Physical Assets by SHS in the Framework of ISRU and ISFR Paradigms for Human Space Missions on the Moon

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Abstract

In this work a brief overview of the most important technologies for space exploration, with particular emphasis on the Moon missions, is presented. It is shown that the focus has been on the technologies to extract consumables (O_2, H_2O, N_2) for human life-support replenishment. The fact that the exploitation of extraterrestrial resources to obtain the desired materials during each ongoing mission, which has been the subject of several investigations since the sixties of the last century, is discussed. The paradigms ISRU (In Situ Resources Utilization) and ISFR (In Situ Fabrication and Repair) are then introduced. In particular, one of the most important process for the production of oxygen, i.e. the reduction of ilmenite by hydrogen is analyzed. In addition, the current iteration of the roadmap which identifies two feasible pathways for human missions after ISS (International Space Station) is addressed. Next, the fabrication of Lunar physical assets is taken into account, while focusing particularly on those processes where combustion-like reactions are exploited. The main results recently obtained in the literature in this regards are also summarized. In particular, the choice of the reducing agent and the influence of the most important processing parameters (composition of the starting mixture, gas pressure level, and gravity conditions) are examined in a systematic manner.

Introduction

It is well known that since the late fifties of the last century Russia and USA have established quite ambitious space programs through the corresponding Agencies, namely ROSCOSMOS and NASA, respectively, that result in both unmanned and manned missions. It has been in the mean time established that the cost associated with the transport of one kilogram of payload into orbit is of about 20000,00 US dollars, while about 10000 kg of propellant are required to reach the Moon [1]. With the aim to reduce the costs associated with space missions, the exploitation of extraterrestrial resources to obtain the desired materials during each ongoing mission has been the subject of several investigations since the sixties of the last century [2]. Along these lines, the paradigms ISRU (In Situ Resources Utilization) and ISFR (In Situ Fabrication and Repair) naturally arose [3-7]. The first one is based on the concept of using extraterrestrial materials otherwise transported from the Earth and implies to establish, evaluate and assess the in situ resources and technologies with the aim to increase of mission-time and economic aspects. As it will be clear in the sequel, the focus has been on the technologies to extract consumables (O_2, H_2O, N_2) for human life-support replenishment and source material for ISFR. As for the latter one, the aim has been to satisfy other human needs such as the development of novel fabrication and repair technologies as well as of habitat structures. Thus, the development of innovative technologies in the framework of the ISFR and ISRU concepts is relevant for facilitating and time extending future human exploration on the Moon, Mars, near Earth asteroids, etc. [8-11].

It should be noted that apart from the classification of the available technologies proposed by McKay et al. [12], the approach was mainly devoted to the development of specific analyses of space resources and the design of a colony on Moon and Mars while considering four main topics which are also nowa-

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days taken specifically into account in space exploration: (a) scenario's analysis, (b) energy, power and transport, (c) materials and (d) social concerns.

From that period Space Agencies all over the world have collaborated to formulate new processes and solutions by organizing their results and analyses in periodical meetings in the framework of the International Space Exploration Coordination Group (ISECG) where different experiences are bounded [13], while covering both technical and economic issues. In addition, manned missions to the Moon started to be foreseen, including government as well as privately funded efforts and lot of plans for lunar future outposts have been proposed [14]. In what follows, a brief overview of the main technologies available to date for Moon exploration is reported, including the in situ production of physical assets for which more details and considerations will be presented.

It should be noted in passing that during the years 2000 s, the People›s Republic of China has initiated a manned spaceflight program, along the lines proposed by the United States, the European Union, Japan, Russia and India. Specifically, in 2010, the United States space exploration program has been presented and, particularly, a new concept of space exploration based on the return to the Moon was introduced. Indeed, future human space exploration scenarios are consistent with the following perspectives: utilization of the International Space Station (ISS) until 2020 and beyond, assembly of post ISS infrastructures, the design and development of long-cruise stages to get to other destinations, and the implementation of human activities on near a planetary body surface (Moon, near Earth asteroids, Mars and its moons). The most recent common program of future space exploration has been drawn by the ISECG that coordinates the global interests of 14 space agencies. Indeed, by developing a common roadmap, agencies hope to coordinate their preparatory investments in ways that maximize return on investments and enable earlier realization of their goals and objectives.

The current iteration of the roadmap identifies two feasible pathways for human missions after ISS: Asteroid Next and Moon Next, which is reported in Fig. 1. They differ primarily with regard to the sequence of sending humans to the Moon and asteroids, and each reflects a stepwise development and demonstration of the capabilities ultimately required for human exploration of Mars. Alternatively, pursuing the "Asteroid Next" pathway aggressively drives advancements in deep space exploration technologies and capabilities such as advanced propulsion or habitation systems. The depicted pathway is elaborated through the development of a representative mission scenario – a logical sequence of missions over a 25-year horizon – which is considered technically feasible and programmatically implement able.

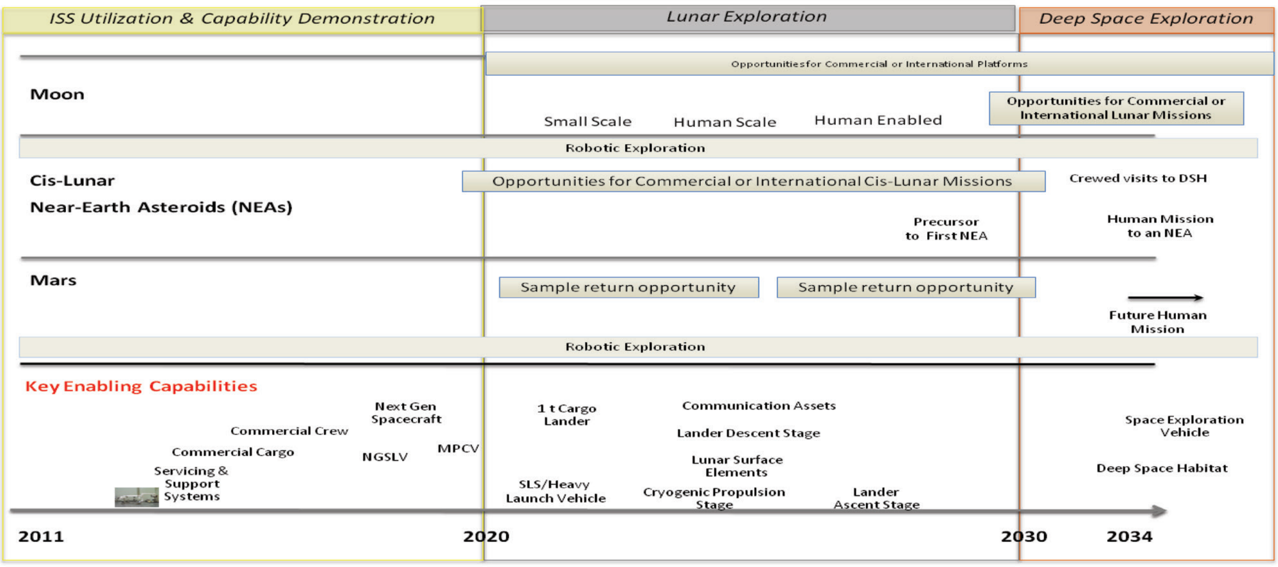

Fig. 1. Mission scenario: Moon Next (adapted from HTTP://WWW.GLOBALSPACEEXPLORATION.ORG/).

Space Exploration Technologies: a Brief Overview

One of the biggest difficulties in performing human space exploration is that each crew member needs to consume specific materials related to the physiological human needs and to handle the corresponding effluents. Specifically, it is necessary to: remove both metabolic and non-metabolic wastes (dirty water, urine, feces, solid wastes, nitrogen from breathing and sweating), produce breathing atmosphere with appropriate content of constituents, guarantee the availability of water for both hygienic and drinkable needs and provide food availability. It should be noted that such needs are currently satisfied by the so-called ECLSS (Ecological Controlled Life-Support System) onboard the ISS so that future Moon outposts should take advantage of such established technologies [15]. More specifically, ECLSS consists of an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and air lock support system. In any case the current ECLSS plants have not yet achieved the goal of the closed cycle, because it is not possible to recover and recycle the materials with 100% efficiency. Specifically, without external supply, the production of the necessary amount of water, food and oxygen is prevented. With the aim of addressing these problems the MELiSSA (Micro-Ecological Life Support System Alternative) project has been started by the European Space Agency (ESA) in 1989. It consists of a multidisciplinary project where the driving element is to develop novel processes for the recovery of edible biomass from waste, carbon dioxide and minerals, using light as source of energy to promote biological photosynthesis.

When planning the development of lunar space outposts, one of the first consideration should be related to power availability for operating machinery and transportation. Propellants used for such purposes are in the liquid, solid or hybrid phases. Among the liquid ones, unsymmetrical dimethyl hydrazine (UDMH) shows the lowest freezing point and has enough thermal stability to be used in large regenerative cooled engines. Consequently, UDMH is often used in launch vehicle applications, even though it is the least efficient of the hydrazine derivatives [16]. The decomposition of hydrazine-type-of propellants produces temperatures up to about 1100 ºC and a specific impulse of about 230 or 240 seconds. Modern solid propellants are heterogeneous powders (mixtures) which use a crystallized or finely ground mineral salt as an oxidizer, often ammonium perchlorate, which constitutes between 60% and 90% of the mass of the propellant. The fuel itself is generally aluminum. The propellant is held together by a polymeric binder, usually polyurethane or polybutadienes, which is also consumed as fuel. Among hybrid propellants, nitrous oxide as liquid oxidizer has been recently burned with hydroxy-terminator polybutadiene (HTPB) rubber as solid fuel [17].

While, for the sake of brevity, the most relevant characteristics of the Moon are reported elsewhere [18], in what follows the relevant ISRU and ISFR technologies for its exploration are briefly analyzed. Since oxygen represents one of the most critical factor for human survival, its production has been addressed in the recent decades and over twenty different chemical and physical processes have been proposed. It should be noted that the latter ones have been taking into account, as primary feedstock, Lunar regolith simulants [19] or ilmenite ($FeTiO_3$), whose content in the lunar regolith is up to 20 wt.%. on Moon soil [1]. Specifically, the following processes have been proposed so far: ilmenite reduction with hydrogen [20], ilmenite reduction with C/CO [21], ilmenite reduction with methane [22], glass reduction with hydrogen [23], ilmenite reduction with hydrogen sulfide [24], extraction with fluorine [25], carbochlorination [26], chlorine plasma reduction [26], vapour pyrolysis [27], ion plasma pyrolysis [27], plasma reduction of ilmenite [28], molten silicate electrolysis [29], fluxed molten silicate electrolysis [30], caustic dissolution and electrolysis [24], carbothermal reduction [31], magma partial oxidation [32], Li or Na ilmenite reduction [33], dissolution with HF [34] and H_2SO_4 [35]. Let us briefly examine one of the most important process for the production of oxygen, i.e. the reduction of ilmenite by hydrogen which involves the following chemical reactions:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$
$$H_2O \rightarrow H_2 + 0.5\ O_2$$

A conceptual design for fluid bed ilmenite reduction consists of a fluidized bed, with the hydrogen flowing upwards and the solid flowing downwards, as schematically shown in Fig. 2. Cold ilmenite fed from a hopper at reactor chamber pressure top bed through a suitable feeder, where is heated by hot recycled hydrogen. In this manner, the hydrogen cools sufficiently for the blower to perform reliably. The unused hydrogen and newly produced water vapor are then channelled into the solid state ceramic electrolyser which operates at the same temperature as the main reactor to avoid the need for cooling the water product and re-heating the hydrogen. Oxygen is removed for liquefaction and storage and the hydrogen returned to the top bed. Spent solids over flow into the bottom chamber where they exchange heat with the returning hydrogen. Although the chemistry of this process is not complicated, lunar ilmenite commonly contains chemical impurities, whose effects upon the kinetics of ilmenite reduction with hydrogen, or any other gas, remains unknown.

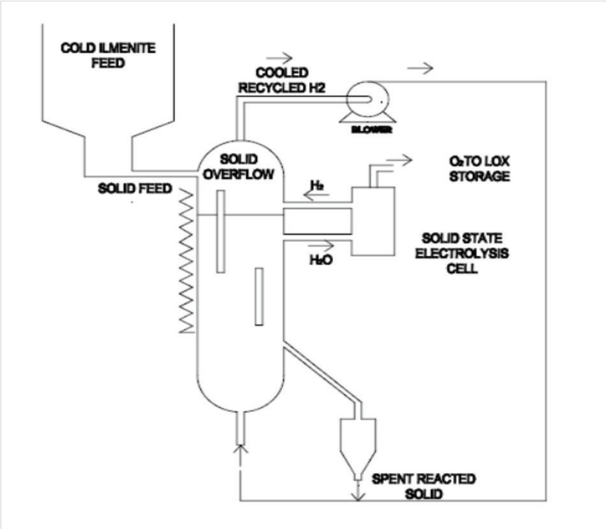

Fig. 2. Schematic representation of the process for the production of oxygen from ilmenite (adapted from [20]).

As mentioned above, in the majority of these processes, specific minerals, particularly ilmenite, are involved. Consequently, the constraints and the requirements of several required activity on the Moon have been analyzed by Satish et al. [36], with particular reference of drilling, blasting, excavation, comminution and beneficiation of lunar regolith. Specifically, in the recent literature lot of methods have been proposed in order to enrich lunar regolith in this oxide mineral [37-41] utilizing both electrostatic and magnetic technologies. In addition, the problem of mining lunar soil has been addressed in last decades [42-46]. One of the most relevant scientific contribution in this field has been proposed by Landis [47], that described some methods to refine lunar regolith to obtain silicon, titanium, metals, calcium, magnesium and glass. Zeng et al. [48] analyzed with deep details the excavation force that will be encountered on the Moon surface.

It has been suggested that solar cells could be produced from the materials present on the lunar surface. In its original form, known as the solar power satellite, the proposal was intended as an alternate power source for Earth. Solar cells would be shipped to Earth orbit and assembled, the power being transmitted to Earth via microwave beams. Despite of much work on the cost of such a venture, the uncertainty lays in the cost and complexity of fabrication procedures on the lunar surface. Consequently, power through solar cells is likely to be the primary method of obtaining electricity on the Moon. Electrical power can be used directly for many operations, and can be the power source for converting the output water of fuel cells back into hydrogen and oxygen. Recently, Freundlich et al. [49] have proposed a method to fabricate power system utilizing lunar resources exploiting the ultra vacuum level on the lunar surface and the presence of some materials from which thin film solar cells could be made by direct evaporation. This experimental activity consisted of heating a regolith simulant up to 1300 °C when it starts soften. The resulting melt was very viscous and evolved in gas bubbles. At 1600 °C the regolith has completely melted and the viscosity is lowered. The sample has been then cooled: the temperature falls quickly (1-2 minutes to around 300°C). The resistivity of the melted regolith glass substrates was found to exceed 10^6 Ωcm. This material could be viewed as a substrate on which by evaporation it is possible to produce a thin film of solar cell.

For their important applications solar cells have been deeply analyzed in recent years [50-52] investigated the electrical needs considering different mission scenarios. In addition Ignatiev et al. [53] analyzed the possibility to generate power on the Moon using solar (photovoltaic) systems. Being the lunar environment a vacuum with pressure levels generally of about 1×10^{-10} torr, such conditions provide an ideal environment for direct vacuum deposition of thin film solar cells using the waste silicon, iron, and TiO_2 available from the lunar regolith processing meant to extract oxygen. Woodcook et al. [52] proposed an integrated solution among the main system of energy production in Space – nuclear, solar and chemical.

Fabrication of Lunar Physical Assets

While more details on the space exploration technologies briefly mentioned above can be obtained for example from a recent publication [54], let us concentrate our attention on the production of specific materials, by taking advantage of lunar resources, to obtain physical assets which in turn allows one to fabricate suitable structures for protection against cosmic rays, solar wind and meteoroids. This aspect represents an important challenge in the framework of space exploration so that several studies have been addressed in last decades on this subject [55-60]. In particular, Waldron et al. [56] proposed an electrochemical refining process for the separation and recovery of principal and trace elements from reduced metallic particles found in lunar soils. Desai et al. [58] developed a versatile engineering materials production from locally available materials in space. Specifically, the development of the technologies for manufacturing structural and construction materials on the Moon utilizing lunar regolith without the use of water has been proposed. In addition, a process to obtain useful ceramic materials by taking advantage of the by-products resulting from lunar oxygen production processes is addressed by Leong et al. [60]. In particular, a process where regolith Lunar simulants were sintered at 1100 °C by radiant and microwave heating was proposed [61]. Lunar regolith was also utilized for fabricating a thermo-plastic material [62] and fiberglass for reinforcing Lunar concrete [63]. Additional studies related to the production and the utilization of in-situ resources to obtain lunar concrete have been performed [64-66].

It should be noted that combustion synthesis-type reactions have been also exploited for the fabrication of ceramic composites using Lunar regolith simulants. Martirosyan and Luss [67] have addressed the preparation of physical assets to be potentially used for "Lunar bricks" starting from a mixture consisting of Lunar soil simulant, titanium and boron that displays a self propagating high-temperature (SHS) behaviour under certain reactant combinations. Another recently proposed route is represented by the direct aluminotherimic reduction of Lunar regolith simulant to produce ceramic composite materials [68-69]. Apparently, this system does not behave like a classical SHS process where a local and very rapid ignition is able to generate a self-propagating conmbustion front, since a relatively long preheating (7-5 min) was needed to activate the reaction in the starting mixture. On the other hand, as recently reported in the literature [70-71], the occurrence of self-sustaining combustion synthesis reaction is possible in mixtures obtained after blending regolith simulant with suitable amount of ilmenite ($FeTiO_3$), to reproduce the enrichment of Lunar soil in this species, and alumimun as reducing agent. This process [72] takes advantage of the strongly exothermic character of the aluminothermic reduction of ilmentite, whose presence is up to 20 wt.% on Moon soil [1]. Briefly, the complete process consists first in the electric power production through a combination of photovoltaic arrays and fuel cells [73-74]. The produced electric power allows then the excavation of Lunar or Martian regolith using suitable tools [75-76]. Lunar regolith is consequently enriched with ilmenite by means of electrostatic or magnetic techniques, respectively [37], [77]. The so-enriched minerals are mixed with suitable amounts of Al powder to obtain mixtures which undergo SHS reactions upon ignition. The obtained physical assets can be suitably mounted to obtain the desired structures. Further details are reported in the original patent [72]. Recently, [78-79] have the use of magnesium as reducing agent preferable, in comparison with aluminium, on the basis of the higher adiabatic temperature of the related system. It should be mentioned in passing that, as clearly demonstrated by Corrias et al. [71], aluminium should be preferred with respect to magnesium because of its lower vapour pressure which allows to significantly mitigate undesired phenomena such as reactants/products losses, sample weight decreasing, product porosity increasing, possible interruption of combustion front propagation, difficulties in process control, etc. However, it has been also shown that care should be taken when using aluminium as reducing agent beyond certain evacuation levels. It is also useful to note that such element could be extracted from Lunar minerals containing it or otherwise recovered from components or portions of vehicles previously utilized for Space Missions and available on the Moon [78]. In what follows, the most important results recently obtained when developing the SHS stage of the process for the in-situ fabrication of Lunar construction materials [72] are reported while providing suitable remarks and considerations.

Remarks on the SHS Fabrication of Lunar Physical Assets

Regarding the development of the processing step of the proposed technology [72] where SHS reactions have been exploited, it should be noted that all the details related to the experimental activities performed so far are not reported here for the sake of brevity. The interested reader should refer to the recent literature [71] where the choice of the reducing agent and the influence of the most important processing parameters (composition of the starting mixture, gas pressure level, and gravity conditions) have been examined in a systematic manner. Briefly, JSC Lunar regolith simulant provided by Orbital Technologies Corporation (Madison, WI, USA) was first sieved, to produce a -45 μm powder fraction, and then blended in suitable proportions with Al (Alfa Aesar, -325 mesh, 99.5% purity) and $FeTiO_3$ (Alfa Aesar, -100 mesh, 99.8% + purity) powders, to obtain the mixtures to be reacted by SHS under either terrestrial or low-gravity conditions obtained inside a special airbus (Airbus A300) through a series of parabolic maneuvers. The general reaction stoichiometry considered to develop the process step of the proposed technology involving SHS reactions has been as follows:

$$FeTiO_3 + xAl + y(wt.\%)\ R_L \rightarrow Products \qquad (1)$$

where, x was varied in the range 0.9-3, while y was increased from 0 to the maximum allowable weight percentage, depending on the corresponding x value, for guaranteeing the SHS character in the resulting reacting system.

It has been established that reaction (1) can be performed also using Lunar regolith, that has to be, however, preliminarily enriched in ilmenite, before being reacted with Al. In particular, the optimal mixture composition able to guarantee the self-propagating behavior in the resulting system, while limiting the expenses for the enrichment treatment, has been identified. In this regard, it has been observed that mixtures with $Al/FeTiO_3$ molar ratio lower than 0.9 do not exhibit an SHS behavior while, when this threshold value is set, no additional simulant is allowed to be added to the mixture to obtain such combustive regime. However, when the amount of the reducing metal in the mixture was gradually increased, the SHS process proceeds faster and the measured combustion temperature becomes higher, as a consequence of the increased system exothermicity. Correspondingly, the amount of regolith that is possible to combine with $FeTiO_3$ and Al reactants could be gradually augmented, thus allowing to identify the optimal mixture composition at the various $Al/FeTiO_3$ molar ratios. This is an important issue in the framework of ISRU applications. Specifically, the minimum amount of Al required by the system for obtaining an SHS reaction increases from 13.5 wt.%, for the case of regolith consisting of pure ilmenite, to 23.5 wt.%, needed when the starting mixture contained 32.5 wt.% of simulant. In particular, the latter condition simulates a system consisting of Al with an enriched Lunar soil containing about 62 wt.% of ilmenite. It should be noted that the introduction of the enrichment step leads to a significant decrease in the amount of Al needed by the process, as compared to that (33 wt.%) utilized by Faierson et al. [68].

Regarding end-product composition, Al_2O_3, Fe, and Ti along with, depending upon the $Al/FeTiO_3$ ratio considered, various Ti oxides, are formed in absence of regolith in the initial mixture. The occurrence of possible global reactions has been postulated to justify the formation of these phases.

On the other hand, very complex composite ceramic-metal materials consisting of additional mixed oxides, such as $MgAl_2O_4$, $Ca(Al,Fe)_{12}O_{19}$, $Ca_2(Al,Fe)_2O_5$ and $CaAl_4O_7$, were produced by SHS when Lunar regolith was present in the starting mixture. An example of final samples obtained is shown in Fig. 3.

Compressive strength properties of the obtained products are in the range 25.8-27.2 MPa, thus showing a significant improvement as compared to materials produced from the direct thermite reaction of Al with Lunar regolith simulant (10-18 MPa). This outcome is likely associated to the most favorable reaction conditions encountered by Corrias et al. [71] due to the higher percentage of ilmenite in the initial mixture. Indeed, the corresponding increase in the exothermicity of the reacting system promotes the interaction among reactant particles towards the obtainment of strongly sintered materials.

As far as the effect of vacuum conditions present inside the combustion chamber is concerned, it is found that the SHS process dynamics and product characteristics change only slightly when the pressure level is decreased from 760 down to about 10 Torr. However, the consequences deriving from the enhanced Al vaporization during the process, i.e. sample weight loss, temperature increase and front velocity decrease, become significant when further evacuating the SHS chamber. Thus, in view of the possible exploitation of this fabrication process on the Moon, the synthesis reaction should be conducted in a closed environment at a proper overpressure (few Torr) as compared to the pressure value (10^{-12} Torr) present on Lunar soil.

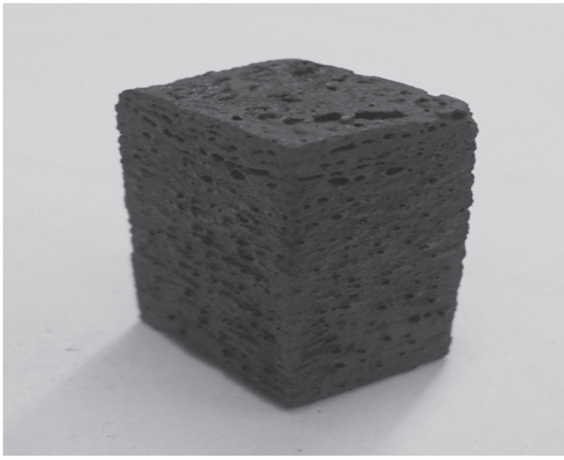

Fig. 3. Example of final parallelepiped sample obtained by the proposed patented process [72].

Finally, the results obtained during parabolic flight experiments, aimed to verify the possible effects caused by the change in gravity when passing from Earth to Moon conditions, reveal that neither SHS process dynamics nor product characteristics are correspondingly influenced in a relevant manner. All the outcomes reported and discussed in Corrias et al. [71] allows us to assess that the optimized results obtained under terrestrial conditions are still valid for in-situ applications in Lunar environment.

Conclusions

In this work a brief overview of the most important technologies for space exploration, with particular emphasis for the Moon missions, has been presented. Next, the fabrication of Lunar physical assets has been addressed, while focusing particularly on those processes where the combustion-like reactions have been exploited. The main results recently obtained in the literature in this regards have been also summarized.

It should be noted that the Lunar initiative was in its peak in 2005 when significant new investments were made mostly by NASA in ISRU technologies [54]. As shown in this work, the main product of these processes is oxygen for which on the other hand, according to the recent project plans, there would not be much demand from ISRU processes on the Moon. Indeed, it would probably not be used as ascent propellant since the latter one has to be brought from Earth if abort to orbit is required and ECLISS would reduce the moderate oxygen requirement for breathing. Furthermore, even if oxygen has to be used as an ascent propellant, the leverage inherent in lunar propellant production is far less than that for Mars propellant production. Apart from the technical difficulty in implementing lunar ISRU processes, there is also the question of affordability. Specifically, such concept related to water extraction from shadowed ice in craters depends on the cost of prospecting to locate the best sources of water ice. Analyses are under way to verify if the cost is not to high to be affordable. On the other hand the development of suitable radiation shields is considered to be a crucial subsystem for eventual use in a human mission to the Moon and also to Mars, for which the development of heavy lift launch vehicles, suitable habitats, possible nuclear power systems, long-life resilient ECLSS, artificial gravity systems, aero entry systems, propulsion systems compatible with ISRU and prototype ascent vehicles are also under investigation. Along these lines, it is apparent that the patent for the production of physical assets on the Moon, Mars and Asteroids [72], recently nationalized in Europe, United States, China, India, Japan and Russia and briefly described in this work, might provide a useful tool to produce suitable protection structures, as depicted in Fig. 4.

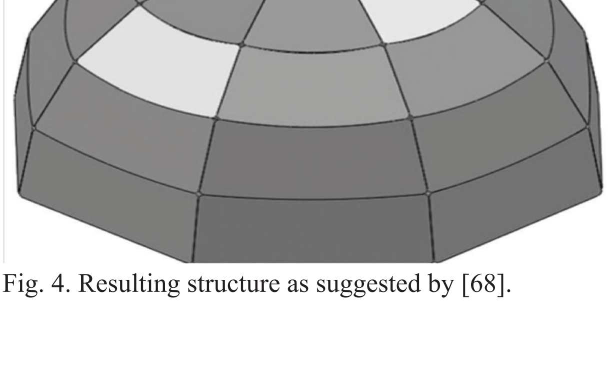

Fig. 4. Resulting structure as suggested by [68].

Acknowledgments

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