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

Bryan Palaszewski
Glenn Research Center, Cleveland, Ohio
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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Bryan Palaszewski
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

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

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3He</td>
<td>helium 3</td>
</tr>
<tr>
<td>4He</td>
<td>helium (or Helium 4)</td>
</tr>
<tr>
<td>AMOSS</td>
<td>atmospheric mining in the outer solar system</td>
</tr>
<tr>
<td>ASC</td>
<td>aerospacecraft</td>
</tr>
<tr>
<td>CC</td>
<td>closed cycle</td>
</tr>
<tr>
<td>delta-V</td>
<td>change in velocity (km/s)</td>
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<tr>
<td>GCR</td>
<td>gas core rocket</td>
</tr>
<tr>
<td>GTOW</td>
<td>gross takeoff weight</td>
</tr>
<tr>
<td>H₂</td>
<td>hydrogen</td>
</tr>
<tr>
<td>He</td>
<td>helium 4</td>
</tr>
<tr>
<td>IEC</td>
<td>Inertial-Electrostatic Confinement (related to nuclear fusion)</td>
</tr>
<tr>
<td>ISRU</td>
<td>In Situ Resource Utilization</td>
</tr>
<tr>
<td>Isp</td>
<td>specific impulse (s)</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>kWe</td>
<td>kilowatts of electric power</td>
</tr>
<tr>
<td>LEO</td>
<td>low Earth orbit</td>
</tr>
<tr>
<td>MT</td>
<td>metric tons</td>
</tr>
<tr>
<td>MWe</td>
<td>megawatt electric (power level)</td>
</tr>
<tr>
<td>NEP</td>
<td>Nuclear Electric Propulsion</td>
</tr>
<tr>
<td>NTP</td>
<td>Nuclear Thermal Propulsion</td>
</tr>
<tr>
<td>NTR</td>
<td>Nuclear Thermal Rocket</td>
</tr>
<tr>
<td>OC</td>
<td>open cycle</td>
</tr>
<tr>
<td>O₂</td>
<td>oxygen</td>
</tr>
<tr>
<td>PPB</td>
<td>parts per billion</td>
</tr>
<tr>
<td>STO</td>
<td>surface to orbit</td>
</tr>
<tr>
<td>UAV</td>
<td>uninhabited aerial vehicle</td>
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</table>
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 H2-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 H2 and 4He are produced. Analyses were conducted to quantify the mass production rates of these other potential fuels. Also, capturing the H2 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 H2 gas would be liquefied and used a rocket propellant for the ascent to orbit, Gaseous or liquid H2 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 H2 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\textsubscript{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\textsubscript{2} was produced each day of 3He production. Figure 6 and Figure 7 depict the relatively large mass fractions of H\textsubscript{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 8 shows the 3He capture time (for 500 kg), the mass of H₂ produced per day, and the H₂ 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 $= 1.52 \times 10^{-5}$ (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 H₂ would be produced per day. To fully fuel an 1800-s Isp gas core ASC is 270,000 kg. A H₂ 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 H₂ 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 H₂ benefits. This case is shown in Figure 9 In the case for Neptune (3He = $1.9 \times 10^{-5}$), at an atmospheric capture rate of 22 kg/s, there is enough H₂ 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 H₂ propellant loads could be completed.

With this high H₂ 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 H₂ produced is quite impressive and is a ripe area for investigating H₂ usage options.
Figure 8.—Helium 3 mining time and H₂ capture (mass per day) versus atmospheric gas capture rate for Uranus.

AMOSS 3He mining time and hydrogen capturing requirements, 
3He = 1.52e⁻⁵, Mdry = 100,000 kg

Figure 9.—Helium 3 mining time and H₂ capture (mass per day) versus atmospheric gas capture rate for Neptune.

AMOSS 3He mining time and hydrogen capturing requirements, 
3He = 1.9e⁻⁵, Mdry = 1,000,000 kg
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 approximately 15 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\textsubscript{2} propellant loads captured per day versus atmospheric gas capture rate—Neptune.

Figure 12.—Number of GCR (mass equivalent H\textsubscript{2}) propellant loads of 4He captured per day versus atmospheric gas capture rate—Uranus.
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 densities1 (Ref. 20).

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

AMOSS: What’s Next?

  - 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...)

References


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