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

Bryan Palaszewski*
NASA John H. Glenn Research Center
Lewis Field
MS 5-10
Cleveland, OH 44135
(216) 977-7493 Voice
(216) 433-5802 FAX
bryan.a.palaszewski@nasa.gov

Fuels and Space Propellants Web Site:
http://www.grc.nasa.gov/WWW/Fuels-And-Space-Propellants/foctopsb.htm

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 (3He) 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
CC	Closed cycle
delta-V	Change in velocity (km/s)
GCR	Gas core rocket
GTOW	Gross Takeoff Weight
H2	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
O2	Oxygen
PPB	Parts per billion
STO	Surface to Orbit

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* Leader of Advanced Fuels, AIAA Associate Fellow

I. 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. 1-8). Uranus' and Neptune's atmospheres would be the primary mining sites, and robotic vehicles would wrest these gases from the hydrogen-helium gases of those planets. While preliminary estimates of the masses of the mining vehicles have been created (Refs. 1-7), additional supporting vehicles may enhance the mining scenarios.

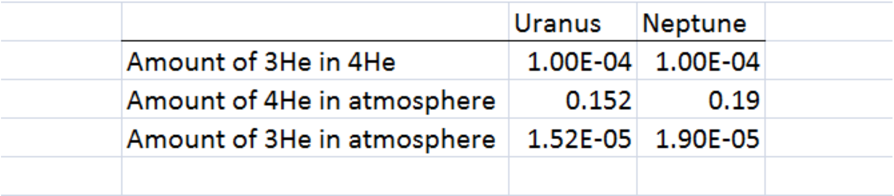
There are vast reserves of potential fuels and propellants in the outer planets (Refs. 1 to 7). While the idea of mining outer planet atmospheres is indeed enticing, the challenges to designing mining vehicles may be somewhat daunting. While past studies related to the Daedalus Project (Ref. 7) have assumed the use of fusion propulsion for the aerostat and aerospacecraft 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 through 11), although closed cycle gas core nuclear rockets may provide high specific impulse and high thrust without invoking fusion rockets (refs. 12 to 21).

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

II. Resource capturing studies

Studies of the gas capture rate and its influence on mining time in the atmosphere were conducted. Aerospacecraft cruisers have been identified as a "best" solution for atmospheric mining (Ref. 1-7). To power these vehicles, atmospheric hydrogen gas would be liquefied and used a rocket propellant for the ascent to orbit. Gaseous or liquid hydrogen would be use to power the engines during atmospheric mining operations. Figure 1 shows an overall schematic of a closed cycle gas core rocket propulsion option. Helium 3 (3He) would be separated from the atmospheric hydrogen and helium (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.

Table I. Fraction of helium 3 and helium 4 in 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

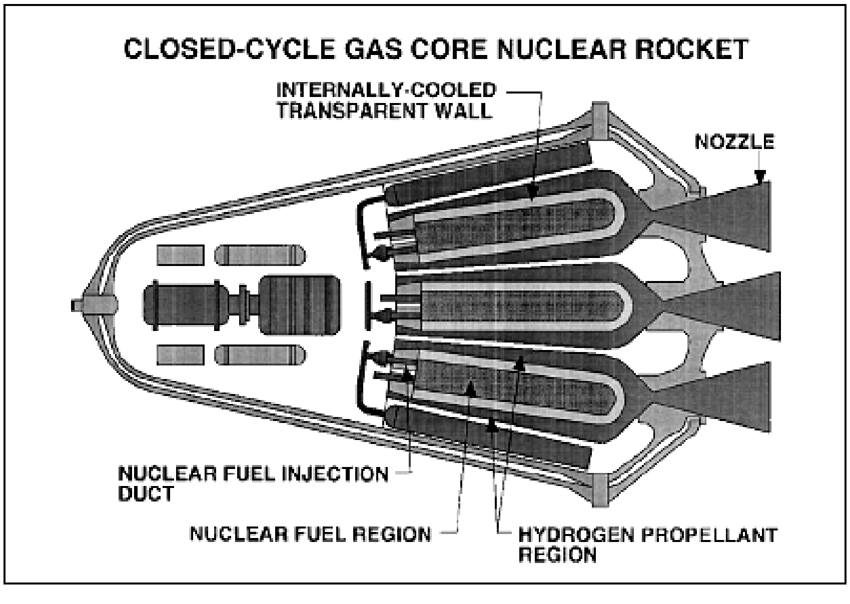


Figure 1. Gas core rocket propulsion for the mining cruiser (Ref. 8).

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

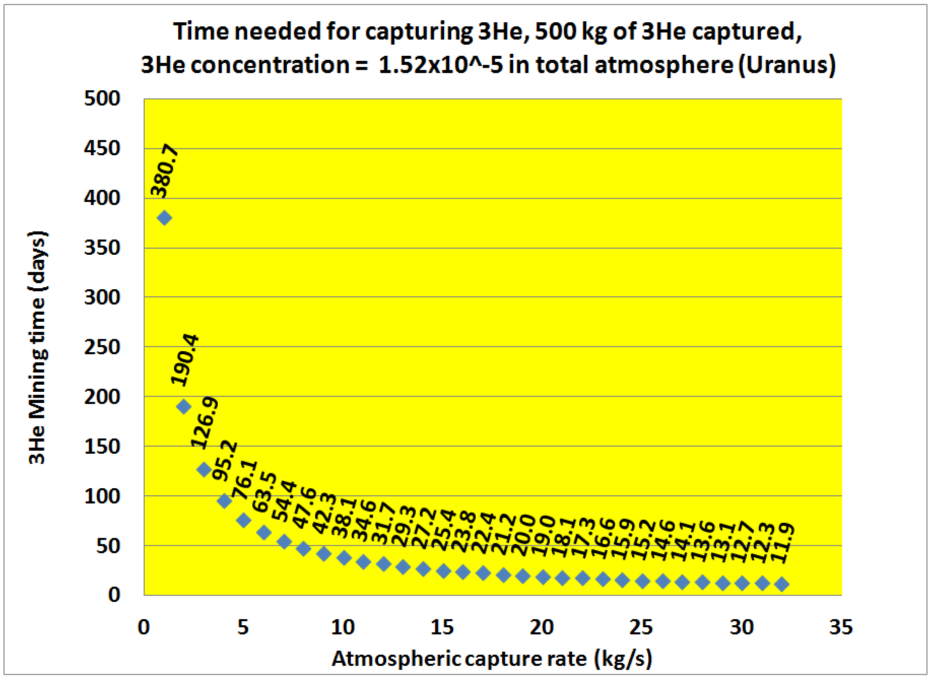


Figure 2. Mining time versus the capture rate for Uranus.

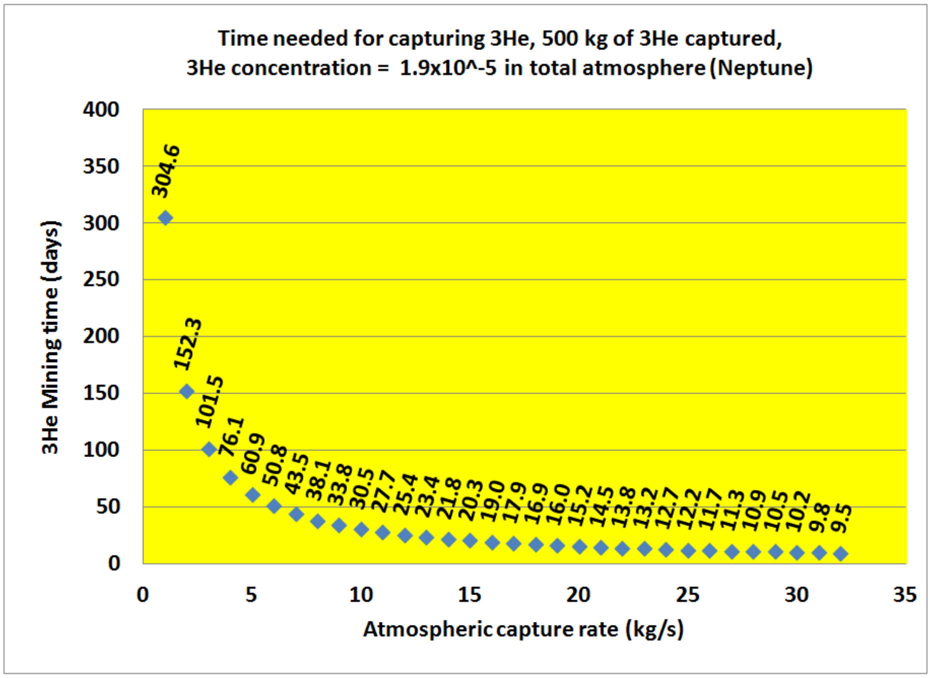


Figure 3. Mining time versus the capture rate for Neptune.

Figure 4 and 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).

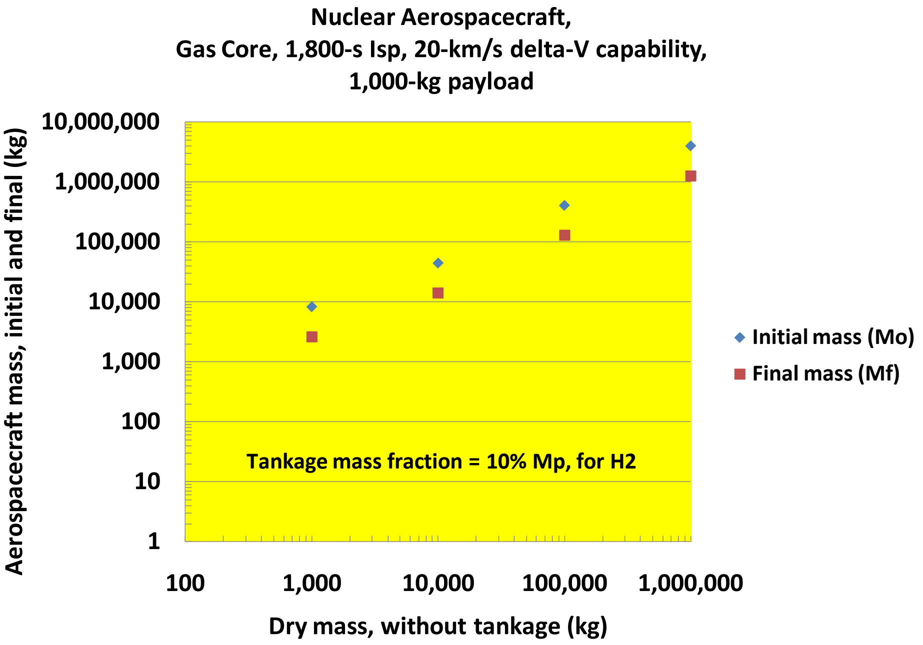


Figure 4. Aerospacecraft (ASC) mass, 1,800-s Isp, Tankage = 10% Mp, representative of gas core nuclear propulsion (Ref. 1).

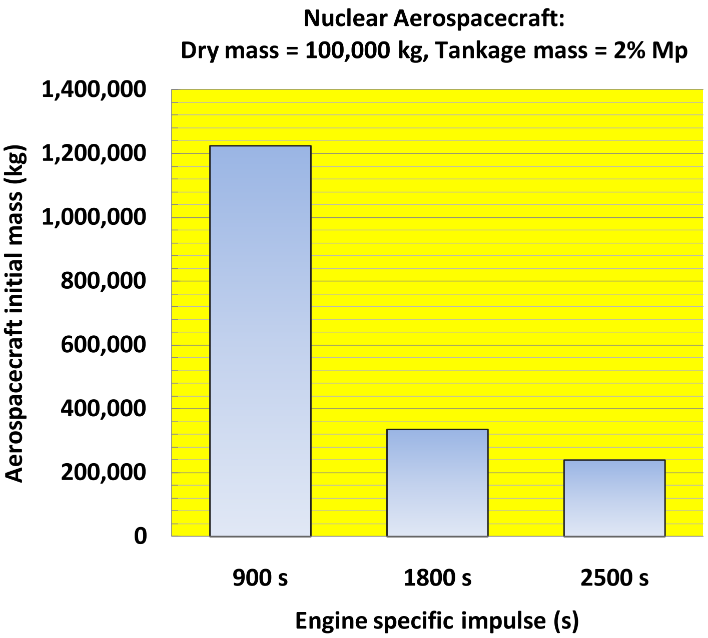


Figure 5. NTP: solid core and gas core vehicle mass comparison, 100,000 kg dry mass, 2% hydrogen tankage mass (Ref. 1).

III. Fueling and Refueling Options

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

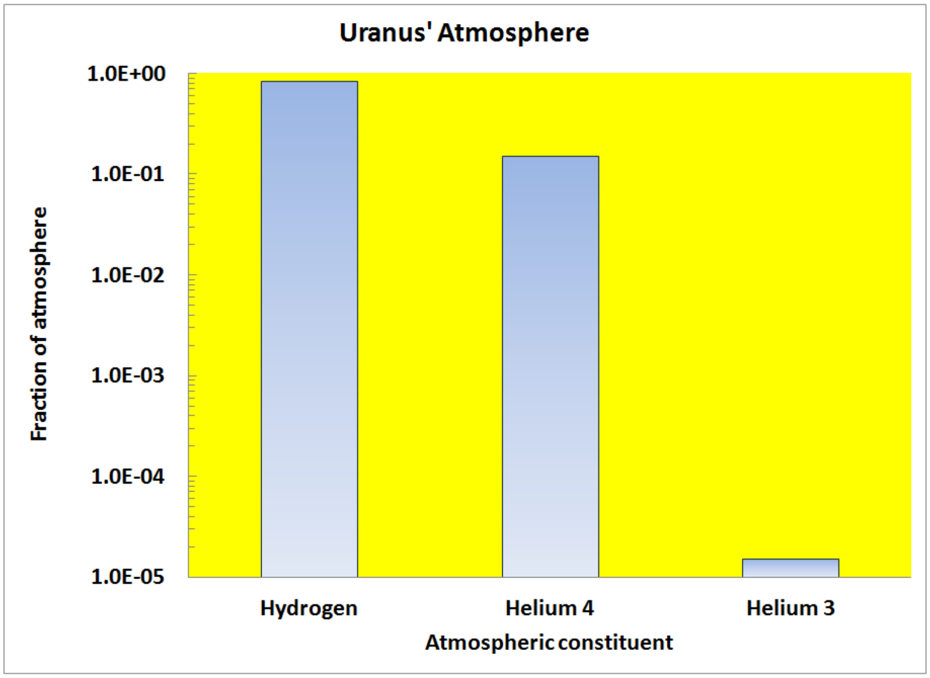


Figure 6. Fractions of atmospheric gases for Uranus

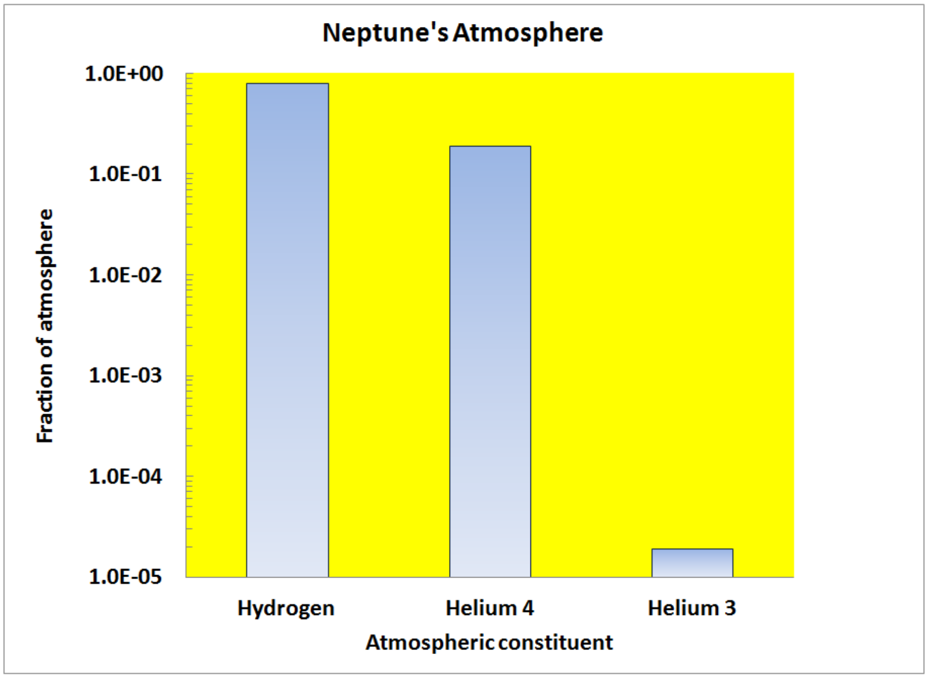


Figure 7. Fractions of atmospheric gases for Neptune

Figure 8 shows the 3He capture time (for 500 kg), the mass of hydrogen produced per day, and the hydrogen needed to fuel gas core rocket powered aerospacecraft (ASC) at a specific impulse of 1800 and 2500 seconds, all as a function of atmospheric gas capture rate. In this case, the 3He in the atmosphere is = 1.52e^-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 hydrogen would be produced per day. To fully fuel an 1800–s Isp gas core ASC is 270,000 kg. A hydrogen 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 hydrogen would be produced per day. Thus, more than two (2) 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.

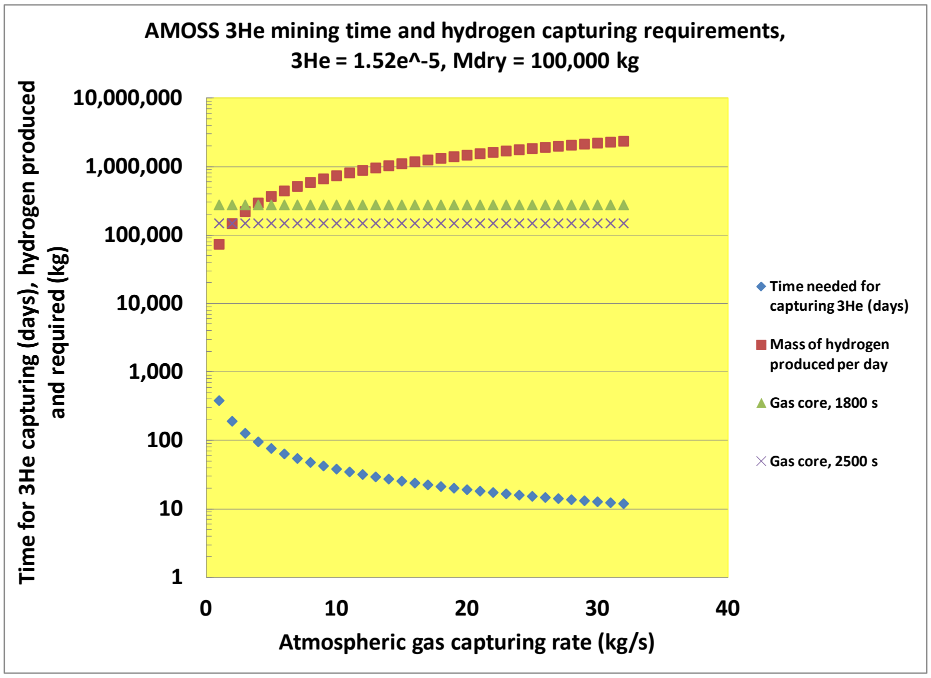


Figure 9. Helium 3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Uranus

For a 1,000,000 kg dry mass, the mining case also show significant hydrogen benefits. In the case for Neptune (3He = 1.9e^-5), at an atmospheric capture rate of 22 kg/s, there is enough hydrogen 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 hydrogen propellant loads could be completed.

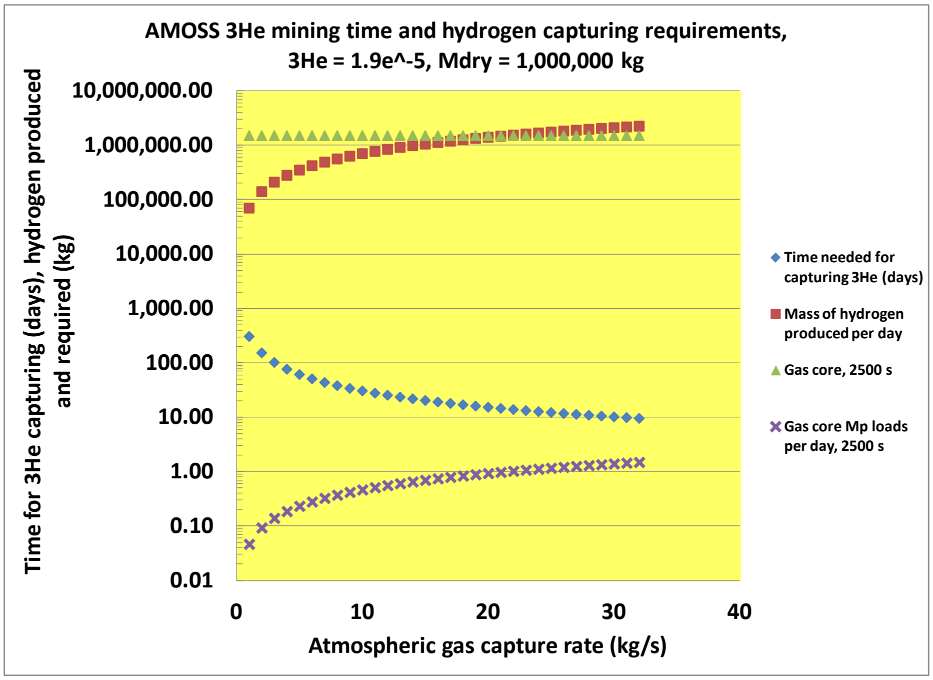


Figure 9. Helium 3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune

With this high hydrogen production rate, fleets of aerospacecraft, 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 hydrogen produced is quite impressive and is a ripe area for investigating hydrogen usage options.

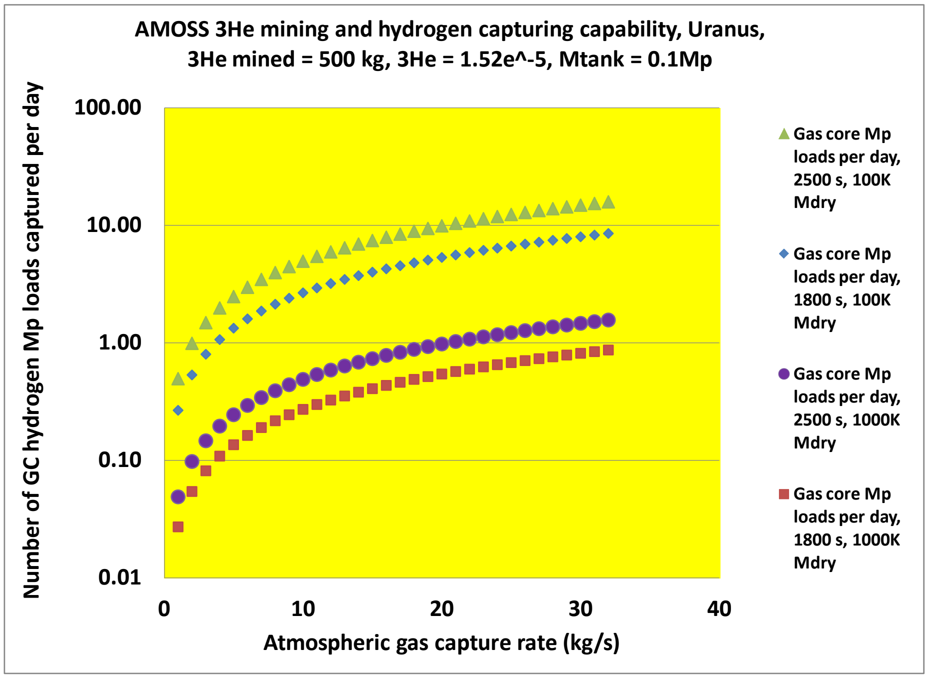


Figure 10. Number of gas core rocket hydrogen propellant loads captured per day versus atmospheric gas capture rate - Uranus.

Figure 10 compares all of the hydrogen capturing cases for Uranus. In the chart, the number of gas core rocket hydrogen 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 hydrogen loads is 4.95 (or just less than 5). The lowest value is 0.27 hydrogen loads per day. Similar analyses are shown for the other vehicle designs for Neptune in Figure 11: 1800 and 2500 s Isp nuclear gas core rocket (GCR) aerospacecraft (ASC) with 100 and 1000 MT dry masses. With the Neptune analysis, the rates of hydrogen capture are slightly lower, and the capture rates are very similar to the Uranus cases.

While capturing helium 3 and hydrogen, there is also a very significant amount of helium 4 than can be captured. Figures 12 and 13 provide the helium 4 capture capability per day. The capture capability of the helium 4 is expressed in the equivalent masses of hydrogen to fuel the gas core rockets. This equivalent figure of merit of GCR propellant loads makes for a more direct comparison of the masses of hydrogen and helium 4. The helium 4 capture masses are approximately15 to 19 percent of the hydrogen capture masses. With this added helium 4 resource, many vehicles could be fueled. Entire fleets of aerospacecraft 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 helium 4 may be designed to probe the higher density regions of the gas giants.

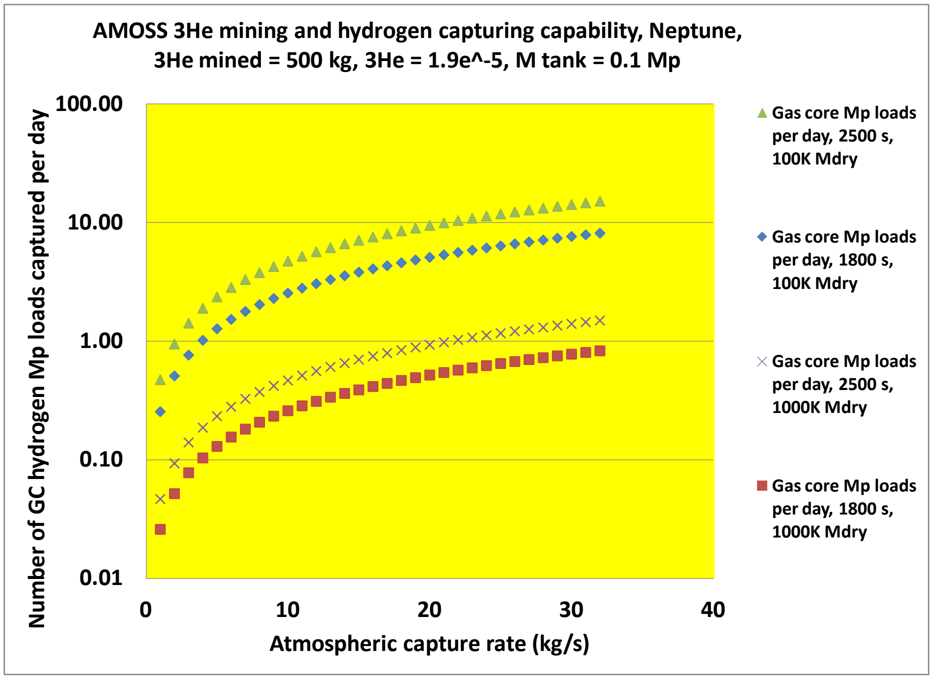


Figure 11. Number of gas core rocket hydrogen propellant loads captured per day versus atmospheric gas capture rate - Neptune

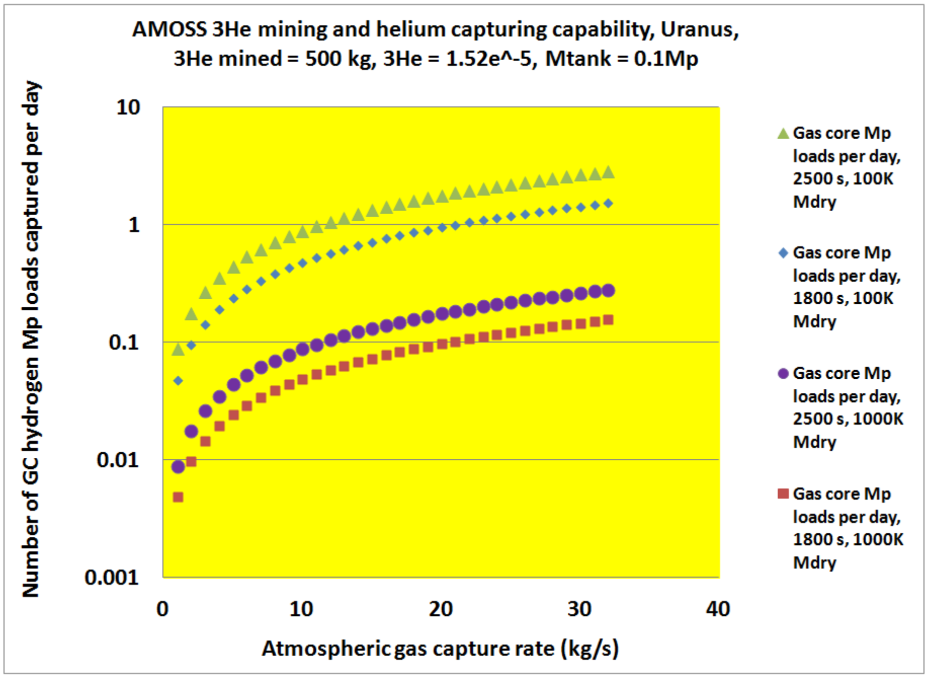


Figure 12. Number of gas core rocket (mass equivalent hydrogen) propellant loads of helium 4 captured per day versus atmospheric gas capture rate - Uranus

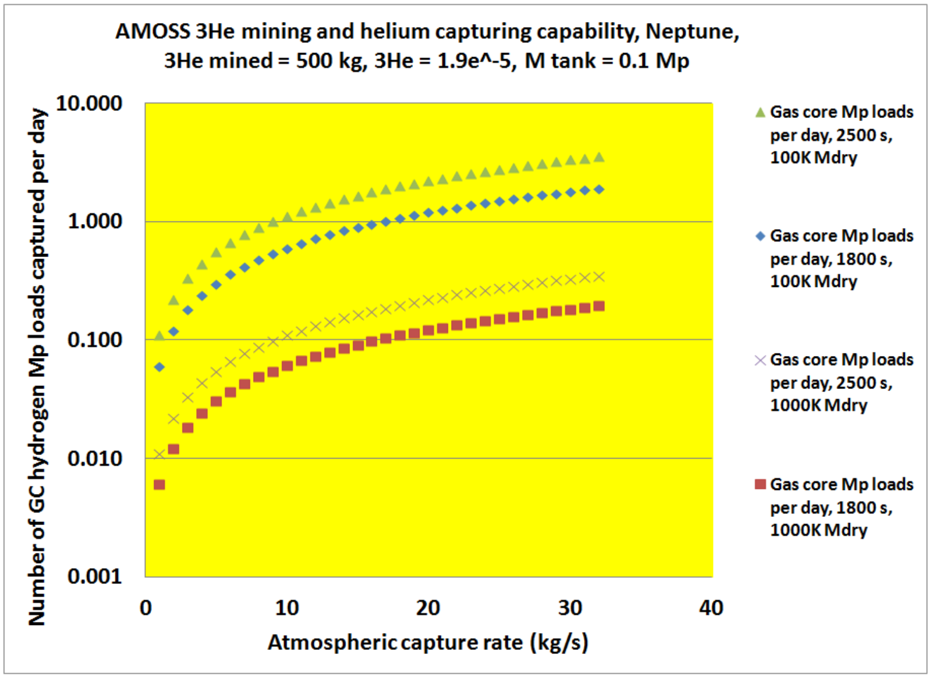


Figure 13. Number of gas core rocket (mass equivalent hydrogen) propellant loads of helium 4 captured per day versus atmospheric gas capture rate - Neptune

IV. 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 electro dynamic 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.

Figures A1 through A4 also illuminate some of the issues to be analyzed.

V. 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 aerospacecraft with gas core rocket nuclear engines for mining the outer planets were developed (Ref. 1). Analyses showed that gas core engines can reduce the mass of such aerospacecraft mining vehicles very significantly: from 72 to 80 percent reduction over NTP solid core powered aerospacecraft mining vehicles. While this mass reduction is important in reducing the mass of the overall mining system, the complexity of a fissioning plasma gas core rocket is much higher than the more traditional solid core NTP engines. Additional analyses were conducted to calculate the capture rates of hydrogen and helium 4 during the mining process. Very large masses of hydrogen and helium 4 are produced every day during the often lengthy process of helium 3 capture and gas separation. Typically, these very large additional fuel masses can dwarf the requirements needed for hydrogen capture for ascent to orbit. Thus, the potential for fueling small and large fleets of additional exploration and exploitation vehicles exists. Additional aerospacecraft 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 hydrogen or helium 4 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.

V. References

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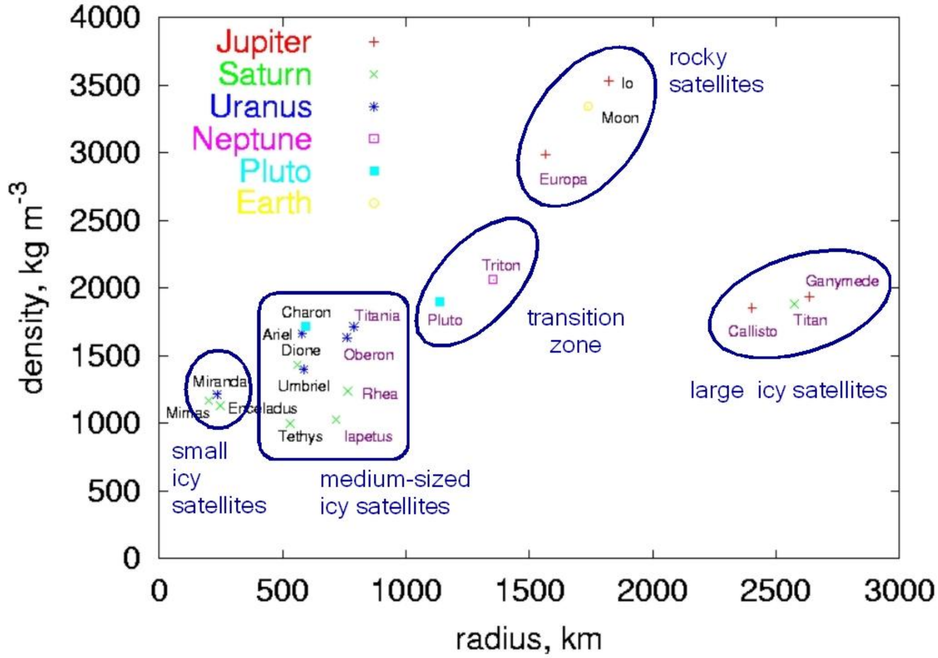
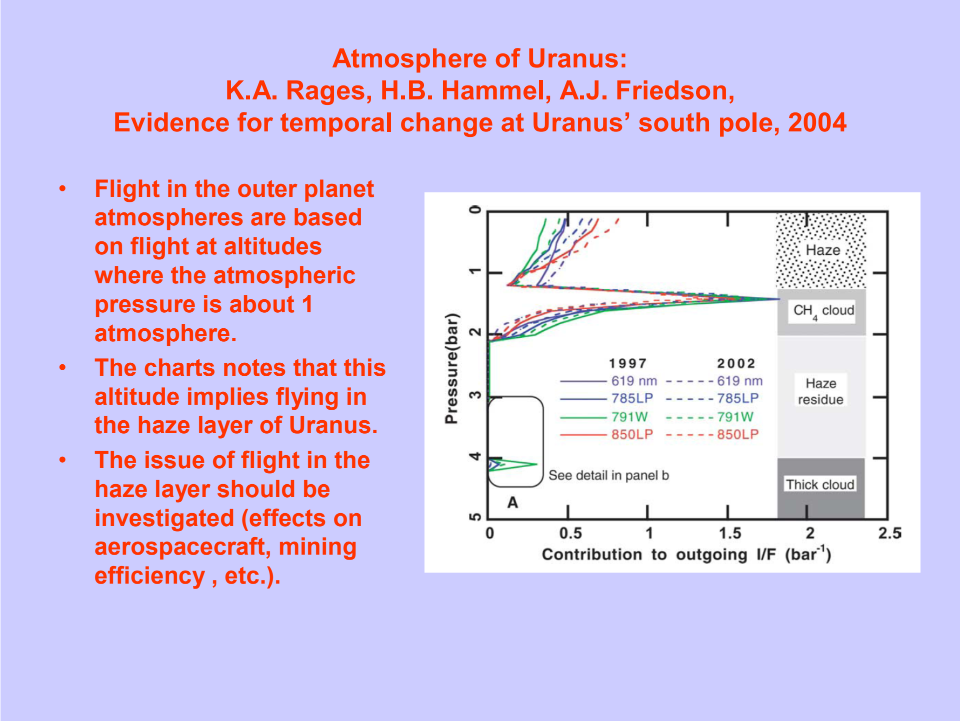


Figure A1. Outer planet moon densities (Ref: Hussmann, Hauke; Sohl, Frank; Spohn, Tilman, “Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects,” Icarus, Volume 185, Issue 1, p. 258-273).

Moon Bases in Cryogenic Environments: Issues

- Power sources
- Seals
- Rotating components
- Adhesives
- Flexible – inflatable surfaces
- Dust, ice characteristics
- Robots, for maintenance, etc.
- Warmth for, maintenance of astronauts

Figure A2. Issues for cryogenic outer planet moon surface operations (RASC, HOPE study, Refs. 20 and 21).



Atmosphere of Uranus:
K.A. Rages, H.B. Hammel, A.J. Friedson,
Evidence for temporal change at Uranus' south pole, 2004

- Flight in the outer planet atmospheres are based on flight at altitudes where the atmospheric pressure is about 1 atmosphere.
- The charts notes that this altitude implies flying in the haze layer of Uranus.
- The issue of flight in the haze layer should be investigated (effects on aerospacecraft, mining efficiency , etc.).

Figure A3. Uranus atmospheric structure, haze phenomena (Ref. - K.A. Rages, H.B. Hammel c, A.J. Friedsond, "Evidence for temporal change at Uranus' south pole," Icarus 172 (2004) pp. 548–554).

AMOSS: What's Next?

- Daedalus Redux (British Interplanetary Society (BIS) Study, Martin, A., et al., 1979).
  - More attention to atmospheric mining for starship fueling.
    - Schedules of ISRU fuel deliveries.
      - Effect on construction – if ISRU process slowed or speeded up?
    - Daedalus study assumed fusion powered atmospheric transfer vehicles and aerostats for gathering helium 3 and deuterium from Jupiter's atmosphere.
      - Move mining location to Uranus or Neptune.
      - Recent studies of AMOSS (Palaszewski, et al. AIAA JPC 2005, 2006, 2007, 2008) have used nuclear thermal propulsion (NTP) aerospacecraft (cruiser aircraft) for fuel mining and orbital delivery.
      - Is NTP effective as a propulsion option? Is fusion required?
  - Development of micro-factories (or macro-factories, or nano-factories(?)) for ship assembly and non-fuel related construction.
    - Time added for nano- or micro-factory versus macro-factory construction (time for assembling atoms and molecules, literally…)

Figure A4. Atmospheric mining issues.