

IAC-13,A5.1,5x18844

ESTABLISHMENT OF A LUNAR BASE BY COUPLING LUNAR IN SITU RESOURCES UTILIZATION AND BIOREGENERATIVE LIFE SUPPORT SYSTEMS WITHIN THE OASIS NETWORK OF SPACEPORTS

Chrishma Singh Derewa
NASA Jet Propulsion Laboratory, United States, Chrishma.Derewa@Jpl.NASA.gov
Lucie Poulet
DLR Institute of Space Systems, Bremen, Germany, Lucie,Poulet@dlr.de
Marc Labriet
International Space University, United States, marc.labriet@gmail.com
Nuno Loureiro
International Space University, Portugal, nunoloureir@gmail.com
Maxime Puteaux
Institut du Droit de l'Espace et des Télécommunications, France, maximeputeaux@gmail.com

The creation of a network of spaceports combining In Situ Resource Utilization (ISRU) and bioregenerative life-support systems would provide an easier and more affordable access to orbital and deep space destinations. In the longer term it would enable the development of extra-terrestrial human habitats in the inner solar system. Following the Operations And Service Infrastructure for Space (OASIS) project, this paper describes in greater details the establishment and development of the second node of the network, on the Moon. Node 2 is based in the Lunar South Pole, where trapped water in craters, almost constant illumination on the craters' rim, and small temperature gradients offer the best environment. Initially unmanned, the lunar outpost is composed of a spaceport to land and launch vehicles safely, a power plant, and an in situ resources processing plant. Water is extracted and sent to node 1 in Low Earth Orbit and is also separated on site into hydrogen and oxygen, which can be used as propellant for various spacecraft and to support habitation and human operations. Other lunar volatiles trapped in the near sub surface include N_2, usable for habitat atmosphere generation and for plant growth medium, H_2, and other carbon compounds. Additionally ilmenite, a common lunar mineral, can be used to produce titanium, oxygen and manufacture semiconducting devices such as photovoltaic cells. Critical technologies, such as regolith excavators and the Moon shuttle, with their concepts of operations, requirements, functions, and design are detailed. The business model and rationale for node 2 in the frame of the network of spaceports, as well as the law and policy framework are described comprehensively. The OASIS infrastructure with a lunar node 2 will reduce space exploration and development costs by providing in situ derived propellants on demand, and ultimately will fundamentally revolutionize how we travel in the solar system.

I. INTRODUCTION

The Operations And Service Infrastructure for Space (OASIS) aims to progressively develop a network of spaceports providing support for space exploration and commercial activities and eventually the expansion of humanity into space. The creation of a network of spaceports combining In Situ Resource Utilization (ISRU) and bioregenerative life-support systems will provide an easier and more affordable access to orbital and deep space destinations. In the longer term it will enable the development of extraterrestrial human habitats in the inner solar system. Getting to and living on distant destinations poses some significant engineering challenges. Current launch systems, while very capable, are unable to provide sufficient mass to orbit at acceptable costs. Current techniques place tons of propellant into orbit solely for raising the spacecraft to its desired destination. This technique wastes much of the launch system's volume and energy; however, recent discoveries of large quantities water on the Moon, Mars and throughout the asteroid belt reveal new alternatives.

The lunar base presented herein outlines the second node in this network of spaceports. This infrastructure waypoint provides services for space vehicles and facilitates their departure and arrival from the earth-moon system. Phase one of the OASIS architecture utilizes propellant and other support items stored on orbit allowing launch systems to lift more usable spacecraft mass into Low Earth Orbit (LEO). The Cargo Autonomous Rendezvous and Velocity Adjustment/Navigation (CARAVAN) space tug will provide transport servicing in proximity to each node; Low Earth Orbit, the lunar surface and the Martian moon of Phobos. The OASIS spaceport node 2 on the

Lunar surface will both reduce the cost of near earth services to include upper stage augmentation/replacement, while enabling reductions in transit time to deep space destinations such as Mars.

Node 2 is based in the Lunar South Pole, where trapped water in craters, almost constant illumination on the craters' rim, and small temperature gradients over the best environment. Initially unmanned, the lunar outpost is composed of a spaceport to land and launch vehicles safely, a power plant, and an in-situ resources processing plant. Water is extracted and sent to node 1 in Low Earth Orbit and is also separated on site into hydrogen and oxygen, which can be used as propellant for various spacecraft and to support habitation and human operations. Other lunar volatiles trapped in the near sub surface include N_2, usable for habitat atmosphere generation and for plant growth medium, H_2, and other carbon compounds. Additionally ilmenite, a common lunar mineral, can be used to produce titanium, oxygen and manufacture semiconducting devices such as photovoltaic cells. Critical technologies, such as regolith excavators and the Moon shuttle, with their concepts of operations, requirements, functions, and design are detailed. The business model and rationale for node 2 in the frame of the network of spaceports, as well as the law and policy framework are described comprehensively.

The OASIS infrastructure with a lunar node 2 will reduce space exploration and development costs by providing in situ derived propellants on demand, and ultimately will fundamentally revolutionize how we travel in the solar system. OASIS proposes a comprehensive solution that includes interdisciplinary objectives, in which it provides a flexible architecture for manned missions to Martian orbit and beyond.

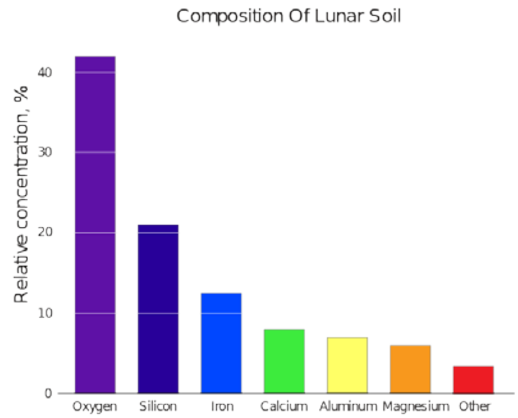
II. LUNAR RESSOURCES

II.I Lunar regolith / oxides and metals

The lunar regolith is a layer of unconsolidated debris whose thickness varies from about 5 m in the mare regions to about 12m on highland surfaces[1]. Depending on the location, the regolith may contain elements in the form of metals, minerals and volatiles. Also in some locations water can be found in the form of ice[2]. Extensive studies and experiments have demonstrated that they can be extracted, processed and used. The regolith mineralogy varies all over the moon but, at the global scale it is composed of four major mineral types: pyroxene (50%), anorthite (20%), olivine (15%), and ilmenite (15%), and over 42% by mass of lunar regolith is oxygen[3].

Oxygen is abundant because it easily bonds with many things lightweight materials at the surface of the Moon. The two most studied Moon minerals are Ilmenite and Anothite.

Fig. 1: Composition of Lunar soil



Mare Regolith			Solar Wind Volatiles	
Pyroxene	50%		Hydrogen	50-150 ppm
$CaO*SiO_2$		36.7%	Helium	3-50 ppm
$MgO*SiO_2$		29.2%	Helium-3	10-2 ppm
$FeO*SiO_2$		17.6%	Carbon	100-150 ppm
$Al_2O_3*SiO_2$		9.6%		
TiO_2*SiO_2		6.9%	**Major Volatiles from LCROSS**	
Anorthite	20%		Carbon Monoxide	5.70%
$CaO*Al_2O_3*SiO_2$		97.7%	Water/Ice	5.50%
Olivine	15%		Hydrogen	1.40%
$2MgO*SiO_2$		56.6%	Hydrogen Sulfide	0.92%
$2FeO*SiO_2$		42.7%	Mercury	0.48%
Ilmenite	15%		Ammonia	0.33%
$FeO*TiO_2$		98.5%		

Table 1: Lunar Regolith and Volatile Constituents[1,4]

The average anorthite concentration in the lunar highlands where the Apollo 16 astronauts landed was between 75 and 98%. Anorthite consists of silicates that have metallic elements bonded to silicon and oxygen: aluminium and calcium. They are both excellent electrical conductors. These are also the primary materials required to manufacture solar arrays. Smelters can also produce pure aluminium, calcium metal, oxygen and silica glass. Raw anorthsite is also good for making fiberglass and other glass and ceramic products. Finally atomized aluminium powder can also be utilized as propellant. It was used as fuel for the Shuttle SRBs.

Ilmenite is commonly found in the mare regions (up to 25 wt% (mass of oxygen per mass of ilmenite)) and is a mixture of iron, titanium, and oxygen. They (including a small quantity of free iron) can easily be extracted from high purity grains for Ilmenite found at the Apollo 17 landing site.

Most importantly Ilmenite is the best source of in situ oxygen[5] because it is easily reduced, and high oxygen yields can be achievable. Oxygen can be extracted from Ilmenite, Basalt, and unprocessed Soil (Oxygen yield from lunar soils is strongly correlated with initial iron content). Current technologies include[6,7]:

- Electrolysis utilizing an acidic ionic liquid
- Extraction of water from permafrost utilizing microwaves
- Molten oxide electrolysis

Some methods of oxygen extraction produce considerable quantities of by-products that are (relatively) enriched in metals such as iron, titanium, and aluminium[8].

Process (O^2 from regolith)	Regolith excavation rate (kg/H)	Reagent Outputs	Specific mass	Specific power	efficiency
Hydrogen reduction from Ilmenite	150	H_2 (g) O_2 (l)	0.15	1.93	1.41%
Carbothermal reduction of silicates	15	$CH_{4(g)}$ or $CO_{(g)}$ $O2_{(l)}$	~0.1	1.35	~14%
Molten silicates electrolysis	10	none $O_{2\,(l)}$	0.065	1.5	21.4%

Table 2: ISRU processes for oxygen extraction from regolith

II.II Hydrogen

Surveys conducted by the probes Lunar Prospector, Clementine, and SMART-1, as well as telescopic observations from Earth[9] have shown indications of hydrogen on the lunar poles. The neutron absorptivity of the lunar regolith, which indicates the presence of hydrogen, is shown as the purple regions in Figure 2.

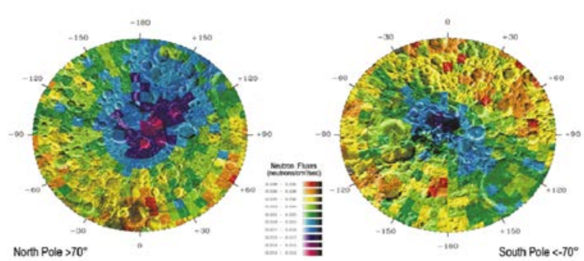


Fig. 2: Indication of Hydrogen at the Lunar Poles[9]

The concentrations of exposed hydrogen remain on the order of 150+/-80 ppm[9] in the craters and permanently shadowed regions at the poles. To confirm the results shown, the Lunar Reconnaissance Orbiter (LRO)/Lunar Crater Observation and Sensing Satellite (LCROSS) mission was conceived. The mission collided one stage of the module with the lunar surface and analysed the plume it created. The results showed that 4–8% of the plume consisted of water, but that this "represents only the sunlit fraction from the upper surface with speeds sufficient to reach an altitude of 830m"[10]. Figure 2 illustrates LCROSS' water identification in blue.

II.III Water/ice

The nature of the hydrogen deposit could vary in amount and nature, though water ice is the most probable source. Further study has shown that polar water comes in two major forms: permafrost and cold trap. Lunar cold traps are "zones of the moon permanently obscured where the temperatures are low enough to preserve ice for billions of years"[11]. Cold trap water exists around 40 Kelvin, and is so hard that it is nearly impossible to mine. Permafrost water exists on the rim of the polar craters, mixed in with the regolith just below the surface, and can be extracted much more easily with current technology. After the extraction of water, it can be stored in extracted-form or broken down into hydrogen and oxygen through electrolysis.

Recent data from the Lunar Cater Observation and Sensing Satellite (LCROSS) confirmed evidence for water-ice in the impact plume from Cabeus crater at a level corresponding to 6 wt % water-ice (~25 gallons)[12]. Several other volatiles including light hydrocarbons, sulphur bearing species, and carbon dioxide were also detected in the impact plume by LCROSS[13].

India's first unmanned lunar probe Chandrayaan-1 discovered more than 40 permanently darkened craters near the Moon's North Pole which are hypothesized to contain an estimated 600 million metric tonnes of water-ice[14]. Enough water-derived fuel to enable daily shuttle flights for the next 1200 years.

III. OASIS NODE 2

The Moon has been considered a top exploration target for most of the space agencies in the world, with eight missions planned until 2020. The resources available on the surface enable the possibility of in situ production of propellants, solar panels and habitation modules.

III.I Description of node 2

The resources could be useful to support Spaceport Node 1 in LEO and represent an important stepping stone towards the development of Spaceport Node 3 on Phobos.

On the Moon surface, apart from operational support such as power generation and communications, a system of elements will be set up. An excavator will gather resources, and an ISRU plant will transform them into their oxygen and hydrogen constituents. There will be a facility for water electrolysis that will generate additional propellant from mined water ice and reduced regolith. Another part of the Moon surface infrastructure will be a spaceport Vertical Takeoff Vertical Landing (VTVL) pad that enables spacecraft to launch and land safely and accurately through the use of navigation beacons. Later on, consumables for life support systems (Oxygen, fresh water, and food) will be provided for a human presence.

The first assumption is that a total amount of 150 tons per year of propellants would be shipped to node 1 in LEO over the course of 5 missions.

III.II Excavation Equipment

Electrolysis is a reasonably energetic process requiring 4.71 kWh/kg of water, and while this is manageable, it will require a significant source of energy.

	#	Component Mass [kg]	Development Cost [$m] 2008	Production Cost [$m] 2008	Total Cost [$m] 2012
Regolith Excavator	3	280.00	21.60	22.73	48.94
Transportation System	3	364.00	24.63	27.31	57.34
Regolith Water Generator	1	1,869.00	96.62	9.10	116.69
Propellant Generator	1	5,136.00	160.18	125.19	314.99
Cryogenic Storage	1	10,040.00	223.95	200.13	468.11
Water Storage	1	1,801.00	94.84	60.10	171.03
Power System	1	660.00	57.42	29.77	96.24
Launch Pad	1	300.00	38.71	17.14	61.65
Reuseable Moon Shuttle	1	3,489.00	1,233.73	237.19	1,623.63
Intermediate Totals		23,939.00			2,876.40
Support Equipment (10%)		2,393.90			
Maintenance (10%)					295.86
System Integration (10%)					295.86
Total Mass [kg]		**26,332.90**			

Table 3: Mass and Cost Breakdown of Node 2

The mass of the components was estimated according to Blair et al. 2002[15] and Christiansen, 1988[16]. The cost was estimated based on the NASA Spacecraft/Vehicle Level Cost Model, which is based on the NAFCOM (NASA/Air Force Cost Model) database and relates mass directly to cost. The model was based on 2008 US Dollars and was therefore corrected with an inflation rate of 3% to 2012 US Dollars. Every element was considered a "Scientific Instrument" except the Reusable Moon Shuttle ("Unmanned Planetary") in the cost model.

III.III Bioregenerative and physico-chemical life-support system

To maintain a crew alive on the lunar surface, three main functions must be ensured: atmosphere revitalization, i.e. removing CO2 and providing O2; water recycling; and food production. This can be achieved by different ways, from shipping all consumables from Earth or resupplying on a regular basis as it is currently done on the ISS, to using physicochemical regeneration, or using bioregeneration with higher plants and micro-organisms or using in situ resources. Shipping all goods from Earth is not a viable solution because current launchers are unable to send sufficient mass of consumables at once to sustain a crew on the Moon and regularly resupplying the crew with water, oxygen and food would cost too much. Total recovery of wastes, air and water in a closed loop would be the ideal case but technology does not enable it yet. A hybrid solution using physicochemical technologies as well as bioregeneration and in situ resources thus appears to be the optimum solution for a life-support system on the Moon. Having both physicochemical and biological technologies for air and water revitalization enable to have a redundancy and prevents a total stop of the life-support system which could be fatal for the crew, in case of failure of one of the two technologies. The use of in situ resources like water and oxygen extracted from lunar regolith, or regolith itself to use as a growth medium for the plants, would greatly reduce costs[17]. Indeed Drysdale et al. in 2004 show that using water on Mars (assuming ISRU water is available) would reduce the equivalent system mass of the mission by 39%[18]. The two problems with using ISRU for life-support systems are first that we need to be able to extract lunar resources, i.e. technologies need to be ready, and second, the life-support system will not function right away since resources need first to be extracted. Therefore the outpost on the Moon will be unmanned in a first phase with robots extracting and gathering resources from the Moon, making the lunar base ready for human arrival in a second phase. Extracting in situ resources might enable to have water and oxygen but it does not solve the problem of food production, which this can only be achieved with growing higher plants and algae. Drysdale et al. in 2004 show that life-support costs will be driven by the equivalent system mass of environment protection for short missions but that the ESM of food will be the main driver for long missions[18]. They also give an estimate of the growing area required per crew member, ranging from 13 m^2 when wheat only is grown[19] to at least 130m^2 when multiple crops are grown and different growing conditions are used[20].

The life-support system for lunar spaceport node 2 will thus be formed by the following elements:

- A bioregenerative loop with a greenhouse module
- A physicochemical (PC) regeneration loop
- External resources extracted from lunar regolith

The bioregenerative loop is built on the model of the MELiSSA (Micro-Ecological Life Support System Alternative) loop[21]. Bioreactors with different micro-organisms degrade wastes of the crew and inedible biomass of plants and algae into single elements. These elements are recovered and later used as nutrients for higher plants in the greenhouse module and algae in bioreactors. They produce food and oxygen for the crew and absorb CO_2 from the crew, therefore revitalizing the air. They can also purify water through evapotranspiration. Although bioregeneration is the only one enabling food production, its reliability and technology readiness level are rather low and coupled to a high complexity. Therefore a redundancy with a PC system is necessary.

CO_2 removal from the crew compartment will be ensured in parallel to the greenhouse module by a Sabatier reactor, as it is currently done on the ISS[22], following this chemical reaction:

$$CO_2+4H_2 \rightarrow CH_4+2H_2O$$

This is in case the greenhouse module cannot absorb the totality of CO_2 rejected by the crew. This reaction necessitates H_2, which is available from lunar regolith. It also enables production of fresh water. For water recycling, the same technology as the one used on the ISS as well as the Alternative Water Processor under development at Ames (forward osmosis and membrane aerated bioreactor) are used. Water is recovered from plant transpiration and human habitat but overall water is only partially recycled, for complexity reasons. When used water is too dirty, it is stored as a waste and fresh water from ISRU is injected into the loop. This also lowers the risk of contamination by undesired organic or inorganic compounds.

Oxygen is extracted from the regolith and from water electrolysis, initially for propellant production. Additional extracted oxygen is used for the life-support system, in parallel with the greenhouse oxygen production. This prevents hazardous situation in case of greenhouse module failure and ensures a constant rate of oxygen is provided to the crew. Additional oxygen is also used to oxidize the inedible biomass to recover nutrients stored in it and return them into the loop[23]. N_2, which is a necessary nutrient for plants, can also be found in lunar regolith and injected into the loop when needed. Figure 3 illustrates the life-support system deployed on lunar

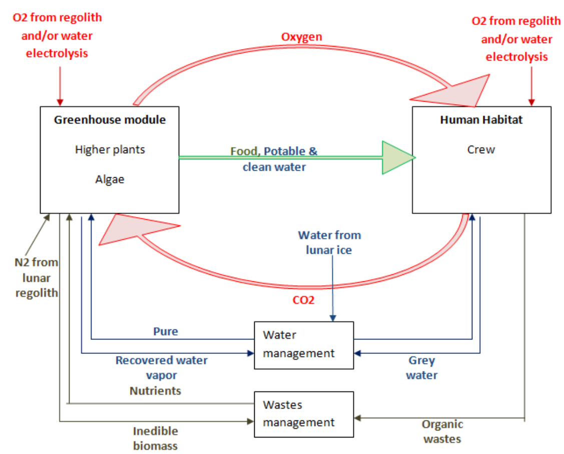


Fig. 3: Schematic drawing of the life-support system

VI. GOVERNING PARAMETERS AND POLICY CHALLENGE

OASIS has defined the governing authority for the viable execution of the network of proposed nodes. The ISECG provides the initial forum for member entities to share their objectives, plans, explore collaborative concepts, and formulate preprogram international partnerships. However, every nation will be permitted to enter the OASIS consortium upon meeting the required commitment levels. OASIS will consist of, at a minimum, the fourteen ISECG members and the transnational corporations wishing to develop the project. This commercial entity combines state reliability and legality with the flexibility of industry on an international level.

In addition to the acquisition and distribution of scientific data, OASIS will be responsible for resource speculation and allocations, ingress and egress routes, and mission resupply making a “Port Authority” model an ideal analogue. Similar to the Suez gateway this model allows a public entity to plan, facilitate, and regulate the initial construction and port extension, acquiring the large amount of capital needed. The port operator is managed by a private entity which operates, develops, and provides services to customers. The model combines creation of vital connections for customers, acts as a commercial space business incubator, provides safety management and allows creation of values and taxes incomes for member entities.

Extensive partnerships with the private sector composed of numerous transnational corporations, enables OASIS to engage resources previously untapped. A request for proposals or call for tenders by OASIS will invite private industry buy-in as equal voting members in the consortium. Once added, these members will be made identical financial contributions as the member states themselves.

The political benefits from such a partnership include: development of local private sector capabilities through subcontracting opportunities and exposure of state owned enterprises. It also creates diversification in the economy by making the country more competitive in terms of its facilitating infrastructure base as well as boosting to its business and industry associated with infrastructure development, while also supplementing limited public sector capacities and preparing for future demand.

OASIS will have sole proprietary rights to the application of technologies resulting from the establishment of the system. Land will be leased to the company for utilization whether through ISRU commodity production, gateway services or habitation. The company will retain the right to use member logos and reserve sole access to media and distribution rights for profit. Distribution of data such as maps, genetic life found, scientific data and more will be available for sale by the company. Given the potential profitability of the project demonstrated in business studies, private entities will have access to the OASIS capital as a way to leverage additional financial capabilities, resulting in public private shareholders. OASIS will also be traded publically, opening up increased public investment motivated by the above incentives.

A Memorandum of Understanding (MoU) will be signed among the states at the highest presidential levels and ratified by the peoples governing body, providing the initial framework for smooth operation and long-term commitments. All basic norms and principles will be in this “treaty”; for instance, all OASIS members will participate in an equitable manner, regarding their financial contribution. The distribution of power in OASIS and therefore decision-making will be equal as long as the member makes the minimum required financial contribution. Members will vote on vital decisions, contract selection, and regulatory decisions.

This authority will enable an integrated program, which will facilitate more efficient sharing of costs while reducing duplication of effort in areas of: research and technology development, design, production, and infrastructure. OASIS will independently manage the funding and securing of full cooperation between states. Through recommending space objectives to its member entities, OASIS will also combine the policies of these states with respect to other national and international organizations to develop and implement a long-term space policy. By using the existing industrial potential of all member states, OASIS ensures that space technology will be developed and maintained and licensed to partners both during and after the mission. OASIS will provide the regulatory framework for diplomatic relations, negotiations, contractor selection, state-to-state/corporate reciprocity, and conflict resolution. Each member entity will receive a vote on such issues. The OASIS will represent every continent, including ISECG members, and shall be open to all states and corporations whether from developed or developing space programs. Membership entities cannot be under sanctions by the United Nations or under adverse legal status in their registered state.

The OASIS model is innovative, combining the experience and vision of the worlds’ national space agencies with the determination and momentum of leading corporations. The equal voting structure and international legal protection for both land and proprietary rights give OASIS the authority to incentivize new sectors of industry. A profit based infrastructure insures that the investment made by both public and private sectors returns value back to their shareholders or taxpayers. Working within the established boundaries of the Outer Space Treaty, the OASIS Consortium of governments and corporations has established a framework for the distribution of land, capitalization of lunar resources, and protection for associated intellectual rights for the invested partners. With these securities in effect the capital required for missions to the Moon will be exceeded and the political will to go to Mars will be firmly established. OASIS represents the ideal way to build a solid economic sustainability for this endeavour.

Given the potential profitability of the OASIS network, OASIS anticipates raising more capital than governments alone can allocate to space initiatives at this time. Providing sound legal and financial assurances to potential partners is key to raising up-front capital.

VI. CONCLUSION

The second spaceport node in the network is located on the lunar surface; it will supply the LEO node with high specific impulse (LO_2 and LH_2) propellant mined and extracted from lunar regolith and/or water ice. Using resources from the Moon could drastically reduce the costs of propellant in LEO and ensure a strong and enabling business case for the network. It is also an important stepping stone to traveling throughout the Solar System and the development of Spaceport Node 3 on Phobos. The Martian surface and Phobos have been identified as important goals of space exploration for many space agencies. Compared to the direct route to Mars, the low gravitational field of Phobos (or Deimos) facilitates easy access to the Martian surface and further celestial objects via staging with the use of ISRU water derived propellants.

The OASIS project enables a logistics and space transportation network in the Solar System and supports the exploration roadmap agenda of the International Space Exploration Coordination Group (ISECG), which sets the goal for human space exploration on Mars, following a stepwise evolution with different exploration missions in the lunar vicinity and on asteroids. OASIS provides the infrastructure for mankind expansion in space and by doing so answers future needs of policy makers.

[1] Mckay D.S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B. M., and Papike., J., 1991, “The Lunar Regolith”, Lunar Source Book, Chapter 7, pp. 285-356, *Cambridge University Press*

[2] Mueller, R., 2012, “Lunabotics Mining Competition: Inspiration through Accomplishment. Earth and Space 2012”, pp. 1478-1497

[3]Sanders, G.B., Larson, W.E., “Progress Made in Lunar In-Situ Resource Utilization under NASA’s Exploration Technology and Development Program”

[4] Personal communication with Tony Colaprete, Principle Investigator for the Lunar Crater Observation & Sensing Satellite (LCROSS) mission.

[5] McKay, D. S. and Ming, D. W., 1989, "Mineralogical and Chemical Properties of the Lunar Regolith." Lunar Base Agriculture: Soils for Plant Growth, ed. D.W. Ming and D. L. Henninger, Madison, WI, pp. 45-68.

[6] Fikes, J.C., Howell, J.T. and Henley, M.W., 2006. “Utilizing Solar Power Technologies for On-Orbit Propellant Production”, International Space Development Conference , 4-7 May 2006 Los Angeles, CA.

[7] Sanders, G.B., Larson, W.E., 2011. “Development and Demonstration of Sustainable Surface Infrastructure for Moon / Mars Missions”, 62nd International Astronautical Congress, 5 October 2011 Cape Town, South Africa, pp. 1–30.

[8] Stefanescu, D.M., R.N. Grugel and P.A. Curreri, 2005, “In situ Resource Utilization for Processing of Metal Alloys on Lunar and Mars Bases, Rodney G. Galloway and Stanley Lokaj, pp. 266 – 274, 1998.

[9] “Full Moon : storage & delivery of oxygen and hydrogen” MSc. 2007 Team Project, International Space University.

[10] Dino, J., 2009, “LCROSS Impact Data Indicates Water on Moon”, NASA Ames Research Center.

[11] Carruba and Coradini, 1999, “Lunar Cold Traps: Effects of Double Shielding”, Icarus 142, 402–413.

[12] Steve Trigwell, 2011, “In-situ Resource Utilization for the Moon, Mars and Beyond”.

[13] A. Coiaprete, et al., 2010, "Detection of Water in the LCROSS Ejecta Plume," Science, vol. 330, pp. 463-468.

[14] NASA, “NASA Radar Finds Ice Deposits at Moon's North Pole” http://www.nasa.gov/mission_pages/Mini-RF/multimedia/feature_ice_like_deposits.html [retrieved August 2013].

[15]Blair, B. R., Diaz, J., Duke, M. B., Lamassoure, E., Easter R., Oderman, M., Vaucher, M.,2002, “Space Resource Economic Analysis Toolkit: The Case for Commercial Lunar Ice Mining,” Final Report to the NASA Exploration Team, SRD Case 1.0, Center for the Commercial Applications of Combustion in Space (CSM)/ Jet Propulsion Laboratory (JPL)/ CSP Associates.

[16] Christiansen, E. L., Euker, H., Maples, K., Simonds, C. H., Zimprich, S., Dowman, M. W., and Stovall, M., 1988, “Conceptual Design of a Lunar Oxygen Pilot Plant”, EEI Rept. No.88-182 (Houston: Eagle Engineering Inc.)

[17] Drysdale A., 2001, “Life Support Trade Studies Involving Plants”, SAE Technical Paper 2001-01-2362.

[18] Drysdale, A. E., Rutkze, C.J., Albright, L.D, LaDue, R.L., 2004 “The minimal cost of life in space”, Advances in Space Research 34, 1502–1508.

[19] Bugbee, B. and Salisbury, F.B., 1989. “Controlled Environ-ment Crop Production: Hydroponics versus Lunar Regolith” p. 107-129. In: D. Henninger and D. Ming (eds.) Lunar Agriculture. Am. Soc. of Agronomy.

[20] Drysdale, A.E., Wheeler, R.M., 2002 "Economics of growing plants in space" (abstract). Gravitational and Space Biology Bulletin 16 (1), 53.

[21] Lasseur, C., Brunet, J., De Weever, H., Dixon, M., Dussap, G., Godia,, F., Leys, N., Mergeay, M., Van Der Straeten , D., 2010, "MELiSSA: the European project of closed life support system", Gravitational and Space Biology 23(2).

[22] El Sherif 2005 ISS CO2 removal

[23] Drysdale, A. E., Ewen, M. K., and Hanford, A. J., 200, "Life Support Approaches For Mars Missions", Adv. Space Res. Vol. 31, No. 1, pp. 51-6.