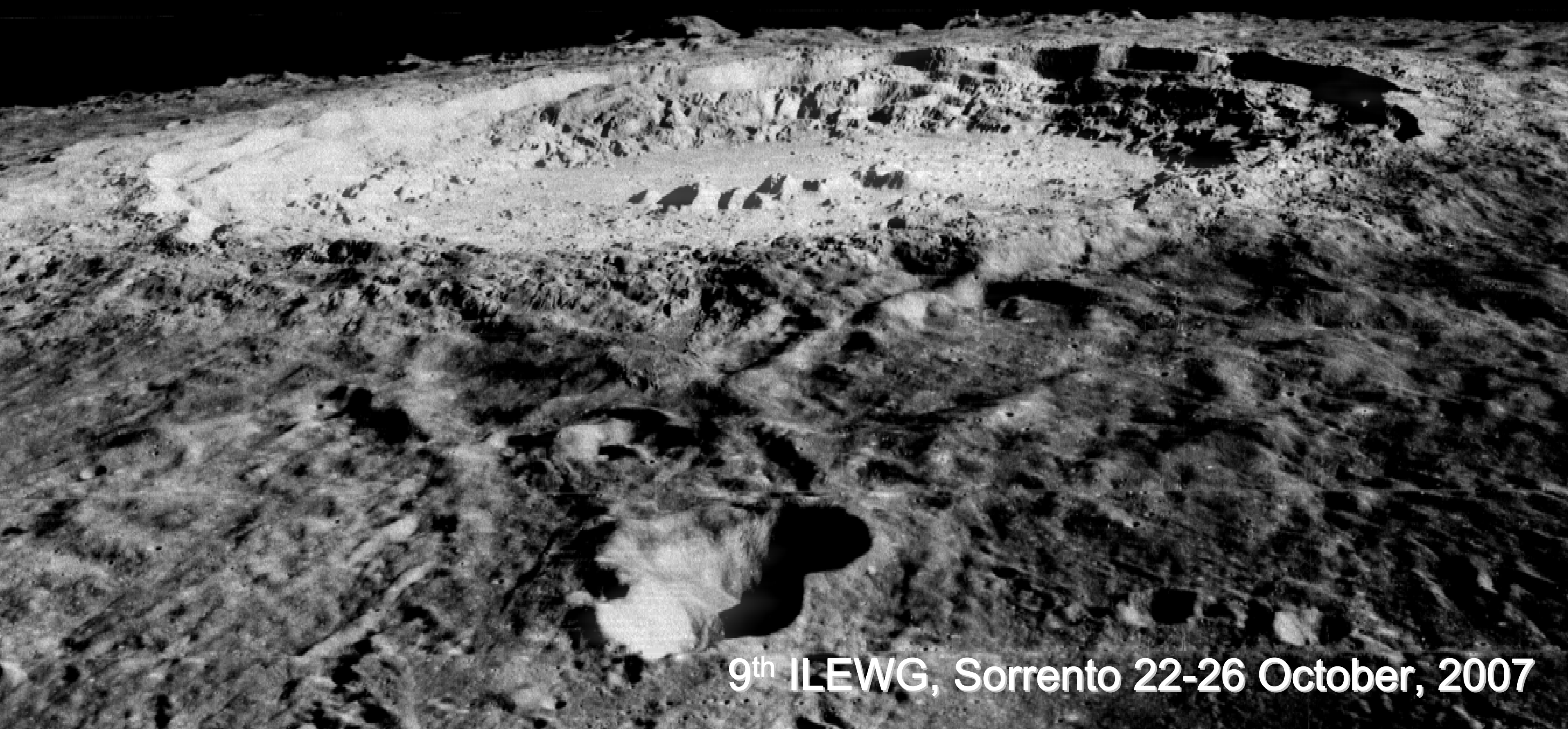
D'APPOLONIA

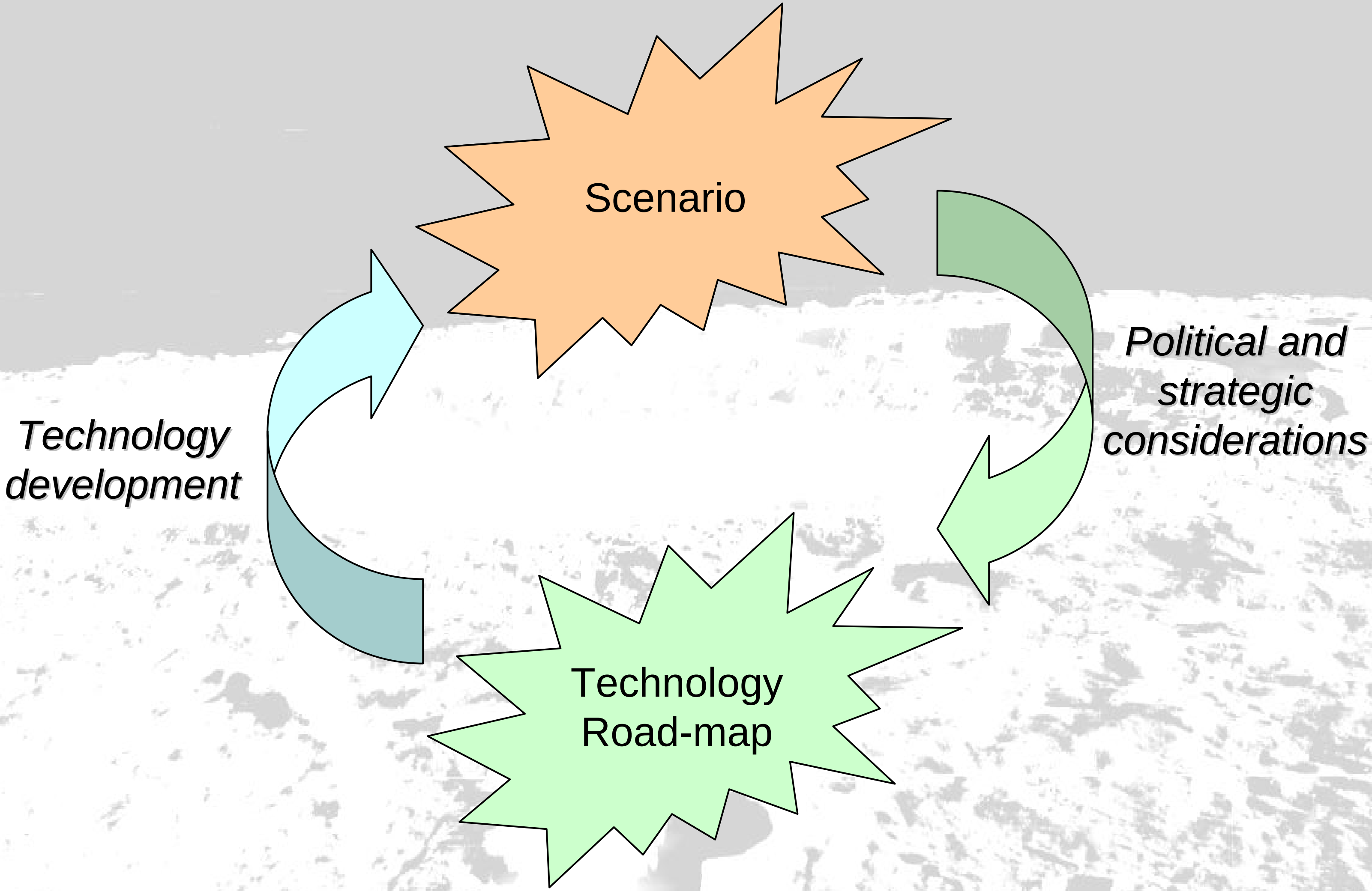
Exploitation of Lunar resources: ISRU and oxygen production

F.Piccolo – D'Appolonia S.p.A.



9th ILEWG, Sorrento 22-26 October, 2007

Conceptual workflow



Lunar Exploration Scenario

Planned Lunar manned missions (info based on publicly available info)

NASA 2018-2020

ISRO 2020

CNSA 2024

РОСАВИАКОСМОС 2025

esa

Lunar Architecture Studies Ongoing

Options for Europe:

- ✓ ***Political Space Actor***
- ✓ ***Economic Space Actor***
- ✓ ***Pragmatic Space Actor***

ISRU Conceptual Road Map

Taking as a reference NASA (source: Sanders/JSC) work publicly known main priorities are:

- ✓ Identify and characterize resources on Moon
- ✓ Demonstrate ISRU concepts, technologies and hardware capable to reduce mass, cost and risk for future Mars missions, e.g.:
  - ☑ *Thermal/chemical processing subsystems for oxygen and fuel production*
  - ☑ Excavation and material handling & transport
  - ☑ Cryogenic fluid storage & transfer
  - ☑ Metal extraction and fabrication of spare parts
- ✓ Use Moon for operational experience and mission validation for Mars
- ✓ Develop and evolve lunar ISRU capabilities that enable exploration capabilities from the start of the outpost phase
- ✓ Develop and evolve lunar ISRU capabilities to support sustained, economical space trasportation, presence on Moon, and space commercialization efforts

ISRU Operational Road Map

As per the deployment of future outpost, NASA (source: Sanders/JSC) work publicly known foresees subsequent steps:

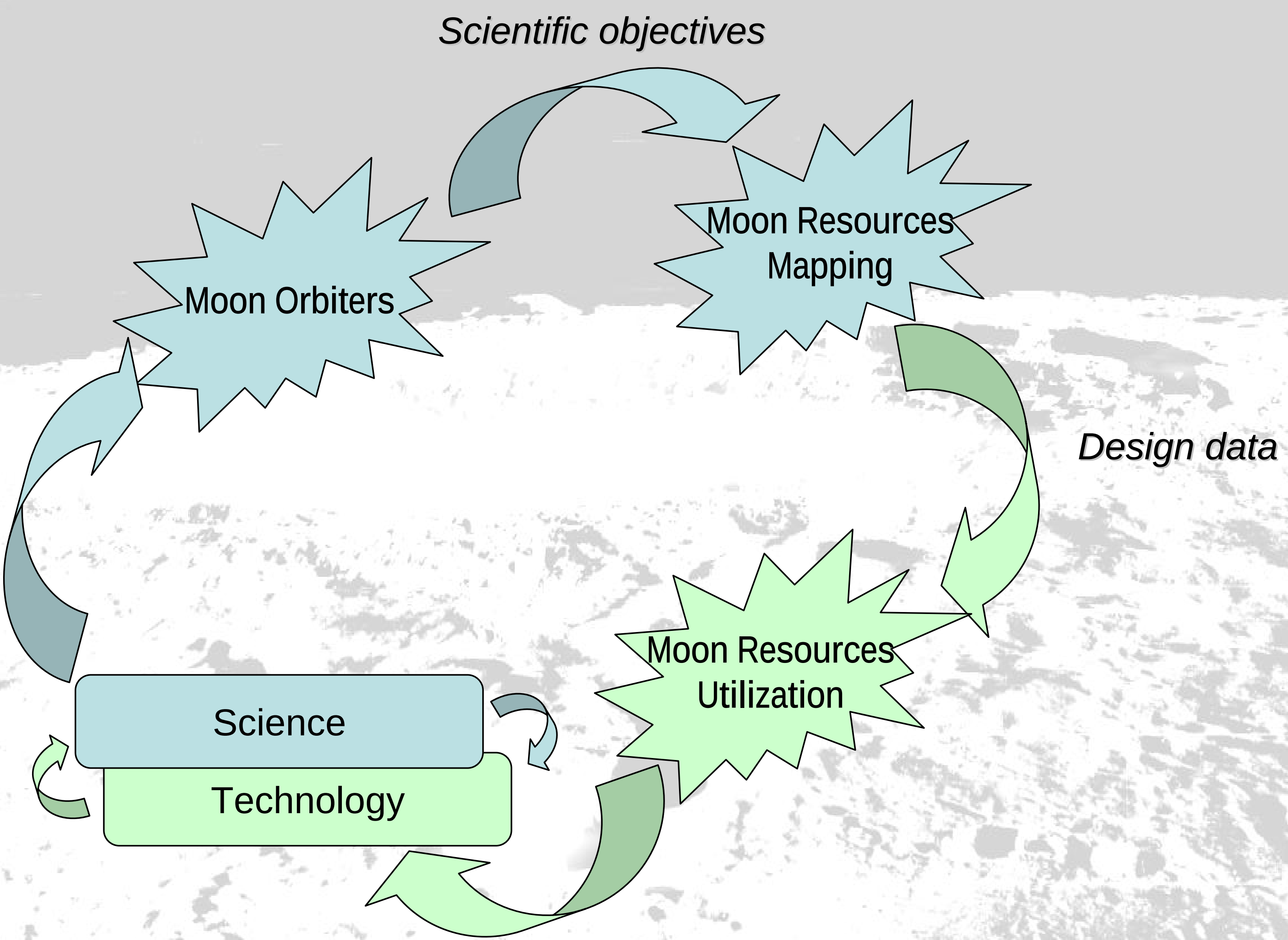
- ✓ Pre-Outpost
  - ☑ Resources determination
  - ☑ Proof-of-concept of ISRU capabilities and link to commercialization
  - ☑ Site characterization
- ✓ Early Outpost: Initial ISRU capabilities (5 years)
  - ☑ ***Pilot scale oxygen production, storage & transfer***
  - ☑ Pilot scale water production, storage & transfer (hydrogen available?)
  - ☑ In-situ fabrication and repair
  - ☑ Other capabilities: Excavation, site preparation, …
- ✓ Mid Term ISRU capabilities – Hub&Spoke growth
  - ☑ ***Propellant production for LSAM***
  - ☑ Consumables for habitation and pressurized rover
  - ☑ Construction and fabrication demonstrations
  - ☑ Nitrogen demonstrations
- ✓ Long-Term ISRU capabilities
  - ☑ In-situ manufacturing and assembly
  - ☑ Habitat construction
  - ☑ ***In-situ life support***
  - ☑ Power generation for Moon and beyond

Moon Architecture Timeline

2015 — 2020 — 2025 — 2030 — 2035

Phase 1	Phase 2	Phase 3
Early Robotics Orbiter 1st Lander **Technology Demonstration for Manned missions** CSTS Propulsion RdV&Docking Radiation Life Support **ISS**	**Extended Robotics** Deep Drill, Sample Returns, RF Telescope **Surface Sorties** **Core Lunar Space Station** SM, Node **Comms & Nav Systems** **Technology Demonstration for Extended Manned missions** EVA, ISRU, Life Support	**Advanced Robotics** Telepresence **Manned LSS** **Lunar Surface Base** **Reusable Vehicles** **ISRU Facilities** **Extended Comms & Nav Systems**

ISRU: Closing the loop



Lunar Resources Composition

Average composition of Apollo and Luna samples

Component	A-11	A-12	A-14	A-15	A-16	A-17	L-16	L-20
SiO_2	42.47%	46.17%	48.08%	46.20%	45.09%	39.87%	43.96%	44.95%
Al_2O_3	13.78%	13.71%	17.41%	10.32%	27.18%	10.97%	15.51%	23.07%
TiO_2	7.67%	3.07%	1.70%	2.16%	0.56%	9.42%	3.53%	0.49%
Cr_2O_3	0.30%	0.35%	0.22%	0.53%	0.11%	0.46%	0.29%	0.15%
FeO	15.76%	15.41%	10.36%	19.75%	5.18%	17.53%	16.41%	7.35%
MnO	0.21%	0.22%	0.14%	0.25%	0.07%	0.24%	0.21%	0.11%
MgO	8.17%	9.91%	9.47%	11.29%	5.84%	9.62%	8.79%	9.26%
CaO	12.12%	10.55%	10.79%	9.74%	15.79%	10.62%	12.07%	14.07%
Na_2O	0.44%	0.48%	0.70%	0.31%	0.47%	0.35%	0.36%	0.35%
K_2O	0.15%	0.27%	0.58%	0.10%	0.11%	0.08%	0.10%	0.08%
P_2O_5	0.12%	0.10%	0.09%	0.06%	0.06%	0.13%	0.21%	0.08%
S	0.12%	0.10%	0.09%	0.06%	0.06%	0.13%	0.21%	0.08%
H	51.0ppm	45.0ppm	79.6ppm	63.6ppm	56.0ppm	59.6ppm		
He	60ppm	10ppm	8ppm	8ppm	6ppm	36ppm		
C	135ppm	104ppm	130ppm	95ppm	106.5ppm	82ppm		
N	119ppm	84ppm	92ppm	80ppm	89ppm	60ppm	134ppm	107ppm

Lunar Resources Composition

Summarizing, all the common soils on the Moon are rich (percentages are given by weight) in:

- ✓ oxygen (about 45% by weight)
- ✓ silicon (about 21 %)
- ✓ iron (6 to 15%)
- ✓ aluminum (5 to 13%)
- ✓ calcium (8 to 10%)
- ✓ magnesium (about 5%)
- ✓ titanium (up to 6%).

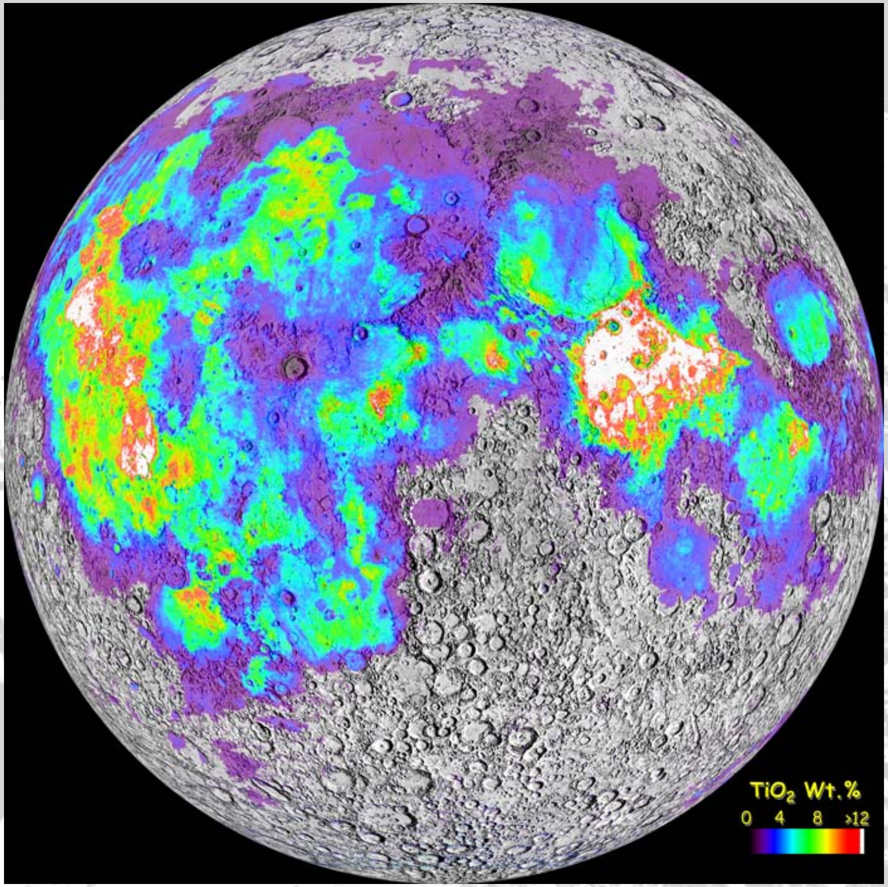
No ore bodies like those found on Earth have been proven to exist on the Moon, but some rock types have concentrated certain minerals; namely:

- ✓ **Ilmenite** (rich in iron, titanium, and oxygen),
- ✓ **Anorthite** (rich in calcium, aluminum, silicon, and oxygen)
- ✓ **Olivine** and **Pyroxene** (rich in magnesium, iron, silicon, and oxygen)

Lunar resources: TiO_2

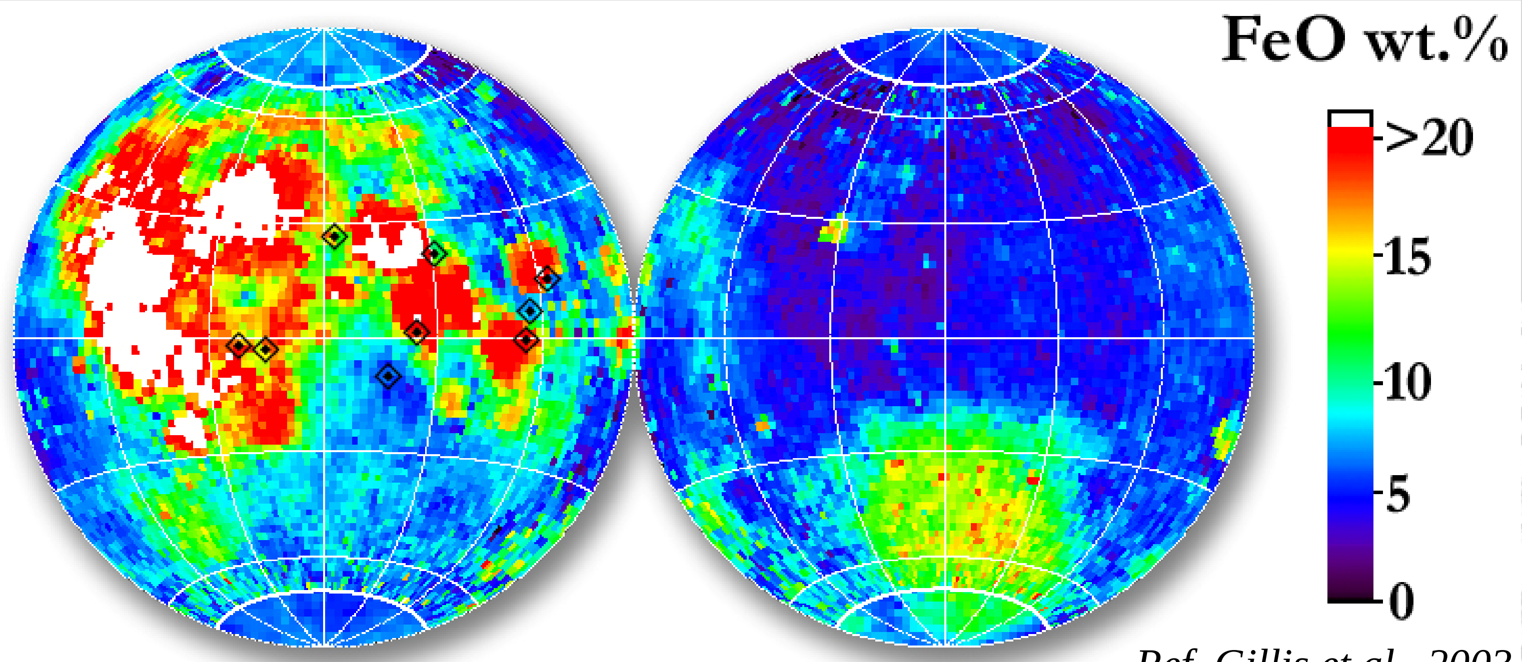
Areas shown in color highlight the highest concentration of TiO_2 on the lunar surface.

Basalt with the highest Ti concentrations is expected to work also as a proxy for solar wind implanted elements and nobel gasses (H, C, N, and ^{3}He)



Ref. Gillis et al., 2003

Lunar resources: FeO

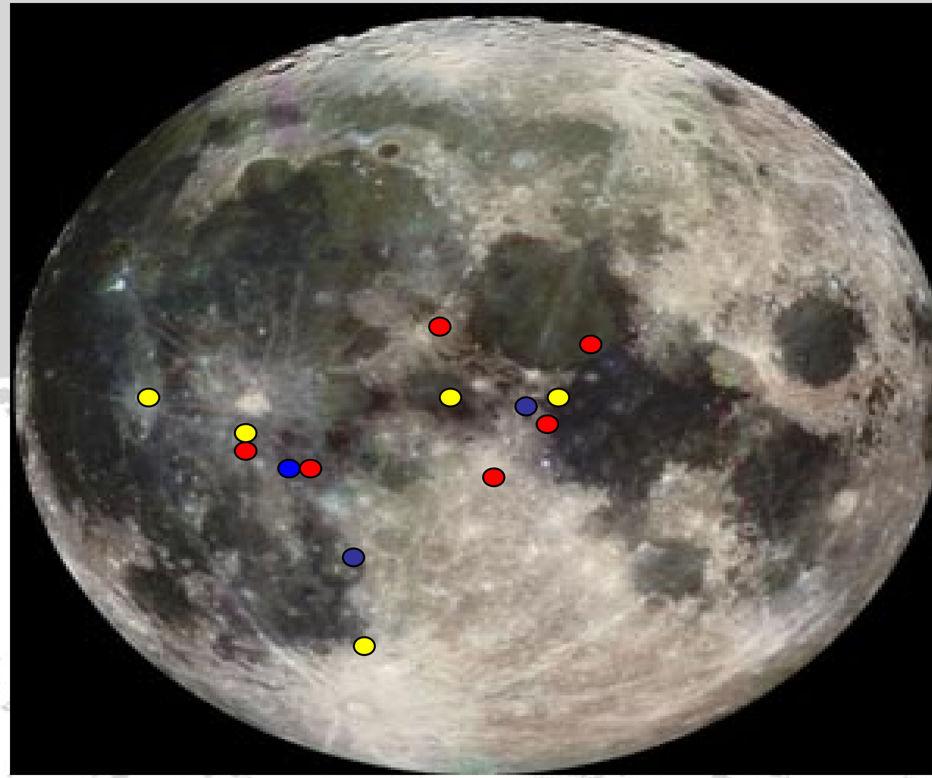


Ref. Gillis et al., 2003

Areas shown in color highlight the highest concentration of FeO on the lunar surface.

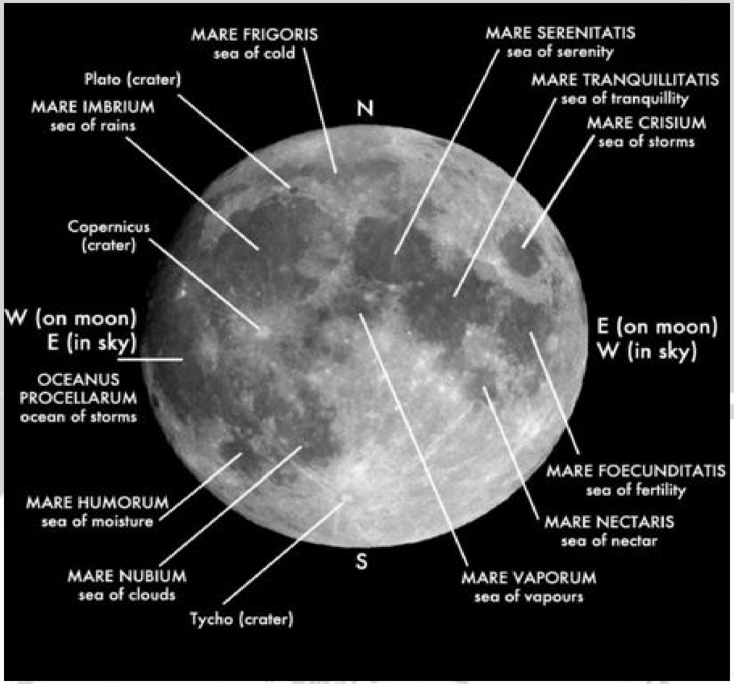
US previous landing sites – Near side

- Surveyor
- Ranger
- Apollo



<u>Oxygen mining appears to be the most promising candidate for early commercial activities on the Moon</u>.
The gas is vital to life-support systems and as a rocket propellant. Most of the mass of lunar spacecraft launched (at great cost) from Earth is oxygen propellant, at a reference cost of around $59,000/year

The starting point: Lunar Raw Materials



Lunar Regolith

Place	Mineral	Composition
Mare	Ilmenite	$FeTiO_3$
	Pyroxene	$(Fe,Mg)SiO_3$
	Olivine	$(Fe,Mg)_2SiO_4$
	Anorthite	$CaAl_2Si_2O_8$
Highland	Anorthite	$CaAl_2Si_2O_8$

Regolith geographical distribution & availability

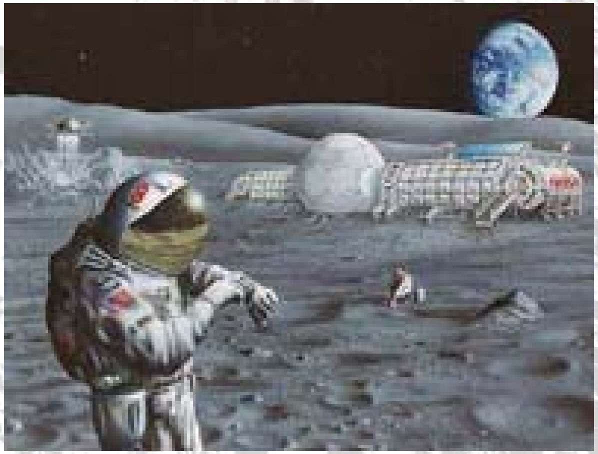
Mineral	Mare	Highlands	Resources
Plagioclase	10-40%	70-95%	Al, Na, Ca, Si, O_2
Ilmenite	2-20%		Fe, Ti, O_2
Olivine	0-20%		Mg, Fe, Si, O_2

Mission Requirements – oxygen production

Based on recent NASA work, reference preliminary mission requirements for the first lunar outpost on the Moon can be selected as follows for oxygen production:

✓ 1 MT per year for the initial outpost (2023)

(EVA and habitation life support needs)



✓ 10 MT per year for the enhanced station (2027)

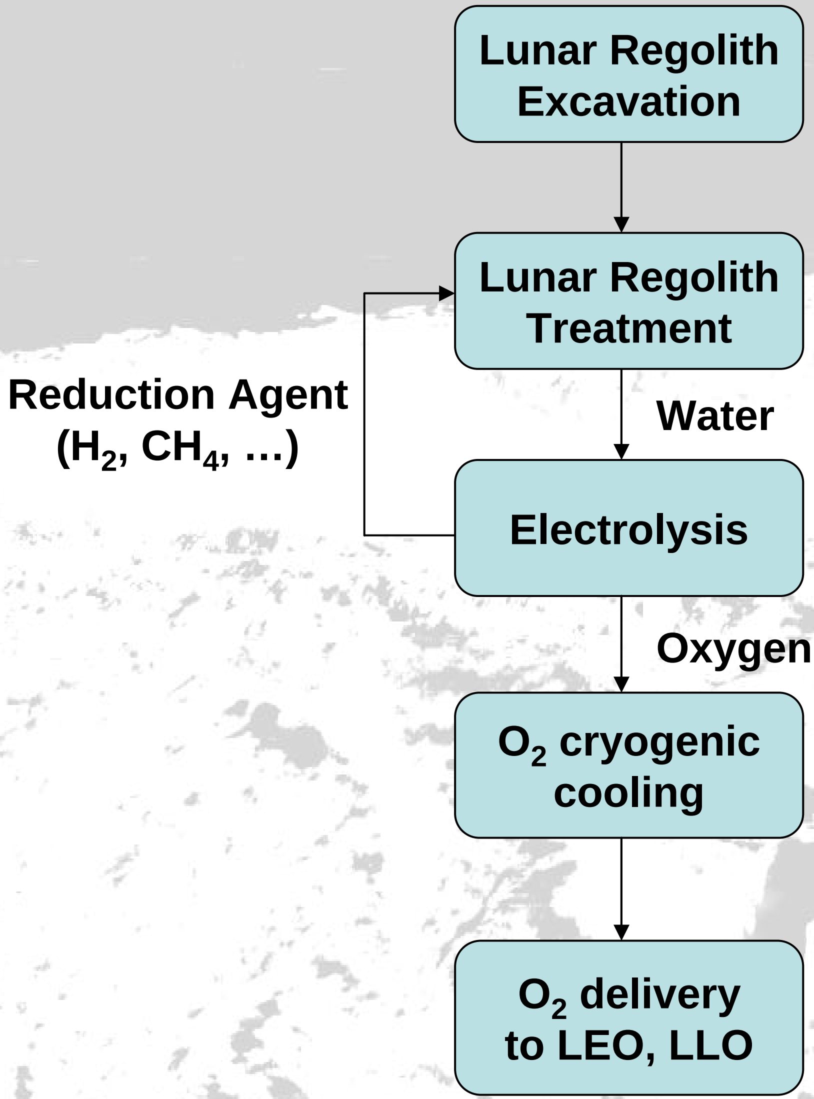
(2 LSAMs, EVA consumables, and

habitat/life support backup)

Photo courtesy of NASA

Oxygen production sample workflow

Phase



Issue

Excavation efficiency

Inputs (reagents, power) availability

Treatment equipment

Cooling process

Lunar vs. Terrestrial miners: Spin-in process?

Extracting oxygen from lunar rocks (and other physiochemical extraction and minerals separation) requires very high temperatures and power.

Several ore-processing cycles are in principle available.

Processing shall differ considerably from terrestial solutions since lunar miners have no water but unlimited access to vacuum and almost continuous solar power.

	Earth	***Moon***
Power	Many	Solar, Nuclear
Water	Any	Nil
Pressure	1 bar	Vacuum
Agents	Coal, Acids	**TBD**

ISRU Candidate Techniques

Solid Gas Interaction:

- Reduction mechanism (H_2, CO, CH_4, H_2S, Cl_2)
- Fluorination replacement
- Carbo-chlorination.

Molten Processes:

- Molten Electrolysis (fluxed melting)
- Molten reduction (carbothermal, Li reduction)
- Oxygen benefication (oxidation and complete reduction)

Pyrolysis:

- Vacuum or Vapor phase
- Plasma (10,000 C) separation, or reduction

Acid Dissolution

Technology	Estimated Efficiency
H_2 reduction	1%(poles) 5% (equator)
Carbothermal reduction	14 to 28%
Molten electrolysis	40%

Source: Sanders (NASA JSC)

Vacuum Pyrolisis

In **vacuum pyrolysis** organic material is heated in vacuum in order to *decrease boiling point* and *avoid adverse chemical reactions*.

Vacuum pyrolysis is based on the vaporization reaction of metal oxides that simultaneously reduces the oxide and produces O_2.

The reduced oxide can be condensed out of the low-pressure gas as the gasses cool.

Vacuum pyrolysis has a high potential efficiency

The process requires no imported chemicals/consumables.

Can potentially produce metallic byproducts from the condensation

Pyrolisis Reactor

$$SiO_2 \rightarrow Si + 1/2O_2$$

$$FeTiO_2 \rightarrow Fe + TiO_2 + 1/2O_2$$

$$FeO \rightarrow Fe + 1/2O_2$$

$$Al_2O_3 \rightarrow Al + AlO + O_2$$

$$MgO \rightarrow Mg + 1/2O_2$$

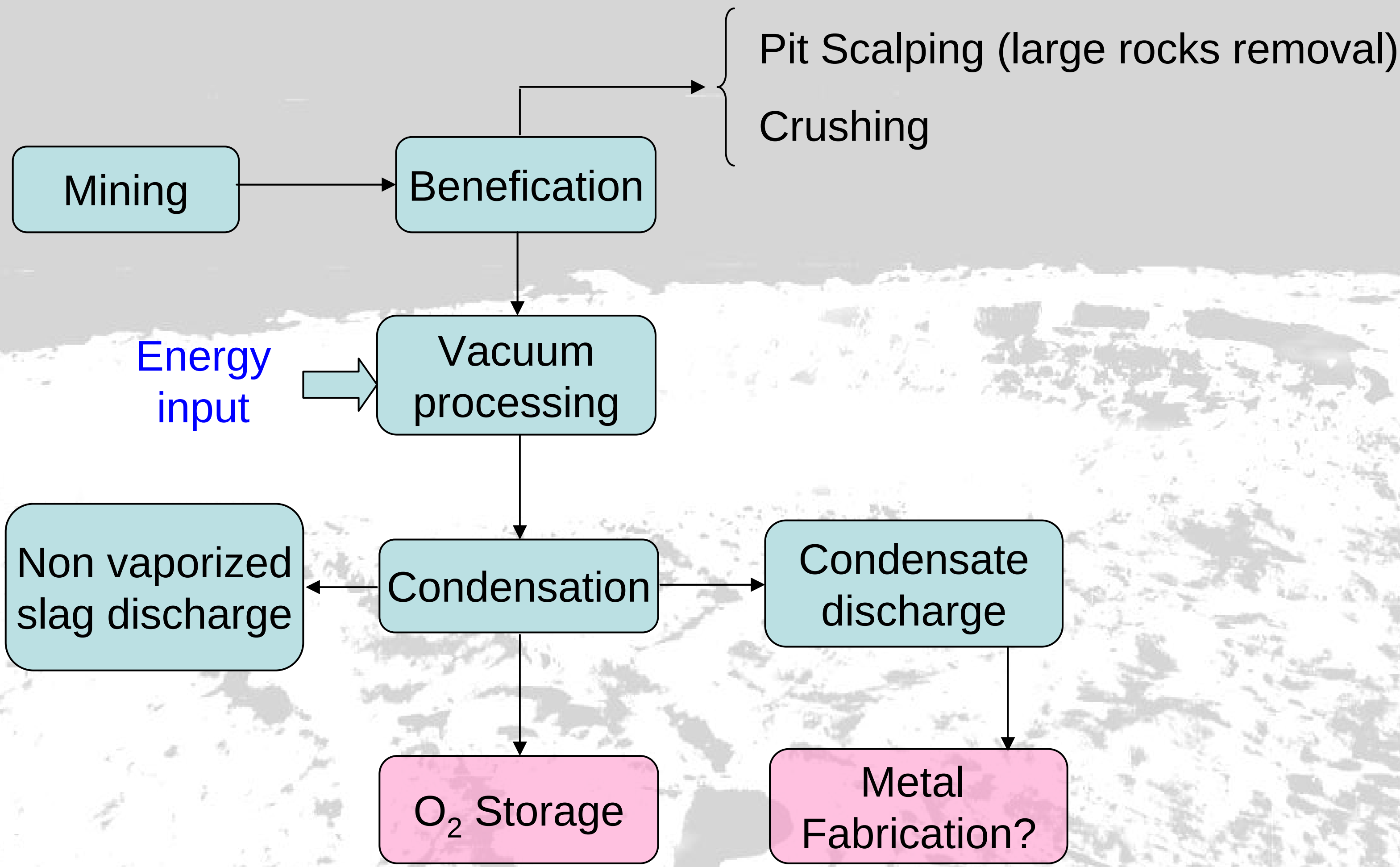
$$CaAl_2SiO_8 \rightarrow Ca + AlO + Al + SiO + 2O_2$$

↓

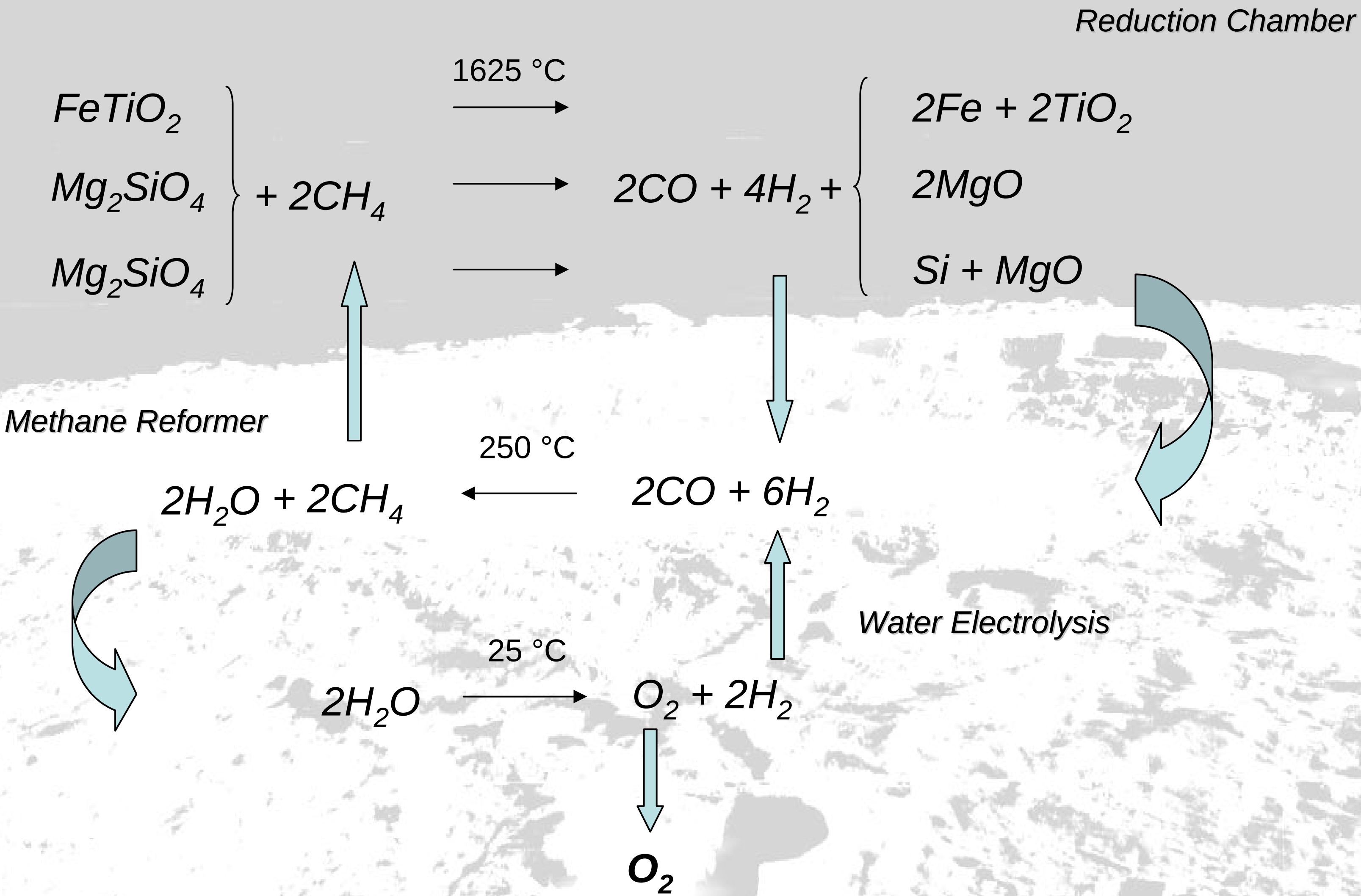
Condenser

$$2SiO + Fe + Al + AlO + Mg + Ca + \boxed{5O_2}$$

Vacuum Pyrolisis



Carbothermal (methane reduction) process



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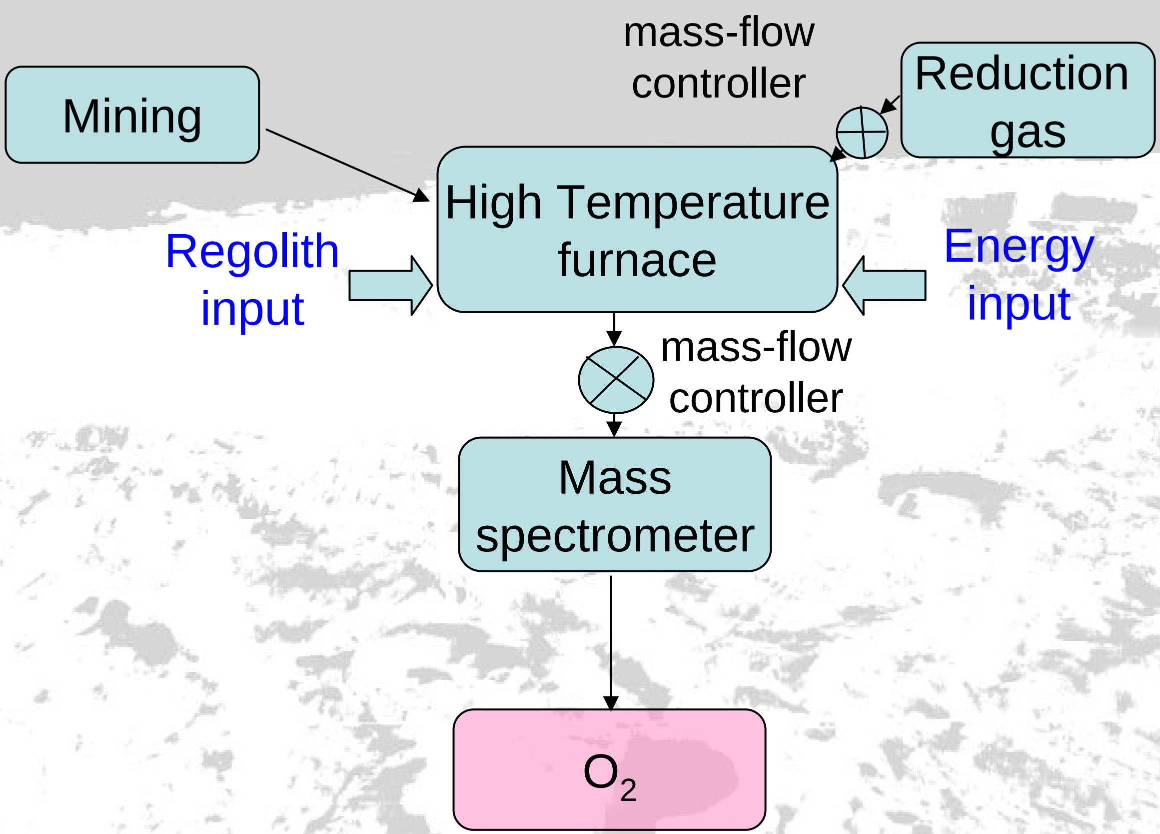
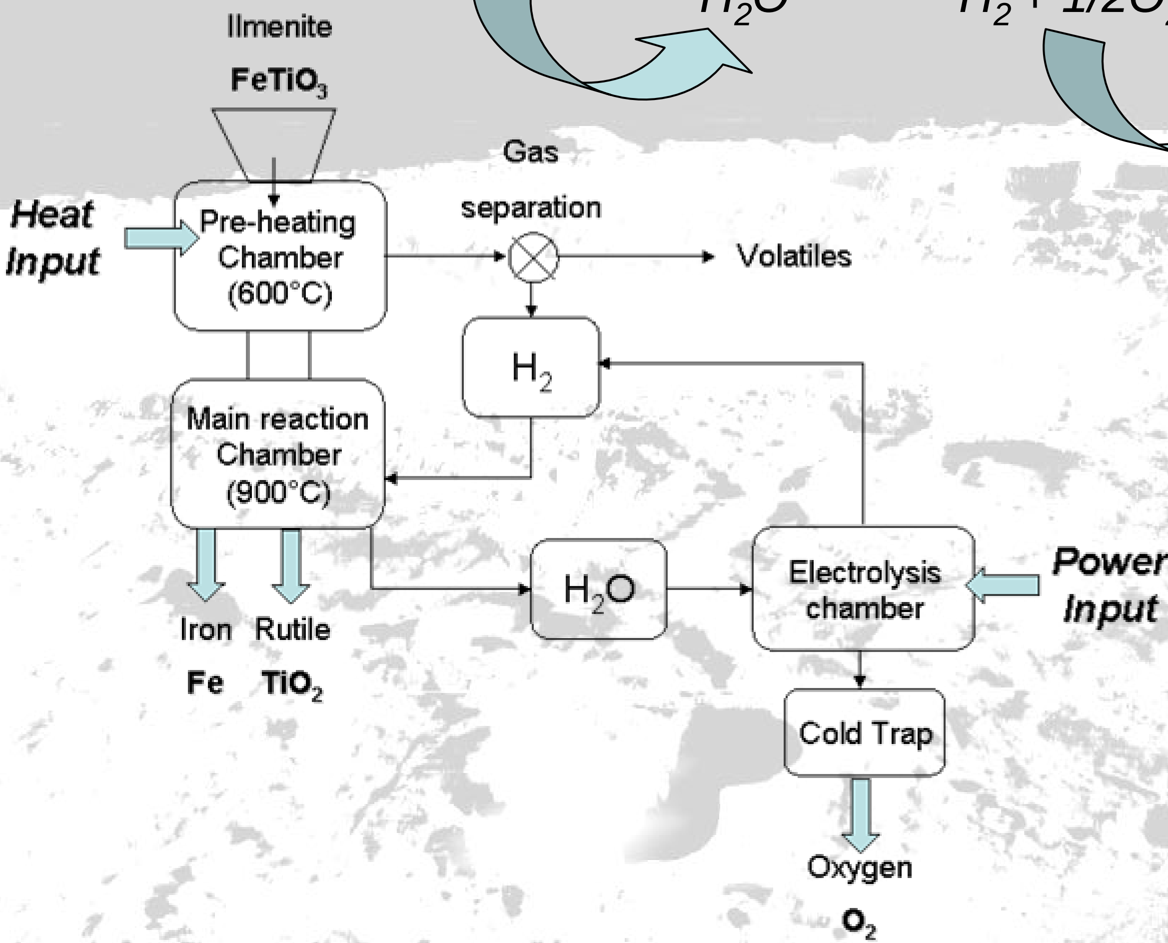


Ilmenite H_2 reduction process

$FeTiO_3 + H_2 \longrightarrow Fe + TiO_2 + H_2O$

$H_2O \longrightarrow H_2 + 1/2O_2$

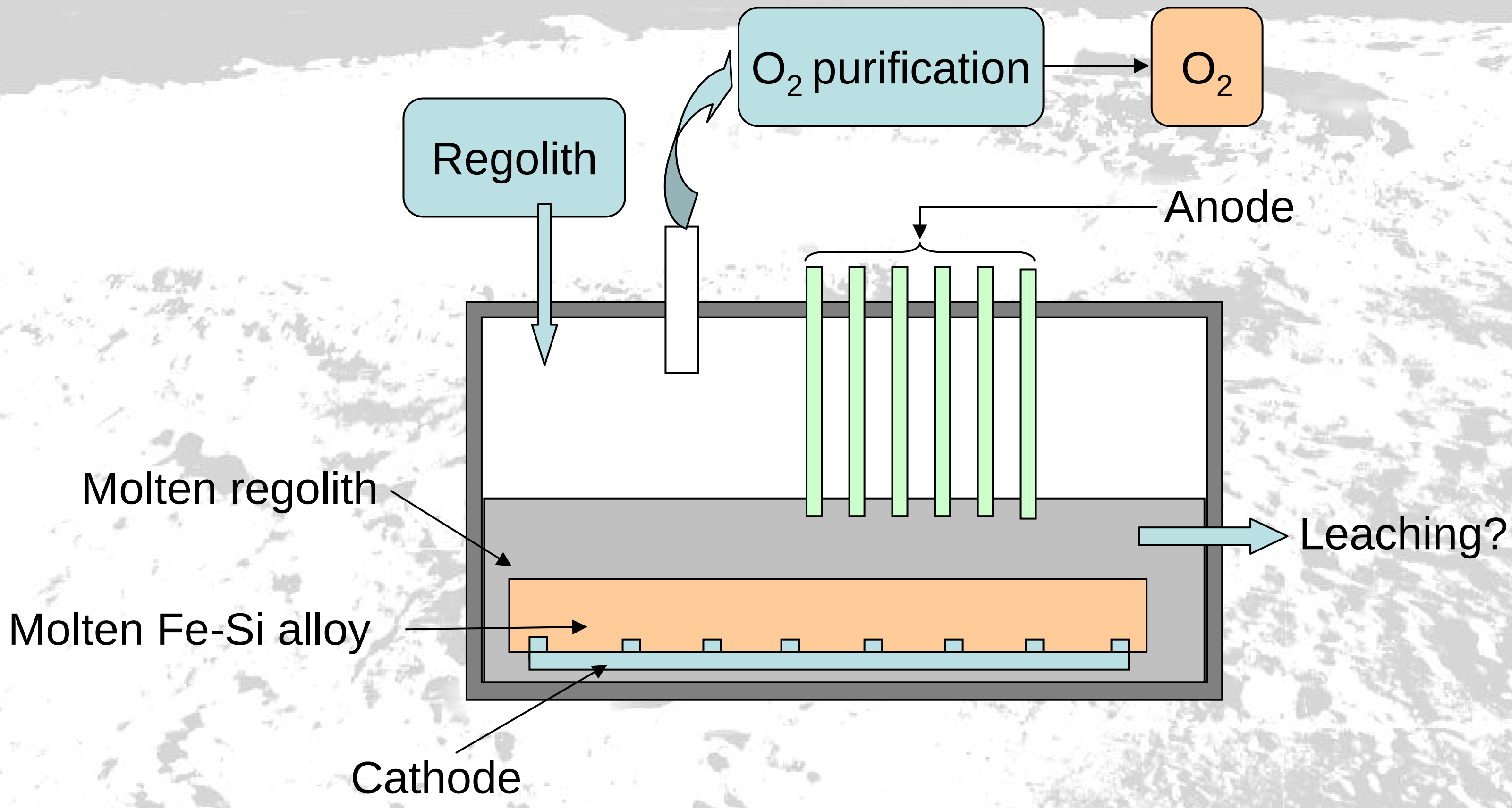
Regolith recovery rate ~ 10%



Molten Electrolysis

Molten silicate electrolysis (source: Hasken, Dietzler) is a process working at 1400-1600 °C able to produce oxygen with useful byproducts:

- ✓ iron
- ✓ iron-silicon alloy
- ✓ silicon



Environmental challenges

✓ ***High Vacuum***

- critical for sealing components
- beneficial for improved insulation

✓ ***Temperature***

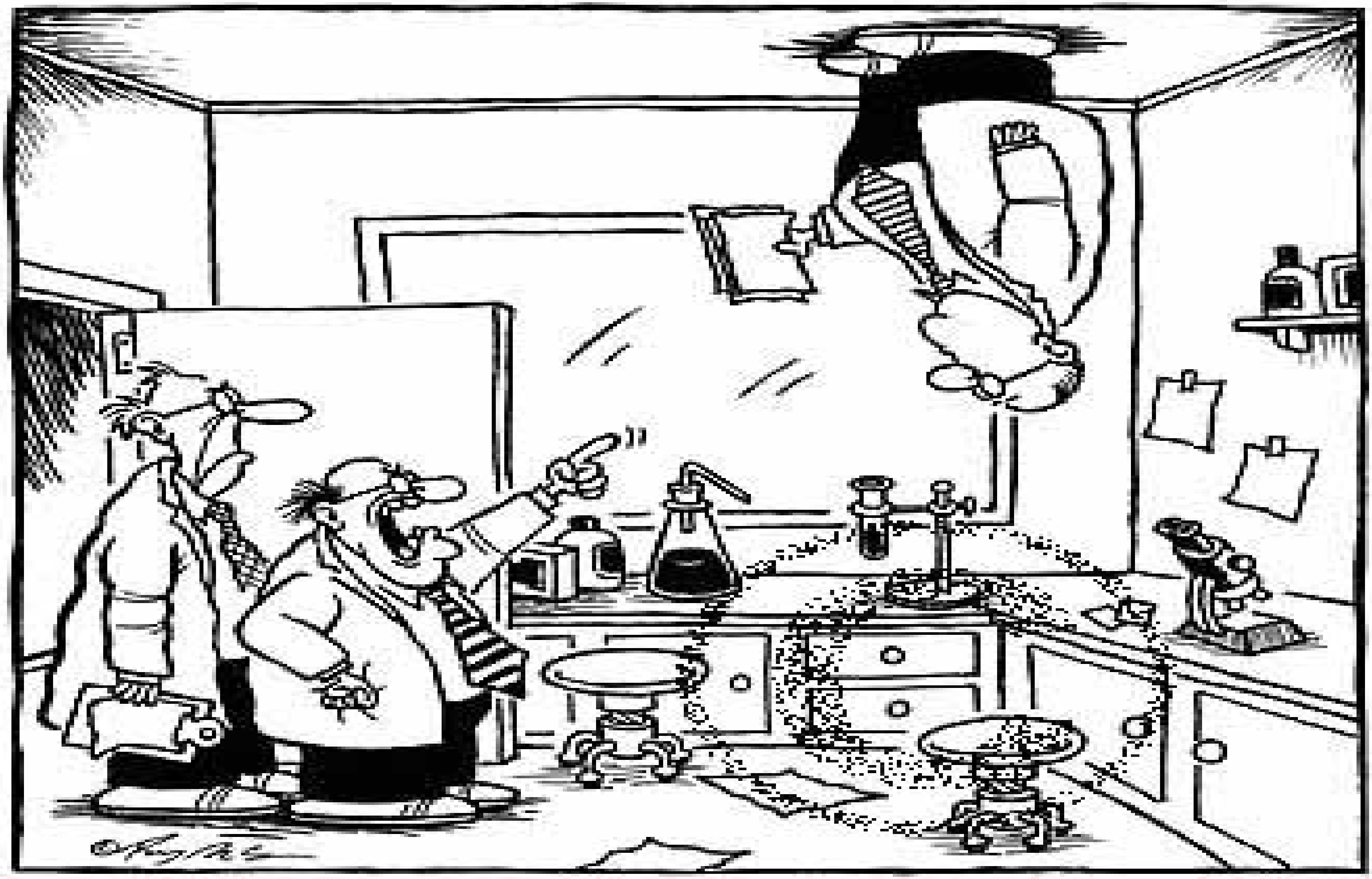
- local surface temperatures run from 100 to 400 K with large temperature swings

✓ ***Soil Composition***

- extremely fine and abrasive powder
- large composition variations depending on location and depth

✓ ***Gravity (1/6 of Earth)***

- representative conditions difficult to replicate



"I'm warning you, Perkins – your flagrant disregard for the laws of physics will not be tolerated!"

NASA Lunar Overarching Objectives

Overall Rank	Objective ID Number	Category	Short Title
1	mCAS2	Crew Activity Support	EVA Suit
2	mLSH3	Life Support & Habitat	Closed Loop ECLSS (physiochemical)
3	mEHM1	Environmental Hazard Mitigation	Radiation Shielding (Background & Solar Flares)
4	mLSH1	Life Support & Habitat	Habitation Systems
5	mHH2	Human Health	Lunar Environment Effects on Humans
6	mOPS1	Operations, Test & Verification	Human Surface Ops (Make EVA easier)
7	mHH1	Human Health	Fundamental Biological & Physiological Studies
8	mOPS10	Operations, Test & Verification	Lunar Repair Techniques
9	mPWR1	Power	Power Generation, Storage, & Distribution
10	mHH3	Human Health	Lunar Health Care
11	mPE2	Program Execution	Exploration Strategy
12	mTRANS2	Transportation	Autonomous Lander
13	mEHM2	Environmental Hazard Mitigation	Dust Mitigation Techniques
14	mCAS3	Crew Activity Support	Human Machine Partnership
15	mPE6	Program Execution	Affordability & Sustainability
16	mOPS9	Operations, Test & Verification	Crew-Centered Control
17	mCOM1	Communications	Scalable Communications
18	mHH4	Human Health	Reduced Lunar Habitation Pressure Effects
19	mLRU6	Lunar Resource Utilization	Tools, Technologies, & Systems for ISRU
20	mOPS3	Operations, Test & Verification	Mars Analog

Ref. Sanders(JSC), Larson (KSC)

NASA Lunar Overarching Objectives (2)

Overall Rank	Objective ID Number	Category	Short Title
21	mSM1	Surface Mobility	Surface Mobility for Crew & Cargo
22	mLRU7	Lunar Resource Utilization	Produce Propellants & Other Consumables
23	mLRU1	Lunar Resource Utilization	**Characterize Lunar Resource Potential**
24	mLRU3	Lunar Resource Utilization	Demonstrate ISRU Technologies
25	mPE7	Program Execution	Program Execution Flexibility
26	mPE3	Program Execution	Maximize Synergy
27	mTRANS3	Transportation	Cryo Fluid Management
27	mGEO8	Geology	**Characterize Potential Resources**
29	mOPS2	Operations, Test & Verification	Remote Training
30	mCAS5	Crew Activity Support	Teleoperations & Telepresence
31	mPE4	Program Execution	Emphasize System Performance
32	mGEO7-1	Geology	**Characterize Lunar Volatiles**
33	mSM2	Surface Mobility	Surface Mobility for Outpost
34	mENVMON1	Environmental Monitoring	Monitor Space Weather
35	mCAS4	Crew Activity Support	Autonomous Robotic Support for EVA & Long Range
36	mLRU9	Lunar Resource Utilization	Lunar Elements that Use ISRU
37	mNAV1	Navigation	GNC Lunar Capabilities
38	mENVCH3	Environmental Characterization	Characterize Surface Radiation Environment
39	mEHM4	Environmental Hazard Mitigation	Thermal Protection
40	mENVCH5	Environmental Characterization	Characterize Dust Environment

Ref. Sanders(JSC), Larson (KSC)

Lunar Exploration Scenario

Planned Lunar manned missions

2018-2020

2020

2024

2025

Lunar Architecture Studies Ongoing

Options for Europe:

- ✓ ***Political Space Actor***
- ✓ ***Economic Space Actor***
- ✓ ***Pragmatic Space Actor***

ISRU Conceptual Road Map

Back to the beginning….

- ✓ Identify and characterize resources on Moon (especially polar region)
- ✓ Demonstrate ISRU concepts, technologies and hardware capable to reduce mass, cost and risk for future Mars missions, e.g.:
  - ☑ *Thermal/chemical processing subsystems for oxygen and fuel production*
  - ☑ Excavation and material handling & transport
  - ☑ Cryogenic fluid storage & transfer
  - ☑ Metal extraction and fabrication of spare parts
- ✓ Use Moon for operational experience and mission validation for Mars
- ✓ Develop and evolve lunar ISRU capabilities that enable exploration capabilities from the start of the outpost phase
- ✓ Develop and evolve lunar ISRU capabilities to support sustained, economical space trasportation, presence on Moon, and space commercialization efforts

Industrial Interest

Conclusions

ISRU is the most market-oriented technology area within space exploration

Power need for oxygen production is the most relevant issue for a profitable use of ISRU

Spin-ins from mining sector can significantly lower the foreseen investment to be made on ISRU technologies and enlarge the industrial base of space activities

There could be room for international cooperation relating to ISRU technologies

Pilot ground demonstration

- ✓ Oxygen production pilot plant (precursor mission?)

Technological Priorities

1. Process Architecture definition
2. Furnace equipment development
3. Precise determination of reaction efficiency
4. Products analysis and precise identification

Oxygen production pilot plant development & validation

TRL 6

D'APPOLONIA

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