

System Architecture of a Lunar Industry Plant Using Regolith

By Roland Antonius GABRIELLI,¹⁾ Jürgen SEELMANN,¹⁾ Agnes GROßMANN,²⁾ Georg HERDRICH,¹⁾ Stefanos FASOULAS,¹⁾ Peter SCHNAUFFER,²⁾ Peter MIDDENDORF,²⁾ Miranda FATERI,³⁾ and Andreas GEBHARDT³⁾

¹⁾Institute of Space Systems, University of Stuttgart, Stuttgart, Germany

²⁾Institute of Aircraft Design, University of Stuttgart, Stuttgart, Germany

³⁾Mechanical Engineering and Mechatronics, FH Aachen University of Applied Sciences, Aachen, Germany

(Submitted May 21st, 2015)

The project MultiRob 3D led by the Institute of Space Systems (IRS) and the Institute of Aircraft Design (IFB) envisage the establishment of Lunar industries for Earth and Space. On one hand, reasonable profit to provide for the venture's self-sufficiency is sought by providing resources scarce on Earth and abundant on the Moon. On the other hand, a Lunar take off industry may emerge from secondary applications of the Additive Layering Manufacturing (ALM) providing the Lunar plant with spare parts, yielding commercial space products. The present paper focuses on a current concept study for the setup of the Lunar plant. Its generic architecture is broken down into the resource extraction chain, the factory, a power plant, and auxiliary systems typical to applications in space. Criteria to identify a suitable site for the Lunar plant are discussed. While some criteria address engineering constraints, other criteria consider the availability of raw materials for the planned Lunar industry. Following that, the options for gas extraction chains are indicated. A pyrolytic approach is outlined and the sizing of relevant subsystems discussed.

Key Words: Space Economy, Disruptive Concepts, In Situ Resource Utilization, Systems Engineering

Nomenclature

c_p	: heat capacity
h	: heat transfer coefficient
m	: mass
T	: temperature
V	: volume
λ	: thermal conductivity

1. Introduction

Currently, the Institute of Space Systems (IRS) and the Institute of Aircraft Design (IFB) of the University of Stuttgart are engaged with the Department of Mechanical Engineering and Mechatronics of the FH Aachen University of Applied Sciences in a project addressing potentials for the development of a Lunar industry.¹⁾

The industrialisation of the Moon is seen as a promising step towards a sustainable development of the Solar System as presented in reference 1. As explained therein, products with a very high value density – i.e. with a huge price per quantity – appear most attractive for the initial business model. The Helium-3 (³He) isotope can be identified as such being highly demanded in fields ranging from cryogenics over magneto resonance tomography technology to neutron detection while being extremely undersupplied on Earth, resulting in an excessive price.¹⁾ Relevant natural deposits are found in the Solar System. The most abundant ones are the atmospheres of the Gas Giants,

and, to a lesser extent, the Lunar regolith. Tapping both is technically challenging, but while the former may be the richer one, the latter may be accessible with less development effort.²⁾

In the project, it is further expected that this business may provide for the funding, hardware, and routine to launch a long term Lunar take-off industry for the further development of the Lunar and interplanetary environment. Recent breakthroughs in the development of Additive Layer Manufacturing (ALM) could induce due to its intrinsic simplicity and versatility a major disruption to In Situ Resource Utilisation (ISRU) and – eventually – space transportation by enabling to create products from local material such as the Lunar regolith.³⁾ At first, simple items such as bricks,⁴⁾ beams, and sheets could be made out of regolith. Soon, elements like photovoltaic cells could be produced, and finally more complex building blocks. These products would henceforth not have to be dispatched from Earth and could consequently be employed to strengthen the autarky of the initial business, but also be sold to further parties. In a more audacious scenario, a permanent human presence could be established on the Moon relying to this infrastructure.

The present contribution discusses a primordial Lunar plant to engage in this development and summarises first efforts in the system engineering and architectural design. The work has been performed in the frame of the projects *Lunarer Berg-Bau* (LBB)^a and *Multidisziplinärer Robotereinsatz zur lunaren Ressourcengewinnung unter Berücksichtigung von 3D-Fertigungsverfahren* (MultiRob 3D)^b; since autumn 2014. The projects also cover the development of interplanetary exploratory

^a Engl: *Lunar Mining*

^b Engl: *Multidisciplinary robot-application for extra-terrestrial resource extraction under consideration of 3D manufacturing processes.*

and industrial robotics. This topic has only recently been introduced at the University of Stuttgart.¹⁾

The present contribution first derives a generic architecture of the Lunar plant drawing on the two main purposes. In the following section, the selection criteria for a suitable site are discussed and preliminary locations indicated before introducing considered extraction processes and devices. The fifth section discusses aspects related to the sizing of the robots and the power supply before concluding.

2. Generic Architecture of a Lunar Plant

The envisaged Lunar Plant has to serve two purposes:

1. Reaping a net profit from Lunar ^3He for Earth to be re-invested in further development, and
2. Running the core of a future Lunar take-off industry dedicated to growing anthropogenic activity in space.

From this, it arises, that the core of this Lunar Plant has to be composed of a ^3He extraction chain and a factory based on regolith to provide for spare parts and commercial products.

The ^3He extraction chain encompasses systems to *excavate* suitable material on the Lunar surface, *transport* it from the excavation site to the plant, the material's *beneficiation*, *gas-extraction*, *-separation*, and *-storage*. At this point of development, it is assumed that the latter four systems are stationary in the initial set-up. A mobile alternative may be considered at a later stage. By contrast, both excavation and transport are services provided by a group of two types of highly mobile robotic rovers. A third type is proposed to act as a telecommanded servicing robot.¹⁾ The *factory* needs to be as versatile and simple as possible at the same time. In recent years, Additive Layer Manufacturing (ALM) has evolved so far that this option is expected to fulfil these requirements.³⁾ In the frame of the concept, an ALM machine is considered to primarily manufacture short lived elements and spare parts for the plant from gas depleted Lunar regolith leaving the ^3He extraction chain. Secondly, while the primary production is idle, the ALM can be used to

commercially create simple elements for third parties or other purposes. Secondary products can range from the simplest elements, like bricks which could be used to build radiation or meteoroid shelters, beams and sheets, to more advanced items like photovoltaic cells.⁴⁾ More detailed information about the work on ALM in the frame of LBB and MultiRob3D can be found in reference 3.

This allows to derive a generic architecture, encompassing additional subsystems as visualised in Fig. 1. The *power supply* provides the necessary electrical or thermal power required to run the system continuously. Waste heat and surplus power are mitigated by the Thermal Control System (TCS). There also has to be a bus system assuring housekeeping activities like the processing and storage of Telemetry and Telecommands (TMTC), communication to the ground segment, approaching service spacecraft, and isolated subsystems of the plant, like the robots. It is thus composed of computers, servers, and short and long range transmitters.

As it is intended to transfer stored ^3He to Earth, a return system has to be considered. For the time being, it is proposed that a service spacecraft is periodically delivering more complex spare parts to the plant, and returning the spoils to Earth, where they are dropped by the means of a re-entry capsule.⁵⁾ It is thinkable to comfort the landing and take-off of the service spacecraft by levelling off a site nearby the plant. A mass-driver as described in reference 4 may be a pertinent alternative, especially with respect to a later stage of development with numerous customers of regolith made products.

The whole system has to be conceived with the general requirements of continuous operation, being incremental, and being tele-operable from the ground-segment on Earth.

3. Site selection

The selection of a suitable site is decisive for the success of the proposed Lunar industry. The plant has to be sited with respect to criteria arising from the intended activities on one hand

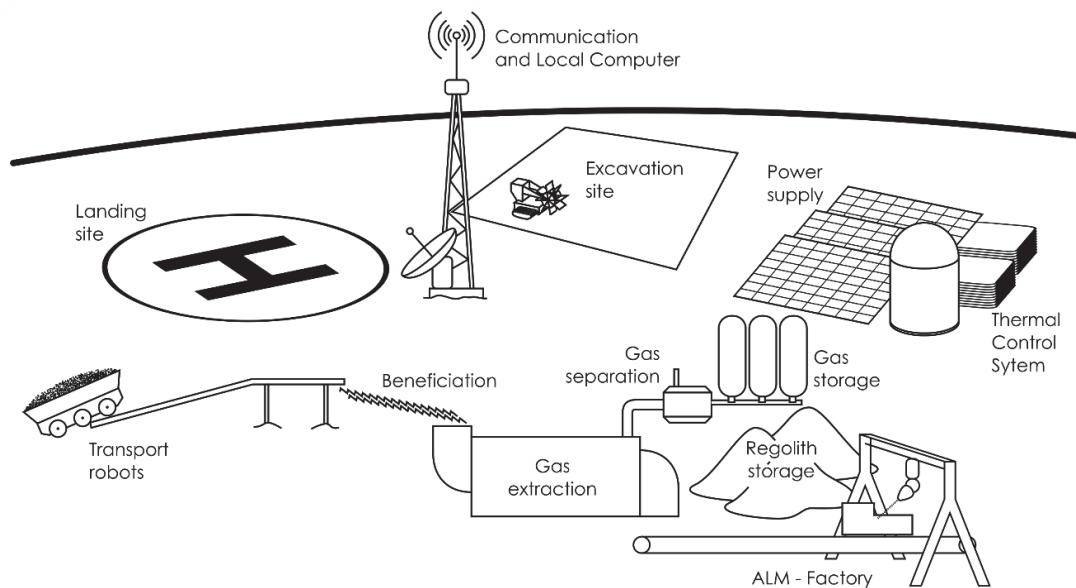


Fig. 1. Illustrative draft of the generic system architecture envisaged in project MultiRob 3D.

and from engineering constraints on the other hand, implying a trade-off.

3.1. Engineering criteria for the site selection

The general requirement of tele-operability from the ground-segment entails a restriction to locations between $\pm 75^\circ$ of longitude and $\pm 80^\circ$ of latitude on the tidally locked near side of the Moon enabling a continuous straight line of sight towards the Earth. The ground-segment would nevertheless require a network of ground-stations or relay satellites around Earth. Additional relay satellites around the Moon could also enable sites on the far sides.⁶⁾ These are not yet available.

Abundance in sunlight is another criterion. With a power density of approximately 1368 W/m^2 ,⁷⁾ sunlight can be used as a primary source of energy, as a source of lighting for the visual observation of the robots' operation, and as a source of warmth, with respect to the TCS: Due to it, a very thin exosphere^c of approximately 400 K is being gassed out during the 14.25 d day time of the Lunar cycle of 29.5 d, contrasting to the 100 K during eclipse. This results in an average temperature of 250 K in equatorial and 220 K in polar regions. There is little seasonal variation as a consequence of the small inclination of $1^\circ 32'$ against the ecliptic.^{4,7)} Note, that about 2% of the Lunar surface are perpetually shadowed, not exceeding temperatures of 40 K.

A third major engineering criterion arises from the orbital mechanics relevant to the service spacecraft. It can be shown, that manoeuvres to shift the inclination of a trajectory demand the most propellant, making a case for a site near the equator.

Other aspects of the Lunar environment may be technically less important: While there may be risks arising from background radiation, particle radiation⁷⁾ – the Lunar magnetic field is practically absent⁴⁾ – and meteoroids,⁸⁻¹⁰⁾ this is at present largely independent of the location. Additionally, these risks can be gradually reduced sheltering critical subsystems with bricks and sheets produced by the plant's ALM factory. Also, the Moon's seismology is negligible. Over the course of a year, there are only 500 Moonquakes compared to 10000 Earthquakes and most of them do not exceed magnitude 2 and none has ever exceeded magnitude 5.^{4,11)}

3.2. Site selection by resource abundance

As the primary activity is to extract ^3He from regolith, a suitable location would be in proximity to abundant deposits. Prospection conducted during the Apollo and Luna missions has revealed that the regolith found in the Moon's Maria contain among other volatiles significant concentrations of ^3He . The relevant data is concentrated in table 1 with respect to the landing sites of the missions and table 2 with respect to the categorisation arising from the data, and visualised in the map given in Fig. 2.^{12,13)}

The Solar wind, the main constituent of the weathering particle radiation, is also the origin of the Lunar ^3He deposit.^{2,4)} The Solar wind is a flux of light weight ions such as protons, electrons or helium cores – among which a small fraction of ^3He ions – emitted by the Sun. A part of it collides into the Moon's exposed surface where the ions are then implemented. This can result in either a weak or a strong binding.^{15,16)} The weak bind-

Tab. 1. Summary of ^3He concentration by sample extraction site.¹²⁾

Mission	^3He / ppb	Approx. thickness of regolith layer / m	Region	Category
Apollo-11	15.1	4.7; 4.6; 4.4	Mare	I
Apollo-12	7.1	3.7; 4.6; 5.3	Mare	II
Apollo-14	5.7	8.1; 8.5	Mare	III
Apollo-15	4.4	6.0; 4.4	Mare	III
Apollo-16	1.4	10.1; 12.2	Terrae	IV
Apollo-17	8.0	7.0; 7-12; 8.5; 6-8	Mare	II
Luna-16	7.9	4.0; 4.0; 1.0-5.0	Mare	II
Luna-20	3.1	9.2; 0.4; 11.6	Terrae	IV

Tab. 2. Categorisation of regolith by TiO_2 and respective assumed ^3He content. Total mass of ^3He : $2469.2 \times 10^3 \text{ t}$ (100%).¹²⁾

Category	I	II	III	IV
Titan oxide (TiO_2) / %	5-10	3-5	1-3	0-1
Area of TiO_2 / 10^5 km^2	4.87	15.19	15.86	343.40
max. ^3He / ppb	15.1	8.0	5.7	3.1
Regolith density / kg/m^3	1900	1900	2000	2000
mass ^3He / 10^3 t	61.5	110.8	146.5	2150.4
^3He [%]	2	4	6	87

ing associated to the so called 'pore gas' is a very loose deposition of gases in the gaps between regolith grains and the eponymous pores. It is assumed weak binding is more likely on regolith with relatively large surface to volume ratio. It is however highly susceptible to vibrations, and hence very difficult to capture.^{12,16)}

Regolith is the loose material cover of the bedrock of planetary bodies, including Earth and the Moon. Its consistence can range from grainy to dusty soils. The Lunar regolith is the result of mechanical weathering of rock inflicted by meteoroid impact and particle radiation.⁴⁾ Accordingly, the average grain size, the chemical composition, and layer thickness depend a lot on the site, as outlined in table 1.

The strong binding is – as the name suggests – a more robust deposition.^{16,17)} It is related to the electrical conductivity of the substrate. While nonconductive minerals are rendered amorphous by ionising radiation, conductive materials maintain their crystal structure in which particles such as ^3He can be captured.^{12,18,21)} This explains why the Moon's Maria are better ^3He deposits than its Terrae: The Maria are 2.5 times more abundant in iron (Fe) and 10 times more abundant in titanium, as documented in table 3. There is about 10 to 100 times more ^3He to be found in Ilmenite (FeTiO_3), a mineral common in the Maria, than in other Lunar rock, as concentrated in table 3.^{13,19)} It is noteworthy that very abundant ^3He deposits appear to be situated around the Lunar landing site of humans, i.e. Apollo 11's site in the Mare Tranquillitatis.

Table 4 summarises the criteria for a landing site: It is by the prospect to extract much ^3He that locations in the Maria appear very attractive. Furthermore, these appear compatible with the engineering criteria. The Maria are on the near side of the Moon,

^c The Moon's atmosphere. It has a total mass of 25 t.⁷⁾

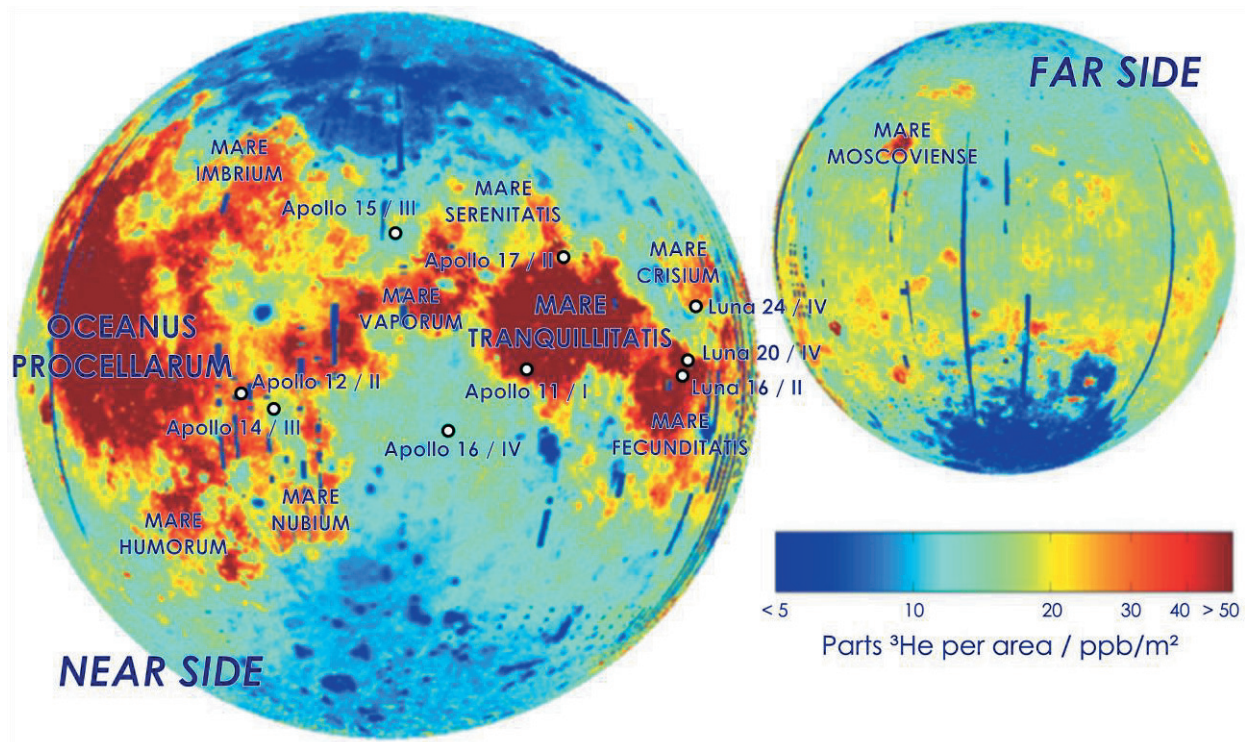


Fig. 2. Map of the near and the far side of the Moon, indicating the parts of ^3He per area in ppb/m^2 .¹³⁾ Also shown are major Lunar Maria and the sites of Lunar landings,¹⁴⁾ related to the locally present regolith category.¹²⁾

in moderate latitudes, and typically rather flat. There are however engineering consequences arising as for the power supply, and the TCS. Since the eclipses' duration on the Moon is 14.25 d, a common combination of solar arrays and secondary cells may raise problems. These could however be resolved by application of space fission reactors.

4. Helium Extraction Facility

The gas extraction facility is supposed to be the core of the initial development phase of the Lunar industry. It has to be designed to the end of obtaining spoils of ^3He to be shipped to Earth, calling for a process chain focussed on the separation of this gas from the regolith of the Lunar Maria, as discussed in the previous section. As outlined in section 2, the ^3He extraction chain begins with the beneficiation of the raw material: It was found out,¹²⁾ that smaller Ilmenite grains were the Lunar regolith with the richest concentration in ^3He , making a case for a preliminary separation of Ilmenite from other rocks, and its larger grains. These would only tap the process energy without contributing to spoils and also cause problems in the following ALM production.

Tab. 3. Chemical composition of the Moon's Maria and Terrae.^{13,19)}

Element	Maria / %	Terrae / %
Oxygen (o)	60,6	61,1
Silicon (Si)	16,8	16,2
Aluminium (Al)	6,6	10,2
Calcium (Ca) and Potassium (K)	4,7	6,3
Magnesium (Mg)	5,3	4
Iron (Fe)	4,5	1,8
Sodium (Na)	0,4	0,4
Titan (Ti)	1	0,1

The next system in the chain would then separate the gas from its substrate. To this end, three approaches have been considered: *Vacuum Crushing*, *Acid Etching*, and *Thermal Pyrolysis*. After this step, the valuable ^3He has to be separated from other volatiles and stored. The present section discusses the ^3He extraction processes.

4.1. Processes in overview

A process already used in the analysis of samples returned from the Apollo missions is the so called Vacuum Crushing (VC).²⁰⁾ In VC, the sample is contained in a cylinder in which it is rammed many times by a metallic piston actuated by an alternating electromagnetic field. It is estimated that about 60%

Tab. 4. Summary of siting criteria

Criterion	Properties	Location
Ressources	^3He deposits	Mare Vaporum, Oceanus Procellarum, Mare Humorum, Mare Crisium, Mare Tranquillitatis, Mare Fecunditatis
Landing site accessibility	Latitude, topography	Equatorial plains
Communication/line of sight	Longitude Latitude	$\pm 75^\circ$ $\pm 80^\circ$
Topography	Flat relief, shadows	Maria Low latitudes
Sun light availability	Lighting, power supply	Low latitudes and Shackleton Crater area
Thermal Control System	Operational temperature	Low latitudes
Particle and background radiation	Doses	Independent of location
Meteoroid impact	Probabilities	Independent of location

of the contained ^3He can be released from the regolith in this process. The process appears rather simple and the moving parts require little mechanic consideration. However, only small sample sizes can be loaded. Since many thousands of tons of regolith would have to be rammed, an industrial extraction of ^3He would require a large battery of devices, or a long time.

Acid Etching (AE)²¹⁻²³ is another process which was used to analysed the returned regolith samples. In the experiments conducted in reference 22 on Lunar soil sample 75081,²⁴ taken during Apollo-17, see Tab. 1, these were first exposed to water for a total of approximately 21 days and then to sulphurous acid for another 31 days. The obtained volumes of ^3He specific to the mass of regolith under standard conditions $17.2 \times 10^{-7} \text{ cm}^3/\text{g}$ for the exposition to water and $21.4 \times 10^{-7} \text{ cm}^3/\text{g}$ to the acid, respectively, thus, in total: $38.6 \times 10^{-7} \text{ cm}^3/\text{g}$. The same sample finally underwent $4 \frac{3}{4}$ h of pyrolysis, in which another $103 \times 10^{-7} \text{ cm}^3/\text{g}$ of ^3He were released, indicating that AE is a lengthy and relatively ineffective process, in which about 75% of the available ^3He may remain enclosed in the regolith. Further drawbacks of the process are however its complicated setup²² and – foremost – its need of water for an aqueous acid solution. Water may not be available near the initial sites in the Maria.⁴

In Thermal Pyrolysis (TP)^{25,26} of regolith, it is envisaged to achieve outgassing by heating the material. Combustion is avoided by excluding oxygen from the process. The data from early experimentation on samples 10084-48²⁵ and 10084-59²⁶ indicates that this process may be the most effective. Sample 10084 was taken during Apollo 11, see Tab. 1.²⁴

While the samples were heated stepwise, the gas release at a given temperature was recorded yielding the progressions depicted in Fig. 3. In both considered experiments, the progression of the thermally induced outgassing of ^3He sets on at temperatures between 200 °C and 400 °C peaks rapidly around 500 °C and then declines until there is no more outgassing at temperatures beyond 1200 °C, suggesting that the material was depleted. Overall, the respective obtained volumes of ^3He specific to the mass of regolith under standard conditions were $9.41 \times 10^{-5} \text{ cm}^3/\text{g}$ for sample 10084-48, and $13.32 \times 10^{-5} \text{ cm}^3/\text{g}$ for sample 10084-59. Fig. 4. visualises the according extracted

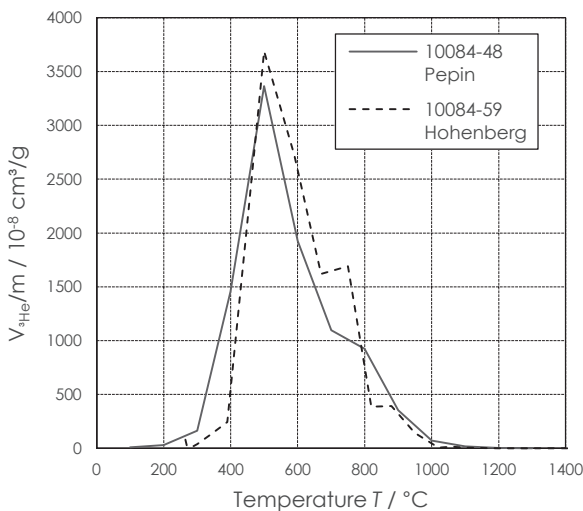


Fig. 3. Released ^3He volume (standard conditions) per sample mass (V_{He}/m) during stepwise pyrolysis on sample 10084 (Apollo 11). Experiments by Peppin²⁵ and Hohenberg.²⁶

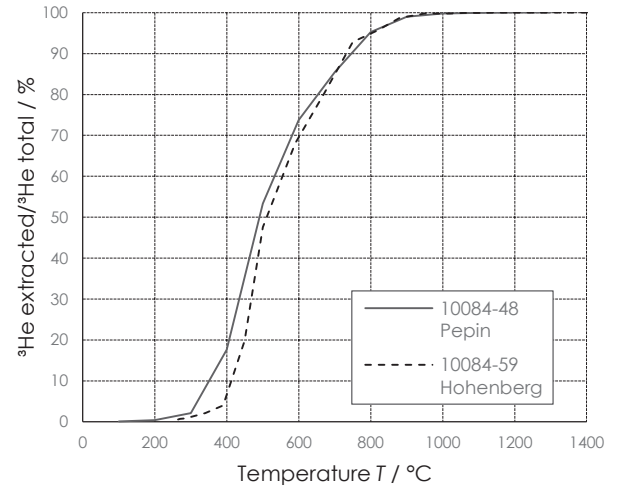


Fig. 4. Fraction of ^3He extracted during stepwise pyrolysis by totally extracted ^3He on sample 10084 (Apollo 11). Experiments by Peppin²⁵ and Hohenberg.²⁶

fraction of the whole as a function of the peak temperature. A fraction of 95% is already extracted at temperatures of approximately 900 °C (1173 K). Note, that the regolith starts glassing or melting at temperatures around 1300 °C.²⁷ Consequently, with such a margin, an extraction device based on pyrolysis can be designed to extract virtually all of the contained ^3He without touching temperatures entailing the problems arising from this transition, such as clogging or increased abrasion, making this the process of choice.

To realise this, thermal parameters proper to the regolith would yet be needed. Reference 27 offers a basic model for its heat capacity below the melting point being

$$c_p(T) = -1848,5 \frac{\text{J}}{\text{kg K}} + 1047,41 \frac{\text{J}}{\text{kg K}} \log_{10}(T) \quad (1.)$$

which allows to estimate the consumed energy. This model is an extrapolation from values measured from sample 10084 in a temperature range from 100 K to 350 K,²⁸ in which the heat capacity ranges from 280 to 800 J/kg K. Note, however, that this may be different for temperatures up to the desired 1200 K. Nevertheless, also the thermal conductivity λ plays a role in the process. According to reference 29, this parameter would range from 0.015 to 0.026 W/(m K), and the heat transfer coefficient h from 0.5 to 1.5 W/(m² K).

4.2. A Brief Discussion on Thermal Pyrolysis Devices

In MultiRob 3D, yearly spoils in ^3He from 5 to 10 kg are stipulated. Preliminary estimations based on the isotopes abundance in category II regolith indicate that vast amounts of regolith up to $6.25 \times 10^9 \text{ kg/a}$ or approximately 200 kg/s are necessary to provide for this target. The arising requirement for large scale industrial devices is challenging since only hardware of a limited size and mass can be initially installed on the Moon due to launch limitations.¹⁾

Nevertheless, available technologies have to be considered. There are various ways to realise an industrial thermal pyrolysis device. The most intuitive one is a blast furnace concept similar to terrestrial devices used to melt vast amounts of iron ore.³⁰⁾ Lunar blast furnaces are likewise vertical cylinders, fed with raw material from the upper end. In contrast to common terrestrial designs using coal layers, towards the lower end of a Lunar

blast furnace, a thermal feed would have to be implemented. At the lowest point, molten material is released via a funnel. Assuming that the released gasses will not escape by this funnel, their pressure would built up towards the feed which would have to be sealed. It appears beneficial that the fresh material is dumped on hotter material and thus heated upon contact promising a regenerative cycling. Further, the release of a liquid would avoid problems with abrasion inflicted to the funnel by regolith. Previous beneficiation could be largely simplified. However, since the melt would then likely re-solidify as a slag like in the case of the terrestrial counterparts, the depleted regolith would no longer be valuable for the ALM factory. Instead, the slag would have to be mitigated prior to causing problems arising from clogging.

As indicated above, the virtual totality of ^3He contained in regolith can be extracted from the solid raw material at temperatures below 1200 K and thus below the melting point around 1300 K. This can be achieved in a rotary kiln, as drafted in figure 5.³⁰⁻³³⁾ In terrestrial industry, rotary kilns are used in the continuous heat processing of powders, grainy solids, and gravels. The material is fed into the upper end of a rotating cylinder with a longitudinal axis slightly inclined towards the horizontal plane. The material is mixed due to an interaction of rotation, inertia, sliding, and friction, easing the heat transfer in the loaded material. Terrestrial kilns are heated either by injection of a preheated working gas, a longitudinal gas burner at the lower end, a number of transversal burners, or conduction. While combustive subsystems are unrealistic in the Lunar situation, approaches relying on working gasses may be feasible, presuming that an escape through the feed, and mostly the release of the depleted regolith can be averted. Note that this requirement is also shared with the purpose of extracting ^3He .

Another option to heat the regolith is the application of microwaves. In this approach the energy is directly coupled into the more interesting parts of the regolith making use of the electric conductivity in Ilmenite.³⁴⁻³⁷⁾

5. Further considerations

At the moment, sizing studies are in progress in the frame of the LBB project. A first benchmark consist in the development of a reliable analytic model describing the excavation rate. The model shall consider parameters deriving from the geometry of

the excavation head – bucket wheel, brush, or other – the excavation kinematics and dynamics, and the strategy. To this end, experiments is planned. The necessary mock excavation robots are currently being constructed and programmed.¹⁾

Another sizing aspect addresses the transport rovers or robots. They have to be sufficient in number and transport volume to provide a transport rate of up to 200 kg/s of raw material to ensure the stipulated yearly spoils. Simultaneously, dispatching the initial population should still be economically feasible. An accompanying activity is the research for alternatives.

Finally, the design of the power supply is of crucial importance. It provides the power of the ^3He extraction chain, the ALM-factory, the subsystems and the rovers. Depending on the eventual choice of device, a primary source can be matched. While both the subsystems and the ALM machine will require electrical power,³⁾ blast furnaces and rotary kilns can also utilise process power in a direct manner.

Electricity may be provided by photovoltaic arrays supported with secondary or fuel cells.^{38,39)} The latter have to be laid to allow for eclipses of 14.25 d, and losses arising from charge, discharge, and – moreover – self-discharge, which can be significant. Secondary cells will also be aboard the robots and laid according to the eventual size and mechanic modelling. Since the stipulated robots have to maintain a relatively large transportation rate, it is likely to assume that they cannot afford to move at the pace that their precursors from Lunar and Martian exploration missions did, and an according requirement will arise from this.

Process heat can be obtained from both nuclear fission reactors and solar thermal machines.^{38,39)} They require some additional working medium. The latter has initially to be dispatched from earth, but at a later stage side product gasses extracted alongside the commercial ^3He can be used for refilling losses.⁴⁾

6. Conclusion and Outlook

The project MultiRob 3D addresses the potentials for the development of a Lunar industry. While a self-sustaining industry is stipulated to evolve in the long run from an ALM machine installed to provide the initial mission's spare parts, a highly valuable product has to assure the business in the beginning. In the project, ^3He has been identified as an attractive commodity. Accordingly, interesting sites near the Apollo landing sites have

been spotted following criteria arising from the resource's abundance, and engineering considerations.

Lunar ^3He is obtained from the regolith of the Maria and thus a process to extract the isotope on an industrial chain has to be found. In experiments, it has been shown that nearly 100% of the ^3He contained in regolith can be extracted in thermal pyrolysis at temperatures below the glass or melting temperature. The gas depleted regolith can subsequently be fed into the ALM machine and processed into spare parts

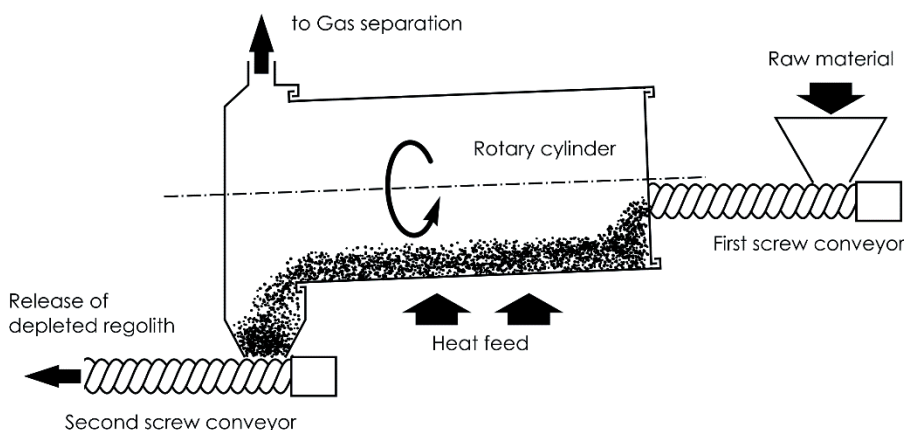


Fig. 5. Draft of a rotary kiln for the pyrolytic extraction of ^3He from Lunar regolith.

and other products.

The investigation of a suitable machine enabling the pyrolysis on an industrial chain is currently in progress at the Institute of Space Systems of the University of Stuttgart. The dynamics of rotary kilns have been studied. In the next step, the work is focussed on the heat transfer in loose regolith. It is expected that a resulting model may enable a sustainable sizing of a Lunar rotary kiln, further allowing an estimation of the power supply and feasible yearly mass of ^3He spoils. A complementary feasibility study covers a parametrisation of blast furnaces. The sizing of the robots is being prepared at the Institute of Aircraft Design of the University of Stuttgart. Regolith based ALM is investigated at the Department of Mechanical Engineering and Mechatronics of the FH Aachen.

Acknowledgements

The work leading to this contribution has been performed at the Institute of Space Systems of the University of Stuttgart, Baden-Württemberg, Germany. It received funding from the programme for quality assurance in academic education under the project LBB.

References

- Großmann, A., Gabrielli, R. A., Herdrich, G., Fasoulas, S., Schnauffer, P., Middendorf, P., Fateri, M., Gebhardt, A.: Overview of the MultiRob 3D Lunar Industrial Development Project, Conference Contribution for the 30th ISTS, 34th IEPC & 6th NSAT Joint Conference, Kobe, Japan, 2015.
- Santarius, J.F.: Fusion Space Propulsion – A Shorter Time Frame than You Think, UWFD-1287, presented at the 53rd Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting, Monterey, California, 5-8 December 2005.
- Fateri, M., Gebhardt, A., Gabrielli, R. A., Herdrich, G., Fasoulas, S., Großmann, A., Schnauffer, P., Middendorf, P.: Additive Manufacturing of Lunar Regolith for Extra-terrestrial Industry Plant, Conference Contribution for the 30th ISTS, 34th IEPC & 6th NSAT Joint Conference, Kobe, Japan, 2015.
- Schrunk, D., Sharpe, B.: The Moon: Resources, Future Development and Colonization, John Wiley & Sons, 1999 (ISBN: 978-0-471-97635-6).
- Gabrielli, R. A., Mathies, J., Großmann, A., Herdrich, G., Fasoulas, S., Schnauffer, P., Middendorf, P., Fateri, M. and Gebhardt, A.: Space Segment Concept for a Lunar Take Off Industry Based on Regolith, Conference Contribution for the 30th ISTS, 34th IEPC & 6th NSAT Joint Conference, Kobe, Japan, 2015.
- Hornig, A., Homeister, M.: TYCHO: Demonstrator and operational satellite mission to Earth–Moon–Libration point EML-4 for communication relay provision as a service, *Acta Astronautica*, Volume 108, March–April 2015, Pages 156-170, ISSN 0094-5765, DOI: <http://dx.doi.org/10.1016/j.actaastro.2014.10.016>.
- Williams, D.: Moon Fact Sheet. <http://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html>, (cited 13 February 2015).
- Neukum, G., Ivanov, B. A., Hartmann, W. K.: *Cratering Records in the Inner Solar System in Relation to the Lunar Reference System*, In: *Space Science Reviews*, Vol. 96, 1/4, 2001, S. 55–86.
- Eckart, P., Aldrin, B.: *The lunar base handbook: An introduction to lunar base design, development, and operations*. McGraw-Hill, 2006.
- Zook, Herbert A.: *The state of meteoritic material on the Moon*, In: *Lunar Science Conference*, Vol. 6, 1975, S. 1653–1672.
- Lammlein, David R.: *Lunar seismicity and tectonics*, In: *Physics of the Earth and Planetary Interiors*, Vol. 14, No. 3, 1977, S. 224–273.
- Slyuta, E.; Abdrakhimov, A.; Galimov, E.: The estimation of Helium-3 probable reserves in lunar Regolith, In: *Lunar and Planetary Science Conference*, Vol. 38, 2007
- FA, W., JIN, Y.-Q.: *Quantitative estimation of helium-3 spatial distribution in the lunar regolith layer*, In: *Icarus*, Vol. 190, No. 1, 2007, S. 15–23
- National Space Science Data Center, NASA's Goddard Space Flight Center: Map of Past Lunar Landing Sites, http://www.nasa.gov/mision_pages/LRO/multimedia/moonimg_07.html, 13 May 2009, (cited 27 April 2015).
- Haskin, L., Warren, P., Lunar Chemistry. In: Heiken, G., Vani-Man, D., French, B. M. (ed.): *Lunar sourcebook : A user's guide to the moon*. Cambridge [England], New York : Cambridge University Press, 1991, S. 357–474.
- Futagami, T., Ozima, M., Nagai, S., Aoki, Ya.: Experiments on thermal release of implanted noble gases from minerals and their implications for noble gases in lunar soil grains, In: *Geochimica et Cosmochimica Acta*, Vol. 57, No. 13, 1993, S. 3177–3194.
- Say, F.-D., Chan, S. I. Sunney I.; Manatt, S. L.: Ferromagnetic resonance of lunar samples, In: *Geochimica et Cosmochimica Acta*, Vol. 35, No. 9, 1971, S. 865–875
- Bernatowicz, T. J.; Nichols, R. H.; Hohenberg, C. M.: Origin of Amorphous Rims on Lunar Soil Grains, In: *Lunar and Planetary Science Conference*, Vol. 25, 1994, S. 105–106.
- Taylor, L. A.: Helium-3 on the Moon: Model Assumptions and Abundances, In: *Engineering, Construction, and Operations in Space IV*, 1994, S. 678–686
- Heymann, D., Yaniv, A.: Breccia 10065: Release of inert gases by vacuum crushing at room temperature, In: *Proceedings of the Lunar Science Conference*, Vol. 2, 1971, S. 1681–1692
- Frick, U., Becker, R. H., Pepin, R. O.: Solar wind record in the lunar regolith - Nitrogen and noble gases, In: *Lunar and Planetary Science Conference*, Vol. 18, 1988, S. 87–120
- Rider, P. E., Pepin, R. O., Becker, R. H.: Noble gases and nitrogen released from lunar soils by acid etching, In: *Geochimica et Cosmochimica Acta*, Vol. 59, No. 23, 1995, S. 4983–4996
- Wieler, R., Baur, H., Signer, P.: Noble gases from solar energetic particles revealed by closed system stepwise etching of lunar soil minerals, In: *Geochimica et Cosmochimica Acta*, Vol. 50, No. 9, 1986, S. 1997–2017
- Meyer, C.: *Lunar Sample Compendium*, NASA Johnson Space Center, Astromaterials Research Exploration Science, Houston, TX, United States, 2009.
- Pepin, R. O., Nyquist, L. E., Phinney, D., Black, D. C.: Rare gases in Apollo 11 lunar material, In: *Lunar Science Conference*, Vol. 2, 1970, S. 1435–1454
- Hohenberg, C. M.; Davis, P. K.; Kaiser, W. A.; Lewis, R. S.; Reynolds, J. H.: Trapped and cosmogenic rare gases from stepwise heating of Apollo 11 samples, In: *Lunar Science Conference*, Vol. 2, 1970, S. 1283–1309
- Colozza, Anthony J.: Analysis of lunar regolith thermal energy storage, In: *International Solar Energy Conference*, 1991
- Robie, R. A.; Hemingway, B. S.; Wilson, W. H.: Specific heats of lunar surface materials from 90 to 350 degrees Kelvin, In: *Science*, Vol. 167, No. 3918, 1970, S. 749–750
- Grott, M.; Knollenberg, J.; Krause, C.: Apollo lunar heat flow experiment revisited: A critical reassessment of the in situ thermal conductivity determination, In: *Journal of Geophysical Research*, Vol. 115, E11, 2010
- Grote, K.-H. (ed.); Feldhusen, J. (ed.): *Dubbel. 24. Aufl. Berlin, Heidelberg. Springer Berlin Heidelberg*, 2014 (in German).
- Specht, E., Becker, F. H.: *Drehrohröfen*. In: Grote, K.-H.; Feldhusen, J. (ed.): *Dubbel. 24. Aufl. Berlin, Heidelberg : Springer Berlin Heidelberg*, 2014, S. 690–699 (in German).
- Mellmann, J.: The transverse motion of solids in rotating cylinders—forms of motion and transition behavior, In: *Powder Technology*, Vol. 118, No. 3, 2001, S. 251–270
- Ginsberg, T.: *Dynamische Modellierung von Drehrohröfen*. Dissertation. Hochschulbibliothek der Rheinisch-Westfälischen Technischen Hochschule Aachen, 2011 (in German).

- 34) Barmatz, M.; Steinfeld, D.; Begley, S. B.; Winterhalter, D.; Allen, C.: Micro-wave Permittivity and Permeability Measurements on Lunar Soils, In: Lunar and Planetary Science Conference, Vol. 42, No. 1608, 2011, S. 1041
- 35) Barmatz, M.; Steinfeld, D.; Winterhalter, D.; Rickman, D.; Weinstein, M.: Microwave Heating Studies and Instrumentation for Processing Lunar Regolith and Simulants, In: Lunar and Planetary Science Conference, Vol. 44, No. 1719, 2013, S. 1223
- 36) Taylor, Lawrence A.; Meek, Thomas T.: Microwave Sintering of Lunar Soil: Properties, Theory, and Practice, In: Journal of Aerospace Engineering, Vol. 18, No. 3, 2005, S. 188–196
- 37) Meek, T. T.; Vaniman, D. T.; Blake, R. D.; Cocks, F. H.: Electromagnetic energy applied to and gained from lunar materials, In: MAGLEV 86 Symposium, 1986
- 38) NASA: Conceptual Design of Power Systems, In: Lunar / Mars Exploration Initiative, 1989.
- 39) Kurtz, H.: Energiesysteme für die Raumfahrt, lecture notes, Institute of Space Systems, University of Stuttgart, 2009 (in German):