AO/1-7914/14/F/MOS
Analogues for Preparing Robotic and Human Exploration on the Moon
-
Needs and Concepts

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Study Background & Objective

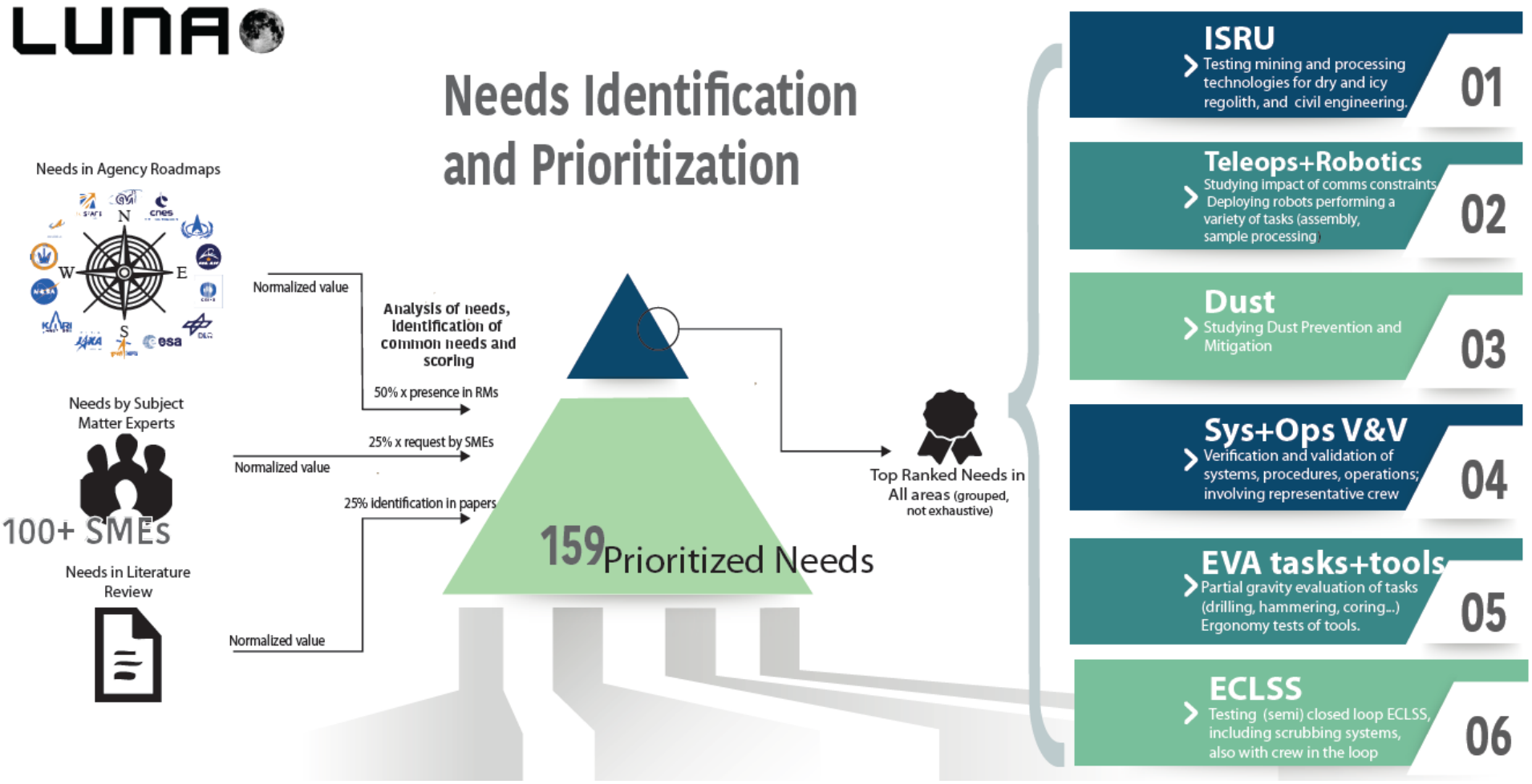
- Artificial Lunar Analogues
  - Definition: Human-made terrestrial facilities and/or tools that provide conditions that are analogue to specific conditions on the Moon and that can be used to simulate and train lunar exploration missions
  - Advantages of Artificial Analogues:
    - Reduced logistical preparations and costs
    - Increased test time (reduced logistics, weather independent)
    - Ability to control & standardise the environment

- Study performed under ESA's General Studies Programme (GSP), Oct2014 - Dec2015

Objective

Identify where ESA can develop capabilities / build up facilities as a contribution to the international effort of exploring the Moon in the future.

Needs analysis



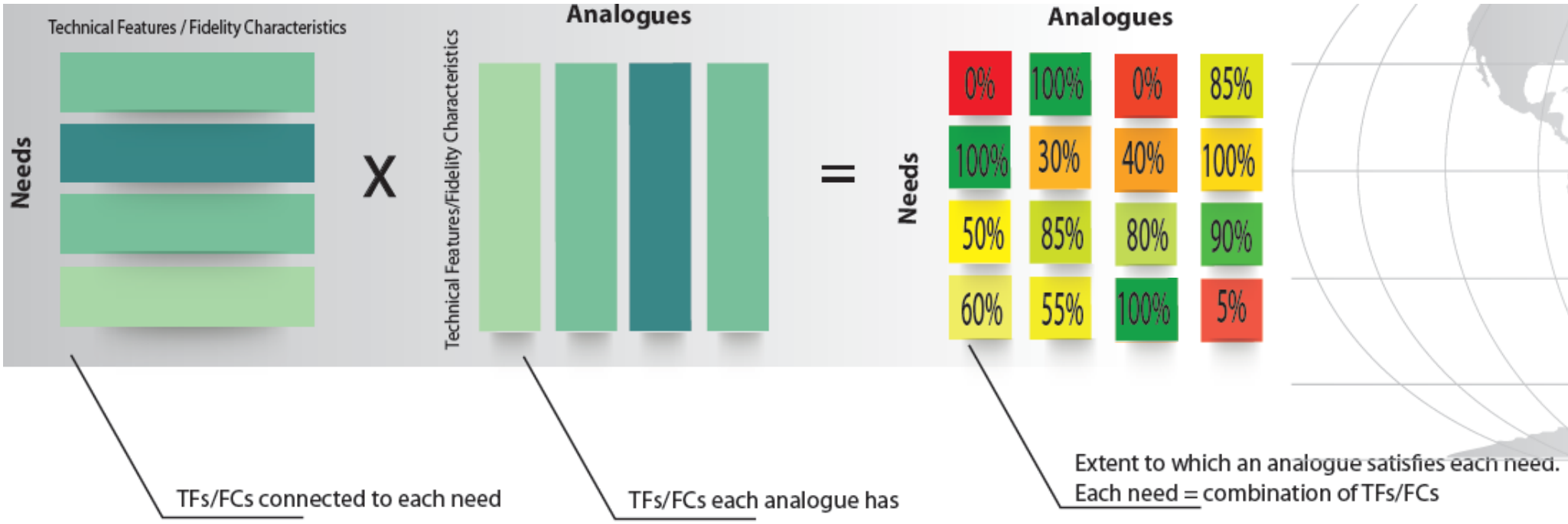
Catalogue of Existing Artificial Analogues

- A catalogue of existing artificial analogues has been developed
  - Analogues that can be used for mission simulation and preparation of future lunar missions
  - Facilities world-wide (not limited to ESA-state facilities)

- 47 facilities identified worldwide, high number in Europe and US
  (non-exhaustive list, data on facilities in e.g. China, Russia, India are sparse)

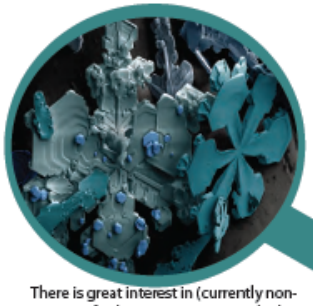
- Clusters of various facilities:
  - Cologne, Germany → European Astronaut Centre, German Aerospace Center (DLR) facilities and :envihab
  - Torino, Italy → Thales Alenia Space and ALTEC facilities
  - NASA's Johnson Space Center (JSC), US

Gap Analysis - Methodology



LUNA

Gap Analysis
Results *



There is great interest in (currently non-existing) facilities to test water-volatile extraction and separation from lunar polar icy material.

Various European science and engineering communities would benefit from the availability of Medium/large amount of physical fidelity lunar simulant in combination with an area which can be used for 3D printing/constructing with the regolith

EVA hardware operating in conjunction with regolith simulants, also electrostatically charged

Exploration roadmaps highlight the importance of testing advanced human-robot cooperation strategies. A permanent analogue facility that supports this kind of tests would be a valuable asset.

Facilities allowing to perform regolith excavation, material transfer, handling, and processing are currently not available in Europe.

Active response robotic off-loading for pressurized crew is missing worldwide, (and for both pressurized and short sleeve, it is missing in Europe) . It would benefit from their combination with a regolith test bed and threadmill.

Europe could become a leader in studying the impact of dust in various system interfaces if habitat/vehicle egress/ingress facilities were available ,operating in a context involving regolith simulant, also electrostatically charged

The thriving field of space teleoperations in Europe would gain from having access to a setup allowing for robotic control, with AOS/LOS, bandwidth throttling; in combination with Lunar terrain features and soil simulant.

Campaigns in habitats located in an environment/setup relevant for Moon exploration, and that are modest-sized R/V or smaller, with 4-6 people are not available in Europe.

Analogue facility suited for high level integrated simulations, combining habitat, lunar terrain, MCC and the related communications simulations, relevant environmental characteristics, and software allowing for system level simulations are not easily available to European researchers and operations developers.

Scientists and Engineers could learn more about the implications and impacts of external exposure to sun 14.77 days, darkness 14.77 days and/or permanent light and darkness; and also to the habitat full internal artificial spectrum, if this was implemented in a facility, in flight-like integrated campaigns.

Researchers and operators would gain a better understanding and practice with HSF Moon operations by having communications where crew experiences Moon One-Way Light Travel, limited comms with the outside

Active European projects such as MELISSA- would benefit from closed or semi-closed loop ECLSS combined with a habitat and food growth facilities.

General recommendations

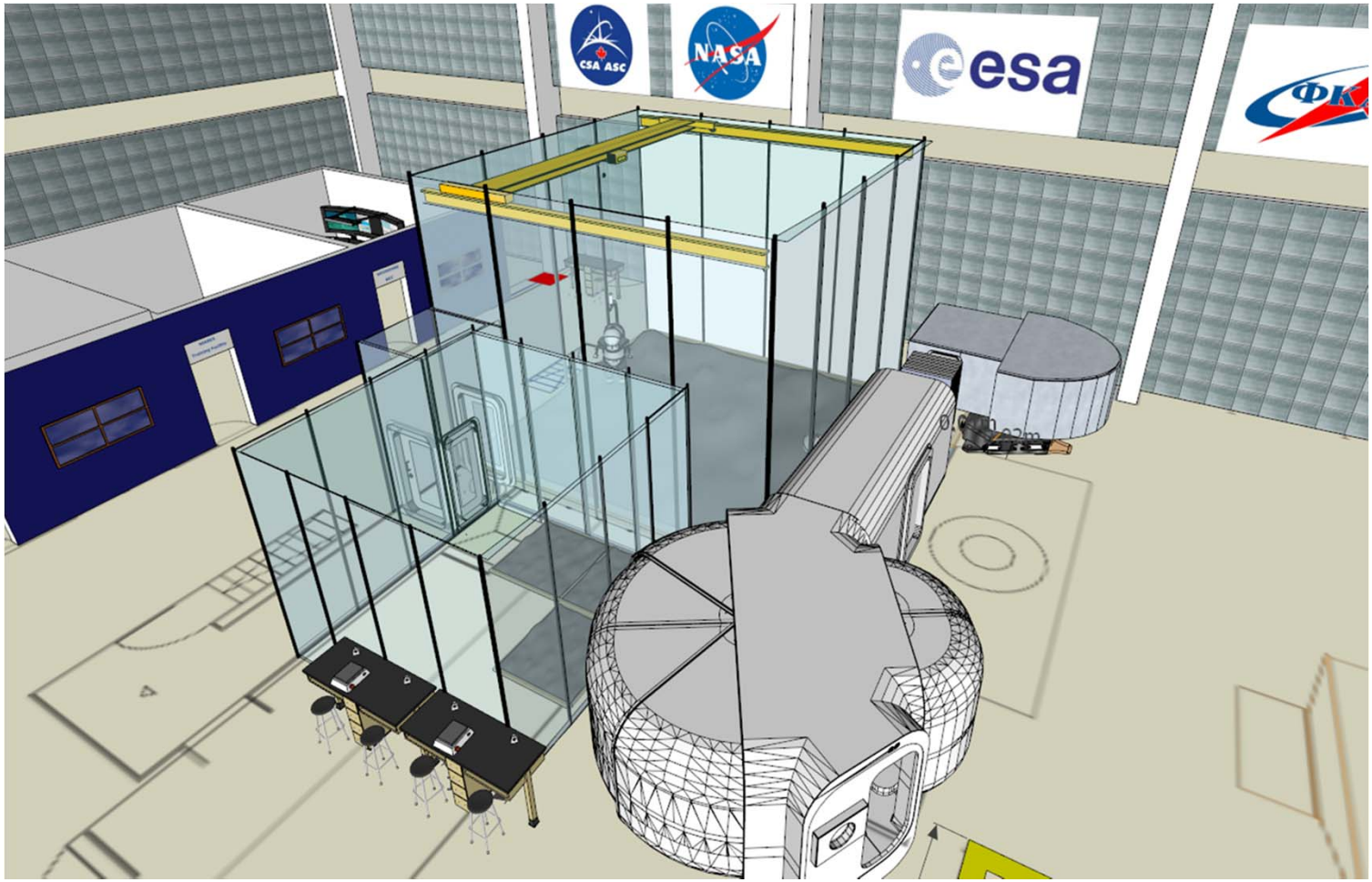
- Implementation of Integrated European Campaigns
- Leveraging existing highly requested Technical Features e.g. DLR/ENVIHAB/EAC
- Enable facilities that satisfy both HSF and Robotics communities
- Enable facilities that address the Moon but also could address other planetary bodies.
- Ensure continued implementation of partial gravity Parabolic Flight Campaigns.
- Implement support TFs in future new facilities or facility enhancements (science coordinator, facility management (booking systems), accessible database of previous campaings)

Technical Feature - related gap

Fidelity Characteristic - related gap

* This infograph provides a high-level summary. Please refer to the detailed gap analysis for more precise identification of TF groups and details on existing and missing TF/FC availability.

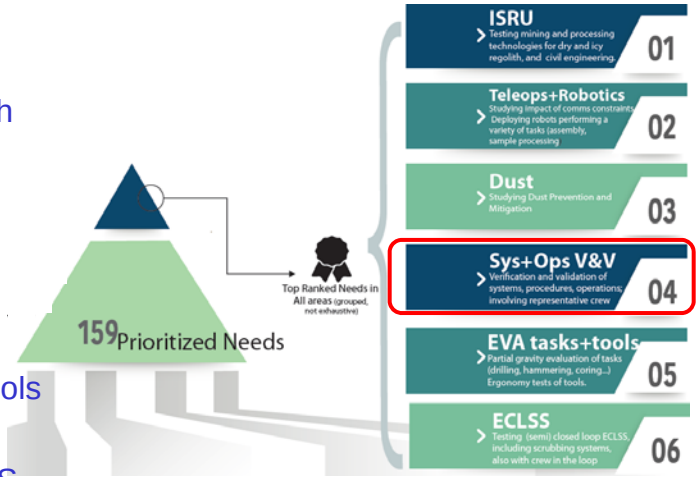
European Surface Operations Laboratory (ESOL)



ESA and International Partners Utilisation

- Preparatory simulations for the HERACLES (Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science) HOPE-1 experiments

- Yearly ESA-organised two-week integrated analogue mission simulation for ESA technology testing, Behavioral Health and Performance research and crew/ground personnel training
  - ISRU technologies/operations testing
    e.g. Luna PROSPECT drill and payload to extract volatiles from icy regolith
  - Robotics technologies/operations testing
    e.g. tele-robotics and haptics lab technology tests
  - Dust mitigation studies
    e.g. electrostatics, physical removal, suit protective covers
  - EVA Tasks & Tools
    e.g. partial gravity evaluation and training of surface tasks, ergonomy of tools
  - ECLSS technologies/operations testing
    e.g. Black Water Treatment & Water Treatment Unit breadboards, MIDASS



- Long-term Isolation Studies in an Operational Environment

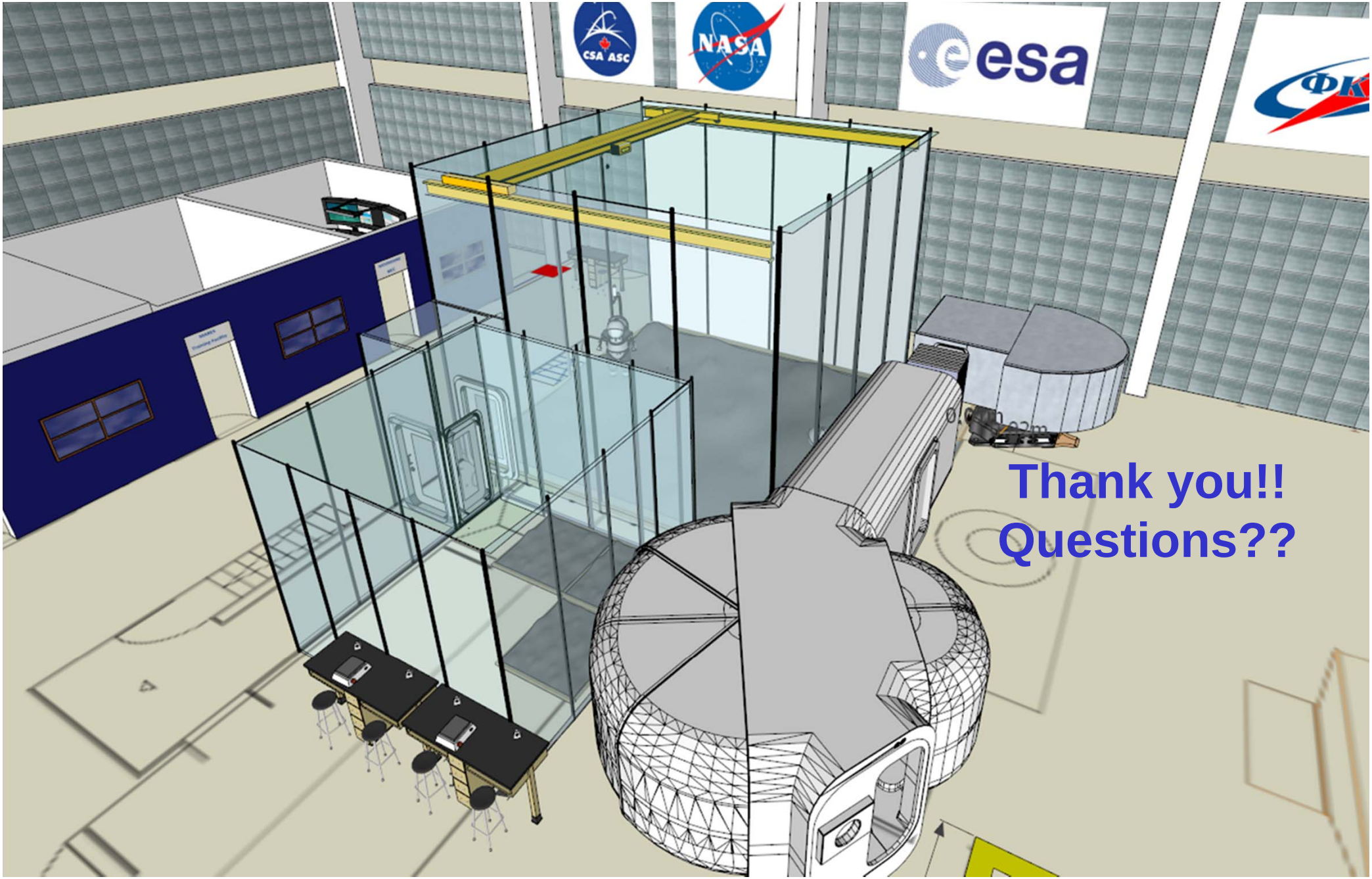
Other Potential Utilisation Scenarios

- German Aerospace Center (DLR) Utilisation
  - ISRU process testing (3D printing and water/oxygen extraction) with regolith simulants
- Spaceship EAC Utilisation
  - The European Astronaut Center has started the ‘Spaceship EAC project’ which has currently ~15 Master Thesis and/or PhD students performing exploration relevant research
  - Strong momentum and substantial growth foreseen in the coming years
- STEM Utilisation
  - International Space University (ISU): yearly analogue simulation campaign part of the MSc curriculum
  - High schools and universities around Cologne
  - Yearly lunar rover competition
- Commercial Utilisation

	Pre-Phase 1	Phase 1	Phase 2	Phase 3
Regolith Simulant Testbed	x			
SHEE Habitat		x	Enhancement (airtight)	Second SHEE
System Level Simulator		x		
EVA, IVA. MCC Information System		x	Enhancement	
EVA Hardware (suit + tools)		2 suits	High fidelity EVA Tools	
Compatible Robot Control Station		x	Enhancement	
Control Room Facilities		x		
Ingress/egress interfaces		x		
Treadmill + VR goggles		x		
Full Motion Simulator			x	
Food Growth Facility				x
Gravity Off-Loading Device			x	
~1000sqm Rover Testbed		Basic facility	Enhancement	
Total ROM Cost	360k€	2.4M€	1.8M€	1.8M€
Utilisation scenarios	• ISRU, Dust • Robotics, Tele-robotics	• HERACLES / HOPE-1 preparatory simulations • ISRU, Dust • Robotics, Tele-robotics • ECLSS (only water recycling)	• EVA Tasks & Tools • ECLSS (air & water)	• Long Duration Isolation Studies (up to 90 days) • ECLSS (air, water, food)
Timeframe	2016	2017	2018	2020

Conclusion

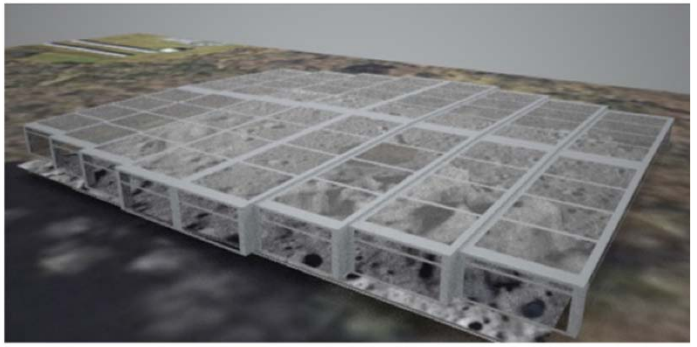
- 3 Artificial Lunar Analogue concepts have been worked out
- Selected concept = ESOL for EAC/DLR site
- 'Mission-focused analogue', i.e. for highly integrated simulations with robots and humans, to test mission scenarios, stress timelines and operations, examine remote operations and procedures, train astronauts for lunar surface operations
- Specialized human capital already available at the European Astronaut Centre (EAC)
  - Astronauts, astronaut instructors, operations support personnel
  - Flight surgeons and astronaut medical support team
  - Education and outreach people
- Unique Selling Points (USP):
  - Habitat and traverse simulator are completely integrated with the (icy)regolith simulant testbed via a suit port module
  - Gravity off-loading device in combination with the (icy)regolith simulant testbed (worldwide gap)
- ESOL concept is strongly back-up by a variety of utilisation scenarios that address the 'driving needs' identified by Subject Matter Experts, in Roadmaps and Literature

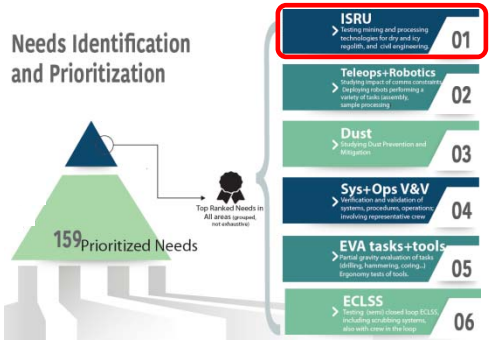

Thank you!!
Questions??

Back up slides

HERACLES / HOPE-1 Experiment Preparation Runs

- Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science
  - → ESA-led study: preparing for Moon robotics tele-operations from cis-lunar habitat
- HERACLES Operations Preparation Experiment (HOPE)
  - → HOPE-1: ground-only experiment with focus on the rover operations part
  - → Simulation of at least 7 days, representative daily schedule (exercise, maintenance, meals)
  - → One crew member in the analogue environment, performing rover operations
  - → Isolated from the outside world, except for voice & data links with MCC
- HOPE-1 Experiment Preparation runs can be completely performed at ESOL:
  - → Habitat Analogue, MCC (incl. delayed communications), and large rover testbed





ISRU Technologies/Operations Testing

- Core drilling / sample retrieval
- Extraction of volatiles
- Excavators

} icy regolith

- Regolith conveyance systems, incl. benefication devices

- <u>ESA focus on core exploration technologies for ISRU:</u> **PROSPECT**

→ Regolith Testbed (incl. icy regolith zone), DLR hypobaric chamber (incl. regolith) for near-vacuum tests

Image: NASA and CSA

Image: NASA Swampworks

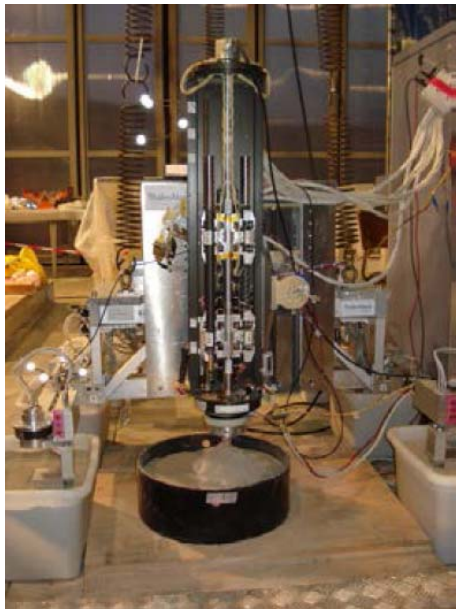
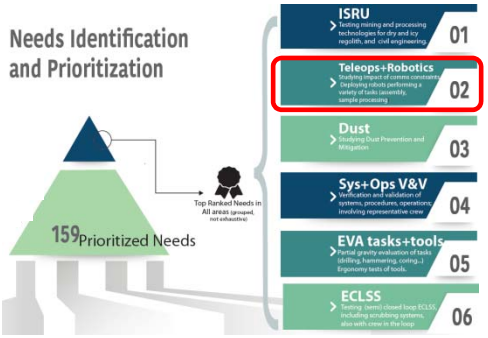


Image: Selex

Robotic Technologies/Operations Testing



- Robotics Tele-Operations
  - Crew in :envihab simulating operations from cis-lunar habitat
  - Crew in SHEE simulating lunar surface operations from the habitat

- Astronaut-Robot Cooperation
  - Crew in Regolith Testbed or Large Rover Testbed
  - Working together with robot/rover
    - Construction tasks
    - Scouting an area difficult to access (e.g. steep slope)
    - Testing different HMIs

Images: ESA-DLR

Image: ICARUS project

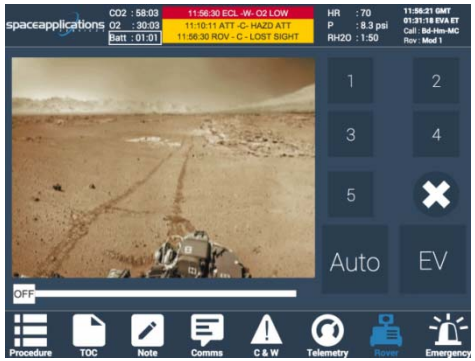
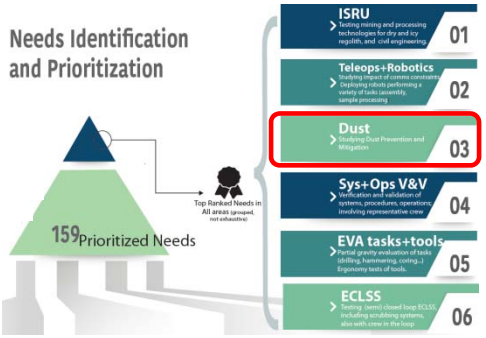


Image: MOONWALK

→ ESOL Regolith Testbed, Large Rover Testbed, Compatible Robot Control Station, Variable Delay Simulation, :envihab, SHEE, Partial Gravity Off-loading (in Phase 2)



Dust Mitigation Studies

- Study effect of dust on spacesuits, suitports, sampling tools
- Test technologies for dust mitigation for habitats and suits (electrostatics, physical removal, suit protective covers)

→ ESOL Regolith Testbed, Habitat and Suitport Interface allow Dust Mitigation Studies

Images: NASA, Apollo missions

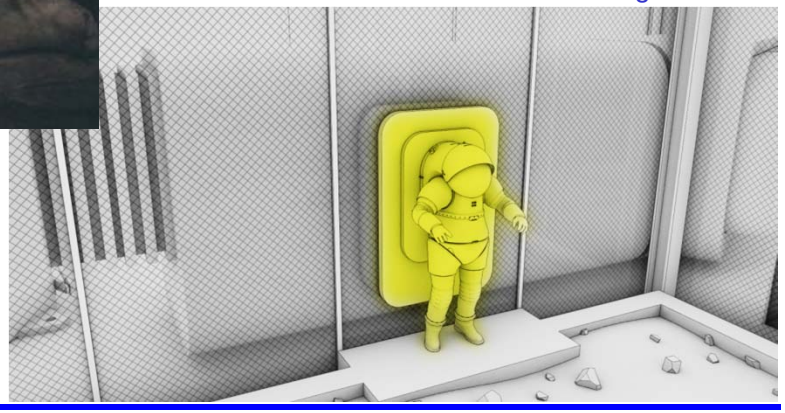
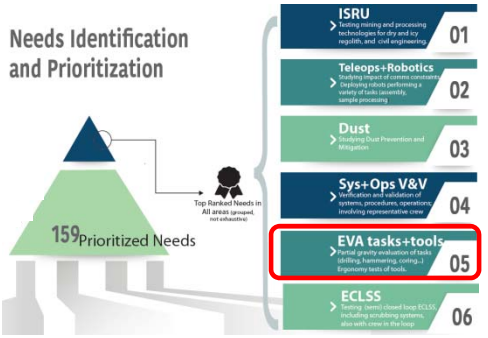
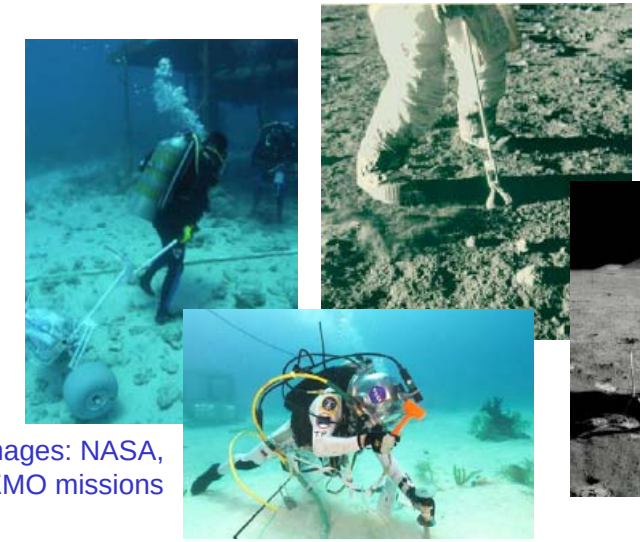


Image: LUNA

EVA Tasks & Tools



- Partial gravity evaluation and training of Tasks
  - Ascent/descent
  - Equipment manipulation (unstow/stow/xfer)
  - Construction
  - Geology tasks (drilling, hammering, coring…)
  - Payload deployment
  - Translation
  - Standing, kneeling
  - EVA human-machine interaction
- Test ergonomy of tools
- Test of future European / International Partner suits (comparison of fatigue, mobility, strength, suit comfort, stability, cognitive performance)



Images: NASA, NEEMO missions

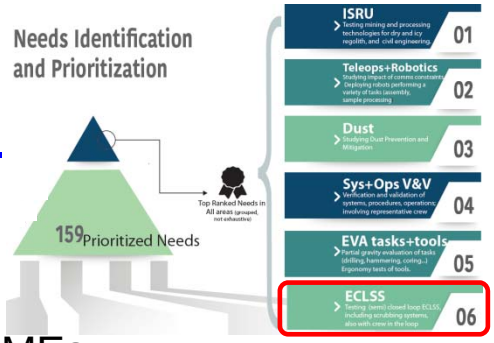
Images: NASA, Apollo missions

→ Neutral Buoyancy Facility

→ Regolith Testbed (Phase 1) in combination with Partial Gravity Off-loading (Phase 2)

→ EVA Training Suit for dry and water immersion + EVA Tools (Phase 1)

→ Omni-directional treadmill in combination with Partial Gravity Off-loading (Phase 2)



ECLSS Technologies/Operations Testing

- Priorities of analogue Habitat characteristics from ESA ECLLS group SMEs:
  1. Air tight: breathable atmosphere in habitat self-sustaining without any gas exchanges with exterior environment.
  2. Water tight: habitat can achieve conservation of water, grey water can be transformed into potable water.
  3. Food: no interaction with external sources is needed to achieve the ESA diet specifications. Turn over of 3-4 months for each batch of food growth. → not the initial scope of ESOL (only in Phase 3)
  4. Hygiene: crew can perform personal hygiene without impacting potable water supply.

- Simulation in the order of weeks to demonstrate 1, 2 & 4

- ESA Technologies that could be used / tested in an operational context:
  - Water Recycling System: already in use at Concordia
  - Black Water Treatment Unit & Water Treatment Unit breadboards, sized for one person (under development, significant testing needed)

  → ESOL / SHEE allows testing in Phase 1

  - ACLS: Advanced Closed Loop System, designed for ISS, sized for 3-persons
  - MIDASS: Microbial Detection in Air System for Space (Phase C/D)

  → ESOL / SHEE allows testing in Phase 2 (air tight)

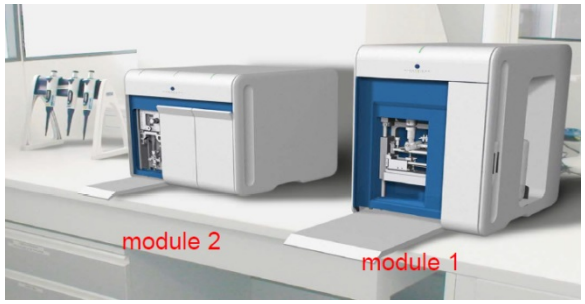


Image: MIDASS, ESA/bioMerieux

Long Term Isolation Studies in an Operational Environment

- ESA acknowledges the need for further isolation campaigns of up to 90 days and has set up an Isolation Steering Committee
  - NASA Human Research Program (HRP) conducts studies of 14 days (2015), 30 days (2016) and eventually 60 days in the HERA habitat
- Campaigns similar to the HERA ones can be conducted at ESOL, with unique integrated capabilities:
  - Habitat integrated with the regolith testbed: EVA surface operations activities for the crew
  - Habitat integrated with the full motion simulator: crew can simulate long traverses in a rover
  - 2 person crew (Phase 1 & 2), 4-6 person crew (Phase 3)

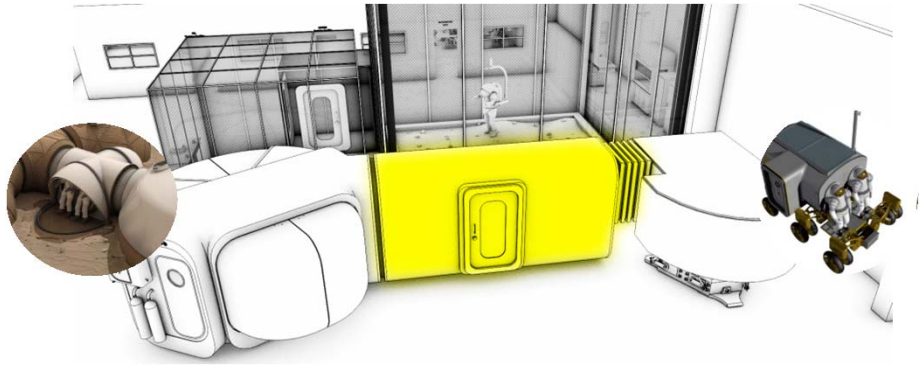


Image: LUNA, LAVA Hive, NASA

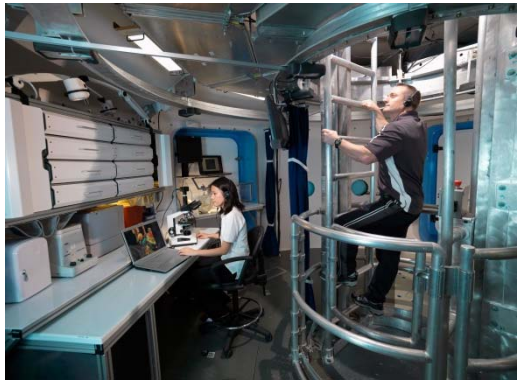
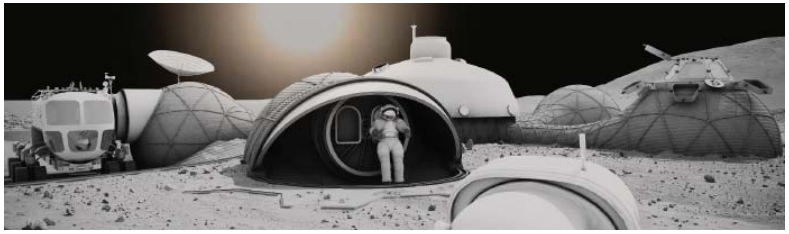


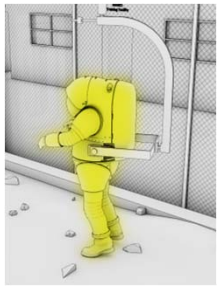
Image: NASA / crew in HERA

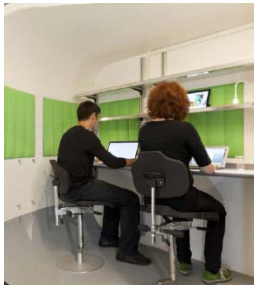
German Aerospace Centre (DLR) Utilisation

- DLR Institute of Material Physics / granular materials:
  - ESA GSTP study: building block to test 3D printing of a future lunar base
  - EU H2020 RegoLight: automated 3D printing via sintering of lunar regolith simulant with solar light



- DLR research groups in the medical area
  - ESOL offers complementary facilities to :envihab → for tests with humans
  - An integrated simulation can be conducted in ESOL and test subjects can be evaluated and trained in : envihab (pre- and post- BDCs)



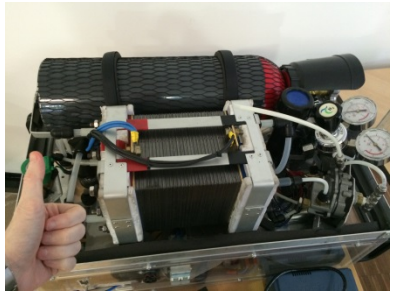


Spaceship EAC

Main objective: develop operational concepts and low-TRL-technologies in support of HSF exploration missions (specific focus on lunar habitation scenarios)

- Projects currently ongoing:
  - Energy research
    - Lunar based Fuel Cell system (simulation and hardware-in-the-loop)
    - Energy provision using lunar regolith, other energy storage concepts with ISRU
  - ISRU, Materials & Additive Manufacturing
    - Processing and sintering of lunar regolith
  - Water purification/recycling
    - Hydroponics and plant growth experiment with DLR
  - Simulation / Habitability research
    - Baseline virtual lunar base, simulating different aspects of its metabolism
    - Develop virtual lunar EVA's for robotic/human mission planners, scientists and Outreach

→ ESOL Lunar Regolith Testbed, Habitat, VRSUS and System Level Simulator will allow **bridging Research and Operations**



Images: Spaceship EAC

STEM Utilisation

- International Space University (ISU): yearly three-day analogue simulation campaign as part of the MSc curriculum, and as part of the ISU Space Studies Programme (SSP)
  - Preparation & execution of 2 days simulation with students as analogue astronauts in habitat, during EVAs and in MCC
  - Hands-on experience and full overview of a Human-Robotic space mission to the Moon / Asteroid
- High schools and universities around Cologne
- Yearly lunar rover competition

Images: NASA

Images: ISU SSP Analogue Workshop