CAN WE BUILD NUCLEAR-ELECTRIC PROPULSION SYSTEMS FROM LUNAR RESOURCES?

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Introduction: The two-week lunar night presents challenges for power generation/storage on the Moon. Extensive electrical power will be required during the lunar night to support lunar habitats [1] and ecologically closed loop life support systems [2]. We explore the construction of nuclear reactor power on the Moon from in-situ resources. Furthermore, our solar system exploration infrastructure must be sustainable. It has long been proposed that mass drivers can provide launch capabilities from the Moon's surface to lunar orbit [3], perhaps to the Gateway. This trades renewable electrical power supply [4] for a Δv of 3.7 km/s against consumption of locally-mined scarce LH_2/LOX from the lunar poles. For in-space propulsion, we can replace LOX/LH_2 or CH_4/O_2 chemical propulsion with nuclear-electric propulsion. For example, the Δv to get to Mars is 3.0 km/s requiring 568 tonnes LH_2/LOX for the Mars Design Reference Architecture 5.0. If nuclear-electric propulsion is employed using an ion engine burning O_2 sourced from lunar minerals, we require only 110 tonnes O_2 *ceteris paribus*, i.e. less than 20% of the fuel. We therefore explore the construction of ion engines from lunar resources. Together, they would constitute a nuclear-electric propulsion system sourced from lunar resources.

Nuclear Fuel Resources: High resolution mapping of lunar U (1764.5 keV) and Th (2614.5 keV) gamma rays have revealed an average ~0.3 ppm U (with large variations of up to 2 ppm especially at Procellarum KREEP basaltic terrane (PKT)) and ~1-2 ppm Th (with large variations of up to 7 ppm at PKT and average U/Th ratio of 0.27 similar to that of chondrites ~0.28) [5]. Change-2's measurements of Th abundance yields higher concentrations within the Imbrium basin at PKT at >3 ppm and high concentrations up to 7.5 ppm Th due to the Fra Mauro Highlands [6]. Elevated Th abundances occur near the Ingenii basin at 3.5 ppm and an anomaly in the farside highlands at the Compton-Belkovich region with 9 ppm [7]. Rare earth elements in lunar KREEP deposits under Oceanus Procellarum and the Imbrium Basin have abundances of 180 ppm Nd and 65 ppm Dy [8]. They resemble their terrestrial counterparts but often with substitutions – apatite ($Ca_5(PO_4)(F,Cl)$), merrillite ($Ca_{17.3}Y_{0.4}(La\text{-}Lu)_{0.88}(Mg,Mn,Fe)_{2.4}(Na,K)_{0.07}(P,Al,Si)_{13.9}O_{56}$), monazite ($(REE,Th,Ca,Sr)(P,Si,S)O_4$), xenotime ($(REE,Zr)(P,Si)O_4$), yttrobetafite ($(Ca,Y,U,Th,Pb,REE)_2(Ti,Nb)_2O_7$ up to 9.45% Y) and tranquillityite ($Fe_8(Zr,Y)Ti_3Si_3O_{24}$ up to 4.6% Y and 0.25% Nd) [9]. Apatite, merrillite and monazite are the commonest rare earth sources and are found in association with each other in all KREEP deposits. They are enriched in U and Th – in yttrobetafite, U is in 38,200 ppm concentrations. Assuming a common terrestrial isotopic ratio $^{235}U/^{238}U$ ~0.72%, lunar U resources yield a ^{235}U peak concentration of 0.014 ppm. Oceanus Procellarum exhibits around ~10 x 10^{-6} g/g of Th [10]. The abundance of thorium on the Moon offers the most obvious nuclear fuel by mining ThO_2 and transmuting it to fissile uranium [11]. Natural Th is almost 100% fertile ^{232}Th isotope with a half-life of 14 By. Th may be extracted chemically from monazite $(RE/U/Th)PO_4$ with 6-7% Th which is ground, for a series of treatments to precipitate out thoria ThO_2 [12]. This requires dissolution in NaOH at 400-500^oC followed by treatment with hot concentrated HCl to dissolve rare earths. $Th(OH)_4$ is precipitated and calcined at 900-1000^oC into ThO_2. NaOH and HCl reagents are already incorporated into the lunar industrial ecology.

Lunar Nuclear Fission Reactor: ^{232}Th must undergo slow neutron irradiation to decay into ^{233}U: ${}^{232}_{90}Th(n,\gamma){}^{233}_{90}Th \xrightarrow{-\beta} {}^{233}_{91}Pa \xrightarrow{-\beta} {}^{233}_{92}U$. This is a breeding process that can be accomplished in a slow neutron thermal reactor with a neutron moderator. The Magnox reactor uses natural uranium fuel without enrichment within Mg-0.8Al-0.004Be (magnesium non-oxidising) alloy cladded fuel rods embedded in graphite bricks as the neutron moderator and hot CO_2 gas coolant at 4.3 MPa pressure with cladding tolerance imposing <450^oC operating temperatures. Magnox was designed as a breeder reactor for generating ^{239}Pu from fertile ^{238}U so conversion to breading fertile ^{232}Th into fissile ^{233}U is simple. Heating the organic fraction of carbonaceous chondrites at 700^oC will release organic volatiles that may be oxidised in O_2 to CO_2 and water. Al may be sourced and extracted from lunar anorthite [13,14]. Mg has low neutron absorption cross section while Be reduces the tendency to oxidation – the 0.004% Be may be omitted because it serves to reduce oxidation sensitivity which may be counteracted by adding small amounts of CH_4 into the coolant to prevent CO production – CH_4 may be generated from CO_2 at 400^oC through the Sabatier reaction with an Ni-on-alumina catalyst as often proposed for Mars ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) [15]. Impure lunar forsterite may be treated with HCl acid: $Mg_2SiO_4 + 4HCl + 4H_2O \rightarrow 2MgCl_2 + H_4SiO_4$. Silica may be precipitated from silicic acid. $MgCl_2$ may be treated with NaOH: $MgCl_2 + 2NaOH \rightarrow Mg(OH)_2 + 2NaCl$. $Mg(OH)_2$ heated to 600-800ºC yields MgO: $Mg(OH)_2 \rightarrow MgO + H_2O$. MgO may be reduced directly into Mg metal through FFC molten salt electrolysis [16]. Magnox control rods are 316 austenitic stainless steel (67% Fe, 18% Cr, 10% Ni, 2% Mo, 2% Mn and <1% S) which is an effective gamma ray shield. Fe may be sourced from the lunar mineral ilmenite ($FeTiO_3$) and Ni from NiFe meteoritic material. For the critical properties of Cr, we require an extension of the lunar industrial ecology [17] to incorporate Cr mining and extraction from lunar chromite ($FeCr_2O_4$) if necessary. Mo and Mn which increase hardness may be dispensed with through design accommodation. Control rod design may be improved by incorporating powdered Co within 316 steel tubes which act as "neutron windows". These may be mixed with ytterbium- and yttrium-containing xenotime as neutron absorbers without separation being necessary. Reactor vessel containment materials and pipework include corrosion-resistant 316 stainless steel among others rated to 20 bar [18] which may be mechanically alloyed oxide (silica and/or alumina) dispersion strengthening steels with 1% ultrafine oxide powder to reduce neutron embrittlement [18], stable up to 650ºC. The thermal efficiency of the Magnox reactor is 25-30% using the CO_2 Brayton cycle.

Electric Propulsion: An oxygen-fuelled Hall effect thruster has been developed yielding thrust of 27 mN and I_{sp} of 2874 s with a power rating of 2238 W [19]. It had an optimum channel length of 13.1 mm that trades length of the ionisation region against energy losses due to wall-plasma interactions. Although BN/$BNSiO_2$ wall material improves performance by 40% due to lower secondary electron emission over Al_2O_3 wall material, the latter is available from in-situ resources [13] or substitutable with SiC. Anode material must not form a non-conductive oxidative layer from the oxygen plasma thereby compromising anode function. 316 stainless steel developed a thin oxidised layer that is conductive and permits anode function for long-term operation. Although thrust is low, these Hall effect thrusters may be arrayed to generate higher thrusts.

Mg fuel may be extracted from the lunar olivine forsterite. A benchmarked Mg-fuelled thruster gave higher I_{sp} of 2700 s than a similar Xe-fuelled thruster at 1550 s [21]. A Hall effect thruster using Mg solid anode fuel that sublimes into a plasma when heated at 450ºC has been demonstrated with an I_{sp} of 4000 s [20]. In gridded ion thrusters, the most significant limit is on grid erosion due to fuel ion sputtering. Ion thruster grids are typically constructed from molybdenum or carbon-carbon. A metal propellant was used in a metal (Mg) ion thruster-magnetron electron bombardment (MTI-MEB) which was bombarded by an electron beam to generate metal ions [22]. A hot ~1300ºC tungsten filament cathode generated thermionic electrons within a ceramic chamber. An electric potential of 1-5 kV accelerated the thermal electrons to higher energies to ionise the metal gas. An Nd permanent magnet ~0.15-0.25 T guided the electrons to the metal target (substitutable with AlNiCo magnets). The metal ions were accelerated through an accelerator grid to generate thrust. A neutraliser downstream of the accelerator grid neutralised the ions.

Conclusions: It appears feasible to manufacture a nuclear electric propulsion system from lunar resources given certain requirements and constraints.

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