ULTRA-SAFE NUCLEAR THERMAL ROCKETS USING LUNAR-DERIVED FUEL

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ABSTRACT

Rocket launch failure rate is slightly higher than five percent. Concerned citizens are likely to protest against private-sector launches involving fission reactors. Yet, fission reactors can power long-duration lunar operations for science, observation, and in situ resource utilization. Furthermore, fission reactors are needed for rapid transport around the solar system, especially considering natural radiation doses for crews visiting Mars or an asteroid. A novel approach is to create nuclear fuel on the Moon. In this way, a rocket launched from the earth with no radioactive material can be fueled in outer space, avoiding the risks of spreading uranium across Earth's biosphere. A solution is to harvest fertile thorium on the lunar surface, then transmute it into fissile uranium using the gamma ray fog which pervades the deep sky. It is only at lunar orbit, at the very edge of cislunar space, that the Earth-launched machine becomes a nuclear thermal rocket (NTR). Thorium is not abundant, but can be concentrated by mechanical methods because of its very high specific density relative to the bulk of lunar regolith. Thorim dioxide (ThO_2) has an extremely high melting point, such that skull crucible heating can be used to separate it from supernatant magma. When filled into a graphite-lined beryllium container (brought from Earth) and set out on the lunar surface, high-energy gamma rays will liberate neutrons from the Be. After moderation by the graphite, these thermal neutrons are captured by the thorium nucleus, which is transmuted into protactinium (Pr^{91}). This element can be extracted using the THOREX process, and will then decay naturally into U-233 within two or three lunar days. The uranium is oxidized and packed into fuel pellets, ready to be inserted into a non-radioactive machine, which now becomes a NTR. Additionally, hydrogen can be extracted from deposits in permanently-shadowed regions on the Moon, providing reaction mass for the NTR. A novel method of solid-state hydrogen storage, which can be entirely fabricated using in situ resources, can deliver said hydrogen to the fission reactor to provide high and efficient propulsive thrust. These combined operations lead to an ultra-safe (for the Earth) means for private sector, commercial transport and power generation throughout the Solar System. With the hydrogen storage material used as radiation shielding for crewed spacecraft, and greatly-reduced transit times relative to chemical rocketry, this innovative approach could fundamentally transform how humans work, play, and explore in outer space.

1. INTRODUCTION

Outer space, beyond the earth's protective coccoon, is pervaded by deadly radiation. Human travel to destinations beyond cislunar space are put at risk because of the long durations. The product of dose and exposure time is so great that present-day humans may not survive a trip to Mars on a conventional, chemically-fueled rocket. This work addresses both factors with fast rockets and integrated shielding.

Approximately five percent of rocket launches fail. A portion of these failures explode, break up, or experience uncontrolled re-entry, spreading their contents through Earth's biosphere. While certain clandestine military payloads have included small fission reactors, there is certain to be public concern and protest over private sector launching of the larger reactors needed for Nuclear Thermal Rockets (NTR). The approach developed in this study avoids launching of any radioactive material from the Earth. The fission fuel, and also the reaction mass, are harvested and processed on the Moon. From a biosphere radioactive contamination perspective, this approach results in "ultra-safe" NTRs.

The processes described herein are second generation, and assume the pre-existance of an atomic pile made using less-refined methods as described in [39]. The second generation fuel pellets are compatible with traditional nuclear reactor design, such that a non-radioactive machine can be launched from Earth and not made radioactive until it reaches lunar orbit, 382,500 km away. An additional method of in situ resource utilization (ISRU) is the storage of hydrogen reaction mass in a long-duration solid-state media based on silicon. All of the consumables are available on the moon, so that the operations only require soft-landing of a lunar factory [8]. Taken together, lunar uranium, lunar silicon, and lunar hydrogen can provide fast, safe transport for humans throughout our Solar System.

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2. METHODS

The techniques described herein build upon a first generation stationary fission reactor built on the Moon using ISRU uranium 233 transmuted from lunar thorium. Thorium-bearing minerals such as thoria (ThO_2) and monazite ($ThPO_4$) are three to four times more dense than the regolith average, and can be concentrated by density sorting [43]. When encased in a beryllium shell and exposed on the surface to the gamma ray fog of the deep sky, the thorium is transmuted into uranium, suitable as a fission fuel [44]. A simple reactor or even an atomic pile is then used to heat a working fluid which drives a thermal cycle to produce electrical power. Such a reactor sized to produce six megawatts-thermal (6 MWth) can produce baseload electric power of two megawatts-electric (2 MWe) for more than six years [39]. This first, crude fission reactor can thus provide the ample power needed for continuous operation of second generation processing of fission fuel, and also for solid-state hydrogen storage [8]. These second generation fuel pellets can be made of a standard size to assemble into fuel rods, and lunar hydrogen from electrolysis of water ice in permanently-shadowed regions can be stored for long durations in porous silicon which surrounds a crew capsule. In this way, fast NTRs with ample radiation protection and plenty of fuel can rapidly move across vast distances in outer space.

2.1 Lunar Resource Extraction

Thorium is found in relatively high abundance on the northern hemisphere of the lunar Near Side, possibly up to 60 ppm, although 20 ppm will be assumed herein to broaden the range of available sites. This study assumes the availability of water for all aqueous chemical extraction processes. Silicon is abundant on the moon, representing 21% of regolith by mass, and can be beneficiated using plasma beam separation [11,12,13,14,45,46].

Jaw crushers are an excellent choice for size-reducing regolith particles in a reduced gravity environment. These biomimetic devices are far less massive than most terrestrial comminution methods, for example the H2550 Telsmith Hydra-Jaw Crusher system [29], and a lunar-designed apparatus will have a mass no greater than 7.5 MT [39]. The comminution facility is used to create a reasonably uniform particle size [30], similar in size to the average regolith particle of about 70 microns

The THOREX process was developed in the United States and has been further refined in India for use in terrestrial breeder reactors [10]. The isotope of uranium produced in this way (U-233) has great advantage in that the radioactive byproducts decay within about 80 years to safe levels, and are poorly-suited to the making of atomic bombs. The THOREX process is aqueous-based, and uses specialized solvents such as tributyl phosphate (TBP) [20]. Mixtures of protonated acids are used to dissolve the actinides, then co-precipitation processes are used to extract the fissile fuel. The fuel is purified, and then oxidized into a powder (UO_2) and compressed into individual fuel pellets [28]. For this work we adapt the THOREX re-processing method [19] to be used on the lunar surface using virgin ore.

2.2 Crucible Heating Analysis

Thoria has an extremely high melting point at 3300 K [32]. Oxides of calcium and magnesium are similarly refractory, but are significantly lower in density. By melting regolith, the CaO and MgO will float on the magma surface while the thoria will drop to the bottom in the lunar gravity. By RF induction heating of the regolith to about 2250 K in a skull crucible configuration, the supernatant can be poured off to leave concentrated thoria.

A one-dimensional model was used to study the power and time required to bring the bulk of the comminuted regolith to the liquidus point. The transient heat conduction equation [33] includes temperature T, thermal conductivity k, specific heat c, density ρ, and x as the distance variable:

$$(1)\ \frac{dT}{dt} = \frac{k}{c\rho}\left(\frac{\partial^2 T}{\partial x^2}\right)$$

Temperature increase with time, due to the RF induction energy, is modeled using Fourier's law, where A is the area of the finite element and $\dot{Q_{in}}$ is the heater power:

$$(2)\ T(x, t+\Delta t) = T(x,t) + \left(\frac{k\Delta t}{c\rho}\right)\left[\frac{\partial^2 T}{\partial x^2} + \dot{Q_{in}}\frac{\Delta x}{kA}\right]$$

The regolith physical model used is based on Apollo 12 samples. The thermal conductivity of regolith is given by [34]:

$$(3)\ k = 0.000922 + (3.19 * 10^{-11})T(x,t)^3\ \frac{W}{mK}$$

The location- and temperature-dependent heat capacity is given by [23]:

(4) $c = -1848.5 + 1047.41log\big(T(x,t)\big)\ \frac{J}{Kg.K}$

Input heater power for a finite element depends on the electric field E and the electrical conductivity σ, according to [35]:

(5) $\dot{Q_{in}}(x, t + \Delta t) = \sigma E^2 \Delta V$

The electrical conductivity of the regolith is taken to be 1.00 mho/m for temperature up to 1445 K, and 5.00 mho/m for higher temperatures [36]. Faraday's equations (6) with the solenoid equation (7) are used with the radial equation for current (8), resulting in equation (9) below:

(6) $\frac{dE}{dx} = -\frac{dB}{dt}$

(7) $B = \mu\frac{NI}{t}$

(8) $I = I_{max}cos\ (\omega t)$

(9) $dE = \mu(NI_{max})wsin(\omega t)$

Where B is the magnetic field, μ is the magnetic permeability. For the induction coils, I is the current, I_{max} is the amplitude of the current, N is number of turns and ω is the RF frequency, set at the industrial standard 13.56 MHz.

Constants	***Value***
ρ	1300 Kg/m^3 [36]
w	84,822,662 rad/s (typical)
μ	0.000201 H/m [37]

Table 1. *Fixed-value constants used for finite element heating analysis.*

Skull heating requires active cooling of the exterior of the bolus to contain the molten regolith within. Heat removal power Q depends on the temperature different (ΔT) between the surface temperature of the regolith bolus and the temperature of the refrigerant, as well as its heat capacity (c_p). The mass flow rate of refrigerant ($\dot{m}$) can then be calculated from:

(10) $Q = \dot{m}\ c_p\ \Delta T$

During lunar night, the low surrounding temperatures allow radiative heat transfer to aid in the formation of a "skull" or skin, such that a separate crucible is not required. Indeed, anecdotal evidence of melting regolith simulants suggests that most ceramics are dissolved in the magma, with the lone exception of a thoria vessel itself [47]. If radiative cooling is inadequate, for example, during lunar daytime, cooling coils can be wrapped around the bolus and use a water-glycol mixture as the working fluid and a refrigerator with a suitably-sized, and shaded, radiative transfer heat exchanger.

One-dimensional finite element analysis including the above factors was modeled using the Excel™ spreadsheet program. The optimizer function was used to determine the minimum power (NI_{max} term) required to full liquify the regolith within the skull/skin. Each cell of the worksheet were treated as a finite element, in which the temperature depends on local heat capacity, thermal conductivity, electrical conductivity, the RF heat input, the temperature of neighboring elements, and active cooling of the exterior cells. The entire diameter of the bolus was modeled through forward time, and then multiplied by the other two dimensions to derive total electrical input power to the induction heater, and the electrical power needed for the cooling coils.

Once the interior of the regolith bolus is mostly liquified and the thoria has settled to the bottom, the supernatant magma is poured off by tilting, or by breaking the skull. That magma can be poured into molds to form pavers or construction blocks. The heat may be recovered for other useful purposes. The remaining disk of thorium-rich solids (hereafter referred to as the "puck") at the bottom of the crucible will initially be too thin to remove. So, multiple rounds of crucible melting will be sequenced to produce a thicker puck. As such, each iteration of the crucible melting will hold slightly less material than the previous iteration until the puck is of sufficient thickness. Once the puck has reached sufficient size, it is transported to a

separate container where chemical processing (i.e., THOREX) will be utilized to extract and purify the desired thorium dioxide ("thoria") to undergo neutron absorption and transmutation into protactinium, and thence to uranium.

2.3 Chemical Processing and Transmutation.

The thorium-rich minerals at the bottom of the skull crucible are dissolved in hot aqueous-based sodium hydroxide (NaOH). Subsequent addition of hydrochloric acid (HCl), titrated to a pH of about 3 will precipitate "thorium cake" [27]. The thorium cake is then dissolved in nitric acid (HNO_3) plus small quantities of hydrofluoric acide (HF) and aluminmum nitrate ($Al(NO_3)_3$), which results in a Th-bearing acidic solution of about 20 g/L at 8-9 M [19].

THOREX uses counter-flowing solvent extraction in which one phase is aqueous and the other is organic. In this case, the nitric acid solution is the aqueous phase, and TBP is used as the organic phase extractant. Oxalic acid is then added to precipitate thorium-rich solids followed by calcination and sintering of the solids produces the desired ThO_2 solids. The solids are then packed into a graphite-lined beryllium containment vessel for transmutations.

The beryllium-graphite-thoria assembly is placed on, or prefereably raised above, the lunar surface, exposed to the deep sky from which gamma rays emerge. The diffuse, isotropic gamma ray "fog" has a spectral distribution such that those energetic photons capable of eliciting a neutron from the Be nucleus, above 0.1 MeV, have a flux of 1.6E13 per square centimeter [48]. The graphite liner between the Be shell and the Th will not absorb neutrons, but collisions with the carbon nucleii will reduce the neutron energy, with velocities equilibrated to the graphite temperature. These slower, equilibrated particles are called thermal neutrons, and can be absorbed and incorporated by the thorium nucleus instead without simply splitting it apart. The neutron-enhanced thorium nucleus decays within seconds to become protactinium, which then decays to U-233 with a half-life of 27 days, as shown in equation 11.

$$(11) \qquad {}^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th + \beta^- \rightarrow {}^{233}_{91}Pa + \beta^- \xrightarrow{27\ days} {}^{233}_{92}U$$

The optimal dimensions for the vessels were determined based on producing a sufficient mass of fissile uranium within two years. The beryllium shell is 1.065 m in height, 0.037 m thick, and has a volume of 6.15E-3 m3. In total, approximately 11.4 kg of beryllium are required to construct the shell. The ThO_2 is formed into a cylinder with a volume of 1.4E-4 m3 and is placed inside the beryllium shell. The Be shell geometry is configured such that most of the Th begins the transmutation process before U formation begins to accelerate. The Pa-rich material is removed from the Be shell and allowed to rest as it undergoes the final transmutation step. In total, it will take approximately 607 Earth days to complete the transmutation of all the requisite thorium into protactinium.

The THOREX process now teaches how to separate the U from the remaining Th, so that the former can be converted to fuel pellets, and any remaining material can be sent back to the skull crucible, ensuring maximum utilization of the mined regolith. To produce the uranium solids a nitric acid solution is used as the aqueous phase, and TBP is used as the organic phase extractant. TBP has the unusual property of dissolving U at low concentrations (3-7 percent), while at higher concentrations it dissolves Th. Multi-stage chemical stripping columns, or centrifugal contactors, are used to shuffle byproducts in and out of the counter-current aqueous and organic streams. In particular, using, for example, a 5% solution of TBP, often thinned with n-dodecane to reduce viscosity, will preferentially complex with U. Th products are scrubbed out using 1-2 M nitric acid, and separated. Then a dilute solution of the same acid (0.01 M HNO_3) will strip the organic complex from the uranium compound. Treatment with ammonium hydroxide (NH_4OH) will now precipitate ammonium diuranium as a solid. Spent solvent is sent for recycling along with the raffinate [26].

2.4 Fission Fuel Production.

The uranium precipitate is washed with water, dried, and then calcined in the presence of oxygen to form U_3O_8 [29-33]. While numerous factors control the character of the resulting powder, calcining temperature is the dominant factor controlling the strength of the powders. A high temperature calcination (~900° C) will yield particles that are resistant to breakup [29]. The powder is then characterized to ensure high purity [34]. This oxide of uranium is hydraulically compressed into cylindrical fuel pellets, which are then ready for insertion into fuel rods for running a fission reactor.

2.5 System Design and Recycling.

For the bulk of the processing facility, polypropylene will be used to contain and facilitate chemical reactions. However, heavier stainless steel (e.g., SS304L or 316) or superalloys (e.g., Hastelloy® or Inconel®) may be required for certain piping and containment of certain processes, because of their resistance to corrosion in the concentrated acids.

TBP will eventually decompose into its dibutyl- (DBP) and even monobutyl- (MDP) forms, or decompose all the way to phosphoric acid under severe radiological and thermal processing. Alternate solvents can be used which are easier to synthesize than TBP, e.g. N,N-dialkyl amides [9]. However, such extractants require more intensive recycling processes, which have historically been studied in far less detail than those utilizing TBP. We selected the TBP-based THOREX processing to adapt to operations on the lunar surface because of the potential to recycle this organic phase in situ.

Initially, the full required mass of TBP will be shipped to the lunar surface. It will eventually decompose by steps into lower index complexes. These may be used to synthesize TBP on the lunar surface. The recycling process begins with the capture of the CO_2 and some of the NO_x produced during calcination which is fed to cyanobacteria. The carbon monoxide and hydrogen produced by the cyanobacteria is synthesized into hydrocarbon intermediates (via Fischer-Tropsch or similar). The remaining NO_x as well as gaseous phosphorous (captured during skull melting) are bubbled through water, producing and recovering nitric and phosphoric acid, respectively. The combination of the hydrocarbons and acids are used to synthesize TBP by [39]:

(12) $$POCl_3 + 3\ C_4H_9OH \Rightarrow (C_4H_9O)_3PO + 3\ HCl$$

Following the synthesis of the crude TBP product, the washed organic phase is separated and the excess *n*-butanol present in solution is recovered. The crude product is then purified of the residual *n*-butanol, mono-phosphoric acid, di-phosphoric acid, water, and other impurities which form during synthesis. Final purification is carried out via batch distillation under vacuum. Under low vacuum, the *n*-butanol and water constituents are removed (these constituents are also sent for *n*-butanol recovery). Following this removal stage, the purified TBP is transferred to a holding tank and is ready for re-use [40].

Overall, the mass of the required materials for this stage of operations is approximately 11 metric tons. The subsystem component masses are presented in Table 2.

Reactants, assumes H_2O in situ:	**0.0865 MT**
H_2O | harvested in situ	0 kg
NaOH | shipped as solid	7.0 kg
HCl | as 6M solution	24 kg
HNO_3 | as 13 – 15M solution	21 kg
TBP | diluted in n-*dodecane*	27 kg
Oxalic acid | as 0.5M solution	7.5 kg
Facility, consisting of:	**10.6 MT**
Reactant containment vessels	3.1 MT
Crushers [39]	7.5 MT
TOTAL	**10.7 MT**

Table 2. Mass analysis of THOREX facility.

2.6 Adapting to Lunar Operations

Adapting THOREX to the lunar environment requires re-analysis of key assumptions. A select list of challenges, along with proposed solutions, is presented in Table 3.

Challenge	***Symptoms***	***Solution***
Temperature (-200 to +250° C over full day/night cycle)	Stress on electronics, risk of freezing or boiling (of chemical constituents)	Controlled environments and utilization of heat by-products (skull crucible, radioactive decay, etc.)

Low gravity (~ 17% Earth's)	Inefficient gravity-driven processes	Multi-stage crushing & sorting
Limited space (components require housing and shielding)	Inability to perform certain operations (i.e. heap leaching)	Controlled environments and small batch processing

Table 3. Challenges & solutions for lunar-based THOREX.

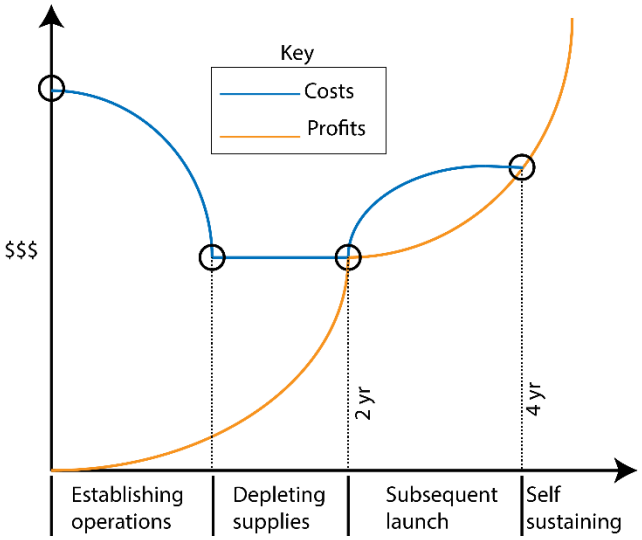

Figure 1. Generic cost-analysis for fission fuel processing operations

2.7 Hydrogen Collection and Storage

Hydrogen reaction mass for the NTR can be stored as a solid-state adsorbate on catalytically-modified porous silicon [1-7]. Silicon is 21% of lunar regolith by mass and can be extracted using an isotope separation process [11-14]. Using such purified silicon, the hydrogen storage media can be synthesized using a self-contained apparatus designed for operation on the Moon [8]. By enclosing the crew quarters of a NTR with this storage media, occupants (and electronics) can be protected against space radiation. Recharging the hydrogen reaction mass can be done at many locations within the Solar System, requiring just water ice and an electrolysis system for hydrogen extraction. Recharging catalytically-modified porous silicon requires just 0.8 MPa of hydrogen pressure. At room temperature, or below, the hydrogen remains absorbed. Release requires just 120 °C.

2.8 Reactor Propulsion Design

The NERVA program is used as inspiration for the configuration and design of the reactor core [41]. Of the four models evaluated, two are compatible with the highly-enriched uranium, as described above. Note that the current process is not techincally enrichment, but rather simply concentration; however, the concentration of fissile isotopes qualifies it as "highly-enriched". The two designs considered for our purposes were a small NERVA engine and a large NERVA engine. The small NERVA requires 27 kg of uranium and uses a 1:1 tie-tube to fuel element ratio. The large engine requires 36 kg of uranium and uses a 2:1 fuel element to tie-tube configuration [41]. The smaller of these engines delivers a total of 152.5 MW of thermal power and delivers 33,200 N of thrust using hydrogen reaction mass through a converging-diverging nozzle of area ratio 300:1. As production of uranium improves, moving to the large NERVA engine would be preferable with its higher thrust to weight ratio, and slightly higher specific impulse. Rocket and trajectory calculations were performed based on producing 27 kg of U-233 within four earth years.

2.9 Thrust

The mass of hydrogen required for a trip from Earth orbit to Mars orbit is calculated using the Tsiolkovsky rocket equation using an exhaust velocity of 8829 m/s [41]. The velocity change (Δv) required is calculated with the vis-viva equation (also known as the orbital-energy-invariance law) and assumes a minimum-energy Hohmann transfer [43]. Momentum and energy were used to calculate burn time and power delivery rate. The quantity of hydrogen, and also, the mass of silicon, needed to reach Mars is very high. The total launch mass can be reduced by combusting oxygen with the hydrogen as it exits the reactor core. Called LANTR (liquid oxygen-augmented nuclear thermal rocket), this approach offers a greater thrust and lower tank storage volume, albeit with a reduced specific impulse. Speficially, with an oxygen/hydrogen mass ratio of 7:1, one can achieve a thrust increase of 440% with only a 45% reduction in I_{sp}. Importantly, the tank volume decreases significantly [40].

2.10 Fuel and Reaction Mass Delivery to Customers

Three major options are considered for delivery of fission fuel (U) and reaction mass propellant (H). Each scenario anticipates rendevous in low lunar orbit (LLO). This architecture avoids an excessive need for hydrogen to lift from the lunar surface, and obviates the need for a deep space vessel to withstand the stresses of lunar gravity. The options to loft the U and H are:

1. Chemical booster to LLO
2. Reusable NTR tug from surface to LLO
3. Modular propulsion system, self-delivered to LLO

Low lunar orbit here is assumed to be 100 miles above the surface.

2.11 Operations

Hydrogen is drawn from the storage tank by heating, which is convenient for a nuclear thermal rocket having ample heat. Released hydrogen at about 8 bar pressure must be pressurized so as to flow through the fission core, which heats and expands the H_2 gas. The preferred blower is a sealed, oil-free system having a compression ratio of 10 or greater. The hydrogen flow into the reactor is then split such that one-fifth of the cores send out hydrogen into a loop that passes through a heat exchanger and then returns back into the reactor to be heated, and optionally mixed with oxygen. A suitable nozzle design directs the exhaust and provides vectorable thrust to the spacecraft.

The thermal energy generated by the reactor core, in addition to releasing hydrogen from the storage media, is also used to generate electrical power for baseload use throughout the spacecraft. Radiators are needed to cool down the working fluid after it passes through a primary heat exchanger. A secondary heat exchanger may be used to mitigate the risk of fluid loss upon micrometeorite penetration. Radiators outside the main body of the rocket cool the working fluid by radiative heat transfer to the deep sky.

3. RESULTS

3.1 Skull Crucible Heating Analysis

Assuming the initial temperature of regolith to be -17 °C and ambient temperature of the lunar surface at night to be -195 °C, a Cold Crucible RF heater requires 1.621 MWh of energy, with a variable power range of 51 kW to 243 kW as shown in Figure 2, to bring 90% of 1,861 kg of regolith to 2250 K in 20 hours. To form a skull around the molten regolith with a thickness of 6 to 7 cm would require an average of 270 W of heat removal power and 6.2 kWh of energy which can be achieved with a maximum mass flow rate of 0.0082 kg/s of water mixed with glycol (30-40%) operating between 260K and 269K [16-18].

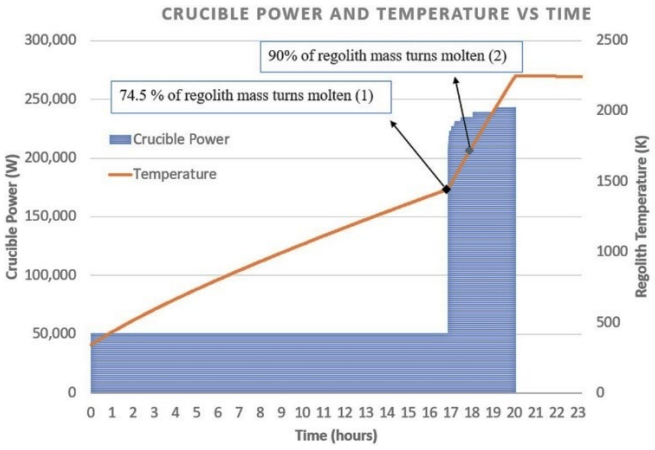

Figure 2. Thermal power absorbed, and temperature of regolith versus time after start of heating.

With an assumed thorium abundance in the regolith of 20 ppm [38], a total of 734 cylindrical charges, of two meters diameter and two meters height, are required to obtain 27 kg of thorium. The total energy required is 1.2 GWh. The apparatus mass is 290 kg, which includes the transformer, induction coils, and a shape-holding exterior crucible made of alumina. With just a single apparatus the time required to produce this quantity of nuclear fuel is 613 earth days. Clearly, shorter durations are obtained with more skull crucible systems, although additional power will also be required.

3.2 Resource Extraction Facility Analysis

The skull heating runs using the above dimensions and concentrations amount to 1937 iterations, and require an average baseload power of 20 kW. With continuous sunlight, this requires most of two years with a 10.7 MT landed mass. With two facilities operating at 50% capacity, the landed mass, net of operators and excavators, is 21.4 MT and produces 27.3 kg of U-233 within 612 earth days.

3.3 Masses of Hydrogen and Oxygen

Velocity change from LLO to low Mars orbit is 3410 m/s and the exhaust velocity of the small NTR is approximately 8829 m/s [41]. From the rocket equation, this gives us a wet mass to dry mass rations of 1.47. With a dry mass (rocket plus payload) of 400,000 kg, this would require 188,600 kg of hydrogen propellant. From our initial and final masses and velocities, we find that the total change in momentum is 1.06 x10^9 kg-m/s. With the small NERVA thrust of 33.2 kN, this gives a burn time of 8.83 hours.

One method for reducing the amount of hydrogen is the use of liquid oxygen to combust with the hydrogen in the nozzle chamber. Figure 3 is a graph on the effect of oxygen on the mass of required hydrogen.

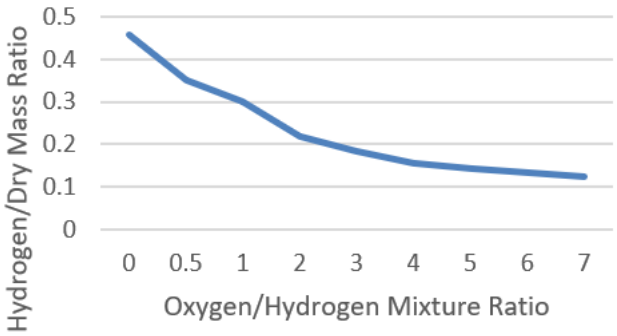

Figure 3. Oxygen effect on hydrogen mass ratio

The hydrogen can be reduced from nearly half of the dry mass, to as low as 12%. This would be about 48,000 kg of hydrogen with our system. Oxygen as LOX is 7 times the hydrogen mass, or 336 MT. Because the solid-state hydrogen storage is approximately 5.8% hydrogen by mass, the displaced hydrogen is 188.6 – 48 = 140.6 MT, and requires 2,424 MT of silicon. Assuming the LOX storage system is 25 percent structural mass (http://www.uigi.com/largetanks.html), this is 1,317 MT for a total of 2,144 MT for H_2 plus O_2 with their attendant storage systems. This is a mass savings of 35 percent relative to hydrogen reaction mass alone. Thus, the LANTR thrust system allows for faster transit and higher payload mass than traditional NTR alone.

3.4 Customer Delivery in LLO

Of the three potential methods for delivering our fuel and propellant to customers, the best for our purposes would be the use of a reusable chemical engine. This avoids the necessity of a higher amount of initial uranium and is easier than completely assembling our nuclear engine on the lunar surface.

The delivery of 188,000 kg of hydrogen reaction mass and 27 kg of fission fuel to LLO requires an additional 115,000 kg of propellant for the chemical rocket. Eventually, a second NTR system will be used for delivery. This would require a lesser mass of propellant (54,000 kg), and will be a second-generation goal. Both options are preferable to having the customer land on the moon and taking off as that would require 309,000 kg of pure hydrogen propellant. Clients will launch a NTR system from Earth in an upper stage, but without any radioactive components. The delivery from the lunar surface will launch, and meet their NTR system in LLO. Once docked, our fuel rods can be placed into the core of the NTR and the filled hydrogen storage tanks can be transferred.

3.5 Reactor Subsystems, Fluid Flow, and Heat Dissipation

Refering to figure 4, the hydrogen flow system has been designed in such a way that the pipes remove the hydrogen from the tanks (1) through inductive heating. Exit pressure of 116 psia hydrogen enters a compressor pump (2), specifically a guided rotor compressor, and exits the compressor at a pressure of 1500 psia. This high pressure hydrogen is then temporarily stored in a surge tank (3) to be used when thrust is demanded. From the high pressure tank (3) the hydrogen then flows into the reactor core (4) after passing around the nozzle (6) to ensure it remains cooled. The hydrogen then splits before flowing through the reactor core (4), $4/5^{th}$ of the hydrogen flows through the reactor (4) to the combustion chamber (5) where it mixes with oxygen at a suitable ratio, is ignited, and then flows out of the nozzle (6), producing thrust. The remaining $1/5^{th}$ of hydrogen flows through the reactor core (4) and then into a heat exchanger (B) that transfers the thermal energy to the secondary thermal fluid. The hydrogen then returns to the reactor core (4) where this circulation process repeats.

For the heat dissipation system and energy generation when thrust is not required, a secondary fluid system is considered, due to concerns of loss of gasses due to micrometeorite impacts on the radiator panels. After studies into the different heat capacities, density, viscosity and other properties, liquid water was selected as the secondary fluid due to its higher heat capacity and lower density compared to the other fluids and low flow rate of liquid required to absorb the 32 MW. The water begins at the water storage tanks (A) and then the flow of the water is split and directed into the compressor (2) to cool it and the remaining flow is directed toward the heat exchanger (B) where it absorbs the thermal energy from the hydrogen. The water from the heat exchanger then flows into the turbine (C) where thermal energy is converted into electrical energy in the generator (F), the flows combine and flows through the compressor (D). The water then finally flows into the radiator (E) where it cools down and returns into the loop. The oxygen flows from the oxygen tank (7) directly into the combustion chamber (5) and out through the nozzle.

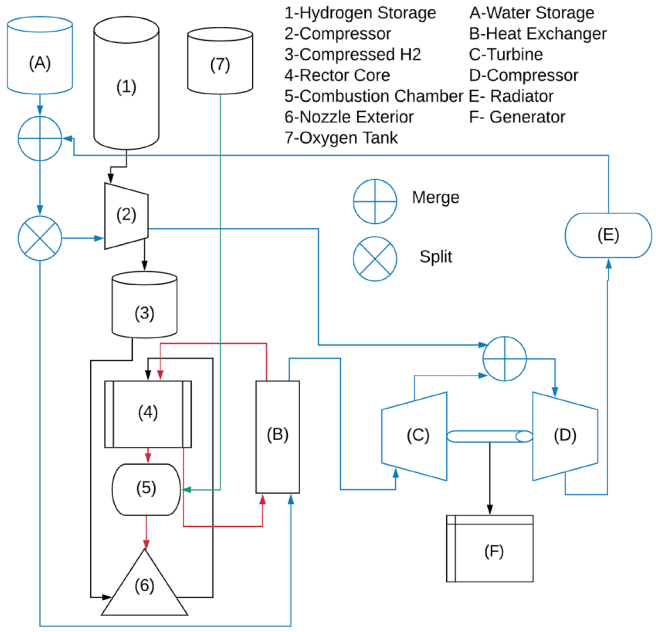

Figure 4. Fluid Flow Diagram

The design of the radiators a carbon composite type radiator follows from the work done by Tomboulian, et al. Considering 32 MW of thermal energy to be removed from the secondary fluid, and each radiator panel of width 4.0 meters, thickness of 0.01 meters and length of 5.0 meters, the area available per fin and each fin working at an efficiency of 50% due to overlap of area of dissipation from each fin requires a total of eight fins. The fins are designed to be simple and extendable when the engine exits earth's atmosphere. A side sectional view of the radiator used is given in figure 5.

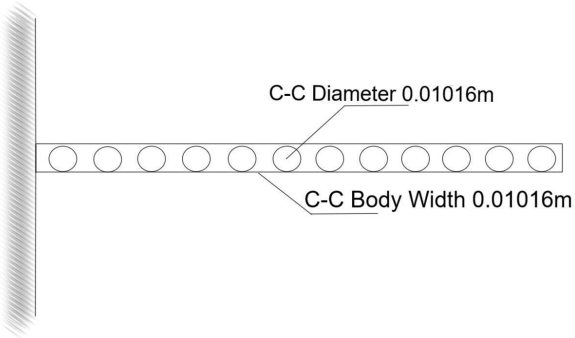

Figure 5. Radiator panel side cross section.

Galactic Cosmic Rays (CGR) are highly energetic photons, subatomic particles and nuclei filling space and coming from every direction. The energy per particle ranges from 1E7 eV to 1E20 eV, although the flux density (particles per square meter per second) falls off exponentially from low to high energy. Figure 6 illustrates how the intensity of 1E7 eV CGR particles are attenuated as a function of the thickness of various shielding materials. Of interest here is the attenuation due to hydrogen and silicon, as these comprise the fuel storage system for the NTR. With a 0.058 w/w ratio of hydrogen to silicon it is apparent that silicon offers excellent radiation protection benefits for a reaction mass storage system based on porous silicon.

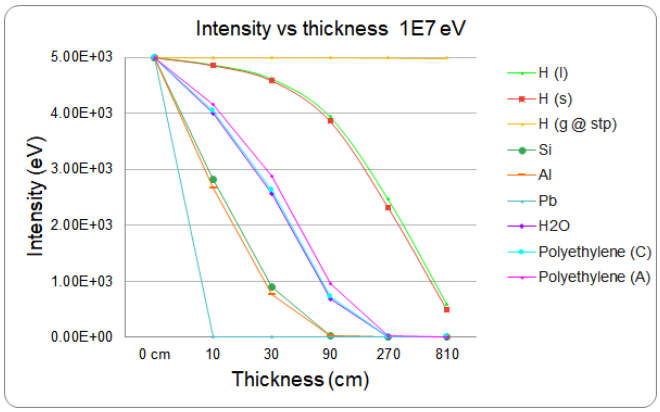

Figure 6. GCR intensity versus thickness of various shielding materials for most-common energies.

A spherical crew volume surrounded by a spherical shell of hydrogen reaction mass stored in porous silicon will reduce GCR flux dramatically. A Hohman transfer from lunar orbit to Mars orbit for a 417 MT spacecraft requires 140.6 MT of hydrogen. The thickness of the hydrogen storage shell depends on the crew volume, so the smaller the volume, the thicker the shell, and the greater the protection against GCRs. Calculations were based on GCRs of 1E7 eV at a flux of 5000/m^2-s through a human body with average cross section of 0.6 square meters, and a relative biological effectiveness of 2.0, for bare protons, which comprise 85% of the GCR flux. In the US, the Occupational Health and Safety Administration goes by Title 10, Part 20 of the Code of Federal Regulations and calls for a limit of 5 rem per year. With no protection, this limit is reached in less than one week spent in interplanetary space. To meet the OSHA requirements, the GCR flux must be reduced to a 0.0168 fraction. The figure below shows the protection provided by the hydrogen storage system as a function of the volume of crew space for a crew of four transiting from Moon orbit to Mars orbit. Faster ships with more fuel provide greater protection.

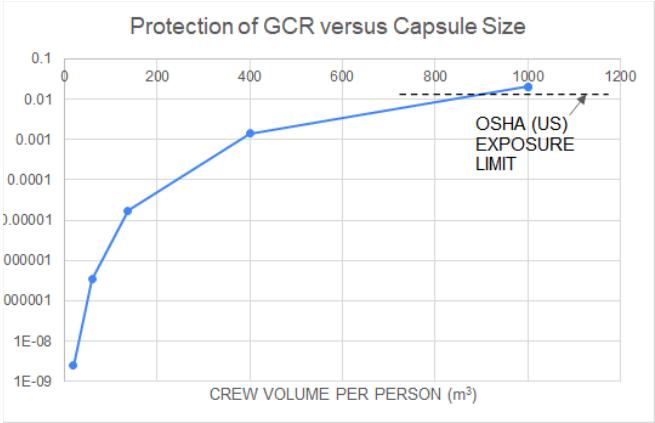

Figure 7. Relative flux reduction from reaction mass storage system versus volume per person, with crew of four.

DISCUSSION & CONCLUSION

Fast, safe transport around the Solar System will require nuclear thermal rockets (NTR). An NTR requires fissionable nuclear fuel and reaction mass to produce thrust. These should not come from Earth because of the hazard risk of launching radioactive materials in rockets, and because of the poor economics of launching many tons of reaction mass through the atmosphere. This study explores the use of lunar resources to synthesize uranium oxide fission fuel pellets, hydrogen from water ice in polar craters, and storage of hydrogen in porous silicon. These products are launched into low lunar orbit (LLO) and fitted into a machine built on earth, which now becomes a NTR. Within about four years, a lunar facility can produce sufficient quantities to provision a large NTR carrying a crew of four to Mars orbit, quickly, with minimal exposure to cosmic radiation. Established practices such as density sorting, transmutation, nuclear fuel processing, porous silicon synthesis, and electrolysis taken together allow for a cislunar infrastructure which underpins a system-wide commercial sphere.

Commercial development of space resources and scientific exploration of space are greatly aided by lunar-fueled NTRs. This approach is called “ultra-safe” for the following reasons:

1) No radioactive material is launched from Earth
2) No radioactive material comes within 360,000 km of Earth.
3) Radioactive byproducts decay to safe levels in about 80 years.
4) Space radiation is nullified when the reaction mass storage system surrounds the crew cabin.
5) Transit times are reduced, requiring less supplies, and presumably fewer equipment failures.
6) Hydrogen is stored in a solid state, which cannot boil-off like liquids, or burst like compressed gases.

The technologies described herein rely on simple excavation equipment capable of digging nine meters into lunar soil which is like sand and gravel. Skull crucible heating concentrates dense phase refractory material such as thorium dioxide. Transmutation to fissile uranium is possible using naturally-occurring gamma rays from the deep sky. An adapted THOREX/UREX process extracts uranium, which is calcined into oxide and then pressed into fuel pellets. Hydrogen electrolyzed from water mined from permanently-shadowed regions (polar craters) on the lunar surface can be stored for long durations in porous silicon which was itself extracted from lunar soil. A NTR returning from a six-month mining mission to the Asteroid Belt with a load of platinum can return to LLO, refuel quickly with hydrogen, swap crews and payload, and be ready for its next run. The transformative power of these capabilities to the human economic universe is considerable. By also making it safe, this approach has great potential for bringing success to those who implement.

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CONFLICTS

The authors declare no conflicts.

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