

Atmospheric Mining in the Outer Solar System: Aerial Vehicle Reconnaissance and Exploration Options

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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
H ₂	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
O ₂	Oxygen
PPB	Parts per billion
UAV	Uninhabited Aerial Vehicle

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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

	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

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

- 1) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: Resource Capturing, Exploration, and Exploitation," AIAA 2013-3765, August 2013.
- 2) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: Resource Capturing, Storage, and Utilization," AIAA 2012-3742, August 2012.
- 3) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: Issues and Challenges for Mining Vehicle Propulsion," AIAA 2011-6041, August 2011.
- 4) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: University Studies of Mining Vehicles and Propulsion," AIAA 2010-6573, August 2010.
- 5) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: Mining Design Issues and Considerations," AIAA 2009-4961, August 2009.
- 6) Palaszewski, B., "Atmospheric Mining in the Outer Solar System: Orbital Transfer Vehicles and Outer Planet Moon Base Options," AIAA 2008-4861, July 2008.
- 7) Palaszewski, B., "Atmospheric Mining In The Outer Solar System: Mission Scenarios and Options For In-Situ Resource Utilization." AIAA 2007-5598, July 2007.
- 8) Palaszewski, B., "Atmospheric Mining in The Outer Solar System: Vehicle Sizing Issues." AIAA 2006-5222, July 2006.
- 9) Palaszewski, B., "Atmospheric Mining in the Outer Solar System," AIAA 2005-4319, July 2005.
- 10) R. Frisbee, "Advanced Space Propulsion for the 21st Century," Journal of Propulsion and Power, Vol. 19, No. 6, Nov-Dec 2003.
- 11) Dunn, Bruce P., "High-Energy Orbit Refueling for Orbital Transfer Vehicles," Journal of Spacecraft and Rockets Volume. 24, No. 6, 1987, pp. 518-522.
- 12) Noca, M.; Polk, J. E. "Ion Thrusters And LFAs For Outer Planet Exploration," AAF 6th International Symposium; Versailles; France, May 2002.
- 13) Hunt, James L., Laruelle, Gerard, Wagner, Alain, "Systems Challenges for Hypersonic Vehicles;" AGARD Interpanel Symposium on Future Aerospace Technology in Service to the Alliance, NASA-TM-112908, AGARD-Paper-C37, 1997.
- 14) Starr, Brett R.; Westhelle, Carlos H.; Masciarelli, James P., "Aerocapture Performance Analysis For A Neptune-Triton Exploration Mission," NASA/TM-2006-214300, April 2006.

- 15) Bussard, R., "ASPEN II: Two Staging and Radiation Shielding Effects on ASPEN Vehicle Performance," LA-26-80, 09/06/1967 and in "ASPEN: Nuclear Propulsion for Earth to Orbit Aerospace Plane Vehicles," Robert W. Bussard, Proceedings International Conference on Spaceflight, Rome. June 1971.
- 16) Bussard, R., and Jameson, L.W.; "The QED Engine Spectrum: Fusion-Electric Propulsion for Airbreathing to Interstellar Flight," AIAA paper 93-2006, 29th Joint Propulsion Conference, Monterey, CA 6/28 to 6/30/1993; in JPP, Volume 11, Number 2, pp 365/372.
- 17) Borowski, Stanley K.; Dudzinski, Leonard A.; and McGuire, Melissa L.: "Artificial Gravity Vehicle Design Option for NASA's Human Mars Mission Using "Bimodal" NTR Propulsion," AIAA Paper 99-2545, 1999.
- 18) Kendall, J. S.; Stoeffler, R. C., "Conceptual design studies and experiments related to cavity exhaust systems for nuclear light bulb configurations," Report Number: L-910900-15; NASA-CR-129298
- 19) Latham, T. S.; Rodgers, R. J., "Small nuclear light bulb engines with cold beryllium reflectors," Report Number: AIAA PAPER 72-1093.
- 20) Latham, T. S., "Summary of the performance characteristics of the nuclear light bulb engine," Report Number: AIAA PAPER 71-642.
- 21) Rodgers, R. J.; Latham, T. S., "Analytical design and performance studies of the nuclear light bulb engine," Report Number: L-910900-16; NASA-CR-129295.
- 22) RONALD GREELEY, et al., "A Scientific Rationale for *Mobility* in Planetary Environments," Committee on Planetary and Lunar Exploration, National Research Council, NATIONAL ACADEMY PRESS, Washington, D.C. 1999.
- 23) Herbert, F. and Sandel, B.R., "Ultraviolet observations of Uranus and Neptune," Planetary and Space Science Vol. 47, pp. 1119 to 1139, Published by Elsevier Science Ltd.
- 24) Sromovsky, L.A., et al., "Episodic bright and dark spots on Uranus" Icarus, Vol. 220 (2012), pp. 6-22.
- 25) K.A. Rages, H.B. Hammel, A.J. Friedsond, "Evidence for temporal change at Uranus' south pole," Icarus, Vol. 172 (2004), pp. 548-554).
- 26) L. A. Sromovsky and P. M. Fry, et al. "Coordinated 1996 HST and IRTF Imaging of Neptune and Triton III: Neptune's Atmospheric Circulation and Cloud Structure," Icarus, Vol. 149 (2001)., pp. 459-488.
- 27) Turba, R.D., "DESIGN OF A NUCLEAR PROPULSION SYSTEM FOR AN UNMANNED AERIAL VEHICLE," Vanderbilt University, Masters Thesis, May 2011.
- 27a) Maise, George; Powell, James; Paniagua, John; Ludewig, Hans; Todosow, Michael, "Exploration of Jovian atmosphere using nuclear ramjet flyer," IAF Paper 98-S608, 1998.
- 28) Borowski, S., "Human lunar mission capabilities using SSTO, ISRU and LOX-augmented NTR technologies - A preliminary assessment," AIAA 1995-0026, 1995.

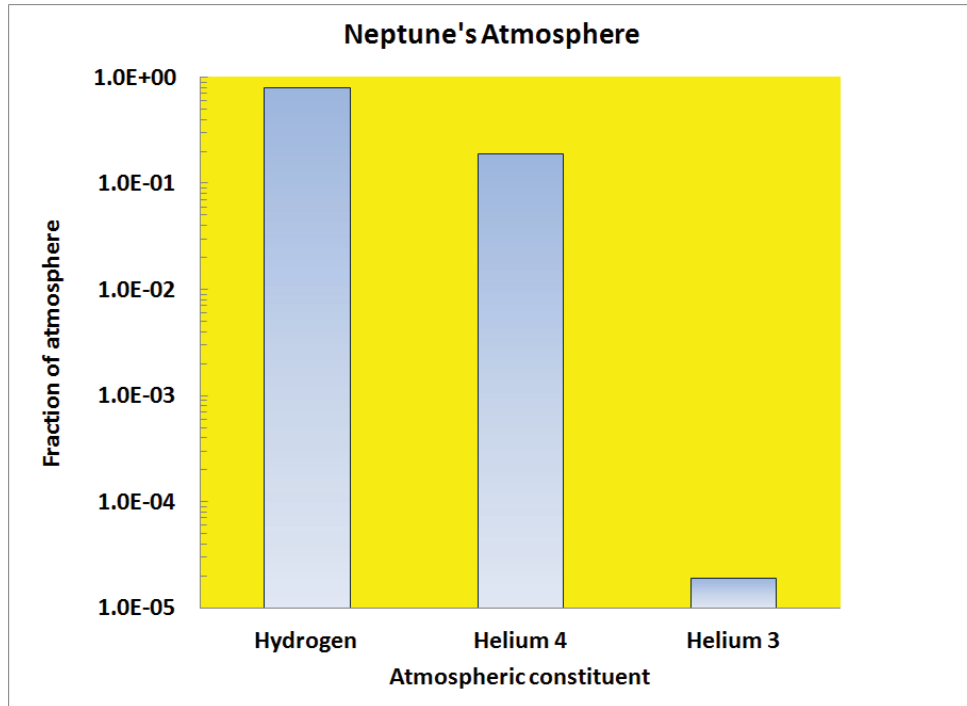


Figure 1. Fractions of captured atmospheric gases for Neptune

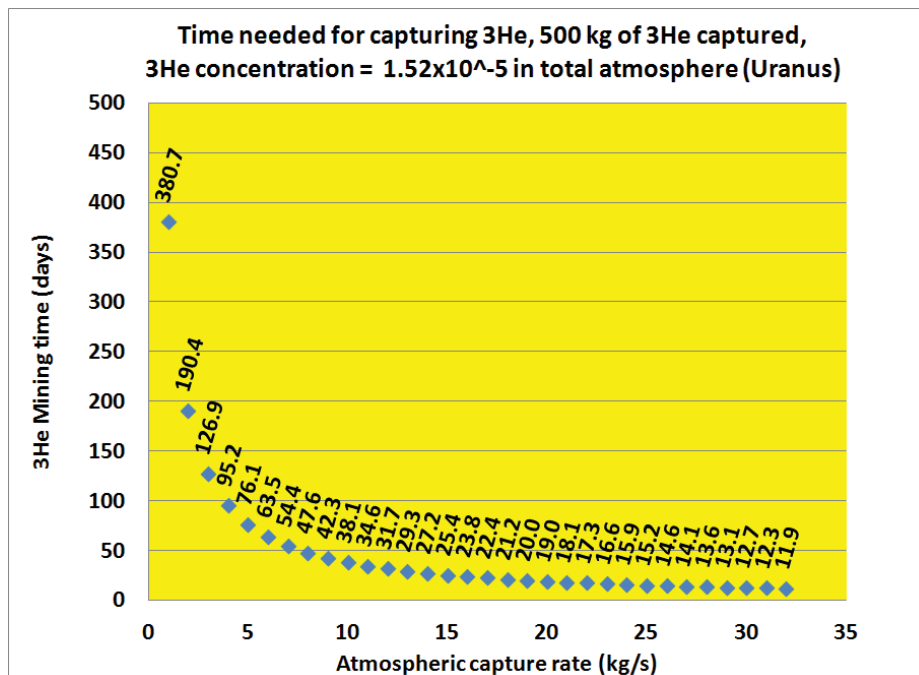


Figure 2. Mining time versus the capture rate for Uranus.

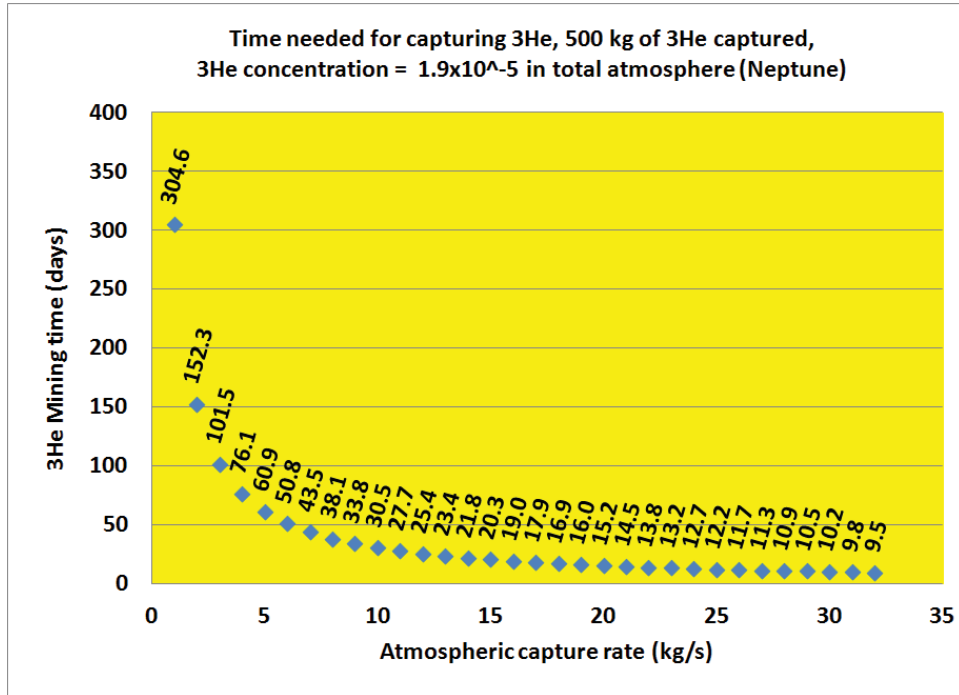


Figure 3. Mining time versus the capture rate for Neptune.

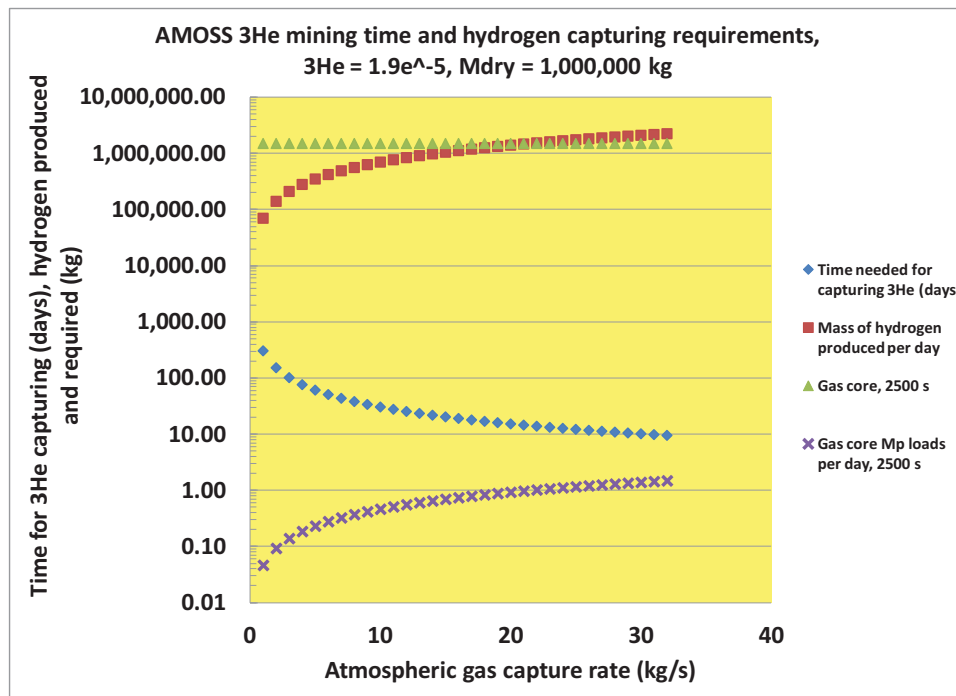


Figure 4. Helium 3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune

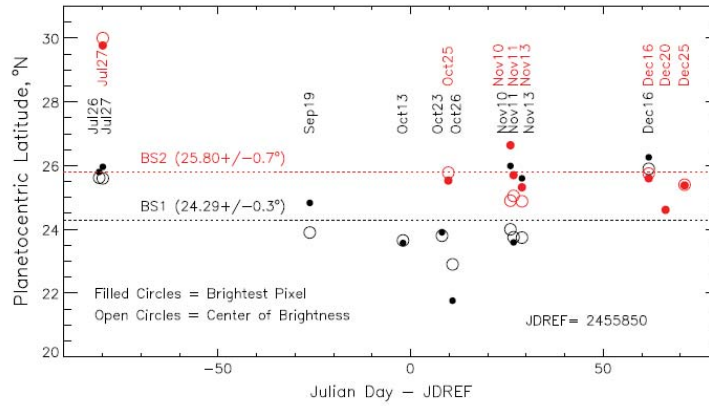


Fig. 8. Latitude observations vs time for BS1 (black) and BS2 (red), using locations of brightness peak (filled circles) and center-of-brightness locations (open circles).

Figure 5. Uranus atmospheric phenomena (Reference 24)

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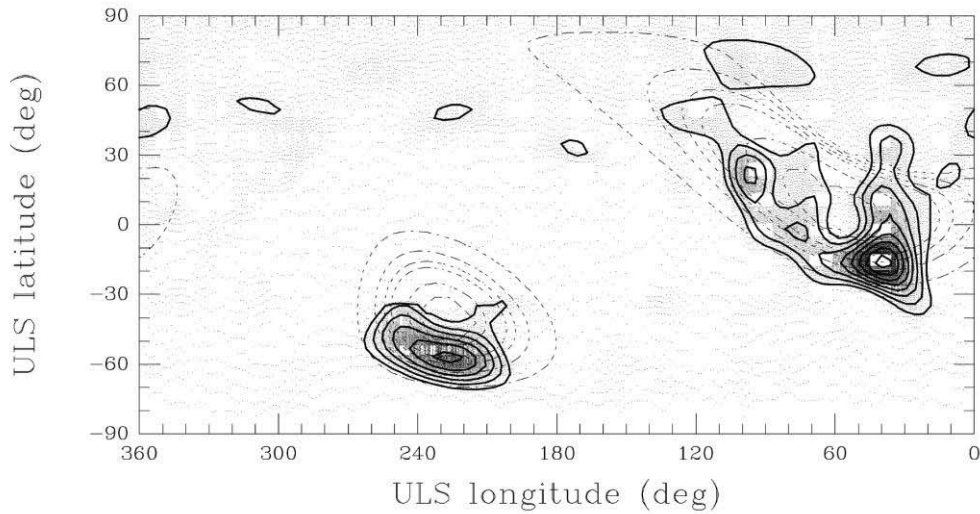


Fig. 19. Map of Uranus' aurora in geographic coordinates ('Uls'), defined by Ness et al. (1986). Contours and half-tone darkening portray the H_2 band emission intensity distribution, with approximately 20 R contour intervals (starting at 60 R, peaks at 170 and 200 R). The dashed lines are contours of constant L (as defined in the text) and so encircle the magnetic poles. The L values, from the outside in, are 2–5, 10, and 20. Figure redrawn from fit data, but similar to Fig. 2 of Herbert and Sandel (1994).

Figure 6. Uranus atmospheric phenomena (Reference 23)

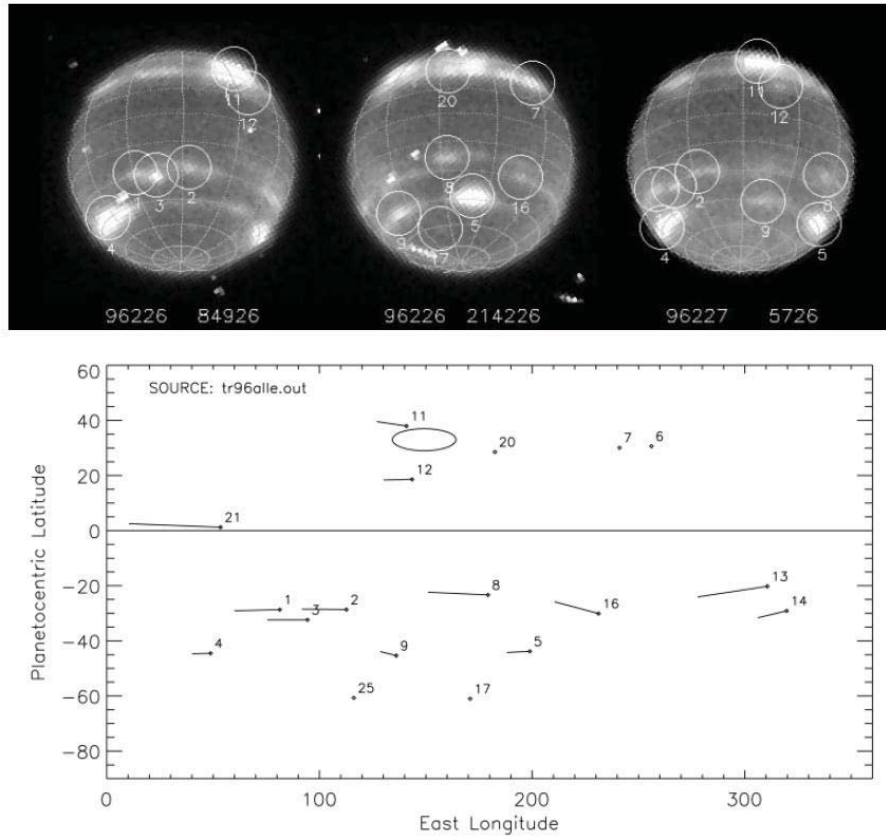
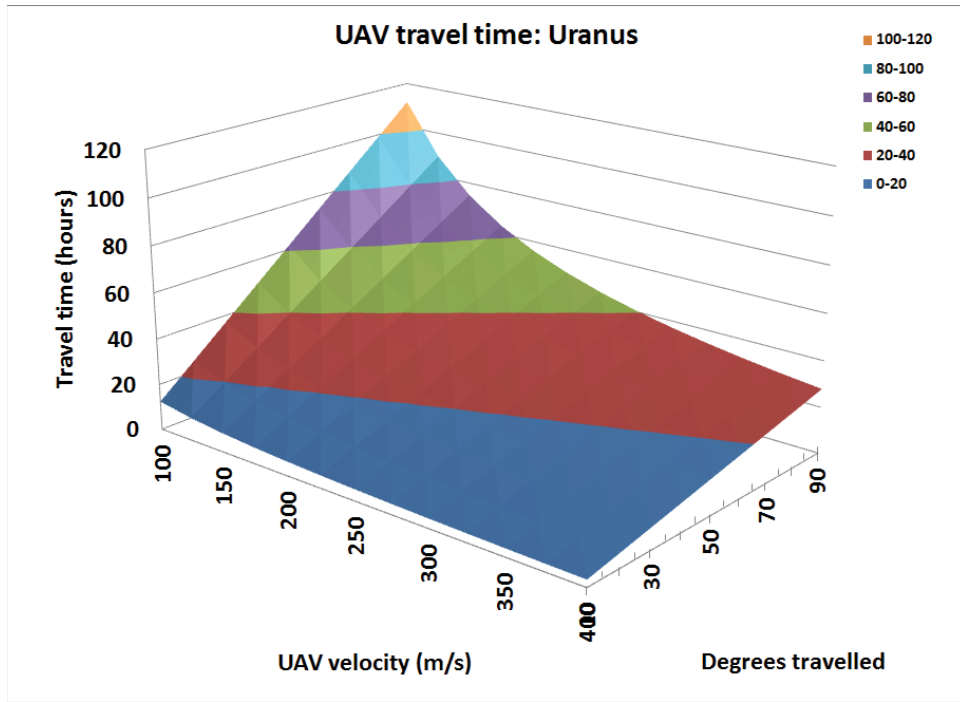


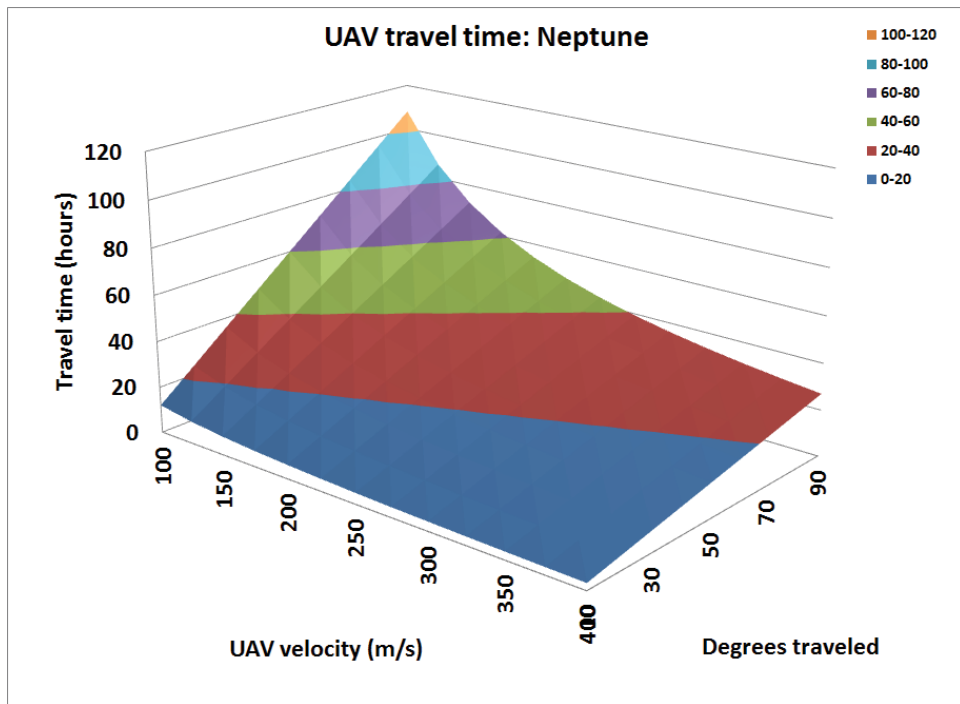
FIG. 1. (Top) Samples of 1996 FQCH4N-D ($0.89 \mu\text{m}$) HST images (left and center) and an F850LP image (right) used for cloud tracking. Circles centered on cloud targets are labeled by target number at the bottom of each circle. Image times at the midpoint of the exposures are noted in YYDDD HHMMSS format. Grid lines are spaced 15° in latitude and 30° in longitude. North is up. (Bottom) The mean locations of bright cloud targets in August 1996 HST observations. Wind vectors with uncertainties $< 80 \text{ m/s}$ for u and $< 50 \text{ m/s}$ for v are plotted with a scale factor of 10 m/s per degree of longitude (u) or latitude (v). The vector tails are at the plotted points. The approximate position of 1996 NGDS-32 is shown as an ellipse (see Section 3.1).

Figure 7. Neptune storm locations (Ref. 26)



Degrees travelled	Time to traverse (hours)												
Distance traveled (km)	100	125	150	175	200	225	250	275	300	325	350	375	400
10	12.4	9.9	8.3	7.1	6.2	5.5	5.0	4.5	4.1	3.8	3.5	3.3	3.1
20	24.8	19.8	16.5	14.2	12.4	11.0	9.9	9.0	8.3	7.6	7.1	6.6	6.2
30	37.2	29.7	24.8	21.2	18.6	16.5	14.9	13.5	12.4	11.4	10.6	9.9	9.3
40	49.6	39.7	33.0	28.3	24.8	22.0	19.8	18.0	16.5	15.3	14.2	13.2	12.4
50	62.0	49.6	41.3	35.4	31.0	27.5	24.8	22.5	20.7	19.1	17.7	16.5	15.5
60	74.3	59.5	49.6	42.5	37.2	33.0	29.7	27.0	24.8	22.9	21.2	19.8	18.6
70	86.7	69.4	57.8	49.6	43.4	38.6	34.7	31.5	28.9	26.7	24.8	23.1	21.7
80	99.1	79.3	66.1	56.6	49.6	44.1	39.7	36.0	33.0	30.5	28.3	26.4	24.8
90	111.5	89.2	74.3	63.7	55.8	49.6	44.6	40.6	37.2	34.3	31.9	29.7	27.9

Figure 8. Mission traverse time from location to location: Uranus



Degrees travelled	Time to traverse (hours)												
Distance traveled (km)	100	125	150	175	200	225	250	275	300	325	350	375	400
10	12.0	9.6	8.0	6.9	6.0	5.3	4.8	4.4	4.0	3.7	3.4	3.2	3.0
20	24.0	19.2	16.0	13.7	12.0	10.7	9.6	8.7	8.0	7.4	6.9	6.4	6.0
30	36.0	28.8	24.0	20.6	18.0	16.0	14.4	13.1	12.0	11.1	10.3	9.6	9.0
40	48.0	38.4	32.0	27.4	24.0	21.3	19.2	17.5	16.0	14.8	13.7	12.8	12.0
50	60.0	48.0	40.0	34.3	30.0	26.7	24.0	21.8	20.0	18.5	17.2	16.0	15.0
60	72.0	57.6	48.0	41.2	36.0	32.0	28.8	26.2	24.0	22.2	20.6	19.2	18.0
70	84.0	67.2	56.0	48.0	42.0	37.4	33.6	30.6	28.0	25.9	24.0	22.4	21.0
80	96.0	76.8	64.0	54.9	48.0	42.7	38.4	34.9	32.0	29.6	27.4	25.6	24.0
90	108.1	86.4	72.0	61.7	54.0	48.0	43.2	39.3	36.0	33.2	30.9	28.8	27.0

Figure 9. Mission traverse time from location to location: Neptune

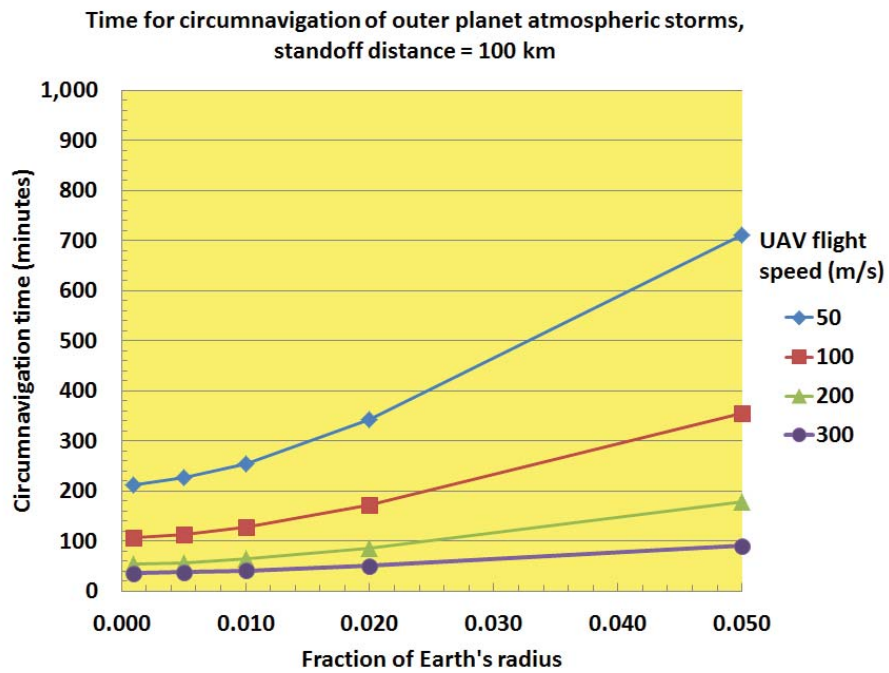


Figure 10. Time versus speed for storm circumnavigation.

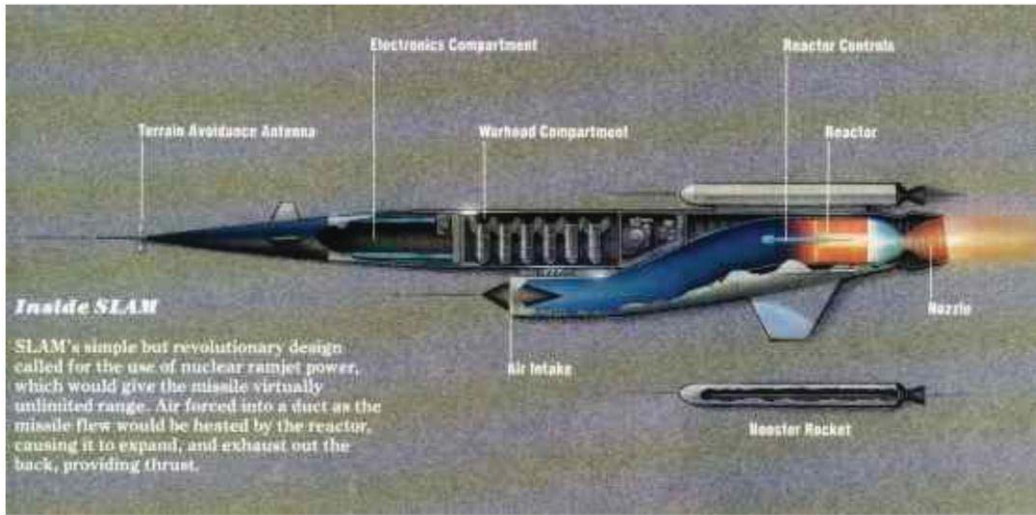


Figure 11. Nuclear Ramjet Engine Integrated into Robotic Aircraft / UAV (Ref. 27)

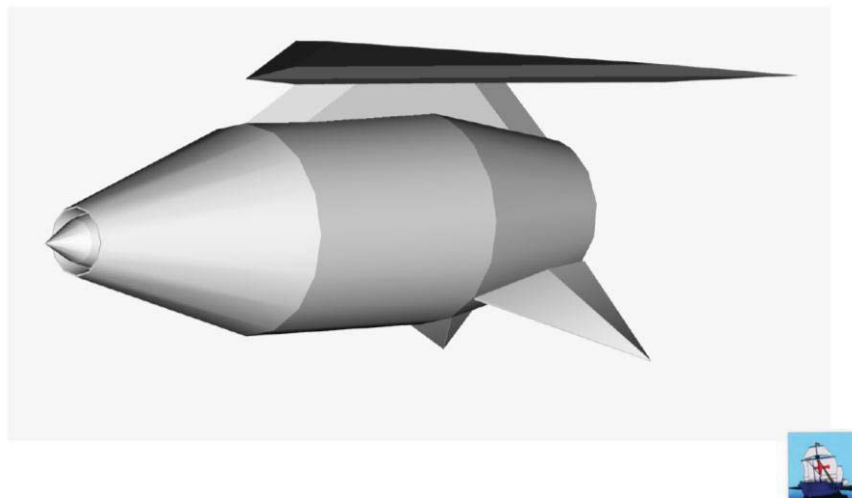


Figure 12. Nuclear Ramjet Engine Integrated into Robotic Aircraft / UAV (Ref. 27a)

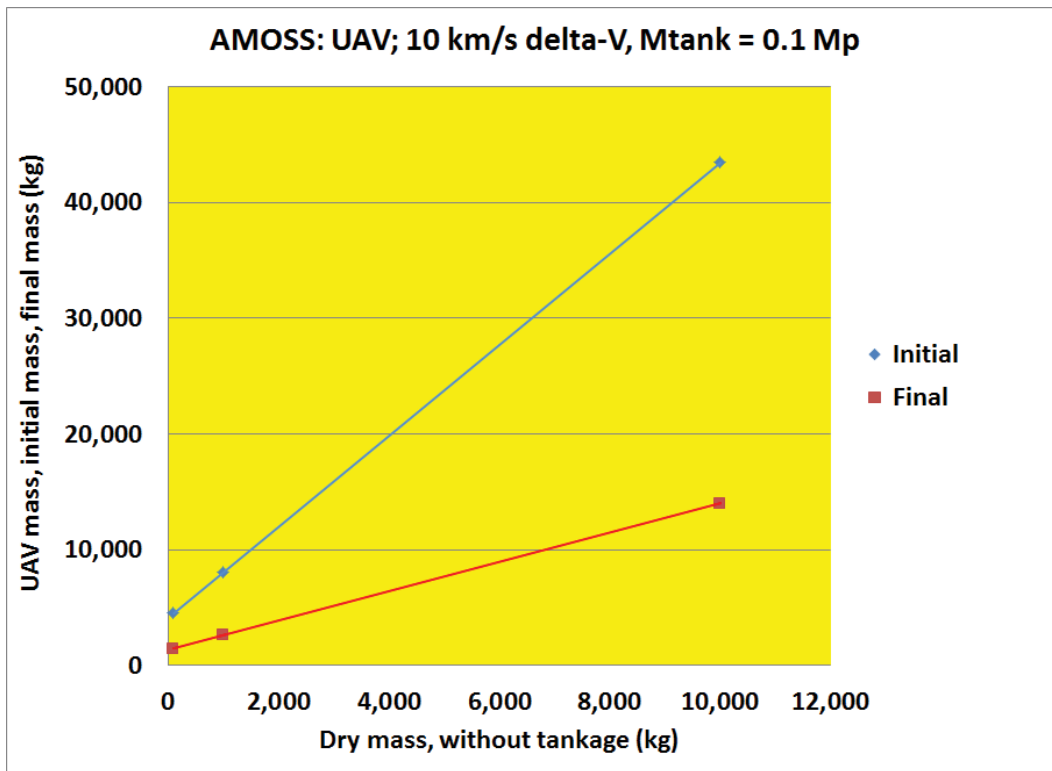


Figure 13. UAV mass, 10 km/s delta-V capability, Mtank = 0.1 Mp.

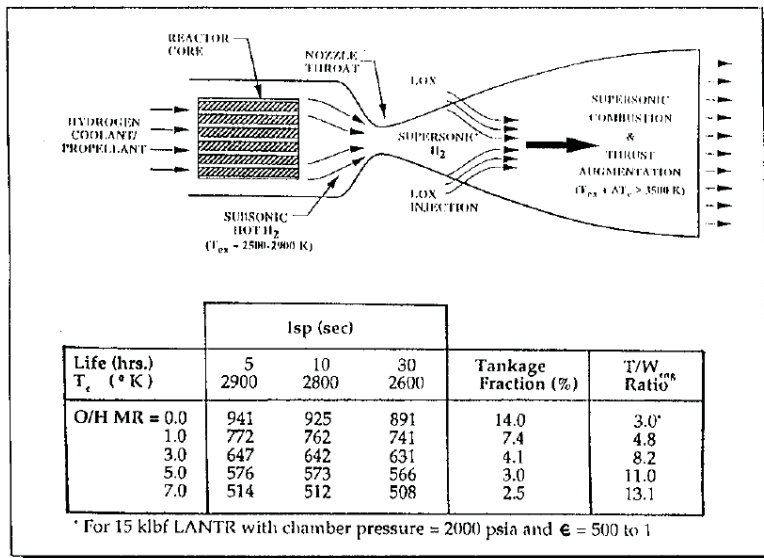


Fig. 3 Schematic/Characteristics of LOX-Augmented NTR

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)**

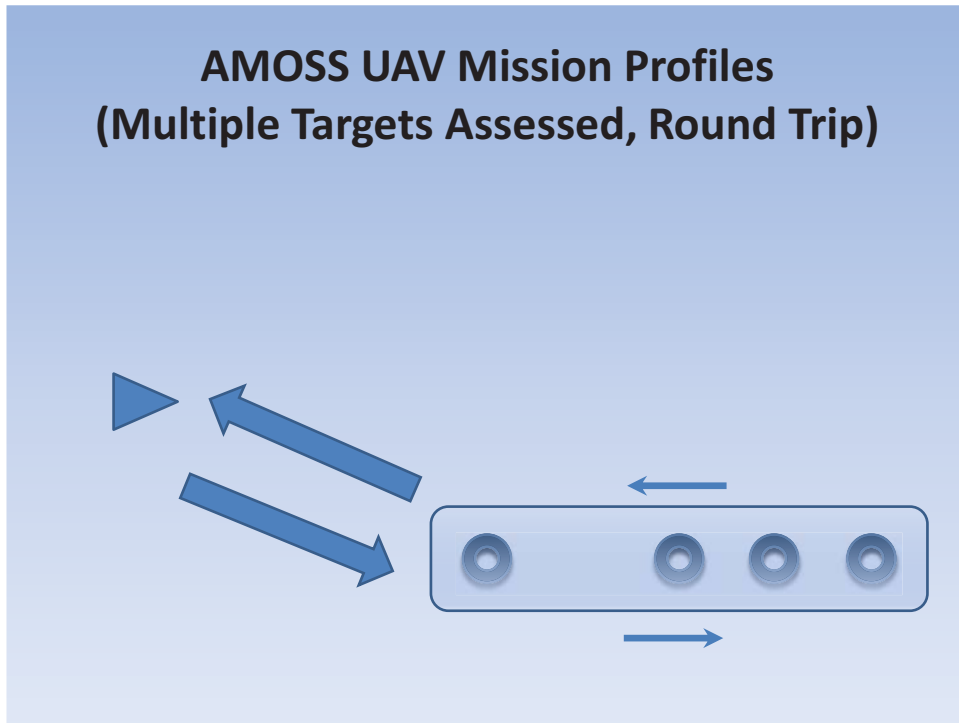


Figure A1. AMOSS Mission planning, multiple targets, round trip.

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

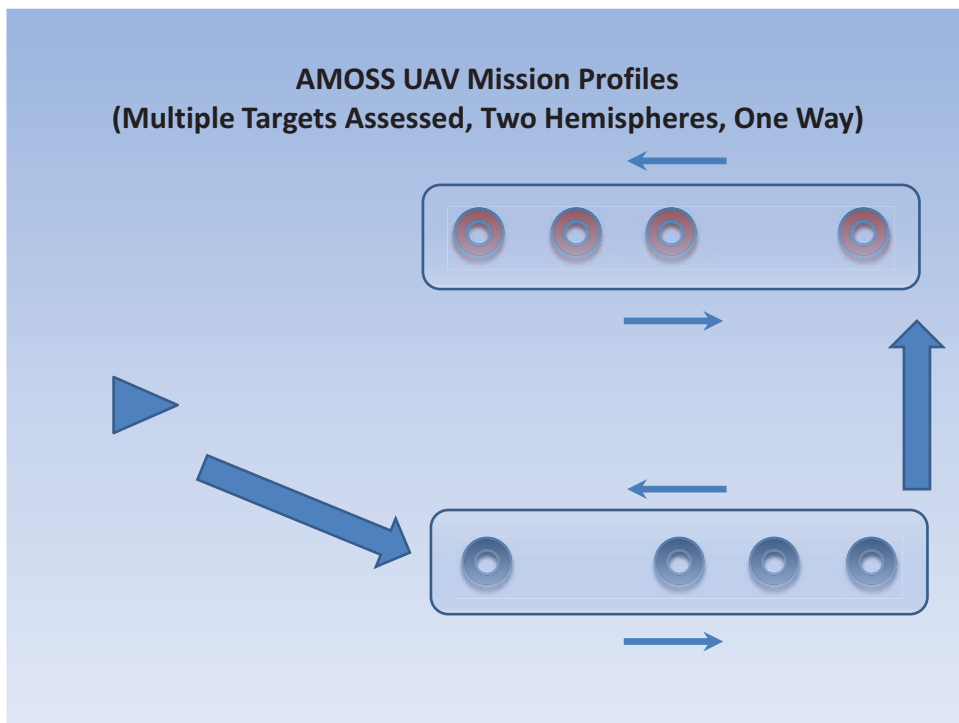


Figure A2. AMOSS Mission planning, multiple targets, two hemispheres, one-way trip.

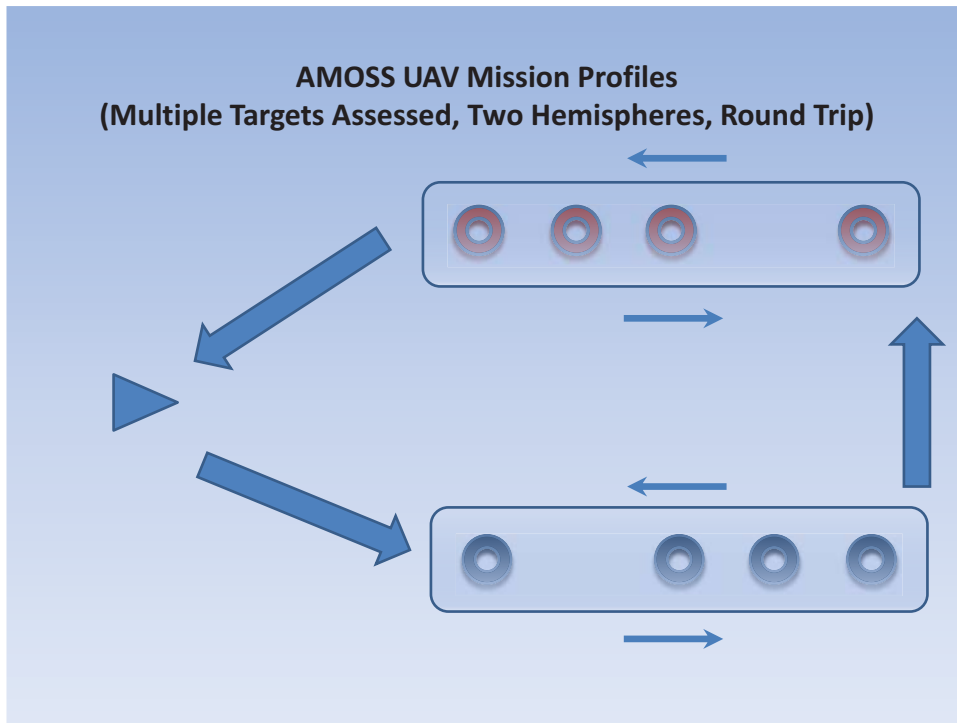


Figure A3. AMOSS Mission planning, multiple targets, two hemispheres, round trip.

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.