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, 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. While capturing 3He, large amounts of hydrogen and 4He are produced. With these two additional gases, 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. Outer planet atmospheric properties, atmospheric storm data, and mission planning for future outer planet UAVs are presented.

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
ISRU  In Situ Resource Utilization
Isp   Specific Impulse (s)
K     Kelvin
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
UAV   Uninhabited Aerial Vehicle

* 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 3He, for future fusion powered exploration vehicles or powering reactors for Earth’s planetary energy. 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. 1-9), additional supporting vehicles may enhance the mining scenarios. Storing the mined gases at automated bases on outer planet moons was conceived to ease the storage requirements on interplanetary transfer vehicles (that would return the cryogenic gases to Earth).

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. 1-9). To power these vehicles, atmospheric hydrogen gas would be liquefied and used a rocket propellant for the ascent to orbit. A gas core rocket is a likely candidate. Gaseous or liquid hydrogen would be use to power the engines during atmospheric mining operations. 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 and Figure 1 provide the amount of 3He in the outer planet atmospheres. Figures 2 and 3 show the mining time versus the capture rate for Uranus and Neptune, respectively. A 500-kg payload of 3He is captured during the mining time.

Table I. Fraction of helium 3 in outer planet atmospheres

<table>
<thead>
<tr>
<th></th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of 3He in 4He</td>
<td>1.00E-04</td>
<td>1.00E-04</td>
</tr>
<tr>
<td>Amount of 4He in atmosphere</td>
<td>0.152</td>
<td>0.19</td>
</tr>
<tr>
<td>Amount of 3He in atmosphere</td>
<td>1.52E-05</td>
<td>1.90E-05</td>
</tr>
</tbody>
</table>

The sizing of the gas core powered vehicles and a comparison of the solid core and gas core vehicle options were conducted (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). Additional study results of the capture, storage, and use of the atmospheric gases were presented in Ref. 1.

Atmospheric mining in the outer solar system is a can be powerful tool in extracting fuels from the outer planets and allow 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 to 3). References 10 to 21 provided the data for the design assessments. 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 (Ref. 3). 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. Figure 4 shows the mass of hydrogen needed for the gas core rocket and the potentially excess hydrogen captured every day. Typically, these very large (excess) 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. Reference 22 alludes to and illustrates the importance of such observations. 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. To take advantage of the large atmospheric resources, the initial designs of such UAVs may include airbreathing (hydrogen or helium) nuclear engines.

III. Outer Planet Atmospheric Phenomena

Storm locations on Uranus – The AMOSS UAVs mission planning will be based on storm locations. Figures 5 and 6 depict the observed Uranus storm locations (Refs. 23 to 25). Many of the storms lie along a narrow set of latitudes. This will simplify the mission planning. The storm locations may however be coincident with the highest planetary wind speeds. UAV
standoff distances may be needed or remote sensing of the lower altitude winds may allow the UAVs to make more close-in measurements.

Storm locations on Neptune - Figure 7 depicts the observed Neptune storm locations (Ref. 25) Many of the storms lie along a wide set of latitudes, a completely different situation from that on Uranus. If only one UAV were available, the numerous storm locations will complicate the mission planning. Numerous UAVs would be required for complete planetary coverage.

Observations of aurorae on Uranus (and perhaps Neptune) may demand the use of sounding rocket like UAVs especially if high altitude measurements are required. To improve data gathering, a small array of GPS-like or communications satellites may be required for continuous coverage during the long data gathering phase while travelling between storms and while loitering to observe the storms or other atmospheric phenomena.

IV. UAV Mission Planning

Patterns for missions were assessed: one way, round trip, multiple observations, loitering at a phenomenon of interest, etc. A series of broad mission planning flight paths were assembled. Sample mission planning is shown in Appendix A. Both one-way and round trip missions were designed. Options for UAV designs to accommodate both short and long missions are addressed in a later section.

The distance between storms is therefore a major issue. The times to traverse from one area of the Uranus and Neptune to another are shown in Figures 8 and 9, respectively. The plots show the travel time for distances of 10 to 90 degrees (latitude or longitude) and for UAV velocities of 100 to 400 meters per second (m/s). For Uranus, the time for traversing 90 degrees at 100 m/s is approximately 111.5 hours. At 400 m/s, the travel time is 27.9 hours. At Neptune, the travel times are slightly lower, given the slightly smaller planet diameter. For examples, at Neptune, the flight at 100 m/s for the 90 degree traverse is 108.1 hours and at 400 m/s to traverse 90 degrees is 27 hours.

Time for circumnavigation of storms was considered. When observing a storm, it will be advantageous to circumnavigate the entire storm. In this way, anomalous behavior, winds, or other unique features can be studied in detail. The time to circumnavigate storms is shown in Figure 10. A 100 km standoff distance from the edge of the circular storm was included. As an example, at 300 m/s UAV speed, the time to circumnavigate a 0.05 Earth radius storm is just under 91 hours.

V. UAV Design Options

Historical studies have investigated nuclear ramjet flyers. Figures 11 and 12 show potential configurations of a nuclear powered ramjet UAV (using the in-situ outer planet atmosphere for propulsion). References 27 and 27a depict possible configurations. Figure 13 provides the mass of a rocket powered UAV, assuming a 10 km/s delta-V capability (Ref. 1). Ref. 28 shows the potential reactor life for a solid core NTP reactor. The lifetime noted implies a short life for such a UAV: less than 30 hours. While round trip missions may be useful for a restricted set of “sample return” missions (gas samples, etc.), the lifetime of the solid core nuclear reactor ramjet engines may only allow for such one-way missions. Alternative designs with longer lived propeller driven UAVs may allow such round trip flights. The compactness and sturdiness of propeller driven UAVs would have to be investigated. Using deployable propellers and high aspect ratio wings may hamper the robustness of the UAV, especially where high winds are to be encountered.

VI. Supporting Analyses and Observations

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

Mission planning.

Global Positioning System (GPS) vehicles in outer planet orbits for navigation.

Observational satellite for outer planet weather monitoring, diverting cruisers from harm.

Cryogenic fuel storage issues.

Cryogenic dust (outer planet moons, ice migration). Mass concentrations (mascons) on the moons, etc.

Also, Figure B1 illuminates some of the issues to be analyzed for cryogenic environments.
VII. Concluding Remarks

Uninhabited aerial vehicles and the related mission planning for Uranus and Neptune atmospheric observations were assessed. Great distances must be traversed to fully assess outer planet storms and other atmospheric phenomena. The time for these traversals is long. For Uranus, the time for traversing 90 degrees at 100 m/s is approximately 111.5 hours. At 400 m/s, the travel time is 27.9 hours. At Neptune, the travel times are slightly lower, given the slightly smaller planet diameter. For examples, at Neptune, the flight at 100 m/s for the 90 degree traverse is 108.1 hours and at 400 m/s to traverse 90 degrees is 27 hours. The limited life of NTP ramjets makes for a relatively short observation period. Therefore, maintaining in-situ atmospheric observations for the numerous planet-wide storms will require a large fleet of UAVs. Alternatively, orbital observations may be preferred, while in-situ observations may be more attractive in only specialized cases.

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.

VIII. References


Figure 1. Fractions of captured atmospheric gases for Neptune.

Figure 2. Mining time versus the capture rate for Uranus.
Figure 3. Mining time versus the capture rate for Neptune.

Figure 4. Helium 3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune.
Figure 5. Uranus atmospheric phenomena (Reference 24)

Figure 6. Uranus atmospheric phenomena (Reference 23)
Figure 7. Neptune storm locations (Ref. 26)
Figure 8. Mission traverse time from location to location: Uranus
Figure 9. Mission traverse time from location to location: Neptune

Table 1: UAV travel time for various distances traveled.

<table>
<thead>
<tr>
<th>Degrees travelled</th>
<th>Time to traverse (hours)</th>
<th>100</th>
<th>120</th>
<th>150</th>
<th>200</th>
<th>225</th>
<th>250</th>
<th>275</th>
<th>300</th>
<th>325</th>
<th>350</th>
<th>375</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12.0</td>
<td>9.6</td>
<td>8.0</td>
<td>6.9</td>
<td>6.0</td>
<td>5.3</td>
<td>4.8</td>
<td>4.4</td>
<td>4.0</td>
<td>3.7</td>
<td>3.4</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>20</td>
<td>24.0</td>
<td>19.2</td>
<td>16.0</td>
<td>13.7</td>
<td>12.0</td>
<td>10.7</td>
<td>9.6</td>
<td>8.7</td>
<td>8.0</td>
<td>7.4</td>
<td>6.9</td>
<td>6.4</td>
<td>6.0</td>
</tr>
<tr>
<td>30</td>
<td>36.0</td>
<td>28.8</td>
<td>24.0</td>
<td>20.6</td>
<td>18.0</td>
<td>16.0</td>
<td>14.4</td>
<td>13.1</td>
<td>12.0</td>
<td>11.1</td>
<td>10.3</td>
<td>9.6</td>
<td>9.0</td>
</tr>
<tr>
<td>40</td>
<td>48.0</td>
<td>38.4</td>
<td>32.0</td>
<td>27.4</td>
<td>24.0</td>
<td>21.3</td>
<td>19.2</td>
<td>17.6</td>
<td>16.0</td>
<td>14.8</td>
<td>13.7</td>
<td>12.8</td>
<td>12.0</td>
</tr>
<tr>
<td>50</td>
<td>60.0</td>
<td>48.0</td>
<td>40.0</td>
<td>34.3</td>
<td>30.0</td>
<td>26.7</td>
<td>24.0</td>
<td>21.8</td>
<td>20.0</td>
<td>18.1</td>
<td>17.2</td>
<td>16.0</td>
<td>15.0</td>
</tr>
<tr>
<td>60</td>
<td>72.0</td>
<td>57.6</td>
<td>48.0</td>
<td>41.2</td>
<td>36.0</td>
<td>32.0</td>
<td>28.8</td>
<td>26.2</td>
<td>24.0</td>
<td>22.1</td>
<td>20.6</td>
<td>19.2</td>
<td>18.0</td>
</tr>
<tr>
<td>70</td>
<td>84.0</td>
<td>67.2</td>
<td>56.0</td>
<td>48.0</td>
<td>41.0</td>
<td>37.4</td>
<td>33.6</td>
<td>30.6</td>
<td>28.0</td>
<td>25.1</td>
<td>24.0</td>
<td>22.4</td>
<td>21.0</td>
</tr>
<tr>
<td>80</td>
<td>96.0</td>
<td>76.8</td>
<td>64.0</td>
<td>54.9</td>
<td>46.0</td>
<td>42.7</td>
<td>38.4</td>
<td>34.9</td>
<td>32.0</td>
<td>29.6</td>
<td>27.4</td>
<td>25.6</td>
<td>24.0</td>
</tr>
<tr>
<td>90</td>
<td>108.1</td>
<td>86.4</td>
<td>72.0</td>
<td>61.7</td>
<td>54.0</td>
<td>48.0</td>
<td>43.2</td>
<td>39.3</td>
<td>36.0</td>
<td>33.2</td>
<td>30.9</td>
<td>28.8</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Figure 10. Time versus speed for storm circumnavigation.
Figure 11. Nuclear Ramjet Engine Integrated into Robotic Aircraft / UAV (Ref. 27)

Inside SLAM

SLAM’s simple but revolutionary design called for the use of nuclear ramjet power, which would give the missile virtually unlimited range. Air forced into a duct as the missile flew would be heated by the reactor, causing it to expand and exhaust out the back, providing thrust.

Figure 12. Nuclear Ramjet Engine Integrated into Robotic Aircraft / UAV (Ref. 27a)
Figure 13. UAV mass, 10 km/s delta-V capability, Mtank = 0.1 Mp.

Figure 14. NTP reactor lifetime, operating temperatures, and specific impulse for solid core NTR (Ref. 28)
Appendix A: AMOSS Mission Planning Profiles

AMOSS UAV Mission Profiles
(Multiple Targets Assessed, Round Trip)

Figure A1. AMOSS Mission planning, multiple targets, round trip.

AMOSS UAV Mission Profiles
(Multiple Targets Assessed, Two Hemispheres, One Way)

Figure A2. AMOSS Mission planning, multiple targets, two hemispheres, one-way trip.
Figure A3. AMOSS Mission planning, multiple targets, two hemispheres, round trip.

Appendix B: Issues for Cryogenic Environments

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 B1. Issues for cryogenic outer planet and moon surface operations.