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PHASE I – FINAL REPORT
Europa Sample Return Mission Utilizing High Specific Impulse Propulsion Refueled with Indigenous Resources

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Abstract

We have conducted studies of a revolutionary new concept for conducting a Europa Sample Return Mission. Robotic spacecraft exploration of the Solar System has been severely constrained by the large energy requirements of interplanetary trajectories and the inherent delta V limitations of chemical rockets. Current missions use gravitational assists from intermediate planets to achieve these high-energy trajectories restricting payload size and increasing flight times. We propose a 6-year Europa Sample Return mission with very modest launch requirements enabled by MITEE. A new nuclear thermal propulsion engine design, termed MITEE (MIniature reacTor EnginE), has over twice the delta V capability of H_2/O_2 rockets (and much greater when refueled with H_2 propellant from indigenous extraterrestrial resources) enabling unique missions that are not feasible with chemical propulsion. The MITEE engine is a compact, ultra-lightweight, thermal nuclear rocket that uses hydrogen as the propellant. MITEE, with its small size (50 cm O.D.), low mass (200 kg), and high specific impulse (~1000 sec), can provide a quantum leap in the capability for space science and exploration missions. The Robotic Europa Explorer (REE) spacecraft has a two-year outbound direct trajectory and lands on the satellite surface for an approximate 9 month stay. During this time, the vehicle is refueled with H_2 propellant derived from Europa ice by the Autonomous Propellant Producer (APP), while collecting samples and searching for life. A small nuclear-heated submarine probe, the Autonomous Submarine Vehicle (ASV), based on MITEE technology, would melt through the ice and explore the undersea realm. The spacecraft has approximately a three year return to Earth after departure from Europa with samples onboard. Spacecraft payload is 430 kg at the start of the mission and can be launched with a single, conventional medium-sized Delta III booster. The spacecraft can bring back 25 kg of samples from Europa.

Europa, in the Jovian system, is a high priority target for an outer Solar System exploration mission. More than a decade ago the Voyager spacecraft revealed Europa as a world swathed in ice and geologically young. NASA's Galileo spacecraft passed approximately 500 miles above the surface and provided detailed images of Europa's terrain marked by a dynamic topology that appeared to be remnants of ice volcanoes or geysers. The surface temperature averages a chilly -200° C. The pictures appear to show a relatively young surface of ice, possibly only 1 km thick in some places. Internal heating of Europa from Jupiter's tidal pull could form an ocean of liquid water beneath the surface. More recently, Ganymede and Callisto are believed to be ocean-bearing Jovian moons based on magnetometer measurements from the Galileo spacecraft.

If liquid water exists, life may also. NASA plans to send an orbiting spacecraft to Europa to measure the thickness of the ice and to detect if an underlying liquid ocean exists. This mission would precede the proposed Europa Sample Return mission, which includes dispatching an autonomous submarine-like vehicle that could melt through the ice and explore the undersea realm.

Because of the large energy requirements typical of these ambitious solar system science missions, use of chemical rockets results in interplanetary spacecraft that are prohibitive in terms of Initial Mass in Low-Earth Orbit (IMLEO) and cost. For example, using chemical rockets to

return samples from Europa appears to be technically impractical, as it would require large delta V and launch vehicle capabilities. On the other hand, use of nuclear thermal rockets will significantly reduce IMLEO and, subsequently, costs. Moreover, nuclear thermal rockets can utilize extraterrestrial resources as propellants, an option not practical with chemical rockets. This "refueling" capability would enable nuclear rockets to carry out very high-energy missions, such as the return of large amounts of extraterrestrial material to Earth.

The Europa missions considered in this proposal will be restricted to starting from LEO only after being placed in a stable orbit by a launch vehicle. This simplifies and eases the safety issues and mitigates political concerns. High propulsive efficiency of the MITEE engine yields the benefits of reduced transit time and a smaller launch vehicle.

Executive Summary

A new and unique system for the robotic exploration of Europa and its possible sub-surface oceans is described. After landing on the Europa ice sheet, the Robotic Europa Explorer (REE) spacecraft would dispatch a compact lightweight probe that would melt a channel down through the ice sheet, descending to the expected sub-surface ocean underneath (likely locations for a sub-surface ocean would have been identified from earlier measurements made by an Europa orbiter, on the basis of gravity anomalies, tidal movements, thermal imaging, structural heterogenerties in the surface of Europa ice sheet, etc.).

The melt probe would be powered by a compact, lightweight nuclear reactor that provided the necessary thermal energy to melt the descent channel. A descent rate of several hundred meters per day would be achieved, with a total descent depth capability of several kilometers. The melt probe would be in constant, real-time, two-way communication with the REE surface spacecraft via an optical fiber link that would trail behind the descending probe. The REE spacecraft in turn, would be in two-way communication with earth via a radio link, subject to a time delay of approximately one hour, due to the finite speed of light. The descent rate, route, and nature of measurements taken by the probe could be controlled and updated by scientists on Earth.

Figure ES-1 shows the descent process of the melt probe through the ice sheet. Figure ES-2 shows a more detailed view of the melt probe descent channel and the melt probe reactor. The reactor consists of an array of fuel elements that heat water to a temperature of approximately 50° C. The outlet warm water is then directed through a set of jets against the bottom of the descent channel, melting the ice ahead of the descending probe. The cooler water then flows back to an inlet at the rear of the unit, where it is collected and returns to the reactor to be reheated.

The weight of the melt probe reactor is small, only a few kilograms for the fuel elements and container vessel, because its water moderator and coolant are derived from melting of Europa ice. This eliminates the need to transport its water coolant and moderator from Earth. Well-developed nuclear fuels and technology are suitable for the melt probe reactor, which could be constructed and tested in a short time.

After reaching the bottom of the ice sheet (Figure ES-1), an Autonomous Submarine Vehicle (ASV) would detach from the melt probe unit to explore the sub-surface ocean in detail. The ASV, as illustrated in Figure ES-3, would have a compact, lightweight nuclear reactor that was very similar to that on the melt probe. The main difference between the ASV reactor and the melt probe reactor is that the coolant flow through each of the individual fuel elements in the ASV reactor would be controlled so that its outlet temperature and fractional steam content could be adjusted using controllable nozzle area over a wide range from warm water at ~ 50° C to a high steam fraction, e.g., 50%, at high temperature, e.g., 250° C or higher, depending on the pressure present in the surrounding sub-surface ocean.

The individual fuel elements in the ASV reactor would be coupled to a set of corresponding jet nozzles at the rear of the ASV. By controlling which nozzles operated with high steam contents, the direction of the thrust on the ASV could be controlled, causing it to move upwards, downwards, left or right, depending on the path that was desired.

The ASV would communicate with a receiver/transmitter/locator device attached to the melt probe unit at the bottom of the ascent channel, using two-way sonar signals. Communication over distances of several kilometers appears practical, allowing the ASV to explore tens of cubic kilometers of ocean volume. Using a gyro or plantable beacons, it should be possible to explore much greater distances, and from the base of the descent channel, i.e., tens of kilometers. The maximum speed of the ASV is on the order of 10 kilometers per hour, allowing it to explore a very large volume in a month long exploration period at a given site on Europa.

After the exploration is complete, the ASV would return to the descent channel and reattach to the melt probe. The combined unit would then melt an ascent channel back up to the REE spacecraft on the surface, following the original descent channel. The optical fiber link to the spacecraft would be rolled up to be used again at the next site. While waiting on the surface and communicating with the melt probe and ASV units during their exploration activities, the REE spacecraft would produce and liquefy fresh H_2 propellant for its hop to the next exploration site on Europa.

The REE spacecraft would use a compact, lightweight nuclear thermal propulsion engine termed MITEE-B (MIniature ReacTor EnginE-Bi-modal). Besides its high specific impulse of 900 seconds or more, twice that of H_2/O_2 chemical engines, which enables high ΔV performance with a low Initial Mass in Low Earth Orbit (IMLEO) for the mission, the MITEE-B engine has the further advantage that its H_2 propellant can be replenished from indigenous resources such as Europa's ice sheet, further increasing its high ΔV capability for planetary science missions.

The MITEE-B engine has the capability to generate 1 kW(e) of continuous electric power while operating in space, and 20 kW(e) of continuous electric power while on the surface of Europa. While in space, the 4 kW(th) waste from the power cycle would be radiated to space from a small, lightweight radiator. While on Europa, the 80 kW(th) waste heat from the power cycle would be rejected to a melt water pool in the ice sheet through a lightweight panel heat exchanger. The 20 kW(e) electric generation from MITEE-B would supply 15 kW(e) to an electrolysis/liquefier unit that would produce and store 7 kg of liquid H_2 per day. The remaining 5 kW(e) would be used for communications, controls, and other spacecraft activities.

The replenished liquid H_2 would enable the REE spacecraft to hop long distances, e.g., up to ~ 2000 kilometers per hop, from a given exploration site to a new exploration site. At the new site, the exploration process would be repeated, with the melt probe descending through the ice sheet to the sub-surface ocean, which the ASV would explore, and then ascend back to the REE spacecraft to be ready for the next hop. After exploring a substantial number of sites on Europa, on the order of 7 to 10, depending on the mission profile, the REE spacecraft would accumulate sufficient liquid H_2 propellant to enable a return trip to Earth, together with 25 kilograms of samples collected from the ice sheet and sub-surface oceans.

The REE mission would collect a wealth of data about Europa, transmitting it back to Earth in effectively real-time, plus the large amount of samples collected from thousands of locations in the ice sheet and sub-surface oceans. REE would search for a wide variety of evidence about the possibility of present and past life on Europa, including the existence of actual life forms, both micro and macroscopic, traces of organic chemicals and DNA, micro and macrofossils, etc. The mission should be able to provide a definitive answer to the question of whether life exists, or previously existed, on Europa, and what is, or was, the nature of that life. If evidence of present and past life is found, samples would be returned to Earth.

In addition, the REE mission would determine the internal structure and geology of the Europa ice sheet, its origin and history, chemical composition, its cosmic ray and solar wind history, thickness topography, etc. REE would also determine for the various sub-surface ocean regions that were explored, their topography, nature of their sea beds, the geology and composition of the oceans and sediments, thermal distributions, current distributions, presence of possible hydrothermal vents, etc.

On a recent paper, "Tides and the Biosphere of Europa", Greenberg (Greenberg, R., American Scientist, Jan-Feb, 2002) describes evidence for periodic upswellings of liquid water through cracks in Europa's ice sheet. The crack patterns correlate with the theoretical tidal tension forces that result from the eccentric orbit of Europa around Jupiter. As the cracks open and then subsequently close, water is forced out onto the ice sheet, building up long parallel ridges adjacent to the cracks. The ice sheet thickness in the vicinity of the cracks is predicted to be relatively thin, a few kilometers at most.

Based on Greenberg's model, a variety of life forms could exist in niches inside and near the surface of the ice sheet, in addition to those in the sub-surface ocean. His model provides another and different type of energy source on which life could develop, besides the deep hydrothermal vent source. Radiolytic decomposition of surface ice and water would generate oxygen, photosynthesis would be energetically possible, and cometary influx could provide organic components. Accordingly, missions aimed at the detection of life forms on Europa should investigate its ice sheet, as well as its sub-surface oceans.

The REE mission would take a little over 6 years to complete, including the journey to Europa, exploration of 7 sites on Europa, and the return trip to Earth. Because of the high specific impulse capability of the MITEE-B engine, and the ability to replenish the H_2 propellant at Europa, the mission would require only a moderate size launch vehicle, e.g., a Delta III. Operational parameters for the REE mission are summarized in Table ES-1.

The Europa exploration mission described here is a more detailed investigation of the original Europa exploration concept proposed in a 1998 paper ["Europa Sample Return Mission Utilizing MITEE Technologies", by J. Paniagua, J. Powell, and G. Maise", Paper No. IAF-98-Q.2.03, 49th International Astronautical Congress, Sept 28 – Oct 2, 1998, Melbourne, Australia].

The technology base for the REE mission appears strong, with no breakthrough required. The MITEE-B engine would use cermet tungsten/UO_2 nuclear fuel developed in the 1960's for the 710 nuclear engine program. The nuclear fuel has demonstrated excellent performance and long lifetimes in H_2 propellant at temperatures up to 3000 K. The thermal hydraulics and neutronic capabilities needed for compact nuclear thermal propulsion engines have been demonstrated by the DOD/SNTP program carried out in the late 1980's and early 1990's. The technology base for the proposed steam power cycle for the bi-modal electric power generation is well established. Development of an operationally ready MITEE-B engine could be carried out in a period of approximately 7 to 10 years, depending on the rate of funding and schedule requirements.

The compact nuclear reactors for the melt probe and ASV use existing nuclear fuels and materials, and could be built and demonstrated within 2 years. The instrumentation and controls required for the REE mission would depend on what requirements and accuracy was desired, and on funding availability. However, development of a sophisticated instrumentation suite within the 7 to 10 year period for the MITEE-B engine appears achievable.

In summary, a REE mission could probably be implemented within the next 10 years. Since the mission is a direct trajectory, without the need for planetary gravitational assists, there will be many launch opportunities, with no need to wait for a narrow launch window.

Looking beyond the Europa mission, development of the REE system and modifications of it would enable a new, unique and much more powerful planetary exploration program, than is currently possible based on existing technologies. The REE system, for example, could be used to explore the ice sheets on other Jovian moons, e.g., Callisto and Ganymede, various moons of Saturn, Uranus, and Neptune, Pluto, Charon, large icy bodies like Chiron, and the North Polar Cap of Mars. Many of these objects probably would not have sub-surface oceans, but some might. Even if sub-surface oceans were not present, however, the data obtained on the material properties of the ice sheets would be extremely interesting and valuable.

In addition to enabling internal exploration of ice sheets, the development of a high performance nuclear engine would enable a new era of important unique missions, including a Pluto orbiter to observe the collapse of its atmosphere in 2020, fast trips to the Kuiper Belt, the Heliopause, and the Gravitational Lensing Point, a Titan sample return, and so forth. Moreover, the savings in launch vehicle costs enabled by the MITEE-B engine would pay for its development many times over.

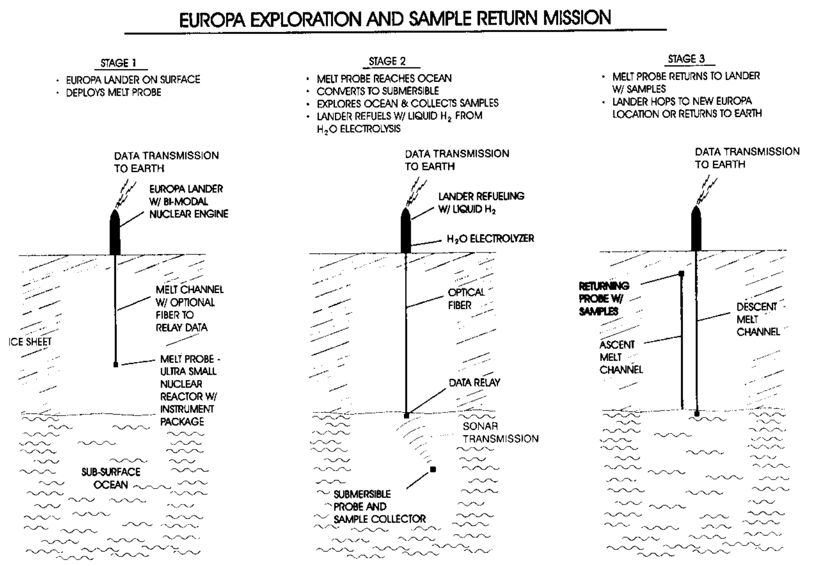

Figure ES-1 Europa Exploration and Sample Return Mission

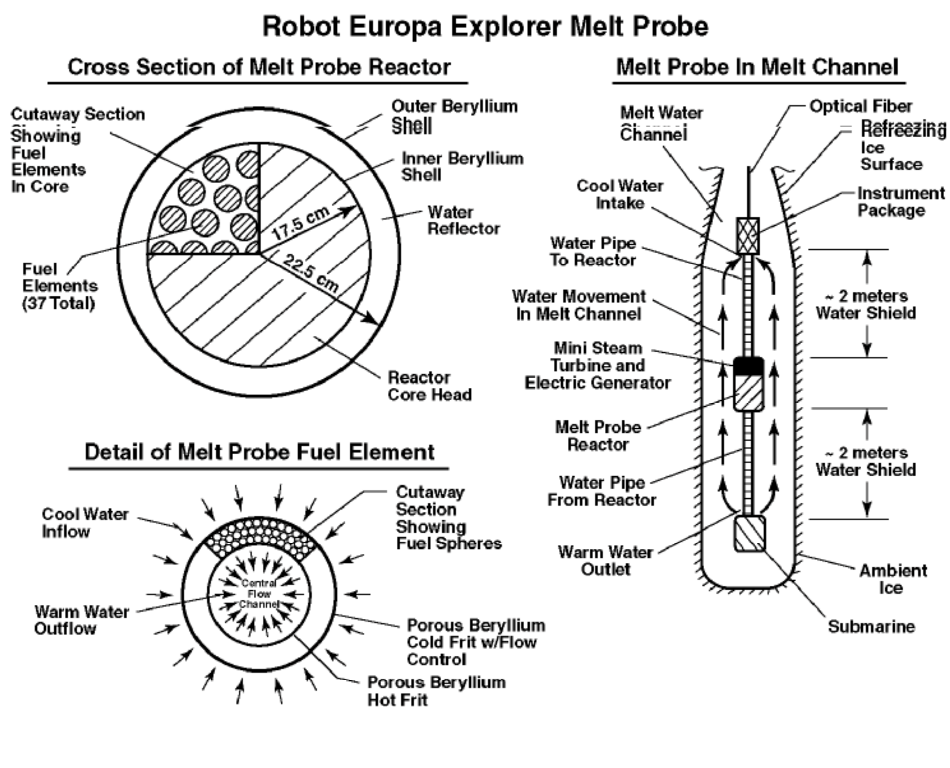

Figure ES-2 Robotic Europa Explorer Melt Probe

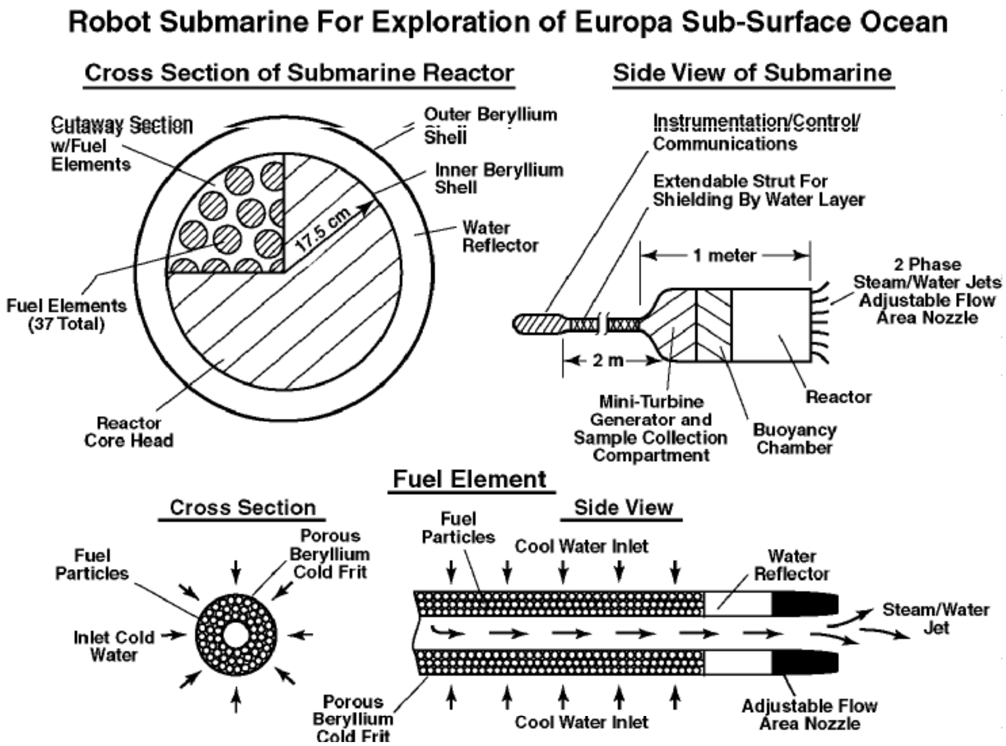

Figure ES-3 Robot Submarine for Exploration of Europa Sub-Surface Ocean

Table ES-1. Operational Parameters for Baseline REE and Sample Return Mission

REE Spacecraft Earth Departure Operational Parameters	
Earth Departure ΔV (km/sec):	6.60
Europa Capture & Landing ΔV (km/sec):	5.00
Time of Flight to Europa:	2 Years
MITEE-B Electric Power Output During Flight:	1 kW(e)
Option B Baseline Design	
MITEE-B Engine Shield:	50 kg
REE Tank Structure/Insulation:	90 kg
MP Unit:	65 kg
ASV Unit:	70 kg
MP/ASV Deployment Mechanism:	40 kg
Landing Gear:	60 kg
Telecommunications:	20 kg
Ion Thrusters (Navigation):	20 kg
Sample Return Tank:	15 kg
Sample Return Tank Aeroshield:	20 kg
Miscellaneous & Contingency:	20 kg
REE Payload Mass:	***470 kg***
MITEE-B Bi-Modal Engine System:	***350 kg***
REE Total Dry Mass:	***820 kg***
Earth Departure ΔV Propellant Loading:	1763 kg
Earth Departure Propellant Tank Mass:	141 kg
Europa Insertion & Landing ΔV Propellant Loading:	626 kg
Cooldown Propellant:	3% Tankage Fraction
REE Total Mass (IMLEO):	***3350 kg***
REE Spacecraft Hop Parameters	
Total Number of Hops:	7 to 10
Hop Lift-off ΔV (km/sec):	1.20
Hop Descent Landing ΔV (km/sec):	1.20
Europa Escape Velocity (km/sec):	2.02
Hop Elevation Burnout Angle (degrees):	30
Hop Range Based on Elevation Burnout Angle (km):	1800
Hop Time of Flight (minutes):	50
REE Spacecraft Hop Propellant Loading:	250 kg
MITEE-B Electric Power Output On Europa Surface:	20 kW(e)
REE Spacecraft Europa Departure Operational Parameters	
Europa Departure ΔV (km/sec):	8.90
Earth Capture & Re-entry ΔV (km/sec):	0.00 (Ballistic Re-entry)
Time of Flight to Earth:	3.3 Years
MITEE-B Electric Power Output During Flight:	1 kW(e)
Option B Baseline Design	
MITEE-B Engine Shield:	50 kg

REE Tank Structure/Insulation:	90 kg
MP Unit:	65 kg
ASV Unit:	70 kg
MP/ASV Deployment Mechanism:	40 kg
Landing Gear:	60 kg
Telecommunications:	20 kg
Ion Thrusters (Navigation):	20 kg
Sample Return Tank:	15 kg
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Miscellaneous & Contingency:	20 kg
REE Payload Mass:	***470 kg***
MITEE-B Bi-Modal Engine System:	***350 kg***
REE Total Dry Mass:	***820 kg***
REE Europa Departure ΔV Propellant Loading:	1050 kg

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1. Introduction & Background

This project is studying a revolutionary new concept for a Robotic Europa Explorer (REE) Mission. Europa, in the Jovian system, is a high priority target for an outer Solar System exploration mission. NASA's Galileo spacecraft passed approximately 500 miles above the surface and provided detailed images of Europa's terrain. The pictures appear to show a relatively young surface of ice, possibly only 1 km thick in some places. Internal heating of Europa from Jupiter's tidal pull could form an ocean of liquid water beneath the surface. If liquid water exists, life may also. NASA plans to send an orbiting spacecraft to Europa to measure the thickness of the ice and to detect if an underlying liquid ocean exists. This mission would precede the proposed REE Mission, which includes dispatching an autonomous submarine-like vehicle that could melt through the ice and explore the undersea realm. Currently, robotic spacecraft exploration of the Solar System has been severely constrained by the large energy requirements of interplanetary trajectories and the inherent ΔV limitations of chemical rockets. MITEE-B enables a 6-year REE Mission with very modest launch requirements. MITEE is a compact, ultra-lightweight, thermal nuclear engine that uses hydrogen as the propellant. Its specific impulse is more than twice that of the best chemical rockets and much greater when refueled with H_2 propellant from indigenous extraterrestrial resources enabling unique missions that are not feasible with chemical propulsion [Powell, et al, *Acta Astronautica*, vol. 44, no. 2-4, 1999.] The MITEE engine operates bi-modally; when not providing high propulsive thrust it generates several KW(e) of electric power. The REE spacecraft has a two-year outbound direct trajectory and lands on the satellite surface for an approximate 9 month stay. During this period, the spacecraft is refueled with H_2 propellant derived from Europa ice by electrolyzing melt water from the ice sheet to produce H_2, which is then liquefied. The spacecraft would hop to a number of promising sites on Europa's surface. At each site it would collect samples and search for life. At each site a small nuclear-heated submarine probe, the Autonomous Submarine Vehicle (ASV), would melt through the ice and explore the undersea realm. The spacecraft has an approximate three year return journey to Earth after departure from Europa with 25 kg of samples onboard.

2. Description of Robotic Europa Exploration and Sample Return Mission Concept

Figure 2.1 illustrates the basic elements of the Robotic Europa Exploration (REE) and Sample Return Mission concept. A single spacecraft is used to explore multiple sites, e.g., on the order of 7 to 10 sites, at widely separated points on Europa. The REE spacecraft would land at the given site to be explored, and lower an exploration package that would melt down through the Europa ice sheet to the ocean beneath. There, an autonomous submarine vessel would detach itself from the exploration package, and explore the sub-surface ocean for kilometers around the entry point, collecting data and samples.

The submarine would communicate in real-time with the REE spacecraft via an optical fiber link between the entry point at the bottom of the ice sheet and the spacecraft. The REE spacecraft would in turn communicate in real-time with Earth, transmitting the data as it was collected, and periodically transmitting updated instructions to the submarine as to where it should go. While there would be an approximate 2 hour roundtrip time delay in communications due to the finite speed of light and the great distance between Europa and Earth, this does not appear to cause any operational problems.

The sites to be explored by the REE spacecraft would be chosen on the basis of previous surveys made by Europa Orbiter spacecraft, to identify those locations where sub-surface oceans appeared to be likely, based on gravity measurements, surface upwellings, tidal motions of the ice surface, etc. As yet, no definitive sub-surface oceans have been pinpointed and it is not known whether if there are sub-surface oceans on Europa, one would find that they were separate individual entities, or whether they were interconnected. By the time that the REE mission was ready to go however, it is likely that the existence of oceans on Europa will either be confirmed or refuted, and that if they do exist, where they are located.

Figure 2.2 illustrates the overall flowsheet for the REE mission. The REE spacecraft would be launched into a nuclear-safe LEO orbit, e.g., at an altitude of approximately 500 nautical miles using a conventional existing launch vehicle such as the Atlas IIAS. The REE nuclear reactors, i.e. the bi-modal MITEE nuclear engine and the melt probe and submarine propulsion reactors, would have been launched in a completely cold and safe state. There would be no radioactive inventory – the U-235 has a half-lifetime of 0.5 billion years and the reactors would have internal poison materials and other safeguards to prevent any possibility of accidental criticality, even in the event of a launch vehicle crash or explosion.

After satisfactory checkout of the REE systems, the spacecraft would depart from its LEO orbit to Europa, using the MITEE nuclear thermal propulsion engine. The use of nuclear thermal propulsion (NTP) for the REE mission is essential. The specific impulse of NTP is approximately 1000 seconds, over twice that from the best chemical engine (H_2O_2 engines have specific impulses of 450 seconds).

Moreover, the NTP engine can be refueled with fresh H_2 propellant derived from indigenous resources, e.g., the Europa ice sheet. This allows it to hop for long distances over Europa's surface, so that it can explore many diverse sites using a single spacecraft. Then, when the

Europa mission is completed, the spacecraft can again be refueled with fresh H_2 propellant for its return trip to Earth. The spacecraft would carry a variety of samples collected from the sites that it explored on Europa.

Such a mission is only possible with an NTP engine. The mass of propellant needed with a chemical engine would be impossibly large. A nuclear electric propulsion engine (NEP) could not perform the high propulsive thrust burns required to land on and take off from Europa, or to hop from one site to the next on Europa. A solar electric propulsion (SEP) engine not only would not have high thrust capability, but also could not operate in the very low solar flux environment available at the orbit of Jupiter.

For the REE mission, it is highly desirable that the NTP engine have the following capabilities for:

1. Multiple restarts
2. Electric power generation during in-space flight periods
3. Electric power generation while on the Europa surface

Electric power generation can be provided by designing the NTP engine to be bi-modal; that is, when the reactor is not operating in its high-power mode with open cycle H_2 propellant to generate large amounts of propulsive thrust, it operates at much lower power with a separate closed coolant system to generate continuous electric power.

A near-term bi-modal nuclear engine system termed MITEE-B (<u>MI</u>niature Reac<u>T</u>or <u>E</u>ngin<u>E</u> <u>B</u>i-modal) that would enable the REE mission is described in detail later in this report. The MITEE-B engine is compact and lightweight, on the order of 350 kg in total mass. Operating in the high propulsive thrust mode, it has a power level of 75 MW and a thrust of 14,000 Newtons. The high thrust mode is used to depart from LEO and to land on Europa, as well as to hop on its surface when the engine operates and to return to Earth. The typical operation time in the high thrust mode is on the order of a few minutes to a half-hour.

On its in-space journey to Europa, as well as the return journey to Earth, the MITEE-B engine would generate approximately 1 KW(e) of continuous electric power to operate controls and communicate with Earth. This power level is substantially greater than that provided by the RTG (Radioisotope thermoelectric Generators) presently used in deep space missions. The corresponding reactor thermal power is approximately 5 kW(th), a factor of 15,000 smaller than that when it operates in the high propulsive thrust mode. When on the surface of Europa, MITEE-B would generate 20 kW(e) of continuous electric power to electrolyze melt water for the production of H_2 gas, along with power to liquefy the H_2 so it can be stored as a propellant.

Figure 2.3 illustrates the various sub-systems involved in the Robotic Europa Explorer (REE). Each of these sub-systems is described and analyzed later in this report, in terms of its performance capabilities, mass, and development requirements.

Two options for the melt probe and Autonomous Submarine Vehicle (ASV) sub-systems are considered. In Option A, the melt probe and ASV are combined into one unit, with a single compact nuclear reactor heat source; in Option B, the melt probe and ASV are separate individual units, each with its own compact nuclear reactor heat source. The advantages and disadvantages of these two options are discussed in the next section of this report.

Figure 2.1 Europa Exploration and Sample Return Mission

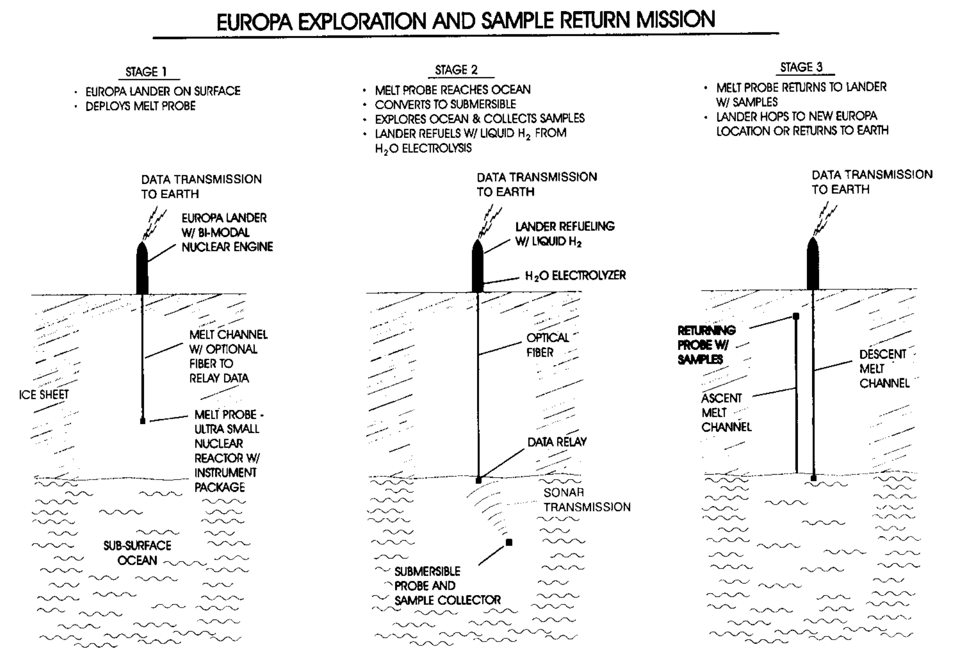


Figure 2.2 Flowsheet for Robotic Europa Explorer (REE)

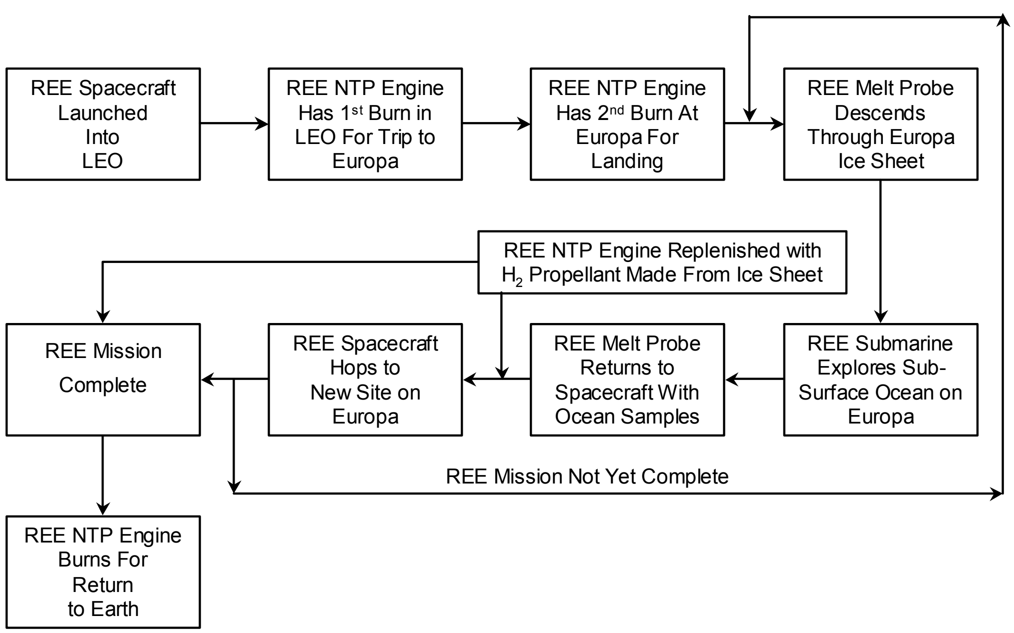
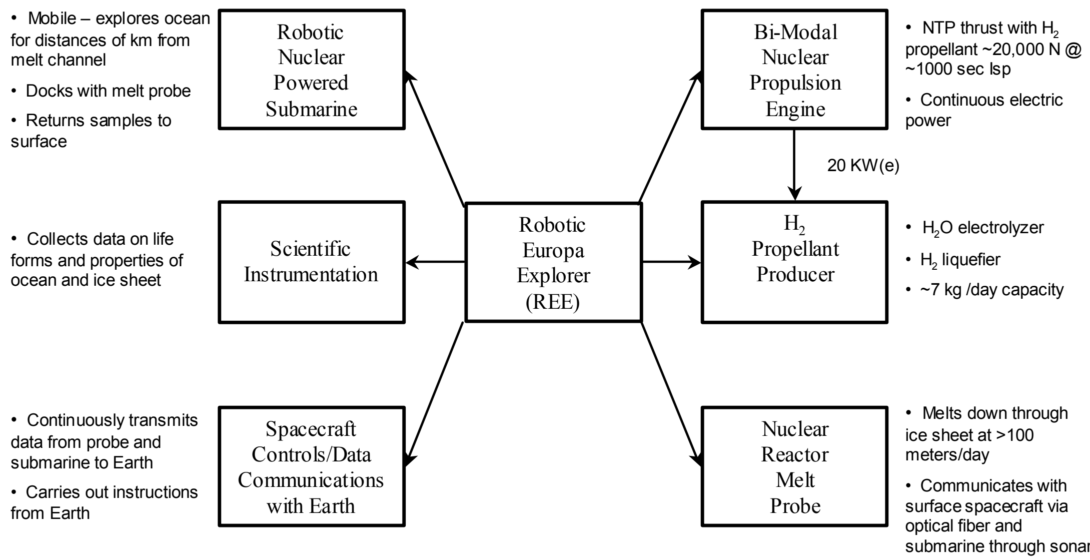


Figure 2.3 Robotic Europa Explorer Sub-Systems



3. Description of REE Melt Probe/Autonomous Submarine Vehicle (ASV) Options

Figure 3.1 summarizes the principal features and capabilities of the two melt probe/ASV options, while Figure 3.2 summarizes their relative advantages and disadvantages. The propulsion, power, and propellant production systems employed in the two options are identical. They only differ in the nature of the melt probe and ASV systems used.

In option A, the single reactor that powers both the melt probe and the ASV is a complete unit with integral Li^7H moderator and reflector. The only addition required to start operating the melt probe/ASV unit is water coolant obtained by melting a small amount of ice from the surface of the Europa ice sheet. This melt process can be carried out using electric power from the bi-modal MITEE engine.

In option B, the melt probe and ASV have separate reactors, enabling them to operate independently of each other. The two reactors are different in construction from the single reactor used in option A. Instead of Li^7H moderator and reflector that would be brought from Earth in the option A reactor, they use water as moderator and reflector. The water is obtained from melting Europa ice, as in option A, using electric power from the bi-modal MITEE engine. The savings in weight made possible by using Europa water as the moderator and reflector rather than solid Li^7H allows the use of two separate reactors instead of one, at a lower total weight than that for the single reactor with Li^7H moderator and reflector.

The two reactors in option B are identical in their construction. The only difference between the two is that the majority of the fuel elements in the melt probe reactor operate at low temperature, e.g., below 100° C, and produce just hot water. [Several elements operate at higher temperatures, e.g., approximately 250° C, to produce steam for a mini-turbine to generate electric power as well as hot water].

In option B, all of the ASV reactors fuel elements are capable of operating at sufficiently high temperatures e.g., 250° C, to generate steam/water jets for propulsion. The fuel elements can also generate at lower temperatures, generating only hot water. The outlet temperature from each element is controlled by the flow rate of the coolant through the element. The flow rate, in turn, is controlled by a variable area nozzle at the exit of each element. The greater the water flow rate, the lower the outlet temperature.

By controlling which elements in the reactor provide propulsion by steam/water jets, and which elements provide just hot water, the ASV can be propelled in any desired direction, i.e., towards the left or right, as well as upwards or downwards the thrust direction can be changed so as to provide any desired track or depth for the submarine.

The next section of this report describes option A in greater detail.

Figure 3.1

Principal Features and Capabilities of REE Options for Sub-Surface Exploration

System/Component	Option A	Option B
Spacecraft Propulsion & Power	**Bi-Modal MITEE Nuclear Thermal Propulsion Engine, With Capability To Generate Electric Power In Space & On Europa Surface.**	**Same.**
Melt Probe	**Melt Probe Heated By Compact Nuclear Rocket Uses Lithium-7 Hydride As Moderator. Lithium-7 Is Part of Reactor That Is Launched From Earth.**	**Melt Probe & ASV Submarine Are Separate Units, Each With Its Own Individual Reactor. Melt Probe Reactor Uses Melt Water From Europa Ice Sheet for Both Moderator & Coolant. Melt Probe Remains At Bottom Of Melt Channel.**
Autonomous Submarine Vehicle (ASV)	**The ASV & Melt Probe Form Single Integrated Unit With One Nuclear Reactor That Provides Both Heat For Melting Descent Channel & Propelling Submarine.**	**At Bottom of Melt Channel ASV Submarine Detaches From Melt Probe Leaving It Behind As ASV Travels Through Sub-Surface Ocean. ASV Nuclear Reactor Is Essentially The Same As Melt Probe Reactor.**

Figure 3.2

Relative Advantages & Disadvantages of REE Options A & B

Option	Advantages	Disadvantages
A. Combined Melt Probe/ASV Unit	**1. Lower Mass For Scientific Instrument Package.**	**1. More Difficult Technically. 2. No Power Source At Bottom of Melt Channel For Communication Between ASV & REE Spacecraft On Surface. 3. Greater Mass Of Reactor.**
B. Separate Melt Probe & ASV Units	**1. Less Difficult Technology. 2. Able To Communicate Over Long Distances To ASV. 3. Simpler Controls. 4. Lower Reactor Mass.**	**1. Higher Mass For Scientific Instrument Package.**

4. Design Studies of Option A: Integral Melt Probe/ASV System

4.1 Integral Melt Probe/ASV System Functions

Figure 4.1 illustrates the design of the integral Melt Probe (MP)/Autonomous Submarine Vehicle (ASV) system that will be used to explore and gather samples from the undersea realm of Europa. The MP/ASV is designed to carry out the following mission functions:

1) Melt a descent channel through the Europa ice sheet. To reach the liquid water ocean beneath, the MP/ASV must melt a vertical descent channel through the ice sheet. The descent rate would be >100 meters per day. At this descent rate, the MP/ASV could reach the sub-surface ocean in a few days, even if it were a kilometer or more below Europa's surface.

2) Explore an extensible volume of sub-surface ocean. The MP/ASV will employ an onboard combination autonomous/directed guidance and propulsion system to extensively explore the sub-surface ocean around its entry point. Horizontal distances of many kilometers and vertical distances of hundreds of meters will be covered during this exploration.

3) Map the undersea ocean. The MP/ASV will map local topography and determine water chemistry, currents, temperatures, etc. in the explored region. It will use visual, radar, and sonic mapping methods where appropriate. It will also search for evidence of life and capture samples of life forms, if present.

4) Autonomously communicate with the surface lander. The MP/ASV will continuously transmit all data and images for relay back to Earth, so that they will not be lost if the MP/ASV is unable to return to the lander.

5) Return to the entry point and melt a path back up to the surface. The MP/ASV will have to return to the surface to deliver the samples it has collected for return to Earth. Presumably, all technical data and images gathered during its oceanic exploration already have been telemetered back to the lander.

The MP/ASV will melt a new ascent channel back to the lander, along the descent channel it followed to reach the sub-surface ocean. It must emerge close enough to the lander so that it can be reattached to the REE spacecraft in preparation for its next hop on Europa. The ascent rate would be on the order of 100 meters or more per day. When the REE spacecraft finally lifts-off for its return journey to Earth, the MP/ASV would remain on the surface after the spacecraft left, or descend again to further explore the sub-surface ocean gathering additional data that would be relayed back to Earth by a surface transmitter for an extended period, i.e., years, after the sample return vehicle left Europa. To carry out the above functions, the MP/ASV would have the following components:

1) Reactor heat source
2) Melt shell/ASV structure
3) Mini-turbine/electric generator
4) Water coolant circulator

5) Propulsion unit
6) Buoyancy control system

4.2 MP/ASV Nuclear Reactor

Most of the reactor power output goes to the production of warm water (T~50° C) for the descent and ascent phases through the Europa ice sheet. At a movement rate of ~100 meters per day (1 km in 10 days), in a melt diameter of 50 centimeters, the MP/ASV would have a thermal power of 130 kilowatts, determined by the thermal energy required to raise the -200° C ice in the path of the MP/ASV to the 0° C melt point, the heat of fusion of ice, and the thermal energy lost by conduction from the 0° C boundary of the melt channel to the surrounding cold ice sheet as the MP/ASV moves past a given point. When the MP/ASV enters the sub-surface ocean, no significant thermal power load is required. However, the MP/ASV will require electric power to operate its propulsion unit, communications, control and guidance systems, and its data acquisition/sample collection packages. The average electric propulsion power for the 0.30-meter diameter MP/ASV can be estimated from the following relationship:

$$P_{PROP} = \frac{1}{2} C_D \frac{\pi}{4} (0.32)^2 V^3_{avg} \frac{\rho_{H_2O}}{\eta_P}$$

where the power is in watts, the drag coefficient, C_D, is ~0.2, ρ_{H2O} is 1000 kg/m^3, the propeller efficiency, η_P, is on the order of 50%, and V_{avg} is the average velocity of the MP/ASV. For the average velocity to be 2 m/sec, the corresponding average electric propulsion power is 200 watts. In practice, the MP/ASV would operate with battery storage so that it could go significantly faster than 2 m/sec when desired. Much of its search time would probably be spent floating in a stationary, or near-stationary, condition. At an average speed of 2 m/sec, the MP/ASV would traverse a path of ~170 kilometers per day. Allowing an additional 100 watts of electric propulsion power for its other functions, the MP/ASV would then require an electric power source of 200 watts. There are several approaches for generating this secondary load using reactor heat that will be discussed later.

The reactor design utilizes a compact homogeneous, hydrogenously moderated and reflected, water-cooled, thermal neutron spectrum assembly (Figure 4.2.1). Lithium hydride (isotropically separated lithium-7, of which there is a large U.S. stockpile) is used for the core moderator and reflector. The core has coated, small diameter (~20 microns in diameter) UO_2 particles dispersed uniformly throughout the ^{7}LiH moderator. ^{7}LiH is an attractive choice for the moderator and reflector - its atomic density of hydrogen is almost equal to that of water - it has high temperature capability (T_{max} of ~950K), it is a solid, and its density is not affected by temperature. Critical mass and size parameters for the MP/ASV reactor are based on Paxton's (1) experimental values for small water moderated homogenous reactor assemblies, with appropriate adjustments for the slight difference in the atomic density of hydrogen. The MP/ASV reactor is cylindrical in shape with a core diameter of 20 cm and a core length of ~30 cm. The core is reflected by 5 cm of ^{7}LiH (effectively an infinitely thick reflector), resulting in a reactor O.D. of 30 cm and an overall length of 42 cm. The H/U_{235} ratio in the core is 100/1, with a corresponding U_{235} mass of 2 kilograms. The MP/ASV core volume is 10 liters. This is somewhat larger than the corresponding 7 liter critical volume for a spherical assembly, due to the slightly lower hydrogen density for ^{7}LiH, a control margin, and the less favorable leakage characteristics of cylindrical geometry.

The MP/ASV reactor is controlled by 6 rotating control cylinders in the reflector. The outer surfaces of the control cylinders contain a neutron poison material with a high neutron cross-section (^{10}B, Gd, Eu, etc.) When turned so that the poison region is next to the core, the k_{eff} of the assembly is below unity, and the reactor is sub-critical. Turning the poison sections away from the core increases k_{eff} to 1 or above, enabling the reactor to go critical and reach the desired power level. Total reactor mass is estimated to be 30 kg, including moderator and reflector, UO_2 fuel, control drum actuators, and structure.

The MP/ASV reactor is cooled by a primary circuit of relatively low temperature water whose outlet temperature is below 100° C. This warm water is used to heat the front hemispherical melt shell and sides of the MP/ASV vessel that encloses the reactor, allowing it to melt and travel through the ice sheet. The water coolant flows along 37 small diameter (0.5 cm) beryllium tubes placed throughout the 20 cm diameter core. The tubes run axially along the core, and are arranged in a hexagonal pattern, with an average thermal transport load of ~3 kW per tube, at the peak reactor power of 30 kW. Average heat flux in the tubes is 60 watts/cm^2, with an average flow velocity of 0.8 m/sec assuming a ΔT of 50 C across the core.

The principal parameters of the option A MP/ASV reactor are summarized in Table 4.2.1. The technology required for the reactor has existed for many years, and it could be built and tested on Earth in less than 2 years.

4.3 Descent and Ascent of the MP/ASV Unit Through Europa Ice Sheet

Figure 4.3.1 shows the MP/ASV unit as it melts a descent channel through the ice sheet. Warm water from the reactor flows through a set of water jets positioned at the front end of the MP/ASV unit. The warm water melts the ice ahead of the unit and also along its sides, as the water flows radially outwards and longitudinally backwards through the annular gap between the unit and the ice walls of the descent channel.

The diameter and descent rate of the MP/ASV unit are controlled by the following parameters:

1. The location of the warm water jets at the front of the MP/ASV unit
2. Temperature of the warm water jets
3. Flow rate of the warm water jets

The first parameter, location of the warm water jets, helps determine the diameter of the melt channel. If the jets are principally located close to the axis of the MP/ASV unit, the diameter of the melt channel will be not much greater than the diameter of the MP/ASV unit, since the thermal energy transfer to the base of the melt channel will be favored. If, on the other hand, the warm water jets are primarily located on the rim of the MP/ASV unit, thermal energy transfer to the sides of the melt channel is favored, leading to a larger diameter channel that descends more slowly.

The temperature and flow rate of the warm water jets determine the total thermal output transferred to the ice sheet. The volume of ice melted per unit time is given by:

$$\frac{dV_{Ice}}{dt} = \frac{C_{pW}}{C_{pIce}} \frac{[T_{wo} - T_{wi}]}{[273 - T_{IceSheet}] + \lambda_m} \left(\frac{dV_W}{dt} \right) \tag{4.3.1}$$

where

C_{pW} = specific heat of water, J/m^{3}K
C_{pIce} = specific heat of ice over the temperature interval $T_{IceSheet}$ to 273 K
T_{wo} = outlet temperature of warm water jet from the MP/ASV unit, K
T_{wi} = outlet temperature of warm water jet from the MP/ASV unit, K
$T_{IceSheet}$ = ambient temperature of Europa ice sheet
$\frac{dV_{Ice}}{dt}$ = flowrate of warm water jets, m^3/sec
λ_m = heat of melting for ice, J/m^{3}K

Since the ambient temperature of the Europa ice sheet is ~70 K, to bring the ice in the sheet from 70 K to the melting point of 273 K, the nominal temperature rise will be ~200 K, making the specific heat input requirement comparable to the melt heat requirement, i.e., 270 J/m^3 for specific heat compared to 290 J/m^3 for the heat of melting (ρ_{Ice}/ρ_{Water} = 0.91).

The rate of descent, in meters per second, of the ice channel, is then:

$$\frac{dh_{ice}}{dt} = \frac{dV_{ice}}{dt} \frac{4}{\pi} \left(\frac{1}{D_{channel}} \right)^2 \tag{4.3.2}$$

Table 4.3.1 gives the corresponding rate of descent of the melt probe as a function of the reactor heat output and the diameter of the melt channel.

The practical maximum descent rate for the MP/ASV unit is on the order of about 120 meters per day for a 50 centimeter melt channel, given a reactor with only 37 coolant tubes in the core. A faster descent rate can be achieved by incorporating more coolant tubes in the reactor core. A factor of 3 to 4 increase in the number of coolant tubes is practical, which would allow a descent rate of ~500 meters per day.

The MP/ASV unit would trail its scientific instrument package behind it on an extendable strut. A separation of 2 meters between the instrument package and the reactor would provide a factor of 10^7 reduction in radiation dose rate, which would be more than sufficient to shield the instruments. The dose rate to them would then be less than 10^5 Rad per year of operation.
The MP/ASV unit would trail a small diameter optical fiber behind it, which would enable real-time communications between it and the REE spacecraft on the surface of the ice sheet. The weight of the fibers would be very small. Using 2 fibers for redundancy, with a diameter of 10 mils, would require only 0.2 kg per kilometer of channel length.

The fibers would not be affected by the refreezing of the melt channel as the MP/ASV unit descended through the ice sheet, and would continue to transmit 2-way data and commands between the unit and the REE spacecraft. When the MP/ASV unit reaches the bottom of the ice sheet, it will detach from a small docking device, and move off through the sub-surface ocean to explore it. The docking device would receive sonar signals from the mobile ASV unit and transmit the information to the REE spacecraft. It would also emit periodic sonar signals that would enable the mobile ASV to update and calibrate its location relative to the docking device. Periodic updates and commands to the ASV unit would be communicated from the docking device via the sonar signals from it.

Since the docking device does not have a nuclear reactor power source, it will have to operate on stored energy in batteries. These would be periodically recharged at intervals of a few days by docking with the returning ASV unit, which would provide the necessary recharging electric power. This periodic redocking procedure does not appear to be a serious drawback to the exploration capability of the ASV. Even with daily redocking the ASV unit could travel a total of 170 kilometers at a speed of 2 meters per second between its return visits to the docking device. Assuming that it could echo locate accurately and sample everything within 100 meters of the unit, this would enable a search volume of approximately 2 cubic kilometers per day, and 60 cubic kilometers per month. This appears very attractive.

After completing its exploration pattern, the ASV would return to its docking unit to begin the upward ascent and return to the REE spacecraft. As illustrated in Figure 4.3.2, the MP/ASV unit would create a melt channel that enabled it to ascend through the ice sheet, rather than descend through it, as originally shown in Figure 4.3.1. The orientation of the MP/ASV unit would be reversed during the ascent phase. The front end of the MP/ASV reactor would now point upwards, rather than downwards, so that the warm water would melt the ice above the reactor, rather than below it. The buoyancy chamber inside the MP/ASV unit would control the orientation, and provide a net upwards buoyancy, rather than a net downwards one as in the case of the descent channel. The scientific and control instrument package would still trail the MP/ASV unit. However, during the ascent phase, the package would be below the MP/ASV unit, and not above it, which was the case during the descent phase. Moreover, the package would have a slight net negative buoyancy to insure the desired separation distance from the MP/ASV reactor, instead of the slight net positive buoyancy it had during the descent phase.

The optical fibers would be rolled back up during the ascent phase, to be ready to be used again when the REE spacecraft landed at the next exploration site. The takeup reel would be positioned at the front of the MP/ASV unit, in contrast to the playout reel which would be at the back. The fiber would then be conveyed from the takeup reel to the playout reel when the MP/ASV unit undertakes its next descent.

4.4 Propulsion and Exploration Capabilities of Mobile MP/ASV Unit in Sub-Surface Europan Oceans

Assuming that there are sub-surface oceans on Europa that can be readied by the MP/ASV unit as it descends through the Europa ice sheet, the unit would detach from its docking device at the bottom of the ice sheet, and explore a large region of the sub-surface ocean.

During the descent/ascent phases of the MP/ASV operation, the principal function of its compact nuclear reactor is to provide warm water at a temperature of approximately 50° C to melt the descent or ascent channel. For this purpose, the reactor maximum power would be about 150 kW. If greater thermal power is desired, the number of coolant tubes in the core could be easily increased from the nominal value of 37, enabling more surface area for heat transfer from the homogeneous $^{7}LiH/UH_3$ moderator/fuel material.

A small amount of electric power, on the order of 100 to 200 watts(e), would also be generated to operate the scientific instruments and to communicate with the REE spacecraft on the surface via the 2-way optical fiber link. The electric power would be generated using a mini- steam turbine, with the steam generated using a few special coolant tubes in the core that operated at a higher temperature, e.g. 230° C, and generated steam for the turbine.

During the mobile operational phase of the MP/ASV unit, however, generation of relatively large thermal power to create the melt channel for descent or ascent of the unit is not required. Rather, the principal need is for electric power for the propulsion unit, instruments, and communications (sonar) and controls. As in the ascent/descent operational phase, this power can be generated using a mini-steam turbine that operates using steam from a few special high temperature coolant tubes in the core.

A small high temperature zone in the core is designed to run with water coolant at a higher outlet temperature than the rest of the core. Steam generated by this higher temperature coolant circuit flows through a mini-turbine to generate the required electric power. An outlet water temperature of 230° C from the higher temperature circuit readily generate saturated steam at 20 atm (T_{sat} = 214 ° C) for the mini-turbine. The thermal efficiency for the power cycle is ~15%. For a peak electric power capability of 600 watts (includes the nominal 200 watt peak power for ASV cruise operation plus 400 watts for instruments, controls, and communications), 4 kW of reactor thermal power is required. Assuming that 3 of the 37 elements were designed to run at higher temperature when necessary, then 600 watts of electric power could be generated with a total reactor thermal power of 48 kW. Only 4 kW of this thermal output power would be used to generate electricity for the cruising ASV, with the remaining 44 kW rejected as heat to the surrounding ocean. Since the ASV reactor would burn at most about 12 grams of its 2000 gram U_{235} inventory during the approximate 9 month exploration phase, burnup is not a problem. With a suitable burnup poison and an increased inventory of U_{235} (to 3 kg), the ASV could cruise for many years with no burnup problems.

The MP/ASV electric generation unit would be sized for a maximum output of 600 watts at a reactor thermal output of 48 kW. If the thermal output is increased beyond 48 kW to allow faster descent/ascent rates through the ice sheet, a portion of the hot coolant output from the 3 hot tubes would be diverted and mixed with the warm water output from the other coolant tubes, so as to add to the thermal energy being used to create the melt channel. In this manner, a maximum of 600 watts(e) would be available for instruments, etc., during the descent/ascent phases – considerably more than is likely to be needed. The excess electric power could be dissipated in resistors, with the thermal heat used for additional melting.

An alternative option to the mini-turbine has been considered, that of using a small, very high temperature heat pipe in the core that would lead to an external thermoelectric converter. This would be much more complex, involve greater technical risk, require a considerably greater development effort, and achieve a much lower power conversion efficiency (~5%) than the mini-turbine approach.

The ASV reactor is enclosed in a cylindrical beryllium vessel. The vessel has a hemispherical melt shield at the front end and a shrouded propulsion unit at the rear, with a total length of ~ 0.7 meters as seen in Figure 4.4.1. The thickness of the beryllium vessel is 1 cm. with a total mass of 11 kg. The outlet warm water from the reactor circulates through beryllium tubes bonded to the vessel, first through the front melt shell where most of the heat transfer occurs through the ice sheet, and then back along the cylindrical shell of the vessel to the rear of the reactor. At this point, the water circulator pumps the cool water through the reactor with modest pumping power. At a thermal output of 48 kW, with a nominal pressure drop of 0.1 atm through the coolant circuit (the actual pressure drop will be smaller), the input electric power is only 5 watts for a circulator efficiency of 50%.

The mini-steam generator/turbine would use conventional technology, packaged into a small size, low mass, small power level unit with a maximum design output of ~ 600 watts(e). Thermal steam efficiency for the 20 atm inlet pressure saturated steam is only 15% compared to the 32% efficiency achieved in much larger nuclear power units. The steam mass flowrate through the mini turbine is very small, only about 2 gram per second. Total mass for the generator unit is estimated at 2 kg.

The propulsion unit is a shrouded propeller/fan device. Intake ducts at the rear of the ASV vessel direct water that is flowing along the cylindrical surface of the vessel into and through the shrouded propeller/fan. The momentum imparted to the output water jet results in a forward thrust on the ASV. Rudder-like surfaces located in the output jet control the path of the ASV, directing it in the up or down direction, or to the left or right. A key feature of the ASV will be its buoyancy control system. There will be several chambers inside the ASV vessel that can be partially or completely emptied or filled, depending on the buoyancy state desired. Most of the time, the ASV will probably be neutrally buoyant, at the same effective density as the surrounding water. Using the buoyancy chambers as trim devices, the ASV vessel could be oriented in a variety of ways. If it was desired to move upwards the vessel could be made positively buoyant by pumping out a small amount of water. To move downwards, we could simply take in a small amount of water. At a 1 km depth and 15% gravity, the hydrostatic pressure is equivalent to 15 atm on Earth. Trimming the ASV by 2% of its 50 liter volume would only require 1500 joules of pump work. One potentially important advantage of buoyancy control would be the ability to use positive buoyancy control to hold the ASV against the bottom of the ice sheet if there were strong transient ocean currents without having to generate large amounts of propulsive power to maintain position.

The exploration pattern followed by the mobile MP/ASV unit will depend very strongly on what it discovers in the sub-surface ocean. The first main branch point, as illustrated in Figure 4.4.2, will be if the seabed is directly accessible by the ASV. Since Europa gravity is only 15% that of Earth, the pressure increase during a deep dive in Europa will also be much less than on Earth. A 2 kilometer dive, for example, will only cause a pressure increase of 30 atmospheres, or 450 psi, which the ASV should readily withstand.

Assuming that the seabed is within a practical diving depth, e.g., 2 to 3 kilometers below the bottom of the ice sheet, the ASV would descend to the seabed and explore it for evidence of life. Examining sediments for fossils, etc., would be an efficient way to see if there was, or had been, oceanic life. Assuming a spiral search path on the seabed centered around the point of entry into the sub-surface ocean, and a maximum search radius of 5 kilometers from the center an average 100 meters between search lines, and an average travel velocity of 1 meter/second, corresponding to 50% of the time devoted to examination/sampling at zero speed, and 50% traveling at 2 meters/second between examination points, the 80 km^2 seabed area could be explored in just 9 days.

Such an exploration pattern would yield a very detailed topographic map of the seabed, detect any hydrothermal vents, even very small ones, sample sediments, at many locations detect fossils and life-derived structures and chemicals if they existed, measure the age, composition, and rate of sedimentation of the seabed, and so on. Not only would the results definitely prove whether or not life had ever existed on Europa, but they would also establish in detail the geologic evolution of Europa.

If the seabed is not reachable from the entry point at the bottom of the ice sheet then the ASV would cruise in an exploration pattern through the sub-surface oceans, measuring its properties, including dissolved solids and gases, typesand compositions of particulates, temperature, pressure, currents, etc. The ASV would also search for evidences of life, including actual life forms, micro and macro, suspended microfossils, and life-derived chemicals. Using sonar the ASV would map out the topography of the seabed underneath it, and detect if there were large hydrothermal vents.

With 100 meters between search lines, and an average velocity of 2 meters/second, the ASV would search a volume of ~2 cubic kilometers per day, or ~20 cubic kilometers in a 10 day period. This would yield an excellent, detailed, extensive search of Europa's sub-surface ocean. This mapping process would be repeated at a number of sites distributed around Europa. As illustrated in Figure 4.3.1, if the seabed exploration process is possible, it would be carried out first. However, it would still be followed by a volumetric exploration of the sub-surface ocean, though the volume explored probably would be smaller than that for the branch where the seabed exploration was not possible, due to less time being available.

4.5 Evaluation of Option A

Option A appears practical and effective for penetrating the Europa ice sheet and exploring the sub-surface ocean, assuming it exists. It principal drawbacks appear to be:

1) Relatively low reactor thermal power – a few hundred kilowatts (at most) which constrains the descent rate and the diameter of the melt channel.
2) Propeller driven propulsion system, which might be a problem in the undersea ocean.

3) Low available power at the docking device. This could limit the maximum distance that the ASV could explore around the entry point into the sub-surface ocean, because of the need to communicate by sonar between the docking device and the ASV.
4) Combining the functions of the melt probe and the ASV into a single unit is technically harder than developing two separate units, one for the melt probe, and the other for the ASV.

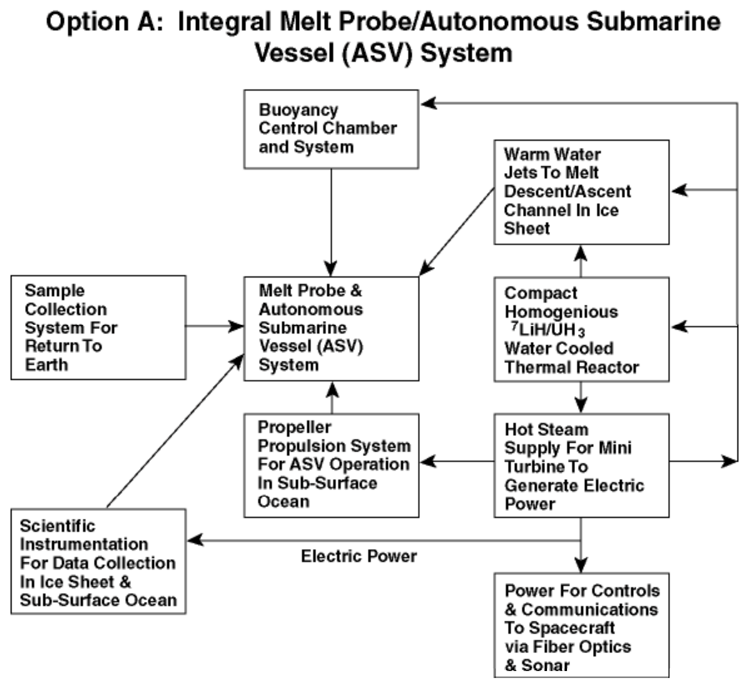


Figure 4.1 Option A: Integral Melt Probe/Autonomous Submarine Vehicle (ASV) System

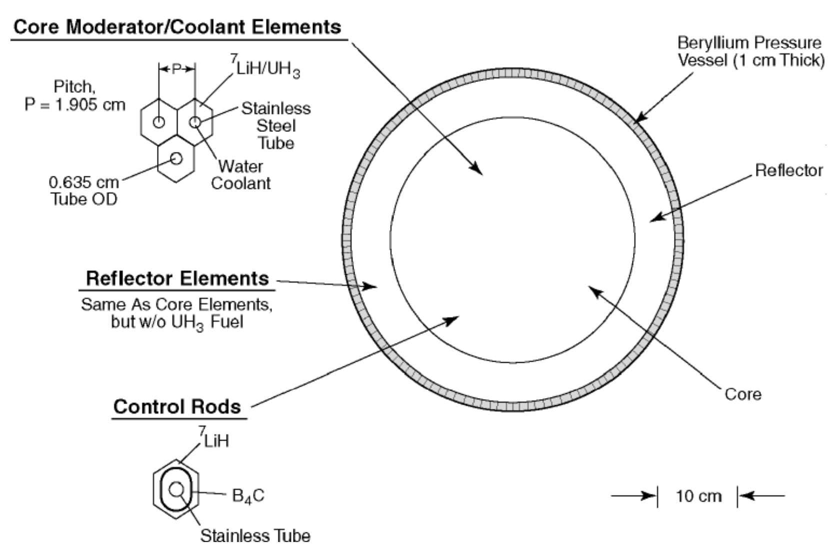


Figure 4.2.1 Cross Section of Homogeneous Nuclear Reactor Powering Option A

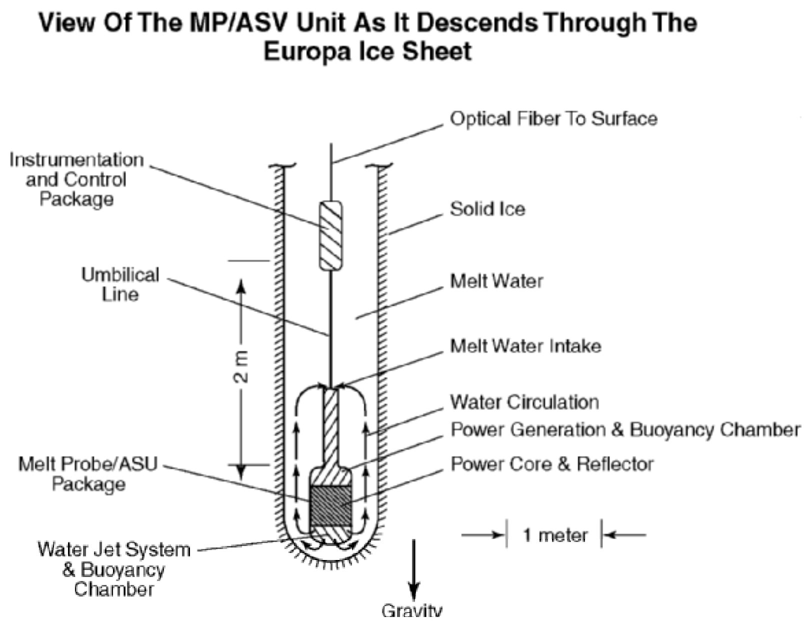


Figure 4.3.1 View of MP/ASV Unit As It Descends Through Europa Ice Sheet

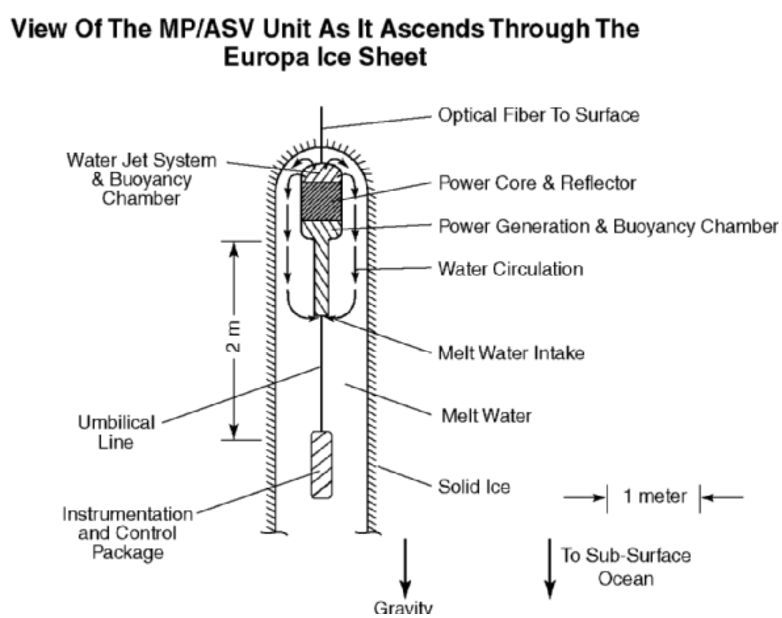


Figure 4.3.2 View of MP/ASV Unit As It Ascends Through Europa Ice Sheet

Figure 4.4.1

Side View of the ASV Propulsion Unit

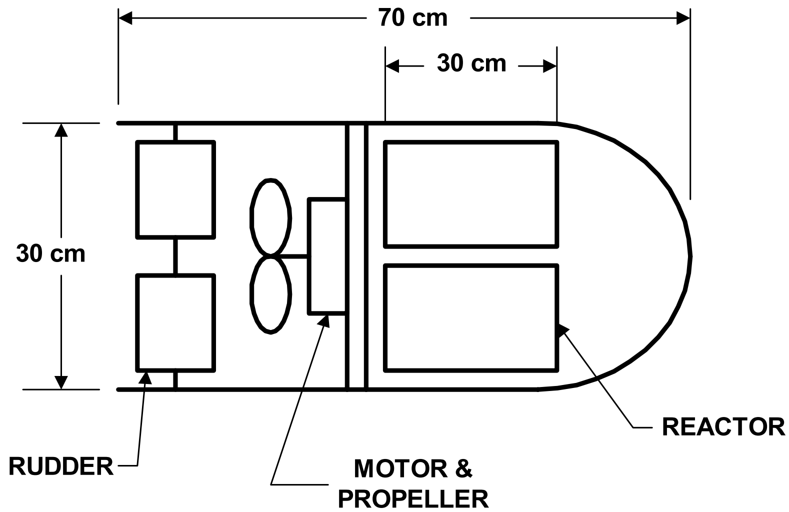


Figure 4.4.2

ASV Exploration Flow Sheet: Sea Bed & Ocean Options

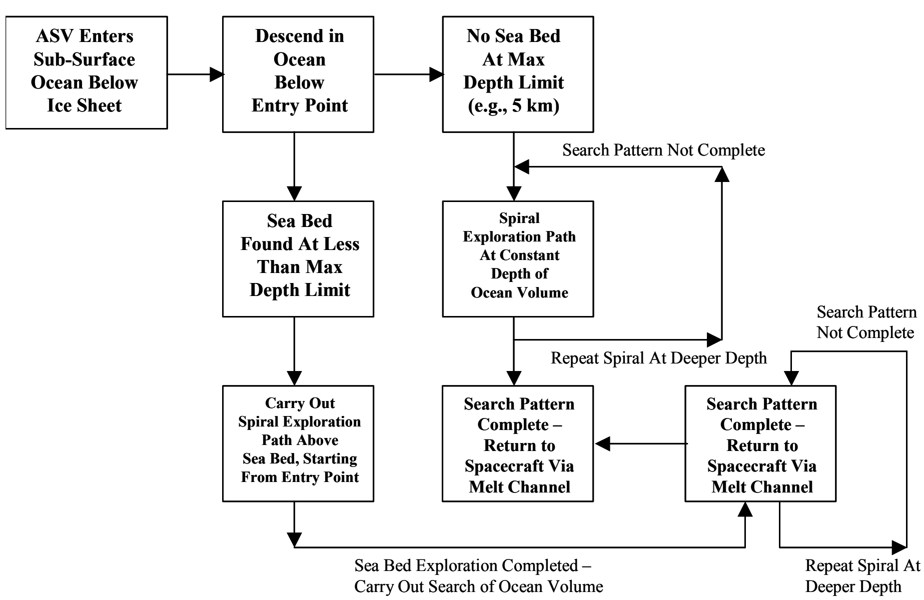


Table 4.2.1

Principal Features for the Nuclear Reactor Powering the Option A Melt Probe/ASV Unit

Feature/Parameter	Value
Reactor Type	Thermal Spectrum Reactor – Homogeneous Mixture of Moderator and Fuel With Internal Water Cooled Metal Tubes
Moderator	Solid Lithium-7 Hydride (mp = 950K)
Fissile Fuel	Solid Uranium-235 Hydride
Fissile Loading	2.2 kg of U-235
Core Diameter	29 cm
Core Height	29 cm
Reflector	5 cm Radial and Axial Thickness of ^7LiH
Coolant Tubes	Stainless Steel, 0.64 cm O.D., 0.10 cm Wall Thickness, 169 Total Number
Coolant Tube Pitch/Diameter Ratio	3.0 (Hexagonal Lattice)
K_{eff} (Criticality Constant)	1.067 (Control Rods Withdrawn)
Total Reactor Mass	48 kg

Table 4.3.1

Rate of Descent of Melt Probe/ASV Unit As Function Of Reactor Thermal Output & Melt Channel Diameter

	Rate of Descent, Meters/Day		
Reactor Output (kW)	**Diameter of Channel = 0.3m**	**0.5m**	**0.7m**
30	66	23	12
50	109	39	20
70	153	55	28
100	218	78	40
150	327	117	60

5. Design Studies of Option B: Separate Melt Probe/ASV Systems

5.1 Functions of Separate Melt Probe and ASV Systems

In Option B, the melt probe and the autonomous submarine vehicle (ASV) each have their own nuclear reactor. This enables the melt probe to continue to generate substantial electric power when it reaches the bottom of the ice sheet, and after the ASV detaches to explore the sub-surface ocean around the entry point.

The capability for the melt probe to continue to generate power enables the ASV to travel much greater distances from the entry point, than would be possible using the battery-powered docking device described in Option A. It also eliminates the requirement for the ASV to periodically return to the docking device to recharge the devices and its batteries. Providing the melt probe and the ASV with separate reactors also enables the two reactors to more efficiently carry out their desired functions, and to do so in a technically simpler manner.

In Option B, the principal function of the melt probe reactor then becomes to produce large amounts of warm water at a temperature of ~ 50° C. A small amount of electric power also has to be produced, in order to operate its scientific instruments and controls, and to communicate with the REE spacecraft on the surface via the optical fiber link. The principal function of the ASV, on the other hand, is propulsion. In Option A, propulsion is provided by an electrically powered propeller system. However, a simpler, non-mechanical system in which propulsion is directly provided by hot steam/water jets from the ASV is possible. This alternative appears attractive, given the uncertainties about what kind of conditions would be present in a sub-surface Europa ocean, and whether a mechanical propeller/rudder unit would be able to adequately function. Eliminating the propeller/rudder also minimizes the risk that it could be damaged during the ascent/descent period through the ice sheet.

Accordingly, in Option B, propulsion for the ASV is provided by steam/water jets from the ASV reactor, rather than by generating electric power for a propeller. In addition to having separate melt probe and ASV units, each powered by their own reactor, rather than an integrated melt probe/ASV unit powered by a single reactor, Option B also uses a different reactor design approach. Instead of a $^7LiH/UH_3$ core with water-cooled stainless steel tubes imbedded in the solid hydride material, in Option B water is used for the moderator, reflector, and coolant for the reactor.

This approach has important advantages over the solid $^7LiH/UH_3$ design. First, the mass of the reactors can be substantially reduced by using melt water obtained from the Europa ice sheet, instead of having to transport solid ^7LiH moderator/reflector from Earth. Second, the power output of the reactors can be substantially increased over that possible with the Option A design, by having the water directly cooled nuclear fuel elements that are configured to have a high surface to volume ratio. Third, it is simpler to control the local outlet temperature of the water coolant from the reactor core in Option B, enabling directional thrust control of the ASV steam/water propulsive jets.

5.2 Design Features of Option B Melt Probe for Descent and Ascent Through Europa Ice Sheet

Figure 5.2.1 shows a schematic of the melt probe descent/ascent process in Option B. The melt probe and ASV are connected together and descend as a unit until the bottom of the ice sheet is readied. At this point, the ASV detaches from the melt probe and moves off to explore the sub-surface ocean. The two-way long distance communication is maintained between the melt probe and the ASV by sonar signals. After exploration efforts at the site are complete, the ASV would return to the melt probe and be reattached to it. The connected unit would then melt its way back to the surface, following the original descent channel, which had refrozen during the ASV exploration phase.

Figure 5.2.2 shows a detailed view of the melt probe reactor and the type of melt channel it would create as it descended through the Europa ice sheet. The melt probe reactor is water moderated and cooled. The water is easily obtained by melting ice from Europa's ice sheet. Using indigenous water instead of a moderator and coolant from Earth thickness greatly reduces the mass of the payload that the REE spacecraft has to transport to Europa.

The melt probe reactor utilizes simple, well-developed nuclear technology. The fuel elements operate with excellent cooling at low outlet water temperatures, e.g., ~ 50° C. The diameter of the reactor core is 35 centimeters; with a radial reflector thickness of 5 centimeters of water, the overall outer diameter of the reactor is 45 centimeters. There are a total of 37 fuel elements in the core. Cool water flow inwards through an outer porous beryllium tube (the "cold frit"), then through a packed bed of small diameter fuel spheres where it is heated, and then through an inner porous beryllium tube (the "hot frit") into a central channel along which it flows to an exit point at the end of the element. The local flow rate of the water coolant is controlled by the local porosity of the cold frit, so that the water flow rate matches the local reactor power density at all points in the reactor. In this manner, the temperature of the water coolant flowing out of each element is controlled to essentially the same value.

The cermet fuel spheres are made of beryllium metal with many small diameter (several microns) particles of UO_2 imbedded inside the metal matrix. Water-cooled, cermet metal matrix fuels have demonstrated excellent performance in the nuclear industry, operating for many years at much higher temperature, with very high burnup levels. The melt channel process is illustrated in Figure 5.2.2. Warm water flows out from the reactor down through a 2 meter long tube, and at the bottom of which it is directed downwards into the melt water pool. There the warm water acts to melt the surface of the ice sheet at the bottom of the pool. The water flow then reverses and travels upwards towards the top of the 2 meter long intake tube above the reactor. Form there, the cool water flows into the reactor to be reheated. The 2 meter distance between the melt probe reactor and its accompanying instrument package and the detachable submarine greatly reduces by a factor of approximately 10^7 in the radiation dose to those systems (Figure 5.2.3). This eliminates any chance of neutron and gamma radiation causing the failure or degradation of sensitive components.

Figure 5.2.4 shows the melt probe descent rate in meters per day as a function of reactor power and the melt channel diameter. The melt probe reactor can readily deliver 20 thermal megawatts of hot water, a much larger amount than the 4 megawatt maximum value shown in Figure 5.2.4. For a 1 meter diameter melt channel, 4 megawatts would enable a descent rate of 600 meters per day. For a 2 meter diameter melt channel, the same 4 megawatts would enable a descent rate of 150 meters per day. The 2 meter diameter channel is considerably greater than required. Accordingly, there appears to be no problem in having the melt probe ascend or descend through the ice sheet at a rate of several hundreds of meters per day.

Most of the 37 fuel elements in the melt reactor only heat water to a modest temperature, e.g., 50° C. A few, e.g., 2 or 3 elements, heat their water to a higher temperature, e.g., 250° C. This is sufficient to make steam for a mini turbine that would generate ~ 10 kW(e) of electric power for operating the melt probe systems.

During the ascent phase, the warm water outlet is at the bottom of the melt channel, - that is, next to the ASV unit – with the intake for the cooler water that returns to the reactor being located ~4 meters above the ASV at the instrument package. During the ascent phase, the warm water outlet is now at the top of the melt channel. The water then flows down along the sides of the melt channel to the new intake point at the ASV. As illustrated in Figure 5.2.2, the Option B melt probe reactor operates in the open cycle mode. That is, the warm water output from the reactor flows directly into the melt channel and then back into the reactor for reheating. This should not be a problem, since the ice sheet should be essentially pure ice. Any particles or pebbles in the ice sheet, which might be of meteoric origin, or brought up by warm water geysers, could be readily filtered out so that they would not enter the reactor.

If it turns out that there is an objectionable amount of solids in the ice sheet, or if it is deemed desirable to be ultra conservative in the melt probe design, the reactor could operate in the closed cycle coolant mode. The output heat would be transferred through a compact lightweight primary heat exchanger to the open cycle water flow in the melt channel. The pattern of water flow would in the melt channel be the same as that in the pure open cycle mode, with the only difference being the transfer of the thermal output power through the primary heat exchanger. The principal parameters and mass budget for the Option B melt probe are given in Table 5.2.1.

5.3 Design Features of Option B ASV for Exploration of Europa Sub-Surface Oceans

Upon reaching the sub-surface ocean the ASV reactor would begin operation. Figure 5.3.1 shows the reactor for the mobile submarine, together with the layout of the submarine. The submarine reactor is essentially the same as that for the melt probe, except that the outlet temperature of the water/steam mixture from the fuel elements is substantially higher than that of the water from the reactor in the melt probe. The outlet temperature will be a function of the depth at which the submarine operates. At a 1 kilometer depth in Europa's ice sheet, the hydrostatic pressure is 14 bars (210 psi). This is much less than would be found on Earth, a result of the much smaller gravity, 0.16 g, on Europa. Assuming that the Europa's ocean started at a depth of 1 kilometer, and the submarine dove to an additional depth of another kilometer, the total pressure at that depth would be 30 bars (450 psi).

The fuel elements generate a two-phase steam/water mixture that flows along the central channel to its exit nozzle, where it jets out into the ambient ocean, providing thrust. The flow area of each nozzle is adjustable. For a given element at a given reactor power level, the thermal energy carried out by the water flowing through the element will be constant. However, the temperature and the steam/water fraction of the output flow can be controlled by suitable adjustment of the flow area of the exit nozzle. That is, a large throat area in the nozzle will lead to a low temperature for the water output, with no steam content. Conversely, a small throat area in the nozzle will lead to a high temperature for the water output, with a high fractional steam content.

A fuel element that emits low temperature water output will not generate thrust, while a fuel element that emits a high temperature water/steam output will generate thrust. The 37 exit tubes that protrude from the rear of the submarine are curved (Figure 5.3.1) radially outwards. By adjusting the temperature/steam output characteristics of appropriate fuel elements, the ASV can be guided in any desired direction, i.e., up or down, left or right. For example, if the exit tubes at the top quadrant of the reactor emit high temperature steam/water jets, while the bottom exit tubes at the bottom quadrant emit low temperature water, there will be a net thrust force that acts to push the submarine downwards.

Quite high speeds appear possible for the ASV if it operates at its maximum power of 4 megawatts. Assuming 1% propulsive efficiency (thermal to propulsive power), which appears very conservative, the ASV would have a maximum propulsive power of 40 kW, enabling it to travel at speeds up to 2 meters/second. It is unlikely to require such a speed, unless it had to outrun a large predator, an improbable but interesting scenario. More likely, speeds in the range of 1 to 3 meters/second will be the norm, requiring at most about 70 kW of thermal power. At 3 meters/second, the ASV could travel a total path length of 250 kilometers in one day.

As shown in Figure 5.3.1, the ASV reactor would nominally operate in the open cycle mode where input water from the sub-surface ocean would directly flow through the reactor to be heated and expelled to generate thrust. If the sub-surface ocean has high content of dissolved solids and/or suspended particulates, this could be undesirable. In this event, the reactor would be desired to operate in the closed cycle mode, with a heat exchanger to transfer the thermal output in the primary water coolant circuit to a secondary open cycle coolant circuit which would then exhaust steam/water jets through nozzles to provide controlled thrust.

As illustrated in Figure 5.3.1, the ASV has an internal buoyancy chamber that can control its net buoyancy, making it positive, neutral, or negative, as desired. This would be done using either hydrogen gas produced by electrolysis of steam, or steam itself. The pressurized gas or steam would be used to push out water from the buoyancy chamber into the surrounding ocean, increasing buoyancy, or let water in, decreasing buoyancy. The pressure level of gas would control whether water moved out or into the chamber. The gas pressure could be adjusted upwards by either injecting gas from a higher pressure reservoir, or admitting additional steam, and be decreased by letting steam out, injecting water droplets to condense steam, or return some gas to its reservoir through a compressor. Alternatively, if hydrogen gas is used, its pressure can be increased by burning a small amount of oxygen in it.

A portion of the generated steam would be used in mini turbine to produce electric power for the ASV to operate its controls, communications package, and scientific instrumentation systems.

The radiation sensitive electronic components of these systems would be shielded from the reactor by placing them at the end of an extendable strut at the nose of the ASV. A 2 meter distance in water would reduce the radiation dose by a factor of 10^7, more than enough to adequately shield them during the submarine's cruise through the sub-surface ocean. Table 5.3.1 summarizes the design features and parameters for the REE melt probe and submarine.

5.4 Evaluation of Option B

Option B, as was the case for Option A, also appears effective for penetrating the Europa ice sheet and exploring the sub-surface ocean. However, it appears to be more versatile and have superior performance capabilities. First, by having separate nuclear reactor power sources as the melt probe and ASV, the ASV will be able to explore a much larger volume around the entry point into the sub-surface ocean, because it will be able to communicate over much greater distances.

Second, the Option B reactor design is capable of much higher output than the Option A design by a factor of at least 10, while being considerably lighter, since it uses water from the Europa ice sheet for moderator, coolant, and reflector, leaving only a relatively small amount of lightweight beryllium structure and nuclear fuel to be brought from Earth. This greater power capability enables much faster descent rate of the melt probe through the Europa ice sheet, and substantially higher velocity capability for the ASV submarine.

Finally, technical development and construction requirements are simpler for Option B than for Option A, since it would be harder to meld the melt probe and the ASV into a single integral device, as compared to having them as separate units.

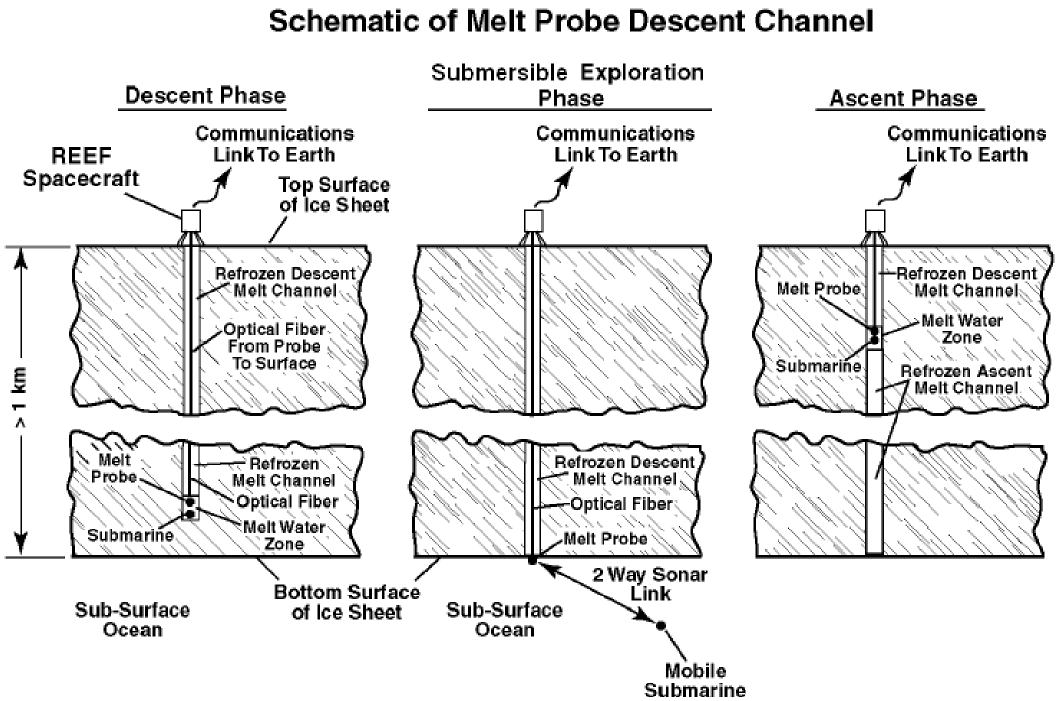


Figure 5.2.1 Schematic of Melt Probe Descent Channel

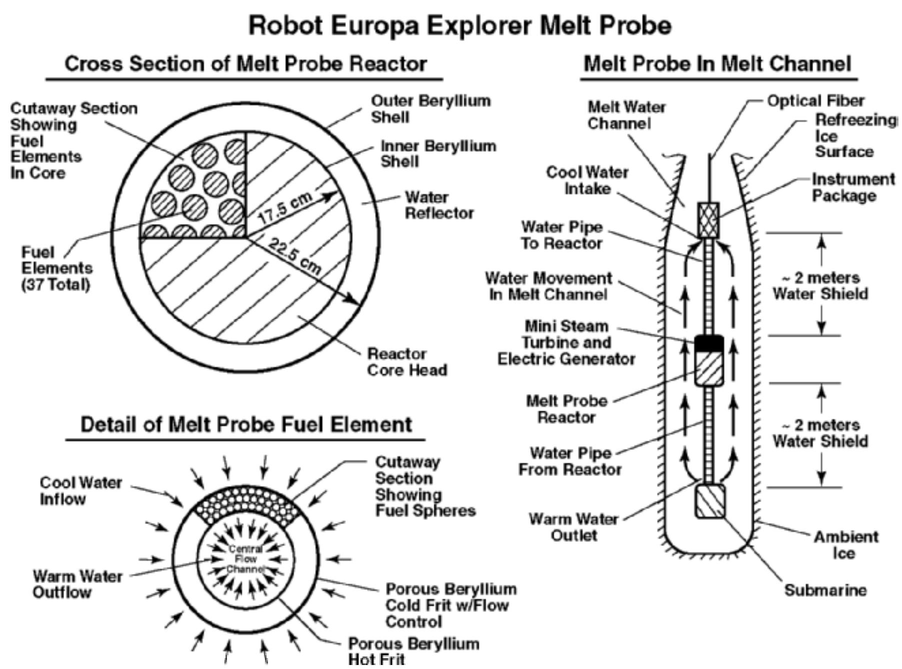


Figure 5.2.2 Robotic Europa Explorer Melt Probe

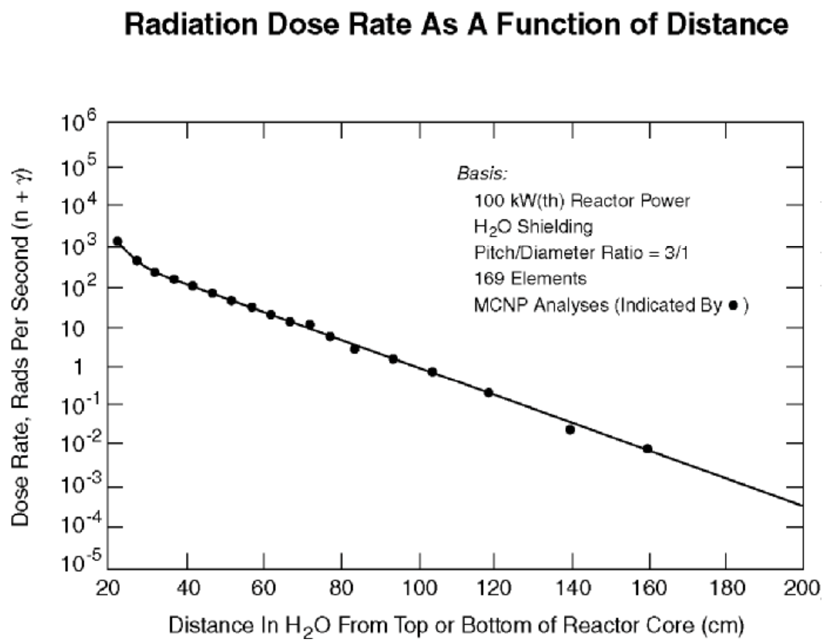


Figure 5.2.3 Radiation Dose Rate As Function of Distance

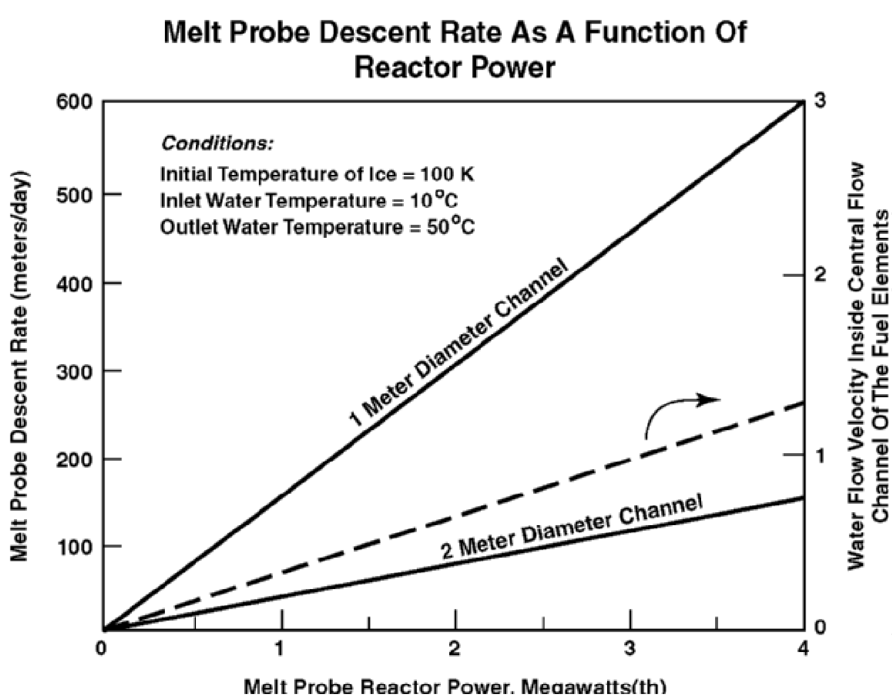


Figure 5.2.4 Melt Probe Descent Rate As Function of Reactor Power

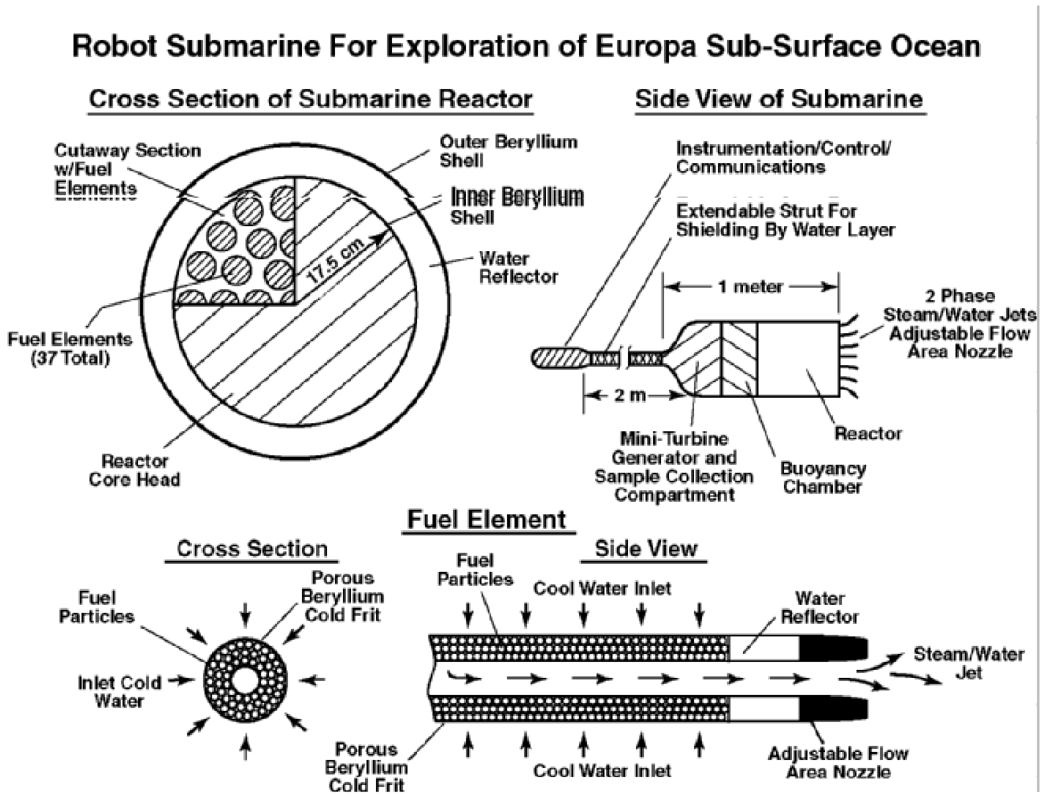


Figure 5.3.1 Robot Submarine For Exploration of Europa Sub-Surface Ocean

Table 5.2.1
Principal Features and Mass Budget of
Option B Melt Probe

Parameter	**Value**
Reactor dry mass, kg (not including H_2O from Europa)	25
U-235 loading, kg	5
Reactor max power capability, MW(th)	45
H_2O coolant outlet temperature, ° C	50° C and 250° C
Maximum ascent/descent rate, meters/day (1 meter diam channel)	600
Instrument package mass, kg	15
Power system mass, kg	10
Misc. and structure mass, kg	10
Total system dry mass, kg	***65***

Table 5.3.1
Principal Features and Mass Budget of
Option B Autonomous Submarine Vehicle (ASV)

Parameter	**Value**
Reactor dry mass, kg (not including H_2O from Europa)	25
U-235 loading, kg	5
Reactor max power capability, MW(th)	45
H_2O coolant outlet temperature, ° C	50° C and 250° C
Maximum speed, meters/sec	10
Instrument package mass, kg	15
Power system mass, kg	10
Misc. and structure mass, kg	15
Total system dry mass, kg	***70***

6. Design Studies of Bi-Modal MITEE Nuclear Engine

6.1 Capabilities of Nuclear Propulsion for Space Exploration

Nuclear propulsion offers the opportunity to dramatically increase the capability for planetary science and exploration, compared with now available using chemical rockets. Two types of nuclear propulsion are possible – nuclear thermal propulsion and nuclear electric propulsion.

In nuclear thermal propulsion (NTP), a reactor heats hydrogen propellant to high temperatures, e.g., up to ~3000 K in some designs. The combination of low molecular weight (two for hydrogen) and high temperature results in a specific that approaches 1000 seconds – over twice the ~450 seconds achieved by the best chemical propellant, hydrogen/oxygen. The high specific impulse and high thrust capability (tens of thousands of Newtons) of NTP enables spacecraft ΔVs that are over twice that from chemical rockets. This enhanced ΔV capability can allow much shorter trip times to the outer planets, elimination of the need for planetary gravity assists, and the use of smaller, lower cost launch vehicles.

In nuclear electric propulsion (NEP), the reactor generates electric power, which in turn powers an electric thruster that produces the propulsive force. Depending on the type of electric thruster used, the specific impulse can be very large, on the order of 5000 seconds or more. In principal, this enables even greater spacecraft ΔVs than possible with NTP. However, the thrust level from NEP is orders of magnitude smaller than that from NTP. Accordingly, an NEP system would have to operate for years to achieve the same spacecraft ΔV that an NTP system would deliver in an hour or so. Moreover, NEP systems are subject to large ΔV penalties if they have to climb out of a deep gravity well like Earth's, and not practical for landing on objects like Europa, Titan, Triton, Pluto, etc.

Accordingly, for the Robotic Europa Explorer (REE) mission, nuclear thermal propulsion (NTP) appears to be the best and probably only choice for a robust exploration program. NTP has two additional and very important advantages for the REE mission. First, the H2 propellant for the NTP engine can be replenished by electrolysis of melt water obtained from the Europa ice sheet. This allows the REE spacecraft to explore a virtually unlimited number of sites on Europa, using the H_2 propellant obtained from the ice sheet to make the hops between sites. It also enables the REE spacecraft to use H_2 propellant from the ice sheet for the return trip to Earth wholly. This greatly reduces the IMLEO launch mass, and results in a much smaller and cheaper launch vehicle for the mission.

Second, The NTP engine can be configured to operate bi-modally. That is, in its high thrust propulsive mode, it would use open cycle H_2 propellant to depart from LEO to Europa, to hop between exploration sites on Europa, and to depart Europa for the return trip to Earth. In its continuous electric power mode the bi-modal NTP engine would use a closed cycle coolant to generate electric power to operate controls, communications, and instrument equipment while in flight to and from Europa, and to electrolyze water to produce H_2 propellant while on Europa. This would eliminate the need for a separate electric power generator. Solar power levels are impractically low at Europa type distances, so any separate power source would have to be nuclear – either an RTG (Radioisotope Thermoelectric Generator) or an additional nuclear reactor. The melt probe and ASV reactors would not be available for generating H_2 propellant on Europa, since they would be deep underneath the ice sheet.

Large development efforts have been carried out on NTP in the last several decades in the US and USSR. A strong technology base already exists for the necessary nuclear fuels, reactor designs, materials, thermal-hydraulics, and the other components for a practical NTP engine for the REE mission. In particular, the MITEE-B (MIniature ReacTor EnginE – BiModal) described below is based on work carried out in the US in the 1960's on high temperature nuclear fuels for NTP engines, and in the 1980's and 90's on very small and lightweight engines.

6.2 Description of the MITEE-B Bi-Modal Propulsion System

NTP systems have undergone extensive development and ground testing in the US and the former Soviet Union (FSU). However, no NTP systems have yet operated in space. A large number (i.e., 31) of low output power thermoelectric nuclear reactors have been operated in space by the FSU, as well as two thermionic Topaz reactors. The US has tested one thermoelectric reactor, SNAP-10A in space in 1965. The US later carried out development work on the 100 kW(e) SP-100 space nuclear reactor, but no ground or flight tests were carried out.

Most of the US and FSU development work on NTP systems carried out during the period of the 1950's through 1970's focused on NERVA-type reactors. These used neutronically inefficient graphite moderator, making the resultant nuclear propulsion engine excessively large, heavy, with a low thrust-to-weight ratio. The US carried out successful ground tests of the NERVA system, but no flight tests. US work on NERVA stopped in the early 1970's, due to the lack of a defined mission. Development work on NERVA type engine continued in the FSU until the 1980's, and successful tests of fuel element assemblies were carried out, though no full-up engine systems were tested.

In the 1980's in the DoD/SNTP program, the US undertook the development of a very compact and lightweight NTP engine. The SNTP engine was based on the Particle Bed Reactor (PBR) design (2), in which ^{7}LiH is used as the moderator, enabling a much smaller and lighter reactor. The PBR fuel elements consist of annular packed beds of small (~400 micron diameter) HTGR type nuclear fuel particles, held in place between two porous frits. Hydrogen propellant flows radially inwards through the outer cold frit into the annular packed bed of fuel particles, where it is heated to 3000 K, and then out through the inner hot frit to a central axial flow channel, along which it travels to the exit nozzle.

The SNTP program developed and successfully tested the various components for the SNTP engine. While a full-up engine was not built and tested, low power critical assemblies were operated. Thermal hydraulic tests of prototype fuel elements demonstrated the capability to operate at extremely high power densities, i.e., 30 megawatts per liter. The PBR/SNTP engine design had a power of 1000 megawatts and a thrust-to-weight ratio of 30/1, comparable to that of high performance chemical propulsion engines. The SNTP program stopped in the early 90's at the close of the Cold War. More recently, design studies of a smaller high performance NTP engine, based in part on the PBR technology, as well as the earlier development of high temperature tungsten-UO_2 cermet fuels in the AEC 710 nuclear engine program, have been carried out. This new NTP engine design, termed MITEE (3,4,5,6) is shown in Figure 6.2.1.

The MITEE design adopts the basic radial flow geometry of the PBR fuel elements. However, it has two fundamental improvements from the PBR. First, instead of having the fuel elements arranged as a core assembly inside a common pressure vessel, each fuel element is positioned inside its own individual pressure tube, which contains besides the fuel element, an annular outer shell of lithium-7 hydride moderator and a small nozzle at the exit end of the pressure tube. This arrangement reduces the weight, and simplifies the construction of the engine. Moreover, it simplifies the nuclear test program and greatly reduces its time and cost. Instead of testing a full-up assembly of 37 or 61 elements, validation tests can be carried out on a single pressure tube/fuel element assembly.

The second fundamental improvement is the use of a multi-layer assembly of perforated tungsten-UO_2 cermet fuel sheets instead of a packed bed of nuclear fuel particles. The tungsten-UO_2 fuel performs excellently in 3000 K hydrogen for many hours. Moreover, the local voidage and propellant flow geometry in the sheet assembly can be controlled more precisely than in a bed of randomly packed particles, reducing the effects of hot channel factors and variation in voidage. Also, the possibility of mechanical distortion due to shifts in particle position caused by the thermal cycling effects during multi-burn operation is eliminated.

A further modification of the small nuclear engine concept is described in this section. This modification adds a bi-modal capability to the MITEE NTP engine design, so that electric power can be generated as well as high propulsive thrust. Figure 6.2.2 illustrates the overall capabilities of the MITEE-B bi-modal engine in the NTP thrusting mode and the electric generation considered here:

- When operating in space, the engine generates 1 kW(e) of continuous electric power, which would eliminate the need for a separate RTG or solar electric system to operate controls and instruments during its mission, as well as provide power for communication with Earth.
- When on the surface of Europa, MITEE-B generates 20 kW(e) of electric power, which in addition to the operations carried out in space, also enables operation of an electrolyzer to produce H_2 propellant.

The modifications to the MITEE reactor to achieve bi-modal capability are relatively minor. Figure 6.2.3 shows a cross-section of a MITEE-B reactor core assembly with 61 pressure tube/fuel elements. Designs having fewer, e.g., 37, pressure tube/fuel elements are also possible. The core assembly is surrounded by a ring of pressure tubes containing only lithium-7 hydride, which acts as a neutron reflector for the core.

Figure 6.2.4 shows a detailed cross-section of an individual pressure tube. To achieve bi-modal capability, 8 small diameter beryllium tubes are bonded to the cold frit of the fuel element. These 8 tubes carry a closed cycle coolant, e.g., helium, when the reactor is operating in the electric power mode. Heat from the tungsten-UO_2 fuel sheets is transferred to the closed cycle coolant through the cold frit and its beryllium tubes, both by thermal radiation and conduction. This thermal energy is then carried to an external electric power generation system by the flowing coolant inside the 8 tubes. During the electric generation mode, there is no propellant flow through the fuel region. The nozzle at the end of the pressure tube is open to vacuum, so the entire region inside the pressure tube is also under vacuum conditions, except for that portion inside the closed 8 coolant tubes. A description of the electric generation system is given later.

The MITEE-B system can be used for a wide variety of missions. Figure 6.2.5 illustrates two types of MITEE-B missions. Type I missions only use NTP propulsion, with ~ 1kW(e) electric output. The NTP can be used with a single burn for Earth departure, or with multiple burns for course correction, orbital capture, or planetary landing. Figure 6.2.6 shows some of the possible Type I missions. A simple flyby mission, e.g., of Pluto, would require only a single high ΔV burn out of Earth's orbit. If it was desired to orbit or land on Pluto, at least 2 NTP burns would be required, one for Earth departure and one at Pluto.

A third example is a SunBurn type mission (7) in which the spacecraft is sent on a trajectory that passes very close to the Sun by an NTP burn from Earth's orbit, and then performs a second NTP burn at Sun perigee, deep in the Sun's gravity well. The gravity well burn results in a very high escape velocity from the Solar System, approaching 100 kilometers/second.

In Type II missions (Figure 6.2.5), the MITEE-B engine can be refueled with H_2 propellant if it lands on a body having an accessible water/ice resource. In the REE mission, a spacecraft with the MITEE-B engine would land on the Europa ice sheet, and electrolyze melt water to obtain H2 for the return trip. The 20 kW(e) of MITEE-B would produce 7 kg/day for return of a landed spacecraft after a few months. Other possible Type II missions include Callisto, Ganymede, Titan, Triton, Pluto, the North Polar Cap of Mars, numerous NEO bodies, (Near earth Objects) and comets. A description of additional MITEE-B mission opportunities is given later in the report.

6.3 MITEE-B Neutronics

Figure 6.2.3 shows the cross section of the 61 pressure tube/fuel element MITEE-B reactor, while Figure 6.2.4 shows a cross section of an individual pressure/tube fuel element. Each beryllium pressure tube has an annular moderator shell of lithium-7 hydride contained inside a beryllium honeycomb structure. The lithium-7 hydride is completely enclosed and not open to vacuum, so that when operating in the electric power generation mode, hydrogen would not slowly evaporate out of the hydride into space. Just inside the ^{7}LiH/Be moderator shell, there is a thin porous metallic beryllium sheet (termed the cold frit). The frit controls the local H_2 propellant flow rate, so as to properly match its flow to the local fission power rate in the element. Eight small diameter beryllium tubes that carry the closed cycle coolant stream are bonded to the cold frit. Inside the cold frit is a multi-layer pack of perforated tungsten-UO_2 cermet sheets, through which the H_2 propellant flows radially upwards, being heated by the fission process. The hot H_2 propellant exits from the tungsten-UO_2 cermet sheets into a central axial flow channel, along which it travels to the end of the pressure tube. At that point, the hot H2 exits through a small nozzle, providing a propulsive thrust force. The H_2 flows from the individual 61 exit nozzles merge into an overall flow field. The total thrust force from the 61 nozzle array is very close, within a few percent, to the thrust that would be generated from a single nozzle that operated at the same propellant flow rate and temperature.

The tungsten-UO_2 cermet consists of a tungsten matrix that incorporates up to 50% volume percent of micron size UO_2 particles. Similar cermet fuels have operated successfully in nuclear reactors for many years with no problems. Tests of the tungsten-UO_2-type cermet fuel were carried out in hot hydrogen at temperatures up to 3000 K in the 710 nuclear engine program (8), and demonstrated the capability to operate for many hours without significant fuel loss. Test pieces of the tungsten-UO_2 fuel were subjected to dozens of thermal cycles and temperature rise rate of 10,000 K per second, without significant problems or degradation. To reduce overall reactor weight, molybdenum-UO_2 cermet fuel is used in the lower temperature zone (below 2000 K) of the fuel element in place of the higher density tungsten-UO_2 fuel, which is retained in the high temperature zone. An extensive set of Monte Carlo neutronic analysis of MITEE reactors have been carried out in earlier studies (3,4,5,6) using the MCNP computer code. These analyses utilized full 3-dimensional geometric representation of the actual reactor geometry, and pointwise cross sections, and provide the most accurate method available for analyzing small, high leakage, very heterogeneous reactors. MCNP analyses were able to very accurately predict the criticality constant, K_{eff}, of small PBR experimental reactors to within 0.5 percent, and could accurately model the other reactor parameters, including moderator coefficient, power distribution, etc.

The criticality of MITEE reactors is strongly affected by the pitch/diameter (P/D) ratio of its fuel elements. As P/D increases, the distance between fuel elements also increases, together with the diameter of the reactor, and the volume of its lithium-7 moderator. As shown in Figure 6.3.1 for a 37 fuel element reactor, the value of K_{eff} initially increases with increasing P/D value, because neutron leakage decreases. However, as the P/D ratio continues to increase beyond the value of 2.5, K_{eff} decreases, because of the increasing absorption of neutrons in the hydrogen atoms of the moderator. However, the reactor mass, which is composed of its U-235 fuel, the tungsten and molybdenum matrices, lithium-7 hydride moderator and reflector, and beryllium structure, continues to increase with the P/D ratio. For this 37 element MITEE reactor, the optimum P/D ratio is 2.0, because it results in an adequately high K_{eff} of 1.07, and an acceptably low reactor mass of 100 kilograms. A value of K_{eff} in the range of 1.05 to 1.10 appears best, since it allows for a good control margin and potential temperature effects on reactivity.

The criticality of MITEE reactors is also strongly affected by the nature of the moderator used, and also the type of fissile fuel employed. Figure 6.3.2 shows the Keff and reactor mass of MITEE for two different moderators. ^7LiH and BeH_2, and 3 different fissile fuels, U-235, U-233, and Am-242m. Using BeH_2 moderator instead of ^7LiH reduces the reactor mass from 100 kg down to 70 kg, at a K_{eff} of 1.07. This occurs because the atomic density of hydrogen in BeH_2 is substantially greater than in ^7LiH, making neutron leakage less for a given diameter reactor. Using U-233 fissile fuel further reduces reactor mass, from 70 kg down to 40 kg, because of the higher net number of neutrons released per absorption in U-233 nuclei, as compared to absorptions in U-235 nuclei. Using Am-242m fuel reduces reactor mass still further down to 25 kg – a result of an even greater number of net neutrons per absorption and a greater absorption cross section.

These studies of MITEE-B assume ^7LiH moderator and U-235 fissile fuel; however, it should be realized that the MITEE-B reactor mass could be reduced substantially by use of a more efficient moderator and/or fissile fuel. Table 6.3.1 summarizes the reactor design parameters used for the MITEE-B neutronic analyses. A 61 element core was chosen instead of the previous 37 element core, in order to maximize its heat transfer capability when it operates in the closed cycle electric power generation mode.

Figure 6.3.3 shows the effect of P/D on the 61 element core, plus the effect of having the beryllium closed cycle coolant tubes on the cold frits. Assuming that all of the 61 pressure tubes/fuel elements are functioning with a P/D ratio of 2.5 and there are 8 beryllium tubes on the cold frit, the value of K_{eff} is 1.09, which is quite adequate. With a P/D ratio of 2, K_{eff} drops to 1.04, which is not adequate. The effect of having the 8 beryllium tubes on the cold frit is modest, about a 0.05 drop in K_{eff}, but still significant. Accordingly, the P/D ratio of 2.5 appears optimum, and necessary, for MITEE-B.

One of the unique attributes of the MITEE pressure tube/fuel element concept is its ability to continue operation even if one of the pressure tube/fuel elements were to fail. Propellant flow to the failed element would simply cut-off, and the remainder of the reactor assembly would continue to operate. This capability is not possible for reactors that are situated inside a common pressure vessel. As shown in Figure 6.3.3, shutting down one of the 61 pressure tube/fuel elements in the MITEE-B core has only a minor effect on the overall K_{eff}, in the range of 0.02 to 0.03 in magnitude. The reactor could continue to operate with 1 of its elements shutdown, and probably 2. The impact on K_{eff} depends on the position of the fueled element in the core – elements in the outer region (rings 4 or 5) have less impact on K_{eff} than elements at the center or in the 2nd or 3rd row. The use of the pressure tube configuration increases system reliability, and reduces the need to establish very high levels of reliability during development and testing. Being able to continue to operate with a failed element, a situation not possible with a single pressure vessel, significantly decreases the required level of reliability for each fuel element.

6.4 MITEE-B Thermal Hydraulics

The molybdenum-UO_2 and tungsten-UO_2 cermet fuel sheets are perforated with a large number of small diameter holes, through which the radially inflowing hydrogen propellant passes as it goes from a given cermet sheet to the next one at a smaller radius. Table 6.4.1 gives nominal thermal hydraulic design parameters for MITEE-B. The diameter of the perforation holes is 0.018 centimeters, with a total hole area of 0.25 cm^2 per cm^2 of sheet surface area. A conservative heat transfer analysis approach was used, in which convective heat transfer was assumed to only occur on the cylindrical inner surface of the perforating holes. This assumption neglects the additional convective heat transfer that occurs on the surfaces of the cermet sheets outside the holes. Since this external heat transfer area is several times greater than that inside the holes, the actual film drop will be substantially smaller than the calculated value.

Using a heat transfer correlation given by Rohsenhow (9), the radial temperature distribution of the fuel sheets and the hydrogen propellant across the fuel region is shown in Figure 6.4.1. The local temperature difference between the fuel sheet and the bulk temperature of the propellant at that point is the film drop required to transfer the heat from the fuel to the propellant. The film drop is relatively large at the cold side of the fuel region and relatively small at the hot side, because the thermal conductivity of hydrogen monotonically decreases with temperature. As discussed earlier, the actual film drop will be substantially smaller because of the additional heat transfer area.

The film drop is also affected by the number of cermet fuel sheets in the annular fuel region. Figure 6.4.2 illustrates the effect of the number of sheets. With fewer sheets, film drop increases, because of the smaller area for heat transfer. A calculated film drop of ~100 K appears acceptable, considering that the actual film drop will be substantially smaller. During the electric power generation mode, the reactor operates at low thermal power. The heat generated in the fuel sheets transfers by a combination of radiative and conductive transport between the sheets (the fuel sheets are in close mechanical contact) in the fuel region to the beryllium cold frit, where it then transfers to the closed coolant circuit through the walls of the 8 tubes bonded to the frit.

The total surface area for heat transfer into the cold frits of the 61 element core is 1.74 m^2. Assuming a thermal efficiency of 25%, the 1 kW(e) MITEE-B has a thermal power of 4 kW(th). This corresponds to an average input heat flux of 0.23 watts per cm^2 for 1 kW(e) generation and 4.6 watts per cm^2 for 20 kW(e) generation. Because the radial thickness of the fuel region is small (0.6 cm) and the fuel sheets are in intimate mechanical contact, the temperature difference between the hottest fuel sheet and the cold frit will be small, on the order of 10 K.

6.5 MITEE-B Electric Power Generation

Three power cycle options have been considered for MITEE-B, as illustrated in Figure 6.5.1. The Brayton and Stirling cycles use an inert gas working fluid, e.g., helium, argon, xenon, or mixtures thereof. The Brayton and Stirling options have undergone extensive analysis and technological development for space power applications. The third option, a conventional steam cycle, has not been considered previously, but appears to be potentially promising for MITEE-B systems. The steam cycle would either use direct heating of the water coolant to form steam inside the 8 beryllium tubes bonded to the cold frits inside the 61 pressure tubes, or would transfer heat from a closed cycle helium coolant stream that flows through the cold frit tubes to a steam generator outside the reactor. Conventional steam cycles operate with low condenser pressures, e.g., well below 1 atmosphere, so as to maximize thermal cycle efficiency. For space power applications, a considerably higher turbine exit pressure is necessary, in order to have a sufficiently high radiator temperature that the radiator area is reasonable.

Figure 6.5.2 shows the thermal cycle efficiency and space radiator area for a steam cycle as a function of condenser pressure, assuming standard steam cycle conditions, e.g., a turbine inlet temperature of 810 K (1000 F) and a turbine inlet pressure of 68 atmospheres (1000 psi). A conservative turbine efficiency of 80% is assumed, together with a radiator efficiency of 0.9, and a thermal radiation from only one side of the radiator. Also, a conservative mean temperature difference of 17 K is assumed between the turbine outlet and the radiator. The optimum operating point appears to be a condenser pressure of 2 atmospheres. It enables a thermal cycle efficiency of 23 percent, which is attractive, and a one-sided radiator of 3 m^2 per kW(e).

Figure 6.5.3 shows a possible radiator configuration for the space steam cycle. The radiator consists of a series of flat metal strips that have internal grooved flow channels that carry the condensing steam/water mixture. The two ends of the flat strips are connected to inlet and outlet headers (Figure 6.5.3). The inlet header carries essentially pure steam, with a small fraction of liquid water droplets, while the outlet header carries a fully condensed liquid water stream. The flat strips are connected along their length by simple flat fins of metal. Heat is conducted from the flat strips to the fins, where it radiates to space. Heat also radiates to space from the surfaces of the flat strips. The fins and strips are fabricated from a high thermal conductivity, low-density metal such as aluminum or beryllium. Beryllium is probably a better choice than aluminum, since it has a lower density (1.8 g/cm^3 vs 2.7 for aluminum), and higher thermal conductivity (2.2 w/cm K vs 1.7 for aluminum).

The temperature difference between the roots of the fins and their midpoints is very small, even for very thin fins. At 1 kW(th) per square meter (one-sided) for example, the center of a 2 centimeter wide, 0.025 centimeter (10 mil) thick beryllium fin is only 1.8 K. The nominal overall thickness of the flat strips is 0.1 centimeter (40 mil) with 0.25 centimeter (10 mil) deep grooved internal channels for the flowing steam/water mixture. As the steam condenses, because of surface tension effects, the mix will form into a linear sequence of individual water and steam slugs that move along the grooved channels. As the steam/water mixture continues to condense, the distance between the water slugs will diminish, until a stream of pure water is discharged into the outlet header.

The flow velocity in the grooved channels is very low. For a radiator strip of 2 meters in length, and 4 centimeters in width (including a 2 centimeter wide fin), the water flow velocity out of the flat strip is only 0.5 centimeter per second, while the steam flow velocity into the strip is 4.5 meters per second. Pressure drop is small, less than a psi, and readily compensated by the suction pump that returns the condensed water back to the reactor. The radiator would be initially coiled into a rolled package, and then extended to form a flat panel after it was launched into space, using expandable truss structural elements. Assuming only a one-sided radiating panel, a 1 kW(e) MITEE-B would require a 1.7 x 1.7 meter panel. With two-sided radiating panels, the MITEE-B panel dimensions would be a factor of the square root of two smaller.

Table 6.5.1 summarizes the power system parameters, including masses for the 3 power cycle options. Clearly, the steam cycle option has a much lower total engine mass than the Brayton and Stirling cycle options, due to the much lighter power cycle management. Mass estimates for the Brayton and Stirling power cycle options are taken from Mason (13).

Figure 6.5.4 compares the relative pros and cons of the 3 power cycle options. The two most practical candidates appear to be the Stirling and steam cycle options. Both operate at a substantially lower source temperature than the Brayton cycle, i.e., 925 K for the Stirling and 810 K for the steam cycle, as compared to a minimum of 1100 K for the Brayton cycle. A temperature of 1100 K is above the melting point of 950 K for lithium hydride. A molten moderator, even in a sealed beryllium structure, raises serious material issues.

Even 925 K represents a close approach to the melt point of lithium hydride and an actual Stirling cycle would probably have to operate at a significantly lower source temperature. The steam cycle option already operates at a lower source temperature, i.e., 810 K. If its source temperature were to decrease to 700 K (800 F), the thermal cycle efficiency (80% efficient turbine) would decrease from 23.4% down to 21.9%, a small effect. The steam cycle is relatively insensitive to the amount of superheat, a definite advantage for MITEE-B in terms of materials.

There is an outstanding technology base for the steam cycle. For the space application, the principal component requiring development would appear to be the radiator, which could be quickly tested on Earth. At this point the steam cycle option appears to be the most desirable choice, because of its lower source temperature requirements and much lower total mass.

After landing on the surface of Europa and beginning the production of H_2 propellant for subsequent hops on Europa and the eventual return journey to Earth, the electric power output of the bi-modal MITEE-B engine would be increased from the nominal 1 kW(e) level used while in space to 20 kW(e). This higher output would produce liquid H_2 propellant at a rate of 7 kilograms/day, or 210 kg/month.

The waste heat resulting from the higher power output would be rejected through a lightweight, compact heat exchanger to melt water from the Europa ice sheet, rather than by thermal radiation to space from a radiator. This substantially reduces the weight of the power system required to produce the 20 kW(e) output. Table 6.5.1 summarizes the operating parameters and the mass budget for the electric power generation system of the MITEE-B engine.

6.6 Evaluation of the MITEE-B Nuclear Engine

The MITEE-B engine appears very attractive for the Robotic Europa Explorer (REE) mission. The REE mission is impossible using chemical rockets because of its very high ΔV requirements. The REE mission is also impossible using a Nuclear Electric Propulsion engine because the spacecraft would not be able to land and take-off from the surface of Europa. The only possible propulsion technology for the REE mission is Nuclear Thermal Propulsion (NTP). However, in order for the REE mission to be practical and affordable, its NTP engine must be small and light in weight. NTP engines based on NERVA-type technology developed in the 1960's and 70's are simply too heavy to be practical for a REE-type mission. The MITEE engine is practical and enabling for REE-type missions. It is lightweight, on the order of 350 kg in total weight with bi-modal thrust/electric power capability; and high thrust level, on the order of 15,000 Newtons, so it can readily land and take-off from the surface of Europa.

Moreover, it uses already developed cermet/tungsten/UO_2 nuclear fuel that has demonstrated the capability to operate for hours in high temperature hydrogen, on the order of 3000 K with minimal loss of fuel. In addition, the cermet fuel can undergo many, e.g., hundreds of thermal cycles without damage. In fact, it can even survive extremely rapid rates of temperature increase, e.g., on the order of 10,000 K per second, without failing.

Development tests carried out in the late 1980's and early 1990's by the DOD/SNTP (Space Nuclear Thermal Propulsion) program on the Particle Bed Reactor (PBR), a precursor of the compact lightweight nuclear engine to MITEE, and a base for certain components of its technology, have demonstrated the feasibility of operating at very high power densities and achieving neutronic criticality in very small, lightweight, nuclear engines similar to MITEE. Because of the existing technology base for its nuclear fuel, materials, thermal hydraulics, and reactor neutronics, MITEE-B could be developed and ready for an REE mission within a relatively short time, i.e., on the order of 7 to 10 years.

The cost of developing the MITEE-B engine would be less than a $1 billion. Since the MITEE-B would enable a broad range of new and unique missions that were impossible with chemical rockets, its development cost would be small, considering the many new and cost effective missions that it would enable. Among the missions enabled by MITEE-B would be orbiter/lander missions to Pluto; sample return missions from Pluto; Neptune and Uranus orbiter missions; sample return missions from the other Jovian moons, as well as the moons of Saturn, Uranus, and Neptune; exploration of and sample return from deep inside the polar caps of Mars; exploration of the interiors of large icy bodies like Chiron; fast trips to the Kuiper Belt, Heliopause, and Gravitational Lensing Point; as well as other unique and important missions.

Many of the above mission capabilities as enhanced by MITEE-B's capability to replenish its hydrogen propellant by electrolysis of indigenous water ice resources – an option not possible with chemical rockets and nuclear electric propulsion. The use of hydrogen propellant from indigenous resources greatly reduces the Initial Mass in Low Earth Orbit (IMLEO) launch requirements, allowing MITEE-B missions to utilize relatively small low cost launch vehicles to orbit. The REE mission, for example, would use a Delta III or Atlas III launch vehicle at a cost of $100 million – far less than would be required if REE had to bring all of its propellant from Earth.

The cost savings just from using smaller launch vehicles for MITEE-B planetary space exploration missions would more than pay for the development of the MITEE-B nuclear engine.

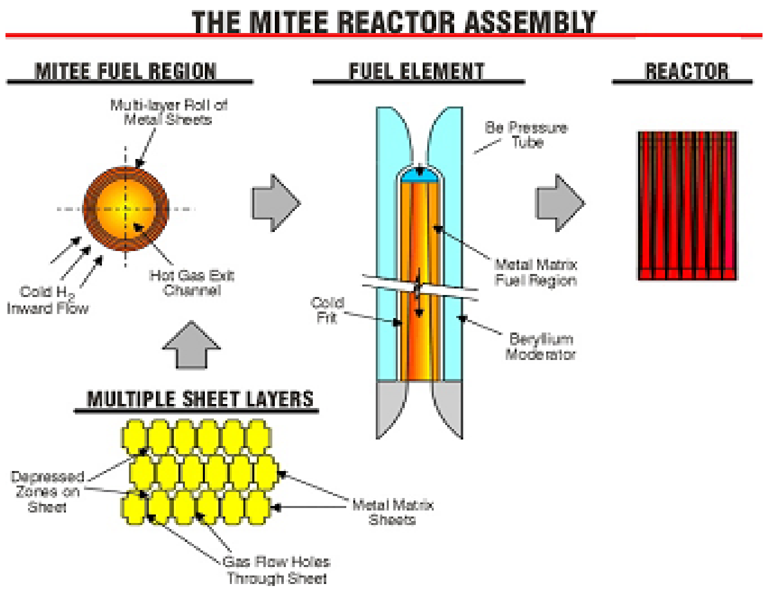


Figure 6.2.1 MITEE Reactor Assembly

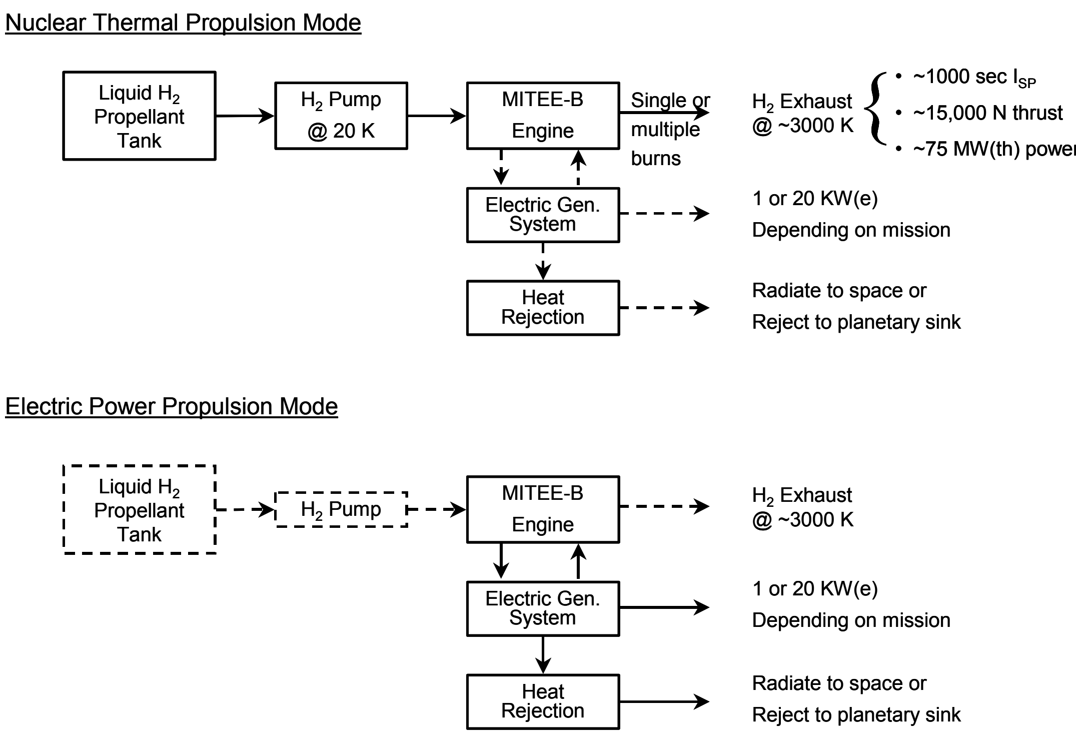


Figure 6.2.2 Operational Modes of MITEE-B Engine

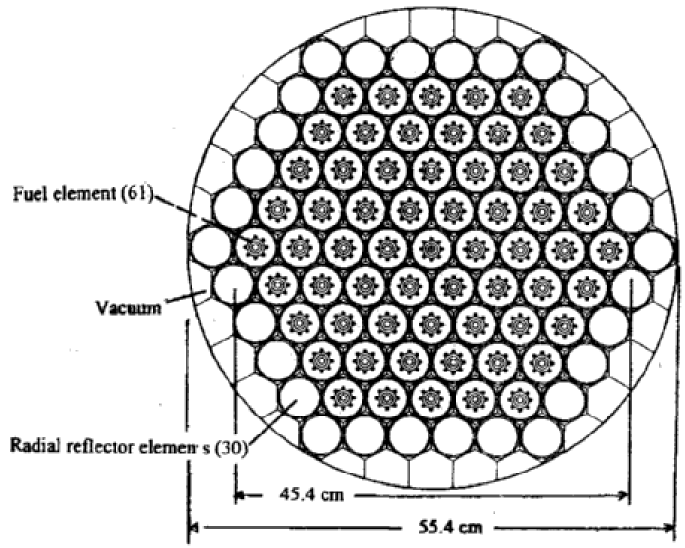


Figure 6.2.3 Cross Section Though MITEE-B Reactor

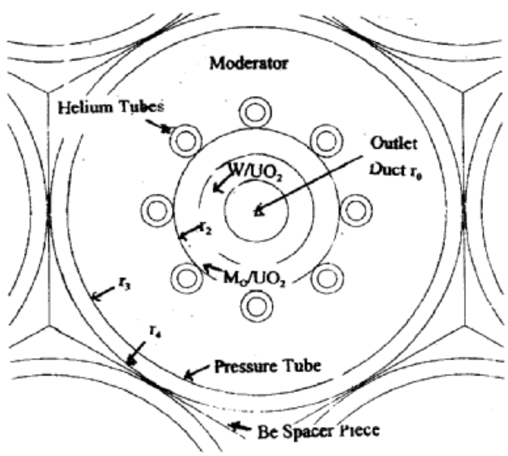


Figure 6.2.4 Cross Section of MITEE-B Pressure Tube/Fuel Element

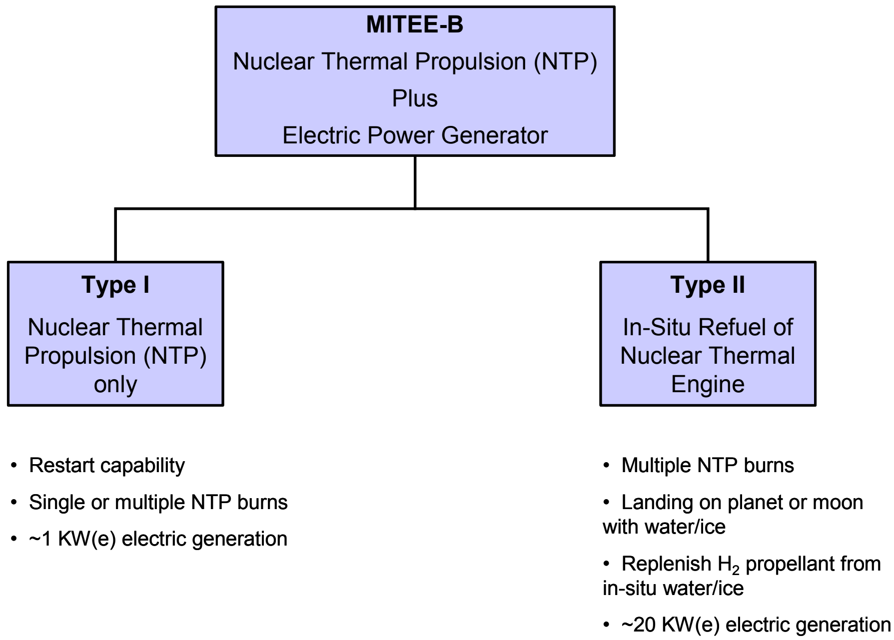


Figure 6.2.5 Types of MITEE-B Missions

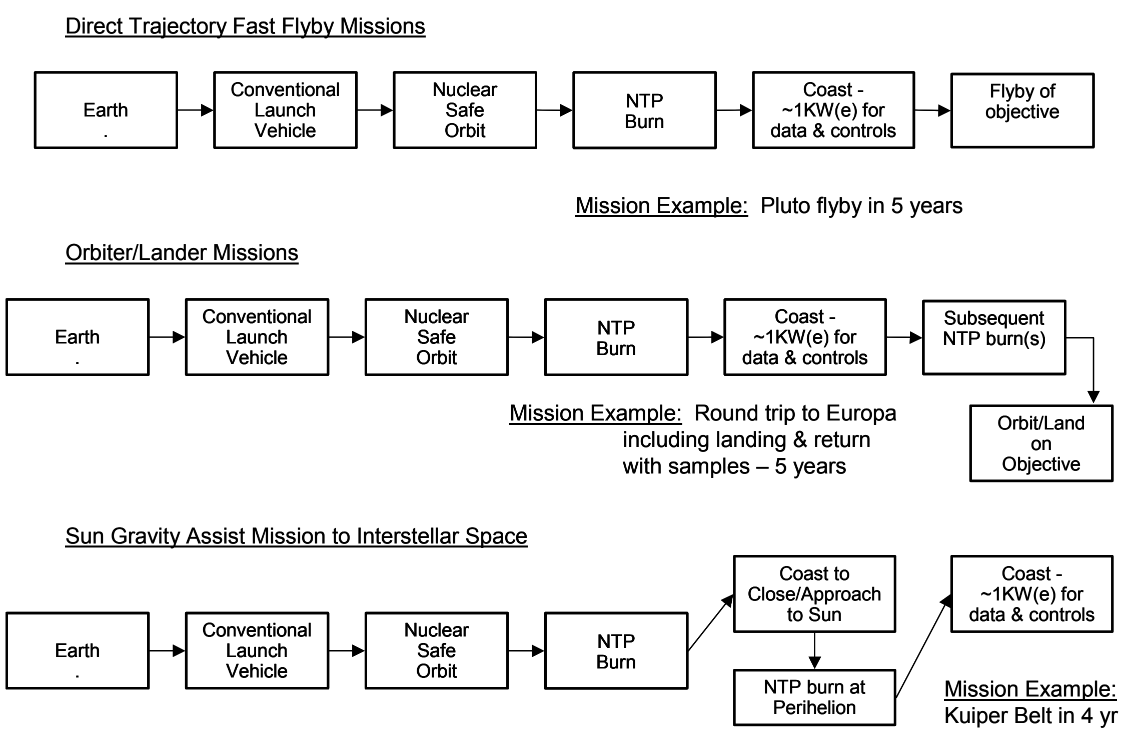


Figure 6.2.6 Type I MITEE-B Missions

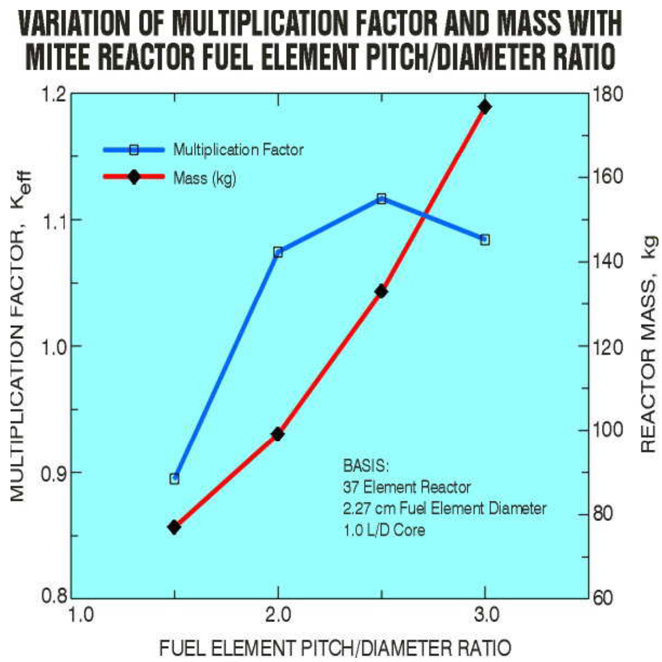


Figure 6.3.1 Variation of Multiplication Factor and Mass With MITEE Reactor Fuel Element Pitch/Diameter Ratio

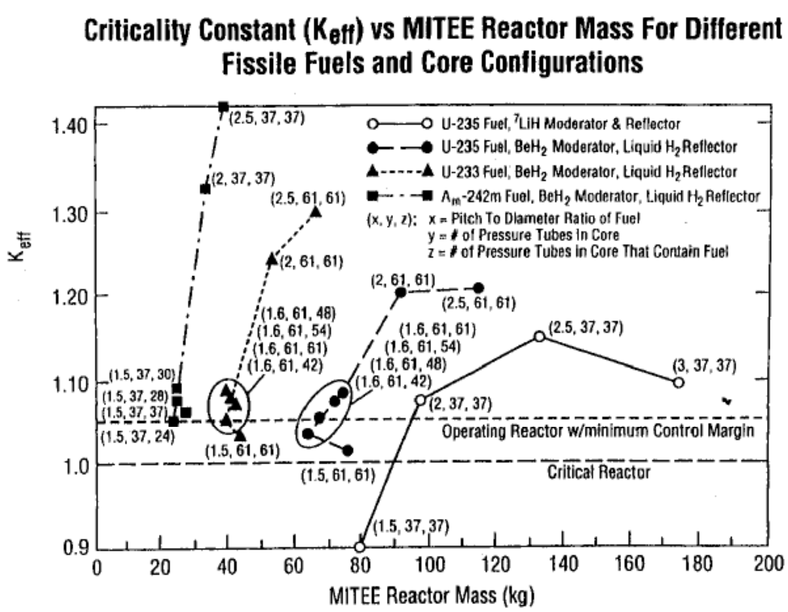


Figure 6.3.2 Criticality Constant (K_{eff}) vs. MITEE Reactor for Different Fissile Fuels and Core Configurations

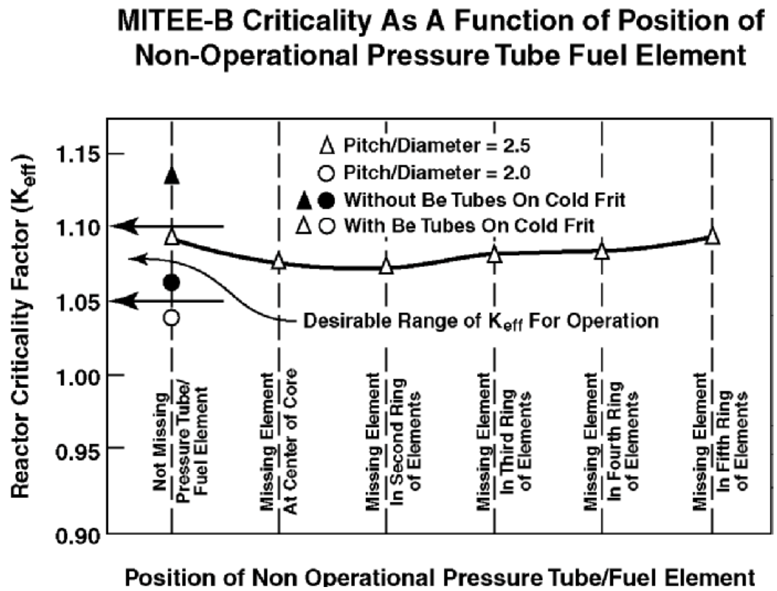


Figure 6.3.3 MITEE Criticality Constant (K_{eff}) As Function of Position of Non-Operational Pressure Tube Fuel Element

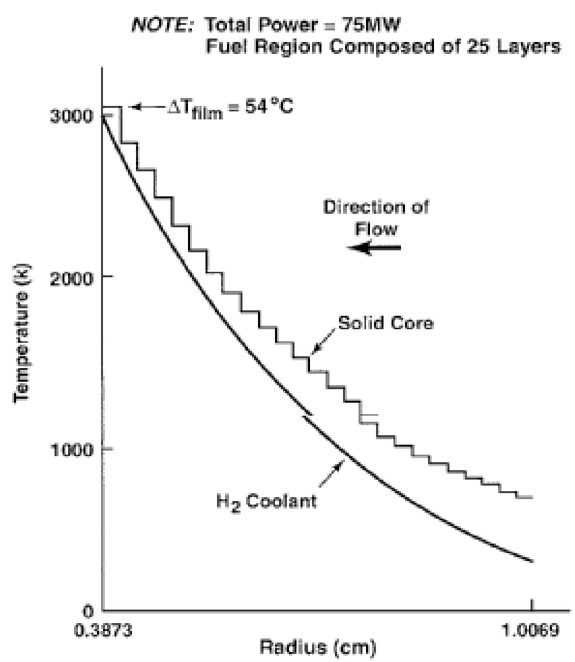


Figure 6.4.1 Fuel and Propellant Temperature Distributions Through the MITEE-B Fuel Element

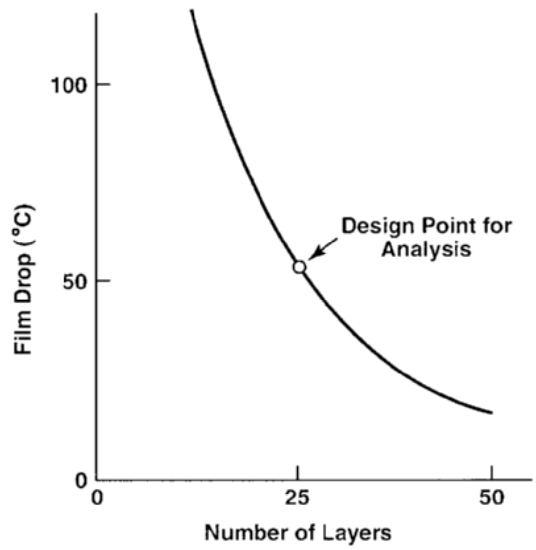


Figure 6.4.2 Film Drop in H_2 Propellant As Function of Number of Fuel Layers

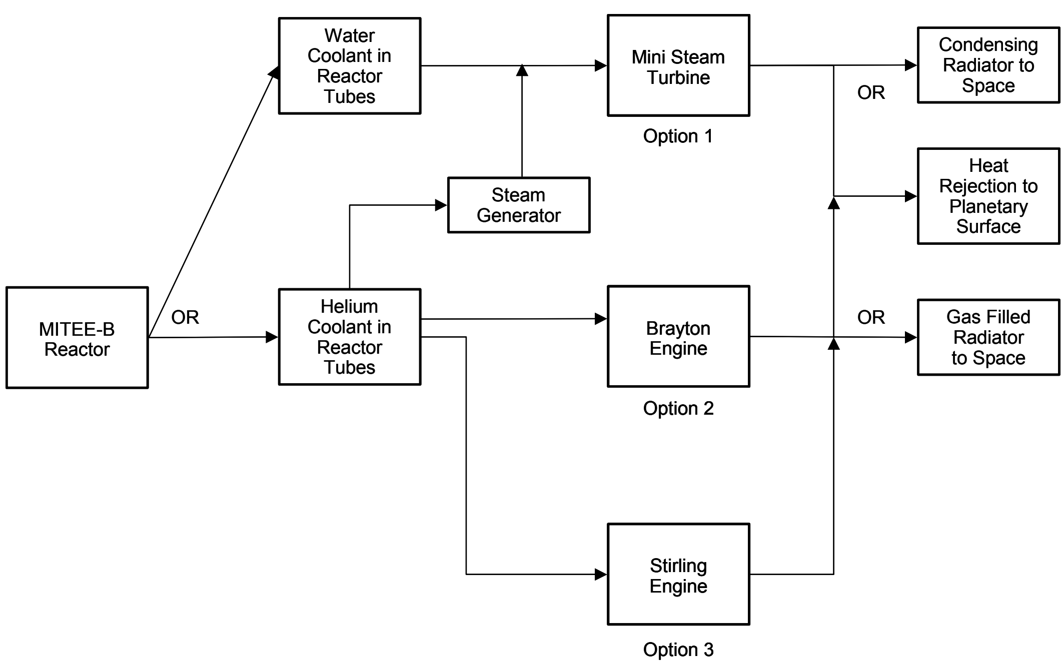


Figure 6.5.1 Electric Power Generation Options for MITEE-B

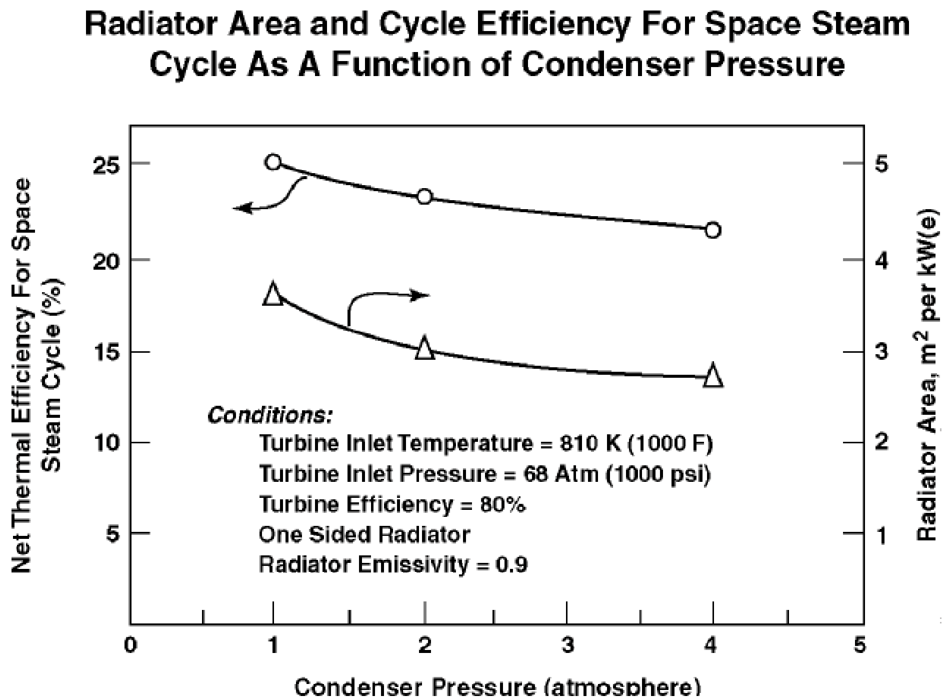


Figure 6.5.2 Radiator Area and Cycle Efficiency For Space Steam Cycle As Function of Condenser Pressure

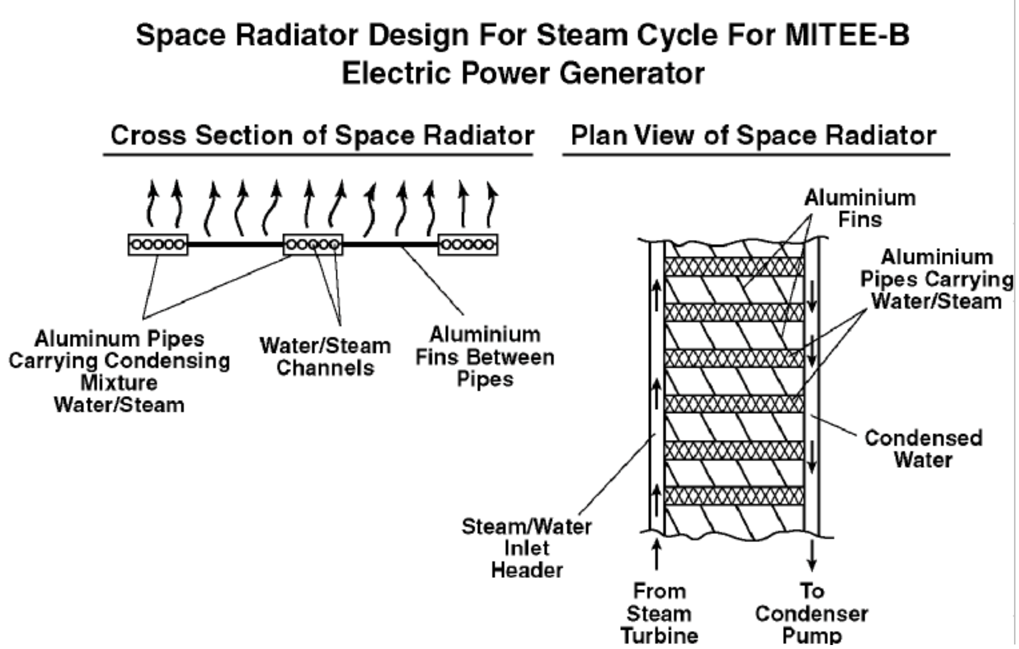


Figure 6.5.3 Space Radiator Design For Steam Cycle For MITEE-B Electric Power Generator

Figure 6.5.4 Pros and Cons of Power Cycle Options

Potential Issue	Power Cycle Option		
	1100 K Brayton	**925 K Stirling**	**810 K Steam**
Power system mass [HX, Conv, radiator]	High [~40 kg/KW(e)]	High [~40 kg/KW(e)]	Low [~10 kg/KW(e)]
Radiator area	Moderate-Low [~2 m^2/KW(e)]	Moderate-Low [~1 m^2/KW(e)]	Moderate-High [3 m^2/KW(e)]
Technology experience	Moderate	Limited	Excellent
Technology suitability for bi-modal MITEE-B system	Good	Good	Good
Components requiring significant development effort	Engine and Radiator	Engine and Radiator	Radiator

Table 6.3.1 MITEE-B Design Parameters

Fuel Element Descriptions

τ_o = 0.3873 cm (hot frit ID)
τ_1 = 0.6971 cm (ID of W/UO_2 cermet section)
τ_2 = 1.0069 cm (IE of Mo/UO_2 cermet section)
τ_3 = 2.3 cm (ID of pressure tube)
τ_4 = 2.5 cm (OD of pressure tube)
Fuel element pitch P = 5.0345 cm
Core OD/Height = 9 x pitch ≅ 45.4 cm
Reactor OD = 17 x pitch ≅ 55.4 cm
Upper axial reflector and grid plate structure thickness ≅ 5 cm (Be)
No lower reflector included
Multiplication factor (k_1) = 1.09
8 Be tubes attached to outside of fuel region for Brayton cycle
Tube OD = 0.195 cm
Tube ID ≅ 0.117 cm
W/UO_2 density = 8.85776 gm/cc
Mo/UO_2 density = 6.1468 gm/cc
Moderator/reflector material density = 0.875415 gm/cc (LiH/Be)

Reactor Mass Description (Masses in kg)

Fuel Mass W/UO_2 = 26.0
Fuel Mass Mo/UO_2 = 28.25
Moderator Mass = 69.44 (includes LiH/Be, Be tubes, and Be spacers between elements)
Radial reflector mass = 27.41 (includes LiH/Be tubes and spacers between elements)
Upper reflector = 12.81
Inlet plenum = 4.15
Reactor total = 168.1

Engine Estimated Masses (kg)

	75 MW	120 MW
Thrust	1456 kg_p 14.268 N_1 3200 lb_f	2330 kg_p 22.834 N_1 55126 lb_f
Reactor	168.1	168.1
Control	10	10
TPA	5	10
Nozzle	25	25
PMS	6.5	10.5
TVC	7.5	12.5
Plumbing	10	16
Contingency	46.4	50.4
Total	278.5	302.5
Thrust/Weight	5.2	7.7

*Individual small nozzles for each

Table 6.4.1 MITEE-B Design Parameters

Parameter	75 MW Operation	120 MW Operation
Reactor Power, MW	75	120
Power Density, MW/liter	10	16
Coolant Mass Flow Rate, kg/sec	0.62	1.00
Coolant Pressure, atm	70	70
Coolant Inlet Temperature, K	20	20
Coolant Outlet Temperature, K	3000	3000
Inlet Film Drop, °C	379	606
Outlet Film Drop, °C	54	64

Table 6.5.1 MITEE-B Electric Generation Options(1)

Parameter	Brayton	Stirling	Steam
Turbine Inlet Temperature, K	1100	925	810
Thermal Efficiency, %	—	—	23.4
HS Heat Exchanger, kg mass	90	210	20
Power Conversion Mass, kg	540	440	40
Heat Rejection Radiator for 1 KW(e) Operation in Space, Mass, kg	35	20	12
Heat Rejection Panel(2) for 20 KW(e) Operation on Surface of Europa, Mass, kg	20	20	20
Total Power System, Mass, kg	685	690	92

(1) Power systems generate 1 KW(e) in space and 20 KW(e) on surface of Europa.
(2) Steam heat rejection panel assumed for all systems when operating at 20 KW(e) on Europa.

7. Design Studies of Robotic Europa Exploration (REE) Spacecraft

Issues that drive the REE spacecraft design include the harsh, intense radiation environment at Jupiter which leads to science mission lifetime constraints, the requirement to return the science data as soon as possible, and the high ΔV requirements for orbital insertion at Europa. Accommodating these requirements while keeping the related mission operations, spacecraft and launch system issues in mind is not a simple task and requires a very iterative design process.

The quickest way to get to Europa would be to launch from Earth direct to Europa and perform an orbit insertion at Europa. Even with MITEE, the propulsion requirements for Europan orbital insertion would result in spacecraft size that exceeds the payload volume limitations of the Delta III or Atlas IIAS. Therefore, a more practical approach would be to launch direct to Jupiter, insert into the Jovian orbit, and then use the Jovian satellites to pump the spacecraft orbit down using gravitational assists to where the Europan orbit insertion and subsequent landing allows for optimum propulsion requirements.

The proposed baseline schedule has the REE spacecraft launching in December 2009 (for illustration purposes – the actual mission would launch some time after 2010) on a direct trajectory to Jupiter. These trajectories are available every 13 months and results in a flight time of 2 years using MITEE. As the spacecraft approaches Jupiter, a flyby of one of Jupiter's moons, Ganymede, is used to lower the arrival velocity to lower the Jupiter Orbit Insertion (JOI) ΔV. JOI places the spacecraft into a highly elliptic orbit around Jupiter where the Jovian moons are subsequently used to place the spacecraft into another highly elliptic orbit around Europa. The spacecraft then proceeds to execute the landing maneuvers for touchdown on Europa.

The main design factor for the Jovian tour is to minimize the spacecraft Initial Mass in Low Earth Orbit (IMLEO) by minimizing the ΔV or propellant requirement by using as much natural or potential energy in the form of gravitational assists as possible. At the start of the Jovian tour, the REE spacecraft spends only a minimal amount of time in the regions of Jupiter where the radiation environment is severe. As the spacecraft orbit is "pumped" down, the REE spacecraft spends more time in this extreme environment and radiation dose is a design concern. By the end of the tour, the REE spacecraft begins to execute apojove maneuvers in conjunction with Europa flybys to pump the orbit down even further. These maneuvers will last approximately three months, during which the REE spacecraft will receive almost half of its total mission radiation dose.

A driver in the design of many components of the REE spacecraft is the severe Jupiter radiation environment. The design requirement for all spacecraft components is to be able to survive a radiation dose of 4 Mrad behind 100 mils of aluminum. Much time continues to be expended in developing radiation hardened spacecraft electronic components, including avionics and optical equipment. Additional shielding may be needed to protect the components that are not radiation-hardened, if any, and will subsequently increase the REE spacecraft mass through additional propellant requirement for the shielding mass.

The final maneuver places the REE spacecraft into a highly elliptical orbit about Europa where the REE spacecraft subsequently performs an orbital insertion and Europa landing burn. The REE spacecraft on Europa ice sheet is shown in Figure 7.1. A summary of the current estimate for the REE Mission ΔV is provided in Table 7.1. The deterministic ΔV is the total amount of velocity change required for the design mission trajectory. The statistical ΔV is the ΔV required to correct for any errors in navigation of the trajectory, spacecraft state, or execution of burning maneuvers to ensure the REE spacecraft follows the deterministic trajectory as close as possible.

For return to Earth, to minimize the ΔV requirements on the propulsion system, aerobraking at Earth for ballistic re-entry would save considerable propellant for the 25 kg sample return thereby eliminating another complex Earth orbital insertion burn. Therefore, the only major burn required for return to Earth is performed lifting-off from Europa and entering into a direct trajectory to Earth. For the mission design, this necessitates the use of an aeroshield and an aerobraking parachute unit (in the sample return stage), for operation when the aeroshield is discarded after main Earth re-entry. The sample return tank with aeroshield is highlighted in Figure 7.2. The estimated total ΔV necessary (including contingencies) for Earth return is 8.9 km/sec. This direct return trajectory results in an approximate three and one-half year time of flight. The MULIMP trajectory code was used to ΔVs for a range of various mission durations centered about the December 2009 Earth departure opportunity.

A detailed parametric analysis of the entire mission design was completed for the Robotic Europa Explorer (REE) spacecraft. The mission design analysis was focused on framing the envelope for the many parameters and factors that influence the overall spacecraft and mission designs. One goal of the mission design is to use a medium-size booster such as the Delta III to reduce the launch costs. The launch vehicle selection parameter is dictated not by its payload-lifting capability, but by the payload fairing volume of the booster. This is due to the nature of nuclear thermal propulsion (NTP) systems, which utilize low-density hydrogen propellant exclusively. NTP vehicles require five times the tank volume of chemical systems for the same propellant loading, resulting in decreased mass efficiency. Use of slush hydrogen would increase the propellant loading per unit volume of tankage.

The Europa mission considered in this analysis is restricted to starting from LEO only after being placed in a stable orbit by a launch vehicle. This simplifies and eases the safety issues and mitigates political concerns. High propulsive efficiency of the MITEE engine yields the benefits of reduced transit time and a smaller launch vehicle.

The REE Mission falls into the category of lander missions, which require additional propellant, as compared to fly-by or orbital capture missions, for landing on the target planet (10). The MULIMP (11) trajectory code was used to calculate IMLEO for a 2009 Earth departure opportunity. No gravitational assists were employed in this analysis. The spacecraft payload is set to 380 kg for Option A configuration and 430 kg for Option B. Included in the payload is the autonomous submarine vehicle (ASV), the indigenous refueling system, instrumentation and controls, the sample return containment system, and an aeroshield for Earth return re-entry. The mission has a two year outbound direct trajectory with an approximate nine month stay on the surface and culminates with a three year return after departure from Europa with the samples onboard and after indigenous refueling.

Because lander missions must perform multiple burns, they require long-term storage of propellant (12). Since nuclear and solar propellant heating both would act to boil-off this stored propellant, mitigation strategies include tank insulation, use of slush hydrogen, and active refrigeration. The system weight of the MITEE engine is estimated at 350 kg (6). IMLEO optimization studies resulted in a single-stage vehicle configuration with two propellant tanks. The first propellant tank, used for Earth departure, is a disposable lightweight tank of 5% tankage fraction that is jettisoned after the burn is completed. The single stage is powered by 900 sec Isp MITEE-B bi-modal engine with restart capability. The second propellant tank belongs to the REE spacecraft has a 10% tankage fraction, and is used for the Jovian system insertion burn and subsequent landing on Europa. Adding restart capability to the MITEE-B engine, required in increased design margins requirements and decay heat removal capability. This, is effect, would result in lowering the Isp to 900 sec instead of MITEE-B's 1000 sec Isp design parameter value.

The decay heating rate after engine firing is sufficient for core meltdown if cooling flow is not provided. The required cooldown propellant is typically an appreciable fraction of the impulse propellant and does amount to extra propellant loading that adds to the MITEE-B engine system weight. For these reasons, for the two-propellant tank vehicle configuration is chosen where the first stage MITEE engine used for an Earth departure burn consumes the first propellant tank fuel and the empty tank is subsequently jettisoned. This configuration is shown in Figure 7.3. This ensures that the Europa capture/landing propellant tank is full for the interplanetary coast and eliminates the issues of a partially full propellant tank.

The REE mass budget is calculated for two options: Option A, shown in Table 7.2, which is the integral MP/ASV design, and Option B, shown in Table 7.3, which contains the MP and ASV as separate units. Initial Mass in Low Earth Orbit (IMLEO) is calculated to be approximately 3221 kg for Option A and 3350 kg for Option B and both options are volumetrically small enough to be housed inside the fairing of a Delta III launcher. The Delta III booster is the newest and most powerful version of the Delta family of medium capacity expendable launch vehicles. The Delta III will provide a payload lift capability of 18,400 pounds to low-Earth orbit and 8,400 pounds to geosynchronous transfer orbit. Launch costs are in the $80 - $100 million range.

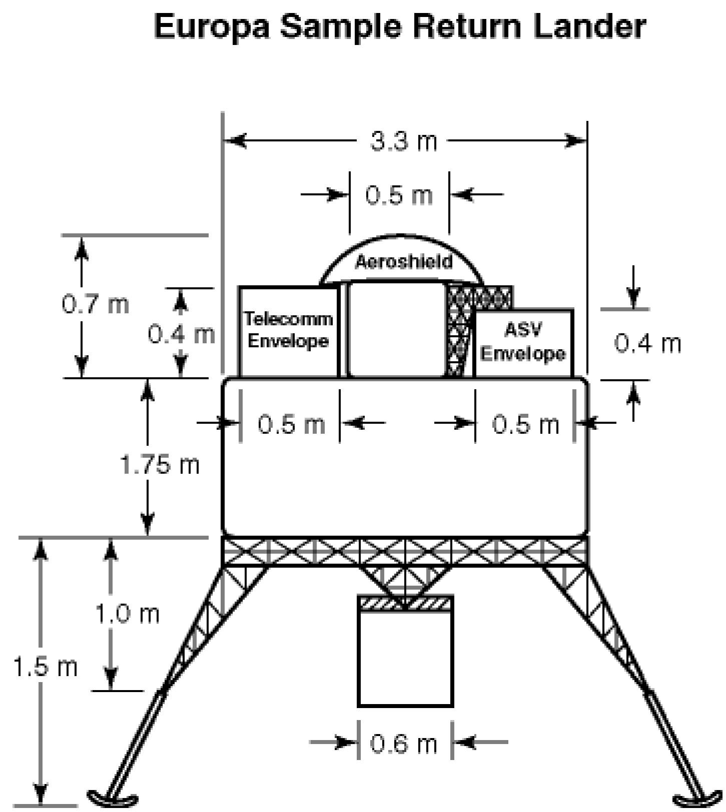


Figure 7.1 REE Spacecraft on Europa Ice Sheet

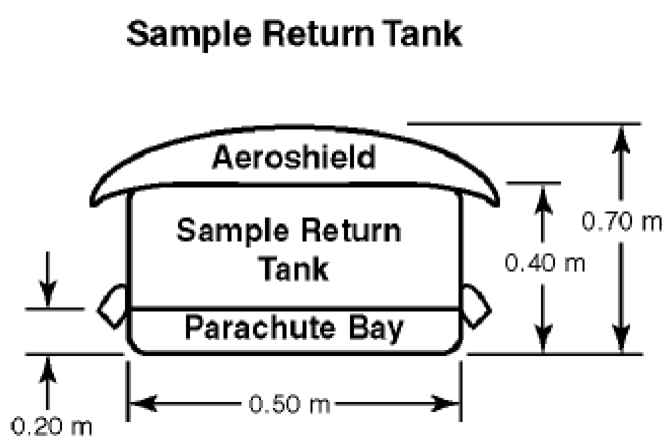


Figure 7.2 Europa Sample Return Tank With Aeroshield

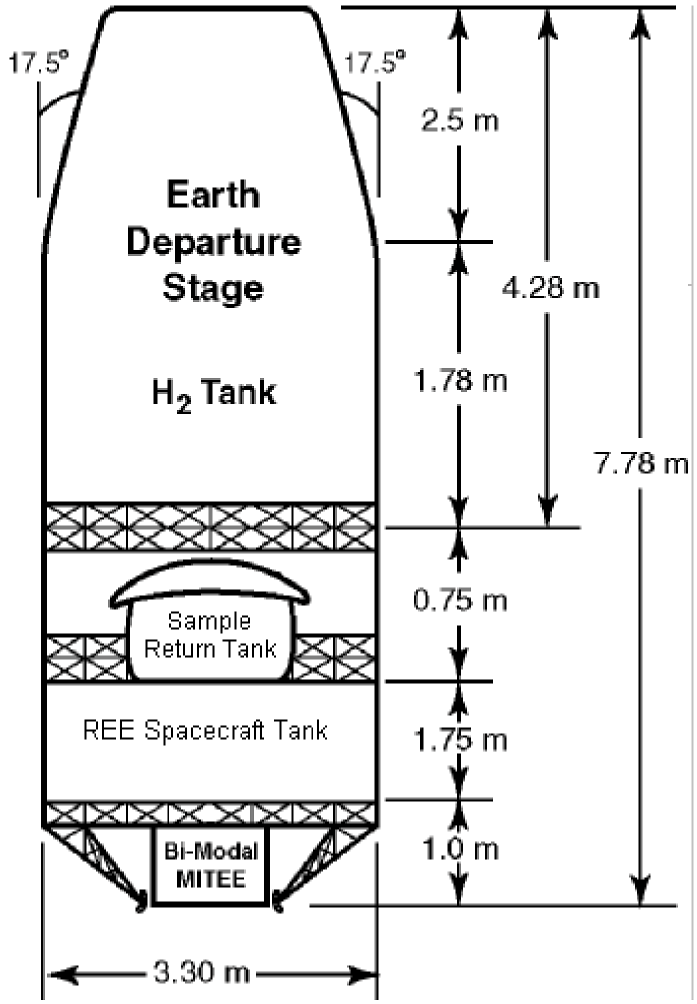


Figure 7.3 REE Spacecraft With Earth Departure Propellant Tank
(Designed to Fit Inside Delta III Fairing)

Table 7.1 REE Mission ΔVs (km/sec)	
Earth Departure:	6.60
Europa Capture/Landing:	5.00
Europa Departure:	8.90
Earth Re-entry:	0.00

MITEE-B Bi-Modal Engine System	350 kg
MITEE-B Engine Shield	50 kg
REE Tank Structure/Insulation	90 kg
MP/ASV Integral Unit	85 kg
MP/ASV Deployment Mechanism	40 kg
Landing Gear	60 kg
Telecommunications	20 kg
Ion Thrusters (Navigation)	20 kg
Sample Return Tank	15 kg
Sample Return Tank Aeroshield	20 kg
Miscellaneous & Contingency	20 kg
REE Total Dry Mass	**770 kg**
Earth Departure ΔV Propellant Loading	1695 kg
Earth Departure Propellant Tank Mass	170 kg
Europa Insertion & Landing ΔV Propellant Loading	586 kg
Cooldown Propellant	3% Tankage Fraction
REE Total Mass (IMLEO)	**3221 kg**

Table 7.2 IMLEO REE mass breakdown for Option A

MITEE-B Bi-Modal Engine System	350 kg
MITEE-B Engine Shield	50 kg
REE Tank Structure/Insulation	90 kg
MP Unit	65 kg
ASV Unit	70 kg
MP/ASV Deployment Mechanism	40 kg
Landing Gear	60 kg
Telecommunications	20 kg
Ion Thrusters (Navigation)	20 kg
Sample Return Tank	15 kg
Sample Return Tank Aeroshield	20 kg
Miscellaneous & Contingency	20 kg
REE Total Dry Mass	**820 kg**
Earth Departure ΔV Propellant Loading	1763 kg
Earth Departure Propellant Tank Mass	141 kg
Europa Insertion & Landing ΔV Propellant Loading	626 kg
Cooldown Propellant	3% Tankage Fraction
REE Total Mass (IMLEO)	**3350 kg**

Table 7.3 IMLEO REE mass breakdown for Option B

8. H_2 Propellant Production Systems Using Melt Water From Europa Ice Sheet

The Europa ice sheet is ideally suited for the production of H_2 propellant for the REE spacecraft because it provides:

1) A simple, easily utilized heat sink for waste heat from the MITEE-B electric power generation cycle.
2) A ready source of melt water for electrolytic production of hydrogen.
3) A very low temperature heat sink for the efficient liquefaction of hydrogen at low energy input.

Figure 8.1 shows the overall flow sheet for the hydrogen propellant production system on Europa. The electric power output of the MITEE-B engine when it is sitting on the surface of Europa is nominally 20 kW(e). Of this, 13 kW(e) is utilized in to electrolyze melt water to H_2 and O_2. The H_2 gas is collected, liquefied, and stored in the REE propellant tank, and the O_2 gas is vented to space.

The electrolyzer uses conventional Solid Polymer Electrolyze (SPE) technology. The H_2 production rate is given by:

$$\frac{dm_{H_2}}{dt} = \frac{P_0 \eta_E M_{H_2}(86{,}400)}{\Delta F_{H_2O}} \quad \text{kg per day} \tag{8.1}$$

where

P_O = Electric power into electrolyzer, kW(e)
η_E = Electrolyzer efficiency, electrical energy to chemical energy
ΔF_{H_2O} = Free energy for the reaction $H_2 + Y_2O_2 \rightarrow H_20$, kJ/kg mole
M_{H_2} = Molecular weight of H_2 (= 2)

Taking P_O = 13 kW(e), η_E = 0.80, and ΔF_{H_2O} = 2.46 x 10^5 kJ/kg mole,

$$\frac{dm_{H_2}}{dt} = \frac{13(0.80)(2)(86{,}400)}{2.46x10^5}$$

which is equal to 7.3 kg of hydrogen per day.

An 80% efficiency for the elctrolyzer appears conservative, and should be readily achievable. The required electrode area is given by

$$A_E = \frac{dm_{H_2}}{dt}\frac{(2C_0)}{J_E} \quad \text{square meters} \tag{8.2}$$

where

C_0 = 96,500 coulombs per gram atom
J_E = current density on the electrodes, A/m^2

The number of gram moles electrolyzed per second, $\frac{d\eta_{H_2}}{dt}$, is given by

$$\frac{d\eta_{H_2}}{dt} = \frac{\frac{dm_{H_2}}{dt}}{M_{H_2}}\left(\frac{1000}{86{,}400}\right) \tag{8.3}$$

The factor 2 in ($2C_0$) arises because there are 2 electrons transferred per molecule of H_2 for a production rate of 7.3 kg per day,

$$\frac{d\eta_{H_2}}{dt} = \frac{7.3}{2}\left(\frac{1000}{86{,}400}\right) \quad = \ 0.042 \text{ gram moles per second}$$

A current density of 10^4 A/m^2 for the SPE electrodes appears conservative; at this current density, the corresponding total electrode area is

$$A_E = 0.042\frac{2 \text{ x } 96{,}500}{10^4} \quad = \ 0.806 \text{ m}^2$$

Electrolyzers are generally built as multiplayer stacks of cells instead of a single cell with a large electrode area. An 80 cell stack, for example, would then have an electrode area of 0.01 m^2 per cell, with dimensions of 10 cm x 10 cm, for example. Optimizing the REE electrolyzer is outside the scope of this study. However, it appears that it will be quite compact and light in weight.

The low temperature of Europa ice sheet, on the order of 70 K, greatly simplifies the liquefaction and refrigeration of the H2 propellant. For a refrigerator operating at a refrigeration temperature T_1, with an ideal Carnot engine carrying heat at T_1 and rejecting it at a higher sink temperature T_2, the reversible work of refrigeration is given by

$$W_{ref} = \frac{\eta_C}{1-\eta_C} \tag{8.4}$$

where the Carnot factor is given by

$$\eta_C = \frac{T_2 - T_1}{T_2} \tag{8.5}$$

Simplifying,

$$\left(W_{ref}\right)^{*} = \frac{T_2 - T_1}{T_2} \tag{8.6}$$

This represents watts of ideal work per watt of heat input at T = T_1

On Earth, to refrigerate liquid H_2 at its normal boiling point of T_1 = 20 K, with an ambient heat sink temperature of 300 K,

$$\left(W_{ref}\right)^{*}_{Earth} = \frac{14 watts(e)}{watt(th)} \quad \text{at 20 K}$$

On Europa, the ideal refrigeration power at 20 K is much less since the heat sink temperature of the ice sheet is much lower, i.e., T_2 ~ 70 K, making

$$\left(W_{ref}\right)^{*}_{Europa} = \frac{2.5 watts(e)}{watt(th)} \quad \text{at 20 K}$$

Actual refrigerators are substantially lees efficient than an ideal Carnot engine for the type of refrigeration system required for the H_2 propellant production and storage an actual refrigerator will require on the order of 5 times the ideal Carnot work, making

$$\left(W_{ref}\right)^{Actual}_{Europa} = (5)\frac{2.5 watts(e)}{watt(th)} \quad \text{or 12.5 watts(e) per watt(th)}$$

The actual electric power to liquefy the H_2 propellant at 20 K is then

$$P_{ref}(e) = W_{ref}{}^{Actual}{}_{Europa} \frac{d\eta_{H_2}}{dt} \lambda_{H_2} \quad \text{watts} \tag{8.7}$$

where

λ_{H_2} = Heat of vaporization of liquid H_2 at 20 K
= 886 Joules per gram mole

For the H_2 production rate of $\frac{d\eta_{H_2}}{dt}$ = 0.042 gram moles per second, the refrigeration power is then

$P_{ref}(e) = (12.5)(0.042)\lambda_{H_2}$
= 460 watts

Additional refrigeration power is required to cool the incoming H_2 gas from 70 K down to 20 K. The enthalpy change per gram mole of H_2 gas is

$$\Delta H_{70K \rightarrow 20K} = (C_p)_{H_2} \Delta T \qquad (8.8)$$

where

$(C_p)_{H_2}$ = Specific heat capacity of H_2 gas
= 7/2 R
= 29.3 J/gram mole K

The enthalpy thermal power is then

$$P_{enth}(th) = \frac{d\eta_{H_2}}{dt}(C_P)_{H_2} \Delta T \quad = 0.042 \text{ x } 29.3 \text{ x } (70 - 20) \ = \ 61.5 \text{ watts(th)} \qquad (8.9)$$

The refrigeration factor to cool the H_2 gas will be less than 12.5 watts(e) per watt(th), since the average temperature of the H_2 gas as it is being cooled down is well above 20 K. However, to be conservative, the same refrigeration factor will be used. The electric power to refrigerate the H_2 gas is then

$$(P_{ref})_{Total} = (W^{Actual}{}_{ref}) P_{enth}(th) \ = \ 12.5 \text{ x } 61.5 \ = \ 770 \text{ watts} \qquad (8.10)$$

The total refrigeration electric power is then

$$(P_{ref})_{Total} = P_{ref}(e) + P_{enth}(e) \ = \ 460 \ + \ 770 \ = \ 1230 \text{ watts} \qquad (8.11)$$

Adding in controls and refrigeration of the propellant tank, the total power for the refrigeration portion of the H2 propellant production system is taken as

$$(P_{ref})^{System}{}_{Total} = 2000 watts(e)$$

Accordingly, as illustrated in Figure 8.1, of the total 20 kW(e) provided by the MITEE-B engine, 13 kW(e) goes to the H_2 gas production system by electrolysis of melt water and 2 kW(e) to liquefaction and refrigeration of the H_2 propellant. The remaining 5 kW(e) is used for a variety of tasks, including communication with the melt probe/ASV unit, transmission to Earth, spacecraft and power system controls, etc.

As discussed earlier, the H_2 electrolysis unit would use existing SPE technology. A simple compressor/expander unit, either a turbine or piston device, would be used to liquefy the H_2 propellant. The H_2 would be compressed to 180 psi (since the electrolyzer would be pressurized, the H_2 input from the electrolyzer would not require the full range of compression) cooled to 33

K in a recuperative heat exchanger by the returning H_2 gas from the expander, and then expanded by the turbine or piston portion of the compression/expansion cycle. At the end point (1 atm pressure) of the expansion phase, 35% of the H_2 stream would be in liquid form. This would be collected and transferred to the H_2 propellant storage tank. The non-condensed H_2 gas would then return to the intake of the compression device, where it would be recompressed to 180 psi. The returning cold H_2 gas would cool the compressed gas down to 33 K. A combined compressor/expander efficiency of 70% is assumed.

The MITEE-B nuclear engine is designed to generate 1 kW(e) of continuous electric power in space, and 20 kW(e) of electric power when on the surface of Europa. The waste heat from the 1 kW(e) power generation cycle is radiated to space during in-space operation using a small, lightweight thermal radiator. When on the surface of Europa, however, the waste heat from the 20 kW(e) power generation cycle is rejected to the Europa ice sheet, rather than being radiated to space. This minimizes the size and weight of the waste heat rejection system while operating in the 20 kW(e) generating mode.

The waste heat rejection unit for operation on Europa is illustrated in Figure 8.2. It is similar in construction to the space radiator shown in Figure 6.5.3, except that the waste heat would be transferred to a pool of melt water formed in the Europa ice sheet rather radiated to space. Steam from the turbine exhaust would be distributed by an input heater to a set of flat aluminum strips inside of which were multiple small channels through which the steam would flow and condensed to liquid water as heat was transferred to the surrounding pool of melt water from the ice sheet.

The liquid water exiting the outlet ends of the flat strips would flow into and be collected by an outlet header, which would return it to the power generation unit where it would be pumped up to the appropriate pressure, turned back to steam, and sent to the turbine inlet.

The waste heat rejection unit would be configured as a flexible coil of the flat beryllium strips and headers. While in space it would be coiled up in a compact roll. After landing on the Europa ice sheet, the coil would be lowered from the spacecraft and unrolled to form a flat panel on the surface of the ice sheet. A variety of possible mechanisms could be used to unroll the waste heat unit, including a memory-shape metal to tension the panel (the shape is controlled by the temperature of the memory metal), a pressurized pneumatic structure to form the backbone of the panel, a mechanical, extendable structure, etc.

When the exploration of the particular site on the ice sheet was complete, the waste heat rejection unit would be rolled back into its normal coil shape, lifted off the ice sheet surface, and reattached to the spacecraft. The REE spacecraft would then hop to a new site on Europa, and repeat the process of deploying the waste heat unit.

The total surface area required to reject the ~ 80 kW(th) waste heat load from the 20 kW(e) power generation cycle is relatively small. A panel having a projected area 1 m^2 (2 m^2 counting both sides) that rejected heat at a flux of 4 watts per square centimeter, for example, could handle 80 kW(th) of reject waste heat. Since the temperature difference between the condensing steam and melt pool water would be large, on the order of 100° C, the 4 watts per square meter is quite conservative. Considerably higher heat fluxes are normally found in conventional heat exchangers.

A 2 meter long, 0.5 meter wide heat rejection panel thus appears sufficient to reject the 80 kW(th) of waste heat. The space waste heat radiator has a unit weight of 2 kg/m2. the unit weight of the surface waste heat unit will be greater, because of its requirement to uncoil, deploy, and recoil the unit. A total weight of 6 kg, 3 times the unit weight of the space radiator, is estimated for the surface waste heat unit.

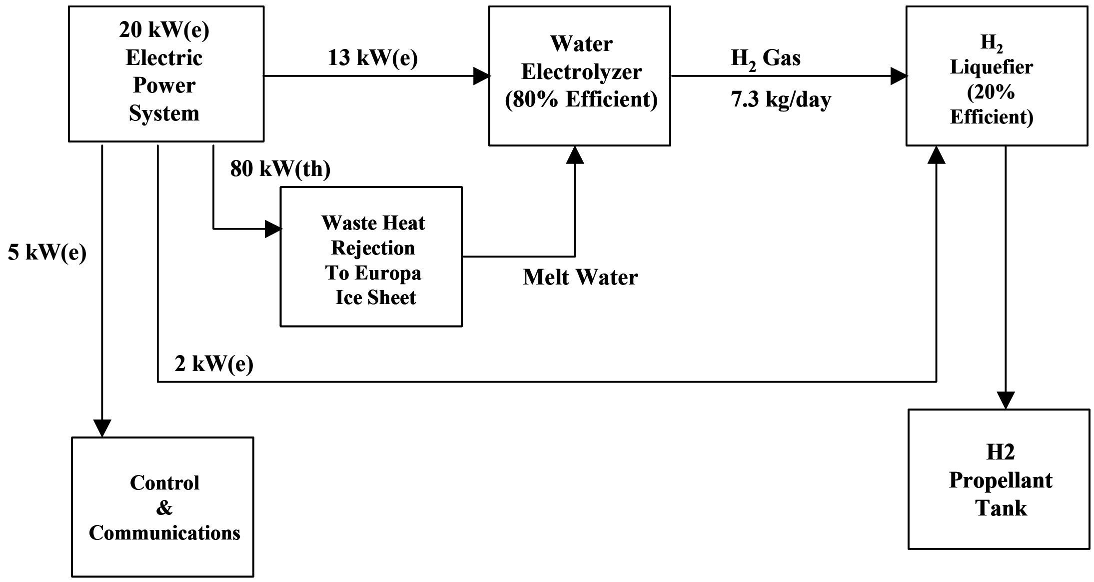


Figure 8.1 Overall Flow Sheet for H_2 Production

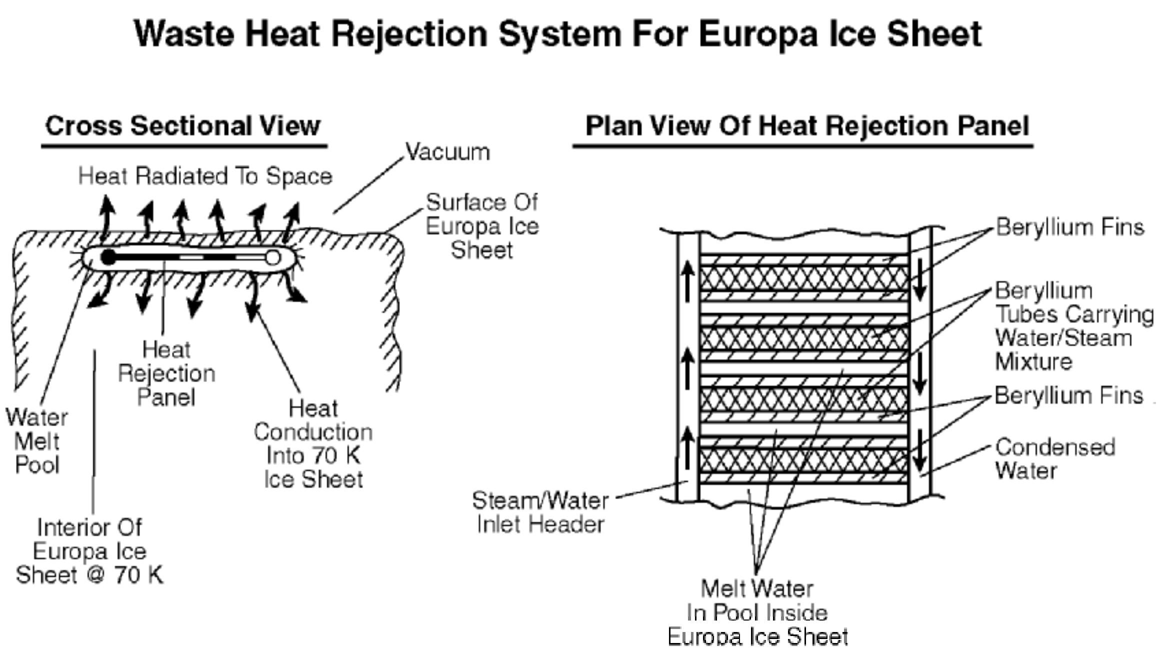


Figure 8.2 Waste Heat Rejection System For Europa Ice Sheet

9. Hop Capabilities of the REE Spacecraft on Europa

When performing hops on Europa, the REE spacecraft essentially travels in a force-free, two-body elliptical trajectory whose perigee happens to be below the surface of Europa. The REE spacecraft poses the interesting problem of traveling from one point on an ellipse to a second point that is moving with respect to the first due to the rotation of Europa. Although the number of possible trajectories is theoretically unlimited, the choice is restricted by the available energy at the first point, the burnout point, where the engines of the REE spacecraft are shut down. The REE spacecraft enters the Keplerian orbit at the burnout point and the specific trajectory is determined by the energy and the elevation angle at that point. The motion of the second point, which is the target, requires consideration of the time of flight in the selection of a trajectory and introduces the need to calculate the lead angle that is associated with a moving target. The REE spacecraft must be aimed at the hop target point.

For this first-order analysis of the hop range calculations, Europa is assumed to be spherical and homogeneous; the effects of oblateness on the trajectory and the target motion are very complicated. Furthermore, Europa is assumed to be nonrotating, so that the effects of changes in the burnout energy and burnout parameters on the range and time of flight are not compromised by consideration of target motion. It is possible to obtain closed-form expressions relating the trajectory to the burnout parameters. If Europa is allowed to rotate in the analysis, the realistic problems associated with the interaction between the target motion and time of flight and the range is such that closed-form expressions and solutions are no longer possible. Although iterative (or graphical) techniques are required for a complete solution, qualitative insight into this interaction can be given with respect to the trajectories.

There are three phases to the trajectory of the REE spacecraft: the boost phase, the Keplerian flight portion, and the landing phase. The boost phase starts with a launch burn on the surface and terminates when the propulsion system shuts down at the burnout point after launch, leaving the payload with a specific position and velocity. The Keplerian phase is the portion of an ellipse with its primary focus at the center of Europa, whose characteristics are determined by the burnout conditions; it starts at burnout and ends at reentry where a second burn initiates the landing sequence.

The total range of the REE spacecraft, the distance traveled over the surface of Europa from the launch site to the target, has three constituents, corresponding to each of the trajectory phases. R_{bp} is the range covered during the boost phase, R_{ff} is the range of the free-flight trajectory, and R_{re} is the range covered during landing. With the assumption of a spherical Europa, each of these ranges is the product of the radius of Europa and the angle between the position vector at the beginning and end of the appropriate phase. For example, if ψ is the angle in radians swept out by radius r_E in going from the burnout point to the reentry point,

$$R_{ff} = r_E \Psi$$

where ψ is the free-fall range angle.

Since the analysis for an asymmetrical trajectory is more complicated and does not provide additional insight into the characteristics and behavior of the REE spacecraft trajectories, the free-fall phase and range will be assumed to start at the burnout point and end at a mirror point on the other side of the major axis, at a point where $r_E = r_{bo}$, $V_{re} = V_{bo}$, and $\varphi_{re} = \varphi_{bo}$. The geometry of the hopping trajectory is shown in Figure 9.1 with ψ symmetrical about the major axis and with Γ as the powered boost range angle and Ω as the reentry landing range angle. Consequently, the total range angle Λ is:

$$\Lambda = \Gamma + \psi + \Omega$$

And the total range R_T is:

$$R_T = r_E \Lambda = R_p + R_{ff} + R_{re}$$

Since the sum of R_p and R_{re} is on the order of 5% of the total range, they will be neglected and the total range will be approximated by the free-fall range alone:

$$R_T = R_{ff} = r_E \Psi$$

The center of Europa is the origin of a central force field and is located at the primary focus of the ellipse. The free-fall trajectory is symmetrical and elliptical and traces a great circle arc on the surface of Europa. The range equation, which defines Ψ, the free-fall angle, as a function of the burnout conditions can be developed algebraically or geometrically. The algebraic development is based on the solution of the two-body polar equation, which is:

$$r = \frac{p}{1 + \varepsilon \cos \nu}$$

where

$$p = \frac{H^2}{\mu_E} \quad \text{and} \quad \varepsilon = \sqrt{1 + \frac{2EH^2}{\mu^2}}$$

The true anomaly in the above equation is replaced by an auxiliary angle O, which is measured from apogee rather than perigee and results in:

$$\theta = \nu + \pi \quad \text{and} \quad \Psi = \theta_{re} - \theta_{bo} = -2\theta_{bo}$$

Without further going through the details of the algebraic development, the resulting range equation is written as:

$$\cot\frac{\Psi}{2} = \frac{2}{Q_{bo}} \csc 2\phi_{bo} - \cot\phi_{bo}$$

where

$$Q_{bo} = \frac{V_{bo}^2 r_{bo}}{\mu} = \frac{V^2{}_{bo}}{V^2{}_{cs}}$$

and V_{cs} is the circular orbital velocity.

The geometric development of the range equation, which results in a different equation form, is based on the geometry shown in Figure 9.2, which shows a suborbital elliptical trajectory where one definition of an ellipse is:

$$2a = r_{bo} + r'$$

After manipulation with other vis-viva integral and other geometric equations, a second range equation is found:

$$\cos\frac{\Psi}{2} = \frac{1 - Q_{bo}\cos^2\phi_{bo}}{\sqrt{1 + Q_{bo}(Q_{bo} - 2)\cos^2\phi_{bo}}}$$

Although the range equations provide the range for a given set of burnout conditions, a more realistic problem is to know the range (the launch and target positions) and to find the burnout conditions. Since V_{bo} and h_{bo} are dependent on the configuration of the booster and the powered trajectory and are relatively restricted to their values, the burnout elevation angle ϕ_{bo} is the easiest burnout condition to control. Consequently, it would be convenient to have an expression for ϕ_{bo} in terms of the range angle Ψ and Q_{bo}, since Q_{bo} is independent of ϕ_{bo}. Referring to Figure 9.3 and continuing with a trigonometric approach, the following equation becomes a function of Q_{bo} and Ψ only:

$$\sin(2\phi_{bo} + \frac{\Psi}{2}) = \frac{2 - Q_{bo}}{Q_{bo}}\sin\frac{\Psi}{2}$$

To develop equations for the suborbital eccentricity ε in terms of Q_{bo}, ϕ_{bo}, or range angle Ψ, the following equation is arrived at with some more manipulation:

$$\varepsilon = \frac{\sin\phi_{bo}}{\sin(\phi_{bo} + \frac{\Psi}{2})}$$

and

$$\varepsilon = \sqrt{1 + Q_{bo}(Q_{bo} - 2)\cos^2\phi_{bo}}$$

The equation for semi-major axis is:

$$a = \frac{r_{bo}}{2 - Q_{bo}}$$

The burnout eccentric anomaly is:

$$u_{bo} = \cos^{-1} \frac{\varepsilon - \cos(\psi / 2)}{1 - \varepsilon \cos(\Psi / 2)}$$

The time of flight equation as a function of ε, u_{bo}, and a is:

$$TOF = 2\sqrt{\frac{a^3}{\mu}}(\pi - u_{bo} + \varepsilon \sin u_{bo})$$

Table 9.1 contains the data for Figure 9.4 and indicates that there is an elevation angle that maximizes the range for a particular V_{bo} or Q_{bo}.

The optimum burnout angle is:

$$\phi_{bo,optimum} = \frac{\pi - \Psi}{4}$$

The minimum burnout energy Q_{bo} for a specified range angle is:

$$Q_{bo,optimum} = \frac{2\sin(\Psi / 2)}{1 + \sin(\Psi / 2)}$$

The maximum range angle for a given Q_{bo} is:

$$\sin \frac{\Psi_{\max}}{2} = \frac{Q_{bo}}{2 - Q_{bo}}$$

These equations establish the relationships required to maximize the range for a given Q_{bo} or to minimize Q_{bo} for a given range. With Q_{bo}, the maximum range or minimum energy equations can be expressed in terms of the appropriate combinations of V_{bo} and ϕ_{bo}.

The design point parameters selected for the REE spacecraft hops on Europa are V_{bo} of 1.2 km/sec with an elevation angle, ϕ_{bo}, of 30 degrees. This results in a total ΔV of 2.4 km/sec for each hop on Europa. The corresponding range based on these parameter values is ~1800 km with the time of flight being ~50 minutes. The propellant mass required for each hop is ~250 kg with a 10% contingency.

The REE spacecraft trajectory is a trajectory in an inertial reference frame that has its origin at the center of a non-rotating Europa. The burnout velocity is measured with respect to the center of the Earth and not its surface. Since the launch and target points are located on the surface of a rotating Europa, they also have velocities with respect to the center of Europa. It is this motion that modifies the trajectory and introduces the need for a lead angle. The range angle is no longer a constant function of the initial locations of the launcher and target. The range angle is a function of the time of flight. To compensate for the target motion, the burnout elevation and azimuth angles must be adjusted to provide the appropriate lead angle. The burnout velocity V_{bo} and altitude are unaffected. The solution of the rotating Europa range problem can be found using graphical and iterative techniques.

The sensitivity of the range of the REE spacecraft to minor changes in the burnout conditions emphasizes the importance of the guidance and control systems, which have the tasks of trajectory corrections in the presence of perturbations. One objective of the guidance and control system is to reach the predetermined burnout point by following a specified boost trajectory. If the REE spacecraft wanders off this course for any reason, the system returns it to the trajectory and attempts to make the actual and design burnout points match. Another objective of the guidance and control system can be to compute a new burnout point and subsequent velocity vector. The system then subtracts the current velocity vector from the old one and strives to make this delta vector zero. Once this new computed delta velocity vector becomes zero, the dynamically-computed burnout point has been reached and the propulsion system shuts down.

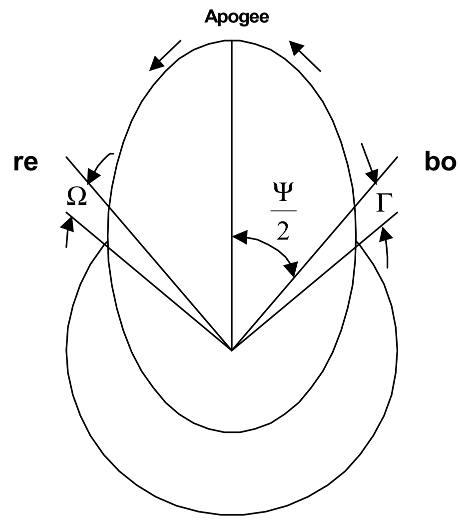


Figure 9.1 Geometry of REE spacecraft hop trajectory

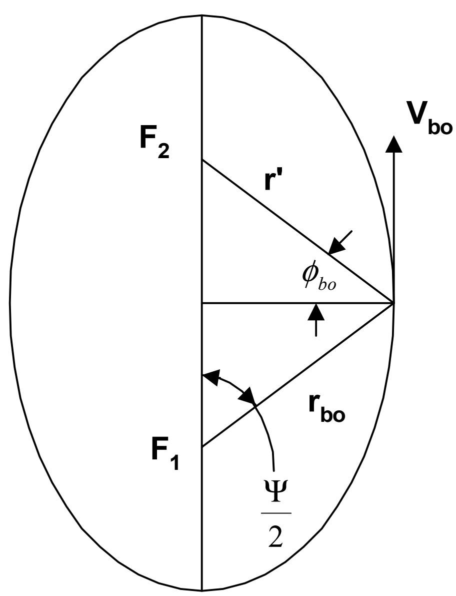


Figure 9.2 Geometry for REE hop range angle

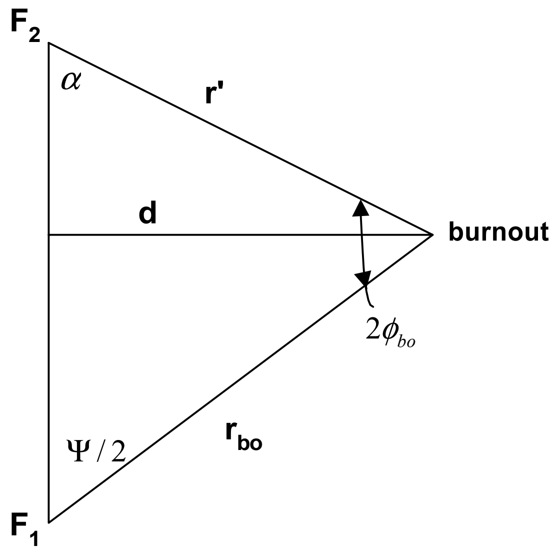


Figure 9.3 Geometry REE hop burnout elevation angle

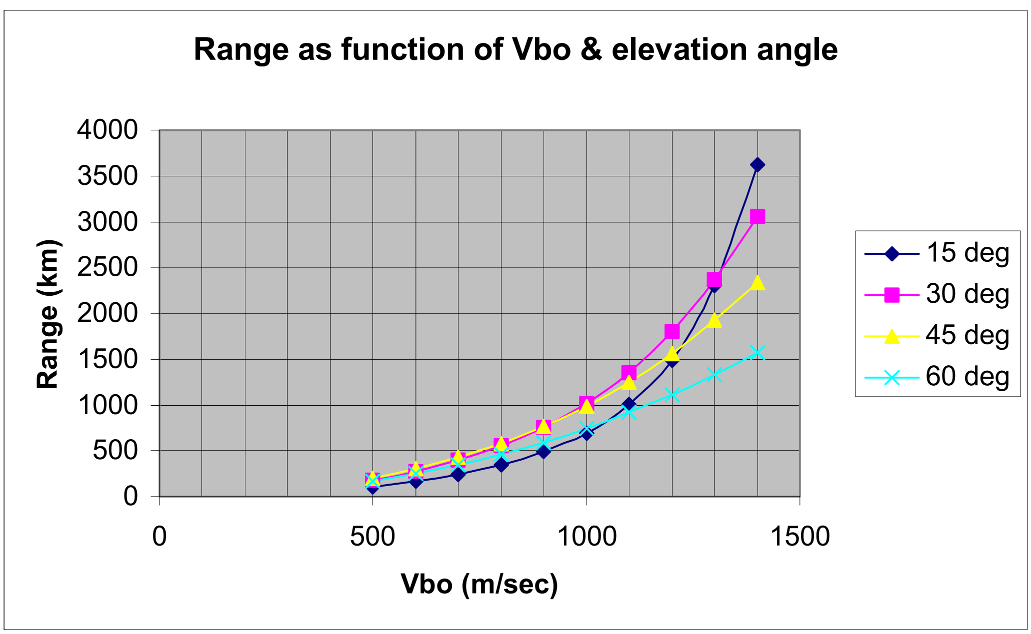


Figure 9.4 Range as function of V_{bo} and ϕ_{bo}

		Range (km) for Burnout Angle (deg)			
Vbo	**Qbo**	**15**	**30**	**45**	**60**
500	0.1223	108	183	204	171
600	0.1761	165	275	302	250
700	0.2396	242	395	425	345
800	0.313	346	550	576	458
900	0.3961	489	751	760	591
1000	0.4891	694	1013	983	743
1100	0.5917	1002	1355	1249	917
1200	0.7042	1489	1802	1563	1113
1300	0.8264	2305	2371	1926	1330
1400	0.9585	3627	3062	2336	1569

Table 9.1 Range vs. V_{bo} and ϕ_{bo}

10. REE Capabilities for Data Acquisition and Transmission of Scientific Data

10.1 Data Acquisition and Communication Equipment Carried By Melt Probe/ASV Unit

The melt probe/ASV unit would carry a suite of instrumentation and communication equipment to acquire and transmit scientific data gathered during the unit's descent through the ice sheet sub-surface ocean exploration and ascent phases. This equipment would also enable the unit to transmit the data to the REE spacecraft in real-time, which would in turn transmit it back to Earth. The two-way communication channel would also enable Earth to transmit updated instructions to the melt probe and the ASV, though there would be a time delay of approximately one hour, due to the finite speed of light.

In addition to having different operational functions, the individual melt probe and ASV units would also have different scientific objectives, requiring different kinds of instrumentation. The melt probe would thus have its own suite of scientific instrumentation that was different and distinct from that on the ASV. The melt probe would carry the following instrumentation and equipment:

1) SIS-MP (Scientific Instrumentation Suite for Melt Probe.)
2) COM-MP/REES (Communication Equipment to generate two-way transmission signals between Melt Probe and REE spacecraft on the Surface of Europa.)
3) CR/TL (Communication Receiver and Transmitter Locator that generates two-way signals between melt probe and the ASV, when it is operating in a mobile mode in the sub-surface ocean. The CR/TL also serves as a locator for the mobile ASV.)
4) CR/TL Cable (CR/TL Cable is a Kevlar cable with an internal fiber optic that carries signals between the melt probe and the REE spacecraft, and two-way signals between the melt probe and the CR/TL unit.)
5) GC-MP (Guidance and Control System for melt probe during its ascent and descent phases.)

The SIS-MP instrumentation is described in section 10.3, and CR/TL and CR/TL cable in section 10.2. The COM-MP/REES equipment would be conventional laser fiber optic equipment.

The GC-MP equipment would control the operation of the nuclear reactor on the melt probe, including power level, outlet water temperature and the water flow rate through the various jets positioned on the unit. The GC-MP unit would also measure the diameter of the melt channel during the descent and ascent phases, the temperature of the water in the melt channel at various locations, the angle of descent, the geometric shape of the melt channel relative to the desired circular shape, and maintain the melt probe/ASV unit at its central position in the channel. In addition, the GC-MP equipment would maintain the MP/ASV in an overall net slightly negative buoyancy condition during the descent and slightly positive buoyancy during the ascent phases. The ASV unit would have a small negative buoyancy, with the melt probe having a small positive buoyancy. The net buoyancy of the whole unit would be slightly negative. Having the two components, i.e., the melt probe and the ASV, with opposing buoyancies would ensure that the separation between them was always maintained at the approximate distance determined by the tensile cable that separated them. The vertical location of the unit in the channel would be determined and maintained by three extendable radial struts from the melt probe that would contact the wall of the melt channel and prevent vertical motion of the melt probe/ASV (MP/ASV) unit.

During the descent phase, the MP/ASV unit would be maintained at a fixed vertical position until the next vertical decrement of the channel had been melted away, e.g., 6 inches or so. The struts would then be slightly retracted, and the unit would slowly sink by the appropriate amount, e.g., 6 inches, and then held in place by a small extension of the struts. Since the net buoyancy of the MP/ASV unit would be small, and the gravity of Europa only 15% that of Earth, the sink rate could be quite small, e.g., inches per minute, and easily controlled. The process would be reversed during the ascent phase, with the MP/ASV unit having small positive buoyancy, heading upwards in small increments, e.g., 6 inches at a time.

The GC-MP equipment appears straightforward and easily developed. It would use conventional temperature measurement devices, e.g., thermocouples and flow meters. It could measure the size and shape of the melt channel using a pulsed laser or sonic device. The neutronic controls also appear straightforward.

The ASV would carry the following instrumentation and equipment:

1) SIS-ASV (Scientific Instrumentation Suite for the Autonomous Submarine Vehicle.)
2) COM-ASV/MP (Communications Equipment to generate two-way transmission signals between the ASV and Melt Probe when the ASV is operating in the mobile phase.)
3) SCES/ASV (Sample Collection and Examination Suite for Autonomous Submarine Vehicle.)
4) GC-ASV (Guidance and Control System for the ASV during its mobile exploration phase.)

The SIS-ASV instrumentation is described in section 10.3, the COM-ASV/MP equipment in section 10.2, and the SCES/ASV system in section 10.4.

The GC-ASV system would guide the exploration path of the ASV, based on instructions transmitted from Earth. It would control the location of the ASV relative to the CR/TL package at the bottom of the descent melt channel in terms of the radial distance from the package, the azimuthal angle relative to a predetermined baseline, and the operating depth of the ASV. As discussed earlier, depending on whether or not the sea bed was within the operational capability of the ASV, it would either explore along the sea bed, keeping a safe distance above it, or conduct a genral search of the desired volume of the sub-surface ocean.

The GC/ASV would maintain the desired buoyancy, either slightly positive or slightly negative, depending on the desired positional changes, as well as the desired attitude, i.e., upwards or downwards moving, and/or left and/or right turning. Determination of location relative to the CR/TL package and entry point into the subsurface ocean would be provided by signals from the CR/TL package, together with a backup gyro system. The GC/ASV system would also operate the nuclear reactor on the ASV, and provide propulsive control by adjusting the outlet temperature of the various steam/water jets at the rear of the ASV.

As with the melt probe, the GC/ASV instruments and equipment appear to be relatively straightforward, and would utilize a well-developed technology base.

10.2 Control and Communication With Melt Probe/ASV Unit

It is useful to describe how the melt probe/ASV unit would be located and guided during its mission. As the unit melts its vertical descent channel through the > 1 kilometer thick ice sheet, it would deploy a small diameter optical fiber encased in a protective cable. The optical fiber would provide two-way real-time communication between the melt probe/ASV unit and the surface spacecraft. The cable would be laid out from a small coil at the rear of the melt probe/ASV unit. A one millimeter diameter Kevlar cable with an internal optical fiber (or fibers) would weigh ~one kilogram per kilometer, and occupy a volume of only one liter. The cable would freeze into the ice sheet a meter or so behind the descending unit, as the melt water was refrozen by the ultra-cold (~ -200° C) ice sheet.

When the melt probe/ASV unit reaches the melt probe would detach to remain at the entry point while the ASV cruised off on its explorations. It, together with its CR/TL (Communication Receiver/Transmitter Locator) package, would be configured to hang on a long cable that dropped into the ocean with the top of the cable anchored at the entry point at of the ice sheet/ocean interface.

The length of the CR/TL cable will depend on the magnitude of the irregularities on the bottom surface of the ice sheet, and how they could limit the line of sight between the CR/TL package and the ASV, since a direct line of sight will be required (this issue also depends on the maximum depth capability of the ASV, since in principle the ASV could dive down for hundreds of meters until it achieved a clear line of sight. A minimal distance of ~100 meters for the CR/TL package below the entry point appears reasonable. This increases the cable weight by only ~ 0.1 kg, as compared to having the CR/TL package directly at the bottom of the ice sheet. The long cable can also be used to position multiple detectors/receivers along it, increasing sensitivity and direction finding capability.

The CR/TL package would use both sonic and laser light transmission to communicate with the ASV, and assist its guidance. The nature of the sub-surface ocean in Europa is uncertain as is direct evidence of its existence, though indirect evidence strongly suggests its presence. The water could be transparent or opaque, saline or fresh, turbid or still, uniform or layered structure, etc. Sonics appears to be the most promising approach for location and guidance at extended distances. With a hydrophone array, the ASV should be able to hear and locate the position of the CR/TL package at distances of at least 10 kilometers so that it could return to “home base”. Similarly, the ASV should be able to sonically communicate with the CR/TL package at the entry point into the ocean. Limited communication would be possible using lasers; however, the ASV would probably have to circle back close to the CR/TL package to communicate. Maximum transmission distances will probably be limited to a few hundred meters at most, and considerably less if there are substantial amounts of suspended solids (the low gravity on Europa will greatly decrease the settling velocity of small solid particles).

Assuming the maximum distance for sonic transmission is ~10 kilometers, The ASV could explore a total volume of:

$$V_{TOT} = \pi \, (10^2) \, H \tag{10.2.1}$$

where H is the maximum depth below the bottom of the ice sheet to which the ASV could go. Taking H as ~ 2 kilometers, the exploration volume would then be ~600 cubic kilometers. A vertical depth of 3 kilometers (2 km below the ice sheet) corresponds to a much smaller hydrostatic pressure on Europa (i.e., ~50 atm) than the same depth in Earth's oceans. This is a result of Europa's gravity being only 15% that of the Earth's. Much greater exploration volumes appear accessible using autonomous guidance to direct the ASV to return to the vicinity of the CR/TL where it would pick up its signals. Alternatively, the return to the location deployable locator beacons could be carried by the ASV which would be attached to the bottom of the ice sheet at appropriate points along its journey. As an example, if the ASV guidance system could find its way back to the CR/TL from a distance of 100 kilometers, the exploration volume would increase to 60,000 cubic kilometers.

The presence of ocean currents (possibly driven by tidal forces) and compensating for their effect on ASV location appears to be the main issue for an autonomous ASV inertial guidance system. If the currents are weak, it should be possible for the ASV to find its way back to a position from which it could locate the CR/TL (i.e., to within 10 km) even if it were hundreds of kilometers distant. If ocean currents are strong, it would probably be necessary to deploy locator beacons a few hundred kilometers apart. These could be retrieved on the way back to avoid having to carry an excessive number on the ASV.

A key feature of the ASV exploration program will be the capability of scientists on Earth to guide the ASV search. While local movement of the ASV has to be autonomous because of time lag considerations, scientists can direct where it will search, i.e., in which direction, the pattern of search, the location, depth range, etc., by communicating through the CR/TL link. Thus if the ASV discovers very interesting results at a particular location, the scientists can examine it in detail, rather than just noting it in passage.

The data acquisition and sample collection/examination packages will probably be located on an extendable strut at the front end of the ASV to minimize radiation exposure levels through shielding by the intervening water. The strut length will be relatively short, on the order of 2 to 3 meters.

At the completion of the exploration period, the ASV would retrun to the melt probe to begin an upwards ascent through the ice sheet to rejoin to the REE spacecraft. The orientation of the melt probe/ASV unit during its ascent phase would be the same as during the descent phase. However, the warm water outlet would be at the top of the unit, instead of the bottom, as was the case for the descent phase. The location of the water intake would also be reversed during its ascent phase, being at the bottom of the unit, rather than the top, which was the case for the descent phase. As the melt probe/ASV unit ascends in the previously prepared descent channel, it will retrieve the optical fiber cable that was deployed during the unit's descent, gathering it up so that it can be redeployed after the REE spacecraft hops to the next site, and a new descent channel is created.

10.3 Scientific Instrumentation Suites for Melt Probe and ASV Units

During the ascent and descent phases of the melt probe/ASV unit, it would be desirable to obtain as much scientific data about the properties and history of the Europa ice sheet as possible. There are many intriguing questions one can ask about the Europa ice sheet, including:

- Does a sub-surface ocean actually exist under the ice sheet and at what depth?
- Is the ice sheet an accumulated heterogeneous agglomerate or is it actively recycled and reconstituted? If it is reconstituted, what is the recycle interval?
- What is the composition of the ice sheet including the composition of trapped gases, dissolved solids, and particulate solids?
- What is the age of the ice sheet as a function of depth?
- Is there any evidence of life forms, either as chemicals, DNA, micro or macro fossils, in the ice sheet?
- Are the mechanical properties of the ice sheet homogeneous or heterogeneous? Are there major variations in local temperature?
- Where did the ice come from? As part of the infant solar system, or later from interstellar space?
- What is the composition, origin, and age of the dust grains and meteoric bodies that have accumulated in the ice sheet during its existence?
- What is the ancient history of cosmic ray activation and solar wind deposition on the ice sheet, including the rate of deposition and composition? What is the ancient history of deposition materials from volcanoes on Io?

The melt probe would carry a suite of instruments to answer these and other questions. These instruments would include among others:

1) Mass spectrometer for elemental and isotopic composition of the ice sheet and its separate constituents.
2) Gas chromatograph for composition and amount of trapped gases in the ice generated by cosmic rays.
3) Gamma-ray spectrometer for measuring types and amounts of residual radioactive species in the ice and its separate constituents.
4) Microfiltration and distillation devices to trap and separate particulate and dissolved solids, including microfossils, and meteoric solids.
5) Visual microscope, SEM, XRD, etc., devices to determine structure and compositions of trapped particles, solids, microfossils, etc.
6) Chemical analysis device to detect the presence and compistion of organic chemicals and DNA.

7) Devices to measure local properties including sound speed, temperature, thermal conductivity, density, compressive strength, pressure, etc.

These measurements would be taken at many locations along the ascent/descent channel, to provide a comprehensive picture of the internal structure of the ice sheet. By carrying out these measurements at many widely separated sites on Europa, the REE spacecraft would be able to determine whether the structure of the Europa ice sheet was heterogeneous or homogeneous.

The ASV will carry out scientific measurements in a quite different environment than the ice sheet. However, to a significant degree, it will address similar questions such as:

- Is there any evidence of life forms in the ocean or on the sea bed, either in living or fossil forms? Is there any associated evidence of organic chemicals or DNA traces?
- What is the composition of the ocean, icluding types and amounts of dissolved solids and gases, and suspended solid particulates?
- What is the topography of the interface between the bottom of the ice sheet and the ocean over a wide area? What is the topography of the sea bed over the same area?
- What are properties of the sub-surface ocean, including density, temperature, pressure, sound speed, etc.? Do the properties vary over a wide area?
- What are the magnitude and direction of the oceanic currents over the explored area? Are there significant tidal currents?
- Are there hydrothermal vents? Oceanic ridges? Subduction zones? Large, high "chimneys" in the bottom of the ice sheet that lead towards the surface?

The ASV would carry a suite of instruments to answer these and other questions. These instruments would include, among others:

1) Microfiltration and distillation devices to trap and separate particulate and dissolved solids, including microfossils, and drilling device to obtain core samples of the sea bed.
2) Visual microscope, SEM, XRD, etc., devices to determine structure and composition of solid particulates, microfossils, sea bed samples, etc.
3) Mass spectrometer for elemental and isotopic composition of the oceanic and sea bed constituents including water, dissolved solids and gases, solid particulates, and microfossils.
4) Gas chromatograph to determine composition and amounts of dissolved gases.
5) Chemical analysis device to detect the presence and composition of organic chemicals and DNA.
6) Gamma-ray spectrometer to measure types and amounts of radioactive species present as dissolved solids and solid particulates, both suspended and in the sea bed.
7) Instruments to measure pressure, temperature, density, sound speed, direction and magnitude of currents in the sub-surface ocean.
8) Thermal imaging device to detect local hot spots in the sea bed.

The suite of instruments would be miniaturized to keep the weight of the REE spacecraft within allowable limits. This probably would require significant technology development for certain components, and weight might dictate the sensitivity and capability of the resultant suite.

10.4 Sample Collection and Examination Suite of the ASV

This is really a more detailed part of the broader ASV instrument suite. Generally, there is not a strong incentive to collect and return to Earth most of the materials examined on Europa. However, there probably will be special materials and objects that would want to return to Earth for more detailed examination. These would include:

- Actual life forms (micro and macro scale).
- Fossils (micro and macro scale).
- Organic chemicals linked to life forms, including DNA traces.
- Meteoric material (micro and macroscopic) collected by the Europa ice sheet.
- Samples of dissolved solids and gases present in the ice sheet and sub-surface ocean.
- Samples of suspended solid particulates in the ice sheet and sub-surface ocean.
- Samples of sea bed sediments.
- Samples of emissions (solid, liquid, and gaseous) from hydrothermal and lava vents.

Assuming an average of one gram per sample, on the order of 30,000 samples covering the above categories could be returned to Earth. This would provide an extremely wide variety of material for scientific study. The above example assumes that any life forms and fossils found on Europa would be small, microscopic, or close to it. If large macroscopic life forms, e.g., much larger than a kilogram, are discovered on Europa, it would be difficult to bring them or their fossils back to Earth.

At an average volumetric density of one gram per cm^3, about 30 liters would be required to hold the 30,000 samples, a practical volume for the ASV, melt probe, and REE spacecraft. If seven sites were explored by REE, one would still have an average of over 4000 samples returned from each site – again an incredibly large number for scientific research.

11. Operational Parameters for Baseline REE and Sample Return Mission

REE Spacecraft Earth Departure Operational Parameters

Earth Departure ΔV (km/sec):	6.60
Europa Capture & Landing ΔV (km/sec):	5.00
Time of Flight to Europa:	2 Years
MITEE-B Electric Power Output During Flight:	1 kW(e)

Option B Baseline Design

MITEE-B Engine Shield:	50 kg
REE Tank Structure/Insulation:	90 kg
MP Unit:	65 kg
ASV Unit:	70 kg
MP/ASV Deployment Mechanism:	40 kg
Landing Gear:	60 kg
Telecommunications:	20 kg
Ion Thrusters (Navigation):	20 kg
Sample Return Tank:	15 kg
Sample Return Tank Aeroshield:	20 kg
Miscellaneous & Contingency:	20 kg
REE Payload Mass:	***470 kg***
MITEE-B Bi-Modal Engine System:	***350 kg***
REE Total Dry Mass:	***820 kg***
Earth Departure ΔV Propellant Loading:	1763 kg
Earth Departure Propellant Tank Mass:	141 kg
Europa Insertion & Landing ΔV Propellant Loading:	626 kg
Cooldown Propellant:	3% Tankage Fraction
REE Total Mass (IMLEO):	***3350 kg***

REE Spacecraft Hop Parameters

Total Number of Hops:	7 to 10
Hop Lift-off ΔV (km/sec):	1.20
Hop Descent Landing ΔV (km/sec):	1.20
Europa Escape Velocity (km/sec):	2.02
Hop Elevation Burnout Angle (degrees):	30
Hop Range Based on Elevation Burnout Angle (km):	1800
Hop Time of Flight (minutes):	50
REE Spacecraft Hop Propellant Loading:	250 kg
MITEE-B Electric Power Output On Europa Surface:	20 kW(e)

REE Spacecraft Europa Departure Operational Parameters

Europa Departure ΔV (km/sec):	8.90
Earth Capture & Re-entry ΔV (km/sec):	0.00 (Ballistic Re-entry)
Time of Flight to Earth:	3.3 Years
MITEE-B Electric Power Output During Flight:	1 kW(e)

Option B Baseline Design

MITEE-B Engine Shield:	50 kg
REE Tank Structure/Insulation:	90 kg
MP Unit:	65 kg
ASV Unit:	70 kg
MP/ASV Deployment Mechanism:	40 kg
Landing Gear:	60 kg
Telecommunications:	20 kg
Ion Thrusters (Navigation):	20 kg
Sample Return Tank:	15 kg
Sample Return Tank Aeroshield:	20 kg
Miscellaneous & Contingency:	20 kg
REE Payload Mass:	***470 kg***
MITEE-B Bi-Modal Engine System:	***350 kg***
REE Total Dry Mass:	***820 kg***
REE Europa Departure ΔV Propellant Loading:	1050 kg

12. Additional Planetary Science Missions Enabled By REE-Type Systems

12.1 Pluto Missions

Pluto, the last planet of our solar system, remains the only planet not yet explored by unmanned spacecraft. Pluto's distance and its elliptical, inclined orbit requires large energy expenditures for successful encounters with this remote planet in a reasonable amount of time. The Jet Propulsion Laboratory (JPL) is currently developing a fast fly-by mission to Pluto and its moon, Charon. The Pluto-Kuiper Express, as previously named, is now tentatively scheduled to be launched in 2006, depending on funding constraints. Pluto's atmosphere, because of its elliptical orbit, is predicted to collapse from its current gaseous state to a liquid state in 2020-2025. This presents an opportunity to observe drastic atmospheric changes on a planetary scale that will not be available again for many years since the orbital period of Pluto is approximately 240 years.

The preferred flight path for a fast Pluto mission is the direct trajectory approach which results in shorter transit times and a relatively benign radiation environment with few maneuvers since there are no gravity assist flybys. However, for flight times under 10 years this requires an expensive Titan IV/Centaur class launch vehicle with an additional upper stage motor. The mission was originally designed to follow a direct trajectory to Pluto and Charon. In order to reduce launch costs, the two spacecraft are now planned to use four gravitational assists, three at Venus and one at Jupiter, to send them to Pluto. Due to the limitations of chemical propulsion systems for fast and low-cost missions, one option the JPL mission is considering consists of two spacecraft, each approximately 100 kg, to be launched on two Molniya or Delta launch vehicles to arrive at Pluto in approximately 12 years. Presently, this mission is being redesigned again due to budget concerns and limitations.

The missions analyzed fall into three categories. The first, category fast fly-by missions, involve only a single burn in LEO and are simple from the standpoint of vehicle configuration. The second category, fast orbital capture missions, require a second burn for orbit capture at the target planet. The third category, lander missions, require additional propellant (as compared to capture missions) for landing on the target planet. The MULIMP trajectory code, as before, was used to calculate ΔV and Initial Mass in Low Earth Orbit (IMLEO) for a range of various mission durations centered about the 2009 Earth departure opportunity, for the three mission categories. No gravitational assists were employed in the analyses.

For the fly-by missions, since there is only a single impulse addition in LEO, the single stage vehicle configuration consists of the MITEE-B engine system, a propellant tank, control avionics, REE spacecraft payload, and contingency. Nuclear thermal propulsion systems have an advantage over chemical propulsion systems because the use of a single propellant simplifies vehicle design. As shown in Table 12.1, a 6-year fast fly-by mission results in an IMLEO of approximately 3300 kg for a 200 kg spacecraft payload. An 11-year Pluto Orbiter and an 11-year Pluto Lander require IMLEOs of 12000 kg and 13900 kg, respectively.

12.2 Solar System Missions

Unmanned exploration of the Solar System has been limited by the large energy requirements of interplanetary trajectories. Current mission strategies involve use of gravitational assists from intermediate planets to assist in achieving these high-energy trajectories with restricted payload sizes. This section describes how an REE-type system removes these limitations and enables unique and scientifically important missions that are not feasible with chemical propulsion systems.

Two classes of Solar System missions are considered. REE-type systems are assumed to be available for flight-ready hardware in the year 2009. Launch opportunities occur during this year for all of the planets. Both mission classes assume LEO start of the engine following an Earth-to-orbit launch of a booster. The first class considered was a high-energy capture mission, similar to the Pluto orbiter mission and the single stage/two-propellant tank vehicle configuration discussed earlier, for the outer giant planets Saturn, Uranus, and Neptune. The payload consists of a 470 kg spacecraft payload. The second class includes the lander/return missions where the vehicle lands on the planet surface, collects sample specimens, refuels indigenously, and then returns to Earth. The spacecraft payload is set again at 470 kg. Titan, one of Saturn's moons and having extensive portions of its atnosphere filled with nitrogen and methane is targeted as for a lander class mission. Similarly, lander missions to Titania, one of Uranus' moons, and Triton, one of Neptune's moons are also analyzed.

Table 12.1 tabulates results for these missions. The IMLEO for a 7-year orbiter mission to Uranus and a 7-year lander mission to Titania are 6750 and 8100 kg, respectively. The IMLEO for a 9-year orbiter mission to Neptune and a 9-year lander mission to Triton are 10100 and 10800 kg, respectively. The 4-year Saturn orbiter mission has an IMLEO of 5300 kg, whereas a 4-year Titan lander mission requires 6400 kg. For comparison, Galileo requires 6 years (14) to reach Jupiter (which includes one Venus and two Earth gravity assists) and the Cassini mission to Saturn (15), as currently planned, requires 7 years to arrive.

An even more exotic mission is the Pluto lander/return sample mission. The outbound flight will take approximately 12 years and is followed by a 30-day stay on the planet for indigenous refueling and sample collecting. The return flight to Earth will also last 12 years with termination of the mission in the year 2033. This results in an IMLEO of 12400 kg as illustrated in Table 12.1.

12.3 Launch Vehicles for Outer Planet Missions

Beginning in 1997, the original Titan IVA was phased out and replaced by the Titan IVB (16) which offers roughly 25% greater performance from new upgraded solid strap-on boosters. The Titan IVB is currently the nation's largest expendable launch vehicle and consists of two solid propellant stage motors, a liquid propellant two-stage core, and a 5 m (16.7 ft) diameter payload fairing. The system can fly with a Centaur upper stage, an Inertial Upper Stage (IUS), or no upper stage. The Titan IV Centaur is capable of placing 6,000 kg (13,000 lb) payloads into GEO, or 22,000 kg (48,000 lb) into low-Earth orbit (LEO). With the high-performance Centaur upper stage the Titan IVB has unmatched capabilities to deliver heavy payloads to high-energy orbits, including injection directly into GEO. Overall length of the launch vehicle is 204 feet when flown with a 26 m (86 ft) long payload fairing. Launch costs are approximately $350-450 million.

In order to meet commercial and government launch service requirements in the next century, Lockheed Martin is developing the Atlas V series of launch vehicles. The Atlas V (16) will use the RD-180 first stage engine and Centaur design from the earlier Atlas III, in conjunction with a new first stage common core booster (CCB). Three basic varieties of the Atlas V will be available. The Atlas V Heavy Launch Vehicle (HLV) is the most powerful variant in the Atlas family, with a payload lift capability in the 8,200 kg (18,000 lb) class range to GTO and 3,750 kg (8,200 lb) to GSO. The Atlas V Heavy uses two additional CCBs like the first stage as liquid strap-on boosters to provide Titan IV class performance. In addition, five strap-on solid rocket motors been added to the booster to increase liftoff thrust and payload lift capability. The Centaur upper stage is powered by a Pratt & Whitney RL10 turbo pump-fed engine that burns liquid oxygen and liquid hydrogen. The length of the launch vehicle large payload fairing is 26 m (86 ft) and the fairing diameter is 5.4 m (18 ft). Launch costs for the Atlas V Heavy are approximately $170 million.

The Delta IV Heavy (16) is a heavy-lift capacity expendable launch vehicle built by Boeing consisting of a Delta IV core vehicle with two additional common booster core stages used as liquid strap-on boosters. The Delta IV Heavy will be the most powerful version of the Delta family of expendable launch vehicles and is slated for operations in 2003. The Delta IV Heavy is capable of placing 26,000 kg (57,000 lb) payloads into LEO. In addition, the large booster can lift 11,000 kg (24,000 lb) to GTO and place 6,100 kg (13,500 lb) in GEO, which is 50% more the payload of the Delta III rocket. Compared to the Delta III, the Delta IV Heavy's most notable changes include a larger composite fairing enlarged from 4 m (13 ft) in diameter to 5.1 m (16.7 ft), larger and a completely new common booster core (CBC) design using the RS-68 engine. The RS-68 is a new, high-performance engine with higher thrust than the Space Shuttle Main Engine (SSME). Two CBCs are added to the Delta IV Heavy to serve as more powerful strap-on liquid boosters, and a new cryogenically propelled single-engine upper stage. Launch costs are approximately $170 million.

The Atlas IIAS (16) is the fourth and most powerful variant in the Atlas family, with a payload lift capability in the 7,000 to 8,000-pound class range to geosynchronous transfer orbit. Four strap-on solid rocket motors been added to the booster to increase liftoff thrust and payload lift capability. The IIAS Centaur upper stage is powered by two Pratt & Whitney RL10 turbo pump-fed engines burning liquid oxygen and liquid hydrogen. The length of the launch vehicle with the large payload fairing is 156 ft. Launch costs are approximately $100 million.

The Delta II (16) is a medium capacity expendable launch vehicle built by McDonnell Douglas that can lift payloads up to 4,120 pounds to geosynchronous transfer orbit. Launch costs are approximately $50 million. The Delta III is the newest version of the Delta family of expendable launch vehicles slated and will provide a payload lift capability of 18,400 pounds to low-Earth orbit and 8,400 pounds to geosynchronous transfer orbit which is twice the payload of the Delta II rocket. Compared to the Delta II, the Delta III's most notable changes include a larger composite fairing enlarged from 9.5 feet in diameter to 13.1 feet, larger and more powerful strap-on solid rocket motors, and a new cryogenically propelled single-engine upper stage.

The Pluto 6-year direct fast-flyby mission can be housed in a single Delta III payload fairing. For comparison, the current Pluto Express was slated to be launched on two Molniya or Delta vehicles scheduled to arrive at Pluto in 12 years after a series of gravitational assists. For the remaining missions discussed earlier a listing of the launch vehicles that can be used include:

- Atlas IIAS or Delta III booster for the 6-year Pluto flyby mission.
- Delta IV Heavy or Titan IV for the 11-year Pluto orbiter and lander missions.
- Delta III booster for the 4-year Saturn orbiter mission.
- Atlas IV launcher for Titan and Titania landers and Uranus orbiter missions.
- Neptune orbiter, Triton lander, and Pluto lander/sample return mission necessitates use of the Delta IV or Titan IV heavy-lift launcher due to the 100 m^3 propellant loading volume required by the spacecraft.

Note this analysis did not utilize gravitational assists of intermediate planets which would reduce the spacecraft IMLEO.

The performance gains described in the mission analyses illustrate the enormous potential of a REE-type system. The above benefits include the substantially reduced launch costs that are achieved through utilization of existing small-to-medium lift boosters, and the large performance increases in mission ΔV. These features will greatly expand our ability to explore the Solar System in both conventional and innovative missions.

Table 12.1

Planetary Science Missions Enabled by REE-Type Systems

MISSION	Delta V (km/sec)	Launch Date/ Trip Time	IMLEO (kg)
Saturn Orbiter	14.81	Nov. 28, 2009 4 Years Outbound	5300 1 Stage/Restart
Titan Lander/ Return Sample	16.10	Nov. 30, 2009 4 Years Outbound 4 Years Return	6400 1 Stage/Restart
Uranus Orbiter	16.61	May 10, 2009 7 Years Outbound	6750 1 Stage/Restart
Titania Lander/ Sample Return	18.04	May 10, 2009 7 Years Outbound 7 Years Return	8100 1 Stage/Restart
Neptune Orbiter	19.60	Apr. 10, 2009 9 Years Outbound	10100 1 Stage/Restart
Triton Lander/ Sample Return	20.02	Apr. 8, 2009 10 Years Outbound 10 Years Return	10800 1 Stage/Restart
Pluto Fly-By	13.93	Feb. 28, 2009 6 Years Outbound	3300 1 Stage/Restart
Pluto Orbiter	20.87	Feb. 14, 2009 11 Years Outbound	12000 1 Stage/Restart
Pluto Lander	21.80	Feb. 14, 2009 11 Years Outbound	13900 1 Stage/Restart
Pluto Lander/ Return Sample	20.95	Feb. 14, 2009 12 Years Outbound 12 Years Return	12400 1 Stage/Restart

13. Technology Development Requirements for REE Mission

Figure 13.1 shows the technology road map for the REE mission. The six systems depicted comprise the principal systems involved in the REE mission. While they are depicted as separate individual systems, there would have to be a great deal of interaction between the various development programs to make sure that the final integrated REE spacecraft functioned properly. For example, the H_2 propellant production option must integrate smoothly and efficiently with the electric power generation system on MITEE-B nuclear engine, as well as the thermal radiator on the REE spacecraft.

The overview shown in Figure 13.1 illustrates the principal operational issues to be resolved in the development of each system, as well as the tests that would be carried out to demonstrate the anticipated performance, and the projected target date when the system would have been fully validated and ready to be implemented.

In general, the operational issues to be resolved relate to performance level and not to basic feasibility. For example, the basic feasibility of cermet tungsten/UO_2 has already been demonstrated. The issues for its use in MITEE-B are what is the mean H_2 outlet temperature it can deliver, taking onto account MITEE-B neutronic power distribution, variations and tolerances in fabricating and positioning the W/UO_2 fuel sheets, neutronic power distributions in the reactor, nozzle variations and wear behavior, operating life and number of operating cycles, etc. Is the appropriate value 3000 K, or more likely, 2750 K? Lower H_2 outlet temperature reduces the effective Isp performance, which in truns affects the Initial Mass in Low Earth Orbit (IMLEO) for the mission, since additional H_2 propellant is needed at lower Isp. It also affects the power level, and/or the length of time the REE spacecraft needs to replenish its H_2 propellant for the next Europa hop, or return trip to Earth.

Figure 13.1 also shows the major tests that will be required to validate the operational readiness of the system. In general, there will be a mix of component tests and system tests. The system tests will, in turn, be a mix of tests powered using electrically heated, non-nuclear analogues of the actual system, and system tests that involve an actual nuclear reactor source. For example, a full-size, full capability melt probe system, using an electrically powered heat source in place of the planned nuclear reactor, could be tested in a deep natural ice sheet on Earth – e.g., Greenland, Alaska, Antartica, etc. – with the nuclear reactor portion tested separately in an existing nuclear facility in the US or Russia. Similarly, the Autonomous Submarine Vehicle (ASV) could be tested in the open ocean on Earth, using an electrically heated power source, with the nuclear reactor portion being tested in an existing nuclear facility.

Figures 13.2, 13.3, 13.4, and 13.5 examine the technology road maps for the MITEE-B nuclear engine, the H_2 propellant production system, the melt probe, and the ASV in greater detail. In the technology road map for the MITEE-B engine, Figure 13.2, extensive testing of the individual components, including the cermet nuclear fuel, the ^{7}LiH moderator, the beryllium pressure tube, the individual nozzles, the closed cycle coolant system, and the mini steam turbine/electric generator would be carried out to determine their performance capabilities and operating limits. Cermet nuclear fuel sheets, for example, would be fabricated with the proper flow holes, tested at high temperatures in flowing H2 propellant, thermally cycled to match the expected MITEE-B operating cycle, and held in vacuum at the appropriate temperature for electric power generation, e.g., months. Appropriate tests on the other MITEE-B components would also be conducted.

Individual full-scale MITEE-B fuel elements would be constructed and tested at actual operating conditions in an existing nuclear facility. This would validate the pressure tube/fuel element MITEE-B design, including the ability to generate the desired H_2 outlet temperature and propellant Isp, the performance of the nozzle and moderator, and so forth. The power level of the fuel element would be in the range of 1 to 2 megawatts thermal, depending on the particular MITEE-B design adopted. Operating with single element tests instead of a fuel reactor that would have a much greater power level would enable the testing costs to be much less, since a new test facility would not be required.

A series of MITEE-B low power critical reactor assemblies would also be built and tested to validate its expected neutronic performance. That is, what are the criticality factor (K_{eff}), what is the control rod worth, moderator temperature coefficient, axial and radial power distribution, as compared to analytical predictions. The intent would be to validate and calibrate the analytic methods. In general, the analytic methods have proved very accurate for similar reactors in the previous DOD/SNTP propulsion program.

The final stage in the MITEE-B development program would be an in-space test of a full-scale MITEE-B engine. Such an in-space test would be considerably cheaper and could be carried out in a shorter time than first performing a ground test of a full up engine, and then performing in-space testing. No testing facility capable of ground testing a full up MITEE engine currently exists. Such a facility would have to be built from scratch at great expense and cost. Furthermore, it would not significantly increase the success probability for the full up MITEE-B engine. Performance capabilities for MITEE-B can be accurately ascertained from tests on single pressure tube/fuel elements.

Finally, even a successful ground test would have to be followed by an in-space test with its own new set of test conditions that could not be duplicated on the ground. If adjustments are needed in the MITEE-B design, it will be faster and cheaper to carry them out with sequential in-space tests than relying on ground testing.

The technology road map for the H_2 propellant production systems (Figure 13.3) is much simpler than for the MITEE-B engine. The electrolyzer would essentially be adapted from already commercialized technology, sized and packaged to fit into the REE spacecraft. The H_2 liquefier would require a bit more development work, principally in the area of the wet expander that produced a mixture of H_2 liquid and gas. Mini-turbines have been used for cryogenic refrigeration systems, and deliver excellent performance. However, it is not clear that a mini-turbine could operate satisfactorily with such a high (~ 35%) liquid fraction in the expansion process. A piston expander probably could, and practical piston expanders have been employed in cryogenic refrigeration systems.

If a mini-turbine approach is not practical, an alternate, very practical approach would be to use an inverse Brayton cycle operating a closed cycle helium coolant to provide refrigeration at 20 K. The 20 K refrigeration would then simply condense the H_2 gas to liquid, which would then be pumped into the storage tank. The helium refrigerator cycle would compress He gas in a small, conventional turbo-compressor at ~ 80 K, reject the heat of compression to the 70 K Europa ice sheet. After cooling to ~ 20 K, (using recuperative heat exchange to the low pressure helium exhaust from the turbo-expander) the high pressure helium would be expanded to low pressure, providing the refrigeration required to condense the H_2 gas.

The remaining component in the H_2 propellant production system is the waste heat exchanger that rejects the 80 kW(th) from the 20 kW(e) power cycleused for H_2 propellant production. This waste heat is transferred from the condensing steam exhaust of the mini-turbine in the 20 kW(e) power cycle through a beryllium heat exchange panel directly to melt water in a pool on the Europa ice sheet. In practice, the melt pool will be an internal pool under the surface of the Europa ice sheet, since surface liquid water would quickly freeze by evaporation to Europa's vacuum, and come to a low temperature determined by the thermal conductivity of ice, the heat flux rate, and the vapor pressure vs temperature change for ice. Underneath this thin frozen surface layer, a liquid melt pool would exist. The size and volume of which would depend on the amount of watse heat rejected to the Europa ice sheet.

The formation of the melt probe would be simple. After the heat exchange panel was deployed on the surface of Europa ice sheet, energizing it with condensing steam would simply result in it sinking into the ice sheet for a few inches to form the melt pool. When it came time to retrieve the heat exchange panel, it would be pulled up against the underside of the thin surface ice layer, causing it to melt. The heat exchange panel is simple and can be readily designed and constructed. The main development task will be constructing it so that it can be easily deployed and retrieved from the environment of the Europa ice sheet. The panel can be easily tested on Earth in a vacuum chamber on an ice surface configured to duplicate the conditions that would be found on Europa, such as temperature.

The technology roadmap for the melt probe (Figure 13.4), while more complex than that for the H_2 propellant production system, is simpler than that for the MITEE-B engine. The anticipated performance of the melt probe, i.e., the ascent and descent rates of the probe, the diameter of the melt channel, the temperature distribution in the melt water and surrounding ice, and the channel freeze rate can be modeled fairly well using existing heat transfer and computational fluid dynamics (CFD) codes. These computational methods would guide the design of the melt probe and predict its performance. Verification of the melt probe design could be carried out using an electronically heated non-nuclear version of the probe with tests of its performance in descending and ascending inside a thick natural ice sheet on Earth, for example, in Greenland or Antartica.

The reactor heat source for the melt probe is based on well known nuclear technology. The reactor would be designed and constructed by an appropriate Department of Energy (DOE) laboratory and tested in an existing facility. The initial tests would be of the reactor itself, i.e., flowrate, temperature, distribution, power output capability, etc. After validation of the reactor design, it would be attached to the proposed melt probe structure and tested in an artificial ice sheet environment at an appropriate facility. The performance of the actual melt probe system utilizing the compact nuclear reactor would be compared with that of the electrically heated analogue in the natural ice sheet. It is anticipated that the performance of the two units would be essentially identical, which would validate the melt probe system for use on Europa. The maximum practical depth of an artificial ice sheet would probably be limited to 40 to 50 feet, which would be sufficient to accurately determine the performance of the nuclear reactor powered unit.

The technology roadmap for the Autonomous Submarine Vehicle (ASV) is shown in Figure 13.5. The ASV involves for principal sub-systems:

1) The ASV structure. This includes the body of the ASV, the propulsion jets, the buoyancy control chamber, the sample collection chamber, and the controls needed to operate these various components.
2) The nuclear reactor heat source and its controls.
3) The sonar link system between the ASV and the melt probe.
4) The gyro/sonar location system that enables the ASV to return to the melt probe for the ascent to the REE spacecraft.

It does not appear likely that open ocean tests of the ASV that had an actual nuclear power source would be permitted on Earth. Accordingly, the ASV would be developed and tested with an electrically heated power source, e.g., batteries or fuel cells, to validate its performance in the open ocean. The nuclear reactor heat source for the ASV would be developed and tested separately. The two sub-systems would be integrated and tested in a combined unit at an existing nuclear facility to validate that the integration process, but the integrated unit would not be operated in the open ocean. Based on the test results of the electrically heated ASV in the open ocean, the integrated ASV with its nuclear reactor heat source in an existing nuclear facility, e.g., in a fuel storage pool – there would be good assurance that the integrated unit would operate satisfactorily in sub-surface oceans on Europa.

The sonar link and gyro/sonar sub-systems would be developed and tested separately and then integrated with the ASV to be tested in the full up unit – first in a tethered condition, and then in the open ocean test. Of particular importance is the distance over which reliable sonar communications could be carried out. The open ocean tests on Earth would establish this distance for Earth-like conditions; between there is no guarantee that conditions in Europa oceans would be like those on Earth in terms of sonar transmission. Accordingly, when the ASV would begin to operate in a sub-surface ocean on Europa, a principal first task will be to establish the distance over which reliable sonar communications could be carried out.

The gyro/sonar location sub-system would be used to help keep the ASV located with respect to the melt probe entry point into the sub-surface ocean, so that it could find its way back.
The gyro capability is very important, since there may be confusing echoes and direction changes in sonar signals in the Europa ocean that would make it difficult to rely exclusively on the apparent direction of sonar signals from the melt probe. The gyro/sonar locator would also be used to map the sub-surface topography of Europa's ocean, e.g., the bumps, holes, and valleys in the underside of the ice sheet, as well as the bumps, valleys, etc., in the sea bed beneath. Sonar and gyro technology for ocean-based applications has been extremely well-developed for various defense, research, and commercial purposes. No major development of new technology is needed for the REE mission – just an adaptation of existing technology.

Development of the scientific instrumentation for the REE mission will involve substantial efforts, which will depend on the relative priorities of the various scientific goals, to what degree of precision the measurements need to be made, and the funding available for development. A detailed specification of the scientific instrumentation for the REE mission, and the consequent development requirements is beyond the scope of this study. Such a specification would be appropriate for the next phase of study for a REE-type mission. At this stage in the concept development, it is sufficient to show that the mission is practical, that the necessary technology can be developed in a reasonable timeframe, and to outline the kinds of and importance of the scientific results that would be obtained. Development of the REE spacecraft should be straightforward. At this point, a more detailed baseline design of the REE spacecraft is needed before its particular development requirements can be specified.

Of the 4 principal sub-systems described here, development of the nuclear propulsion engine would appear to require a longer development time and more funding than the other sub-systems. For the engine, a development period of 10 years and a total funding of approximately $1 billion appears reasonable. Of the remaining 3 sub-systems, the ASV would require a greater time and funding than the other two, i.e., the melt probe and the H_2 propellant production sub-systems. A rough order of magnitude estimate for development would be on the order of a half-billion dollars total for the combination of the three systems.

It is important to keep in mind that there already exists a strong technology base for the various REE systems and that no fundamental breakthroughs are needed. This not only helps to ensure that the development will be successful and timely, but also helps in keeping costs down. Moreover, it is also important to keep in mind that development of the REE-type systems can be used for a wide range of other planetary exploration missions that are now not possible, so that the benefits of development are not limited just to one particular mission.

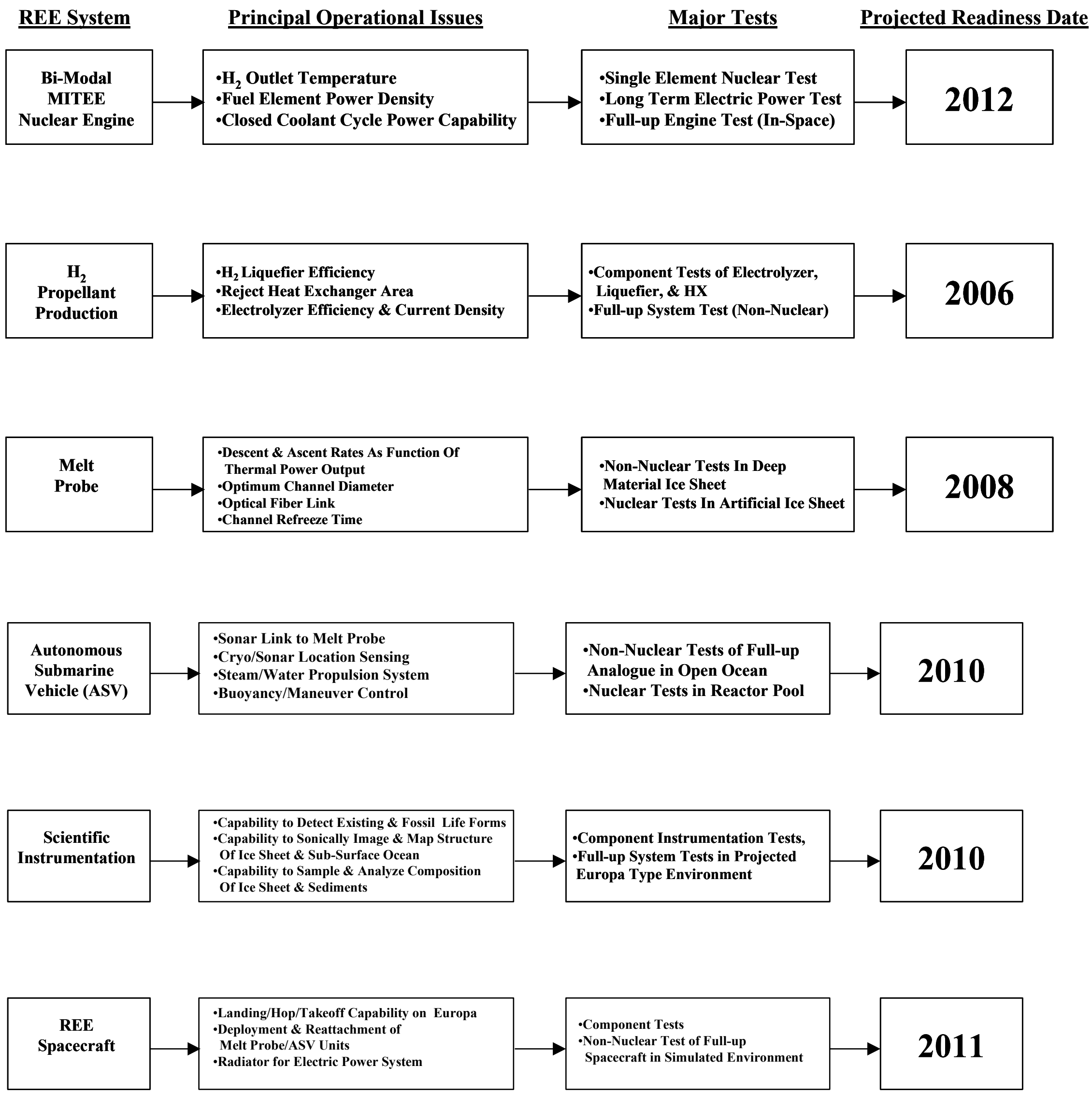


Figure 13.1 Technology Road Map for REE

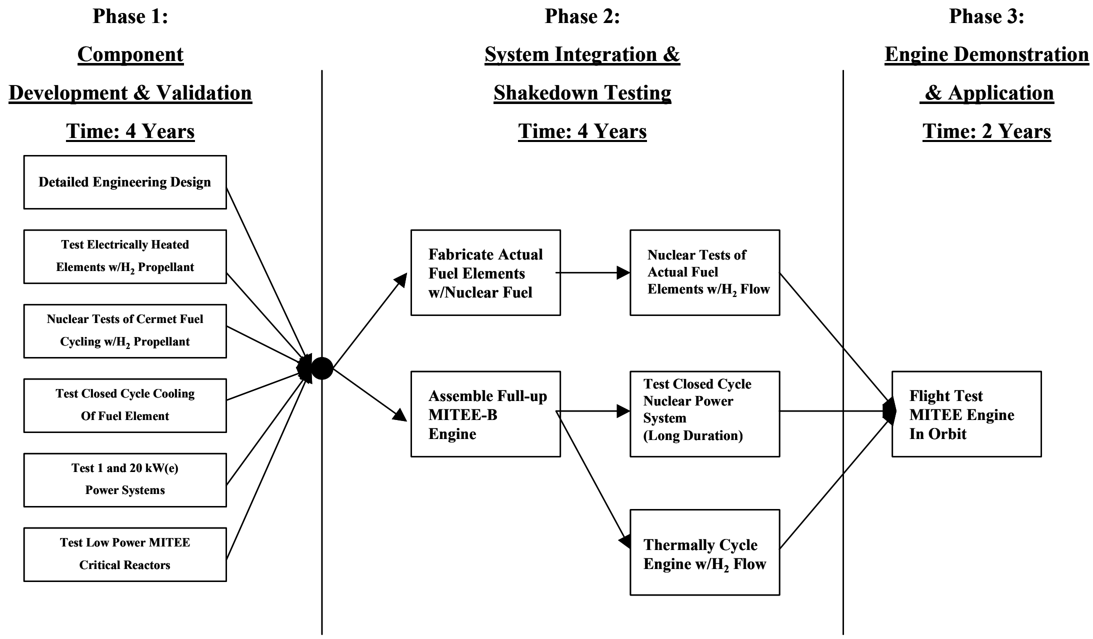


Figure 13.2 Technology Road Map for MITEE-B Engine System

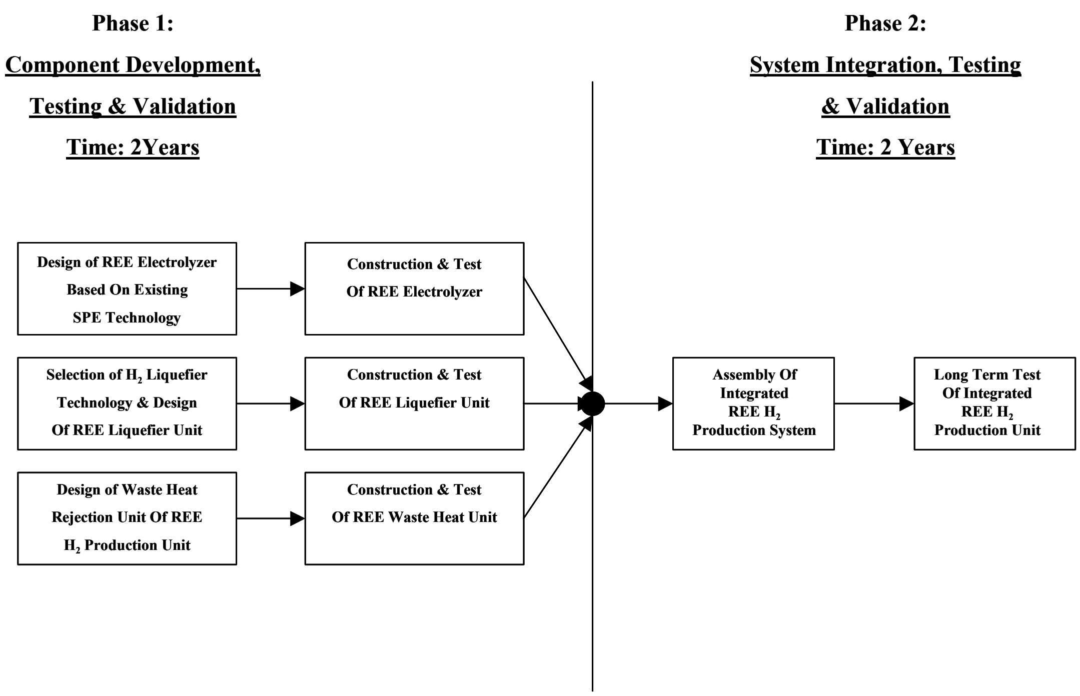


Figure 13.3 Technology Road Map for H_2 Propellant Production System

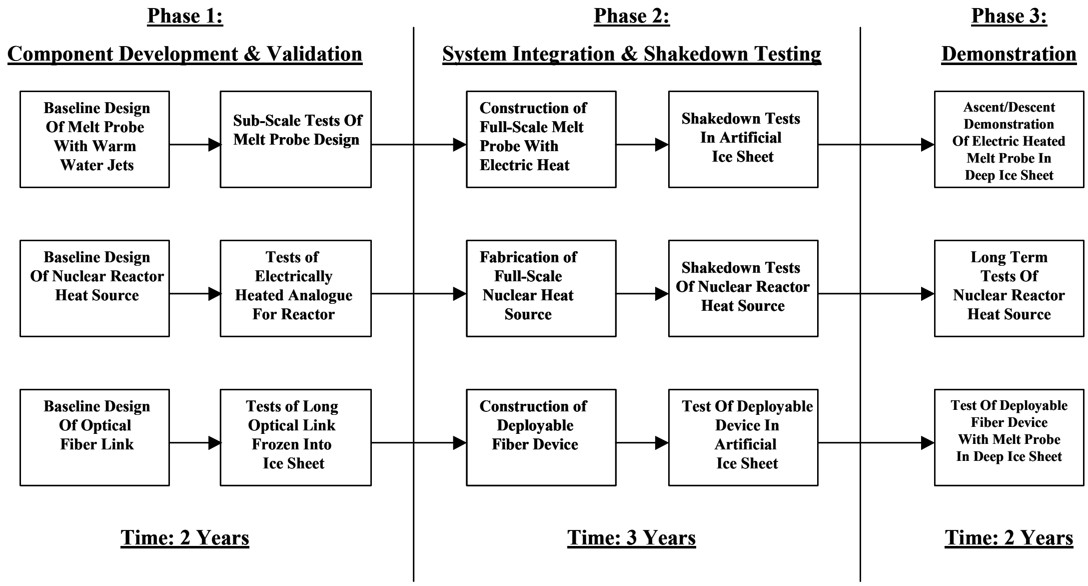


Figure 13.4 Technology Road Map for REE Melt Probe System

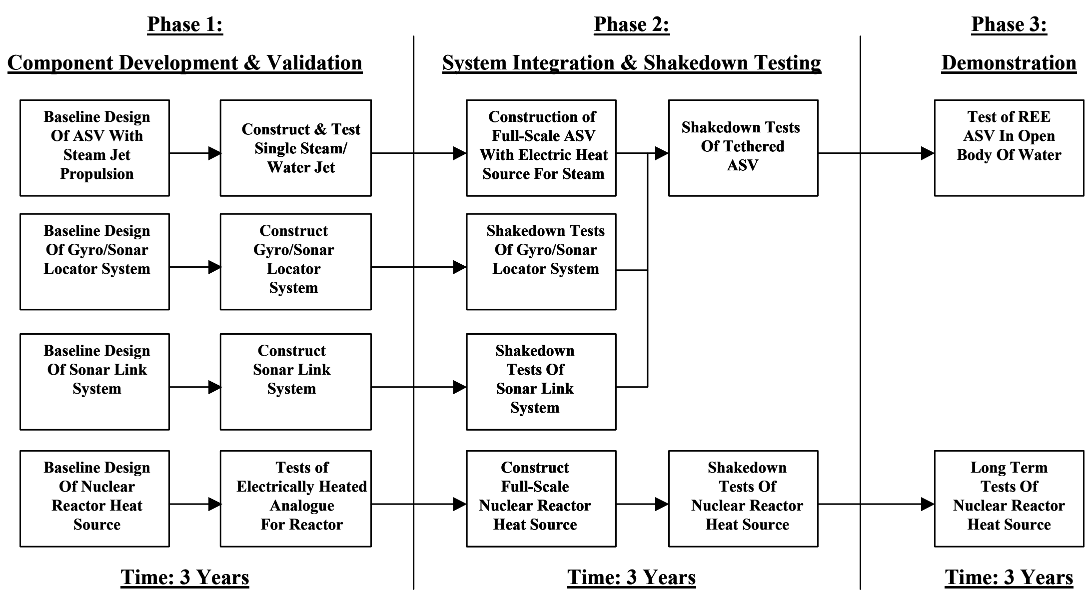


Figure 13.5 Technology Road Map for Autonomous Submarine Vehicle (ASV) System

14. Summary & Conclusions

Answering the question of whether or not life currently exists on Europa, or has existed in the past, will require detailed exploration of the interior regions of Europa's ice sheet and its sub-surface oceans, if they exist. Moreover, it will also probably require return of a large number of samples from the interior of the ice sheets and the sub-surface ocean.

Such an exploration program is impossible based on existing chemical rocket and power sources. The exploration can only be carried out using a high performance nuclear thermal propulsion engine heating H2 propellant to high temperature, plus a compact nuclear reactor that would provide the thermal and electric energy needed to descend deep into the ice sheet and explore in detail the possible sub-surface oceans.

The kind of nuclear engine and power reactor systems needed for a detailed exploration of the interior of Europa appear practical, and could be developed and ready for a mission to Europa within the next 10 years. There already exists a strong technology base for a compact lightweight high specific impulse nuclear propulsion engine. The engine design described in this study, termed MITEE (MIniature ReacTor EnginE) utilizes this technology base. MITEE uses cermet tungsten/UO_2 fuel that was developed in the 1960's as part of the 710 nuclear thermal propulsion program carried out by the US Atomic Energy Commission. The W/OU_2 fuel can operate for hours at 3000 K hydrogen propellant with minimal weight loss, achieving a specific impulse of close to 1000 seconds, twice that available from H_2/O_2 chemical rockets.

The thermal hydraulic and neutronic design of the MITEE engine is based on the Space Nuclear Thermal Propulsion (SNTP) program carried out by the US Strategic Defense Initiative (SDI) in the late 1980's and early 1990's. SNTP was a major program (total funding of $200 million) that developed and tested components for a compact, lightweight nuclear engine. Very high power density fuel elements were demonstrated, together with critical reactor assemblies and high temperature nuclear fuel particles. The nuclear reactors that would supply heat and electric power for the proposed Europa exploration program would use technology similar to that already developed for conventional power and research reactors. These reactors could be developed, tested, and ready for a Europa mission in just a few years.

The present study describes a baseline mission for exploration of Europa's interior termed Robotic Europa Explorer (REE). The REE spacecraft would be launched into a nuclear-safe Earth orbit by a mid-sized launch vehicle, e.g., Delta III or Atlas IIAS. The MITEE engine would then send the REE spacecraft on a direct trajectory to Europa (no gravity assists), with a trip time of 2 years. During the journey, the MITEE engine, which can operate in a bi-modal fashion to generate both high propulsive thrust plus continuous electric power, would provide 1 kW(e) of electric power to operate communications and control systems on the spacecraft.

Upon arrival at Europa, the REE spacecraft would land at a designated site on Europa, using the MITEE engine for a thrusted landing. After landing, the spacecraft would deploy a compact unit consisting of a melt probe and an attached small Autonomous Submarine Vehicle (ASV). The melt probe would create a melt channel down through Europa's ice sheet, enabling the probe and the attached ASV to descend to a depth of a kilometer or more, at a descent rate of several hundred meters per day. The melt probe would create the melt channel using warm water jets heated by a compact, lightweight nuclear reactor in the probe. The probe would two-way communicate continuously in real-time with the REE spacecraft using a deployed optical fiber that connected the two. The REE spacecraft, in turn, would be in real-time two-way communicate with Earth, subject to a delay of approximately one hour due to the finite speed of light. Scientific data in the structure, geology composition, history, etc., of the ice sheet would be continuously taken during the descent, along with examination of the ice sheet for evidences of past or present life forms, including microfossils, organic chemicals, DNA traces, etc.

After reaching the sub-surface ocean, if one exists beneath the ice sheet at the designated exploration site, the ASV would detach from the melt probe and explore the subsurface ocean for many kilometers around the entry point of the descent channel into the ocean. Continuous two-way real-time communication between the melt probe and the ASV would be maintained using sonar signals. The melt probe, in turn, would continuously communicate with the REE spacecraft, and from there, with the Earth.

The ASV would be powered by a second compact lightweight nuclear reactor, similar in design to that on the melt probe. The ASV would gather scientific data on the topography and composition of the sub-surface ocean and its sea bed floor, temperature and current distributions, and search for evidence of life forms both past and present in the ocean itself and the sea bed sediments. Both micro and macro life forms would be observed, if present, along with fossils – again both micro and macro, organic chemicals, DNA traces, etc. Promising sites for life, such as hydrothermal vents, would be investigated in detail. Samples of the ocean, sediments, life forms, fossils, etc., would be collected for return to Earth.

After exploration of this site was completed, which would probably require on the order of a month, the ASV would return to the melt probe. After reattachment, the melt probe would then create an ascent channel that followed the original descent channel back to the REE spacecraft using warm water jets directed upwards, instead of downwards, as was the case for the descent channel (the melt descent channel would have refrozen during the exploration of the sub-surface ocean).

Liquid H_2 propellant for the REE spacecraft would have been replenished during the ASV exploration period, using the electric power from the bi-modal MITEE-B engine to elctrolyze melt water obtained from the ice sheet to generate H_2 gas, which would then be liquefied and stored in the propellant tank of the REE spacecraft. 20 kW(e) would be generated which would produce 7 kg of liquid H_2 per day, with 5 kW(e) left over for the controls and communication systems on the REE spacecraft. After the melt probe and ASV reached the spacecraft and were reattached to it, the spacecraft would then hop to a new designated exploration site on Europa, using the liquid H_2 propellant that had been replenished by the REE electrolysis/liquefier unit. Hop distances of up to 2000 kilometers appear practical.
Upon completion of the designated exploration sites on Europa, which would probably number between 7 and 10 sites, the REE spacecraft would then lift off Europa and return to Earth using the H_2 propellant produced on Europa. The return journey would take approximately little over 3 years. The overall mission time, starting from Earth orbit and arriving at Earth with the collected samples from Europa (total weight of approximately 25 kg) would be approximately 6 years total.

The technology for the REE mission could be developed and ready for implementation in about 10 years. Development of the REE technology would enable a much greater number of important new missions that cannot be carried out using chemical rockets and current power sources. These include REE-type missions to many of the other moons (Titan, etc.) around Jupiter, Saturn, Uranus, and Neptune. The REE technology would also enable orbiter/lander missions to Pluto and Charon, and sample return from them. It would also enable fast trips to the Kuiper Belt, Heliopause, and Gravitational Lensing Point. Moreover, development of REE would substantially reduce the cost of planetary exploration, by allowing the use of smaller, lower cost launch vehicles for the various missions. In fact, it appears likely that the savings in launch costs alone would more than pay for the cost of developing a MITEE-type system, integrated over time.

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