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# Atmospheric Mining in the Outer Solar System

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# Atmospheric Mining in the Outer Solar System

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## Abstract

Overviews, analyses, and assessments of various mining options for outer planet atmospheres are presented. Options for mining include aerostat borne factories that process the atmosphere and cruisers or scoopers that dip into or reside in the atmosphere. Assessments of the mission complexity for several mining scenarios are presented. Propulsion options for these scenarios are also assessed. Options for mining and transporting atmospheric constituents from the outer planet of our solar system were reviewed. Comparisons of the mining and transportation techniques were also assessed. Comparisons of the complexity of lunar helium 3 (3He) mining and mining in the outer solar system planetary atmospheres were conducted. Mission options that reduce the complexity of the transportation systems are suggested.

## Nomenclature

| | |
|---|---|
| 3He | Helium 3 |
| 4He | Helium (or Helium 4) |
| delta-V | Change in velocity (km/s) |
| DS–1 | Deep Space One |
| H2 | Hydrogen |
| He | Helium |
| ISRU | In Situ Resource Utilization |
| Isp | Specific Impulse (s) |
| KBO | Kuiper Belt Object |
| kWe | Kilowatts of electric power |
| MT | Metric tonnes |
| NEP | Nuclear Electric Propulsion |
| NTP | Nuclear thermal propulsion |
| O2 | Oxygen |
| PPB | Parts per billion |
| SR | Sample Return |

## Introduction

Exploration of the solar system is a monumental task. The distances to the outer planets are quite large, and the radiation produced by the planets can be deadly to humans (refs. 1 and 2). Also, the sunlight is quite weak at the outer planets, requiring new power systems for sustainable power for short and long duration missions (refs. 3, 4, and 5) to be developed. In the far future, enormous amounts of energy might be derived from extraterrestrial locations, even one day powering our entire planet (ref. 5).

Mining in the outer solar system is an important option for exploration and exploitation (refs. 5 to 10). Launching and transporting all of the materials for exploration from Earth is expensive and may make the idea of exploration untenable. The large reserves of atmospheric gases in the outer planets are an excellent resource for fuels and other life sustaining or colony building gases (ref. 10). The moons of the planets can be a great resource for oxygen, ceramic precursors, and metals. Outer planet moons, such as Europa, Ganymede, and Callisto, may have reserves of liquid and frozen water. Specialized factories created in the outer solar system can leverage all of these resources and allow for extended stays in that cold, dark environment.

## In-Situ Resources Utilization

Many decades of research have been focused on using the natural resources of the solar system to allow sustainable human exploration and exploitation of the environments of the planets and the Sun (refs. 4 to 23). Everything from preliminary experiments in propellant production to creation of human colonies in space has been proposed (refs. 11 to 23). Studies such as those of reference 10 have shown that the outer planets can provide the rich resources for interstellar exploration and the eventual human colonization of the galaxy.

As human exploration is initiated in the outer solar system, the travel time and other natural hazards (planetary radiation belts, solar coronal mass ejections, etc.) will create new challenges for the explorers. In-situ resources will likely be a great asset in this exploration. Shielding from radiation can be created with rock from the moons or with hydrogen and other liquefied gases from the planetary atmospheres. High speed travel will be augmented by nuclear fission (ref. 24) and advanced future fusion propulsion (ref. 25), fueled by the atmospheric gases.

## Atmospheres of the Outer Planets

Highly energetic materials are available in the outer planet atmospheres. The composition of the outer planet atmospheres are shown in tables I and II (refs. 1, 26, 27, and 28). The elements of greatest interest are gases and ices. Figures 1 and 2 depict the atmospheric structures of the outer planets.

TABLE I.—OUTER PLANET ATMOSPHERE COMPOSITION
(by vol%, ref. 26)

| | | |
|---|---|---|
| Jupiter: | | |
| | Hydrogen | 89.8 |
| | Helium | 10.2 |
| | Other trace elements | |
| Saturn: | | |
| | Hydrogen | 96.3 |
| | Helium | 3.3 |
| | Other trace elements | 0.4 |
| Uranus: | | |
| | Hydrogen | 82.5 |
| | Helium | 15.2 |
| | Methane | 2.3 |
| | Other trace elements | 1.0 |
| Neptune: | | |
| | Hydrogen | 80.0 |
| | Helium | 19.0 |
| | Methane | 1.0 |
| | Other trace elements | |

TABLE II.—SUMMARY OF ATTRACTIVE RESOURCES
(ref. 26)

| | |
|---|---|
| Main Gases: | |
| | Hydrogen |
| | Helium |
| | Methane |
| Trace gaseous elements (present at ppm levels): | |
| | Helium 3 |
| | Hydrogen deuteride |
| | Ethane |
| Ices deep within the atmosphere: | |
| | Hydrogen |
| | Hydrogen deuteride |
| | Methane |
| | Ammonia |
| | Water |

The gases found in the atmospheres are excellent for fuels for chemical and nuclear propulsion systems. Hydrogen and methane are excellent fuels for chemical rockets that can be used for the ascent from and descent to the moons' surfaces. Also, hydrogen can be the fuel of choice for nuclear fission and fusion rockets. Helium 3 (3He) is another future fusion reactor fuel and can be found in these atmospheres (refs. 5 to 10). The hydrogen, helium, and / or other ices found deep in Uranus and Neptune may be crucial to the exploration beyond the solar system (refs. 5 to 10).

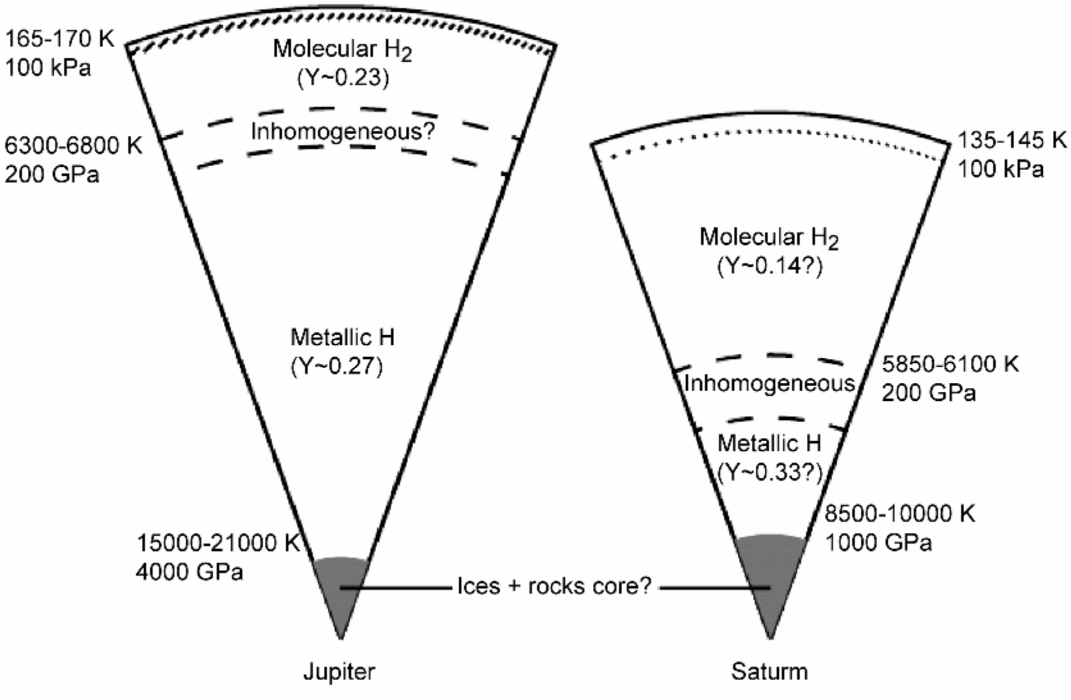

Figure 1.—Atmospheres of Jupiter and Saturn (Refs. 27 and 28).

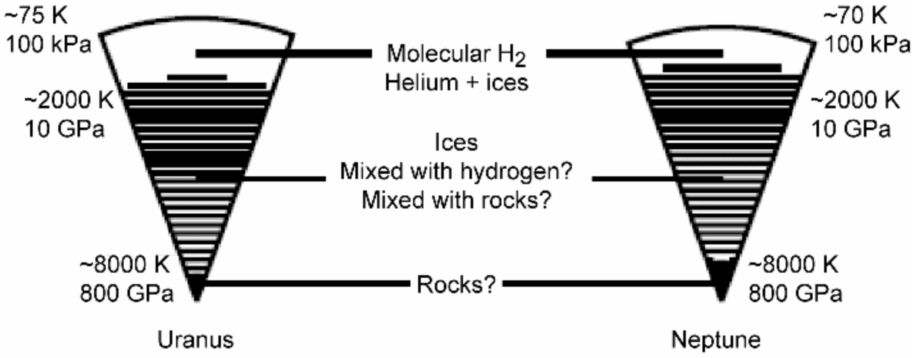

Figure 2.—Atmospheres of Uranus and Neptune (Refs. 27 and 28).

## Why Perform Mining in Atmospheres?

It is possible that atmospheric mining may be easier than mining from outer planet moon surfaces. Also, the sheer abundances of gases and the locations of the planets give us a good place for way stations for exploration beyond the edges of the solar system. On the other hand, the delta-V required to closely approach Jupiter or any of the outer planets for repetitive atmospheric access and then returning to orbit can be quite high. Also, as the planets typically have powerful magnetic fields, the vehicle's resistance to radiation will be important for reliable operation.

One of the attractive materials that can be extracted from the solar system is 3He. It is deposited in lunar regolith and exists in the outer planet atmospheres (ref. 5 to 19). This material can be an excellent nuclear fusion fuel and can reduce the neutron radiation created during the fusion process, extending the life of future power reactors (refs. 19 to 22).

Using 3He from the lunar regolith has been extensively studied (refs. 11 to 22). Deposited over billions of years by the solar wind, 3He is resting in the first hundred centimeters of lunar regolith, waiting for extraction. The fraction of 3He in the lunar regolith is quite small: perhaps less than 5 to 100 parts per billion (ppb) in some regions. Thus, large robotic machines were envisioned to conduct the mining of the surface and slowly and carefully wrest the precious fuel from the Moon.

Predictions of the 3He concentration in the helium of the atmosphere of Uranus are about $1\times10^{-4}$ (by mass) (refs. 3 and 4). Though the levels seem quite small, the argument has been made that it is easier to extract the 3He from the gaseous helium in the outer planet atmosphere. Factories stationed in the atmosphere could robotically mine the gas, and await orbital vehicles to gather the 3He for delivery to other parts of the solar system.

If atmospheric mining can be made highly efficient, there may be great benefits for gathering 3He from an atmosphere rather than the Moon's surface. Once a pipeline of deliveries is established, the flow of 3He from the outer solar system might be more attractive than lunar regolith mining.

## Wind Speeds in Atmosphere

Though atmospheric mining shows advantages, there are very high winds speeds and wind shears in these atmospheres (refs. 29 to 32). Figures 3 and 4 present the wind speeds and wind profiles for the 4 gas giants (ref. 29). Given the typical lightweight nature of aerospace vehicles, the predictability of wind speed in the atmosphere will have a powerful effect on the factory design and the related aeronautical vehicles.

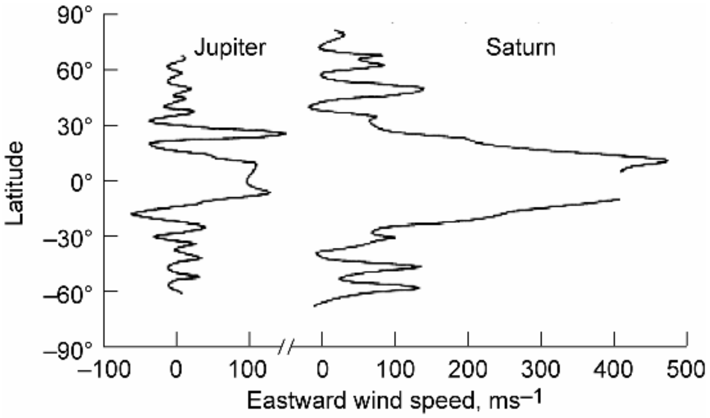

Figure 3.—Winds at Jupiter and Saturn (Ref. 29).

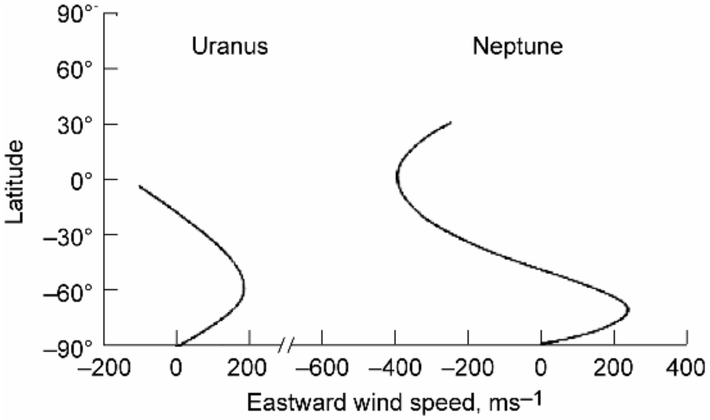

Figure 4.—Winds at Uranus and Neptune (Ref. 29).

While Jupiter and Saturn have more dramatic changes in wind shear, Uranus and Neptune appear to have more calm changes in wind profiles. The stresses imposed on any vehicle entering Jupiter's or Saturn's atmosphere may be too much for a conventional aerostat.

Due to more predictable atmospheric conditions and wind speeds, mining with aerostat borne stations seems more applicable for use at Uranus and Neptune, while more aggressive aerodynamic options (high speed cruisers) may be needed at Jupiter and Saturn.

## Mining Methods

The nature of the mining stations may be a series of buoyant stations in the planetary atmosphere, aerodynamic scoopers that dive into the atmosphere or cruisers that ply the atmosphere, gathering the needed gases and liquefying them. The vehicle types and overall scenarios are described in figures 5, 6, and 7. In all cases, there are many highly interrelated systems and elements. The various scenarios are discussed below, with emphasis on the atmospheric mining elements.

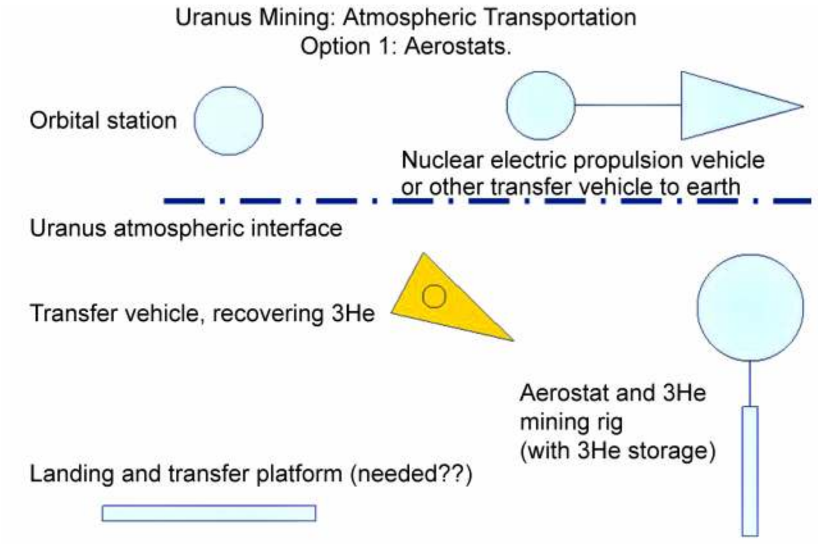

Figure 5.—Atmospheric mining with aerostats.

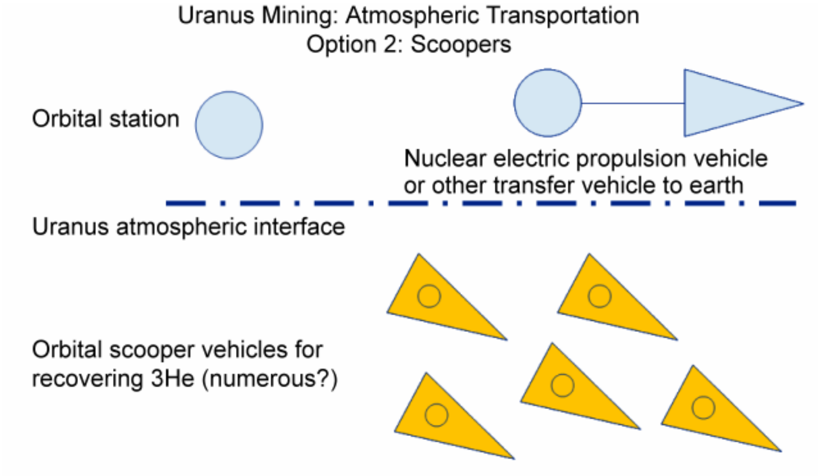

Figure 6.—Atmospheric mining with scoopers.

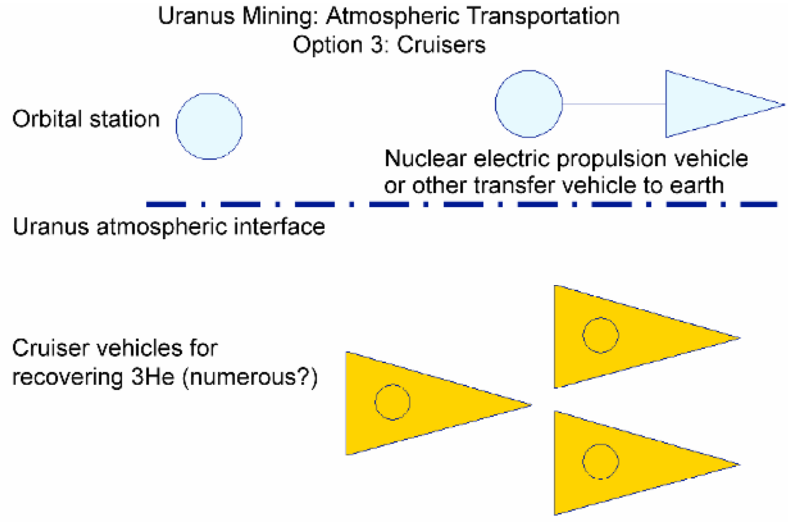

Figure 7.—Atmospheric mining with cruisers.

## Aerostat stations

Figure 5 shows the aerostat scenario. Aerostat vehicles are buoyant stations that would persist in the atmosphere, and continually process atmospheric gases for the needed final products—3He, 4He, and H2, etc. Orbital vehicles would perform round trip visits to the aerostat to deliver the final product to orbit or any other destination (a moon of the planet, transfer vehicle back to Earth, etc.). Aerostats have been considered for mining Jupiter’s atmosphere (refs. 33 to 38). The size of the overall plant was estimated with historical information, and the sizing of balloons (ref. 33). Figures 8 and 9 illustrate the overall conceptual design of an aerostat mining vehicles (ref. 33). The aerostat station was to be visited on a regular basis by vehicles in orbit, and the propellants and other gases derived from the atmosphere were delivered to the vicinity of Jupiter’s moon, Callisto. Callisto is an attractive way station as it can provide materials for vehicle construction from its surface, and it is outside Jupiter’s major radiation belts, thus making it safer for human explorers. Such a scenario may be the most attractive of the three atmospheric mining options.

## Scoopers

Scoopers (ref. 33, 39 to 45) are atmospheric entry vehicles that scoop a small amount of the planet’s atmosphere and gather it aboard the vehicle for processing and/or consuming it as fuel for the vehicle itself. The scooper vehicles can provide a short term option for fuel capturing, and the processing may take place in orbit. The complexity, mass, and volume of the scooper may make it impractical to place all of the subsystems for processing on the entry vehicle.

To gather large amounts of gas, the scoopers would perform many hundreds of missions in to the atmosphere. Overall, the lifetime of the scoopers may be limited by the heating and other stresses due to multiple entries and exits, as well as the on-board propulsion component life. Also, the atmospheric composition may impose new stresses on materials. Flying through icy particles and potentially reactive materials (hydrogen, ethane, etc.) will no doubt create new challenges for long lived vehicles.

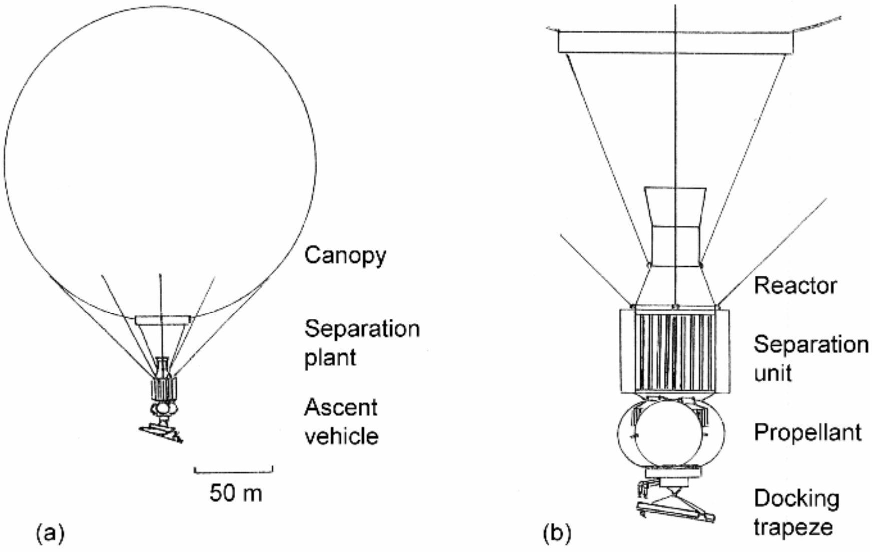

Figure 8.—Aerostat conceptual design (Ref. 33). (a) Overal scheme with the ascent vehicle docked. (b) Detail of the factory complex.

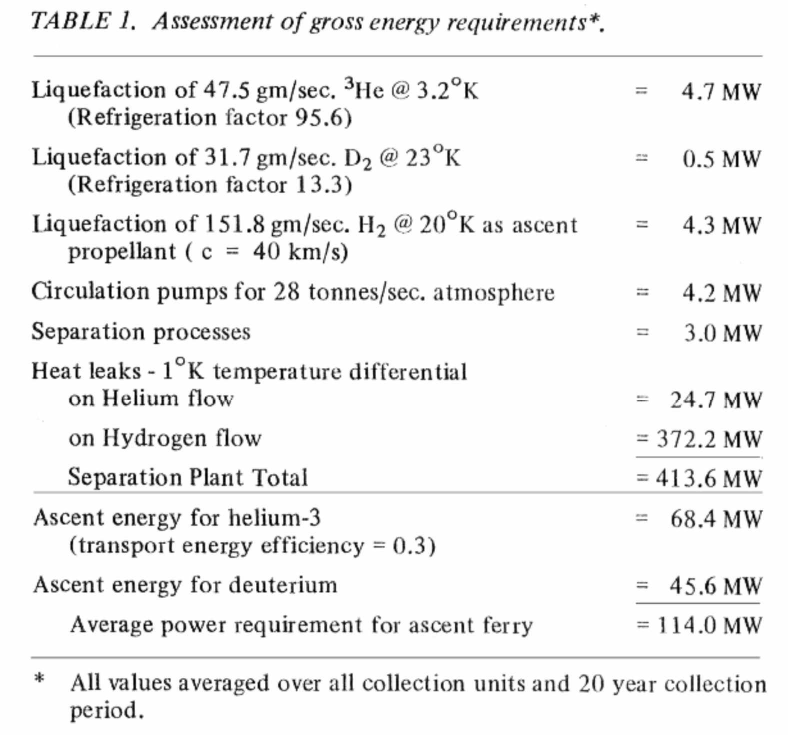

*TABLE 1. Assessment of gross energy requirements*.*

| | |
|---|---|
| Liquefaction of 47.5 gm/sec. $^3$He @ 3.2°K (Refrigeration factor 95.6) | = 4.7 MW |
| Liquefaction of 31.7 gm/sec. $D_2$ @ 23°K (Refrigeration factor 13.3) | = 0.5 MW |
| Liquefaction of 151.8 gm/sec. $H_2$ @ 20°K as ascent propellant ( c = 40 km/s) | = 4.3 MW |
| Circulation pumps for 28 tonnes/sec. atmosphere | = 4.2 MW |
| Separation processes | = 3.0 MW |
| Heat leaks - 1°K temperature differential on Helium flow | = 24.7 MW |
| on Hydrogen flow | = 372.2 MW |
| Separation Plant Total | = 413.6 MW |
| Ascent energy for helium-3 (transport energy efficiency = 0.3) | = 68.4 MW |
| Ascent energy for deuterium | = 45.6 MW |
| Average power requirement for ascent ferry | = 114.0 MW |

* All values averaged over all collection units and 20 year collection period.

Figure 9.—Estimated power requirements for aerostat conceptual design (Ref. 33).

Typical mission life for orbiting or flyby spacecraft has been from 8 years for Mars Global Surveyor (refs. 46 and 47) to 40 years for Voyager (ref. 48). The lifetime for vehicles which repetitively enter atmospheres is not known but can be estimated from historical data and engineering estimates. Hypersonic vehicles used in the past have usually been expendable vehicles, such as reentry bodies for national defense or military missiles. Their heating rates are quite high and they used ablative materials to withstand the heat fluxes for those missions. These vehicles were by definition designed for short lifetimes. The Space Shuttle has experienced many hypersonic reentries but only after much ground maintenance after every entry. Long life hypersonic vehicles may be a truly Olympian challenge.

Cooling of the vehicle surfaces to allow the entry and the scooping of the atmosphere has been studied (refs. 33 and 39 to 45). The aerothermodynamics of the inlet, liquefier and compressors will be a significant challenge. As the technology for this type of vehicle is very complex from many points of view, the overall vehicle complexity and potentially short vehicle lifetime of the scooper scenario may make it the least attractive of the three mining options.

### Cruisers

A cruiser vehicle would be more akin to a traditional aircraft, remaining in the atmosphere, and gathering atmospheric gases as it flies. Smaller vehicles would visit the cruiser and return the liquefied gases to orbit. Many launch vehicle and transatmospheric vehicle designs have been investigated using a liquid air cycle engine (LACE) technology (refs. 49 to 52). A similar design for liquefying hydrogen, helium and 3He would be used in the outer planet atmospheres. Due to the density differences between air and hydrogen, the vehicle size and mass would be much larger, or many more cyclical visits to the atmosphere and the cruisers would be needed to deliver the same amount of liquefied gases for the same mass of vehicle. Again, delivering this complex vehicle or fleets of vehicles from Earth may be a prohibitive task. In-situ construction and maintenance of such vehicles may be more attractive.

## Interplanetary Transportation Options

After suggesting the possible mining options in the atmosphere, the transportation to and from the planet must be addressed. To support the scenarios discussed earlier, there will be both interplanetary spacecraft as well as transportation from orbit to the atmosphere and back to orbit. Earlier studies suggested that the potential complexity of lunar 3He mining should lead to consideration of outer planet atmospheric mining. Theoretically, the extraction of 3He from a gaseous atmosphere will be easier than extracting it from lunar regolith (refs. 5 to 19). The transportation complexity and time of flight may however create a barrier to using the outer planets for powering Earth related activities.

Figure 10 shows the changes in velocity (delta-v) required for Neptune and other outer planet missions (ref. 3). The delta-Vs required are quite high and necessitate some advanced propulsion concept beyond chemical propulsion. A likely first choice is nuclear electric propulsion for the interplanetary missions. Solar energy is quite difficult to use at distances beyond Mars and the main asteroid belt. Nuclear electric transfer vehicles would be a critical part of any scenario. Additional vehicles for transportation in the atmosphere and factories for extracting the hydrogen, helium, or 3He would also be required. Nuclear thermal propulsion (NTP) has also been suggested (ref. 7) however, due to the lower specific impulse (Isp) for NTP, the resulting higher total mass of propellant needed for NTP is higher than NEP. Therefore, especially for cargo missions there trip time is not a critical issue, the selection process for the vehicle usually favors NEP (refs. 47 and 48).

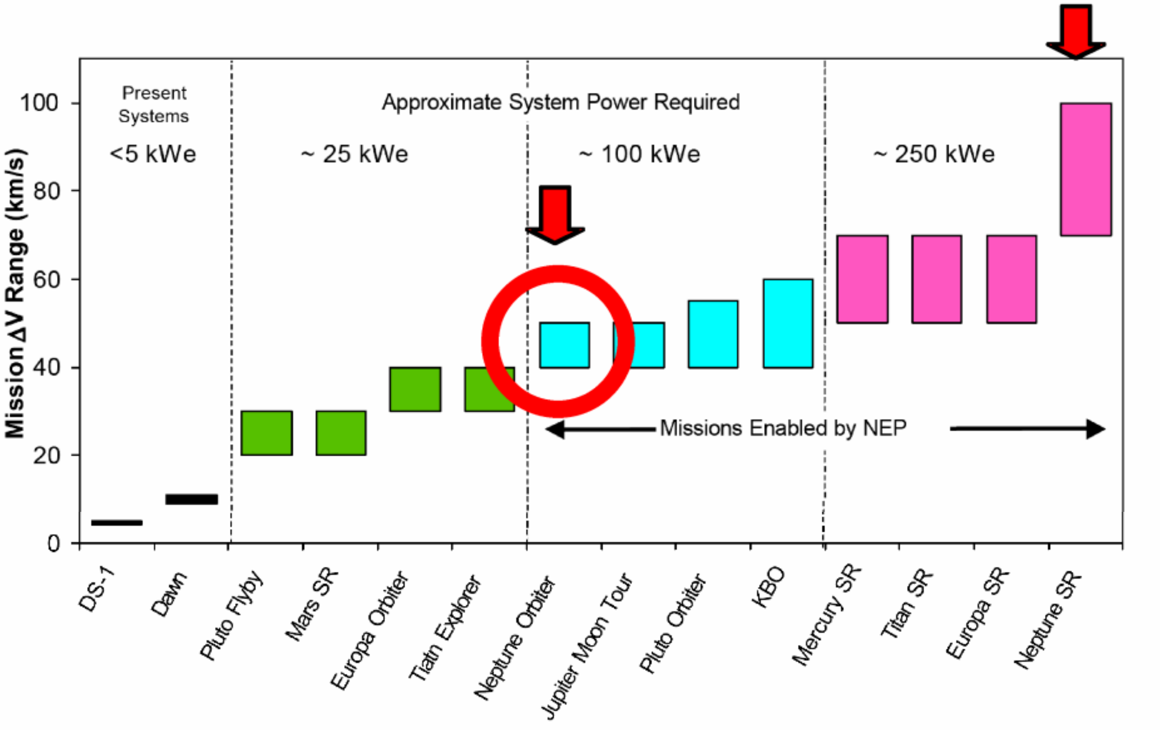

Figure 10.—Mission velocity changes for outer planet missions (Ref. 3).

## Planning Scenarios for Development

The three scenarios were assessed and comparison of the maneuvers and their potential complexity were made. Figures 5, 6 and 7 illustrate the three options for atmospheric mining. Table III provides a list of possible vehicle maneuvers for a Uranus mission set. The major variations in complexity lie in the maneuvers in the atmosphere. In some cases, the scenarios have a large number of platforms and maneuvers required. The number of vehicles needed and their associate maneuvers will have to be managed to create a manageable set of vehicles for the selected scenario. Repetitive maneuvers requiring multiple entries and exits of the atmosphere will stress many aspects of materials, design, crews, robots, and scheduling.

### Mission complexities

Mission complexity is a serious consideration for the success of any space endeavor. The limits of machines and their crews are often stressed during any space mission. There seem to be some fundamental limits to some of the atmospheric mining options. The number of maneuvers and the complexity of those maneuvers may make some options unacceptable for long term robotic or human missions.

The table III list of planned maneuvers for the atmospheric mining missions gives some implication of the number of and complexity of the maneuvers. With scoopers vehicles, the entry velocities are usually very high, and the time in the atmosphere is quite short—the gas scooping time may be only minutes to less than 1 hour. Cruising in the atmosphere is another possibility, but the size of such a cruiser may be prohibitive. The many visits of smaller 3He recovery vehicles (going from orbit, to the atmosphere, and back to orbit) to off load the cruisers may take a toll during the many atmospheric visits. Previous studies of Liquid Air Cycle Engines (LACE) for air separation have shown that the vehicle may have to remain in the air for long periods to make a relatively small amount of propellants. Using aerostat borne factories may be the only realistic option for long term missions. They can remain for long periods in the atmosphere, and have ships visit to recover the processed gases and liquids from the factory. Deployment of the very large aerostats or balloons may be another issue.

TABLE III.—MISSION MANEUVER SUMMARY
FOR ATMOSPHERIC MINING

Maneuvers for Uranus mining flights

- Mission maneuvers
  - Depart from Earth
    - Launch from Earth, orbit established around Earth
  - Depart for Uranus
    - Trans Uranus injection
  - Coast to Uranus
    - Low thrust to Uranus
    - High thrust to Uranus
  - Arrival at Uranus
    - Uranus orbit insertion

  - Arrival at Uranus
    - Uranus orbit insertion
      - Aerocapture?
      - Propulsive orbit insertion
  - Descend to atmosphere
    - Descent orbit initiation
    - Aerobraking to lower orbit
    - Prior to descent into the atmosphere
  - Enter atmosphere
    - Maneuver to destination
  - Arrival at atmospheric station
  - Arrival at atmospheric scooping altitude

  - On-station maneuvers
    - Station keeping at atmospheric station
    - Station keeping at atmospheric scooping altitude
  - Exit the atmosphere
    - Depart from atmospheric station
    - Depart from atmospheric scooping altitude
  - Depart Uranus
    - Trans Uranus injection

  - Coast
    - Low thrust to Earth
    - High thrust to Earth
  - Return to Earth
    - Aerocapture
    - Propulsive capture, insertion
    - Rendezvous
    - Offload cargo
    - Refurbish or dispose of vehicle

## Mass Delivery Implications

In previous studies (ref. 9), the mass of 3He delivered to Earth was about 450 to 500 MT per year. In order to support Earth based power systems, the number of vehicles required may be extremely large. Overall, the processing of 3He from the atmosphere will likely take hours to days to months, depending on the available power level. Only preliminary estimates were developed by the Daedalus Project (ref. 33). Reference 33 showed 3He production of 1500 MT per year for 20 years for the Daedalus vehicle. It is likely that small amounts will be delivered to orbit at any one time, requiring many vehicle flights to traverse the atmosphere to recover the 3He fuel. Until very high velocity vehicles are developed, delivering large masses to the Earth may have to wait. Until such fast transportation is available, performing initial experiments and perhaps constructing large vehicles in the outer solar system and using this precious fuel for exploration may be much more attractive in the near term.

## Comparisons with Lunar Mining

Lunar Helium 3 (3He) may have a large amount of time and effort associated with it, but the travel time to Earth is very short (refs. 9 to 19). The large mining equipment can be sent to the lunar surface and repaired in a low gravity environment, with spare parts available from Earth factories. Currently, servicing an outer planet factory, which is many years and millions of kilometers away may be a great hindrance.

Outer planet 3He extraction has many issues associated with the additional atmospheric constituents. The number and complexity of maneuvers required for 3He mining may make it prohibitive, as noted in table III. Also, returning a sample or large load of 3He to Earth may take a prohibitive amount of time. A round trip time of flight for a Uranus mission may be several years. However, once a pipeline of many continuing flights is established, the long flight time may not be a critical issue.

Figure 11 shows the percentages of Helium in the lunar regolith, up to 70 parts per million (refs. 55 and 56). Figure 12 shows the fraction of 3He in the lunar regolith or dust (refs. 55 and 56). Only a fraction of the total helium in the dust is 3He (with overall only 5 to 100 PPB of 3He in the dust). In the outer planet atmospheres, it is estimated that the 3He mass fraction in the helium mass fraction in the atmosphere is $10^{-4}$ (refs. 5 to 9). Even if the total fraction of 3He in the outer planet helium (4He) is so much higher in the Uranus atmosphere, the other operational factors discussed in this paper may make the idea of 3He mining in the outer planet regions difficult to implement.

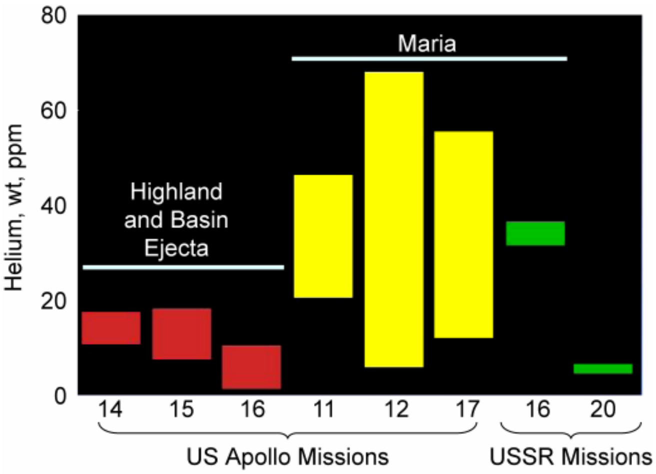

Figure 11.—Helium 4 in the lunar dust (ref. 55). http://fti.neep.wisc.edu/neep602/FALL97/LEC19/lecture19.html

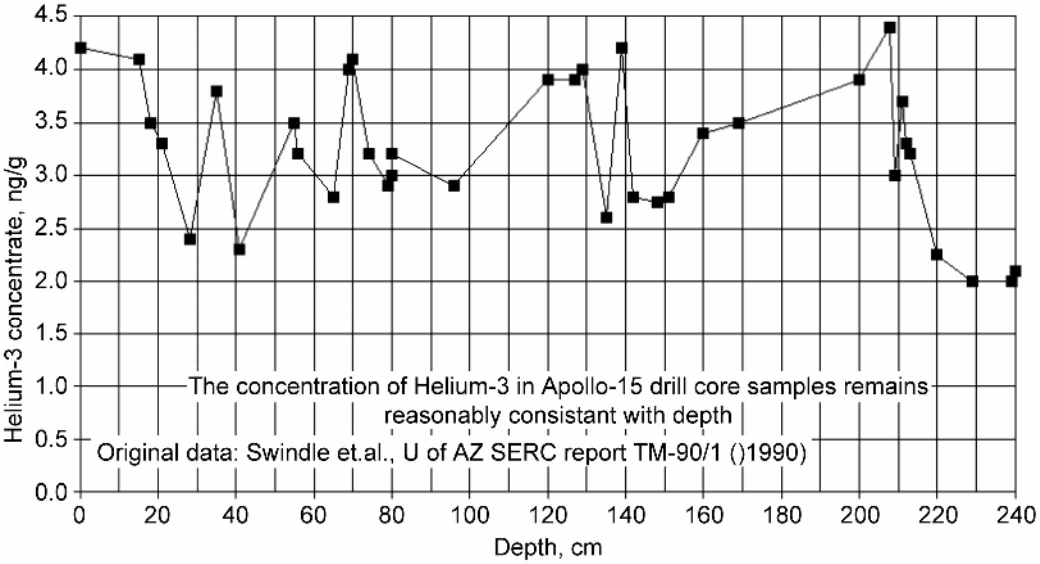

Figure 12.—Helium 3 in the lunar dust (ref. 55). http://fti.neep.wisc.edu/neep602/LEC18/IMAGES/fig25.gif

## Concluding Remarks

It is likely that the delivery of 3He to Earth from the outer solar system will be a difficult and lengthy task. The number of maneuvers, the time scale for transportation, the complexity of the vehicles, and the lifetime of the mining factories or atmospheric vehicles are all important factors to investigate.

An alternative option is the use of the 3He in the outer solar system (not returning it to Earth). Interplanetary and interstellar missions have been investigated (refs. 25 and 33 to 38), and the fuel needed for these missions might be more effectively used in transportation in the solar system. Given the complexity, using the gathered fuel for transportation about or beyond the solar system is likely to be a better option than returning it to Earth.

Production rates for such in-situ missions will be important for mission effectiveness. Supplying the Earth with approximately 450 to 500 metric tonnes (MT) per year of 3He for fusion power has been suggested (ref. 9). Creating the infrastructure for sustainable Earth delivery will likely be a daunting task. Several hundred flights a year to Earth is an admirable goal, but right now it is beyond our reach. An even more audacious idea is the fueling of interstellar vehicles. An extreme example of very high production rates is the Daedalus Project. Based on the Daedalus Project work (refs. 33 to 38), the mass of an initial robotic interstellar vehicle may be 54,000 MT (ref. 35). Approximately 50,000 MT of this mass is the fuel needed for propulsion: 60 percent of the total propellant mass is 3He (ref. 35). At a production rate of 1 MT per visit to the atmosphere, the feasibility of such production systems is unattractive. So many flights would be needed; the time for the project would be prohibitive, extending many years or decades. The Daedalus Project suggested 1500 MT per year for a 20 year period and perhaps this rate may be attractive. Producing 50,000 MT per year is attractive, but may place an undue burden on the human crews in such a harsh environment. Robotic systems, tended by humans, will likely be needed for effective construction and fuel production.

Alternative methods of producing 3He on the Earth have been investigated (refs. 20 to 22). Production from past weapons caches (tritium decay) and production from primordial sources (natural gas and helium stores) seem to have a small upper limit on production mass of approximately 17 kg per year (refs. 20 to 22). For the nearer term, lunar production may prove to be effective in the future for many tons or ultimately hundreds of tons of 3He per year (refs. 5 and 11 to 19). With all such in situ resource usage, small experiments will come first, to prove the technologies, and allow a more effective scale up to the enormous tasks of outer planet exploration.

Highly efficient ISRU plants will be needed to reduce the potential for damage to planetary environments that might be harbors for either past or future alien life. The human exploration of the solar system and others like it will come with time. In very advanced future times, creating new starships or titanic "world ships" (containing entire oceans, continents, and colonies of humans) will require the ability to manipulate or even dismantle entire moons of our outer planets or the moon about the planets of other solar systems (refs. 33 to 39).

## Conclusions

Mining of the outer planets may take many directions, the two most important of which are mining the moons and the atmospheres of those planets. Using specialized factories, the energy of hydrogen, helium, and helium 3 gases can allow us to power nuclear fusion propulsion systems. Chemical rockets for landing and ascending from the moons can also derive their propellants from the moons' ices and/or the planetary atmospheres.

Many issues may make the implementation of these ideas more complex than was originally thought. The dynamics of the atmosphere, radiation, and the energy for orbital transfer all call for very energetic and reliable propulsion systems to allow for rapid, reliable, and repetitive visits to the planets and their moons. For example, due to the more predictable atmospheric conditions and wind speeds at Uranus and Neptune, mining with aerostat borne stations seems more applicable for use there, while with more dynamic winds at Jupiter and Saturn, more aggressive aerodynamic options (high speed cruiser aircraft) may be needed.

The numerous maneuvers and extended vehicle lifetimes required for wresting the resources from the outer planets will likely lead us to more easily completed options. Mining of outer planet moons, especially if water is detected there, will be an excellent option. Initial experiments to prove the efficacy and lifetime of atmospheric scoopers need to be conducted before committing to such ambitious vehicles.

There are great possibilities for human exploration of the solar system. Effective gathering and conversion of the resources in outer planet atmospheres will control the timetables for this human exploration. Indeed the use of these resources of the outer planets can lead us to our first steps toward the stars.

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Overviews, analyses, and assessments of various mining options for outer planet atmospheres are presented. Options for mining include aerostat borne factories that process the atmosphere and cruisers or scoopers that dip into or reside in the atmosphere. Assessments of the mission complexity for several mining scenarios are presented. Propulsion options for these scenarios are also assessed. Options for mining and transporting atmospheric constituents from the outer planet of our solar system were reviewed. Comparisons of the mining and transportation techniques were also assessed. Comparisons of the complexity of lunar helium 3 (3He) mining and mining in the outer solar system planetary atmospheres were conducted. Mission options that reduce the complexity of the transportation systems are suggested.

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