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Atmospheric Mining in the Outer Solar System: Resource Capturing, Storage, and Utilization

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Abstract

Atmospheric mining in the outer solar system has been investigated as a means of fuel production for high energy propulsion and power. Fusion fuels such as helium 3 and hydrogen can be wrested from the atmospheres of Uranus and Neptune and either returned to Earth or used in-situ for energy production. Helium 3 and hydrogen (deuterium, etc.) were the primary gases of interest with hydrogen being the primary propellant for nuclear thermal solid core and gas core rocket-based atmospheric flight. A series of analyses were undertaken to investigate resource capturing aspects of atmospheric mining in the outer solar system. This included the gas capturing rate for hydrogen helium 4 and helium 3, storage options, and different methods of direct use of the captured gases. Additional supporting analyses were conducted to illuminate vehicle sizing and orbital transportation issues.

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)
GCR	gas core rocket
GTOW	gross takeoff weight
H_2	hydrogen
He	helium 4
IEC	Inertial-Electrostatic Confinement (related to nuclear fusion)
ISRU	In Situ Resource Utilization
Isp	specific impulse (s)
K	Kelvin
kWe	kilowatts of electric power
LEO	low Earth orbit
MT	metric tons
MWe	megawatt electric (power level)
NEP	Nuclear Electric Propulsion
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
OC	open cycle
O_2	oxygen
PPB	parts per billion
STO	surface to orbit
UAV	uninhabited aerial vehicle

1.0 Atmospheric Mining in the Outer Solar System

Atmospheric mining of the outer solar system is one of the options for creating nuclear fuels, such as helium 3 (3He), for future fusion powered exploration vehicles or powering reactors for Earth's planetary energy needs (Refs. 1 to 8). Uranus' and Neptune's atmospheres would be the primary mining sites, and robotic vehicles would wrest these gases from the H_2-He gases of those planets. While preliminary estimates of the masses of the mining vehicles have been created (Refs. 1 to 7), additional supporting vehicles may enhance the mining scenarios.

There are vast reserves of potential fuels and propellants in the outer planets (Refs. 1 to 7). While the idea of mining outer planet atmospheres is indeed enticing, the challenges to designing mining vehicles may be somewhat daunting. While past studies related to the Daedalus Project (Ref. 7) have assumed the use of fusion propulsion for the aerostat and aerospacecraft (ASC) that mine the atmosphere and carry the fuel to Jupiter's orbit, nuclear thermal rockets may also allow a more near term propulsion option. While the mass of the NTP options will, in most cases, be higher than the fusion powered options, the more near term NTP vehicle may still be attractive (Refs. 8 to 11), although closed cycle gas core nuclear rockets may provide high specific impulse and high thrust without invoking fusion rockets (Refs. 12 to 22).

During the 3He capturing, large amounts of H_2 and 4He are produced. Analyses were conducted to quantify the mass production rates of these other potential fuels. Also, capturing the H_2 and 4He to fuel additional exploration and exploitation vehicles was addressed. New options for fleets of small and large ASC for exploration and exploitation missions are discussed.

2.0 Resource Capturing Studies

Studies of the gas capture rate and its influence on mining time in the atmosphere were conducted. ASC cruisers have been identified as a "best" solution for atmospheric mining (Refs. 1 to 7). To power these vehicles, atmospheric H_2 gas would be liquefied and used a rocket propellant for the ascent to orbit. Gaseous or liquid H_2 would be used to power the engines during atmospheric mining operations. Figure 1 shows an overall schematic of a closed cycle gas core rocket (GCR) propulsion option. Helium 3 would be separated from the atmospheric H_2 and 4He captured, liquefied and stored as a payload that would be returned to orbit. Table I provides the fraction of 3He in the outer planet atmospheres.

Figure 2 and Figure 3 show the 3He mining time versus the atmospheric capture rate for Uranus and Neptune, respectively. A 500-kg payload of 3He is captured during the mining time.

Figure 4 and Figure 5 provide the sizing of the gas core powered vehicles and a comparison of the solid core and gas core vehicle options, respectively (Ref. 1). The relatively low thrust to weight of the nuclear engines may necessitate the use of a more advanced gas core nuclear engine over the solid core nuclear thermal propulsion (NTP).

TABLE I.—FRACTION OF 3He AND 4He
IN OUTER PLANET ATMOSPHERES

	Uranus	Neptune
Amount of 3He in 4He	1.00×10^{-4}	1.00×10^{-4}
Amount of 4He in atmosphere	0.152	0.19
Amount of 3He in atmosphere	1.52×10^{-5}	1.90×10^{-5}

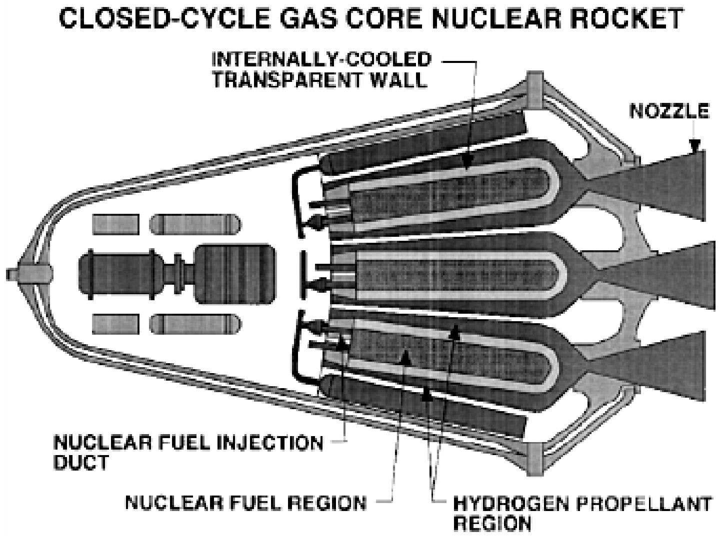

Figure 1.—GCR propulsion for the mining cruiser (Ref. 8). R. Frisbee, "Advanced Space Propulsion for the 21st Century," reprinted by permission of the American Institute for Aeronautics and Astronautics, Inc.

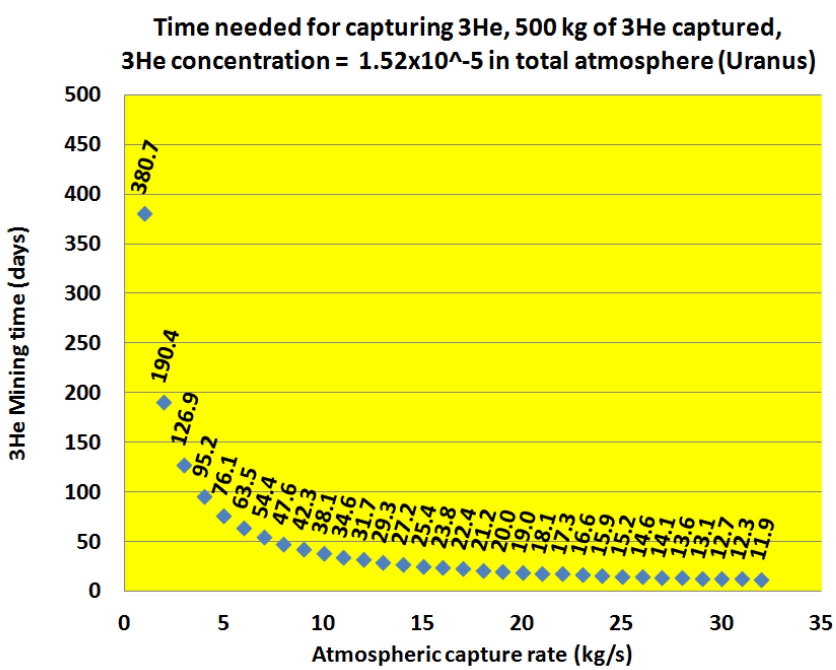

Figure 2.—Mining time versus the capture rate for Uranus.

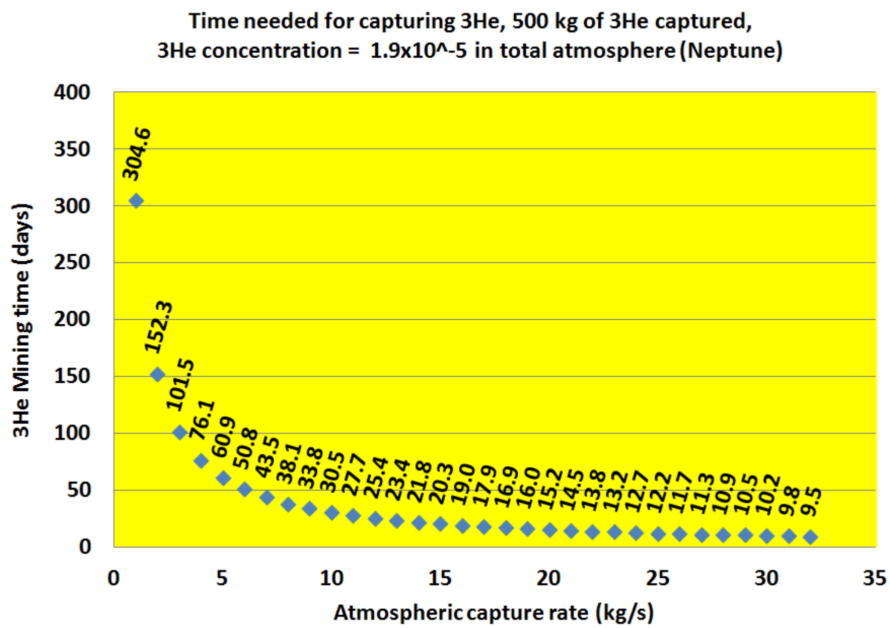

Figure 3.—Mining time versus the capture rate for Neptune.

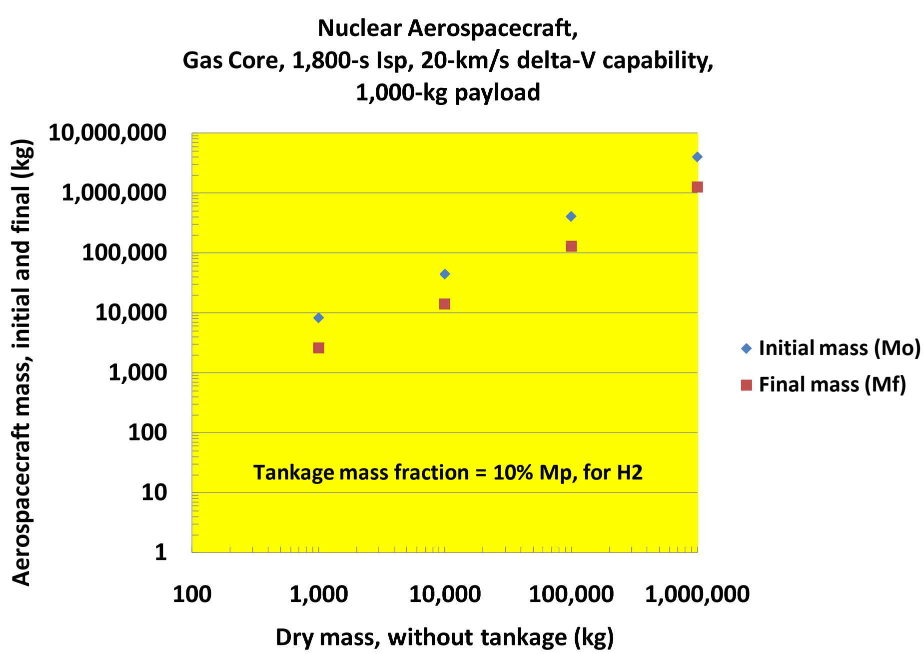

Figure 4.—ASC mass, 1,800-s Isp, Tankage = 10 percent Mp, representative of gas core nuclear propulsion (Ref. 1).

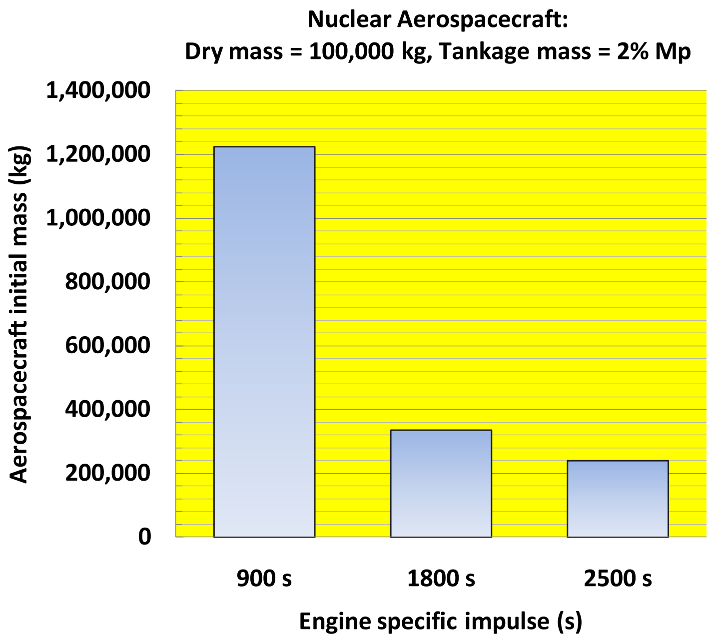

Figure 5.—NTP: solid core and gas core vehicle mass comparison, 100,000 kg dry mass, 2 percent H_2 tankage mass (Ref. 1).

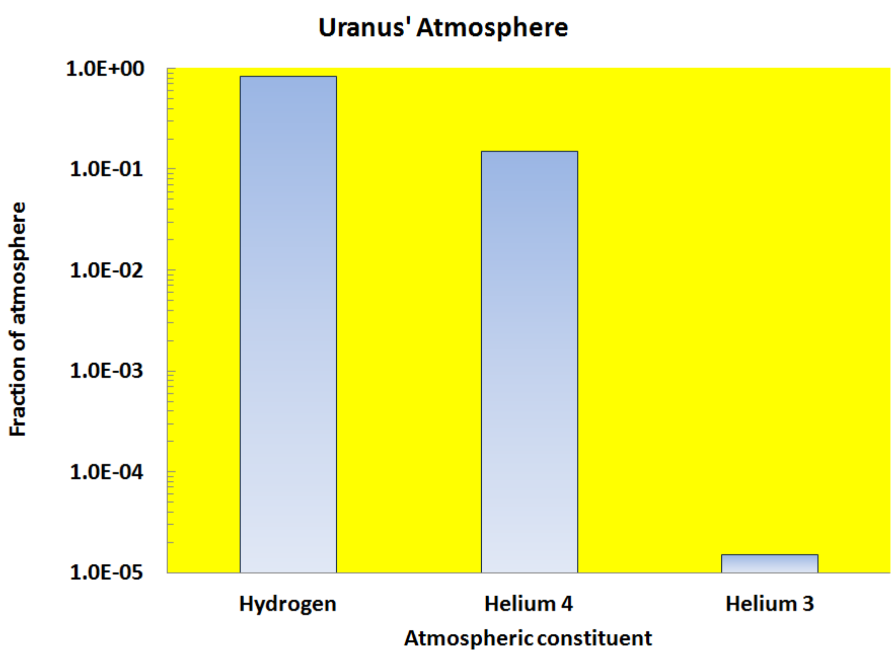

Figure 6.—Fractions of atmospheric gases for Uranus.

3.0 Fueling and Refueling Options

After completing the analyses of the time for propellant capture it became clear that a large amount of LH_2 was produced each day of 3He production. Figure 6 and Figure 7 depict the relatively large mass fractions of H_2 and 4He that are processed to extract the desired 3He. It is clear that such large masses will be useful for not only refueling the mining cruiser ASC, but may be important for other related applications.

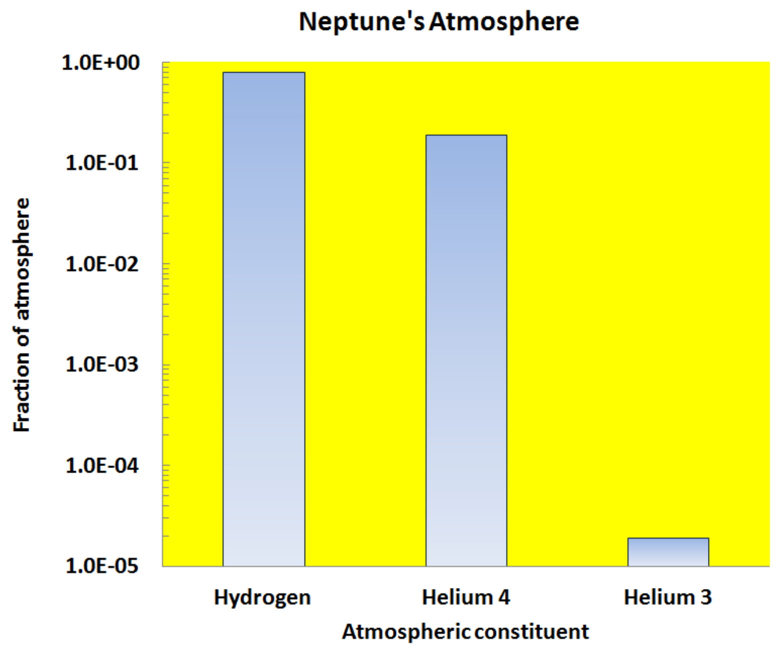

Figure 7.—Fractions of atmospheric gases for Neptune.

Figure 8 shows the 3He capture time (for 500 kg), the mass of H_2 produced per day, and the H_2 needed to fuel GCR powered ASC at a specific impulse of 1800 and 2500 s, all as a function of atmospheric gas capture rate. In this case, the 3He in the atmosphere is = 1.52×10^{-5} (a case for Uranus), and the ASC dry mass = 100,000 kg. As an example, of the atmospheric capture rate were 4 kg/s, there required amount of 500 kg of 3He would be captured in 95.2 days. During that time, 293,000 kg of H_2 would be produced per day. To fully fuel an 1800-s Isp gas core ASC is 270,000 kg. A H_2 propellant load of 148,000 kg is needed for the 2500-s Isp gas core powered ASC. Similarly, if the atmospheric capture rate were 10 kg/s, the time for capturing the 500 kg of 3He would be 38.1 days. During those 38.1 days, 732,600 kg of H_2 would be produced per day. Thus, more than two 1800-s gas core ASC vehicles could be refueled per day. While the mining vehicle (ponderously and politely) continues its 3He capturing, additional vehicles could flit about far from the mining ASC and gather needed information on potential storms or other disturbances that the mining ASC must avoid.

For a 1,000,000 kg dry mass, the mining case also show significant H_2 benefits. This case is shown in Figure 9 In the case for Neptune (3He = 1.9×10^{-5}), at an atmospheric capture rate of 22 kg/s, there is enough H_2 produced to refuel a 2500-s ASC every day. At that capture rate, it takes 13.8 days to mine the required 500 kg of 3He. So 13 orbital missions could be conducted or numerous sorties in the atmosphere by UAVs requiring smaller H_2 propellant loads could be completed.

With this high H_2 production rate, fleets of ASC, of a variety of sizes, could be fueled during the nominal time of capturing the 3He. Such a fleet could be atmospheric sampling uninhabited aerial vehicles (UAVs), small orbital missions, or UAVs for in-situ planetary meteorological studies.

Refueling of cryogenic ASC vehicles will no doubt be a challenge (in robotic aerial refueling, etc.), and there will be additional cryogenic transfer losses and propellant tank chilldown requirements, however, the mass of H_2 produced is quite impressive and is a ripe area for investigating H_2 usage options.

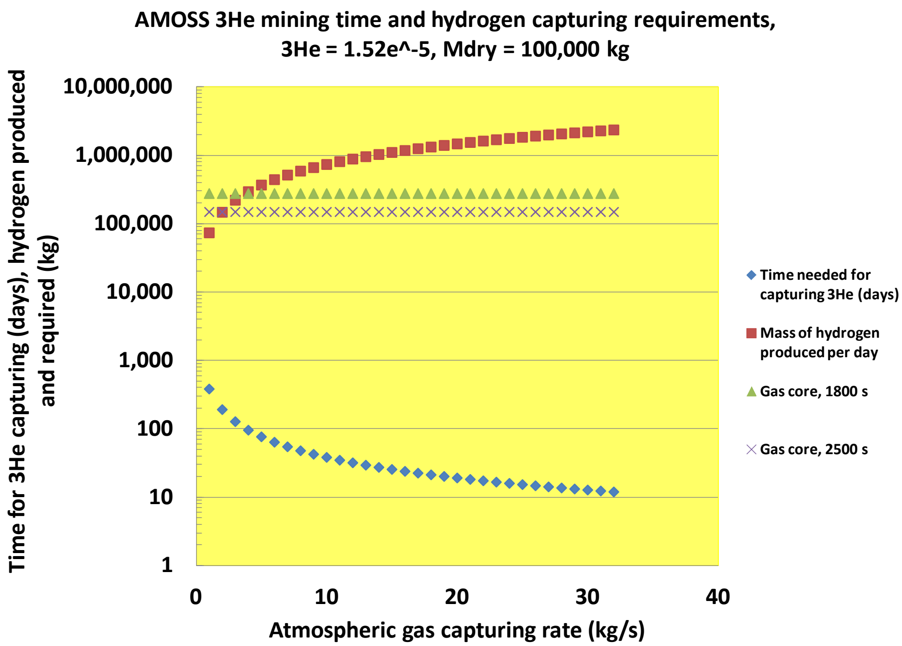

Figure 8.—Helium 3 mining time and H_2 capture (mass per day) versus atmospheric gas capture rate for Uranus.

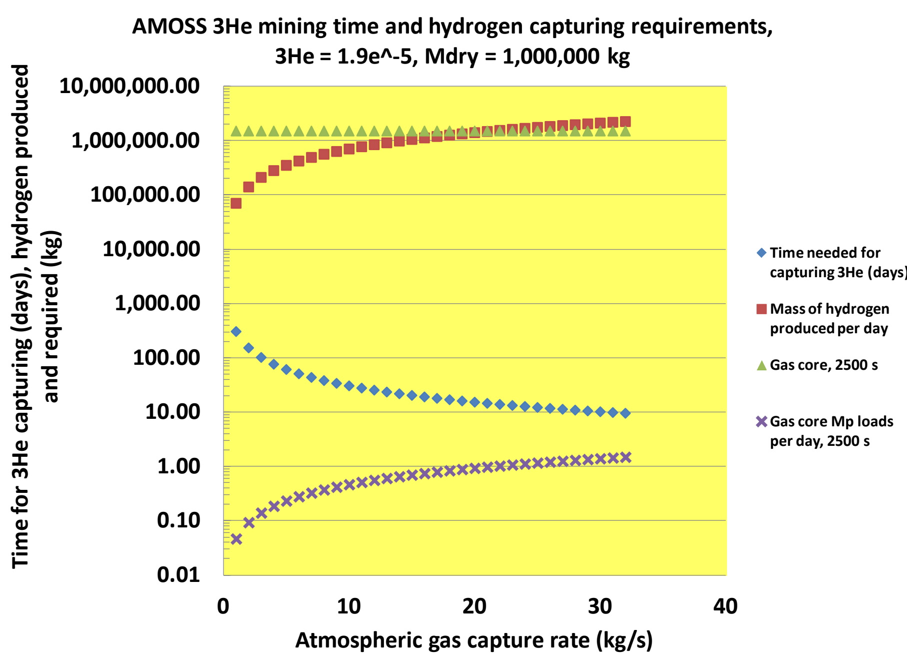

Figure 9.—Helium 3 mining time and H_2 capture (mass per day) versus atmospheric gas capture rate for Neptune.

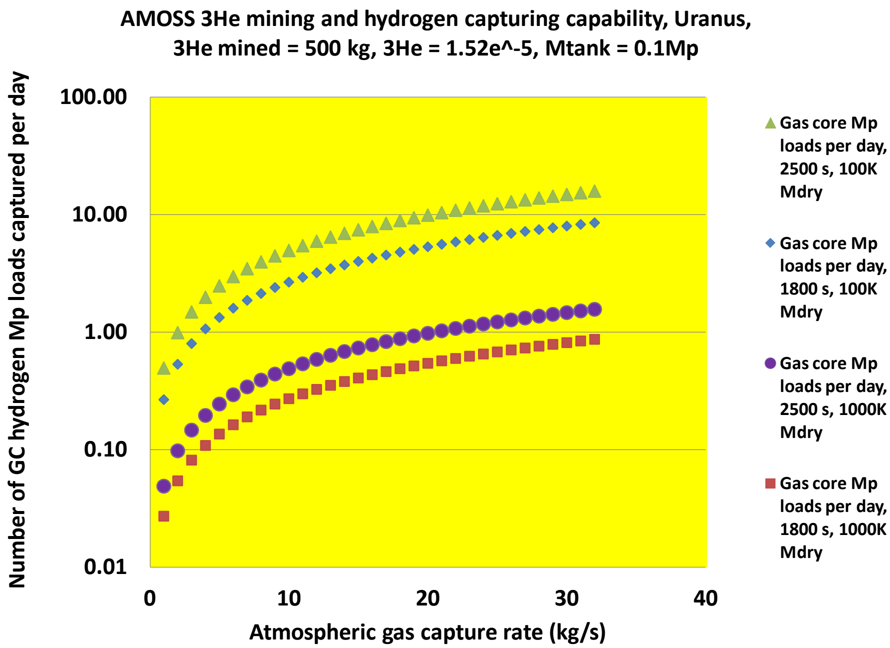

Figure 10.—Number of GCR H_2 propellant loads captured per day versus atmospheric gas capture rate—Uranus.

Figure 10 compares all of the H_2 capturing cases for Uranus. In the chart, the number of GCR H_2 propellant loads captured is as high at 15.8 for the 2500-s GCR cases (with a 100,000 kg dry mass, 32 kg/s capture rate). At a 10 kg/s atmospheric capture rate, the maximum number of H_2 loads is 4.95 (or just less than 5). The lowest value is 0.27 H_2 loads per day. Similar analyses are shown for the other vehicle designs for Neptune in Figure 11: 1800 and 2500 s Isp nuclear GCR (SC with 100 and 1000 MT dry masses. With the Neptune analysis, the rates of H_2 capture are slightly lower, and the capture rates are very similar to the Uranus cases.

While capturing 3He and H_2, there is also a very significant amount of 4He than can be captured. Figure 12 and Figure 13 provide the 4He capture capability per day. The capture capability of the 4He is expressed in the equivalent masses of H_2 to fuel the GCRs. This equivalent figure of merit of GCR propellant loads makes for a more direct comparison of the masses of H_2 and 4He. The 4He capture masses are approximately15 to 19 percent of the H_2 capture masses. With this added 4He resource, many vehicles could be fueled. Entire fleets of ASC or other aerial vehicles (UAVs, balloons, rockets, etc.) could fly through the outer planet atmospheres, for global weather observations, localized storm or other disturbance investigations, wind speed measurements, polar observations, etc. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the 4He may be designed to probe the higher density regions of the gas giants.

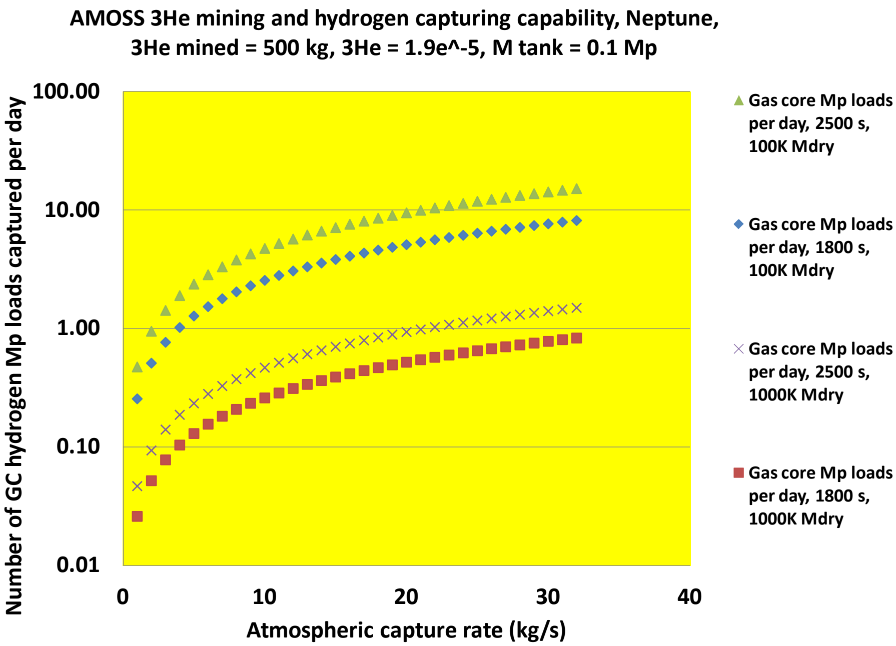

Figure 11.—Number of GCR H_2 propellant loads captured per day versus atmospheric gas capture rate—Neptune.

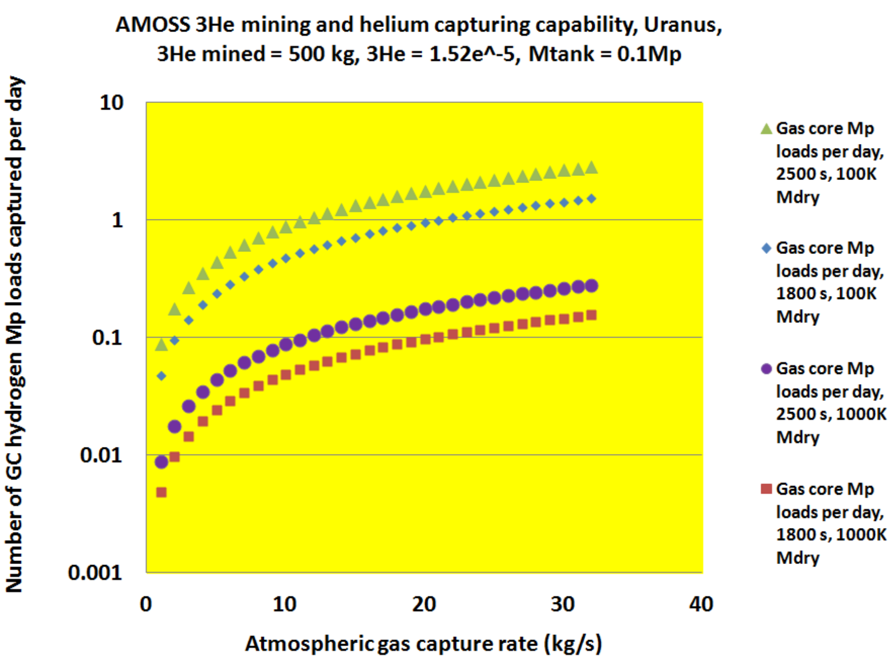

Figure 12.—Number of GCR (mass equivalent H_2) propellant loads of 4He captured per day versus atmospheric gas capture rate—Uranus.

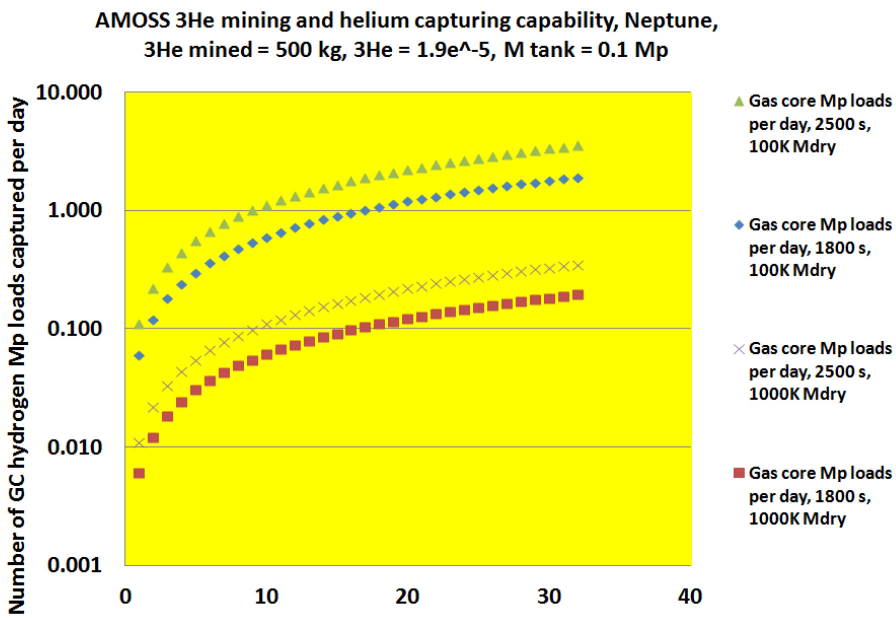

Figure 13.—Number of GCR (mass equivalent H_2) propellant loads of 4He captured per day versus atmospheric gas capture rate—Neptune

4.0 Supporting Analyses and Observations

In addition to the capturing studies, reviews of outer planet spacecraft design issues were initiated. A list of the issues to be addressed is noted below:

- Mission planning.
- Cryogenic fuel storage issues.
- Cryogenic dust (outer planet moons, ice migration). Mass concentrations (mascons) on the moons, etc.
- Drilling into ice, walkers on ice-dust surfaces.
- Possible power generation using electrodynamic tethers (EDT), cutting across the outer planet magnetic field lines.
- Global Positioning System (GPS) vehicles in outer planet orbits for navigation.
- Observational satellite for outer planet weather monitoring, diverting cruisers from harm.

Figure A.1 to Figure A.4 also illuminate some of the issues to be analyzed.

5.0 Concluding Remarks

Atmospheric mining in the outer solar system can be a powerful tool for extracting fuels from the outer planets and allowing fast human and robotic exploration of the solar system. Preliminary designs of ASC with GCR nuclear engines for mining the outer planets were developed (Ref. 1). Analyses showed that gas core engines can reduce the mass of such ASC mining vehicles very significantly: from 72 to 80 percent reduction over NTP solid core powered ASC mining vehicles. While this mass reduction is important in reducing the mass of the overall mining system, the complexity of a fissioning plasma GCR is much higher than the more traditional solid core NTP engines. Additional analyses were conducted to calculate the capture rates of H_2 and 4He during the mining process. Very large masses of H_2 and 4He are produced every day during the often lengthy process of 3He capture and gas separation. Typically, these very large additional fuel masses can dwarf the requirements needed for H_2 capture for ascent to orbit. Thus, the potential for fueling small and large fleets of additional exploration and exploitation vehicles exists. Additional ASC or other aerial vehicles (UAVs, balloons, rockets, etc.) could fly through the outer planet atmospheres, for global weather observations, localized storm or other disturbance investigations, wind speed measurements, polar observations, etc. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess H_2 or 4He may be designed to probe the higher density regions of the gas giants.

Based on these analyses, there will likely be several possible future avenues for effective use the gases of the outer planets for exciting exploration missions. When focusing on Uranus and Neptune, these planets offer vast reservoirs of fuels that are more readily accessible than those from Jupiter and Saturn and, with the advent of nuclear fusion propulsion, may offer us the best option for the first practical interstellar flight.

Appendix A.—Issues for Cryogenic Operations

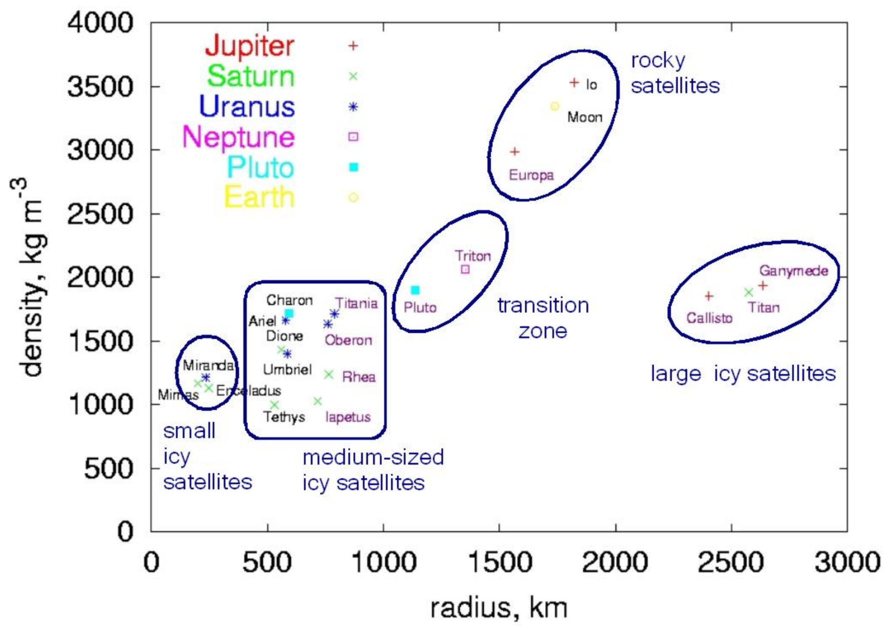

Figure A.1.—Outer planet moon densities[1] (Ref. 20).

Figure A.2.—Issues for cryogenic outer planet moon surface operations (RASC, HOPE study, Refs. 21 and 22).

[1] Reprinted from Icarus, Volume 185, Issue 1: Hussmann, Hauke; Sohl, Frank; Spohn, Tilman: "Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-Neptunian objects," pp. 258-273, Copyright 2006, with permission from Elsevier.

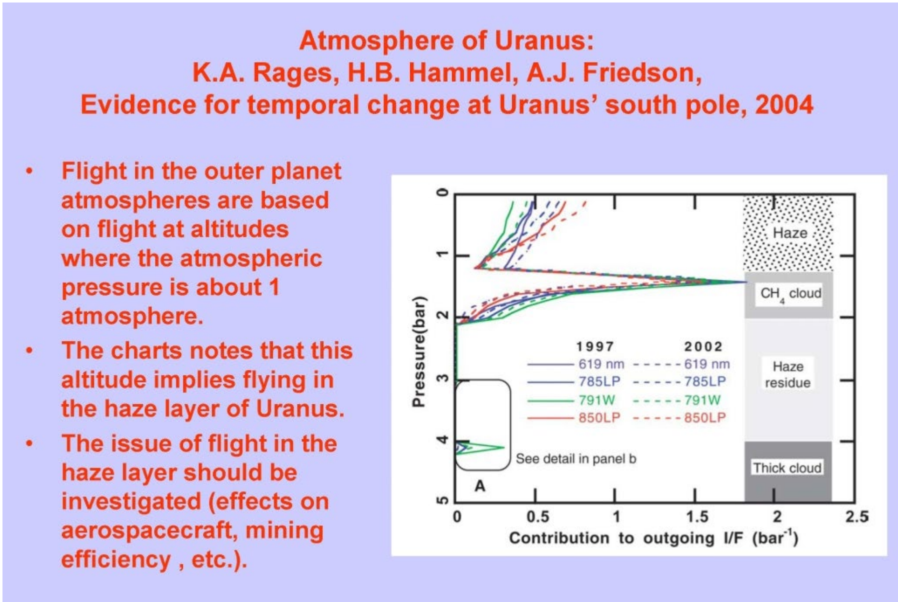

Figure A.3.—Uranus atmospheric structure, haze phenomena[2] (Ref. 23).

Figure A.4.—Atmospheric mining issues.

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[2] Reprinted from Icarus, Volume 172, Issue 2: K.A. Rages, H.B. Hammel, A.J. Friedsond: "Evidence for temporal change at Uranus' south pole," pp. 548–554, Copyright 2004, with permission from Elsevier.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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