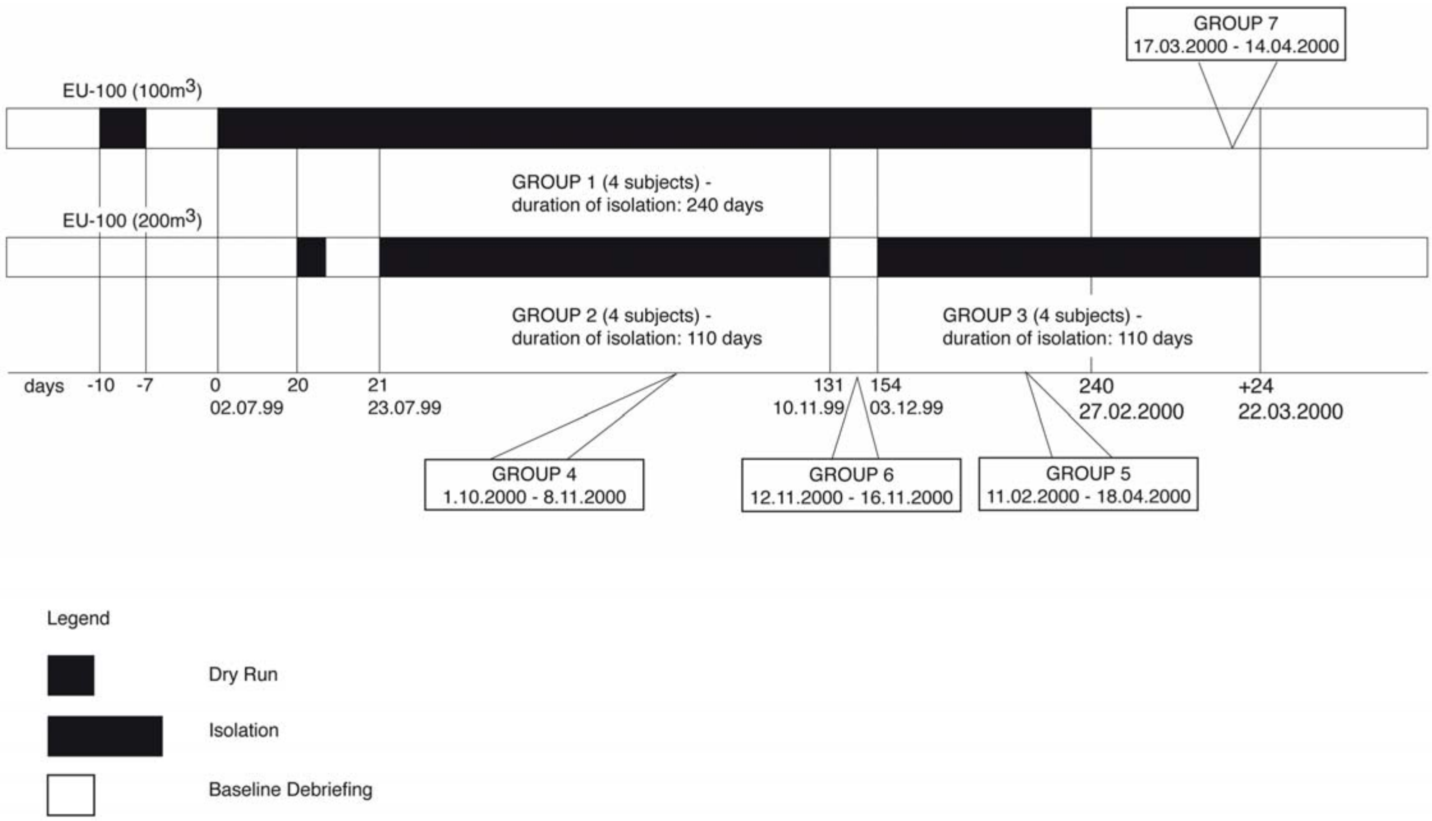

Figure 4. SFINCSS-99 Project Scenario (Source: IBMP)

Equipment and food supplies were provided once a month to each module. Crews were required to observe the work-rest schedule as determined by the mission managers and underwent medical checkup by a physician. Inside the modules, they exercised on a recommended training program and administered other counter-measures utilized in long-term space missions. The psychological care was analogous to what had been typically provided to crews on real Mir flights. The hermetic isolation chamber consisted of three interconnected modules with a total volume of 350 m^3 (about the size of three large interconnected trailers). Group-1 (i.e. Russian core crew) occupied a 100 m^3 module and their sleeping areas were like those found on the Mir station, separated from the work area and each other by a curtain only. Group-2 and Group-3 stayed in a 200 m^3 module that had individual sleeping cabinets and a large 'living room' area. During their stays, crewmembers kept in contact with the outside world through telephone, Internet and television.

Environmental Parameters:

- Temperature: from 18-24 (+/-) 4 deg. Celsius
- Humidity: 40-75%
- Air flow rate: 0.08-0.2 m/s
- Barometric pressure: 660-860 mm Hg
- Oxygen partial pressure: 140-200 mmHg
- Carbon dioxide partial pressure: up to 8 mmHg
- Acoustics: 60 dBA
- Dust loading: 0.15 mg/m (daily average). Maximum 0.5 mg/m^3
- Lighting: 50-300 lux (10 lux under the blue filter at night)

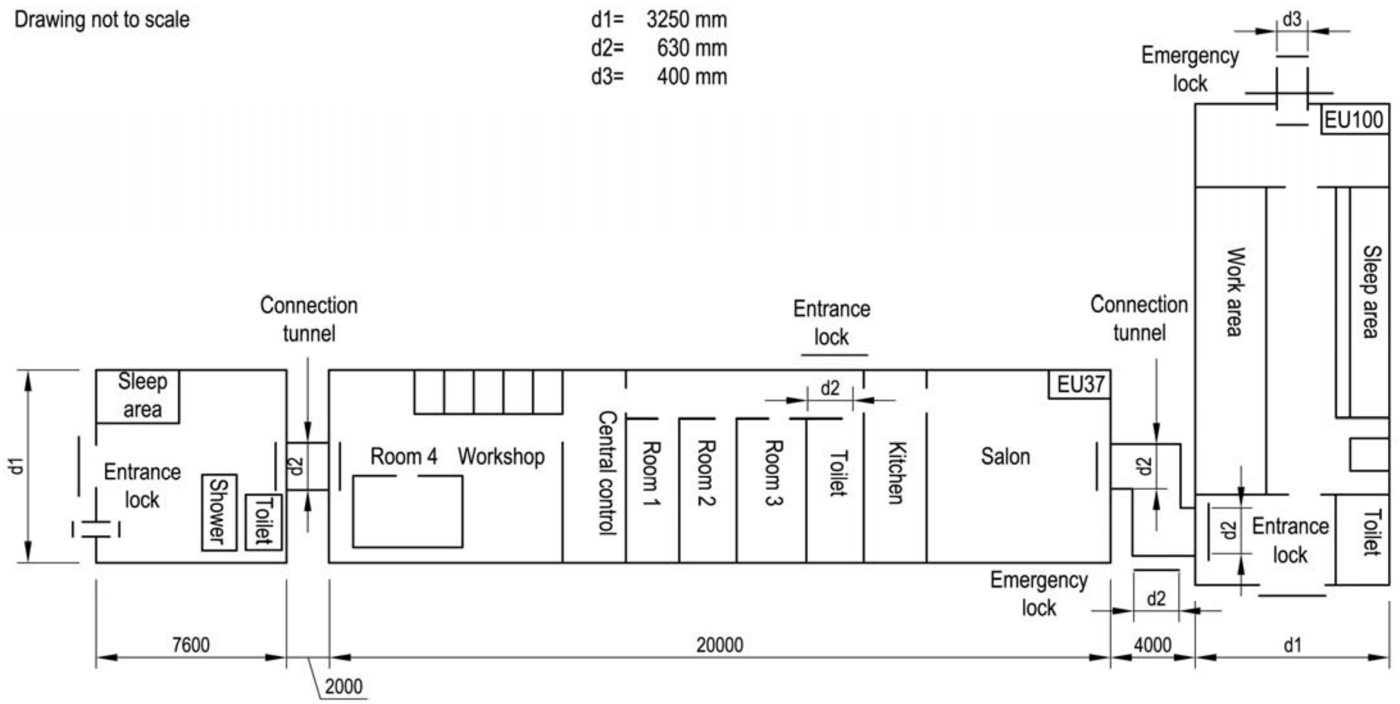

Figure 5. General schema and layout of the SFINCSS Habitat (Source: IBMP)

Figure 6. Images of the (a) hyperbaric chamber (exterior), (b) international crew, (c) working area (interior) (d) food (Source: NASDA)

The SFINCSS crews were supplied with thermo-stabilized, freeze-dried, sublimated and partially dried and fresh foods, which were considered consistent with the diet of Mir crews. With regards to personal hygiene, items and techniques were provided to the crew with the intent to prevent skin or dental problems. A shower cabin was provided for full body bathing. A washbasin and tap water were available for hygienic needs and for washing dishes. Crewmembers were allowed to have personal hygiene items of their choice.

The experimental flow proceeded without incidence until part way through Group-3's stay – when conflict arose between Group-1 and Group-3 and resulted in the transfer hatch between two of the modules being locked. The conflict situation persisted for just over one month and was only resolved through the efforts of the project management team. Once resolved, the hatch was re-opened and the crews renewed their contact.

The SFINCSS project has been documented in a book edited by Dr. V. M. Baranov, an Associate of the Russian Academy of Medical Sciences, and one of the Principal Investigators for the Project. The book is titled '*Simulation of Extended Isolation: Advances and Problems*'.

LESSONS LEARNED: EXCERPTS FROM SELECTED CAMPAIGNS

This section presents excerpts of lessons learned from the simulation campaigns highlighted in the previous section: ISEMSI-90, EXEMSI-92, HUBES-94, LMLSTP, and SFINCSS-99. With each excerpt listed below, the name of the associated simulation campaign is included in a parenthesis. This list is illustrative rather than comprehensive. The objective of the lists presented below was to provide the FIPES Study team an overview of the nature and diversity of issues involved in the design of simulators and simulation campaigns.

Lessons learned are based on stated findings, observations, commentaries, or conclusions documented in the publications listed below. Due to the complex nature of the various simulator experimental flows, and also the diversity of approaches in different parts of the world (e.g. Europe, Russia, and the United States), it is not within the scope of this paper to attribute cause and effect. Furthermore, while there was no indication of the degree of agreement required for the citing of findings, the value of including this information was considered substantial enough for the objectives of the survey.

Data has been excerpted from:
- Lessons learned from ISEMSI and EXEMSI: Isolation Campaign for the European Manned Space Infrastructure [14],
- Isolation: NASA Experiments in Closed-Environment Living [22],
- Simulation of Extended Isolation: Advances and Problems [32], and
- Project SFINCSS-99: Simulation of a Flight of International Crew on Space Station [33].

Data is classified into four broad categories, which have been defined as they apply to key aspects of simulator planning and design:

OPERATIONS AND LOGISTICS: simulation planning, operations, data management, crew selection and training issues;

HUMAN FACTORS: physiological, psychological and sociological issues;

HABITABILITY: habitat design issues e.g. configuration and function, stowage, privacy, group interaction, noise, temperature, lighting, windows, housekeeping, etc; and,

ENVIRONMENTAL CONTROL AND LIFE SUPPORT: issues related to air, water, food and waste management.

OPERATIONS AND LOGISTICS

- Earth simulations permit study of scientific and operational aspects of space missions at a fraction of the cost of an in-orbit precursor mission. (EXEMSI-92)
- Careful simulation planning is required to yield useful information and to maximize mission relevant experience. (EXEMSI-92)
- Larger, more representative, multi-disciplinary campaigns are needed with extensive planning for crew selection and training. (ISEMSI-90)
- Crewmembers should be made aware of criteria that could cause their de-selection prior to strating the candidate selection process. (LMLSTP)
- Crew changes late in the preparation phase risk compromising a simulation, and should be avoided, especially for long-duration mission simulations. (LMLSTP)
- Further improvements are indicated in operational management, mission and simulation control. (GLOBEMSI-96)
- Advanced data management and planning (e.g. identification of parameters, ranges, measurement techniques, sources of error) are essential for organization and access of data for experimental analysis. (GLOBEMSI-96)
- Technologies, procedures and protocols that enable crew autonomy are indicated for long duration mission simulations. (GLOBEMSI-96)

HUMAN FACTORS

- Aerobic and resistive countermeasures provided a training stimulus when performed on separate days. Further work is needed to explore possible negative effects on strength training when aerobic exercise is performed on the same day as resistive training. (LMLSTP)
- Increasing variety of exercise protocols, exercise devices and addition of virtual reality headgear or other forms of entertainment during exercise may improve exercise compliance. (LMLSTP)
- Physical exercises in the course of extended isolation and confinement are more than countermeasures as they also play the role of a means of psychological support diluting the monotony inherent to this environment. (LMLSTP)
- The most reliable instruments for psychological survey have included: group methods, non-obstructive tests, indirect instruments, and qualitative tools. The least reliable have included: strictly quantitative methods, self-evaluations, and standard debriefing techniques. (EXEMSI-92)
- The incidence of fewer stress-related psychosomatic complaints, psychopathological reactions, and socio-psychological factors led to teams with lower conflict rates.(EXEMSI-92)
- Role and responsibility clarification must be made clear and specific to an extraordinary degree to help mitigate the misunderstandings and erroneous assumptions that naturally arise between groups that are physically and visually separated. (EXEMSI-92)
- LMLSTP adopted lessons from other environments, which fell within three general themes: 1) further inclusion of the Control Room (CR) group as an integral part of the team and acknowledgment of their contribution, 2) mutual understanding of the daily issues facing the crew and the CR groups and strategies for managing that interface, and 3) a reasonable work-rest schedule for individuals in the CR. (LMLSTP)
- Prior explanation of mission objectives to the subjects, giving clear and complete information, establishes confident and cooperative relations with the crew. (EXEMSI-92)

- It is essential to allow dialogue, to take opinions and suggestions of the crew seriously, and to establish clear rules of confidentiality. (EXEMSI-92)
- Reviewing lessons, issues and strategies from prior missions, from a psychological perspective as well as from a mission perspective, helps prepare the crew and contributes to crew beliefs. (LMLSTP)
- Taking data from past simulations and educating crews about teamwork styles for extended missions helped with familiarization and integration of the team members. (LMLSTP)
- Public distances increase in the longer duration simulations (EXEMSI-92) compared to shorter duration simulations (ISEMSI-90) where personal distances are more frequent. (GLOBEMSI-96)
- Social orientations were more frequent in the HUBES-94 campaign, over the EXEMSI-92 campaign, thus suggesting that the social adaptation process may be achieved more rapidly during longer duration isolation and confinement. (GLOBEMSI-96)
- Inclusion of family members is a powerful crew support method for many reasons, and a source of strength for the crew member families. (LMLSTP)
- Several problems in the course of the project were of the type that had been earlier documented in space flights including cross-cultural interactions between carriers of various national traditions. According to the investigators from different countries participating in the project, these problems stemmed from objective nuances in mentality, customs and treatment of various situations. (SFINCSS)
- Arrival of the visiting crew was a mighty stress and posed additional challenges to relations between groups. (SFINCSS)
- Co-work of several crews very much alike by their composition but with different spaceflight or/and ground-based test experience begins with inter-adaptation. The presence of another crew is perceived as an external factor to fit to. On the average, it takes three weeks to make relations of the crews comfortable. (SFINCSS)
- Joint leisure hours and off-duty communication considerably expedite mutual adjustment while cultural differences, poor knowledge of a partner's language complicate informal communication and appreciably impede the process. (SFINCSS)

HABITABILITY

- Include a simulator operations panel within the simulator environment that displays the problem and its source so the cause and seriousness of the problem can be ascertained. Audible alarm notifications on computer screens (individual and shared) could be very useful (e.g. when something goes wrong with a piece of equipment). (LMLSTP)
- Provide more acoustic insulation between low noise (e.g. sleep, relaxation) areas and high noise areas (e.g. equipment bay). Provide crew members with earplugs. (LMLSTP)
- Loud equipment should be run at night and away from the sleep quarters. Equipment should be tested prior to a mission in an integrated operational setting, and predetermined noise levels should be identified as acceptable. (LMLSTP)
- Ensure placement of hygiene facility and trash away from the dining and public gathering areas. (LMLSTP)
- Provide both dedicated use and multi-functional areas. (LMLSTP)
- For future crew quarters designs, the types of activities that the crew will conduct should be traded with the amount of space required to support those functions. In addition, the crew, if so desired, should be able to reconfigure their personal spaces within the limitations of the exterior geometry. (LMLSTP)
- Internal configurations of the simulator facilities and their evaluations should be developed and designed in tandem with those disciplines addressing human performance. (LMLSTP)
- Ensure gradation of public to private areas. (LMLSTP)
- Before the mission, allow each crew to thoroughly plan where to stow supplies and hardware that are not constantly passed in and out. Have crew establish dedicated labeling system for these items. (LMLSTP)
- There is a need to investigate and test a palette of materials, colors and textures to determine their viability for various applications and locations. (LMLSTP)

ENVIRONMENTAL CONTROL AND LIFE SUPPORT

- There is a need to develop advanced air, water, food, and waste management systems to sustain crews autonomously, with limited or no re-supply potential, on long duration missions. (LMLSTP)
- Closed-loop life support system development goals can be achieved only in a controlled test chamber due to the complex interactions between the sources and sinks. The complexity of these interactions will rise as food preparation and waste processing systems are integrated into habitats. (LMLSTP)
- Comprehensive air quality analyses is indicated to determine whether preventative measures to limit pollution are effective, to ascertain if the Air Revitalization System (ARS) is capable of dealing with the pollutant load on a sustained basis, to detect any new sources of air pollution, and to judge whether the air has been acceptable for crew health. (LMLSTP)

- Future research should focus on understanding the risks that specific pollutants pose to crew health, and then developing analyzers capable of addressing those risks using a minimum of resources. (LMLSTP)
- A food and nutritional management system is a powerful tool for future missions to permit optimal management of food and eating onboard while also allowing online analysis of crew member nutritional status so that food intake and supplements can be adjusted on an as-need basis. (EXEMSI-92)
- Direct involvement of the crew in menu planning and selection, in addition to menu variety, and extra food supply, allows crew members choice in regards to food intake and contributed to overall food and mission satisfaction. (EXEMSI-92)
- A menu could be developed from the basic crop list. This menu was acceptable for a crew for 10 days and met most of the nutritional requirements; it was, however, a very labor-intensive diet with excessive waste. Comprehensive research is needed in the areas of food processing and preparation in an enclosed environment. (LMLSTP)
- Contamination study findings for a particular simulator revealed that although there were established rules for hygiene, the rules were not followed. Findings showed that the disinfectants used were not effective for eliminating microbial growth, the crew lacked training in environmental hygiene, and the crew did not appoint anyone as responsible for hygiene matters. (EXEMSI-92)
- There is a need for clear definition of wet and dry trash. It is also important that each crew member understands the difference and be trained on how to handle both kinds of trash. (LMLSTP)
- The galley should be supplied with a trashcan that has a foot control for its lid. A lid which pivots open easily would also be acceptable. This can ensure sanitary conditions when the trashcan needs to be used during meal preparation. (LMLSTP)
- There is a need to address and eliminate odor issues resulting from trash and lack of hygiene amongst certain crew members. (EXEMSI-92)

DISCUSSION

The simulator survey presented a collection of interesting findings about simulator design and operations, as well as about simulation research objectives and methods. This section attempts to synthesize and present some of the key characteristics identified by the LSG research team members conducting the survey review.

‘SINGLE EVENT SIMULATOR’ VERSUS ‘FULL MISSION SIMULATOR’

Space mission simulators come in various formats. Some are short duration, some long. Some are “partial simulators” or “single event simulators”, while others are “full mission simulators”. A significant number of past simulators have been ‘single event simulators’. It is important to note that the nomenclature does not limit the number of simulated events to one; it could be more than one event. Over the years, ‘single event simulators’ have had a fair degree of success. As with flight or submarine simulators, these “single events space mission simulators” fully immerse the simulation subjects in the simulated event/s and help research certain focused aspects of the mission.

A ‘full mission simulator’, on the other hand, takes an integrated approach to simulating the entire mission (launch, transit, landing on the planet, surface stay, ascent from the planetary surface, transit back to Earth, and landing on Earth) rather than parts of it. In a sense, a “full mission simulator” may be regarded as comprising several “single event simulators” either running in sequence or in parallel. To date, there have been no ‘full mission simulators.’ For testing long duration planetary missions, a planetary simulator stay that enables full interface with all surface exploration systems and performance of live field geology is imperative.

‘DEDUCTIVE’ VERSUS ‘INDUCTIVE’ RESEARCH METHODOLOGY

The research methodology popular with most space agencies uses a *deductive* approach where one gets answers to predefined questions, based on a primarily quantitative approach. This can be problematic due to limited numbers of test subjects. It is perhaps acceptable for the *physiological* tests to be based on a deductive method, but *psychological* and *sociological* protocols could miss out on important information if subjects were only to do test batteries and fill out questionnaires. In the future, it would be interesting and of considerable research value to pursue an *inductive* approach for *psychological* and *sociological* research. This would open up the possibility of getting more in-depth information from individual test subjects and would allow development of the investigation while the experiments are in progress. Finally, it would serve to provide a means to explore and validate ‘lessons learned’ during any multi-phase experimental flows.

INTEGRATING HABITAT DESIGN INTO THE RESEARCH AGENDA

Various simulation studies provide some insight into various habitability and human factor issues, but the interplay of these issues has yet to be thoroughly investigated. In most simulations, habitat design is not given serious consideration, despite research findings indicating it could serve as a significant countermeasure to stressors, especially during long duration space missions. Thus habitat design needs to be integrated better into the overall research agenda. Habitat design parameters (e.g. windows, lighting, color, layout, etc.) should be treated as variable parameters that could be modified in response to findings with every successive mission or even during a mission. We need to better understand how the various habitat design parameters could positively or negatively influence crew moods, behavior, and performance.

INTERNATIONAL GUIDELINES FOR DATA MANAGEMENT

Despite having numerous simulation campaigns over the past three decades, there is no easy way to access and compare the data collected by each of these campaigns in the absence of planned data collection, archival and analysis at the onset of a mission. The ISEMSI-90, EXEMSI-92 and HUBES-94 campaigns have been exemplary in this respect. ESA developed and used what it called Global Analysis of Scientific Data from the European Manned Space Infrastructure' (GLOBEMSI).

Space agencies, institutes, and academics involved in simulation research would benefit from collaborating on the development of international guidelines for data collection, archival and analysis. Data emerging from the various campaigns could then be pooled together and used by cooperating parties. This data could be made available accessible via the Internet such that researchers worldwide could access data without having to navigate time consuming bureaucratic and logistical hurdles.

FIDELITY BENCHMARKS

The simulator survey revealed that there is a lack of established benchmarks for simulator or simulation fidelity. It became evident that practically all simulators and simulations are designed under budgetary as well as programmatic constraints and often end up focusing narrowly on a few research objectives, while compromising the overall fidelity of the simulator architecture and operations. While it is understood that simulators cannot replicate everything, given the constraints, it is important to aim for greater rigor and higher fidelity standards to the maximum extent possible. The objective is to find ways to mitigate risk, both in the spacecraft systems and the human system (mission crew). If simulator fidelity is compromised, then the simulation data generated is not credible, and thus inappropriate for the design of real missions.

CONCLUSION

In 2008, the European Space Agency (ESA) and the Institute for Biomedical Problems (IBMP) in Moscow plan to conduct a new series of long-duration space mission simulations called 'Mars500' [67, 68] leading up to a final unprecedented long-duration Mars mission simulation of nearly 520 days. This will involve a crew of six who will live and work in a lattice of six interconnected hermetically sealed modules in a Moscow laboratory. This campaign will reflect all aspects of a future mission to Mars (e.g. transit times, surface stay and exploration, communication lags, autonomous decision making, limited consumables). The Mars mission scenario includes (a) interplanetary outbound flight - 250 days, (b) Mars surface operations - 30 days, and (c) interplanetary return flight - 240 days. This is the most ambitious duration ever attempted in a ground-based simulator.

Carrying forward the value of lessons learned from past simulator campaigns, The Mars500 campaign could aim for architectural and operational fidelity higher than all its predecessors. It could build upon the GLOLBEMSI data management techniques developed by ESA. In addition to the traditional research areas observed with past campaigns, it could focus on habitat design as a countermeasure to boredom and socio-psychological stressors associated with long-term isolation and confinement. It could also experiment with inductive methodologies, in addition to the deductive approach usually used for psychological and sociological research. Thus, as Mars500 is set to be the first 'full mission simulator' of its kind it provides an excellent opportunity to achieve substantial improvements on past simulation campaigns and serve as a benchmark for future simulators.

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ABBREVIATIONS

AAS	American Astronautical Society
ALS	Advanced Life Support
ARC	Ames Research Center
ARS	Air Revitalization System
ASCE	American Society of Civil Engineers
ASU	Arizona State University
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
CAPSULS	Canadian Astronaut Program Space Unit Life Simulation
CEEF	Closed Ecology Experiment Facilities
CIC	Crew Interface Coordinator
CP	Conference Proceedings
CR	Control Room
CSM	Command/Service Module
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ECLS	Environmental Control and Life Support
EMSI	European Manned Space Infrastructure
EnviHab	Environmental Habitat
ESA	European Space Agency
EU	European Union
EVA	Extra-Vehicular Activity
EXEMSI	Experimental Campaign for the European Manned Space Infrastructure
FIPES	Facility for Integrated Planetary Exploration Simulation
FMARS	Flashline Mars Arctic Research Station
GLOBEMSI	Global Analysis of Scientific Data from the European Manned Space Infrastructure
GRC	Glenn Research Center
HUBES	Human Behavior in Extended Spaceflight
ILSSTF	Integrated Life Support System Test Facility
IPEV	Institut Paul Emile Victor
ISEMSI	Isolation Study for the European Manned Space Infrastructure
ISS	International Space Station
JIS	Joint Integrated Simulation
JSC	Johnson Space Center
LBNPD	Lower Body Negative Pressure Device
LMLSTP	Lunar Mars Life Support Test Project
LSSIF	Life Support System Integration Facility
MARS	Mars Analog Research Station
MDRS	Mars Desert Research Station
MSFC	Marshall Space Flight Center
MUST	Medical Unit Self-contained, Transportable
NASA	National Aeronautics and Space Administration
NEK	Ground-based Experimental Facility
NEEMO	Extreme Environment Mission Operations

NOAA	National Oceanic and Atmospheric Administration
PNRA	Programma Nazionale di Ricercha in Antartide
SAE	Society of Automotive Engineers
SMEAT	Skylab Medical Experiments Altitude Test
SML	Skylab Medical Laboratory
SPF	Space Power Facility
TCS	Thermal Control System
TDC	Test Director Console
TM	Technical Memorandum
TN	Technical Note
US	United States
VPGC	Variable Pressure Growth Chamber
WRS	Water Recovery System

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