Nuclear Fuel Resources of the Moon:

A Broad Analysis of Future Lunar Nuclear Fuel Utilization

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Abstract

The potential lunar energy resources of various nuclear fission and fusion fuels are analyzed. The much vaunted ^{3}He is compared to uranium, deuterium, thorium, and lithium as a source for tritium. We find that fissile fuels along with tritium bred from lithium can provide up to 2 orders of magnitude more energy than either ^{3}He or deuterium fuels by themselves. This information may prove useful for planning any large scale settlements of the lunar surface or use of the lunar surface for support of large scale space industry.

I. INTRODUCTION

As plans for human lunar missions and lunar bases continue to get funding and national support [1], the discussion of lunar resources has come to the forefront yet again. Although this discussion is primarily focused on lunar water resources for chemical fuel and life support [2], the possibility of extracting nuclear fuel in the form of the isotope ^{3}He has been mentioned yet again [3]. Lunar ^{3}He is the resource commonly discussed in the public and science fiction, but the lunar surface also contains a variety of potential nuclear fuels such as uranium, thorium, deuterium and lithium [4–7]. To properly discuss nuclear fuel extraction on the Moon, it is important to look into potential extractable resources and the maximum theoretical amount of energy that can be extracted from said resources. This paper will not dive into the respective difficulty of using each nuclear fuel except to note that nuclear fission is currently used to provide power around the world, while nuclear fusion is still in the research and development phase and is almost entirely focused on the much easier to ignite deuterium-tritium (DT) reaction [8–12].

II. LUNAR ^{3}HE

^{3}He has been a focus of lunar nuclear fuel extraction for many years now due to the relative rarity of ^{3}He on Earth, and the favourable characteristics of the two potential fusion reactions that it can sustain [3, 8]. When reacted with deuterium, the deuterium-^{3}He (D^{3}He) fusion reaction only produces charged particles in the primary chain ($D + {}^3He \rightarrow {}^4He + p + 18.3\,MeV$) and is considered an advanced potential fusion fuel that requires more extreme conditions than the current fusion fuel of focus, deuterium-tritium (DT). Secondary reactions during the burn of D^3He do make neutron radiation, but far less than the other more near term potential fusion fuels. D^3He fuel has an energy density of 3.53E+08 MJ/kg [3, 8], which is the highest of all nuclear reactions that are commonly considered for energy production.

The other potential fusion reaction using this fuel is ^3He-^3He ($^3He + {}^3He \rightarrow {}^4He + 2p + 12.9\ MeV$), which requires even more extreme conditions but has the benefit of not only emitting zero neutrons in the primary reaction, but also not having any secondary reactions that emit neutrons [3, 8]. Tertiary reactions and low probability secondary reactions may still create neutrons, but at far lower rates than most other fusion fuels. This fuel mix has an energy density of 2.07E+08 MJ/kg [3, 8] but does require twice as much of the rare ^3He isotope and much more extreme temperatures.

Lunar ^3He is deposited in the soil from the solar wind and is found at ~ 4.2 ppb or 0.007 g/m^3 of lunar regolith on average [3, 6] with higher concentrations on the order of 20 ppb found in Mare Tranquillitatis and Oceanus Procellarum due to the rich titatnium despoits found there. Volatiles such as ^3He are expected to be roughly evenly deposited through the first couple meters of lunar soil due to the slow churn of the lunar surface. At the absolute extreme if the surface of the Moon were to be strip mined 3 meters deep and processed for ^3He roughly 7.98E+05 tons of ^3He could be expected to be extracted. The richer resources mentioned above may add another ~2E+05 tons to this total.

Assuming perfect burn-up with the ^3He-^3He reaction, there is ~57.5 million TWh (one TWh is 3.6E+09 MJ) of available nuclear energy in the form of ^3He in the lunar surface. This is nearly 500 years of the current world primary energy consumption [13]. If we utilize the D^3He reaction then there is ~163 million TWh of energy available assuming deuterium is also mined for use. This translates to roughly 1400 years of current world primary energy consumption. It is important to note though that considerable energy will be needed to mine the lunar soil, heat it to over 700 C to extract the volatiles, separate the ^3He, and then transport it to Earth for use in fusion reactors that do not yet exist [3, 6]. As such the comparison to primary energy usage of Earth is not being done to advocate for lunar nuclear fuel (^3He or otherwise) use on Earth, but as a common metric to compare each lunar nuclear fuel resource to.

III. DEUTERIUM RESOURCES

Deuterium is useful in three potential fusion reactions: deuterium-tritium (DT) fusion, deuterium-^{3}He (D^{3}He) fusion, and deuterium-deuterium (DD) fusion [8, 9]. DT and D^{3}He are looked into in other sections, so we will focus on DD fusion here. There are two potential reactions with one generating a neutron and a ^{3}He ion ($D + D \rightarrow {}^3He + n + 3.27\ MeV$) and the other path generating a proton and a tritium ion ($D + D \rightarrow T + p + 4.03\ MeV$). If these extra nuclear fuel ions are allowed to escape then the DD reaction has an averaged energy density of 8.8E+07 MJ/kg [8]. However, if one or both species of usable fusion fuel (both the tritium and ^{3}He) can be kept in the reactor and used, then the reaction (known as catalyzed DD fusion) rises in energy density to 3.47E+08 MJ/kg [10] . Catalyzed DD fusion is considered a more difficult challenge than more typical DD fusion, and both are considered an advanced fusion fuel just like D^{3}He and as such are not the focus of current large scale fusion research.

Deuterium is found on the Moon in three forms: in lunar ice, in water trapped in the lunar soil, and in hydrogen trapped in the lunar soil from the solar wind [6, 14]. The lunar D/H ratio varies quite widely depending on the source of the hydrogen in question, but we will use a median value of 7E-05. There is a high end estimate of ~2.1E+09 tons of lunar ice available on the surface [6], which is of great interest for producing rocket fuel as well as oxygen and water for manned missions. In addition to these ice resources there is also water directly trapped in the soil of the Moon in the form of hydrated minerals at roughly 10 ppm on average [6], although specific locations can hold far more. The solar wind also deposits hydrogen into the lunar regolith in a manner similar to the ^{3}He. The average concentration is 46 ppm or 76 g/m^3 with some potential for richer deposits in the lunar poles [6]. Using the same logic as ^{3}He extraction (i.e. strip mining the entire lunar surface 3 meters deep) as well as complete extraction and processing of the polar ice deposits, we find that ~2E+06 tons of deuterium could be extracted from the Moon. This is enough deuterium to allow for complete lunar fueling of D^{3}He reactors or to act as fuel for pure DD reactors.

For the typical DD reaction, this ~2E+06 tons of deuterium translates to almost 41 million TWh of primary energy. Catalyzed DD has the potential to produce 161 million TWh of primary energy. This is roughly 1380 years of world primary energy consumption at current rates [13]. Thus there are roughly equivalent lunar nuclear energy resources when comparing deuterium and ^{3}He and both fuels are liable to be extracted together from processed regolith.

IV. LITHIUM RESOURCES

Unlike the previous nuclear fuels mentioned, lithium is not directly usable in an energy producing reaction outside of some exotic fusion proposals [8]. Instead, lithium is fertile material that can be used to breed tritium for use in DT fusion reactors [8–12]. DT fusion has the easiest to obtain fusion ignition conditions and is considered the reaction most likely to fuel any near term fusion reactors. Extensive research has gone into DT fueled reactors and this technology is the closest to achieving fusion ignition and commercial utilization of all potential fusion fuels. Since tritium is a radioactive form of hydrogen with a very short (~12 year) half-life, it must be produced via some external means [12]. Notably, tritium decays into ^{3}He and could possibly serve as another source for ^{3}He on the Moon, however this is not considered in this analysis as such a scheme would require an external neutron source to function. When lithium is bombarded with neutrons it undergoes a fission reaction that generates one alpha particle, one tritium ion, and potentially either an extra neutron ($n + {}^7Li \rightarrow T + {}^4He + n - 2.467\,MeV$) or extra kinetic energy in the ions ($n + {}^6Li \rightarrow T + {}^4He + 4.784\,MeV$) depending on the isotope [8–12]. Luckily every DT fusion reaction makes a neutron, so a sustainable breeding scheme can be achieved once the reactor is started up, although a mild neutron multiplier (often beryllium) is mixed into the lithium to make up for neutron losses [12]. This multiplier material is not included in this analysis of potential lithium to tritium resources, nor is the potential boost in energy produced from ^{6}Li included. DT fusion also has a very high energy density of 3.39E+08 MJ/kg [8] which further increases its attractiveness compared to other fusion fuels.

Lithium is present in the lunar soil at roughly 12.9 ppm on average [7]. This is roughly an order of magnitude less than current lithium brine concentrations, but conceivably extractable with aqueous methods [15] and as such lithium extraction will mostly likely be closely tied with lunar water extraction. If the same lunar surface strip mining assumptions as for ^{3}He are used then ~221E6 tons of lithium can be extracted from the lunar surface. Every lithium atom can generate one tritium atom [8, 12], so there are potentially ~96E6 tons of tritium that can be created. This is significantly more than the available deuterium, so a pure lunar DT fusion economy would be deuterium limited.

If we assume only lunar supplies of lithium to tritium and deuterium, the total available energy is ~393 million TWh, which is over two times the amount available from any form of ^{3}He or deuterium based fusion. If external deuterium supplies are brought in, then the total extractable energy from DT fusion becomes ~9030 million TWh! This is over fifty times more energy than the available energy from any of the other reactions and represents over 77,000 years of world primary energy consumption [13] while also using a fusion fuel that is much easier to ignite [8].

V. FISSILE RESOURCES

There are two potential fission fuels available on the lunar surface, uranium and thorium [5, 6]. Both can be used as fertile material to breed directly fissionable material [6, 9] rather than require uranium enrichment. This technique has been shown in experimental power production reactors [16], although not at large scale. Although this technology is not fully commercialized, it is far closer to large scale energy production then even the most optimistic expectations for fusion and as such the total energy density of each fission fuel will be used assuming perfect breeding and burning. Uranium is converted to plutonium ($^{238}U + n \rightarrow {}^{239}Pu$) and then fissioned, with a total energy density of 8.06E+07 MJ/kg [9, 17] while thorium is converted into the fissionable uranium isotope ^{233}U ($^{232}Th + n \rightarrow {}^{233}U$) for a total energy density of 7.94E+07 MJ/kg [9, 17].

The lunar surface has been shown to covered with fissionable material and may have even more buried beneath the surface [5, 6]. The average distribution is ~0.3 ppm of uranium and ~1.2 ppm of thorium, although the Copernicus Crater has concentrations nearly an order of magnitude higher (see Figure 1). Analysis on thorium and uranium extraction at similar concentration on Earth has shown it to be energetically favourable with an energy return on investment of at least 400 even with the technology available in the 1950's [18]. Modern mining and extraction techniques may be able to do significantly better as well as capitilize on the lack of crushing needed to processed lunar regolith. If we utilize the same strip mining assumptions as the ^{3}He mining that translates to ~177E6 tons of uranium and ~690E6 tons of thorium available on the lunar surface.

Assuming perfect breeding and fissionable fuel burn-up, the lunar uranium resources can

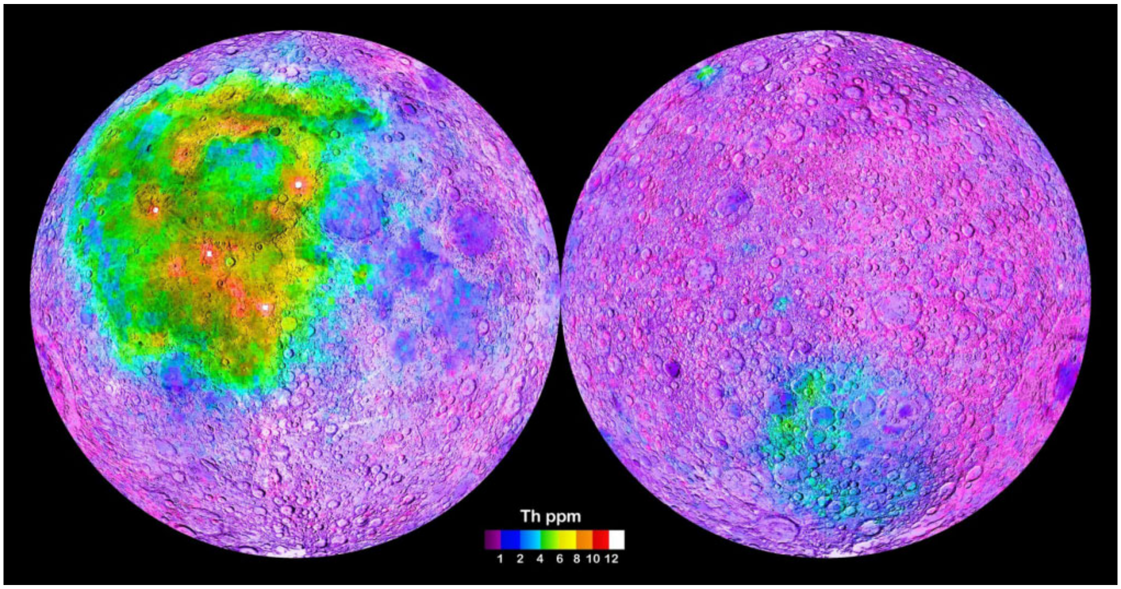

FIG. 1. Surface map of thorium concentrations on the near (left) and far (right) side of the Moon measured using the Gamma Ray Spectrometer on NASA's Lunar Prospector Spacecraft (Crawford, 2006; image courtesy of NASA).

produce ~3960 million TWh of energy which is 10 times more than any pure lunar fusion fuel option. For thorium there is the potential to produce ~15200 million TWh which is 1.5 times more than even the potential energy resources of lunar lithium combined with an external source of deuterium. The lunar fission energy resources are much larger than fusion energy resources and should be considered when discussing future utilization of the lunar resources for space exploration and settlement.

VI. IMPACTS ON FUTURE USE OF THE LUNAR SURFACE

The previous results have shown that the largest pure lunar energy resources are fissionable materials followed by DT fusion as shown in Table 1.

The smallest energy resources available are in the form of deuterium and ^{3}He fusion, which is not surprising considering the relative rarity of helium and deuterium on the lunar surface [3, 6]. Considering that even the much easier DT fusion reaction has yet to reach break-even in a fusion reactor along with the small lunar resources, it seems prudent to take ^{3}He out of the discussion as an energy source for both the Moon and Earth. Additionally,

TABLE I. Comparison of Potential Lunar Nuclear Fuels for Extraction

Fuel	Cycle	Energy Density (MJ/kg)	Lunar resources (tons)	Lunar resources (million TWh)
Th	Th-U233	7.94E+07 [9, 17]	6.89E+08	15200
U	U-Pu239	8.06E+07 [9, 17]	1.76E+08	3960
T	Li-T + External D	3.39E+08 [8]	9.59E+07	9030
T	Li-T + Lunar D	3.39E+08 [8]	4.12E+06	393
D	Catalyzed DD	3.47E+08 [10]	1.67E+06	161
D	DD	8.8E+07 [8]	1.67E+06	41
^{3}He	^{3}He + Lunar D	3.53E+08 [3, 8]	1.66E+06	163
^{3}He	^{3}He + ^{3}He	2.07E+08 [3, 8]	9.98E+05	57.5

if pure deuterium fusion ever becomes a viable energy source, Earth based extraction will be far more prudent due to the far larger amounts of hydrogen present on Earth and higher D/H ratio [14].

Recent progress has also been made on ultra-small fission reactors for use on the Moon [19] and on fission based nuclear propulsion [20] for use in cislunar space. Since both of these technologies have been shown to be operational on the surface of Earth, they are also most likely to be the nuclear technologies in use on and near the Moon for the foreseeable future. Due to the much larger fissile resources and ease of construction of a working fission reactor, it is best to plan on any future lunar nuclear fuel extraction being entirely focused on fission. The complexities of uranium enrichment may necessitate the construction of a fuel breeding cycle on the lunar surface so that both reactors and nuclear fission rockets can be supplied from local materials. Future exoatmospheric nuclear technology research should be focused on the design of extremely compact breeder reactors and reprocessing technology to better utilize these resources. Further down the line there may also be interest in lithium extraction to create tritium for higher performance fusion rockets [11] or fission/fusion schemes that utilize both reactions [21]. Pure lunar resources of lithium and deuterium could refuel an estimated 1.35 million VISTA fusion rocket flights to Mars for instance.

VII. CONCLUSIONS

The lunar nuclear fuel resources were analyzed and found to be dominated by fissile material. Both uranium and thorium provide the potential for tens of billions of TWh of primary energy just based on extraction of dilute fissile material from the regolith. Fusion fuels are present, with a lithium to tritium to DT cycle providing the most potential nuclear energy and the nearest term method of achieving fusion. ^{3}He and deuterium were found to provide far smaller lunar nuclear energy resources, with the best potential option being D^{3}He at a ~163 million TWh compared to the billions of TWh available from fission and DT fusion. As such it is recommended that ^{3}He be excluded from all future discussions of lunar resources. The most likely nuclear fuels to be extracted on the Moon for the foreseeable future are fissionable fuels, followed by lithium. Concepts involving ^{3}He are less compelling in light of these much more numerous resources and the far higher difficulty of utilization of ^{3}He compared to fission fuels and tritium.

ACKNOWLEDGEMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank the ToughSF Discord community for inspiring this paper and for many productive discussions on space settlement and exploration through the years. We would also like to thank the very helpful reviewers for helping create a much better final product with their encouraging comments and critiques.

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