Lunar ISRU - Love it or Leave it!

by Donald Rapp (independent contractor)

It's all just a dream babe, a vacuum, a scheme babe, ... - Bob Dylan

If a committee is allowed to discuss a bad idea long enough, it will eventually adopt it because of all the work they put into it. - K. Kruickshank

I. Introduction

In situ resource utilization (ISRU) is a concept for increasing the efficiency of space missions by utilizing indigenous resources on a planet or moon in order to reduce the amount of materiel that must be brought from Earth. If the savings resulting from reduction of resources brought from Earth outweigh the cost of prospecting, developing, testing, validating in situ, and implementing ISRU in missions, it follows that ISRU will have a favorable benefit/cost ratio. While many ISRU advocates within NASA seem to take it on faith that the benefit/cost ratio is always favorable for ISRU, my analysis indicates that this is not always so. Whereas a stronger case can be made for use of ISRU on human missions to Mars, the case for lunar ISRU in the current ESAS architecture does not stand up to scrutiny. Nevertheless, the belief in the virtues of ISRU has been proclaimed so many times by NASA that in an Orwellian sense, it is widely accepted – at least within a certain community. The recent NASA exploration architecture analysis for lunar exploration (popularly known as the "ESAS Report") mentions the term "ISRU" 110 times. The ESAS Report repeats the standard mantra:

"*ISRU: Technologies for 'living off the land' are needed to support a long-term strategy for human exploration." (p. 89)*

However, NASA's approach to lunar mission analysis and its connection to ISRU is often disjointed. For example, the ESAS Report says:

"*The lander's ascent stage uses LOX/methane propulsion to carry the crew back into lunar orbit to rendezvous with the waiting CEV. The lander's propulsion system is chosen to make it compatible with ISRU-produced propellants and common with the CEV SM propulsion system.*" (p.27)

However a later modification of the architecture eliminated use of oxygen propellants for ascent, making the architecture incompatible with ISRU.

If NASA does not develop an oxygen-based ascent propulsion system then lunar ISRU would be moot.

According to the JSC ISRU Technology Development Plan,

"*the key to fulfilling the goal of sustained and affordable human and robotic exploration will be the ability to use resources that are available at the site of exploration to 'live off the land' instead of bringing everything from Earth, known as In-Situ Resource Utilization (ISRU).*"

Another related NASA document (ISRU Capability Roadmap Team Report) says:

"*Four major areas of ISRU that have been shown to have great benefits to future robotic and human exploration architectures are:*

- *Mission consumable production (propellants, fuel cell reagents, life support consumables, and feedstock for manufacturing and construction)*
- *Surface construction (radiation shields, landing pads, walls, habitats, etc.)*
- *Manufacturing and repair with in-situ resources (spare parts, wires, trusses, integrated systems etc.)*
- *Space utilities and power from space resources.*

Numerous studies have shown that producing propellants in-situ can significantly reduce mission mass and cost, and also enable new mission capabilities, such as permanent manned presence and surface hoppers."

Unfortunately, no references are given to the "numerous studies" and "great benefits" referred to in these quotations are speculative. My own studies lead to diametrically opposite conclusions – at least for lunar ISRU.

II. Potential Products of ISRU

Most discussions of lunar ISRU seem to assume that resources are readily available, and they proceed to emphasize processing, while minimizing logistics (excavating, regolith transport, deposition and removal of regolith from reactor, dumping waste regolith, etc.) and side-stepping prospecting (locating resources, validating existence and accessibility, and determining requirements for excavation and utilization). However, the quantity and composition of end products provides the entire basis for value added by ISRU, and for setting the requirements for ISRU systems. Therefore, we begin here with the potential end products.

Ascent Propellants

In the initial NASA ESAS architecture, the propulsion system for ascent from the Moon was based on $CH_4 + O_2$ propellants in order that ISRU-generated oxygen from the Moon could be used. Although methane had to be brought from Earth, it provided an implicit connection to future Mars ISRU that is likely to be based on $CH_4 + O_2$. Later, when the realities of cost and schedule to develop $CH_4 + O_2$ propulsion systems became clearer, this ascent propulsion system was dropped in favor of space-storable hypergolic propellants (NTO/MMH) that are incompatible with lunar ISRU. However, the entire architecture, which was riddled with inconsistencies, is being re-engineered. If the final architecture returns to use of oxygen as an ascent propellant, that oxygen can potentially be provided by lunar ISRU. In the original architecture, the plan was to have two ascents per year from the outpost, each requiring about 4 metric tons (mT) of oxygen as oxidizer, for an annual need of roughly 8 mT of oxygen. It is not clear what fuel would be used in conjunction with the oxygen. If it is methane, it will have to be brought from Earth. If it is hydrogen, it could conceivably be produced from putative polar ice (but not from equatorial regolith).

Since the "gear ratio" (mass in LEO)/(payload mass delivered to lunar surface) for polar outposts is about 4:1, the potential mass saving in LEO is ~ 16 mT per launch based on 4mT saved on the lunar surface. However, because the launch vehicles are designed without ISRU, they will remain unaffected by ISRU. Hence the benefit of ISRU will be an ability to deliver extra cargo payloads (~4 mT) to the lunar polar outpost with each launch (but rather late in the campaign - probably beginning in the late 2020s). Even this minor benefit disappears if NASA persists in its present plan to use space storable propellants (NTO/MMH) for ascent, thus eliminating oxygen as an ascent propellant. The "value" of the ~4 mT increase in payload delivery per launch using

ISRU can be estimated because over a period of years, with continual cargo deliveries to the outpost, a cargo delivery launch every few years might be replaced by small incremental increases in each launch along the way.

However if NASA insists on an "abort-to-orbit" capability during descent, then ascent propellants will have to be available in lunar orbit prior to descent and the applicability of ISRU to ascent propellants becomes moot.

Life Support Consumables

Oxygen requirements for life support depend on crew activity but an average value is about 1 kg per crew-member (CM) per day.

Water requirements for life support have been estimated by JSC to be about 27.5 kg/CM-day.

To support a crew of 4 during one year, we therefore require 4 × 1 × 365 = 1460 kg ~ 1.5 mT of O_2, and 4 × 27.5 × 365 kg ~ 40 mT of water.

It is likely that an Environmental Control and Life Support System (ECLSS) will be used to recycle these resources, thus greatly reducing mass requirements. JSC has estimated the mass of ECLSS systems. Using ISS experience as a basis, JSC estimated the mass and power requirements of ECLSS systems for a crew of six on Mars for 600 days. We can scale this to a crew of 4 for 365 days to estimate the mass of an ECLSS system for the Moon. For each resource (oxygen or water) there is a system mass and backup cache mass to replenish losses.

The results are:

Oxygen ECLSS:

Physical plant mass = 510 kg

Backup cache mass = 380 kg

Total mass = 890 kg

Water ECLSS:

Physical plant mass = 4500 kg

Backup cache mass = 2700 kg

Total mass = 7200 kg

Even though ISRU might supply the required amounts of oxygen and water, environmental control will still be required. An oxygen-only ISRU system would save very little mass from the ECLSS and is probably not worth integrating to ECLSS. An ISRU system that produces water and oxygen would provide greater benefits but it is likely that the reduction in ECLSS mass would be only a few mT, whereas the ISRU system would have to supply the full required 40 mT of H_2O per year. Exactly how a water-based ISRU system would be integrated to an ECLSS remains to be determined. There might be some mass benefits, but they appear to be modest at best. If the ECLSS works as well as NASA hopes, there may not be much benefit to joining the ISRU and ECLSS systems. Use of ISRU to produce life support consumables on the Moon is unlikely to have net value.

Propellants Delivered to LEO

For a typical Mars-bound vehicle in LEO prior to trans-Mars injection, about 60% of the total mass consists of $H_2 + O_2$ propellants for trans-Mars injection. If Mars-bound vehicles could be fueled in LEO with H_2 and O_2 delivered from the Moon, then only the remaining 40% of the total vehicle wet mass would need to be delivered from Earth to LEO. The other 60% would be provided from lunar resources. For example, a Mars-bound vehicle that weighs say, 250 metric tons in LEO, would include about 150 mT of propellant for trans-Mars injection. If fueled by hydrogen and oxygen from the Moon, the mass that would have to be lifted from Earth to LEO would only be about 100 mT instead of 250 mT. This would have a huge beneficial impact on the feasibility of launching very large Mars-bound vehicles.

The question that we must deal with is: how feasible is it to transfer water (and then by electrolysis, produce $H_2 + O_2$) from the Moon to LEO? If this process is efficient, the scheme of supplying propellants to LEO from the Moon may be less costly than launching from Earth. If the transfer process from the Moon is very inefficient, it is likely to be less costly to simply deliver propellants to LEO from Earth.

It is implicitly assumed here that accessible water ice can be exploited on the Moon. If that is not the case, this entire concept becomes moot. Furthermore, the process may become untenable if the masses of the transfer vehicles are too high. If the vehicles are too heavy, all the water excavated on the Moon would be used to produce $H_2 + O_2$ to deliver the vehicles and ultimately no net transfer of water to LEO would be feasible. Therefore, it is necessary to examine the details of the transfer process and estimate what percentage of water excavated on the Moon can be transferred to LEO. The percentage of water mined on the Moon that can be transferred from the Moon to LEO for fueling Mars-bound vehicles can be estimated as shown in:

http://www.mars-lunar.net/Reality.or.Fantasy/Appendix.5.Fueling.pdf

The figure of merit is the net percentage of water mined on the Moon that can be transported to LEO for use by Mars-bound vehicles. As this percentage increases, the cost of transporting water to LEO from the Moon becomes more favorable. My best estimate is that most of the water excavated on the Moon is used up in transferring the tankers to LEO, and almost no net water is transferred to LEO. On the other hand, if these tanker vehicles can be made much less massive, such transfer might become feasible.

Propellants Delivered to Lunar Orbit for Descent (and Ascent)

Whereas the amount of oxygen required for ascent from the Moon to lunar orbit is a rather puny ~ 4 mT, the amount of oxygen required for descent from lunar orbit to the surface is over 20 mT. If oxygen (and less importantly hydrogen as well) can be delivered to lunar orbit for fueling Moon-bound descent vehicles, the potential payoff from ISRU would be much higher than if ISRU were used only for ascent propellants. The gear ratio for delivery of mass to lunar orbit from LEO is roughly 2.5 so use of ISRU to generate descent propellants would save > 50 mT in LEO. The combination of ISRU-provided ascent and descent propellants would save about 70 mT in LEO, and this is likely to increase if vehicle masses increase (as they always do) in the forthcoming revised Constellation architecture.

The concept would then be as follows.

NASA would begin by establishing an outpost in a shadowed polar crater of the Moon to excavate regolith, extract water, and electrolyze water and store hydrogen and oxygen. This would have to be done robotically without crew participation. Is this possible? Who knows?

NASA would design and implement a tanker system for transferring water from the surface of the Moon to lunar orbit, and establish a "filling station" in lunar orbit to electrolyze water and fill propellant tanks on incoming vehicles with hydrogen and oxygen. This tanker system would act like a shuttle to move back and forth between the lunar surface and lunar orbit, carrying full tanks on the way up and empty tanks on the way down. A back of the envelope, very crude estimate is that perhaps 40% of the water extracted on the lunar surface could be delivered to lunar orbit while providing propellants for descent of the empty tanker.

Incoming Lunar Surface Access Module (LSAM) vehicles on their way to the surface of the Moon would carry empty ascent and descent tanks, and would be fueled in lunar orbit prior to descent. In case of an unexpected problem, the crew could return to Earth from lunar orbit in the CEV and never descend in the LSAM.

This system works (at least on paper) after it is established, but how does it get established? If NASA must send crew members to the surface to establish the outpost and set up the tanker/refill system, then we are back to square one because NASA must send the LSAM with full descent and ascent tanks prior to the establishment of the outpost and the tanker/refill system. The potential equivalent mass saving in LEO is ~ 70 mT per launch. However, as in the case of ISRU providing only ascent propellants, this ~ 70 mT reduction will not be realized in terms of reduced launch vehicle capability if ISRU is adopted as an afterthought late in the campaign.

Since propellants for ascent and descent are brought to lunar orbit, this scheme is not vitiated by a need for abort-to-orbit capability.

Regolith for Radiation Shielding

This is probably a legitimate use of in situ resources, but the requirements and benefits require further study. However, it is not at all clear whether habitat designs and emplacements allow use of regolith to be piled on top of them. All habitat designs and surface plans that I have seen are incompatible with use of regolith as shielding.

Visionary Concepts

Visionaries and futurists who can see further into the future than I can, have identified six rationales for going back to the Moon:

1. *Expansion of humans into space - the quest for expansion*
2. *Providing energy to the Earth*
3. *The industrialization of space*
4. *Providing fuel depots in space for exploration and development of the Solar System*
5. *The Moon as a Planetary Science Laboratory*
6. *Astronomical Observatories on the Moon*

There seems to be a wide gap between the ISRU enthusiasts, who crank out ever more imaginative and futuristic concepts for ISRU, and JSC mission planners who do not seem to have much regard for ISRU and unenthusiastically tack it on as an addendum late in the overall campaign – seemingly as a public relations stunt.

Summary of Near-Term Lunar ISRU Benefits - Current ESAS Architecture

The main near-term benefit of lunar ISRU according to the current lunar campaign definition is replacement of about 8 mT/yr of oxygen for ascent propulsion from a polar outpost beginning rather late in the campaign (late 2020s). It is not immediately obvious how this reduction in mass requirements would be utilized by the exploration enterprise. Since sortie missions will manifestly be designed to function without ISRU, the lunar enterprise will have to develop a launch vehicle (LV) and LSAM based on no use of ISRU. When, at a later date, outposts are set up, the same LV and LSAM will be employed. They will NOT be reduced in size or capacity.

At some point in the late 2020s, if ISRU is tacked on to this exploration scheme, the LV and LSAM may not have to carry ascent oxygen (and possibly some life support consumables - but very doubtful) and thus they can deliver higher cargo payloads (about 4 mT per launch) to the outpost than if ISRU were not used. However, as mentioned previously, if abort-to-orbit is required during descent, even this benefit disappears.

III. Lunar Resources

There are basically four potential lunar resources:

- Silicates in regolith containing typically > 40% oxygen.
- FeO in regolith that varies from about 5% FeO in highlands up to perhaps 14% in some mare areas.
- Imbedded atoms in regolith from solar wind (typically parts per million).
- Water ice in regolith pores in permanently shadowed craters near the poles (unknown percentage but possibly a few percent in some locations – vertical and horizontal distributions are not known).

The imbedded atoms from the solar wind appear to be far too dilute to be a practical source of resources, although some ISRU enthusiasts conjecture processing ~ 100,000 tons of regolith to recover 1 ton of product.

That leaves regolith silicates and FeO and polar ice as the remaining potential feedstocks for ISRU.

IV. Oxygen from Regolith Silicates

Lunar ISRU based on extraction of oxygen from regolith has two advantages:

(1) Regolith contains typically > 40% oxygen which is a considerable amount.

(2) Regolith is available everywhere and solar energy may be applicable for processing.

Unfortunately, the oxygen in regolith is tied up in silicate bonds that are amongst the strongest chemical bonds that are known, and breaking these bonds inevitably requires very stringent conditions, particularly temperatures as high as 2600 K. While JSC continues to remain optimistic about such processes for extracting oxygen from regolith, preliminary testing has not produced any encouraging results. More to the point, the hope to dump regolith into a reactor that functions at such high temperatures and remove spent regolith would be an engineering nightmare on Earth, and unimaginable on the Moon.

We note that according to JSC correspondence,

"*multiple molten salt electrolysis efforts have been funded for ISRU by NASA and one major development effort is planned for the upcoming years.*"

It is also noteworthy that JSC admits that

"*to date no testing has come close to 35% oxygen yield (although definitely better than 2% has been demonstrated), a significant quantity of the oxygen produced is not in the form of oxygen but in the form of CO and* CO_2*, the anode materials attempted to date have been consumed by the electrolysis process (the source of the carbon), and there stands an excellent chance that we will not be able to recover all of the salt per batch.*"

A process under serious consideration by JSC is the carbothermal process in which the regolith would have to be heated to ~2600 K. To prevent the vessel walls from melting, they conjecture use of beamed solar energy into the center of the vat. Exactly how it functions, and how regolith is added and removed from the reactor remains a mystery that only JSC can understand.

Despite the great challenges involved in extracting oxygen from regolith, documents indicate that JSC remains optimistic that they will succeed. It is difficult not to admire the tenacity of these stalwarts, for whom no engineering challenge is too great or too impractical, who are willing to work on technologies requiring reactors at incredibly high temperatures that must take in lunar regolith and discharge spent regolith or slag. However, the probability that a practical process for autonomous lunar operation will come from any of this research appears to be very small.

In the unlikely case that a high-temperature processor for oxygen from regolith on the Moon can be made into a practical unit, one would still be faced with the challenges (and costs) for development and demonstration of autonomous ISRU systems for excavation of regolith, delivery of regolith to the high-temperature processor, operation of the high-temperature processor with free flow of regolith through it (with no caking, agglomeration and "gunking up" of regolith), and removal of spent regolith from the high-temperature processor to a waste dump.

V. Reduction of FeO Using Hydrogen

Another approach for extracting oxygen from regolith is use of hydrogen as a reducing agent to react with FeO in regolith at ~ 1200 K, producing water. The water is electrolyzed and oxygen is saved, while resultant hydrogen is recirculated. This process appears to be more feasible than the carbothermal process but it also suffers from the need for delivery of regolith to the high-temperature processor, operation of the high-temperature processor with free flow of regolith through it (with no caking, agglomeration and "gunking up" of regolith), and removal of spent regolith from the high-temperature processor to a waste dump. In addition, the FeO content of lunar regolith may vary from about about 5% FeO in highlands up to perhaps 14% in some mare areas, so that actual hydrogen content varies from about 1% to 3%. Therefore, large amounts of regolith must be processed and power requirements are considerable. JSC continues to hope that solar energy can be used but it seems likely that a nuclear reactor would be needed – however NASA does not seem inclined to develop a reactor.

VI. Utilizing Polar Ice Deposits

Introduction

The other alternative is to hope for accessible ground ice in permanently shadowed craters near the poles. This approach has the great advantage that removal of water from regolith is a physical (rather than a chemical) process and requires far less energy and much lower temperatures. However, on the negative side, it will take a considerable investment to locate the best deposits of ground ice (if indeed they are accessible), the percentage of water ice in the regolith is likely to be low, necessitating an extensive prospecting program, ultimately requiring processing a great deal of regolith, excavating ice-filled regolith may prove difficult, the logistics of autonomous regolith delivery, water extraction, and regolith removal from a reactor may prove difficult, and a significant part of the process must be carried out in dark permanently shadowed craters at perhaps 60 K, necessitating use of nuclear power (or some cockamamie scheme for beaming solar power from a distant site).

Observations from orbit with a neutron spectrometer provide a horizontal resolution of many tens of km. Locating the best sites within such regions will require a series of prospecting missions. Initially, long-range rovers equipped with neutron spectrometers would be used to locate the best sites. At the best sites, follow-on missions would take subsurface samples to validate neutron spectrometer indications, and make measurements of soil strength. This campaign to locate and validate accessible water ice resources is likely to require at least four and possibly as many as six in-situ landed missions with long distance mobility, at a probable cost of ~ $1B each. If sorties with human crews are used for the final missions in this series, the cost will go up considerably. The NASA Robotic Lunar Exploration Program (RLEP) seems to have grossly underestimated the requirements and cost of prospecting, the need for mobility on such precursor missions, the requirements for taking subsurface samples with preservation of volatiles, and the extent of the overall campaign to locate the best putative ice deposits.

Development and demonstration of autonomous ISRU systems for excavation of regolith, delivery of regolith to a water extraction unit, operation of the water extraction unit with free flow of regolith through it (with no caking, agglomeration and "gunking up" of regolith), and removal of spent regolith to a waste dump will require quite a few more billion. It is noteworthy that there is no evidence that NASA is planning to provide funds to develop the nuclear reactor power systems needed for operation in the cold darkness of polar craters. Instead, JSC appears to be planning to use radioisotope thermal generators (RTGs) for power within the crater and solar energy on the crater rim. However there are not enough RTGs in the universe, nor is it likely that enough plutonium will be available to produce the needed RTGs, nor is it likely that NASA and DOE would be able to produce the RTGs even if sufficient Pu could be found. JSC also contemplates dragging the extracted water across perhaps 10 km of crater up the crater wall, and using solar energy for electrolysis. It is not clear whether this is done under human supervision or robotically, but either way, it is a nightmare.

Overall, the required investment to do prospecting and validation of resources, and development and demonstration of regolith excavation and transport, and operation of a water extraction system, appears to be many billions of dollars. The benefit/cost ratio remains uncertain but it may take many years to "break even" on the investment.

Any scenario that we develop for any step (whether that be prospecting or demonstration) should be elements of an overall campaign. A scenario for an individual step only has value as part of that campaign to the degree that it contributes to the campaign because the overall campaign produces the end result.

Campaign to Utilize Polar Ice Deposits

Unfortunately, NASA has not adequately defined the campaign for prospecting, demonstrating and implementing lunar ISRU. Note: in the present context "lunar ISRU" means oxygen (and possibly hydrogen) production, mainly for ascent propellants. While lunar-tics have plans for manufacturing spare parts on the Moon, producing silicon solar cells on the Moon from regolith, and extracting parts per million of solar-wind deposited atoms, fortunately such work is not yet funded even though it is included in JSC project plans.

Both JSC and NASA appear to have simplistic notions about what it will take to prospect for polar ice resources and demonstrate ISRU systems, that will not hold up to any serious scrutiny. In addition, the RLEP Program is very badly under-funded, under-scoped, and grossly inadequate to do the necessary job.

A campaign is an end-to-end sequence of missions and programs to accomplish a goal. Our view of the first five steps of the required campaign for developing lunar ISRU based on polar ice is as follows:

[1] The Lunar Reconnaissance Orbiter (LRO) will use a neutron spectrometer (NS) to locate hydrogen signals in horizontal spatial pixels of dimension ~ 50 km and possibly down to ~ 30 km for low passes over the Moon. These are likely to encompass several subordinate craters within the south polar region, leaving considerable uncertainty as to which of these extended areas are the best for further investigation, and great uncertainty as to the detailed distribution of hydrogen signal within each 50 km pixel.

[2] Despite the fact that neither JSC nor NASA seem to have the intention of doing this, what is required next is to send several long-distance rovers equipped with dynamic active NS to several of these craters, to cover a few tens of km in each one to determine at the outset: (a) whether the hydrogen signals and interpretations of them from LRO are substantiated by the more reliable ground measurements, (b) how the hydrogen signal is distributed within each crater to ~ 1 m pixel size (is the distribution fairly uniform or some kind of checkerboard?), and (c) a much better estimate of the vertical distribution of the hydrogen signal to a depth of perhaps 1 to 1.5 m and in particular the depth of any desiccated upper layer covering the ice-containing layer.

[3] From the results of [2], a decision can be made as to which specific site (or sites) will be selected for more detailed measurement and verification. It is presumed that if for example, the LRO data indicate an average of 1% water-equivalent content across ~ 50 km, there are bound to be stretches of a few km in extent with essentially constant water-equivalent content that are higher than average. Therefore, for purposes of very early planning it can be assumed that a several-km area has been located with at least 2% water-equivalent content. When actual data are available, this can be made more specific.

Note: the required areal extent of the ice field depends upon the water ice content and the cumulative need. If the outpost requirement is to produce ~ 24 kg/day of O_2, this requires 27 kg/day of water (with no losses) and maybe 30 kg/day of water with losses. If we can roughly assume 2% water content in 70% of the top 1 m, then each square meter excavated yields about

1500 kg x 0.7 x 0.02 ~ 20 kg of water. Hence the full-scale outpost ISRU system requires excavating about 1.5 sq. meters [down to 1 m depth] per day, processing about 2250 kg of regolith per day, and extracting about 30 kg of water per day. In one year, an area of about 1100 sq. meters is excavated. Over ten years, an area of about 5500 sq. meters (~75 meters by ~75 meters) is needed.

[4] We would then send a short-range rover system to the selected site(s) to (a) map out the site with NS in great detail, (2) take subsurface samples to validate rover-mounted dynamic active NS measurements of water-equivalent content, (3) determine the actual form of hydrogen-containing compounds - which are almost surely dominated by water ice, (4) extract water ice from some samples and determine the water purity and the potential need for purification, and (5) determine the soil strength and requirements for excavation of the site. In some studies, this step would be implemented with support of a human crew who land in the Lunar Surface Access Module (LSAM). But if in fact step [4] can be done robotically, why would anyone (other than NASA) want to send a human crew to do it?

[5] Develop a ~1/10 scale ISRU demonstration system for use at this site, deliver it with human oversight, get it started, and leave it to operate autonomously. In this task, several factors will be challenging:

> **a.** Even at 1/10 scale, there is a need to excavate 225 kg of regolith per day, transport it to the water extraction unit (WEU), heat the regolith to well over 300 K to drive off water vapor, remove spent regolith from the WEU, dispose of the spent regolith and any dry regolith layer that may lie atop the ice-containing layer, and purify and store 3 kg/day of water produced. If the water is to be electrolyzed and the hydrogen and oxygen stored, that needs to be designed into the system. All of this takes place in the dark at very low temperatures.
>
> **b.** Definition of autonomous operations, including disposal of waste regolith, methods of excavation, and vehicles for transporting regolith to and from the WEU will require a great deal of study and analysis.
>
> **c.** Power is likely to be a major show-stopper at every stage of this enterprise. If the demonstration must run autonomously after the crew leaves, how is it going to get sufficient power? It seems highly unlikely that enough RTGs will be available. Will NASA develop a nuclear reactor? There is no evidence that it will.

It seems clear that neither JSC, nor NASA have given adequate thought to the big picture of lunar ISRU, its requirements and its benefit/cost ratio for the whole campaign. A sober assessment of the requirements for developing and implementing lunar ISRU compared to the "value" of mass saved, creates significant doubt as to the value of lunar ISRU.

Nevertheless, even if lunar ISRU is not a paying proposition, it still needs to be done effectively, and the approaches taken by JSC and NASA do not seem to fit that requirement.

JSC Campaign Overview

In contrast to the campaign laid out above, the JSC/NASA Plan appears to provide only two lunar demonstrations prior to human sortie missions:

[A] "... a ***lunar polar resource characterization mission*** requiring hardware to be at TRL 6 by FY09 for a notional launch in FY12. In order to meet the requirement of polar volatile resource characterization, collection and separation an experiment to determine the form and concentration of the volatiles will be required. The RLEP 2 mission will carry this experiment and the ISRU Project will dedicate a significant portion of it’s funding to design and develop this experiment package to TRL 6."

[B] "... a ***lunar oxygen extraction demonstration*** requiring hardware to be at TRL 6 by FY11 for a notional launch in FY14." The RLEP 3 mission would carry this experiment. While it is not explicitly stated as such, there is a strong implication that this would be an equatorial landing with oxygen extraction from regolith via a high-temperature process.

The JSC plan also says: "RLEP payload mass and power requirements are unknown at this time. However, notionally, payloads should be between 10 and 100 kg and not exceed 100 Watts of average power."

Note that neither NASA nor JSC have any plan or expectation to rove around the various craters that LRO identifies from space (via the neutron spectrometer (NS)) as hydrogen-containing, to locate (a) the best local crater, and (b) the best site within the best local crater. The JSC/ESAS/NASA viewpoint has always been, and seems to remain, that they can just *plop down* anywhere in the region to "characterize, collect and separate volatiles."

The subject of lunar volatiles often gets confused in JSC documents. There are two sources of volatiles on the Moon. One is the impact of energetic ions from the solar wind on the lunar surface that mirrors the composition of the Sun: mainly H, then less He, then lesser amounts of higher elements. Such deposits were found at the surface by Apollo and they appear to amount to 1 to 50 parts per million (ppm) depending on species and location. While some lunar-tics have proposed tapping these resources, the amount of regolith that needs to be processed appears to be too excessive to be practical. The other source of volatiles is repeated impacts of comets on the Moon over the eons. It is well known to those who know it that comets typically contain a great deal of water (and possibly CO_2, NH_3, and other small molecules in lesser amounts). (In fact, a recent paper suggests that 250,000 tons of water were released in the Deep Impact mission). As these comets crash into the Moon, some of the water may be retained, and the theory is that these water molecules will slowly migrate to the coldest spots on the Moon where they will be trapped. Such deposits, unlike solar wind deposited hydrogen, can lead to macroscopic amounts of water (in the percent range rather than ppm). This is presumably what Lunar Prospector detected - and it isn't hydrogen, its water. There may be other volatiles included and we ought to find that out, but there is every reason to believe that water is the dominant constituent. Any practical plan to exploit lunar polar resources needs water, not "volatiles." Yet the JSC/NASA Plan keeps alive the notion that "volatiles" are all worth collecting, regardless of whether they are at the parts per million level or the percent level. No distinction seems to be made between solar wind deposition vs. accumulation of cometary volatiles at the poles.

The JSC/NASA plan appears to be bottom-heavy with significant activity after sorties begin, and is woefully lacking in precursors to the sorties.

In addition to these two RLEP payloads, the JSC Plan calls for developing "technologies to support human Sortie mission objectives of performing demonstrations and mission applications of ISRU subsystems and systems on the Moon." Requirements are stated as:

- "Demonstrations should be notionally 1/5th scale of early Outpost mission needs and no smaller than 1/10th scale in excavation/production rate."

• "Payloads should be ~ 250 to 500 kg in mass since total instrument payload is ~2000 kg. Power requirements should be self-contained on ISRU demonstrations with recharging/refueling from the Lander as an option to be considered." ***Note***: Preliminary estimates made by myself suggest that 250-500 kg will not be adequate for a 1/5-scale demonstration. Power remains a major question mark. While it is conceivable (though not necessarily likely) that the LSAM could recharge batteries on rovers and processors in a demonstration unit for a limited number of days while the crew is present, there does not seem to be enough RTG production or plutonium to power them, to provide "self-contained" power after the LSAM departs.

• "Payloads should be autonomous with crew involvement only for setup, collection of raw material and product samples for return to Earth, and contingency recovery from failures."

• "Payloads should operate a minimum of 7 days. Provisions should be made to allow ISRU hardware to continue to operate after the crew left to obtain operation life, performance, and wear characteristic data on ISRU demonstration hardware." As mentioned above, power remains a major challenge for operation after the crew leaves.

VII. Cost Analysis for ESAS ISRU

In this section, we compare costs of an outpost with and without ISRU. The following basic assumptions are adopted:

- Costs to develop various vehicles (CEV, LSAM, ...) are borne by Constellation and do not enter the ISRU vs. non-ISRU comparison.
- The various vehicles used for sorties (CEV, LSAM, ...) are also used for outpost deliveries and returns.
- The outpost is operated for 10 years with two exchanges of crew per year.
- A cargo delivery of 32 mT to the lunar surface is made once/year to deliver infrastructure at a cost of $1.2B for launch and launch ops.
- LOX-Methane propulsion is developed for ascent propulsion whether ISRU is used or not.
- Ascent from the Moon requires 4 mT of oxygen propellant.
- The "gear ratio" (mass in LEO/payload landed on the Moon) for cargo deliveries to the pole is around ~ 4.
- The benefit of ISRU is elimination of 4 mT of oxygen ascent propellant, twice per year.

The benefit of ISRU is difficult to assess. Whether ISRU is used or not, there will be two crew deliveries and two crew returns per year. The same vehicles are used whether ISRU is used or not. The only difference is that in the ISRU case, the LSAM can be landed with empty oxygen ascent tanks. Simplistically, it would appear that in the ISRU case, an extra 4 mT of payload can be carried to the lunar surface with each crew delivery (8 mT per year). The increased payload to the lunar surface would acquire value if we assume (as stated in the assumptions above) that periodic (maybe once a year) cargo deliveries are made to the Moon in which no CEV is used and no return is made. It is likely that such a cargo delivery system could deliver perhaps 32 mT to the lunar surface, assuming its IMLEO is about 4 x 32 ~ 128 mT. In that case, using ISRU with its annual increase of 8 mT of cargo to the lunar surface in crew deliveries, every 4th cargo delivery would be eliminated by supplying extra payload with each crew delivery. The net saving from use of ISRU is one cargo delivery every four years. If the cost of launching a cargo delivery mission is say, $1.2B, the annual saving from use of ISRU is $300M.

However, it is unlikely that the ISRU system would last for 10 years for a number of reasons. One is that with each passing year, the local ice field adjacent to the processing unit tends to get depleted and the rovers transporting regolith to and from the processor must travel greater distances. Another is that these working rovers are constantly excavating and transporting regolith, and are likely to need periodic replacement. Other components are likely to need periodic replacement or upgrade. Hence, part of the assumed increase in cargo delivery capability with ISRU would have to be used for ISRU deliveries. Nevertheless, we will neglect this effect and optimistically assume that the benefit from use of ISRU is $300M/yr.

The cost of an ISRU system includes the following items (not a complete list):

Development:

- Development of processing technology. This includes a system that can receive regolith, heat it to drive off water vapor, condense and collect the water, and release spent regolith (with no caking, agglomeration and "gunking up" of regolith).
- Development of excavation and regolith transport technology. This includes autonomous systems to excavate regolith, transfer it to a processor, and dispose of spent regolith.
- Simulation and test of systems on Earth. This may involve very large, cold evacuated chambers where simulated field operations can be tested on Earth prior to test on the Moon.
- A nuclear reactor power system must be developed that would not be used except for the fact that the location is in the dark near the south pole.

The development cost for the ISRU components is difficult to estimate. The JSC ISRU Technology Development Plan says: "Limited funding, especially in first four (4) years of development will limit the scope and number of concepts that can be evaluated. Also, funding constraints may require early down-select before adequate characterization and mission studies have been performed." However funding for the first five years of this program totals up to over $60M, and it is limited to laboratory type systems and preparation of payloads for RLEP-2 and RLEP-3. The cost of developing 1/5-scale or 1/10-scale demonstrations for sorties will be much higher. A rough guess is that the development cost for ISRU components will be $800M. In addition, a wild guess for the cost to develop a nuclear reactor is $5B.

Prospecting:

Prospecting will likely involve the following stages:

- LRO observation from orbit: $460M
- Ground truth long distance rovers equipped with NS to locate sites (4 missions at $800M each)
- Ground truth local mission to validate selected site with subsurface access (1 mission at $1.2B)

Total cost for prospecting ~ $5B.

In Situ Test and Validation:

Beginning with a 1/10-scale system, and extending this to a larger scale "dress rehearsal," two significant installations for autonomous ISRU operations need to be developed, delivered, installed, debugged and set to operating on the lunar surface. Since each of these involve sorties operated by human crews, the cost is roughly estimated to be $8B for the two demonstrations.

Total Cost for ISRU:

The total cost to implement ISRU is estimated to be:

Development	$6B
Prospecting	$5B
In Situ Test and Validation	$8B
TOTAL	$19B

Saving $300M per year would require >60 years to break even, and it would be worse if a net present value estimate is made to account were taken of the fact that ISRU investment is up front whereas return on investment is delayed many years.

VII. A New Paradigm for Lunar ISRU

Introduction

The problems in using ISRU within the current lunar architecture include:

- Lunar sorties must be fully capable of landing, ascending and returning without utilizing ISRU.
- ISRU is tacked on as an afterthought to lunar missions well after outposts are set up.
- Required capabilities for landing, ascending and returning that must be developed in the beginning without ISRU are not mitigated by later use of ISRU.
- Of all the many masses that must be sent to the Moon, ascent propellants (to lunar orbit) represent only one small element (~4 metric tons).
- If ISRU is used only to supply propellants for ascent to orbit, the mass benefits are modest - resulting in modest equivalent cost savings.
- The investment needed for prospecting, validation of resources, validation of regolith excavation and handling, and validation of the lunar polar ISRU end-to-end system is large.
- If we ignore mass savings from ISRU, and concentrate on return on investment in ISRU, lunar polar ISRU does not pay back the initial investment in the current ESAS architecture.
- This implies that setting up an outpost near the pole has no justification.
- This, in turn casts doubt on the entire basis for the enterprise of returning to the Moon.

Current NASA plans call for ascent propulsion based on space storable NTO-MMH. If NASA does not replace this with an oxygen-based ascent propulsion system, then even the meager potential benefits from ISRU in the current ISRU architecture (providing ascent LOX) will disappear, and lunar ISRU would have essentially no value.

On top of everything else, if abort to orbit capability is required for the descent vehicle, then ascent propellants ***must*** be brought from Earth and the main value (such as it is) for lunar ISRU disappears.

Given that ISRU does not mesh with the current ESAS architecture, alternative architectures must be considered – either that or eliminate ISRU entirely from the current architecture. (***ISRU - love it or leave it!***)

This leaves us with significant mass challenges. To justify retention of ISRU:

- Cryogenic propulsion utilizing LOX and possibly LH2 must be used throughout descent and ascent from the Moon
- A high-leverage user of ISRU products must be found in addition to ascent propellants
- Significant reductions in IMLEO must result from use of ISRU
- A very significant potential target is descent propellants – totaling some 20 to 25 mT of propellants

In order for ISRU to significantly impact the lunar exploration campaign, the following conditions must be fulfilled:

a) ISRU must be built into the very fabric of the lunar campaign so that all space and launch vehicles are designed and sized to use ISRU from the beginning. (This is as opposed to the ESAS approach of only using ISRU rather late in the campaign as an add-on to a system that does not use ISRU).

b) In order for (a) above to be possible, an extended robotic campaign must precede the human campaign, to establish a working ISRU plant as a fundamental asset for the first human sorties. This will undoubtedly delay return of humans to the Moon by several years.

c) Lunar polar ice must be the ISRU feedstock of choice because it is the only reasonable hope for a workable system.

d) Oxygen must be retained as an ascent propellant. It would also be useful to use hydrogen for ascent as well.

e) Utilization of ISRU products must be expanded to include descent propellants as well as ascent propellants.

Although the benefit/cost ratio for this approach is still not favorable, it is far superior to that based on ISRU generation of only ascent propellants.

Glossary

CEV	Crew Exploration Vehicle – carries crew from LEO to lunar orbit and return.
CM	Crew member
DOE	Department of Energy
ECLSS	Environmental control & life support system (The system that controls the human environment in a habitat and recycles resources).
EDS	Earth departure system (Propulsion system for departure from LEO to go toward the Moon or Mars).
ESAS	Exploration systems architecture study (2005 study of architecture for human return to Moon).
IMLEO	Initial mass in low earth orbit (Total mass that must be transported to LEO from Earth to implement a space mission).
ISRU	In situ resource utilization (Production of useful products (e.g. ascent propellants) on Moon or Mars from indigenous resources).
ISS	International Space Station
JPL	Jet Propulsion Laboratory (NASA)
JSC	Johnson Space Center (NASA)
LEO	Low earth orbit (Typically a circular orbit with altitude in the range 200 to 400 km).
LH2	Liquid hydrogen
LLO	Low lunar orbit (Typically a circular orbit of altitude 100 km).
LOR	Lunar orbit rendezvous (Process of transfer of crew from ascent vehicle to Earth return vehicle in lunar orbit).
LOX	Liquid oxygen
LRO	Lunar Reconnaissance Orbiter (Space mission to observe the Moon from orbit).
LSAM	Lunar surface access module (Transports crew from lunar orbit to lunar surface and return).
LV	Launch vehicle
MMH	Mono-methyl hydrazine (space storable propellant).
mT	Metric tons
NS	Neutron spectrometer (detects H)
NTO	Nitrogen tetroxide (Space storable oxidant for rockets).
RLEP	Robotic lunar exploration program (NASA program to utilize robotic precursors to gain information prior to human landings on Moon).
RTG	Radioisotope thermal generator (Device to convert heat from radioisotopes into electric power on spacecraft).
TLI	Trans-lunar injection (The process of using propulsion to depart from LEO and head toward the Moon).
TMI	Trans-Mars injection (The process of using propulsion to depart from LEO and head toward Mars).
WEU	Water extraction unit (Conceptual system to remove water from putative ice-containing regolith on Moon).