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Atmospheric Mining in the Outer Solar System: Resource Capturing, Exploration, and Exploitation

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Summary

Atmospheric mining in the outer solar system (AMOSS) 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. ^3He 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 AMOSS. These analyses 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 helium 4 (^4He) are produced. With these two additional gases, the potential exists for fueling small and large fleets of additional exploration and exploitation vehicles. Additional aerospacecraft or other aerial vehicles (UAVs, balloons, rockets, etc.) could fly through the outer-planet atmosphere to investigate cloud formation dynamics, global weather, localized storms or other disturbances, wind speeds, the poles, and so forth. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess hydrogen or ^4He may be designed to probe the higher density regions of the gas giants.

Nomenclature

^3He	helium 3
^4He	helium (or helium 4)
AMOSS	atmospheric mining in the outer solar system
delta-V	change in velocity (km/s)
GPS	Global Positioning System
ISRU	In-Situ Resource Utilization
I_{sp}	specific impulse (s)
M_p	propellant mass
MT	metric tons
NTP	nuclear thermal propulsion
NTR	nuclear thermal rocket
UAV	unmanned aerial vehicle

Atmospheric Mining in the Outer Solar System

Atmospheric mining of the outer solar system (AMOSS) 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's 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. Preliminary estimates of the masses of the mining vehicles have been created (Refs. 1 to 8), and additional supporting vehicles may enhance the mining scenarios (Refs. 9 to 20). 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 or deliver them to other destinations).

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 (Refs. 1 to 8). To power these vehicles, atmospheric hydrogen gas would be liquefied and used as a rocket propellant for the ascent to orbit. A nuclear gas-core rocket is a likely candidate for the cruiser (Figure 1, Refs. 17 to 20). Gaseous or liquid hydrogen would be used to power the engines during atmospheric mining operations. Helium 3 (^{3}He) would be separated from the atmospheric hydrogen, and helium (helium 4, ^{4}He) would be captured, liquefied, and stored as a payload that would be returned to orbit. Table I and Figure 2 provide the amount of ^{3}He in the outer-planet atmospheres (Ref. 1). Figure 3 and Figure 4 show the mining time versus the capture rate for Uranus and Neptune, respectively (Ref. 1). A 500-kg payload of ^{3}He is captured during the mining time.

Figure 5 and Figure 6 provide the sizing of the gas-core-powered vehicles and a comparison of the solid-core and gas-core vehicle options, respectively (Refs. 1 and 2). The relatively low thrust-to-weight ratio of the nuclear engines may necessitate the use of a more advanced gas-core nuclear engine over the solid-core nuclear thermal propulsion (NTP). Although the gas-core engine is likely more attractive for mining missions that require a return to orbit, other smaller nuclear thermal engines will be more applicable to atmospheric exploration missions that do not require orbital access.

AMOSS can be a 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 have been developed (Refs. 1 and 2). The 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. Although 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 ^{4}He during the mining process. Very large masses of hydrogen and ^{4}He are produced every day during the often lengthy process of ^{3}He capture and gas separation. Figure 7 shows the mass of hydrogen needed for the gas-core rocket and the potentially excess hydrogen captured every day (Ref. 1). 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. Aerial vehicle designs can take on many configurations. Additional aerospacecraft or other unmanned aerial vehicles (UAVs), balloons, rockets, and so forth, could fly through the outer-planet atmospheres for activities such as global weather observations, localized storm or other disturbance investigations, wind speed measurements, and polar observations. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess hydrogen or ^{4}He may be designed to probe the higher density regions of the gas giants.

Based on these analyses, there will likely be several possible future ways to effectively use the gases of the outer planets for exciting and scientifically important atmospheric exploration missions. The analyses focused on Uranus and Neptune, as these planets offer vast reservoirs of fuels that are more readily accessible than those from Jupiter and Saturn (as Uranus and Neptune require lower energies needed to attain orbit and present less danger from powerful atmospheric lightning) and, with the advent of nuclear fusion propulsion, may offer us the best option for fast interplanetary travel and the first practical interstellar flight.

Atmospheric Exploration Missions and Vehicles

This section will discuss the issues of future atmospheric exploration and the vehicles that may conduct that exploration.

Uranus and Neptune—Clouds and Dynamism

A series of exploration missions for the Uranus and Neptune clouds and overall atmosphere would yield many great discoveries of their dynamics. Appendix A provides a number of cloud images from Earth-based (Keck) and space-based (Hubble) telescopes and spacecraft (Voyager). Appendix B notes the cloud changes of many years of observations (Refs. 21 to 29). As an example, when the Voyager spacecraft flew by Neptune in 1989, it photographed the Great Dark Spot at 15° south latitude. Imaging conducted by the Hubble Space Telescope in 1991, 1996, and 1998 revealed that the Spot had completely disappeared, and no other clouds or disturbances were seen on or near that latitude (Refs. 25 to 29). At Uranus, the cloud structures were revealed with Earth-based telescopes and the Hubble Space Telescope in the 1990s and 2000s, whereas previous Voyager flyby images (from 1986) showed no clouds (Refs. 21 to 24). Gathering data on the clouds' dynamics and the related atmospheric wind speeds can be accomplished with in situ UAV flights. Measuring wind velocities at varying altitudes can lead to improved understanding of the lifetime of the cloud features noted in the telescopic observations of the atmosphere. Also, atmospheric sampling may reveal the best places or safest places for ^{3}He or hydrogen mining, or both. Thus, with the right array of probes and UAVs, exploration and exploitation of the atmospheric phenomena and resources can be simultaneously conducted.

Atmospheric Exploration Vehicles

A series of UAV and probe concepts were identified for atmospheric exploration. Table II provides the classes of probes and UAVs that can significantly augment future atmospheric exploration. Probes that use free fall or parachutes as they take data in the atmosphere are the first and most mature option. The Galileo Probe shown in Figure 8 (Refs. 30 and 31) is the baseline for many future atmospheric probe missions. A more aggressive approach to probe- or UAV-based exploration is the rocket assisted probe. As it can take many hours to access the deeper parts of the atmosphere (Ref. 32), a rocket assist to accelerate the probe to deep depths was considered. In addition to this, a rocket return was also conceived. Of course, high-pressure atmospheric flight operation of such vehicles will be a major challenge. Table III shows the ranges of masses for the probes and UAVs. The mass of the vehicles may be high based on the structure and wall thicknesses to withstand many atmospheres of pressure. Unique designs using pulsed detonation engines have been conceived, and such high-pressure detonation engines may be crucial to any future designs. Alternatively, balloons may be inflated to allow rapid ascent of the probe to higher altitudes. Balloons for rising to higher attitude may be a lower mass option than the rocket return, but a high-speed option for gaining altitude may be essential (for escaping high winds, wind shear, etc.), favoring the rocket return option. Taking advantage of more traditional UAV designs will also provide many operational benefits. Remote-sensing instruments on subsonic winged UAVs can potentially provide extensive data sets on outer-planet winds, cloud dynamics, and cloud formation. References 33 to 41 provide a range of applicable UAV designs and engine options.

Short-term observations (of several hours) can be accomplished with atmospheric entry probes that enter and then begin parachuting to lower altitudes. After a Galileo-class probe's atmospheric entry, it would slow to Mach 1 and deploy a parachute, sending back data for approximately 60 min (Ref. 30). Alternatively, the probe can be cut free of the parachute, and the lower altitudes can be attained more quickly in free fall. Figure 9 depicts the descent time for atmospheric probes exploring Uranus's and Neptune's atmosphere (Ref. 32).

As noted in Reference 32,

> "The times to descend to a given pressure level are shown in Figures 7(a) and 7, for Uranus and Neptune, respectively. The maximum time boundary is associated with a complete descent on the parachute as shown by the upper descent profile in the figures. Descent times to a pressure level of 200 bar on the parachute are about 5.5 hr in the Uranus atmosphere and 4.4 hr in the Neptune atmosphere. To descend to 400 bar will require 8 hr at Uranus and 7 hr at Neptune. These times are very large compared to with the actual descent time for the Galileo Probe at Jupiter (of 1 hr). The Galileo Descent Module was designed to reach a pressure level of about 10 to 20 bar before either the system fails or the communications are terminated.
>
> The principal design problems associated with long descent times for Uranus and Neptune are: (1) maintaining the line of sight communications between the UAV or aerospacecraft and the probe for such a long period and (2) providing sufficient power during the long descent."

A UAV for AMOSS can be used as a data relay for the deep probes to cover their descent, which can take many hours. With nuclear atmospheric gas-powered UAVs, the relay and exploration functions can be completed by two complementary vehicles. One UAV will fly near the top of the atmosphere while the other conducts the deeper atmospheric surveys. Figure 10 shows the line-of-sight data transmission visibility geometry (Ref. 32). As the complementary UAVs will both be in the atmosphere, the transmission visibility issues will be ameliorated.

Figure 11, Figure 12, and Figure 13 provide a series of UAV configuration options: supersonic and subsonic (Refs. 36 and 37). Atmospheric gases are very attractive fuel for future UAV nuclear engines (Refs. 38 to 41). A ramjet UAV was investigated for operation on the Jovian atmosphere (Refs. 39 and 40). Figure 13 illustrates the nuclear ramjet (Refs. 39 to 42). The ramjet design is based on a small nuclear reactor called MITEE (Refs. 39 to 41). The engine inlet takes in the outer-planet atmospheric gases, feeds it to the reactor, and the reactor heats the gases and expands them through a nozzle for propulsion. Engine masses for the reactors are noted in Table IV (Refs. 38 to 41). Final designs must be based on specific configurations and the pressure field during the deep atmospheric flight.

The mass of each of the rocket-assisted UAVs was predicted for a range of vehicle delta-V values. Total UAV delta-V values were selected at 1, 5, and 10 km/s. Figure 14 and Figure 15 are for the 1 km/s delta-V cases, Figure 16 and Figure 17 represent the cases for the 5-km/s delta-V values, and Figure 18 and Figure 19 show the results for UAVs with a 10-km/s delta-V capability. The vehicle dry mass (tank dry mass, without propellant) range was 0 to 10 000 kg. This mass range was selected to accommodate a range of dry mass values for a wide range of expected atmospheric pressures. More detailed analyses are needed to assess the specific masses for specific configurations. Tankage dry mass fractions were set at 2 and 10 percent of the total propellant mass (or 0.02 and 0.10 M_p). The engine specific impulse (I_{sp}) was selected to represent a nuclear engine at an I_{sp} of 900 s. The UAV payload mass was 1000 kg. For a 1-km/s delta-V UAV, a tankage mass of 0.10 M_p, and a 10 000-kg dry mass, the mass is approximately 12 530 kg. For 10-km/s delta-V, a tankage mass of 0.10 M_p, and a 10 000-kg dry mass, the mass is approximately 44 450 kg. For example, the 10 km/s delta-V UAVs would have a capability of 1/2 orbital speed and may allow simultaneous measurements with two of more UAVs on opposite sides of the planet. More detailed mission analyses can lead to specific mission selections for polar or more equatorial exploration flights or multivehicle campaigns.

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, and so forth
- Global Positioning System (GPS) vehicles in outer-planet orbits for navigation
- Observational satellite for outer-planet weather monitoring, diverting cruisers from harm

Also, Appendix B illuminates some of the issues to be analyzed. Appendix C contains gas and shock properties for a hydrogen-helium atmosphere (85 percent hydrogen and 15 percent helium by volume), and Appendix D provides some data of detonation engines operating in extremely high-pressure environments.

Concluding Remarks

Atmospheric mining at Uranus and Neptune can allow for the production of fuels for significant exploration and exploitation missions. While capturing helium 3 (^3He), large amounts of hydrogen and helium 4 (^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 (unmanned 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 UAV aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess hydrogen or ^4He may be designed to probe the higher density regions of the gas giants. Both nuclear ramjet and other rocket-powered probes were suggested. As there are powerful wind shear forces in the atmosphere, a compact ramjet UAV may be a best choice. The high aspect ratio and flexibility of a low-subsonic UAV may lead to serious damage during its flight due to wind shear.

The mass of the rocket-assisted UAVs was predicted for a range of vehicle delta-V values. For a 1 km/s delta-V UAV, the highest mass is approximately 12 530 kg. For 10 km/s, the largest mass was approximately 44 450 kg. The 10 km/s delta-V UAVs would have a 1/2 orbital speed capability, and may allow simultaneous measurements with each on opposite sides of the planet. Issues of storing the large caches of propellants not needed for the orbital ^3He deliveries must be addressed. Small or large cryogenic hydrogen and helium tank farms in the atmosphere may be a solution. As the production rate and the amount of hydrogen and helium are high, the tank farms may have a similar configuration to the large aerospacecraft that carry the ^3He to orbit.

TABLE I.—FRACTION OF ^{3}He IN OUTER-PLANET ATMOSPHERES

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

TABLE II.—PROBE AND UNMANNED AERIAL VEHICLE (UAV) CLASSES

Probes in free fall (no parachutes)
Probes (with parachutes)
Probes with rocket booster for accelerated attainment of low altitude (deep probe)
Probes with rocket (booster) return for return to high altitude
UAV (long persistence)
Mining aerospacecraft (long persistence)

TABLE III.—PROBE AND UNMANNED AERIAL VEHICLE (UAV) MASS REGIMES

Exploration UAV size ranges	
Probe design	Mass, MT
Free fall	1 to 10
Parachute	1 to 10
Rocket boost	10 to 100
Rocket return	10 to 1000
Long duration, subsonic	10 to 1000
Aerospacecraft (mining)	100 to 10 000

TABLE IV.—UNMANNED AERIAL VEHICLE (UAV) NUCLEAR ENGINE MASSES AND THRUST LEVELS (REFS. 38 TO 41)

Engine	Mass, kg	Thrust, lbf
MITEE	200.0	14 000
Nuclear thermal rocket (NTR)	2223.5	15 000

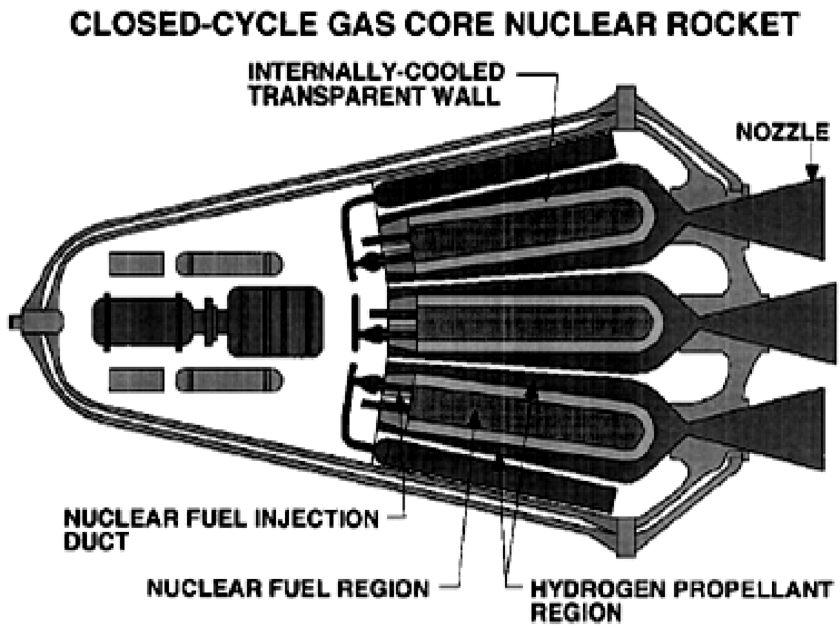


Figure 1.—Gas-core propulsion for cruiser (from Refs. 1 and 9).

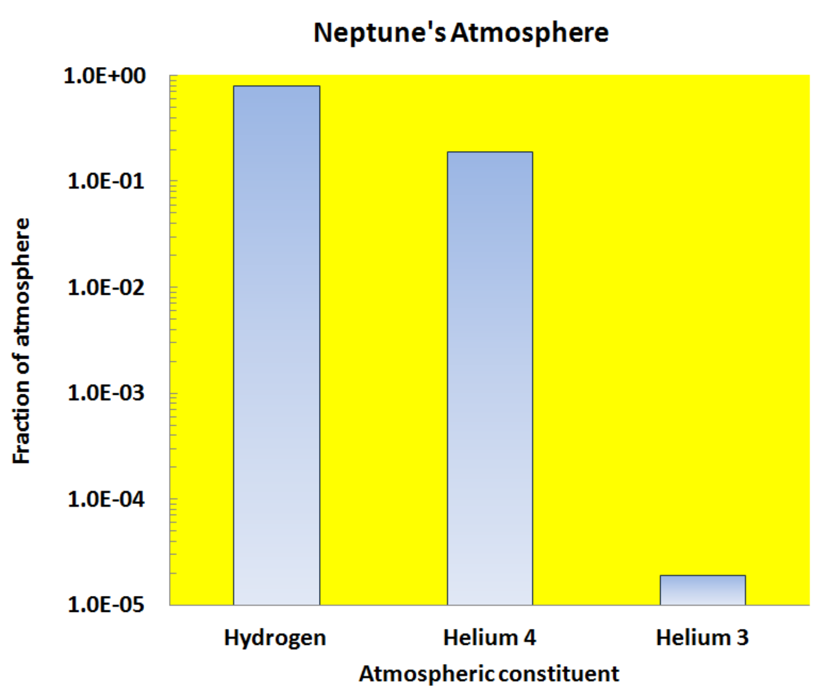


Figure 2.—Fractions of captured atmospheric gases for Neptune (from Ref. 1).

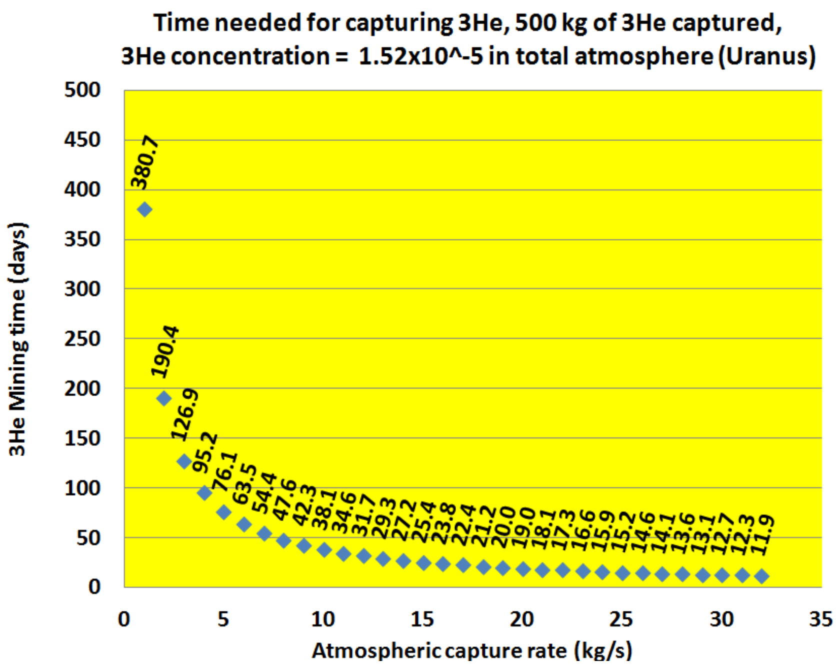


Figure 3.—Mining time versus capture rate for Uranus (Ref. 1).

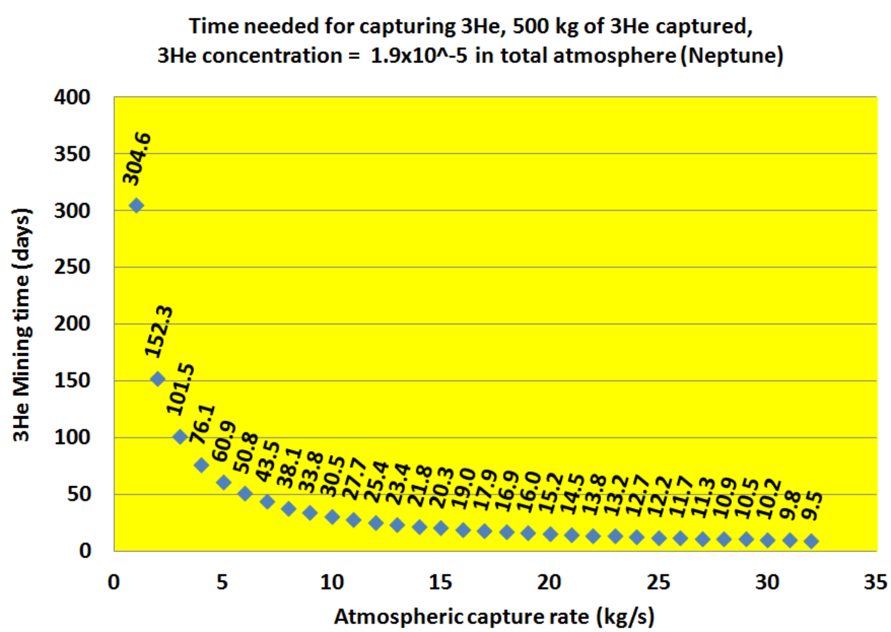


Figure 4.—Mining time versus capture rate for Neptune (Ref. 1).

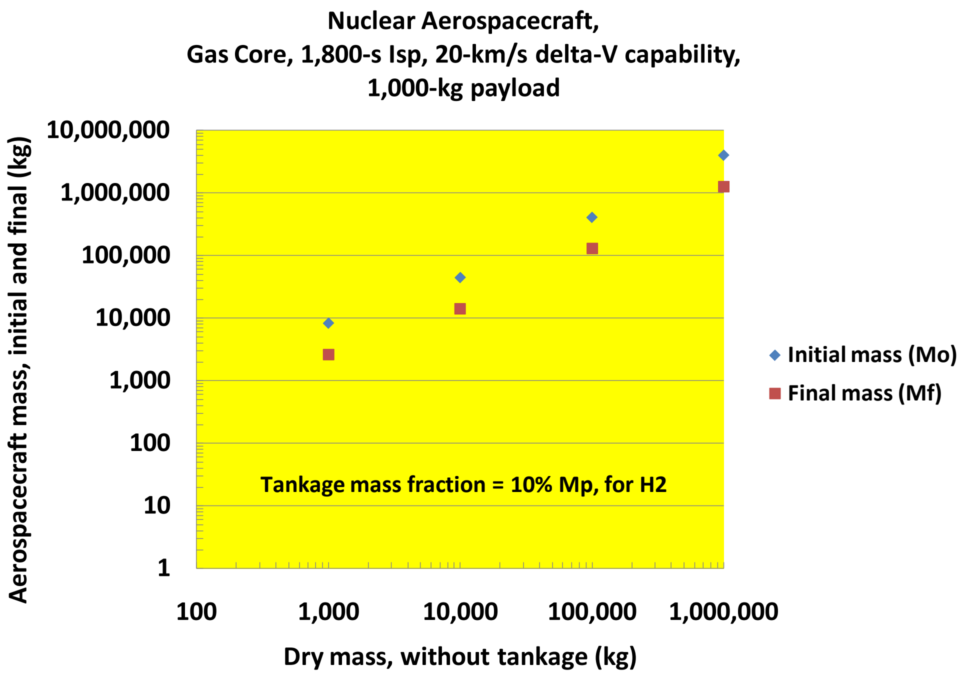


Figure 5.—Aerospacecraft mass, 1800-s I_{sp}, Tankage mass = 10 percent M_p for H_2, representative of gas core nuclear propulsion (Ref. 1).

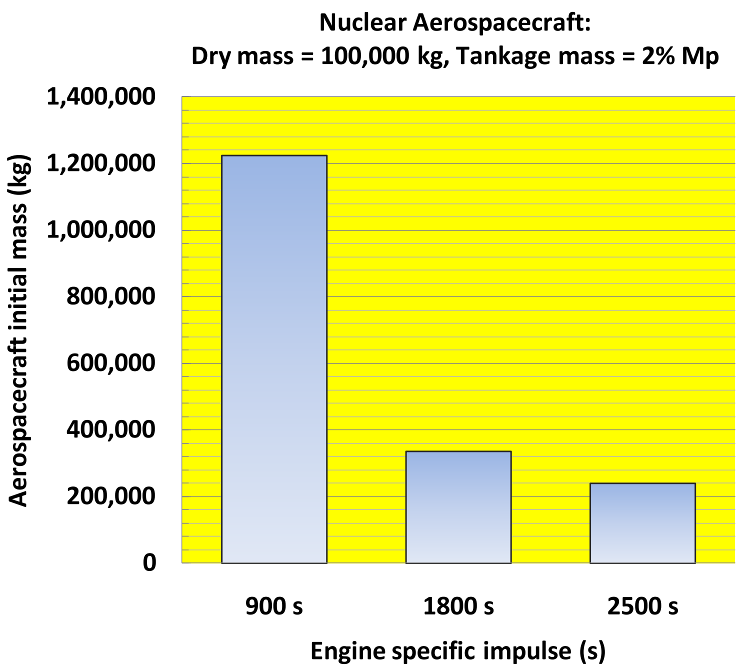


Figure 6.—Nuclear thermal propulsion: solid-core and gas-core vehicle mass comparison, 100 000 kg dry mass, 2 percent M_p for H_2 (Ref. 1).

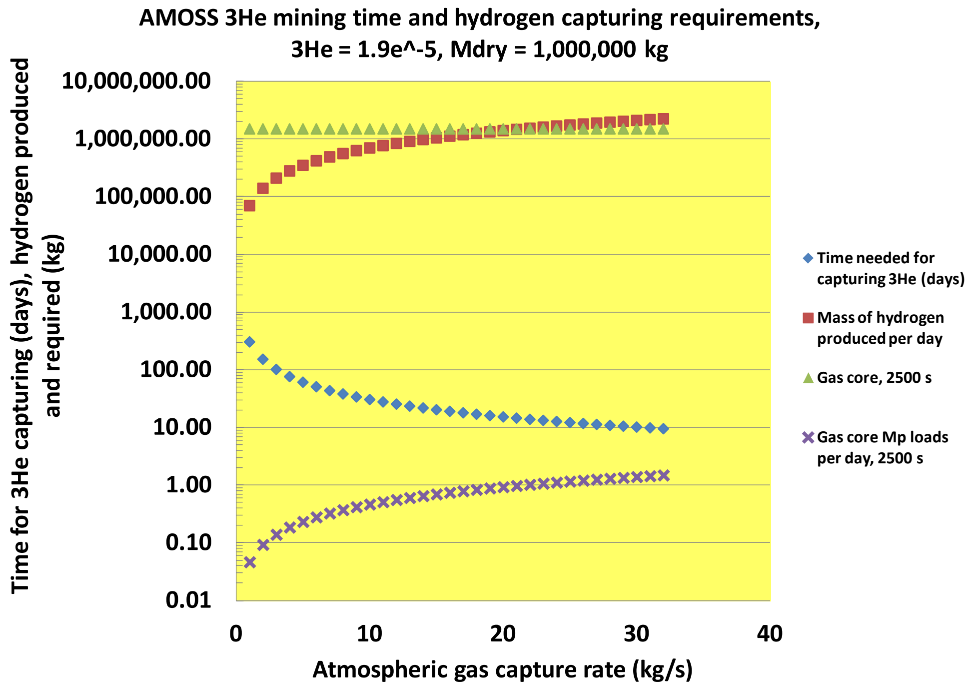
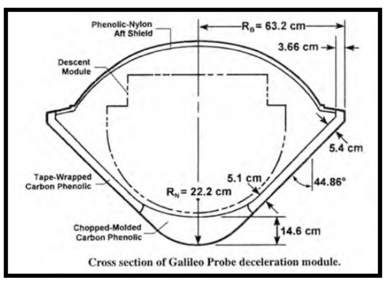
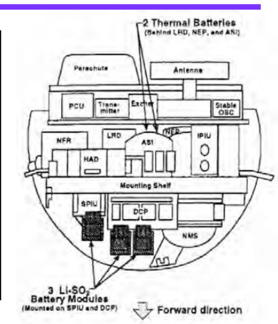


Figure 7.—^{3}He mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune (Ref. 1).

Galileo Probe Physical Properties and Key Scalability Challenges

Item / Subsystem	Mass (kg)	Mass Subtotals (kg)
Deceleration Module		221.8
Forebody heat shield	152.1	
Afterbody heat shield	16.7	
Structure	29.2	
Parachute	8.2	
Separation hardware	6.9	
Harness	4.3	
Thermal control	4.4	
Descent module		117.1
Communications subsystem	13.0	
C&DH subsystem	18.4	
Power subsystem	13.5	
Structure	30.0	
Harness	9.1	
Thermal control	4.3	
Science instruments	28.0	
Separation hardware	0.8	
Probe Total		338.9





- Overall Challenge: What is the probe mass allocation amongst subsystems as we scale the probe?
  - Deceleration Module
    - TPS
  - Descent Module
    - Pressure Vessel mass - different than Galileo
    - Other subsystems mass allocations are made but need to be validated with future refinement

6/22/05 *Ref: Galileo Probe Deceleration Module Final Report, Doc No. 84SDS2020, General Electric Re-entry Systems Operations, 1984*
AIAA, "Project Galileo Mission and Spacecraft Design", Proc. 21st Aerospace Science Meeting, Reno, NV, January 10-13, 1983 <PW> - 5

Figure 8.—Galileo mission atmospheric probe mass summary (reprinted from Ref. 30 with permission).

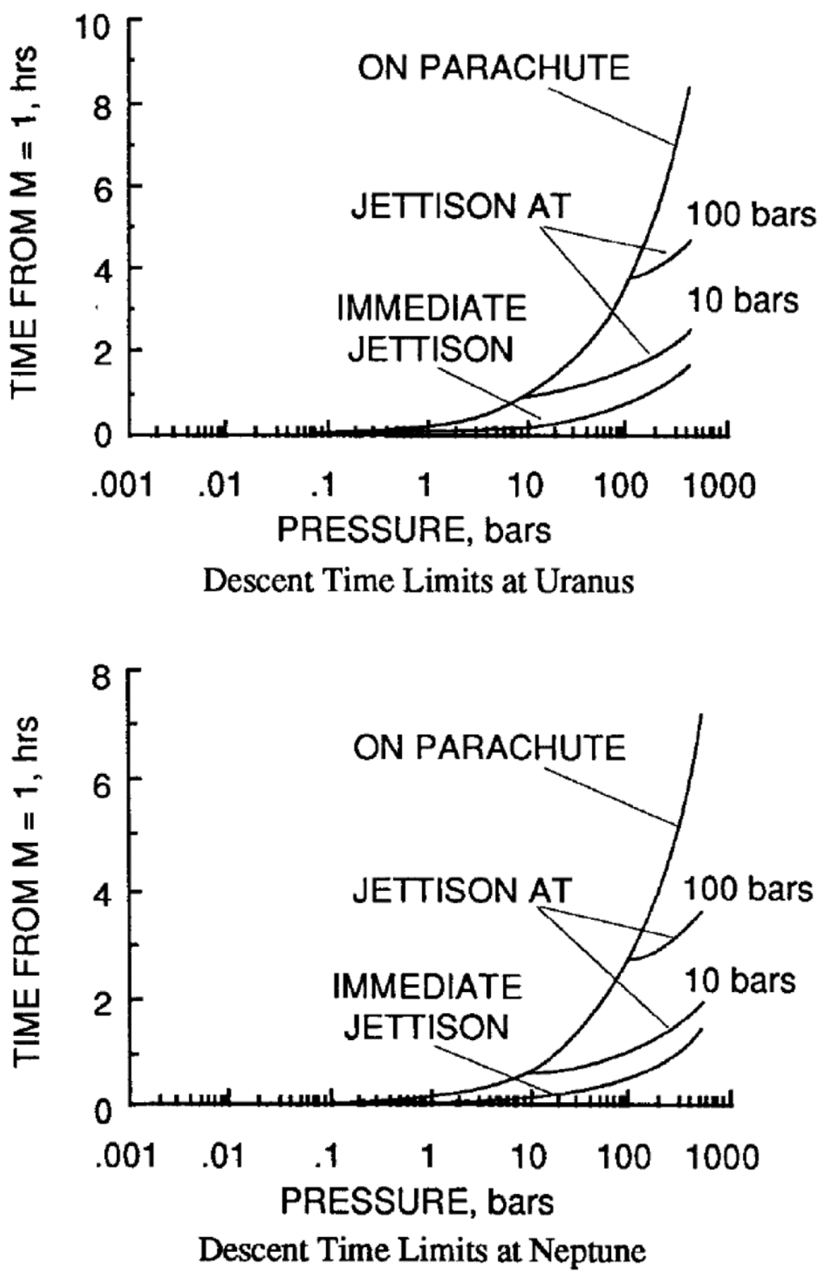


Figure 9.—Probe descent times for Uranus (upper) and Neptune (lower); descent time begins at Mach = 1.0 (Ref. 32). From Deep Atmospheric Probe Missions to Uranus and Neptune, Byron L. Swenson et al.; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

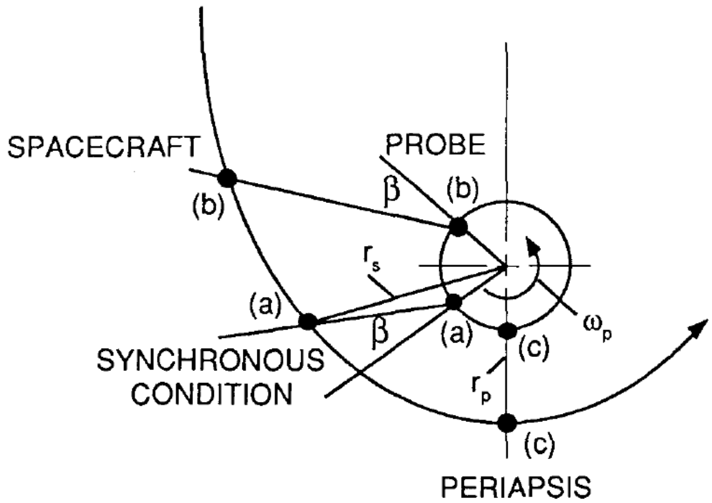


Figure 10.—Probe and receiver (unmanned aerial vehicle (UAV) or aerospacecraft) data transmission visibility geometry (Ref. 32). From Deep Atmospheric Probe Missions to Uranus and Neptune, Byron L. Swenson et al; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

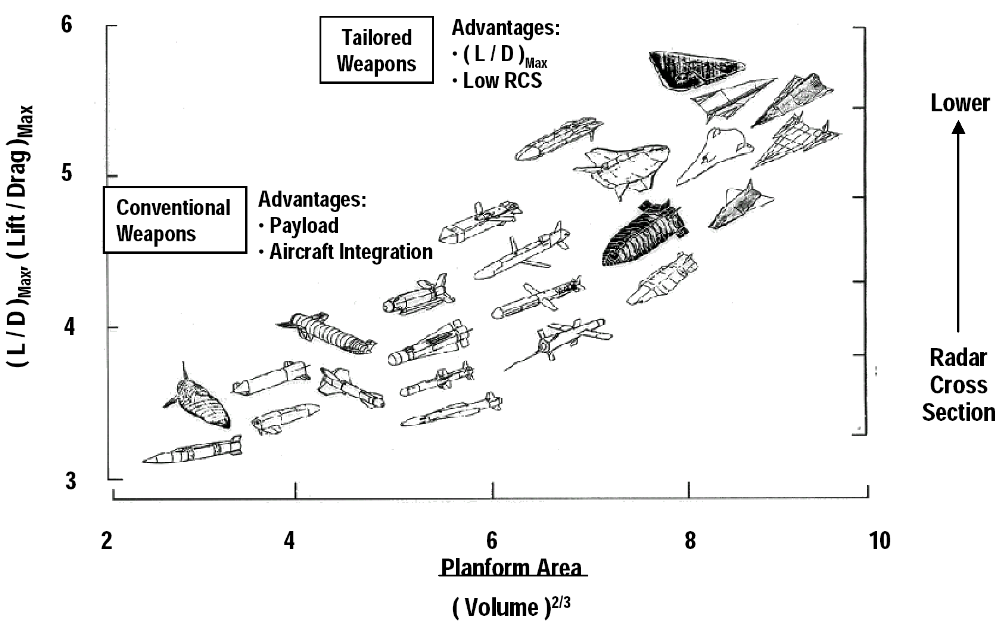


Figure 11.—UAV configuration options (reprinted from Ref. 36 with permission).

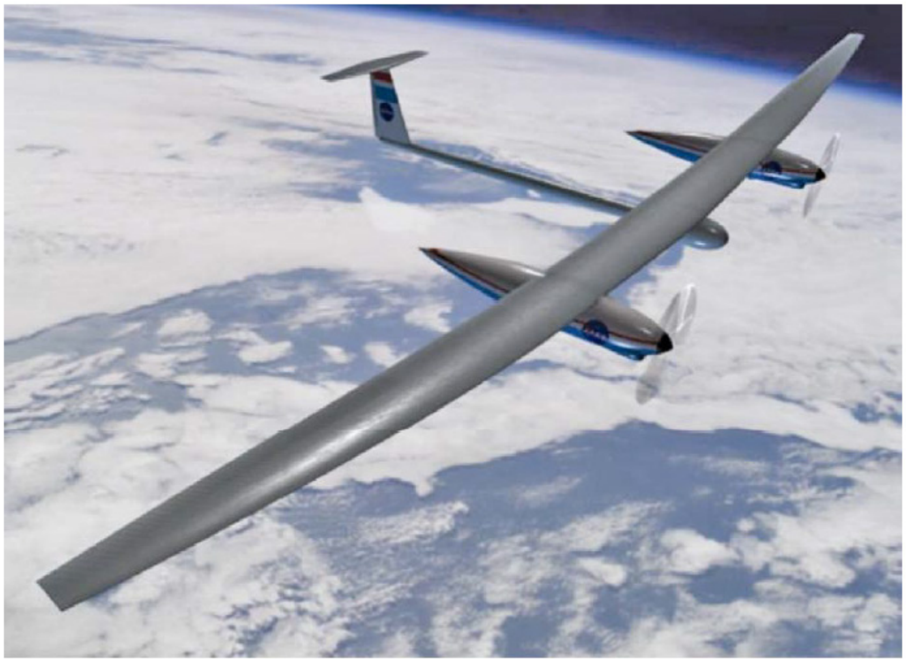


Figure 12.—Low-subsonic-speed-class UAV (Ref. 36).

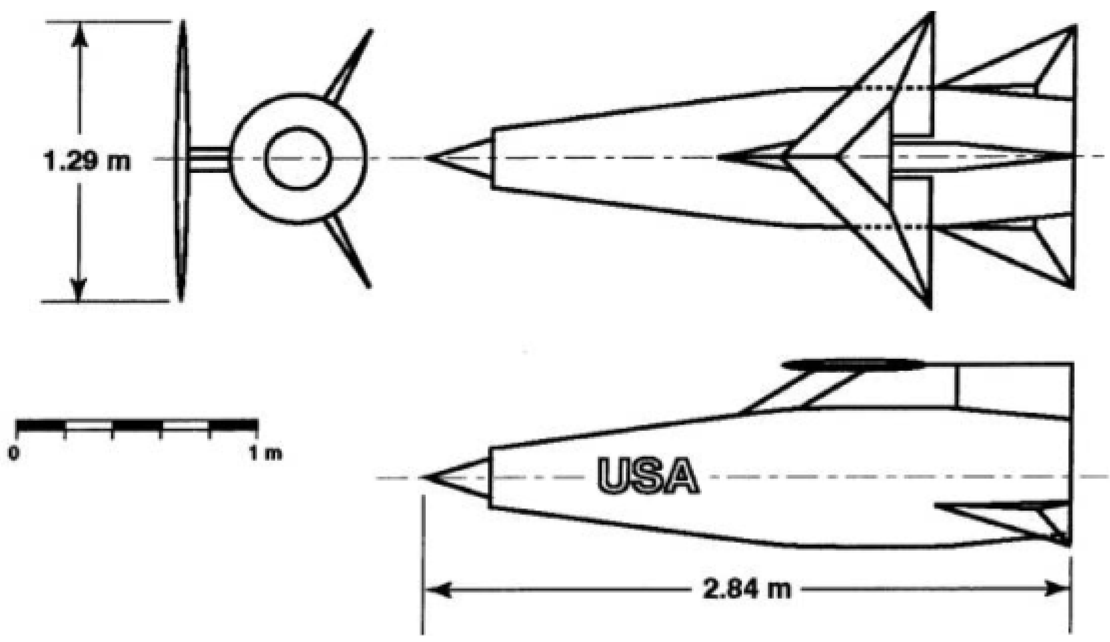


Figure 13.—Nuclear ramjet engine integrated into aircraft/UAV (Ref. 42). From Application of the MITEE Nuclear Ramjet for Ultra Long Range Flyer Missions in the Atmospheres of Jupiter and Other Giant Planets, George Maise et al.; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

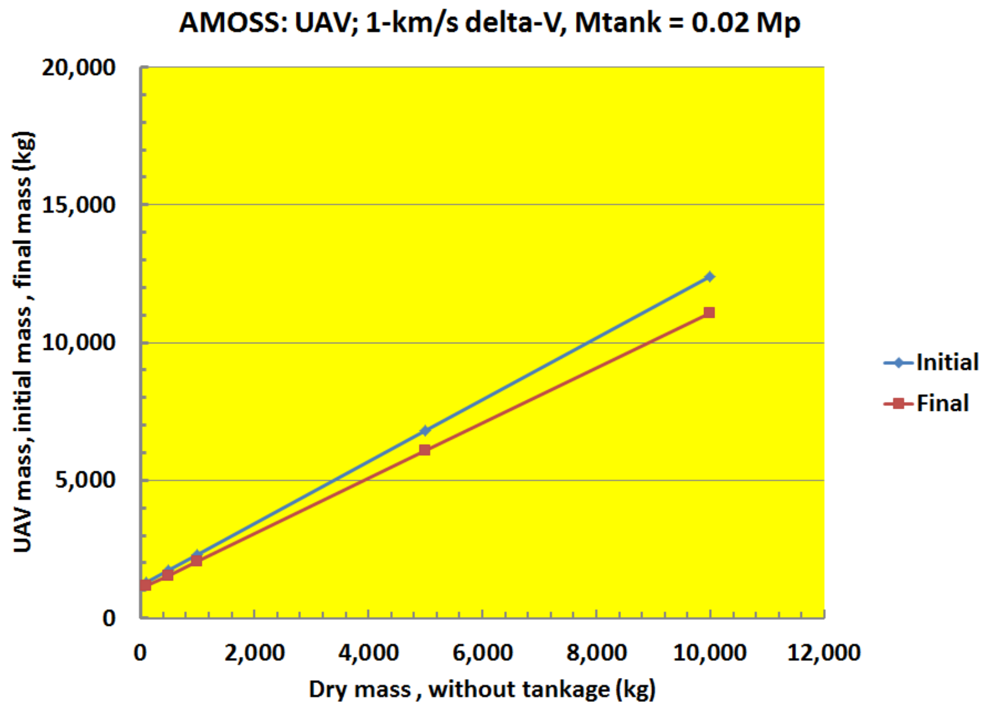


Figure 14.—Mass of UAV for atmospheric mining in the outer solar system (AMOSS) at 1 km/s delta-V capability and M_{tank} = 0.02 M_p.

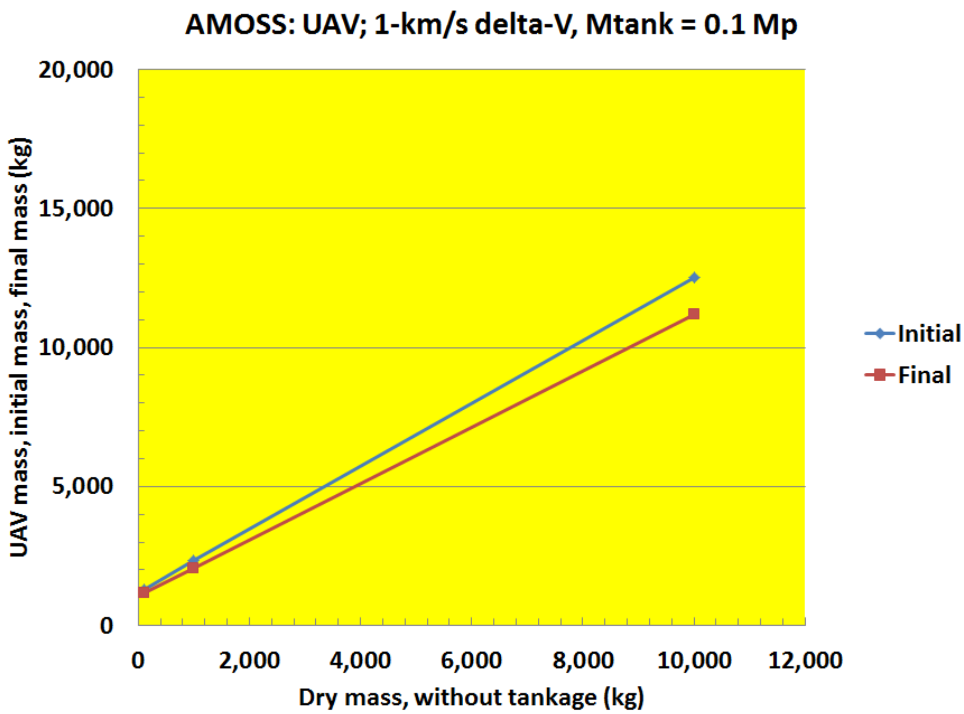


Figure 15.—Mass of UAV for AMOSS at 1 km/s delta-V capability and M_{tank} = 0.1 M_p.

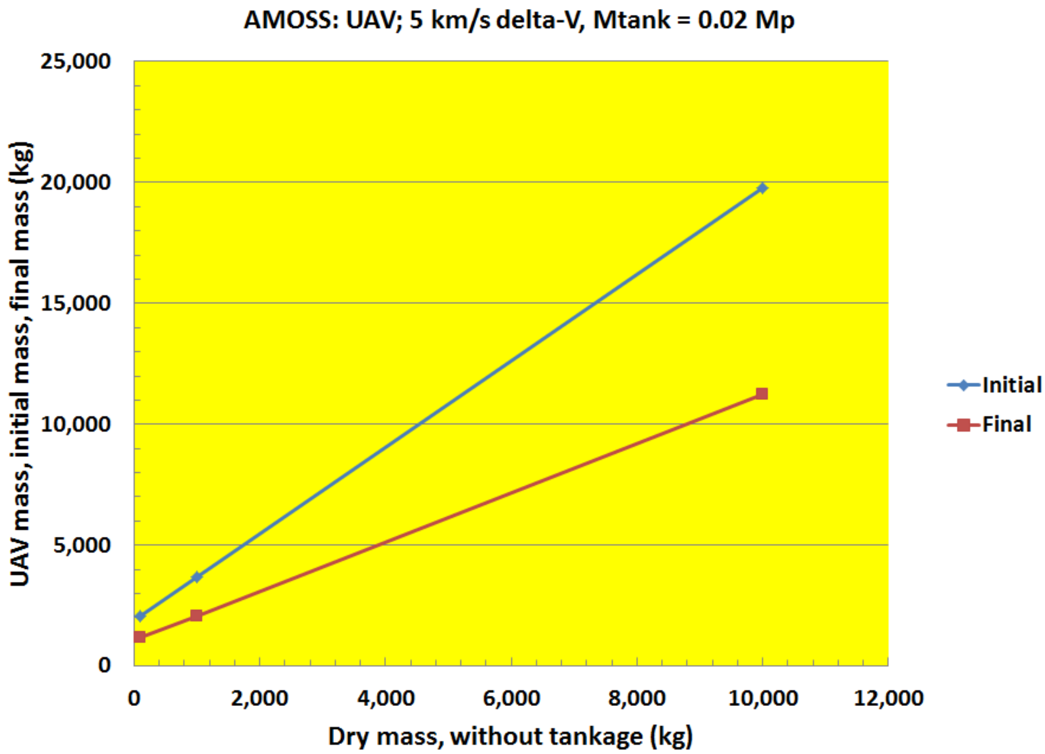


Figure 16.—Mass of UAV for AMOSS at 1 km/s delta-V capability and M_{tank} = 0.02 M_p.

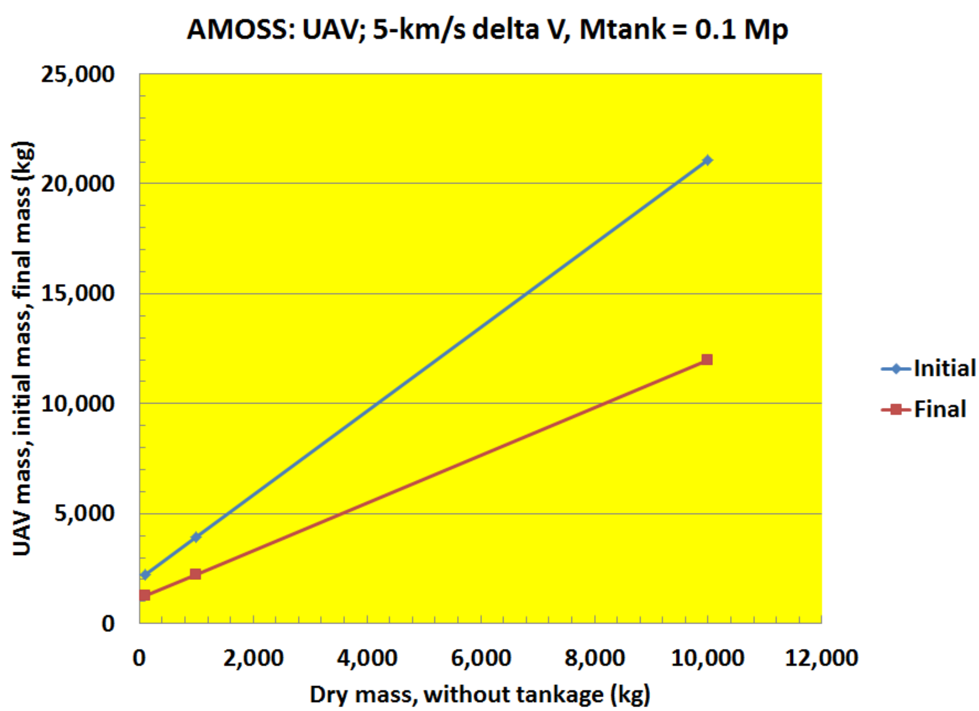


Figure 17.—Mass of UAV for AMOSS at 5 km/s delta-V capability and M_{tank} = 0.1 M_p.

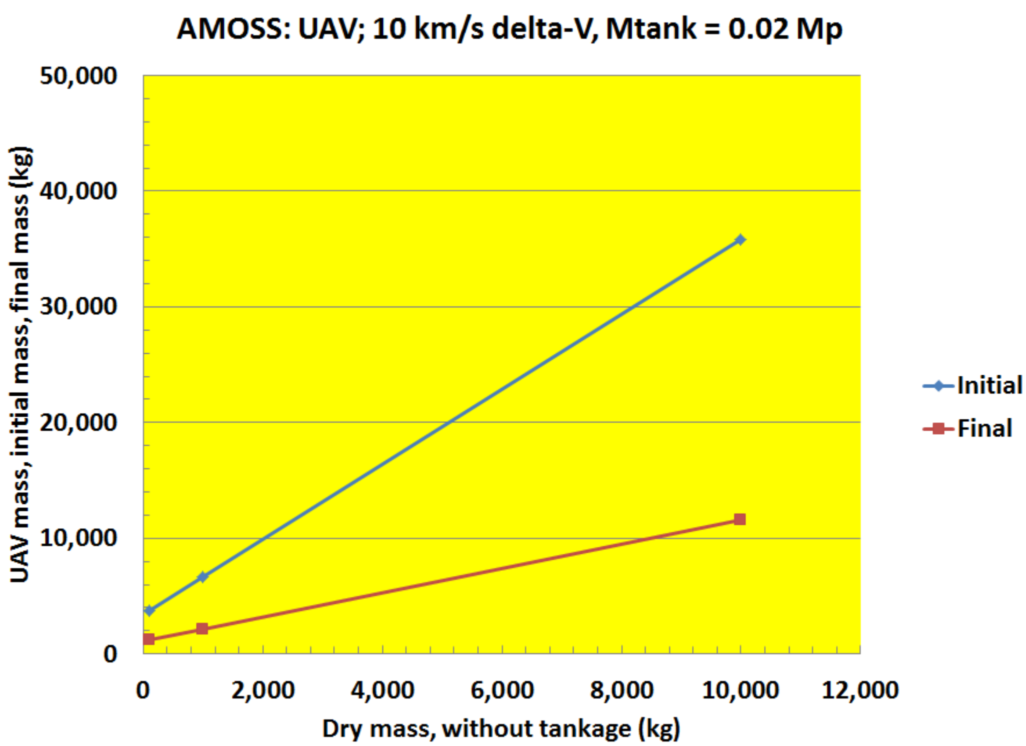


Figure 18.—Mass of UAV for AMOSS at 10 km/s delta-V capability and M_{tank} = 0.02 M_p.

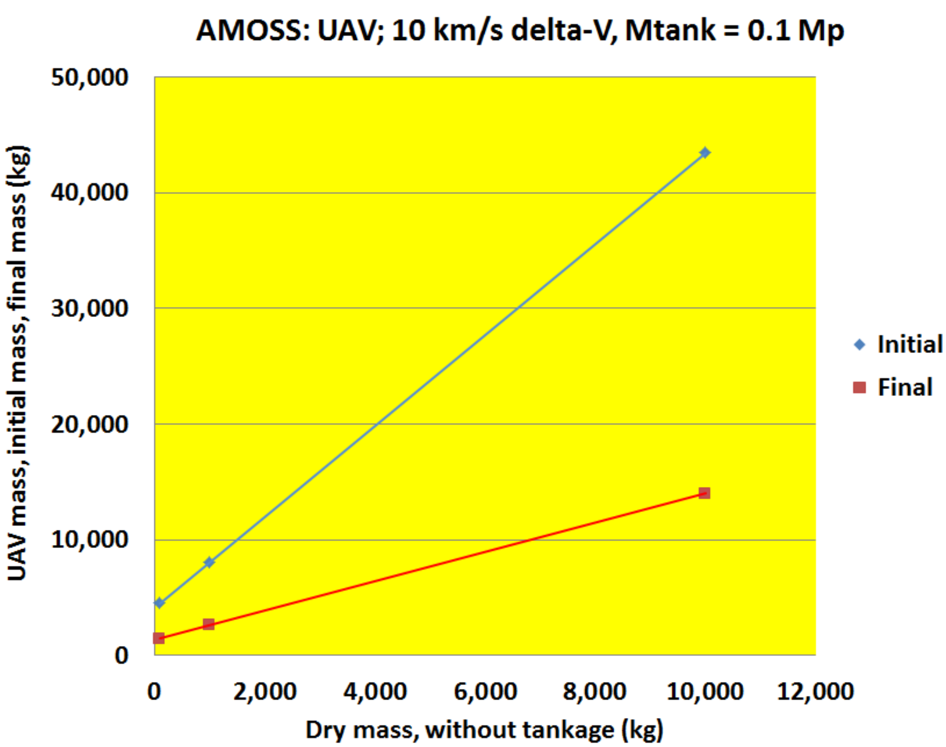


Figure 19.—Mass of UAV for AMOSS at 10 km/s delta-V capability and M_{tank} = 0.1 M_p.

Appendix A.—Planet Data—Uranus and Neptune

This appendix presents cloud images from Earth-based (Keck) and space-based (Hubble) telescopes and spacecraft (Voyager). Figure 20 to Figure 24 show the cloud changes over many years of observations.

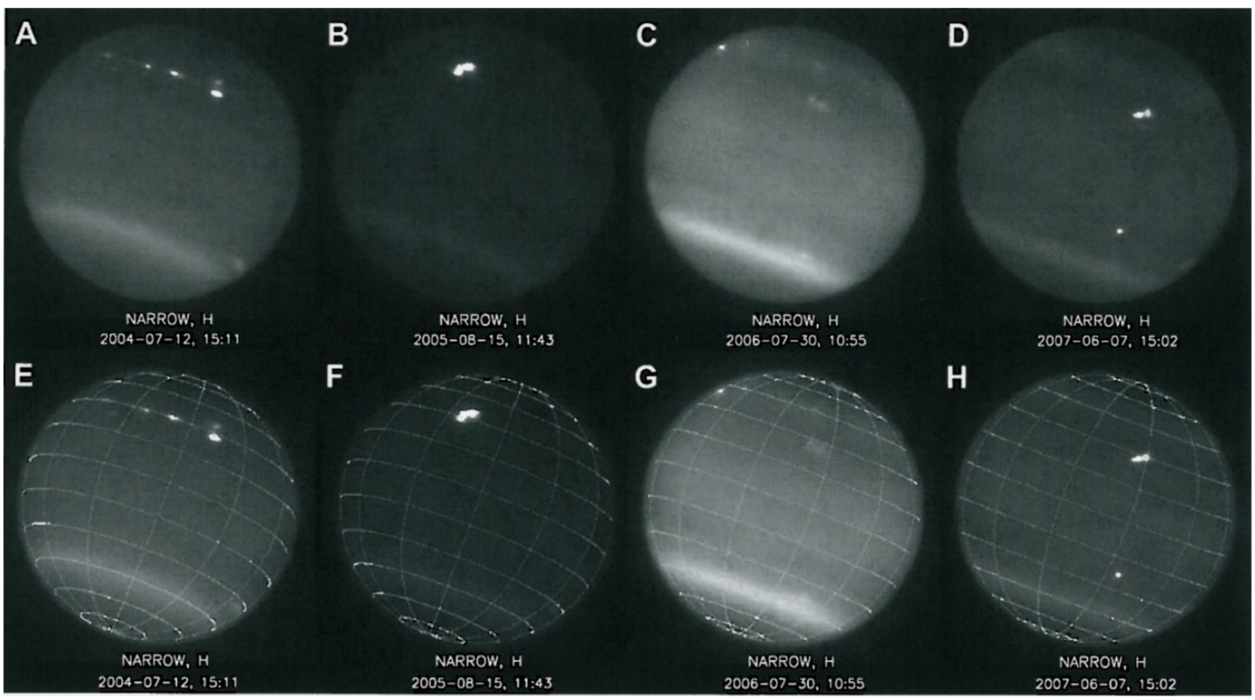


Figure 20.—Uranus cloud features (Keck II, Ref. 25).

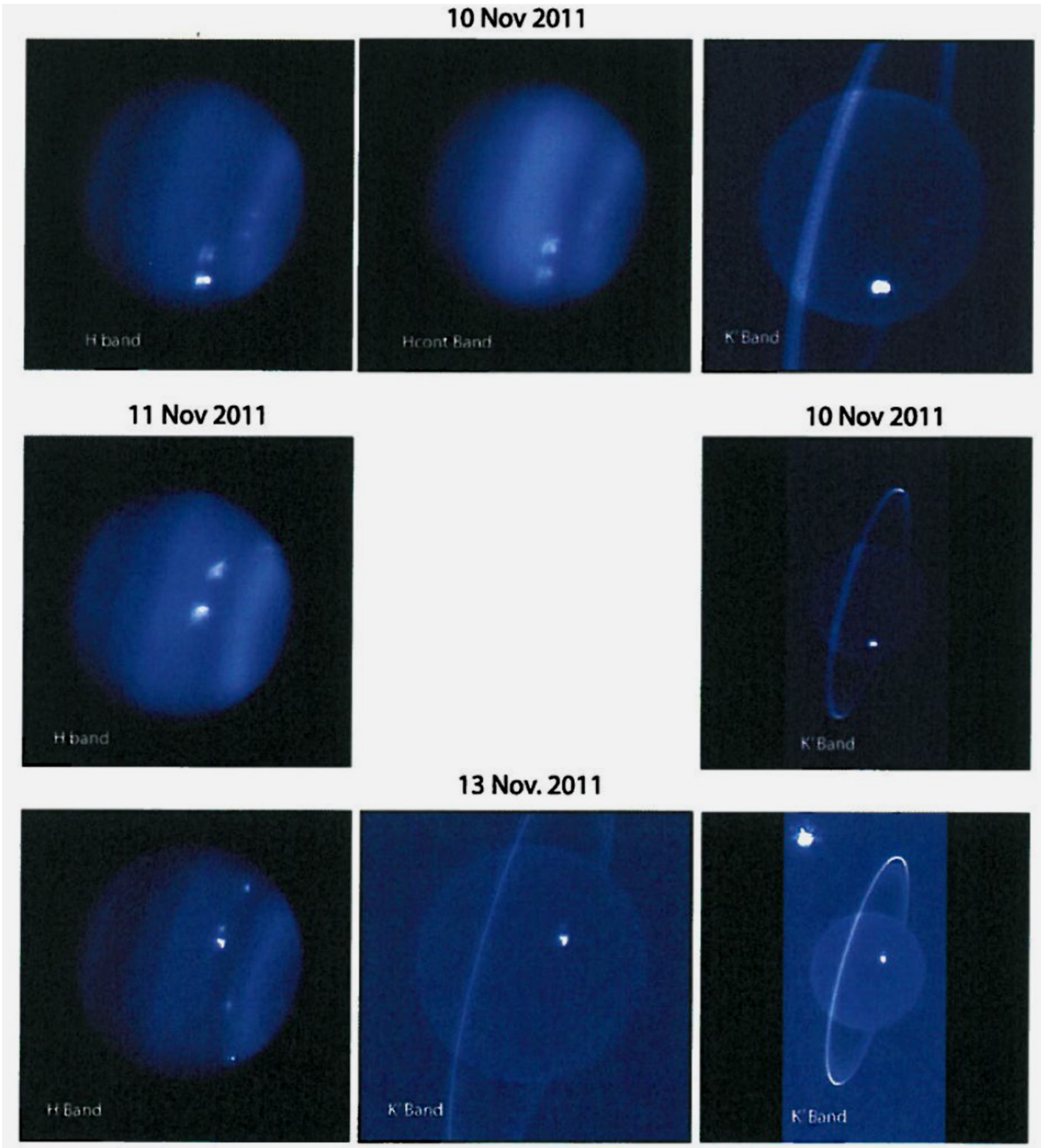


Figure 21.—Uranus cloud features and rings (Keck II, Ref. 25).

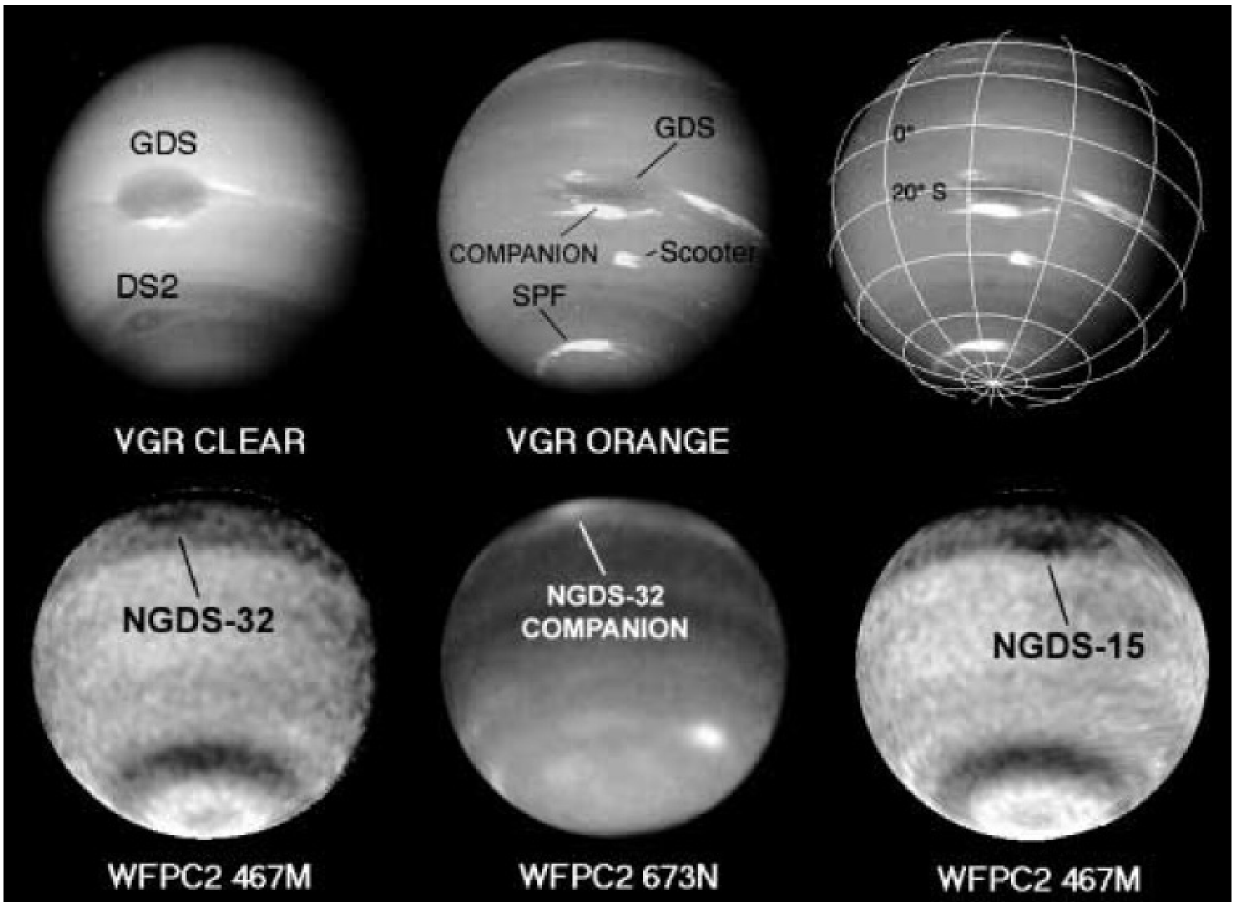


Figure 22.—Neptune cloud features (Voyager, Hubble, Ref. 27).[1]

[1]Reprinted from Icarus, vol. 156, no. 1, L.A. Sromovsky, P.M. Fry, and K.H. Baines, The Unusual Dynamics of Northern Dark Spots on Neptune, pp.16–36, 2002, with permission from Elsevier.

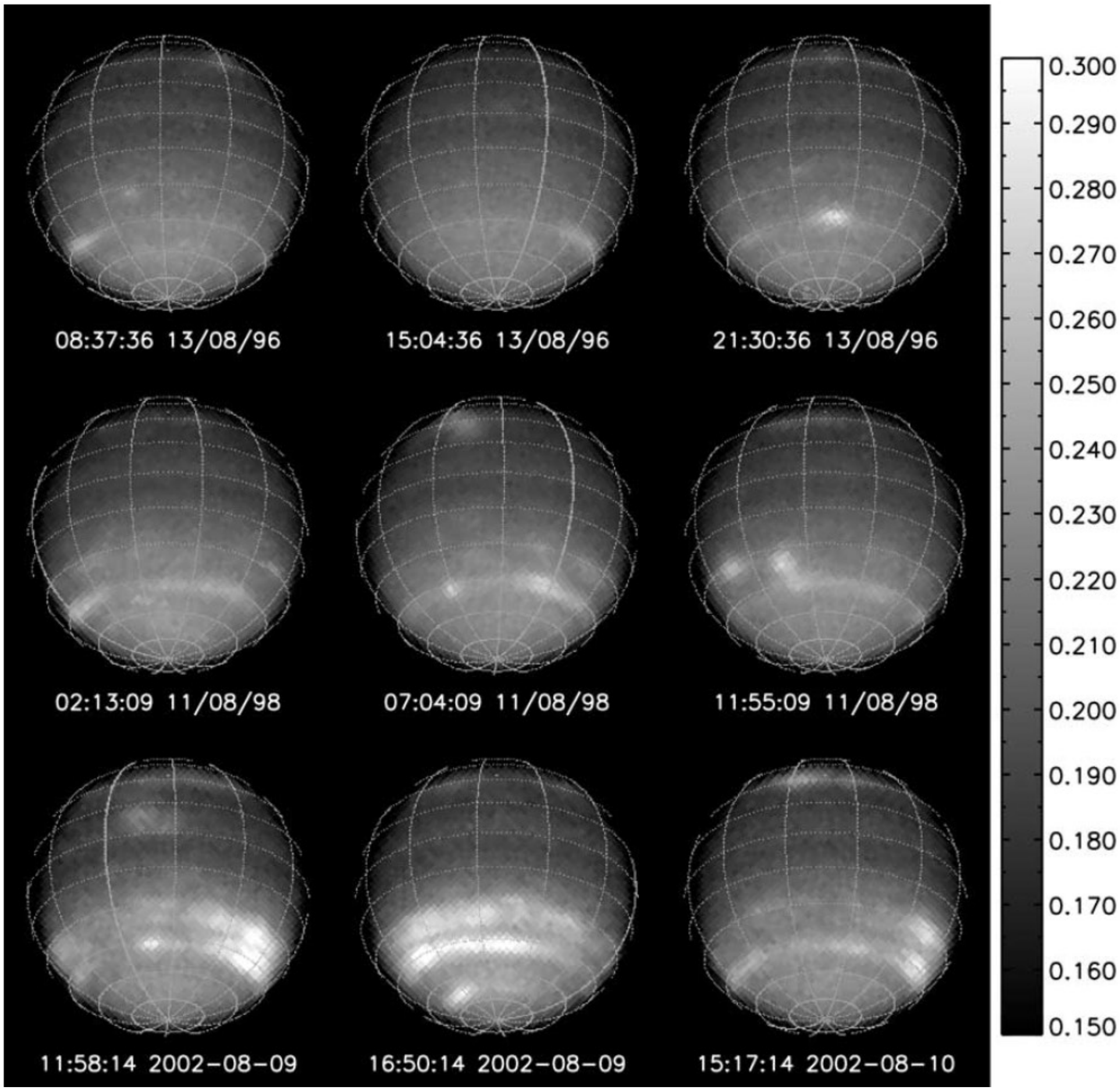


Figure 23.—Neptune cloud features (Hubble, Ref. 26).[2]

[2]Reprinted from Icarus, vol. 163, L.A. Sromovsky et al., The Nature of Neptune's Increasing Brightness: Evidence for a Seasonal Response, pp. 256–261, 2003, with permission from Elsevier.

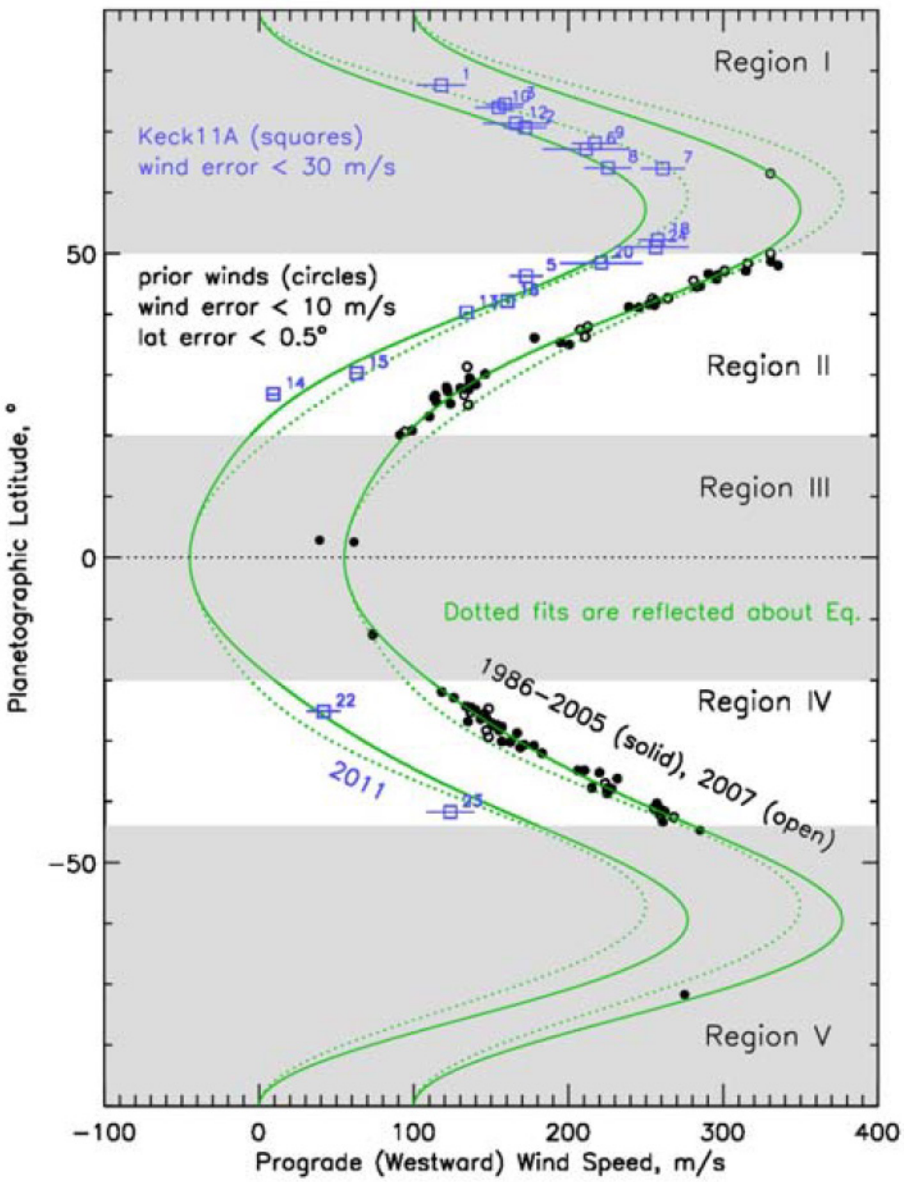


Figure 24.—Uranus winds velocities (from Ref. 43).

Appendix B.—Issues for Cryogenic Operations

Cryogenic moons and operations on those bodies is important for outer-planet moon and planet exploration. Data for identifying the moons, their apparent densities, and the technological consideration in operations on those moons are presented in Figure 25 to Figure 28.

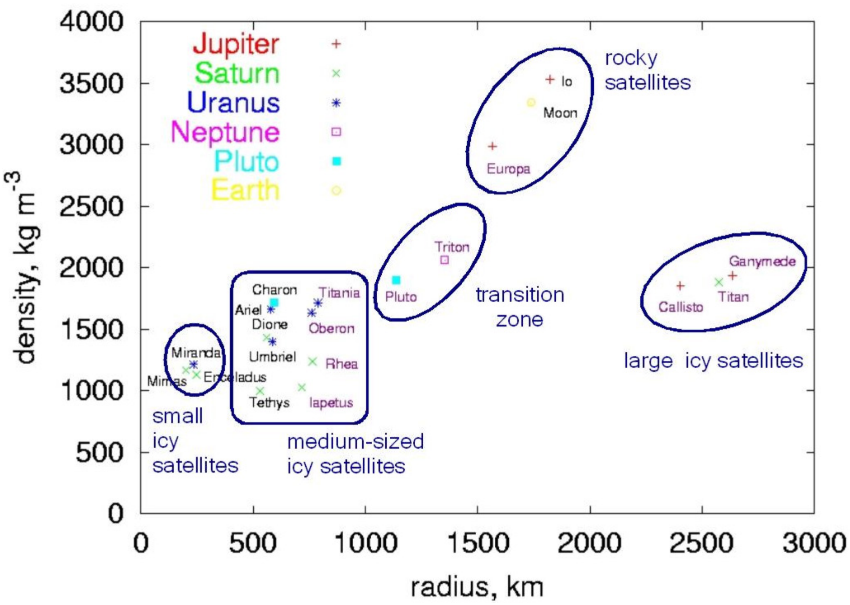


Figure 25.—Outer-planet moon densities (Ref. 44).[3]

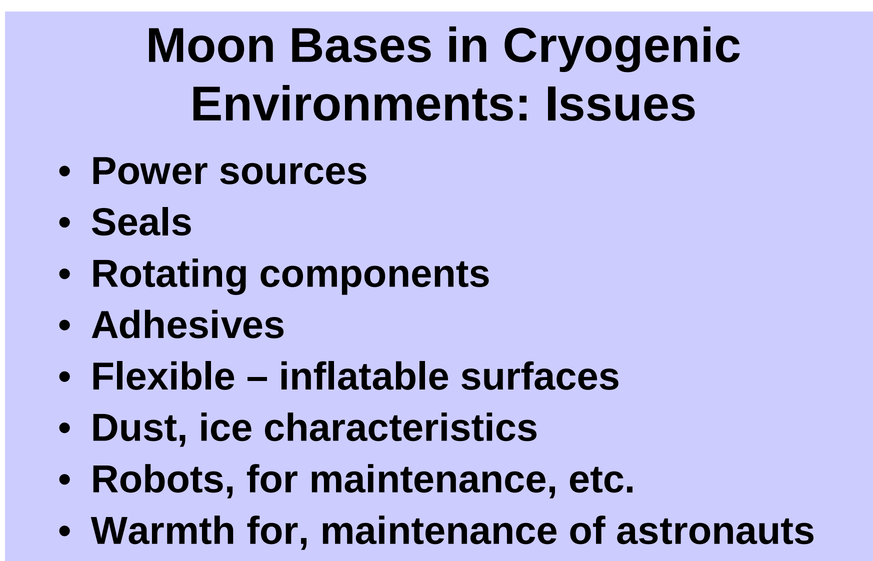


Figure 26.—Issues for cryogenic outer-planet moon surface operations (Revolutionary Aerospace Concepts (RASC), Human Outer Planet Exploration (HOPE) study, Ref. 45).

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[3]Reprinted from Icarus, vol. 185, no. 1, Hauke Hussmann, Frank Sohl, and Tilman Spohn, Subsurface Oceans and Deep Interiors of Medium-Sized Outer Planet Satellites and Large Trans-Neptunian Objects., pp. 258–273, 2006, with permission from Elsevier

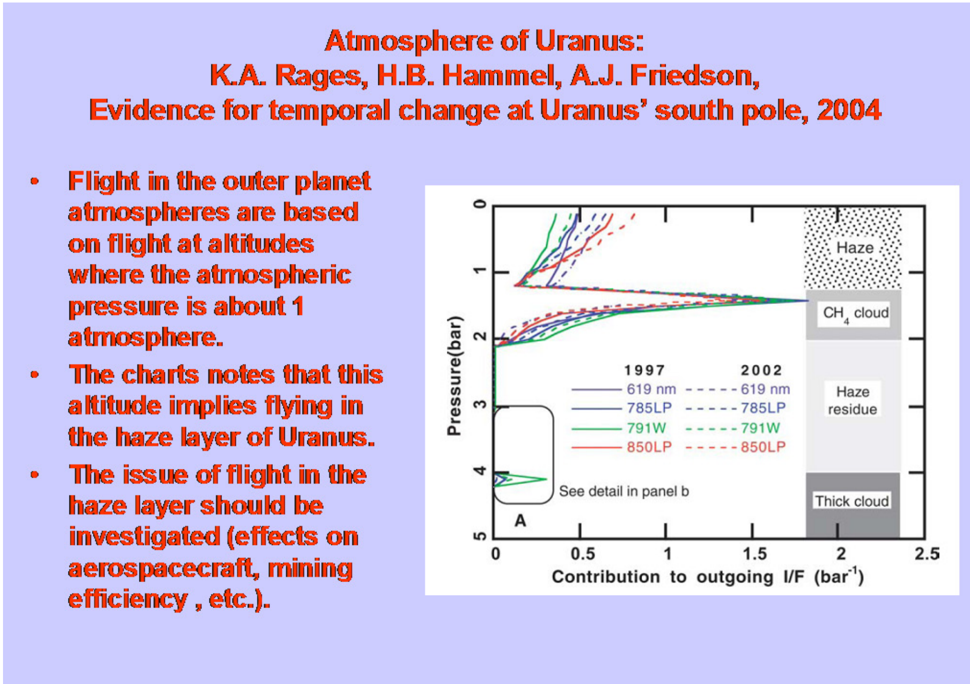


Figure 27.—Uranus atmospheric structure, haze phenomena (Ref. 46).[4]

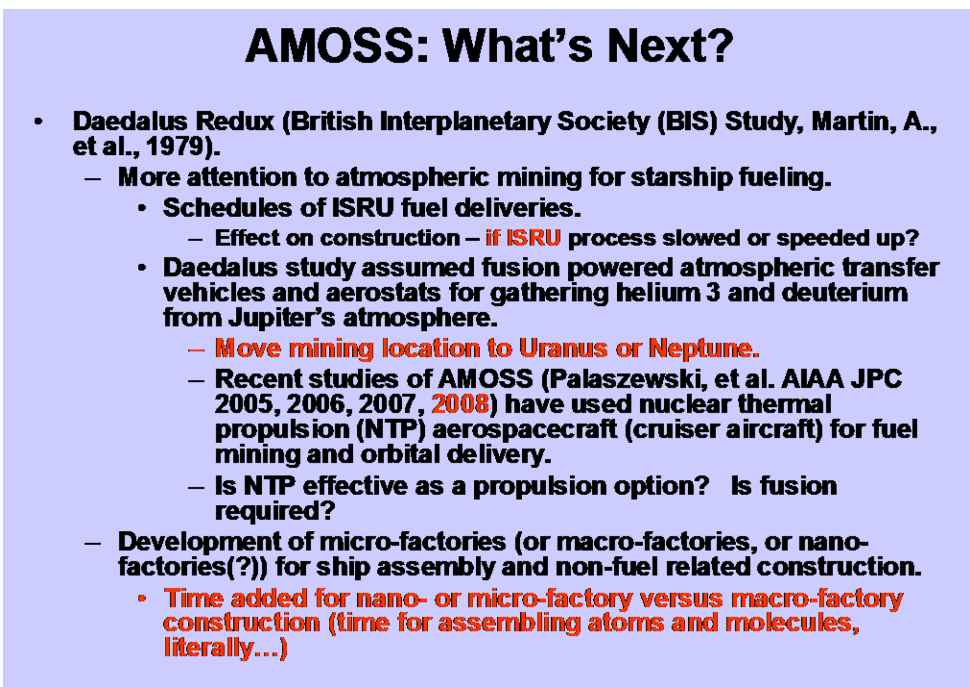


Figure 28.—Atmospheric mining issues.

[4]Reprinted from Icarus, vol. 172, K.A. Rages, H.B. Hammel, and A.J. Friedson, Evidence for Temporal Change at Uranus' South Pole, pp. 548–554, 2004, with permission from Elsevier.

Appendix C.—Gas and Shock Properties (85 Percent Hydrogen, 15 Percent Helium by Volume)

Figure 29 and Figure 30 (Ref. 47) present normal shock properties for hydrogen-helium mixtures with velocities to 70 km/s.

INITIAL CONDITIONS AHEAD OF INCIDENT NORMAL SHOCK

IN $0.85H_2$-$0.15He$

T_1 = 300 K

W_o = 2.314 kg/kmol

h_1 = 3.526 MJ/kg

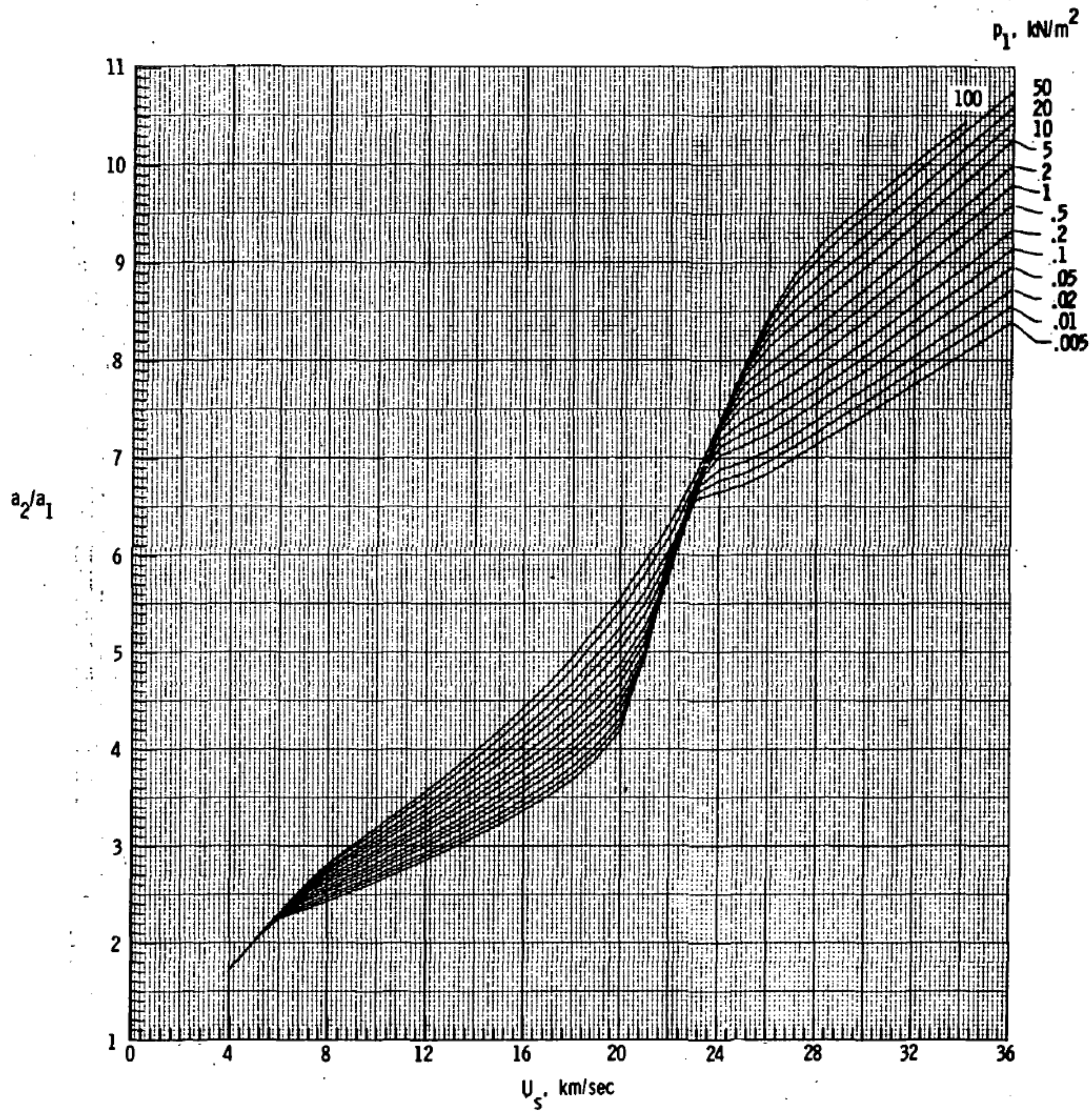
a_1 = 1.239 km/sec

$\gamma_{E,1}$ = 1.426

Z_1 = 1.000

p_1, N/m^2	ρ_1, g/m^3	s_1W_o/R
5	0.004638	25.98
10	.009277	25.28
20	.01855	24.59
50	.04638	23.67
100	.09277	22.98
200	.1855	22.29
500	.4638	21.37
1 000	.9277	20.68
2 000	1.855	19.98
5 000	4.638	19.07
10 000	9.277	18.38
20 000	18.55	17.68
50 000	46.38	16.77
100 000	92.77	16.07

Figure 29.—Initial conditions ahead of incident normal shock in 0.85 H_2-0.15 He (Ref. 47).



(e) Speed of sound a_2/a_1.

Figure 30.—Thermodynamic properties and flow velocity behind an incident normal shock into a 0.85 H_2-0.15 He mixture (Ref. 47).

Appendix D.—Detonation Engine Data

The appendix presents detonation rocket engine performance in Figure 31 and Figure 32. This type of engine was proposed for flight in high-pressure atmospheric environments.

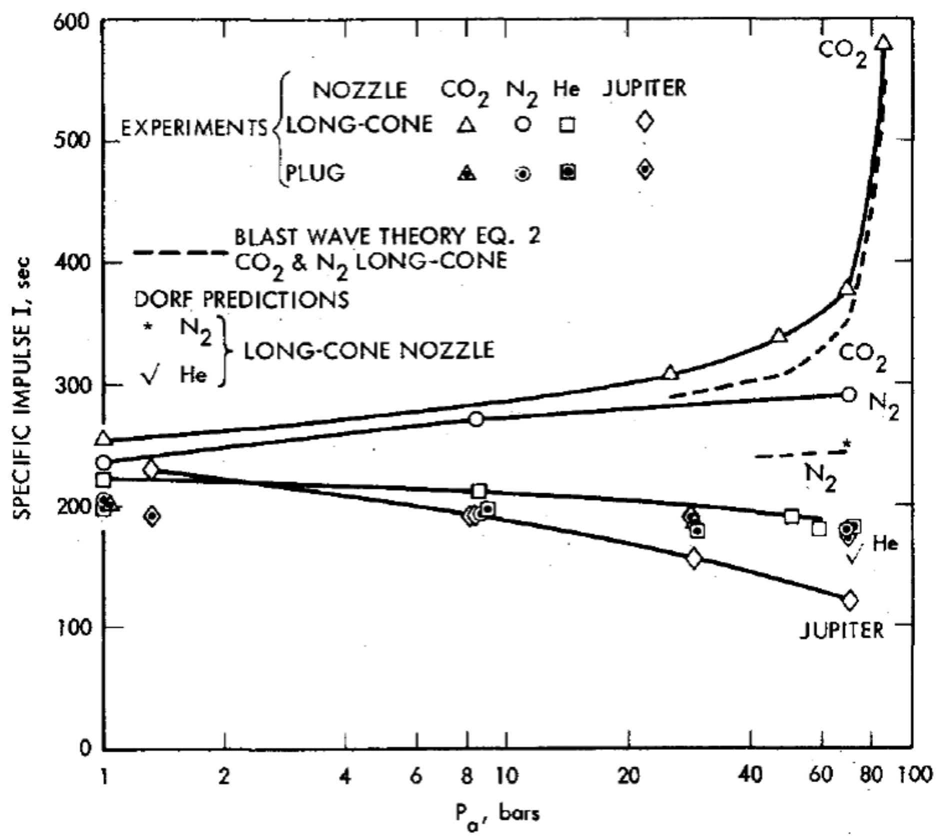


Figure 31.—Variation of specific impulse with ambient pressure for various ambient gases (carbon dioxide (CO_2), nitrogen (N_2), and helium (He)). with long-cone and firing-plug nozzles (Ref. 33). From Detonation Propulsion Experiments and Theory. Measurement of Detonation Propulsion in Helium and Performance Calculations, Lloyd H. Back, Warren L. Dowler, and Giulio Varsi; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

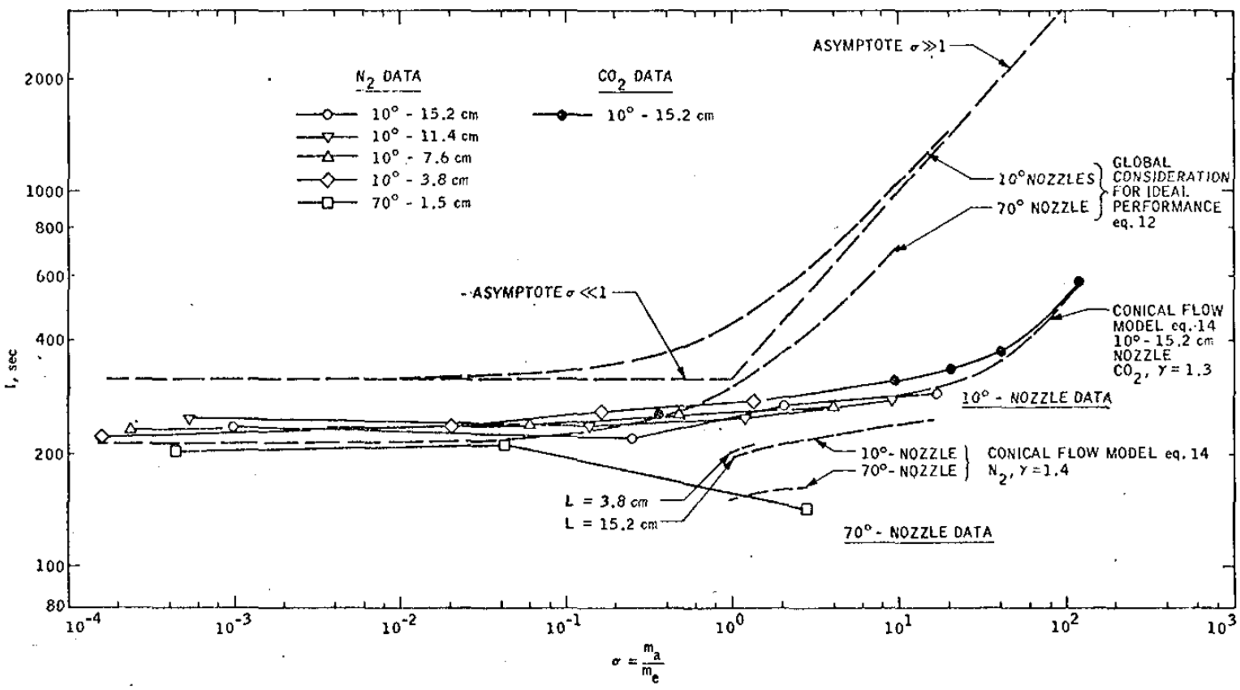


Figure 32.—Engine specific impulse, including high angle nozzles (Ref. 34). From Detonation Propulsion for High Pressure Environments, Giulio Varsi and Lloyd H. Back; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Atmospheric mining in the outer solar system (AMOSS) has been investigated as a means of fuel production for high-energy propulsion and power. Fusion fuels such as helium 2 (^{3}He) and hydrogen can be wrested from the atmospheres of Uranus and Neptune and either returned to Earth or used in-situ for energy production. ^{3}He 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 AMOSS. These analyses 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 ^{3}He, large amounts of hydrogen and helium 4 (^{4}He) are produced. With these two additional gases, the potential exists for fueling small and large fleets of additional exploration and exploitation vehicles. Additional aerospacecraft or other aerial vehicles (UAVs, balloons, rockets, etc.) could fly through the outer-planet atmosphere to investigate cloud formation dynamics, global weather, localized storms or other disturbances, wind speeds, the poles, and so forth. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess hydrogen or ^{4}He may be designed to probe the higher density regions of the gas giants.

15. SUBJECT TERMS
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