Solar System Exploration Augmented by Lunar and Outer Planet Resource Utilization: Historical Perspectives and Future Possibilities

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Establishing a lunar presence and creating an industrial capability on the Moon may lead to important new discoveries for all of human kind. Historical studies of lunar exploration, in-situ resource utilization (ISRU) and industrialization all point to the vast resources on the Moon and its links to future human and robotic exploration. In the historical work, a broad range of technological innovations are described and analyzed. These studies depict program planning for future human missions throughout the solar system, lunar launched nuclear rockets, and future human settlements on the Moon, respectively. Updated analyses based on the visions presented are presented. While advanced propulsion systems were proposed in these historical studies, further investigation of nuclear options using high power nuclear thermal propulsion, nuclear surface power, as well as advanced chemical propulsion can significantly enhance these scenarios.

Robotic and human outer planet exploration options are described in many detailed and extensive studies. Nuclear propulsion options for fast trips to the outer planets are discussed. To refuel such vehicles, atmospheric mining in the outer solar system has also 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 have investigated resource capturing aspects of atmospheric mining in the outer solar system. These analyses included the gas capturing rate, storage options, and different methods of direct use of the captured gases. 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.

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)

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GCNR	Gas core nuclear rocket
GCR	Galactic Cosmic Rays
GTOW	Gross Takeoff Weight
H2	Hydrogen
He	Helium 4
ISRU	In Situ Resource Utilization
Isp	Specific impulse (s)
K	Kelvin
kT	Kilotons of explosive power
kWe	Kilowatts of electric power
LEO	Low Earth Orbit
M dry, stage	Stage dry mass (kg)
M, dry coefficient	Stage dry mass coefficient, B
M p	Propellant mass (kg)
MT	Metric tons
MWe	Megawatt electric (power level)
NEP	Nuclear Electric Propulsion
NPP	Nuclear Pulse Propulsion
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
OC	Open cycle
O2	Oxygen
PPB	Parts per billion
UAV	Uninhabited Aerial Vehicle

I. Introduction

Human and robotic missions have been planned for targets throughout the solar system. Both types of missions can benefit greatly from the resources available from the planets and /or their moons. These benefits include water on many of the outer planet moons and large asteroids. With this water, oxygen / hydrogen rocket propulsion systems can be fueled, breathing oxygen can be extracted, and other life support functions (cooling fluids, etc.) can be facilitated. In addition, the atmospheres of many planets have ready reserves of gases for propellant production. Carbon dioxide on Mars can be separated into oxygen and carbon monoxide or methane. The outer planets offer enormous amounts of energetic gases such as hydrogen, helium 3, methane, and ammonia. By using these in-situ resources, robotic precursor missions can double or triple their payloads to the surface and return double or triple the samples from the solar system targets. Without in-situ resource utilization (ISRU), solar system exploration will be exceedingly limited. For future large scale human missions, the possibilities of ISRU for of human exploration and finally settlement offer the best opportunities for sustainability and success.

II. Human Exploration Options

In the 1950's, 1960's, 1970's, and 1980's, ambitious robotic and human mission were planned, spanning from Mercury to the outermost reaches of the solar system (Refs. 1-10). While investments in robotic missions have continued, human exploration of the solar system has awaited new invigorating steps. While lunar and Mars missions are in the early step-wise planning stages, many cost barriers have prevented their implementation. Future human missions to other destinations such as Mercury and Saturn will also require long-term investments. Currently, Mercury and Saturn have robotic missions returning invaluable data on those planets and their environs (Refs. 11 and 12). These data have provided insights that will ensure the success of future missions. With its proximity to the Sun, Mercury has extremely high temperatures and requires special high heat flux considerations for long-term human visits or bases. In contrast, temperatures at Saturn and its moons require designs for cryogenic environments. The possibilities for in-situ resource utilization (ISRU) may allow more effective robotic missions and human visits to these planetary targets.

A. Mercury

Mercury is the closest planet to the Sun; ranging from a perihelion of 46 million km to an aphelion of nearly 70 million km. The high temperature, high heat flux environment at Mercury and the tenuous surface emanations of several major chemical species (sodium, etc.) surrounding it will likely pose challenges to long term human visits. Permanently shadowed craters offer a valuable niche for longer term human visits and planetary bases. Such craters offer cryogenic temperatures while the sun facing surface is at a temperature of 590 to 725 degrees K. The north polar regions of Mercury have been identified as a likely location for such permanently shadowed craters (Ref. 11, 12, and 13). Water ice is also likely to be in these craters, further aiding and assisting any human explorations. Short exploratory missions can be accomplished with hopping ascent-descent vehicles from the base at the shadowed crater.

Figure 1 shows the locations of the shadowed craters (Ref. 12). Figure 2 depicts the temperatures that would exist in and near the craters (Ref. 13). The crater could accommodate a small base or at least an initial landing site. The lander’s temperature could stay within the nominal operating temperatures of traditional spacecraft. The temperature distribution in the crater would allow construction of the base at the warmer side of the crater and then the frozen volatiles would be extracted with cryogenic mining machines.

B. Saturn and its moons

Saturn is one of the outer planets. Its orbit has a perihelion 1,352.6 million km and an aphelion 1,514.50 million km. An extensive series of flybys of the Saturnian moons have been conducted by the Cassini spacecraft. During these flybys, cameras and instruments capture and data on the moons’ composition, atmosphere and cloud cover (on the moon Titan), volcanos, plumes, rotation, and gravity.

Titan is the largest moon of Saturn. Its intriguing nature includes a nitrogen and methane atmosphere and a subsurface ocean (Ref. 4). Recent flybys of the Cassini spacecraft have shown direct visual evidence of the northern lakes which are likely composed of methane. Based on measurements and theories of the evolution of Titan, a large ocean of water and ammonia may exist below the icy surface. Large lakes in the north polar regions have been seen on Titan’s surface, and they are likely composed of liquid methane. Figure 3 shows the possible nature of Titan’s interior, surface, and atmosphere. While methane can be used as an effective rocket propellant, its nitrogen could be used in cold gas propulsion or electric propulsion (resistojet, arcjet or magneto-plasma-dynamic (MPD) thrusters).

C. Enceladus

The moon Enceladus is producing a large plume of water that is escaping into space. Speculation on the production of that water varies. The south polar region has several hot spots (a cryogenic, volcanic area), known as the tiger stripes, matching the location of the plume of water exiting Enceladus (Ref. 15).

In-situ resources from the Titan water ocean can be used for rocket propellants. Access to the ocean may only require drilling a short (or km long) distance into the icy crust. At Enceladus, the water plume may be captured, or the ocean of reservoir feeding the plume will be tapped. Capturing this water may prove difficult, however, and additional research is needed to find the best manner of fluid capturing.

D. Asteroids

An excellent additional target may be Ceres, the largest asteroid in our solar system. Ceres may provide substantial water from its water ice and the potential ocean below the ice (Ref. 16). As with Enceladus, drilling through many km of ice may be required and finding sufficiently deep crevasses will no doubt be useful in easing the drilling requirements.

III. Mission studies

A. Mercury Missions

A human round trip mission to Mercury was assessed. The mission delta-V values for the round trip Mercury missions were derived from Refs. 17 to 20. The highest delta-V case was selected from this data: an Earth departure delta-V of 5.2 km/s, a Mercury arrival delta-V 0f 10.9 km/s and a Mercury departure delta-V of 8.7 km/s (Ref. 17). Each delta-V was delivered by a separate single stage; thus a 3 stage vehicle is used. At Earth, a capsule enters the atmosphere to return the crew directly to Earth. The capsule’s mass is 4,350 kg (Ref. 17). The round trip time is 585 days with a 40 day stay time at Mercury (Ref. 15). In this case, the vehicle does not land on Mercury. The LEO masses of both chemical propulsion and nuclear thermal propulsion vehicles were estimated. Figure 4 compares the LEO masses for 2 types of chemical propulsion systems and 2 nuclear thermal propulsion (NTP) systems. The interplanetary chemical propulsion systems used tankage dry mass coefficients of 3% and 5% of the total propellant mass in the tankage. In many cases, these dry masses may be deemed to be optimistically low; however, they allow some relative comparison of the chemical propulsion and the nuclear mission cases.

The NTP vehicles dry mass was 15% of the propellant mass. In current NTP designs, an Isp of 900 seconds is nominally used (Refs. 23 and 24). Somewhat lower Isp values were used for these missions: 800 and 850 seconds, respectively. These lower Isp values were assumed given the high heat flux environment of Mercury and the degraded Isp values would reflect the added propellant used for propellant cooling and/or refrigeration. The chemical propulsion systems required between 17,150 MT and 27,000 MT to accomplish the mission. The NTP vehicles required approximately an order of magnitude less mass in LEO: 1,700 MT to 2,300 MT.

Table I. Space vehicle dry mass coefficient and rocket engine specific impulse (Isp)

Technology	Isp (s)	M, dry coefficient (kg/kg M,p)
Chemical-1	450	0.03
Chemical-2	450	0.05
Chemical lander	480	0.20
NTP-1	800	0.15
NTP-2	850	0.15

Based on Ref. 21, the stage and lander mass was estimated with the following mass scaling equation:

M dry,stage (kg) = M, dry coefficient * M p (kg)

A Mercury landing vehicle mass was also estimated. The one-way delta-V for the lander was 3.5 km/s (Ref. 22). The ascent delta-V was also 3.5 km/s. These delta-V values accommodate approximately 19% for gravity losses for each maneuver; this gravity loss delta-V is added to the orbital velocity for a 100 km orbit which is 2.945 km/s. The lander Isp was 480 seconds. The higher Isp was chosen for the lander as the engine used a higher engine expansion ratio that the interplanetary transfer vehicle (Ref. 21). The smaller engine size would allow a higher expansion ratio, given the typical volume constraints for space vehicles. The dry mass coefficient was 20% of the total propellant load. While the Mercury missions will likely require more aggressive thermal control (propellant shielding, cooling, etc.), that thermal control system mass is accommodated in the payload mass of the vehicle. The payload delivered to the surface was 10 MT. Figure 5 compares the mass in LEO of a one-way lander and a round trip lander. The masses were 140 MT for the round trip lander and 27 MT for the one way lander. Thus, using ISRU on the surface of Mercury to replenish the lander's propellant would allow a savings of 113 MT on this mission. Additional analyses are needed to investigate the mass reductions for the interplanetary transfer vehicle to carry the lander to Mercury. Another option would be to carry 5 landers to Mercury rather than carry simply one lander; many more permanently shadowed craters could then be visited on one mission. The interplanetary vehicle carrying the 5 landers could be sent on a lower energy trajectory than the human flights, thus saving additional mass launched into LEO in the overall Mercury architecture.

Additional summary data on mission design is summarized in Ref. 20. Figure 6 provides map of the one-way delta-V and trip time for a wide range of planetary targets (Ref. 20). Fast missions to Jupiter and Mercury are possible with delta-V values of 80 to 100 km/s. Nuclear propulsion systems may someday allow such ambitious missions and if augmented by ISRU, such mission will be within our technological reach

B. Atmospheric Mining in the Outer Solar System (AMOSS)

Atmospheric mining in the outer solar system can be a powerful ISRU 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 (Refs. 23 and 24). Helium 3 (3He), a nuclear fusion fuel, would be extracted from the atmosphere and stored for final delivery to orbital assets. Analyses showed that gas core nuclear rocket (GCNR) engines can reduce the mass of such aerospacecraft mining vehicles very significantly: from 72 to 80 percent reduction over nuclear thermal propulsion (NTP) solid core powered aerospacecraft mining vehicles. 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 3He 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 (multi-day) of helium 3 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. 23). Typically, these very large (excess) additional fuel masses can dwarf the requirements needed for hydrogen captured 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 uninhabited aerial vehicles (UAVs), or 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.

Based on these past analyses, there will likely be several possible future avenues for effective use of 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 these latter planets 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.

C. Nuclear Underground Explosions

Based on recent measurements and simulations of the lunar radiation environment, it appears that long term occupancy of the lunar surface may be detrimental to human beings. In addition to the long term exposure to natural radiation sources (galactic cosmic rays, solar flares, etc.), there is additional scattered radiation on the lunar surface (Ref. 25). Based on these most recent measurements and the past work in lunar bases, it seems reasonable to assess living and working in underground facilities on the Moon. Using small of large nuclear devices on the Moon may provide an option for creating a series of large habitable underground spaces. Project Plowshare in the 1960s' (Refs. 26 to 33) addressed some of the issues with using nuclear devices to complete large scale redirection of rivers, building canals, and many other massive civil engineering projects.

Past Earth based nuclear weapons testing often was done underground due to the Nuclear Test Ban Treaty of 1963. The tests often left sizable craters on the surface. When a nuclear device is sufficiently deeply buried, the explosive force can be completely contained underground (Ref. 26, Figure

8). The blast vaporizes some of the surrounding rocky material which then expands and creates an underground cavity, as shown in Figure 8. In most cases the weight of overhead rock soon crumbles the roof of the void chamber and a vertical column (or chimney) is created by the successively falling loose rocky layers. The material in the chimney undergoes compaction after the roof collapse but the initial amount of void space created by the blast just after detonation is distributed in this broken rocky debris. Small robotic mining systems could be used to manage the debris. Based on historical data, such a space can also be spherical if the blast size is sufficiently small. After the radiation has fallen to acceptable levels, people could potentially create comfortable living spaces.

In Ref. 7, this technique was proposed for not only living spaces, but for large scale ISRU. Nuclear explosions would be used to melt and vaporize lunar regolith. Figure 9 illustrates four different processes using nuclear detonations (Ref. 7). There are 2 chambers: one for the nuclear explosion, and one for the reaction product capturing. This processing would essentially chemically reacting oxygen, hydrogen, or other species. The processes range from creating oxygen and metal oxides to producing water and metal carbides. From Ref. 7:

> *"A nuclear charge of one kiloton, detonated underground, fractures approximately 80,000 cubic meters or 330,000 tons of lunar rock, containing 130,000 MT of oxygen. At least 1%, or 33,000 MT, of the rock is fully evaporated. The silicon and metals condense quickly. But, since they are in an essentially pure oxygen atmosphere, they also reoxidize vigorously. Estimating, very conservatively, that only 20 to 30% of the liberated oxygen can be extracted and stored, this means that through the underground detonation of a one-kiloton nuclear charge, of a systems mass of a few hundred pounds, 6,000 to 10,000 MT (Earth weight) of oxygen can be provided."*

Certainly, extensive processing will require maintenance of the nearly spherical cavities and effective pumping schemes to introduce the gases into the underground chambers for the planned reactions. However the rates of production may be high enough to warrant the use of nuclear detonations.

D. Lunar Slide Lander

The lunar slide lander uses friction between a descending tubular spacecraft and a prepared runway of lunar regolith. The operations of the slide lander are in 8 phases (Ref. 8):

1) Elliptical orbit descent.
2) Perilune maneuver (pre-landing retro-thrust).
3) Approach to touchdown (cut in supporting (vertical) thrust at the end of Phase 3).
4) Touchdown with harenodynamic tail brake. A positive angle of attack is maintained by the supporting thrust.
5) Initiation of main drag phase. Touchdown of harenodynamic side brakes.
6) Main drag slide phase with supporting thrust.
7) Main drag slide phase without supporting thrust.
8) Final braking by means of additional braking devices, or brief retro-thrust, for a controlled stop.

The slide lander was an attempt to reduce the total propellant load required for lunar landings. While the approach velocity of the lander is over 1,500 m/s, the long slide process may reduce the total delta-V required to 200 to 450 m/s. This is in comparison to the 2,000 m/s typically used for lunar landing (Ref. 34). Precise landing control is required and the length of the landing strip area is approximately 80 km. Additional studies have identified that the dust from the initial phase of the slide landing may attain an attitude of 1,300 of km (Ref. 8). Thus, while the landing methods saves much precious propellant, the implications of the flying dust on other lunar surface and orbital operations must be addressed.

E. Nuclear Pulse Propulsion

Using nuclear devices for propulsion is another product of the creativity of the 1960's engineering and physics community (Refs. 35 to 38). The nuclear pulse propulsion (NPP) systems were seriously considered for fast transportation throughout the solar system. Small nuclear devices would be detonated behind a large piloted spacecraft, and the detonation would power the vehicle. Many 1000's of such pulses were required for outer planet missions. The predicted specific impulse for these vehicles is between 1,800 and 6,000 seconds (Ref. 34). The NPP vehicles were considered a logical precursor to the pulsed fusion propulsion systems, noted in many of the AMOSS studies (where 3He and deuterium nuclear fuels are mined from the gas giant planets).

Nuclear pulse propulsion freighters were conceived to return 3,000 MT payloads of raw or processed materials from many targets in the solar system. Figure 10 shows the mission energies, the transportation and propellant costs for such a large nuclear freighter (Ref. 7). These analyses noted NPP Isp values from 6,000 to 10,000 seconds (Ref. 7). To support such operations perhaps nuclear bomblet factories would be constructed all through the solar system. While constructing large nuclear facilities on every location of human exploration may be optimistic, certainly several locations for extended exploration should be chosen for such nuclear sites. Smaller nuclear facilities will be a first step, using smaller reactors.

III. Observations

While human missions to Mercury and Saturn and all of the other planets will be challenging and require long-term investments, the results from these missions and their development will no doubt have great influences on our economy and improve our technological prowess.

Krafft Ehricke envisioned a poly-global civilization, with branches of humanity in many far flung places in our solar system (Ref. 1). His vision was uniquely expressed in Ref. 36. Here is a short excerpt from that work:

> *"Our helionauts, as these men who fly our large interplanetary vehicles call themselves in this era of continuing specialization, have covered the solar system from the sun scorched shores of Mercury to the icy cliffs of the Saturn moon, Titan. They have crossed, and some have died doing so, the vast asteroid belt between Mars and Jupiter*

and have passed through the heads of comets. Owing to the pioneer spirit, the courage and the knowledge of our helionauts and of those engineers, scientists, and technicians behind them, astrophysicists today work in a solar physics station on Mercury; biologists experiment on Mars, backed by a well-supplied research and supply station on the Mars moon, Phobos; planetologists have landed on Venus; and teams of scientists right now study what have turned out to be the two most fascinating of our solar system, Jupiter and Saturn, from research stations on Callisto and Titan."

These helionaut flights would be the precursors of human outposts and then colonies all through the solar system. Multiple systems employing planetary ISRU could enable all of these ideas and concepts.   Krafft Ehricke envisioned an entire extensive lunar economy, producing power, finished and raw materials, and NPP launching bases for extensive exploration of the solar system. The poly-global civilization was considered a natural expansion of the human experience, pioneering new frontiers and using technology in the best interests of all humanity.

IV. Concluding Remarks

A wide range of space exploration technologies have been assessed in many studies from the 1960's to today. In an optimistic future, lunar exploration will lead to base construction and, with time, lead to extensive lunar industrial investments. There are a wide range of potential lunar industries: raw materials processing, oxygen and other propellant production, nuclear and solar power, etc. These industries may lead to small scale devices and large scale products: from microchip production to the creation of completely new space vehicles.   Many of the suggested industries were related to power production to be transmitted to Earth or other attractive locales in the Earth-Moon space.

The need for safe lunar bases may lead to creating underground structures. If extended visits or permanent colonization of the Moon is needed, humans will require protection from long term radiation exposure as well as intense solar events such as coronal mass ejection, galactic cosmic rays, and lunar surface scattering of radiation. Using explosive forming of underground cavities may lead to an attractive lunar base or colony.   Additional industrialization options include nuclear explosion based processing of raw lunar materials. Large scale mining of lunar raw materials and gas production and capture from underground nuclear processing of the in-situ materials has been suggested.

Missions to several planetary targets in the solar system were considered: Mercury, Saturn, and its moon, Titan and Enceladus, as well as the asteroid, Ceres. The LEO masses were estimated for the Mercury mission scenarios.   Lander (ascent/descent) vehicles for Mercury were also assessed. The mass of the lander vehicles for Mercury was 140.1 MT for the round trip lander and 27 MT for a one-way deliver lander to the surface. Each carried a 10 MT payload.   With ISRU, five landers could be delivered to Mercury's surface rather than one.   The LEO masses for the human round trip Mercury missions was reduced by an order of magnitude, from 27,000 MT to 2,300 or 1,700 MT, using nuclear thermal propulsion over chemical oxygen /hydrogen propulsion systems. Using ISRU at Mercury would likely further benefit a range of such missions.

Atmospheric mining in the outer solar system can produce nuclear fusion fuels such as 3He which are rare on Earth. In addition, while extracting the small fraction of 3He in the gas giant atmospheres, each day enormous amounts of hydrogen and helium are produced. These amounts can far outstrip the needed for propellants to return the mining aerospacecraft to orbit. These additional hydrogen and helium gases can augment many additional UAVs and probes for extended exploration of those planets' atmospheres and local environs.

Solar system exploration using in-situ resource utilization can allow higher quality missions with much large data return. Larger more effective research and sample return missions are possible. Faster missions are possible by using the local planetary resources to return to Earth. By not carrying all of the return propellants, larger propellant loads in LEO can enable shorter mission flight times. Truly impressive interplanetary missions can be within our reach with focused investments.

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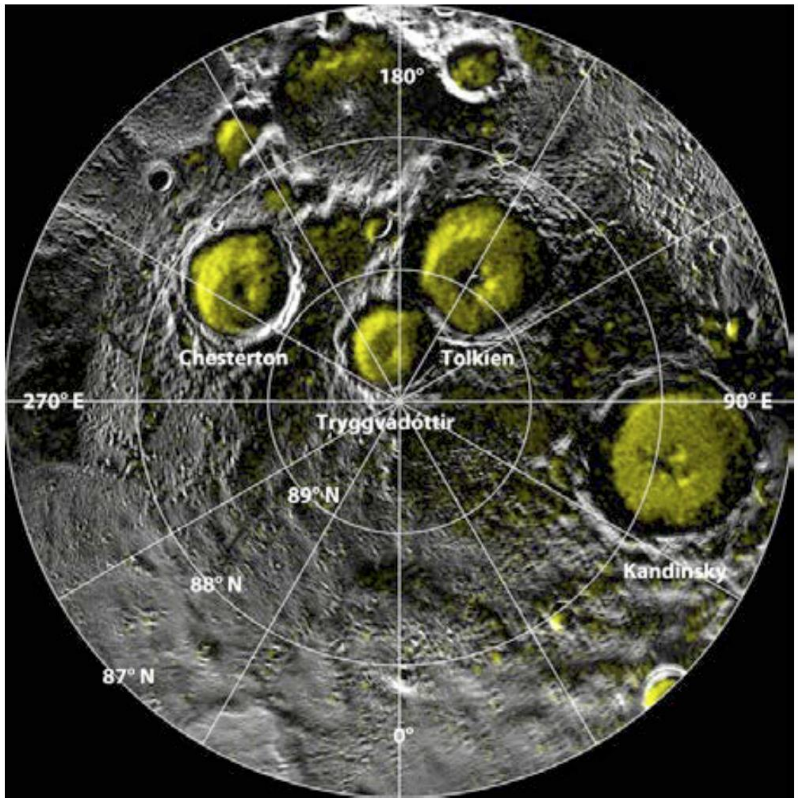

Figure 1. Permanently shadowed craters in Mercury's north polar region (Ref. 12).

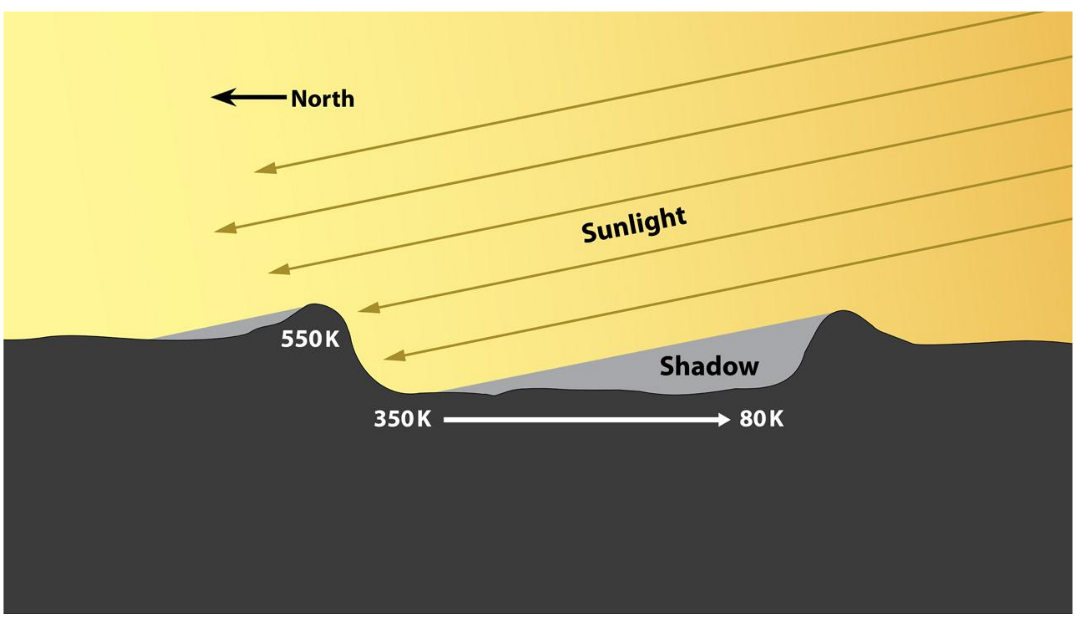

Figure 2. Temperature ranges outside and inside permanently shadowed craters (Ref. 13).

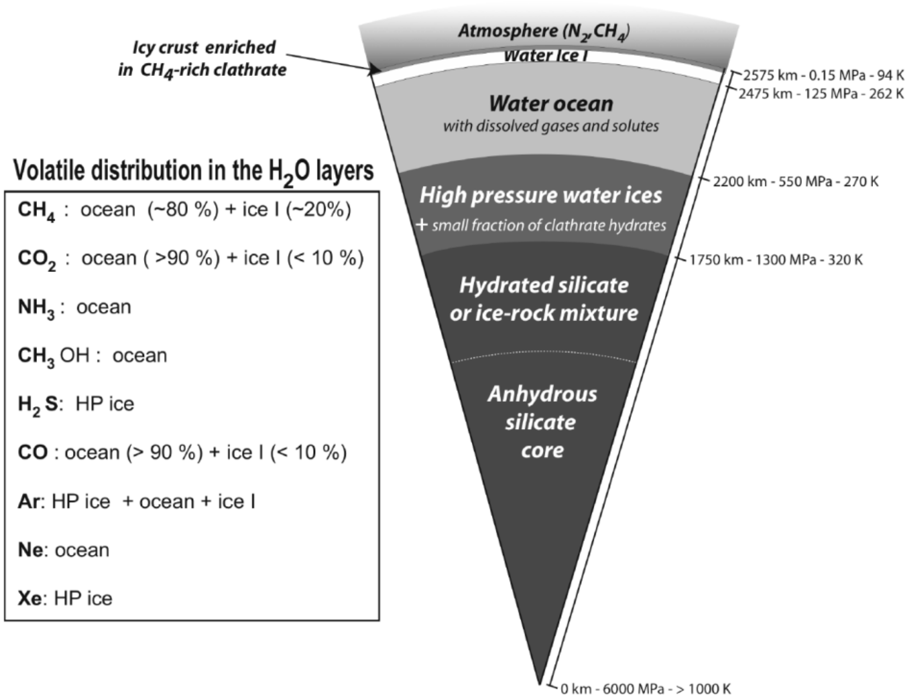

Figure 3. Possible present day cross section of Titan (Ref. 14).

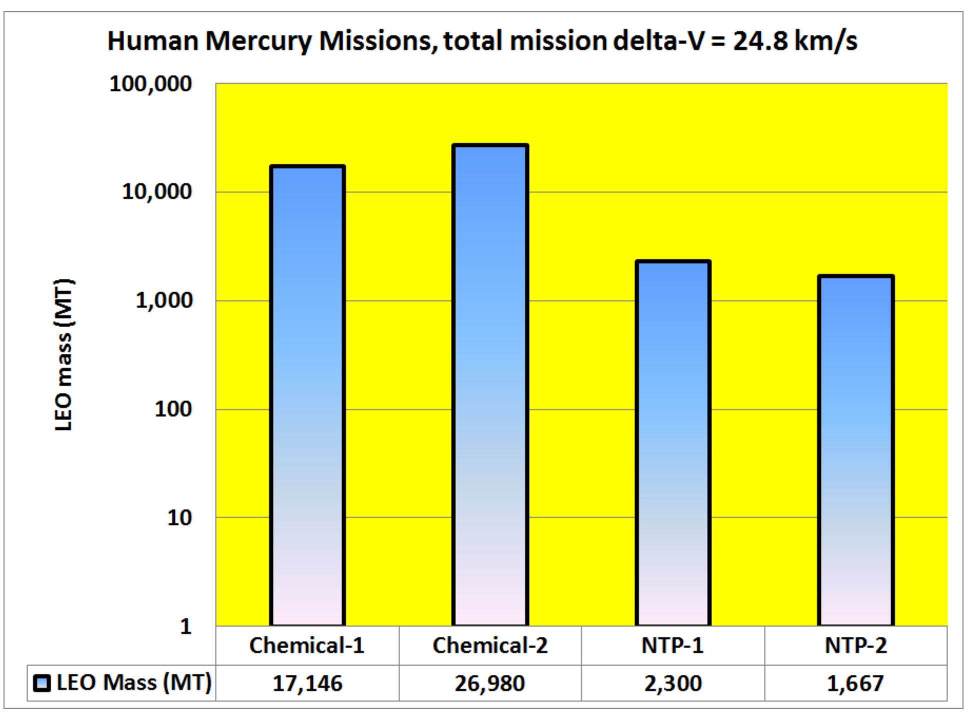

Figure 4. LEO masses of human round trip missions to Mercury.

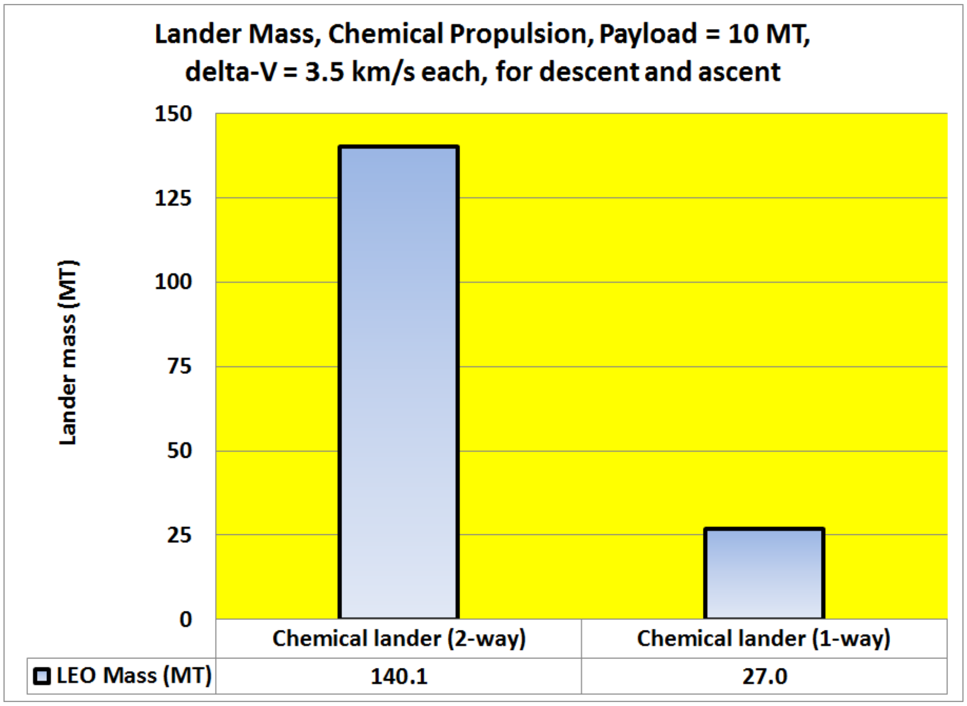

Figure 5. LEO masses of lander vehicles for missions to Mercury.

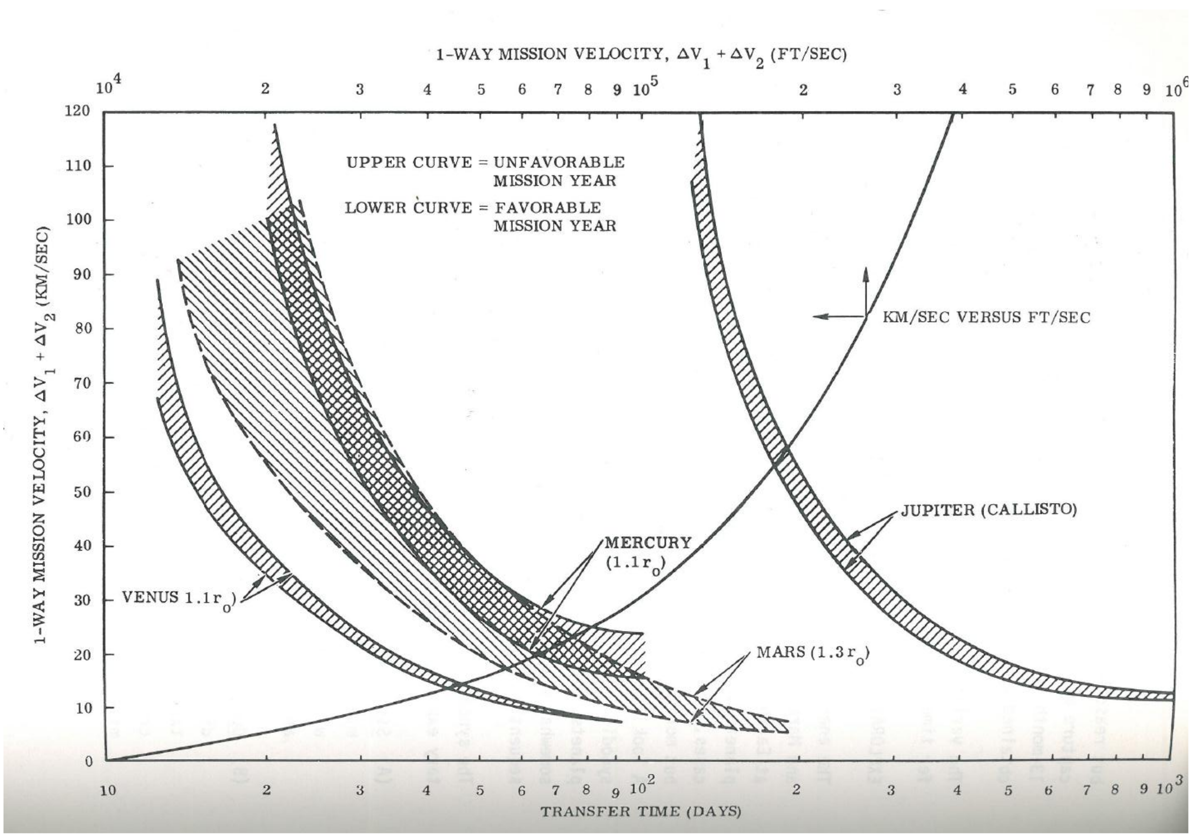

Figure 6. One-way interplanetary mission delta-V versus trip time for various targets (Ref. 20).

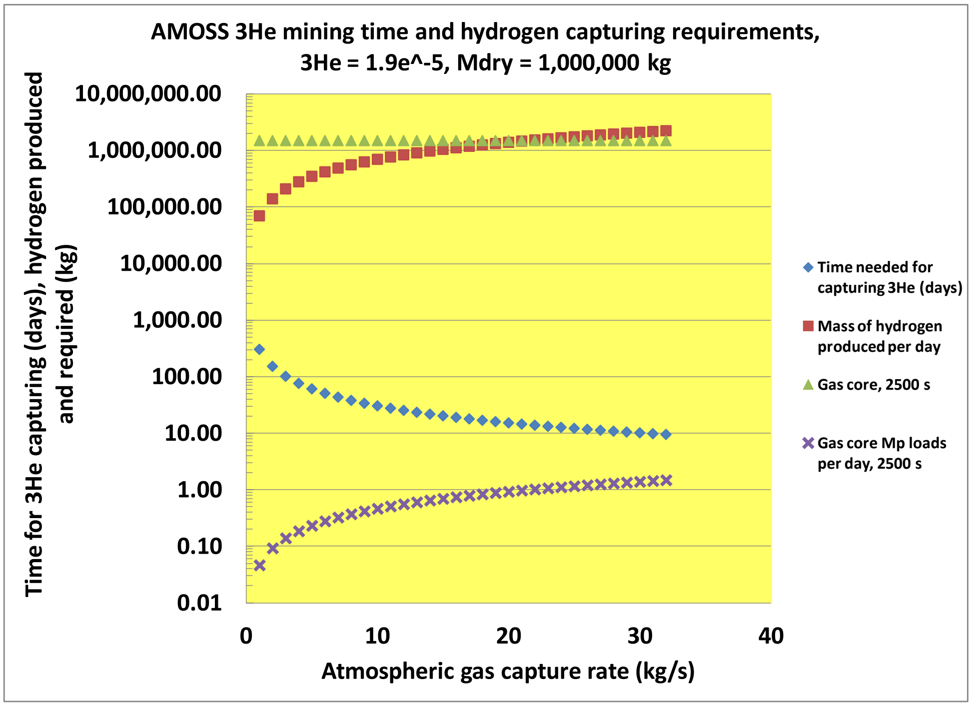

Figure 7. Helium 3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune AMOSS (Ref. 23).

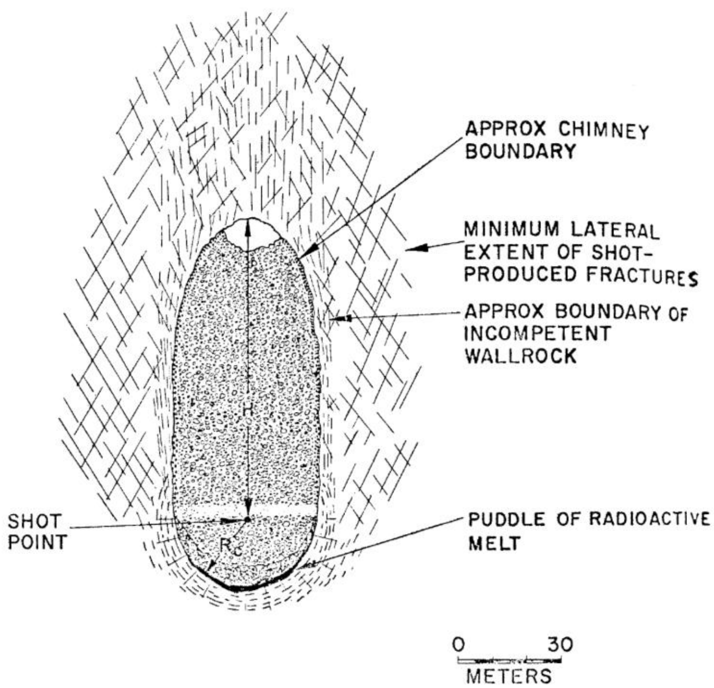

Figure 8. Schematic cross section of a hard rock medium after contained nuclear explosion (Ref. 25).

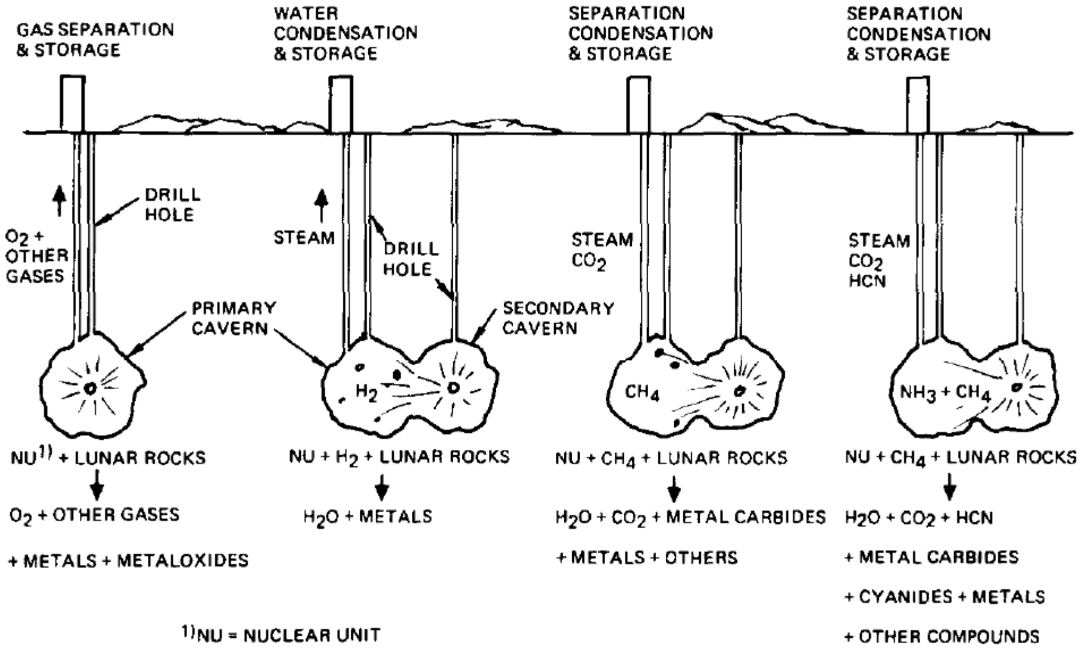

Figure 9. Nuclear detonation processing (Ref. 7).

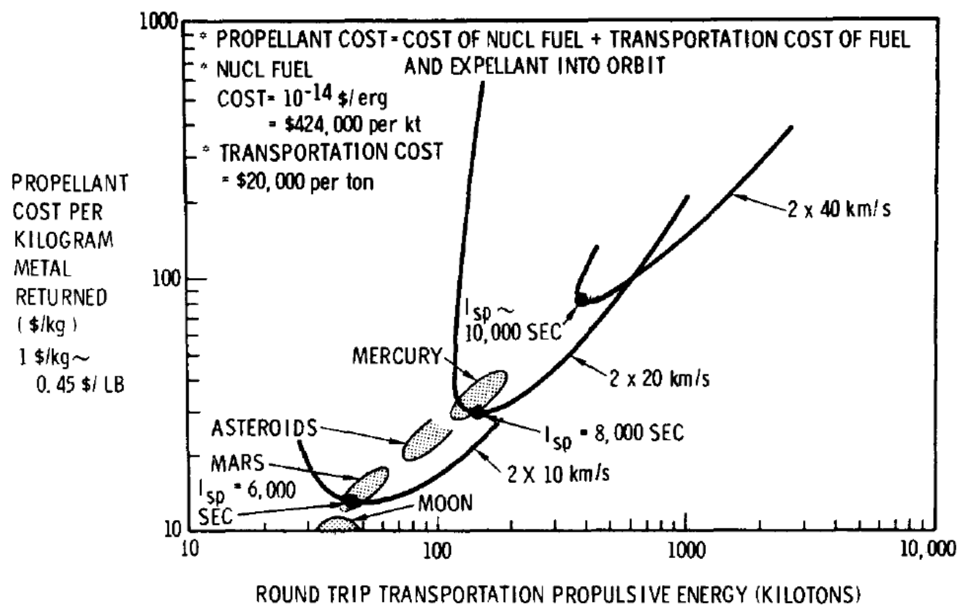

Figure 10. Nuclear pulse propulsion freighter propellant costs for 3.000 MT payload (Ref 7).

Appendix A (Ref. 17; Manning, L. "Comparison of Several Trajectory Modes for Manned and Unmanned Missions to Mercury 1980-2000," AIAA 67-28, 1967).

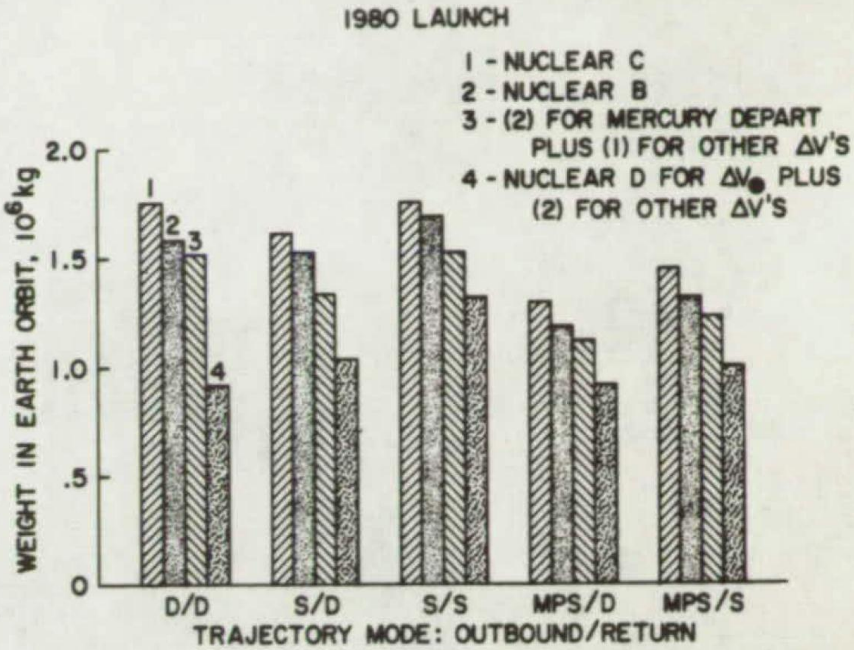

Fig. 10.- Comparison of Earth orbit weight requirements; manned Mercury stopover missions.

D	direct transfer
S	unpowered Venus swingby transfer
MPS	modified pericenter Venus swingby transfer

Propulsion and performance data.

- Engine characteristics

Engine	I_{sp}, sec	Weight (W_E), kg	T/W	Propellant
Chemical	450	Variable	80	O_2/H_2
Nuclear A	800	1,600	2.9	H_2
Nuclear B	850	8,000	4.4	H_2
Nuclear C	850	17,000	6.2	H_2
Nuclear D	2,000	115,000	2.0	H_2

Appendix A (continued)

Table 1 Minimum ΔV requirement; manned Mercury stopover mission

(a) Trajectory mode comparison: 1980 launch

Item \ Trip type[1]	D-D	S-D	MPS-D	D-S	S-S	MPS-S
Depart Earth	4366[2]	4370	4336	4551	4370	4336
$\Delta V_{\oplus}$ (km/sec)	6.8	5.3	4.3	5.4	5.3	4.3
Pass Venus	---	4489	4412	---	4489	4412
Altitude (km)	---	346	250	---	346	250
$\Delta V_{♀}$ (km/sec)	---	---	0.9	---	---	0.9
Arrive Mercury	4456	4594	4460	4681	4594	4460
$\Delta V_{☿}$ (km/sec)	6.5	7.6	6.4	10.0	7.6	6.4
Depart Mercury	4634	4634	4634	4704	4704	4704
$\Delta V_{☿}$ (km/sec)	6.2	6.2	6.2	6.2	6.2	6.2
Pass Venus	---	---	---	4820	4820	4820
Altitude (km)	---	---	---	355	355	355
Arrive Earth	4734	4734	4734	4970	4970	4970
V_E (km/sec)	14.5	14.5	14.5	12.4	12.4	12.4
ΔV_T (km/sec)	19.5	19.1	17.8	22.2	19.1	17.8
Trip time (days)	368	364	398	419	600	634
Stay time (days)	178	40	174	23	110	244

[1]Outbound leg - inbound leg.
D = direct
S = Venus swingby
MPS = Venus swingby with ΔV to raise pericenter radius at passage
[2]Julian date from 2440000.

(b) Trajectory mode comparison: 1983 launch

Item \ Trip type	D-D	S-D	D-S	D-MPS	S-S	S-MPS
Depart Earth	5468	5484	5615	5615	5484	5484
$\Delta V_{\oplus}$ (km/sec)	8.9	4.8	5.2	5.2	4.8	4.8
Pass Venus	---	5569	---	---	5569	5569
Altitude (km)	---	277	---	---	277	277
Arrive Mercury	5608	5628	5730	5730	5628	5628
$\Delta V_{☿}$ (km/sec)	6.5	9.4	10.9	10.9	9.4	9.4
Depart Mercury	5684	5684	5770	5860	5770	5860
$\Delta V_{☿}$ (km/sec)	7.4	7.4	8.7	5.5	8.7	5.5
Pass Venus	---	---	5979	5969	5979	5969
Altitude (km)	---	---	5460	250	5460	250
$\Delta V_{♀}$ (km/sec)	---	---	---	0.5	---	0.5
Arrive Earth	5834	5834	6200	6140	6200	6140
V_E (km/sec)	16.5	16.5	18.2	12.4	18.2	12.4
ΔV_T (km/sec)	22.8	21.6	24.7	22.0	22.8	20.2
Trip time (days)	366	350	585	525	716	656
Stay time (days)	76	56	40	130	142	232

Selected mission design

Table 2(c) Minimum delta-V trajectory characteristics - manned Mercury stopover mission: Manning, AIAA 67-28.

Launch year	Earth departure date (Julian)	delta-V, Earth (km/s)	Venus swingby date (J)	delta-V, Venus (km/s)	Mercury arrival date (J)	Mercury arrival delta-V (km/s)	Stay time (days)	Mercury departure delta-V (km/s)	Mission duration (days)
1980	2444336	4.3	2444412	0.9	2444460	6.4	174	6.2	398
1981	4716	8.9	---	---	4801	7.6	183	6.5	383
1982	5000	4.2	5168	---	5305	8.6	28	7.0	463
1983	5484	4.8	5569	---	5628	9.4	56	7.4	350
1984	5828	8.1	---	---	5958	6.3	76	7.8	371
1985	6196	7.0	---	---	6306	6.3	180	6.4	365
1986	6562	6.7	---	---	6657	6.3	177	6.2	362
1987	6918	6.9	---	---	7003	6.9	181	6.4	371
1988	7330	5.6	7519	0.9	7630	4.7	18	9.7	383
1989	7680	6.3	7865	---	7922	8.3	72	8.7	379
1990	8022	8.6	---	---	8157	6.4	77	7.6	367
1991	8356	7.6	---	---	8506	6.3	182	6.8	372
1992	8752	6.8	---	---	8857	6.1	179	6.3	364
1993	9116	6.8	---	---	9206	6.4	178	6.2	368
1991	9650	4.2	9824	---	9940	7.6	143	7.0	563
1995	9812	6.7	---	---	9897	8.9	186	7.0	401
1996	2450180	4.5	2450305	3.0	2450390	6.8	44	7.4	404
1997	810	4.0	976	---	1100	7.9	136	6.4	421
1998	946	7.0	---	---	1056	6.5	180	6.4	365
1999	1312	6.6	---	---	1407	6.3	177	6.2	362