Chapter

Solar System Exploration Augmented by In Situ Resource Utilization: Lunar Base Issues

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Abstract

Creating a presence and an industrial capability on the Moon is essential for the development of humankind. There are many historical study results that have identified and quantified the lunar resources and analyzed the methods of obtaining and employing those resources. The idea of finding, obtaining, and using these materials is called in situ resource utilization (ISRU). The ISRU research and development efforts have led to new ideas in rocket propulsion. Applications in chemical propulsion, nuclear electric propulsion, and many other propulsion systems will be critical in making the initial lunar base and future lunar industries more sustainable and will lead to brilliant futures for humanity.

Keywords: in situ resource utilization, ISRU, lunar base, rocket propulsion, systems analysis, specific impulse, nuclear propulsion

1. Introduction

Human and robotic missions have helped humankind see and understand the many resources of the solar system. The resources have been analyzed, and numerous lunar benefits and industries have been suggested [1–10]. The lunar regolith contains many oxides from which oxygen can be extracted. Water ice in permanently shadowed regions (PSRs) and craters may provide the critical resources for a successful lunar base and lunar cities. The new abilities developed on the Moon can be applied to future human and robotic missions to inner planets, the asteroids, and the outer planets. Mission design studies have shown the great benefits of ISRU in increasing the sample return capability of future planetary missions and vastly extending the reach of exploration. For future large-scale human missions, the possibilities of ISRU for of human exploration and finally settlement offer the best opportunities for sustainability and success.

2. Human exploration options

Since the 1950s, numerous mission studies have identified many effective methods of planetary exploration [1–15]. Robotic exploration has employed the methods of orbital mechanics, systems engineering, and propulsion. Human exploration of the Moon has been conducted, but humans have not yet ventured to Mercury, Mars, and the outer planets. While future human lunar and Mars missions are in the planning stages, the costs of these missions have prevented their implementation. Extensive mission analyses have identified new strategies for human planetary exploration [16–20]. Cost reductions using advanced propulsion are very critical. In almost every propulsion scenario, ISRU will allow more effective robotic missions and human visits to these planetary targets.

3. The Moon, ISRU, and advanced mission planning

The Moon is the first stepping stone to the rest of the solar system. Since the 1950s, lunar mission planning has yielded many scenarios for exploration, base development, resource mining and use, and industrialization. Many visions of human lunar exploration have been developed, and they all address different possibilities for using in situ resources. A few of the past mission scenarios are summarized here for technology comparisons and insights into new technology infusions.

Many recent studies of the Moon and the use of its resources have been completed [21–25]. While lunar oxygen has been the focus of many of the study teams, water ice in permanently shadowed regions (PSRs) has been analyzed in great detail [26, 27]. Both the oxygen and water ice are critical resources for a more self-sustaining lunar base and a lunar economy. In addition, metals from the oxides in the lunar regolith can provide for construction materials, and lunar regolith can be used for effective radiation shielding from galactic cosmic rays and solar flares.

3.1 Lunar mission scenarios

Large-scale and aggressive lunar base construction was studied by Koelle and his teams [18]. With the advent of the Apollo program, it was deemed reasonable to plan for large lunar operations. His teams at NASA created lunar base construction scenarios using Saturn V class rockets. (**Figures 1** and **2**) illustrates the potential cost per person and the number of base personnel [18]. Since the time of its publication, many of the model cost assumptions are no longer valid. However, the example is illustrative of the elements that must be included in future cost estimates. While chemical propulsion was used for the flights from low lunar orbit (LLO) to the surface (called the shuttles), nuclear thermal propulsion (NTP) ferries were used for the round

$$\text{Cost/Man-Year} = \frac{\text{Cost/Ferry Mission}}{\text{10-Man Years/Mission}}$$

where:

Cost/Ferry Mission = (Wt in orbit) (Del. Cost) + (No. Passengers) (Del. Cost) + $\frac{\text{Ferry Cost}}{\text{Reuses}}$ + $\frac{\text{Shuttle Cost}}{\text{Reuses}}$

Cost assumptions are as follows:

1. Payload Cost to Earth Orbit = 25, 50, 75 dollars/pound
2. Passenger Cost to Earth Orbit = 100, 200 thousand dollars/man
3. Nuclear Ferry Unit Cost = 25, 50 million dollars
4. Nuclear Ferry Reuses = 10
5. Lunar Shuttle Unit Cost = 10, 15 million dollars
6. Lunar Shuttle Reuses = 10

Figure 1.
Lunar base cost assumption [18].

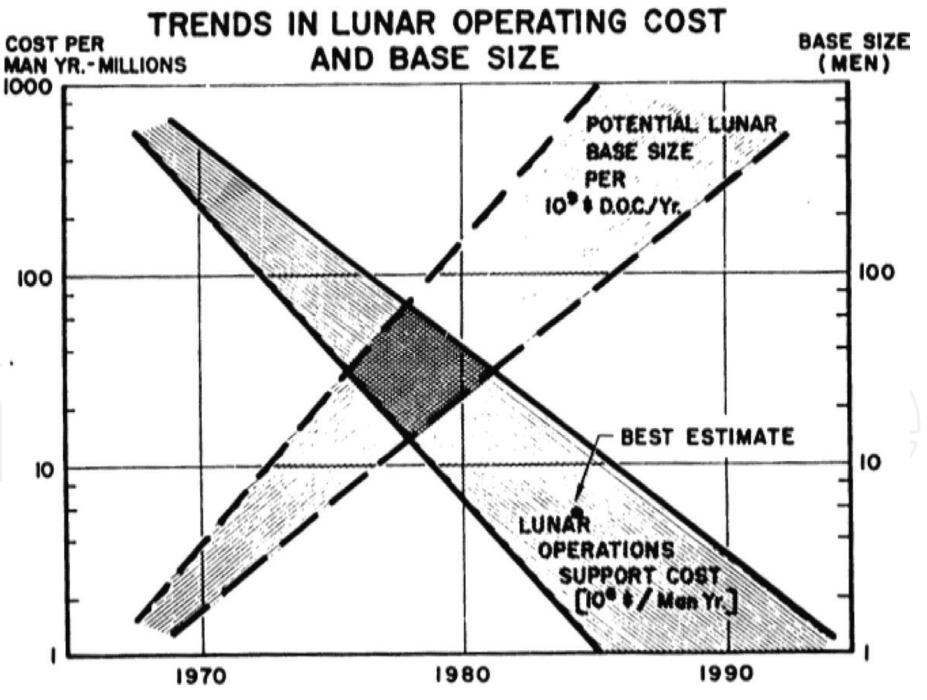

Figure 2.
Lunar base cost and personnel [18].

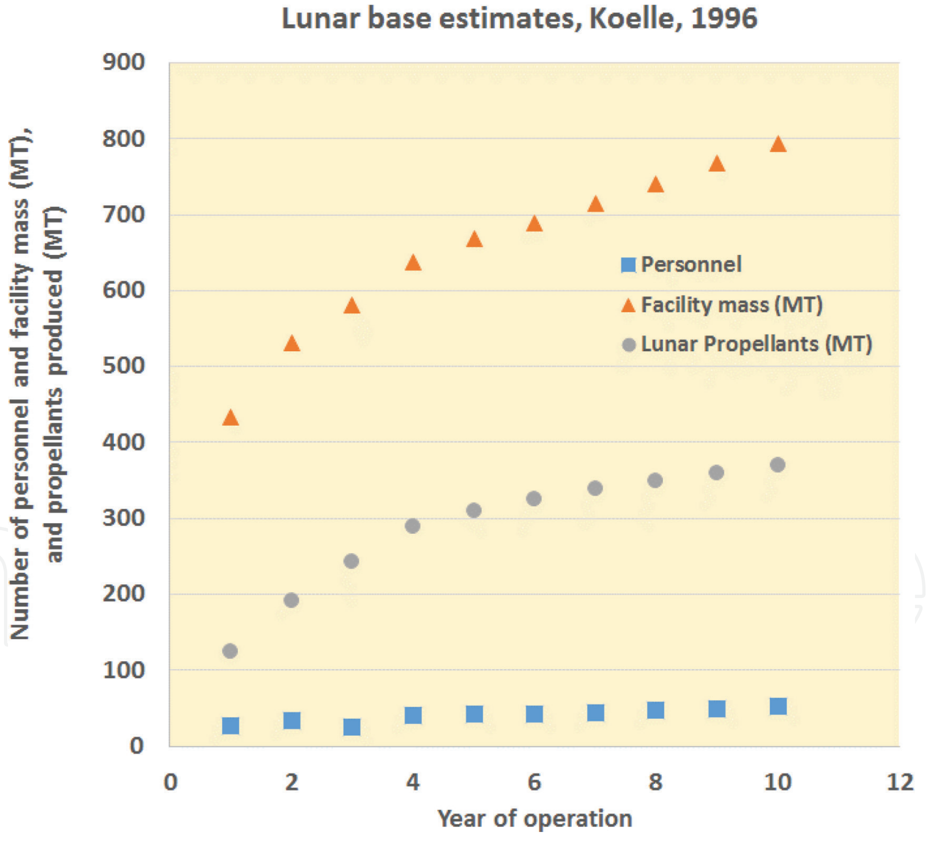

Figure 3.
Lunar base mass, personnel, and propellant produced (derived from [19]).

trips from Earth to LLO. Also, the assumption of ten flights for either the NTP ferry or the chemical propulsion shuttle was included. The NTP ferries carried 20 people with 36.3 metric tons (MT) (80,000 pounds mass (lbm)) of cargo for 6 months of base operations [18].

Later studies by Koelle [19] made more detailed estimates of the lunar base mass and ISRU lunar oxygen production capabilities (**Figure 3**). Over a 10-year period, the lunar base was to be constructed and required approximately 794 MT on the lunar surface. After 10 years, the base would accommodate 52 people and be producing 370 MT of lunar propellants in the tenth year.

3.1.1 Eagle engineering

In 1984, a study was conducted of lunar base construction and the additional accommodation that might be needed at the planned Earth-orbiting space station [20]. Large masses for the lunar base buildup were transported by oxygen/hydrogen orbital transfer vehicle (OTVs) and landers. The OTVs were two-stage vehicles, while the landers were both one-way cargo landers and two-stage human return landers. In this study, 1645 metric tons (MT) of payload was delivered to LLO low lunar orbit. The base would be constructed over a 19-year period. All of the launch vehicles from Earth were space shuttle or space shuttle-derived vehicles.

3.1.2 Spudis

A more modest lunar base scenario has been proposed [26, 27]. In their studies, a more sustainable lunar base was planned. Also, public-private partnerships (PPP) were essential for the success of the lunar base and its ISRU activities. Lunar water ice mining in permanently shadowed regions (PSRs) has been suggested [22]. Mining in the permanently shadowed craters (PSCs) will be challenging. [27] (Commercial Lunar Propellant study, 2018) suggests several solutions to these challenges, which include heliostats to provide lighting in the dark shadowed craters.

3.2 Lunar transportation options

Many techniques have been suggested for reducing the cost of space transportation [28–31]. A recent development is the propulsive landing and reuse of launch vehicle booster stages [28, 29]. While reuse of these launch vehicle stages is a relatively new development, future designs are planned for larger-scale lunar flights [28]. Additional options for lunar exploration and exploitation include a lunar orbital platform or gateway [30, 31]. A gateway may become a central point for propellant storage and distribution to several markets in the Earth-Moon system. These markets included LEO, GEO, LLO, and Earth-Moon libration points [27]. Many study results have identified the potential benefits of these markets, in which the commercial revenue may be many billions of dollars [27].

3.3 Advanced propulsion options

Several advanced propulsion options for lunar base construction and industrialization were investigated. They include nuclear electric propulsion options, lunar base design options, propellant industrialization, and outer planet mining with associated outer planet moon bases. Chemical propulsion and nuclear electric propulsion (NEP) for Earth-Moon orbital transfer vehicles (OTVs) were assessed. Design parameters, vehicle mass scaling equations, and summaries of these analyses are presented.

3.3.1 Chemical propulsion OTV sizing

In sizing the chemical propulsion OTVs, a vehicle mass scaling equation is used [16, 32]:

$$M_{dry,stage}\ (kg) = M_{dry,coefficient} \bullet M_p\ (kg).$$

where.

$M_{dry,stage}$ = the stage dry mass, including residual propellant (kg).

$M_{dry,coefficient}$ = the B mass coefficient (kg of tank mass/kg of usable propellant mass).

M_p = usable propellant mass (kg).

The chemical propulsion OTVs had a B coefficient of 0.2. The Earth-Moon OTVs were two-stage vehicles (**Table 1**).

3.3.2 NEP OTV sizing

The NEP OTV mass and trip time were estimated based on the power system and the propulsion system design [32]. The following dry mass scaling equation was used [32]:

Mdry,stage (kg) = reactor specific mass (kg/kW) • P (kWe) + 0.05 • Mp (kg) + fixed mass (kg).

The OTV sizing was conducted for a wide range of power levels: 0.5 MWe to 30 MWe. Three nuclear reactor specific masses were used: 10, 20, and 40 kg/kWe (kilograms per kilowatt, electric). The OTV propulsion fixed mass, apart from and in addition to the reactor mass, was 20 MT, and the propellant tankage mass was 5% of the mass of the required propellant.

The Isp and efficiency of the electric propulsion systems were 5000 seconds with thruster efficiencies of 50% for each design. These design points are typical of advanced designs of either magnetoplasmadynamic (MPD) or pulse inductive thrusters (PIT). While hydrogen is suggested for both propulsion system thrusters, the possibilities of the higher Isp option using inert gases (xenon, krypton, etc.) are also viable. The low thrust OTV delta-V value was 16 km/s for the round trip Earth-Moon missions.

Figure 4 shows the propellant masses needed a lunar base scenario; four different propulsion technologies are compared. There is the all-chemical propulsion option and three NEP options with 1, 2, and 5 MWe (megawatts, electric) power levels.

The all-chemical option includes 47 flights of a 35 MT round trip payloads. Each of these OTVs has an initial mass of 155.44 MT. The initial mass of the smaller 6 MT cargo OTV is 26.7 MT. The total propellant loading for the two-stage vehicle is 17.2 MT. To accommodate the 47 human crew flights in each of the NEP options, an 808 MT O_2/H_2 propellant mass is included.

NEP OTV parameters	Values
Specific impulse (s)	5,000
Engine efficiency (%)	50
Mission payload (MT)	29
Mission delta-V, total (m/s)	16,000

Chemical OTV parameters	Values
Specific impulse (s)	470
Mission payload (MT)	6
Mission delta-V, total (m/s)	5,250
delta-V breakout (m/s):	
Earth departure	3,200
Lunar arrival, LLO	900
Lunar departure, LLO	900
Earth aerobraking	250

Table 1.
NEP and chemical OTV design parameters.

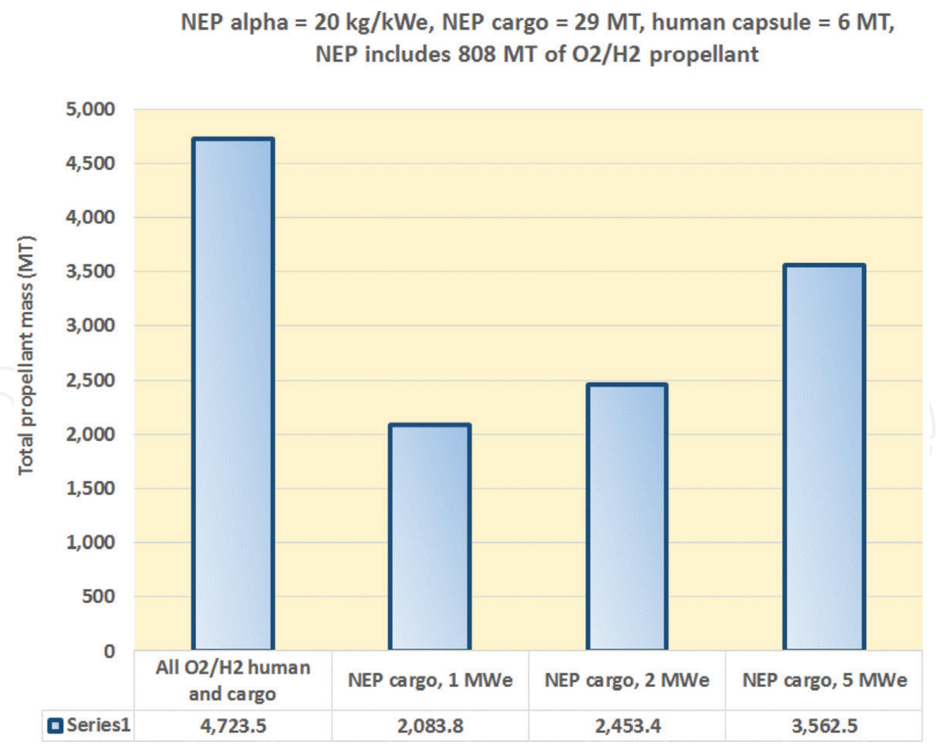

Figure 4.
Chemical propulsion and NEP option comparison (for 1645 MT delivered to LLO).

In all of the NEP options, there are 47 flights of 29 MT payloads. The payloads are carried on the full round trip missions. Once a 29 MT payload is delivered to lunar orbit, it is reasonable to say that a 29 MT payload will be returned to Earth orbit. This payload may be lunar ISRU propellants; lunar landers that may require recycling, updates, or repair; and other finished materials from the Moon.

With advanced nuclear electric propulsion systems, the effectiveness of the lunar base development is enhanced. Using NEP at a reactor alpha of 20 kg/kWe and a 1 MWe power level, over a 19-year assembly period, the propellant mass needed for base transportation can be reduced from 4700 MT to less than 2100 MT. Using NEP at a reactor alpha of 20 kg/kWe and a 1 MWe power level, over a 19-year assembly period, the propellant mass needed for base transportation can be reduced from 4700 MT to less than 2100 MT. Lunar ISRU may allow even further propellant mass reductions. While the NEP trip times are longer for the lower power levels, the overall mass savings is quite significant (**Figure 4**).

3.3.3 Lunar NEP parametric mass analyses

Figures 5–8 provide the initial mass, the propellant mass, and the trip times of the lunar OTVs. The payload mass was 29 MT for the round trip. The range of power levels that were investigated were 0.5–30 MWe. To obtain a balance of trip time and mass savings, a 1–2 MWe OTV is "best" operating point. The broad range power levels and reactor mass scaling parameters in the analyses are presented for additional mission planning purposes.

3.3.4 Lunar lander scenarios

The lander's mission is to deliver lunar propellants or crew or both to the lunar OTV and return to the Moon with cargo from Earth. The round trip delta-V values are provided in **Table 2**. The lander was designed with an oxygen /hydrogen main propulsion system. Lunar lander sizing was conducted for a variety of payload delivery

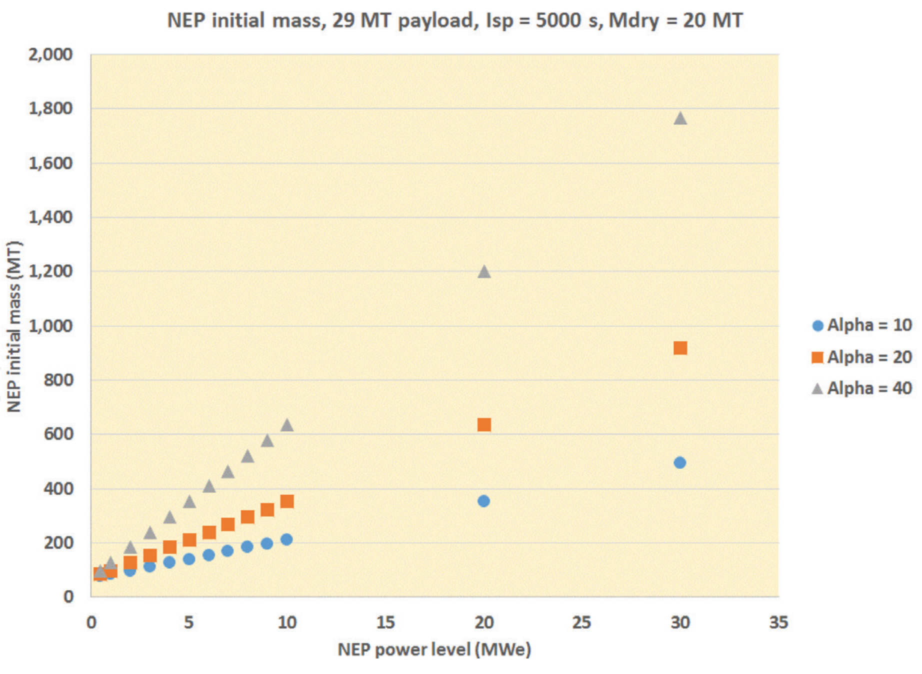

Figure 5.
NEP OTV initial mass versus power level: 0.5–30 MWe.

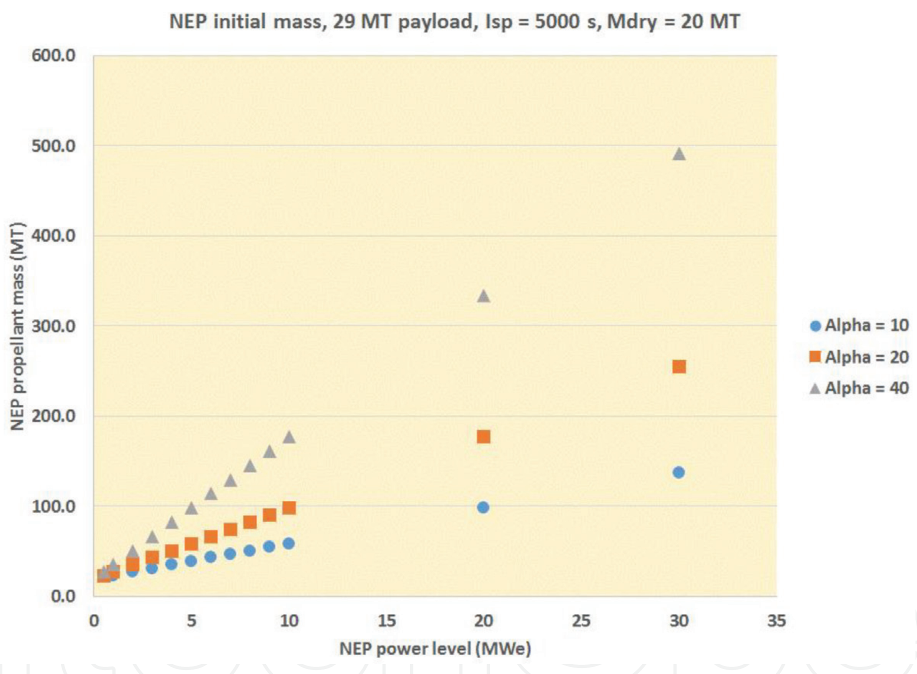

Figure 6.
NEP OTV propellant mass versus power level: 0.5–30 MWe.

missions, rocket engine-specific impulses (Isp), and mission delta-V values. The payload masses were 10, 20, and 50 MT. The rocket engine Isp values ranged from 450 to 480 seconds. Three overall mission delta-V values were selected: 2, 4, and 6 km/s. The 2 km/s delta-V represents a one-way mission from the LLO to the lunar surface. The 6 km/s delta-V represents a lander that can attain near escape velocity conditions about the Moon. Thus, nearly any mission in a wide range of lunar orbits is possible.

Figures 9–11 depict the suggested lunar lander scenarios. For lunar base support, both one-way and two-way lander trips are envisioned. At the outset of the base's construction, there will likely be no significant ISRU propellant production capability; thus a two-way lander is used to assure round trip access from lunar orbit to the base and back to orbit. **Figures 9** and **10** depict the flight profiles for the two-way lander flights. Initial lander flights would begin from orbit and arrive at the surface.

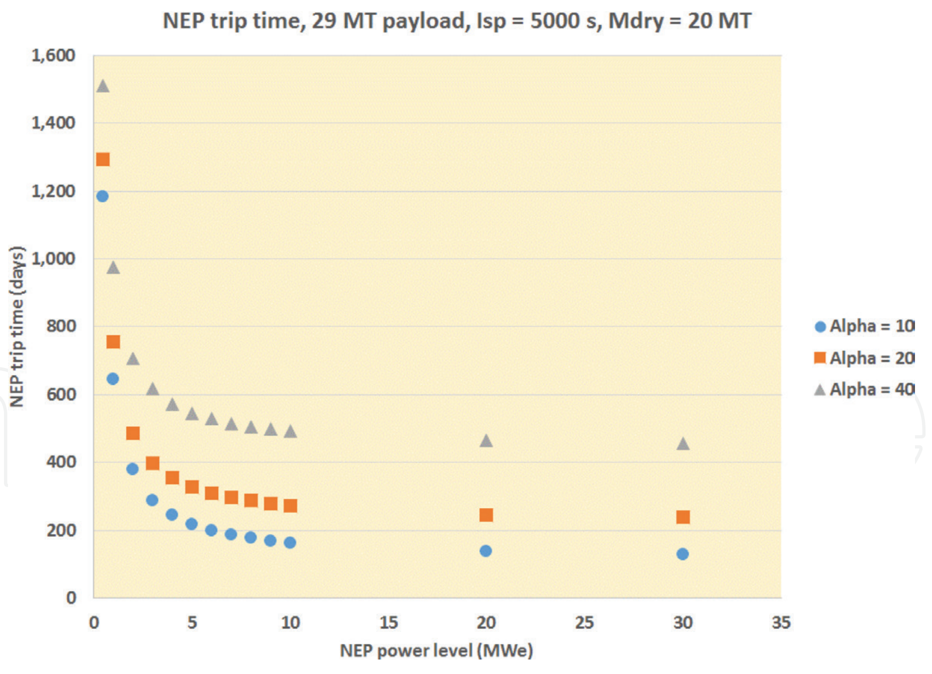

Figure 7.
NEP OTV trip time versus power level: 0.5–30 MWe.

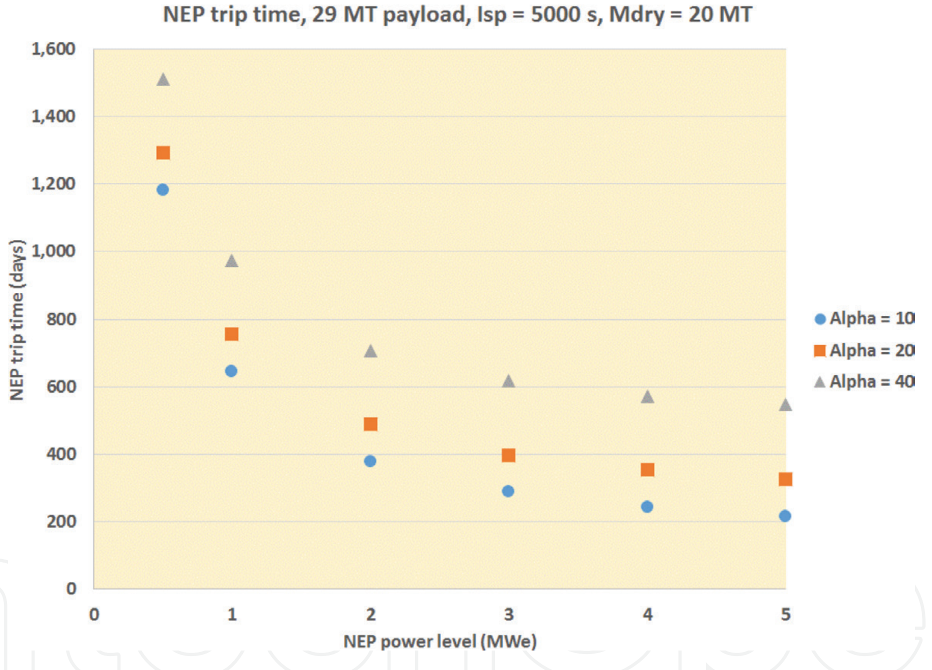

Figure 8.
NEP OTV trip time versus power level: 0.5–5 MWe.

Once a significant ISRU propellant capability is available, a combination of two-way and one-way landers can be used. The one-way lander would have only the propellant capacity to perform a one-way trip, either from orbit to the surface or from the surface to orbit. **Figure 11** illustrates the one-way lander flights. Additionally, a two-way lander can be used to depart from the surface, deliver a payload to orbit, and then return to the surface. A new ISRU-produced propellant load would be available for a subsequent two-way flight.

3.3.5 Lunar lander vehicle masses

The lunar landers are sized with the same mass scaling equations used for the chemical propulsion OTVs. All of the landers were single-stage vehicles. For the lunar

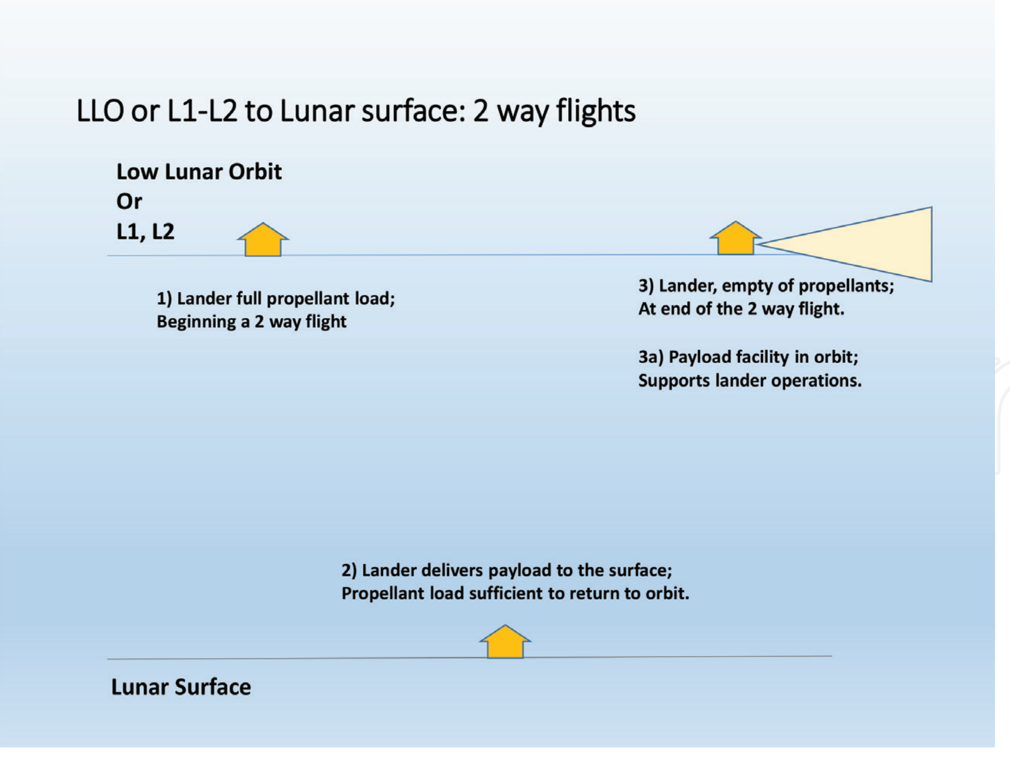

Figure 9.
Two-way lander flight profile with no ISRU.

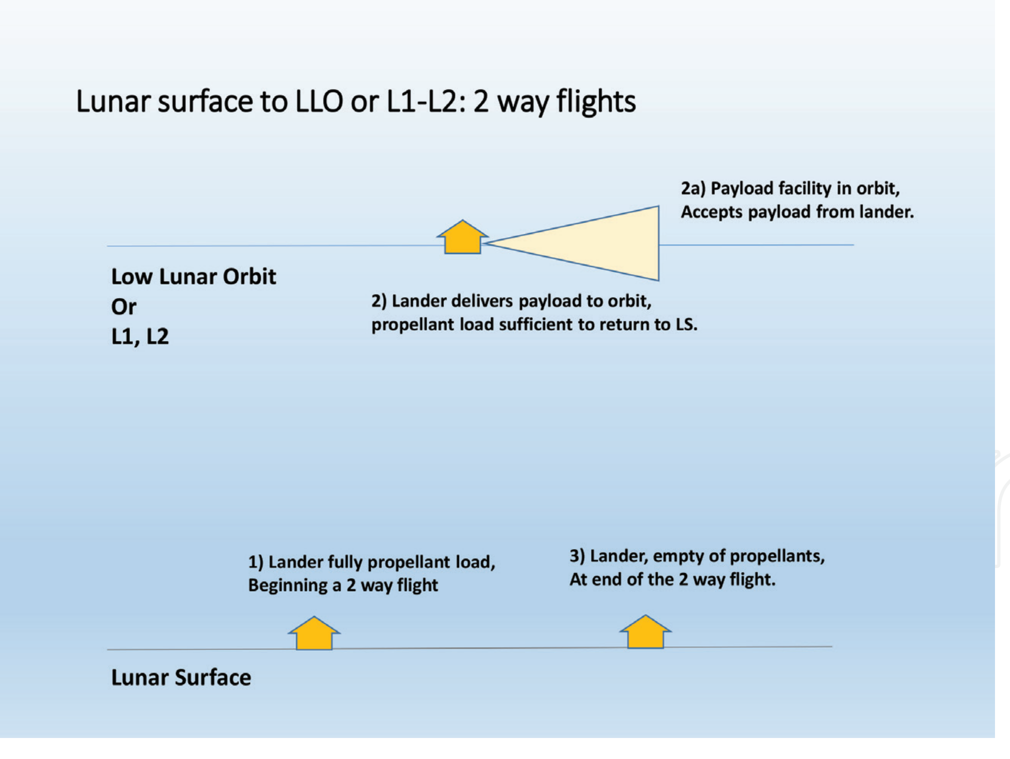

Figure 10.
Two-way lander flight profile with ISRU on the surface.

landers with 2 and 4 km/s delta-V values, the B coefficient was 0.4; in the high delta-V cases for 6 km/s, the B coefficient was 0.2. A 0.2 B coefficient was used as the lander design will not close with a 0.4 B coefficient. As the propellant load is quite high with the 6 km/s lander, and based on historical designs, the 0.2 B coefficient is justified.

Figures 12–14 provide the lunar lander masses for the three delta-V cases: 2, 4, and 6 km/s, respectively. The lander initial mass with a 2 km/s delta-V, a 470-s Isp, and a 10 MT round trip payload mass was 19.7 MT. While such landers will be used

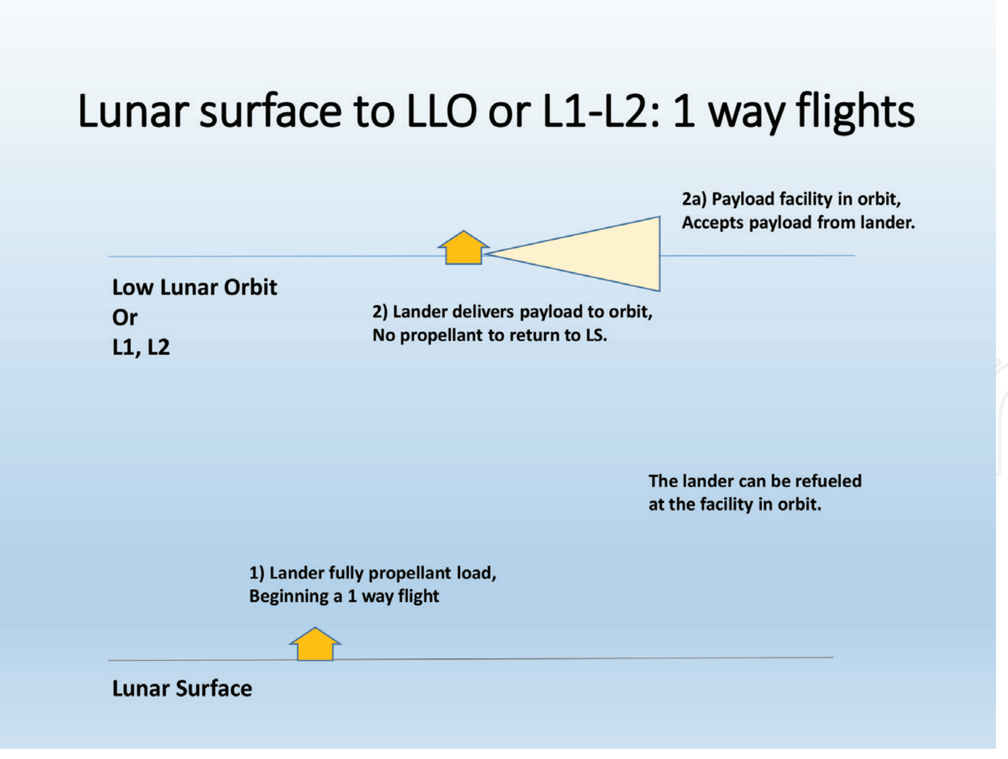

Figure 11.
One-way lander flight profile with ISRU-produced propellants stored on orbit.

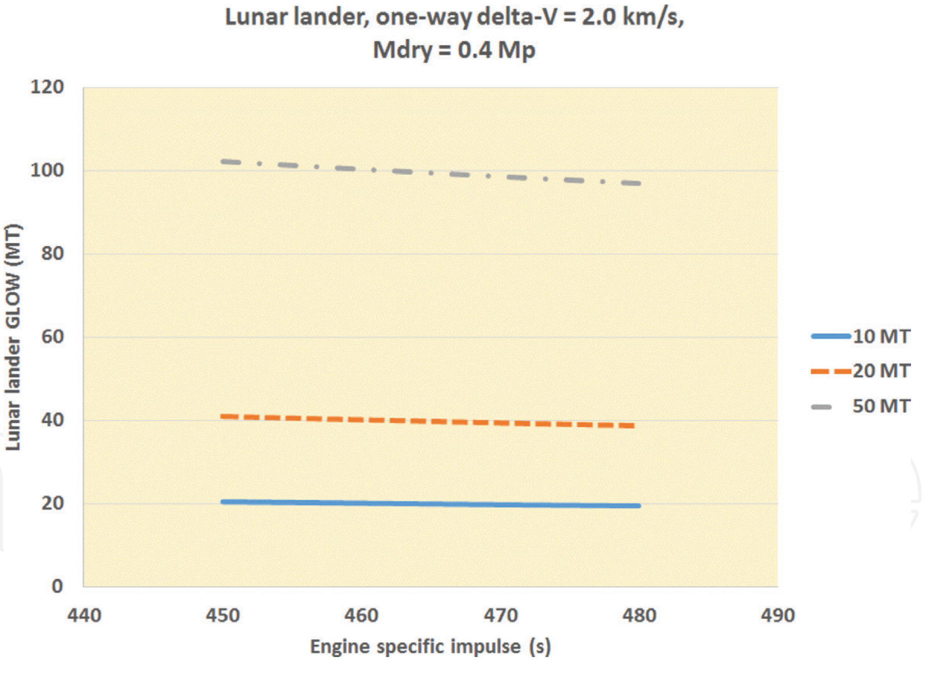

Figure 12.
Lunar lander masses versus specific impulse: 2 km/s delta-V capability.

early in the lunar base construction, these 2 km/s lander cases may also be attractive once lunar oxygen and hydrogen are made available. These smallest delta-V of the landers can be refueled on the Moon to return to lunar orbit. Once there, they can additionally be refueled from on-orbit propellant depots.

The 4 km/s delta-V lander is sized for a round trip with its full payload mass of 10–50 MT. The 4 km/s lander, with a 470-s Isp, and a 10 MT payload, has a mass of 53.2 MT. This delta-V capability offers a propellant load for an abort scenario. If the lander were descending to the Moon, and it were to experience issues during the

Lander parameters	Values
Specific impulse (s)	**450, 460, 470, 480**
Mission payload (MT)	**10, 20, 50**
Mission delta-V (m/s)	**2,000, 4000, 6,000**
delta-V, LS to LLO, one-way	2,000
delta-V, LS to LLO, two-way	4,000
delta-V, LS to libration point, two-way	6,000

Table 2.
Lunar lander mission parameters.

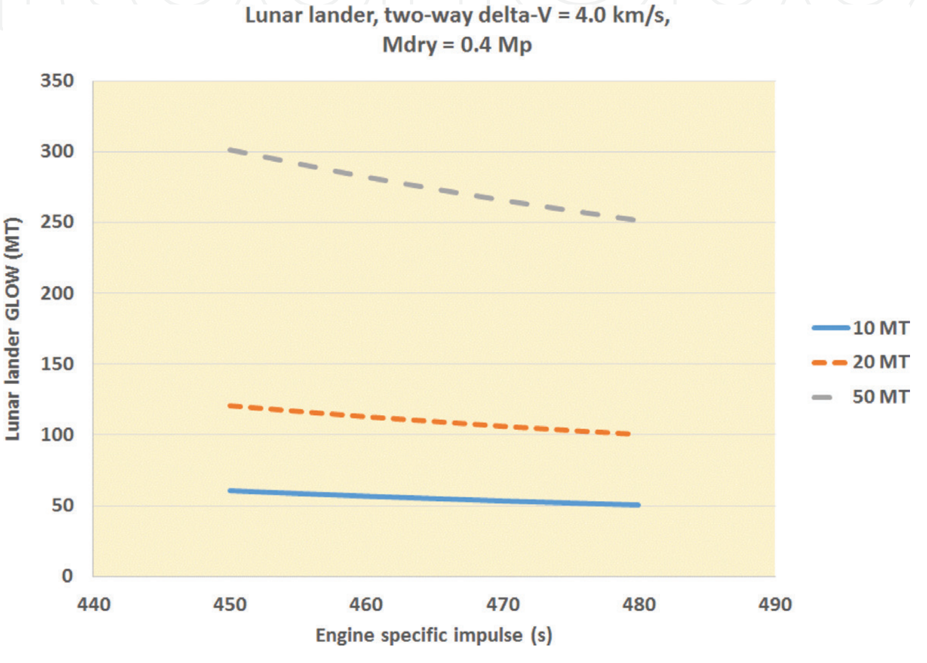

Figure 13.
Lunar lander masses versus specific impulse: 4 km/s delta-V capability.

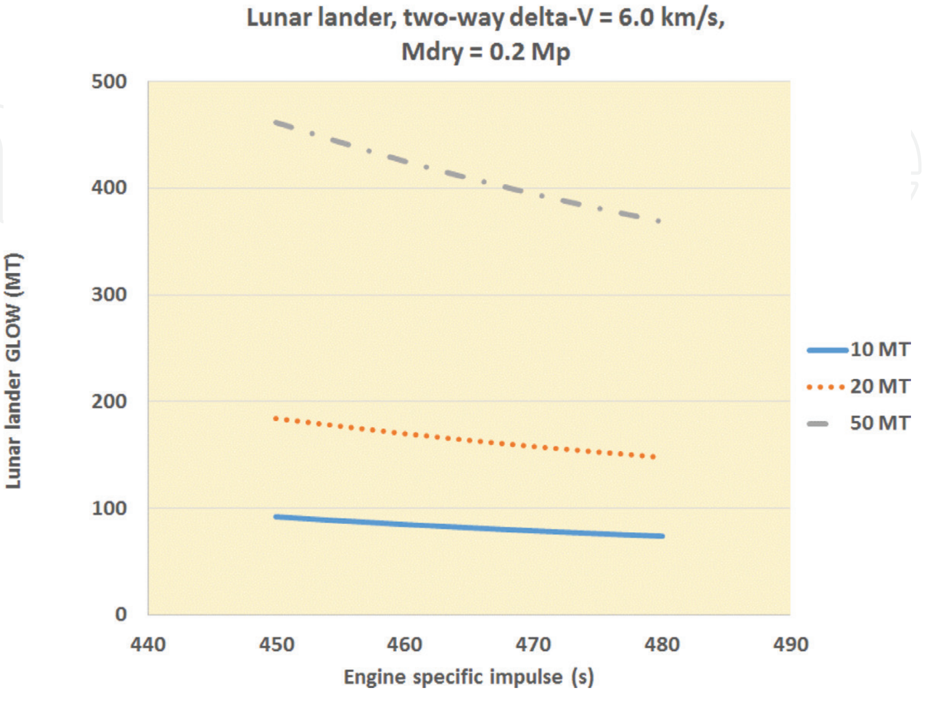

Figure 14.
Lunar lander masses versus specific impulse: 6 km/s delta-V capability.

descent, it would have the full delta-V capability to descend to the surface and then immediately return to orbit without refueling (**Table 2**).

3.3.6 NTP options, with ISRU

Using nuclear thermal propulsion for lunar missions was proposed in the 1960s. Investments and programs to prove the technical feasibility were successful, but these propulsion systems were never flown in space. Since the 1990s, many extensive analyses and experiments have been conducted for nuclear thermal propulsion for lunar and interplanetary missions and demonstrated important payload and trip time benefits [33–35].

A lunar NTP architecture can be refueled with lunar hydrogen, and a specialized design using a liquid oxygen afterburner can increase the thrust level of the lunar NTP shuttle, allowing a shortened 24 hour lunar flight [33].

3.3.7 Lunar base locations

The lunar surface has a wide range of elements available for extraction and use. Lunar water would be most important in sustaining the base. While the Moon has many potential resources available in the regolith, the potential for mining water ice at the lunar poles is strong but challenging. Mining the water will require vehicles that can operate at cryogenic temperatures in the craters. Not only will the robots or other vehicle have to operate in the craters, the light levels will be very low, perhaps requiring operation with light sources fixed at the crater's rim. Onboard power for the robots may have to be provided with nuclear reactors or remotely from a central power recharging station.

Base locations or sites for gathering the water ice must be addressed. The bases in the PSC will be located near the edge of the ice deposit. Locating the base or mining sites at the top (near the crater lip but in the shadow) or the left and right sides of the water ice deposit (and not at the bottom of the crater) were suggested [27]. These sites would provide access to the water ice and remain in the permanently shadowed part of the crater. Potential methods for extracting the water ice are discussed in Refs. [21, 22]. A tent for capturing the water would have a heat source to melt the frozen water ice. A layout for a lunar base is presented in **Figure 15** [36]. The photovoltaic array would be placed outside of the shadowed area, allowing for solar power to support the base and ISRU operations.

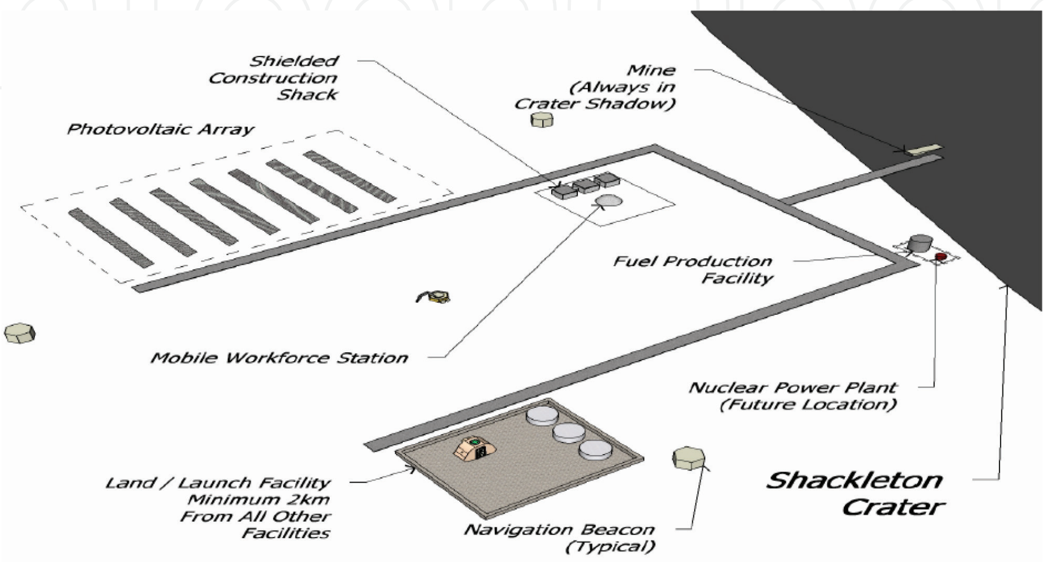

Figure 15.
Lunar base site for mining water ice from a PSC [36].

4. Future lunar base options

4.1 Nuclear underground explosions

Based on recent measurements and simulations of the lunar radiation environment, long-term occupancy of the lunar surface may be detrimental to human beings. In addition to the long-term exposure to natural radiation sources (galactic cosmic rays, solar flares, etc.), there is additional scattered radiation on the lunar surface [28]. Therefore, living and working underground on the Moon may be necessary. Using small of large nuclear devices on the Moon may provide an option for creating large habitable underground spaces. Project Plowshare [37–45] addressed issues with using nuclear devices to complete large-scale civil engineering projects.

Past Earth-based nuclear testing was done underground due to the Nuclear Test Ban Treaty of 1963. The tests often left sizable craters on the surface. When a nuclear device is sufficiently deeply buried, the explosive force can be completely contained underground [39–42]. The blast vaporizes some of the surrounding rocky material which then expands and creates an underground cavity [39–42]. The rocky debris in the cavity undergoes compaction after the explosion, but the initial amount of void space created by the blast just after detonation is distributed in broken rocky debris. Small robotic mining systems would be used for debris removal. Based on historical data, such a space can also be spherical if the blast size is sufficiently small. After the radiation has fallen to acceptable levels, people could potentially create comfortable living spaces.

In Ref. [7], this technique was proposed for not only living spaces but for large-scale ISRU. Ref. [7] illustrates four different ISRU processes using nuclear detonations. There are two chambers: one for the nuclear explosion and one for the reaction product capturing. This processing would essentially chemically reacting oxygen, hydrogen, or other species. The processes range from creating oxygen and metal oxides to producing water and metal carbides.

4.2 Lunar slide lander

In an attempt to reduce the propellant mass needed for lunar landing, the lunar slide lander was conceived. The lander uses friction between a descending tubular spacecraft and a prepared runway of lunar regolith. The operations of the slide lander are in eight phases Ref. [8]:

1. Elliptical orbital descent

2. Perilune pre-landing retro-maneuver

3. Approach to touchdown (begin (vertical) thrust at the end of Phase 3)

4. Touchdown of tail brake

5. Touchdown of side brakes

6. Main drag slide phase with support thrust

7. Main drag slide phase without support thrust

8. Final braking with brief retro-thrust

The slide lander was an attempt to reduce the total propellant load required for lunar landings. While the approach velocity of the lander is over 1.5 km/s, the long slide process may reduce the total delta-V required to 0.2–0.45 km/s; this is a significant delta-V reduction over the 2.0 km/s used for a traditional lunar landing [46]. Using this technique has several drawbacks. The length of the landing strip area is approximately 80 km. Also, the dust from the initial phase of the slide landing may attain an attitude of 1300 of km [8]. Thus, while the landing methods may save landing propellant, the implications of the dust on other orbital operations may be unwieldy.

4.3 Nuclear pulse propulsion

Using nuclear devices for propulsion is another option provided by engineering and physics community [47–50]. The nuclear pulse propulsion (NPP) systems were considered for fast transportation throughout the solar system. Small nuclear devices (physics packages, or PPacks) would be detonated behind a large piloted spacecraft, and the detonation would provide the primary vehicle propulsion. Thousands of nuclear pulses were required for Mars and outer planet missions. The predicted specific impulse for these vehicles is between 1800 and 6000 seconds [47]. The NPP vehicles were considered a logical precursor to the pulsed fusion propulsion systems, noted in many of the atmospheric mining in the outer solar system (AMOSS, [51, 52] studies.

5. Atmospheric mining in the outer solar system

Atmospheric mining of the outer solar system (AMOSS) is one of the options for creating nuclear fusion fuels, such as 3He and deuterium [32, 51, 52]. Uranus' and Neptune's atmospheres would be the primary mining sites. While preliminary estimates of the masses of the mining vehicles have been created [32, 51, 52], supporting OTV and lander vehicles are needed to complete the mining scenarios. Storing the mined gases at automated bases on cryogenic outer planet moons is needed, and lunar base designs for operation in cryogenic environments will be critically important for these outer planet moon base designs.

5.1 Resource capturing studies

Aerospacecraft cruisers have been identified as a "best" solution for atmospheric mining [32, 51, 52]. The main cruiser propellant is atmospheric hydrogen gas, which would be liquefied and used as rocket propellant for the cruise phase and the ascent to orbit. A nuclear gas core rocket is a likely candidate. Deuterium and helium 3 (3He) would be separated from the atmospheric hydrogen, and helium (4He) captured, liquefied, and stored is the primary payload that would be returned to orbit. On each cruiser round trip, a 500 kg payload of deuterium or 3He is captured during the mining time. **Table 3** provides the amount of 3He in the outer planet atmospheres.

	Uranus	Neptune
Amount of 3He in 4He	1.00E-04	1.00E-04
Amount of 4He in atmosphere	0.152	0.19
Amount of 3He in atmosphere	1.52E-05	1.90E-05

Table 3.
Fraction of helium 3 in outer planet atmospheres.

5.2 Vehicle, mission, and propulsion studies

5.2.1 Moon base transportation and mission planning

Several steps are needed to store the nuclear fuels. An aerospacecraft (ASC) must mine the gases from the planet's atmosphere. After mining, the ASC ascends to low orbit and then rendezvous with an orbital transfer vehicle. The OTV and ASC rendezvous at an altitude of at 800 km. After the rendezvous, the OTV accepts the mined cryogenic gases from the ASC, and, the OTV begins a low thrust spiral trajectory to the storage point, an outer planet moon. However, an alternative storage point is an in-space base with artificial gravity; the in-space base would be in orbit about the target Moon. At the Moon, the OTV and outer planet moon lander will rendezvous in high orbit about the outer planet moon. The OTV will deliver the mined fluids to the lander. The lander will refuel the OTV from hydrogen mined on the Moon. The OTV will return to low orbit about Uranus or Neptune to await the next ASC delivery. The lander will return to the Moon with the mined fluids. On the Moon, the lander propulsion system will be refueled with oxygen and hydrogen from the water ice from the Moon. Refs. [23, 42, 43] provide many options for nuclear power and nuclear propulsion to support these mining operations.

6. Observations

Krafft Ehricke envisioned a poly-global civilization, with branches of humanity in many far-flung places in our solar system [1]. His vision was uniquely expressed in Ref. [48]. Here is a short excerpt from that work:

> *Our helionauts, as these men who fly our large interplanetary vehicles call themselves in this era of continuing specialization, have covered the solar system from the sun scorched shores of Mercury to the icy cliffs of the Saturn moon, Titan. They have crossed, and some have died doing so, the vast asteroid belt between Mars and Jupiter and have passed through the heads of comets. Owing to the pioneer spirit, the courage and the knowledge of our helionauts and of those engineers, scientists, and technicians behind them, astrophysicists today work in a solar physics station on Mercury; biologists experiment on Mars, backed by a well-supplied research and supply station on the Mars moon, Phobos; planetologists have landed on Venus; and teams of scientists right now study what have turned out to be the two most fascinating of our solar system, Jupiter and Saturn, from research stations on Callisto and Titan.*

These helionaut flights would be the precursors of human outposts and then colonies all through the solar system. Multiple systems employing planetary ISRU could enable all of these ideas and concepts. The poly-global civilization was considered a natural expansion of the human experience, pioneering new frontiers and using technology in the best interests of all humanity.

7. Concluding remarks

The Moon represents a critical location for the expansion of humanity into the solar system. In an optimistic future, lunar exploration will lead to a base and perhaps extensive lunar industries. The industries include raw material processing, oxygen and other propellant production, nuclear and solar power, and the creation of completely new space vehicles. For protection against radiation, lunar bases may include underground habitats. Using explosive forming of underground cavities may lead to an attractive lunar base or colony. In addition, large-scale mining of lunar raw materials and gas production and capture from underground nuclear processing have been suggested.

With advanced propulsion systems, the effectiveness of the lunar base development is enhanced. Using NEP at a reactor alpha of 20 kg/kWe and a 1 MWe power level, over a 17-year assembly period, the propellant mass needed for base transportation can be reduced from 4700 MT to less than 2100 MT. Lunar ISRU can allow even further propellant mass reductions. With NTP, the payload mass delivered to lunar orbit can be doubled over oxygen/hydrogen chemical propulsion. Further benefits of water mining ISRU can allow refueling of the NTP from lunar hydrogen. Using the option of the liquid oxygen afterburner, the NTP system can allow a 24 hour lunar flight. The added liquid oxygen reduces the NTP Isp but allows a higher thrust level and therefore a shorter flight time. Both the NTP hydrogen and oxygen can be derived from lunar water ice.

Atmospheric mining in the outer solar system can produce nuclear fusion fuels such as 3He which are rare on Earth. In addition, while extracting the small fraction of 3He in the gas giant atmospheres, each day enormous amounts of hydrogen and helium are produced. These amounts can far outstrip the need for propellants to return the mining aerospacecraft (ASC) to orbit. These added propellants may be captured and used for other chemical or nuclear propulsion applications.

Solar system exploration using in situ resource utilization can allow larger and more effective research and sample return missions. Faster missions are possible by using the local planetary resources to return to Earth. Truly impressive interplanetary missions can be within our reach with focused lunar base investments.

Nomenclature

3He	Helium 3
4He	Helium (or helium 4)
AMOSS	atmospheric mining in the outer solar system
ASC	aerospacecraft
CC	closed cycle
delta-V	change in velocity (km/s)
EML1, 2	Earth-Moon libration point 1, 2
GCR	gas core rocket
GTOW	gross takeoff weight
H2	Hydrogen
He	Helium 4
ISRU	in situ resource utilization
Isp	Specific impulse (s)
K	Kelvin
kWe	Kilowatts of electric power
LEO	low earth orbit
LLO	low lunar orbit
LS	lunar surface
MT	metric tons
MWe	Megawatt electric (power level)
NEP	nuclear electric propulsion
NPP	nuclear pulse propulsion
NTP	nuclear thermal propulsion
NTR	nuclear thermal rocket

OC	open cycle
O2	Oxygen
PPB	parts per billion
PSC	permanently shadowed craters
PSR	permanently shadowed regions

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References

[1] Ehricke KA. Lunar industrialization and settlement—Birth of poly-global civilization. In: Lunar Bases and Space Activities of the 21st Century Conference; Houston, TX, Lunar and Planetary Institute; 1985. pp. 827-855

[2] Ehricke KA. Harenodynamic cooling - The use of lunar sand as cooling medium. Acta Astronautica. 1984;**11**:319-325

[3] Ehricke KA. Profitability of manufacturing in space in view of lunar industrial development and geo-socio-economic benefits, Manufacturing in space. In: Proceedings of the Winter Annual Meeting, Boston, MA, 13-18, November 1983; American Society of Mechanical Engineers; 1983. pp. 183-198

[4] Ehricke KA. A socio-economic evaluation of the lunar environment and resources. III—Selenospheric economics and cislunar/terrestrial market analysis. In: IAF PAPER 82-235, International Astronautical Federation, International Astronautical Congress, 33rd, Paris, France; 27 September-2 October 1982; p. 25

[5] Ehricke KA. A socio-economic evaluation of the lunar environment and resources. II—Energy for the selenosphere, In: IAF PAPER 79-A-16, International Astronautical Federation, International Astronautical Congress, 30th, Munich, West Germany; 17-22 September 1979; p. 25

[6] Ehricke KA. A socio-economic evaluation of the lunar environment and resources: I. Principles and overall system strategy. Acta Astronautica. 1981;**8**(11-12):1389-1405

[7] Ehricke K. Lunar industries and their value for the human environment on Earth. Acta Astronautica. 1974;**1**:585-622

[8] Ehricke K. Further analyses of the slide lander and of drop delivery systems for improved lunar surface access. Acta Astronautica. 1983;**10**(9):629-650

[9] Ehricke KA. Economy of large launch vehicles including orbital labor cost. AIAA. 1963. p. 277

[10] Ehricke K. A comparison of propellants and working fluids for rocket propulsion. American Rocket Society (ARS) Journal. 1953;**23**(5):287-300

[11] Lawrence DJ et al. Evidence for water ice near Mercury's North Pole from messenger neutron spectrometer measurements. Science. 2013;**339**:292

[12] Manning L. Comparison of several trajectory modes for manned and unmanned missions to Mercury 1980-2000. AIAA. 1967;**67-28**

[13] Marx G. Model study of fuel requirements for fast interplanetary flights using advanced nuclear propulsion systems and refueling at destination [thesis]. German: Technical University of Berlin (West Germany); 1967

[14] Ehricke K. Study of Interplanetary Missions to Mercury Through Saturn with Emphasis on Manned Missions to Venus and Mars 1973/82 Involving Capture. In: Engineering Problems of Manned Interplanetary Exploration; 1963. AIAA. pp. 1963-1514

[15] Ehricke K. Perspective and systems engineering of manned planetary flight, AAS 70-037. In: Space Shuttles and Interplanetary Flight. Vol. 28. Advances in Astronautical Sciences; 1970

[16] Palaszewski B. Metallized propellants for the human exploration of Mars, NASA-Lewis Research Center, NASA TP-3062, presented at the Case For Mars IV Conference, Boulder, CO,

June 4-8 1990. Journal of Propulsion and Power. 1992;**8**(6):1192-1199. Also in the AIAA

[17] Bensky M. Propulsion Requirements for Soft Landing in Extraterrestrial Environments. Rocketdyne, NAS7-124, NASA CR-55088. 1963

[18] Koelle HH, Rutland CH. An example of a reusable earth-lunar transportation system. NASA-TM-X-51436, Paper Presented to the AIAA Summer Meeting, Los Angeles; 01 June 1963

[19] Koelle HH. A Preliminary Concept and Life-Cycle Analysis of a Lunar Settlement. Aerospace Institute, Technical University Berlin, Marchstr.12, D-10587 Berlin, ILR Mitt. 306 (1996); 15 June 1996

[20] Babb G. Impact of Lunar and Planetary Missions on the Space Station. Eagle Engineering, Report Number 84-85D, Contract Number NAS9-17176. November 1984

[21] Li S, Lucey PG, Milliken RE, Hayne PO, Fisher E, Williams J-P, et al. Direct evidence of surface exposed water ice in the lunar polar regions. Proceedings of the National Academy of Science (PNAS). 2018;**115**(36):8907-8912

[22] Stoica A et al. Transformers for Lunar Extreme Environments: Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures. Phase; II. NASA Innovative Advanced Concepts (NIAC), Report Number: HQ-E-DAA-TN58829. 2017

[23] Linne Diane L, Gerald S, Suzuki N, Eisenman D, Hintze P, Araghi K, O'Malley T. Current Activities in the Advanced Exploration Systems ISRU Project. In: Joint Space Resources Roundtable/Planetary & Terrestrial Mining and Sciences Symposium; June 2018

[24] Borowski SK, Ryan SW, Burke LM, McCurdy DR, Fittje JE, Joyner CR. Robust Exploration and Commercial Missions to the Moon Using Nuclear Thermal Rocket Propulsion and In Situ Propellants Derived From Lunar Polar Ice Deposits. NASA/TM—2018-219937, AIAA–2017-5272; November 2018

[25] Connolly JF, Drake B, Joosten BK, Williams N, Polsgove T, Merrill R, et al. The Moon as a Stepping Stone to Human Mars Missions, Paper IAC-18/A3,1,3,x43905. 2018

[26] Spudis P, Lavoie A. Using the Resources of the Moon to Create a Permanent, Cislunar Space Fairing System. AIAA. 2011-7185

[27] Kornuta D. Commercial Lunar Propellant Architecture—A Collaborative Study of Lunar Propellant Production. 2018. Available from: http://www.isruinfo.com/

[28] Gunn JM, Amadieu PJ, Cruzen CA, editors. In: Space Operations: Exploration, Scientific Utilization, and Technology Development: SpaceX Mission Operations. pp. 281-290, Copyright © 2011 by the American Institute of Aeronautics and Astronautics, Inc

[29] Foreman VL, Siddiqi A, De Weck O. Large Satellite Constellation Orbital Debris Impacts: Case Studies of OneWeb and SpaceX Proposals. AIAA 2017-5200, 2017

[30] Smitherman D, Polsgrove T, Rowe J, Simon M. "Safe Haven Configurations for Deep Space Transit Habitats." In: AIAA 2017-5285, AIAA Space 2017 Conference

[31] Polsgrove T, Simon MA, Waggoner J, Smitherman DV, Howard RL, Percy TK. Transit Habitat Design for Mars Exploration. In: AIAA 2018-5143, 2018 AIAA SPACE and Astronautics Forum and Exposition

[32] Palaszewski B. Atmospheric Mining in the Outer Solar System: Orbital

Transfer Vehicles and Outer Planet Moon Base Options. In: AIAA 2016-4889; July 2016

[33] Borowski et al. Vehicle and Mission Design Options for the Human Exploration of Mars/Phobos Using Bimodal NTR and LANTR Propulsion, AIAA 1998-3883; 1998

[34] Bulman MJ et al. High Area Ratio LOX Augmented Nuclear Thermal Rocket (LANTR) Testing. AIAA 2001-3369; 2001

[35] Houts M et al. Nuclear Cryogenic Propulsion Stage. In: Nuclear and Emerging Technologies for Space (2012), 2012

[36] Khan Z, Vranis A, Zavoico A, Freid S, Manners B. Power System Concepts for the Lunar Outpost: A Review of the Power Generation, Energy Storage, Power Management and Distribution (PMAD) System Requirements and Potential Technologies for Development of the Lunar Outpost. In: NASA/TM—2006-214248, DOE/NV/11718-1118; June 2006

[37] Looper M. Radiation environment near the lunar surface CRATER observations and GEANT4 simulations. Space Weather. 2013;**11**:142-152

[38] Cohen GD, Sand FM. Water Resource Applications, Underground Storage of Natural Gas, and Waste Disposal Using Underground Nuclear Explosions. Mathematica Inc Princeton NJ; 31 August 1967. Available from: http://www.dtic.mil/get-tr-doc/pdf?AD=ADA395557

[39] Morrey CB Jr, Pinney E, Stoneham RG, Chambre PL, Lakness RM. Underground Explosion Theory. California Univ Berkeley; 1952. Available from: http://www.dtic.mil/get-tr-doc/pdf?AD=AD0608885

[40] Sachs DC, Swift LM. Underground Explosion Effects. Stanford Research Inst., Menlo Park, CA; 03 March 1958. Available from: http://www.dtic.mil/get-tr-doc/pdf?AD=AD0617181

[41] Brode HL. Nuclear Explosions in Cavities. Santa Monica CA: Rand Corp.; 1965

[42] Brode HL. More Nuclear Explosions in Cavities. Santa Monica: Rand Corp.; 1968

[43] Hoffman GA. Thermoelectric Powerplants Utilizing Contained Nuclear Explosions. Santa Monica, CA: Rand Corp.; 1960

[44] Gruber S. Charged Particle Beam-Plasma Interactions for Thermonuclear Power Generation, Final Report, Case Western Reserve Univ., Cleveland Ohio, Dept. of Electrical Engineering and Applied Physics; 1974

[45] Wong HV, Kotschenreuther MT, Breizman BN, Van Dam JW, Hazeltine Richard D. Assessment of Compact Low Neutron Fusion Reactor Concepts, Final Rept. 15 Jun 1999-30 Nov 2000, Texas Univ. At Austin Inst. For Fusion Studies, 16 February 2000. Available from: http://www.dtic.mil/get-tr-doc/pdf?AD=ADA387427

[46] Palaszewski B. Lunar Missions Using Advanced Chemical Propulsion: System Design Issues. In: NASA-Lewis Research Center, NASA TP-3065, AIAA 90-2341, presented at the 26th AIAA/ASME/SAE Joint Propulsion Conference, Orlando, FL, July, 1990, Also in AIAA Journal of Spacecraft and Rockets. Vol. 31, No. 3, May-June 1994. pp. 458-465

[47] Interplanetary maneuvers in manned helionautical missions. (Ehricke, 1965). AIAA. 1965-695

[48] Ehricke KA. Solar Transportation. In: Presented to the 4th Goddard Memorial Symposium, Am. Astronautical Soc., Washington, D. C., 15-16 March. 1966

[49] A Grand Vision of Man's Role in Colonizing the Universe by Oyang Teng, LaRouche Youth Movement (Book review)—Marsha Freeman, Krafft Ehricke's Moon: The Extraterrestrial Imperative, Technology Editor of Executive Intelligence Review, 2009. Available from: http://www.21stcenturysciencetech.com/Articles_2009/Summer-2009/Extraterrestrial_Imperative.pdf

[50] Schmidt GR, Bonometti JA, Irvine CA. Project orion and future prospects for nuclear pulse propulsion. Journal of Propulsion and Power. 2002;**18**(3)

[51] Palaszewski B. Atmospheric mining in the outer solar system: Resource capturing, storage, and utilization. AIAA. 2012;**2012-3742**

[52] Palaszewski B. Atmospheric Mining in the Outer Solar System: Issues and Challenges for Mining Vehicle Propulsion. AIAA. 2011-6041; August 2011