Ocean World Exploration Rover

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With the contemporary search for life in space, exploring the eight ocean worlds of our solar system would be the prominent place to start. These ocean worlds are located far from our Sun and have a thick shell of ice. A new type of rover will need to be developed to get to the ocean layer. This rover would need to be capable of deploying in space, landing safely on the surface, penetrating through kilometers of ice, surviving extreme temperatures and pressures, collecting data, and transmitting that data back to Earth. Assessing the habitability, fluid dynamics, astrobiology, gravity, radiation, and many more groundbreaking research topics on these ocean worlds could revolutionize and lead to new developments in technologies on Earth. This paper will focus on the overview of what a possible mission to an ocean world would look like. It will outline the design of our rover, a mission plan, failure analysis, and finally, a cost analysis.

I. Introduction

As the search for extraterrestrial life continues, a few possible places that have yet to be explored are our solar system's ocean worlds. Ocean worlds are planets or moons containing an abundance of water. This would be key in trying to find evidence of extraterrestrial life. All life, as we know it, needs water to survive [1]. It is one of the basic requirements for all living things. Also, all life on Earth originated from the ocean nearly 4.3 billion years ago [2]. Therefore, if extraterrestrial life were to exist elsewhere, the best place to continue the search would be one of the ocean worlds.

In our solar system, there are eight ocean worlds [3]. Of these eight, seven are moons, and the other is the dwarf planet, Pluto. The other seven are Jupiter's moons Europa, Ganymede, and Callisto, Saturn's moons Enceladus, Titan, and Mimas, and Neptune's moon Triton. These eight ocean worlds present a massive opportunity for potential research. It is a great place to look for extraterrestrial life. A mission to an ocean world also offers the chance to assess fluid dynamics, gravity, radiation, habitability, and other research topics.

However, some of the oceans on these worlds are easier to access than others. Probably the most feasible for exploring and researching is likely to be Europa. Compared to the others in the solar system, Europa has the thinnest layer of ice on the surface, followed by the largest ocean underneath. This is why Europa will be the sole focus of this mission analysis.

II. Europa

Europa, also known as Jupiter II, is a moon of Jupiter. There has never been a spacecraft to land on Europa. However, there have been fly-by missions that have collected data. The data gathered shows that Europa has a thick surface layer of ice acting as the moon's crust. This ice crust is estimated to be between 15 and 25 kilometers thick. Although, there is an ocean estimated to be 60 to 140 kilometers deep [4]. This may not seem like a lot, but it is. In comparison, the deepest part of the Earth's Ocean, Challenger Deep, is nearly 11 kilometers [5]. So, despite its much smaller size, Europa has roughly double the amount of water than Earth does [4]. These fly-by missions also concluded that Europa emits a specific magnetic signature that correlates with salty water.

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Europa's thick ice shell cuts off access to the Sun, making the presence of any organism which depends on photosynthesis impossible. However, there is still hope for life. Due to Jupiter's massive gravitational pull, scientists claim that Europa's core is hot enough for a volcanic sea floor. Despite being a frozen world, a seafloor containing hydrothermal vents adds another necessary component of life, heat, and energy [6].

Fig. 1 Surface of Europa. Taken by the Juno Probe (NASA/JPL-Caltech/SwRI/MSSS/Thomas Thomopoulos)

III. Europa Clipper

One critical aspect of this mission will be finding the best place to land the rover on Europa for the most efficient ocean descent. Thankfully NASA is already working on a solution for this. In late 2024 NASA plans on launching Europa Clipper. Europa clipper is a satellite that will orbit Jupiter to study Europa and its oceans. Although this mission will not send any physical lander or rover onto Europa's surface, it will perform around fifty of the closest fly-bys of Europa to date. These fly-bys will collect crucial data on Europa's makeup [7]. This data includes detailed measurements of the thickness of Europa's icy outer layer, the composition of the outer layer, and characterize its geology [7]. This will be done using multiple cameras, spectrometers, magnetometers, and more. Though most essential for this mission is the data that MISE will collect.

MISE is the mapping imaging spectrometer for Europa. It will be able to measure the strength of Europa's surface and find weaknesses or shallow spots in the ice layer. This is done using infrared light and detecting changing wavelengths, frequencies, and periods [8].

IV. Thermodynamic Properties of Water

The Galileo mission, launched by NASA in the late 1980s, revealed on a fly-by mission that the surface of Europa has an approximate pressure of 0.1 micro-Pascals, or 10-7 Pascals [9]. This is 10-12 times the atmospheric pressure of the Earth. The Galileo mission also estimated Europa's surface temperature by analyzing its infrared radiation. The data showed a maximum temperature of 130 Kelvin on the surface and temperatures as low as 60 Kelvin closer to the poles [9]. Temperatures are the highest at around midday on dark patches of ice. Due to this low pressure, combined with low temperatures, the ice melted in the presence of this atmosphere will sublimate or turn directly into water vapor. Based on these environmental factors, the sublimation temperature on the surface of Europa is around 200 Kelvin [10].

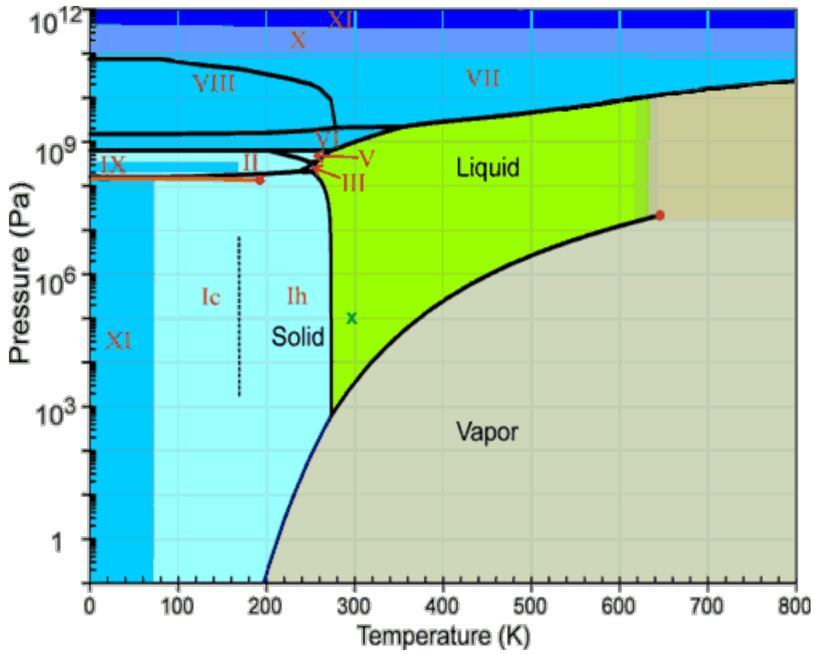

Fig. 2 Phase Diagram of Water. Reprinted from Water Structure and Behavior (London South Bank University)

A significant obstacle in exploring Europa is getting through the thick ice shell. Finding the most energy-efficient approach is extremely important as this process will take some time. Two viable options for getting through this ice are sublimating and melting. As mentioned earlier, Europa has a very thin atmosphere of only about 0.1 micro-Pascals, and any ice will sublimate at 200 K. Using these parameters, a device will be needed to heat the ice to 200 K, and then a large amount of energy will be needed to sublimate the ice. The other option is sealing off the top cavity, allowing pressure to build, so it is possible to melt the ice instead. At a pressure of 1000 Pascals, fusion will occur at around 275 K [10]. At this point, more energy is required to convert ice to its liquid state. However, it is important to note that this energy is less than the energy for sublimation. This process has downsides, however, as the liquid will always be present in the cavity and will continue to embezzle valuable energy from the heat probe.

V. Exploration Process

A rover tasked with exploring Europa or other frozen worlds differs significantly from successful rovers deployed on Mars or the Moon. A rover primarily focuses on surface exploration and data collection on these bodies. However, on frozen worlds, the focus shifts more to what lies under the surface: liquid water. The proposed rover operates by deployment to a given site, in which it lands and releases its tethered probe. This probe has four main parts: the tether, the sealer, the heating probe, and finally, the research probe.

The tether is responsible for relaying data back to the primary rover and supplying power to the heat probe and scientific instruments. Europa's ocean has never been accessed before, so there is a plethora of data to be collected and analyzed. One of the primary instruments is a mass spectrometer, which will analyze a liquid water sample. This is critical in determining if life is possible in this ocean by finding salt and mineral concentrations. More fundamental yet essential sensors include the temperature, depth, pressure, and camera sensor. This data will give valuable insight into habitability, chemical composition, and the collection of basic properties of Europa's large ocean.

On the surface of Europa, there will be a seal on top of the cavity produced by the probe. Running through this seal will be the tether. As mentioned earlier, increasing the pressure of this cavity will allow the ice to melt instead of directly sublimating, which will be more energy efficient. This seal will also regulate pressure to whatever is necessary for peak efficiency.

The most important part of this design is the melt probe. In previous NASA missions, a radioisotope thermoelectric generator was used for producing power. This device is quite simple as it uses energy from radioactive decay and converts it to electricity through solid-state thermocouples [11]. Plutonium-238 was the element of choice in this process. Plutonium-238 has a half-life of 80 years, making it highly dependable during long space missions [11]. It provides 0.56 Watts per gram. Through innovation, these thermoelectric generators have decreased in size and weight over recent years. Their efficiency, simplicity, and reliability make them the perfect choice to power a melt probe. The melt probe itself will use conduction to heat the ice and will be a conductive metal attached to our thermoelectric generator.

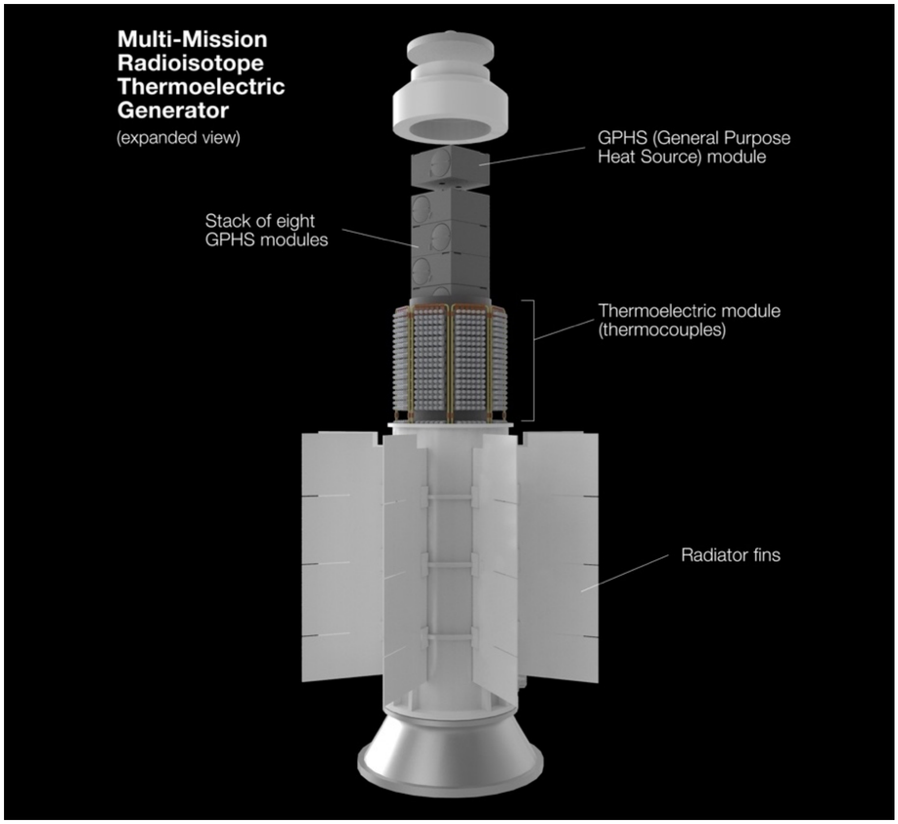

Fig. 3 Radioisotope Thermoelectric Generator. Reprinted from NASA.

VI. Rover Design

ARAGOG is a rover designed to be deployed from an orbiting body and land onto the icy surface of Europa. ARAGOG stands for Autonomous Resource Acquisition and Geological Observation Gizmo. ARAGOG is equipped with six legs, two less than a spider, with sharp spikes to stabilize it in the ice. These legs are connected to the body by a hinge and a pneumatic mechanism to adjust their angle to get the best traction into the ice. Although ARAGOG can move on the ice, ideally this won't be necessary with the proper deployment location. The shape of the body is a lofted hexagon. Europa has an extremely small atmosphere, so on deployment air resistance is not a big factor, so the shape is solely aesthetic. However, the small atmosphere introduces a problem as some sort of rocket booster will need to be used on entry to slow down instead of something simple like a parachute.

Fig. 4 Conceptual Design of the Rover.

In terms of external components, the top of ARAGOG is a solar panel to power the internal electronics. As mentioned earlier, the rover will contain a radioisotope thermoelectric generator. This generator is solely for the heat probe, so everything else can be powered by the solar panels. This won't be a problem as there isn't much secondary equipment to power, just the antenna and the scientific instruments.

The bottom face of the rover contains the interface for the tether. It is connected internally to a large spool, holding thousands of meters of tether. As the probe is quite heavy, we can rely on gravity to unspool the tether. The most difficult part of melting a pathway to the ocean is initiating the hole. Ideally, some sort of drill would be attached at the bottom of the rover to guide the probe initially.

Fig. 5 Conceptual Design of the Rover with Probe.

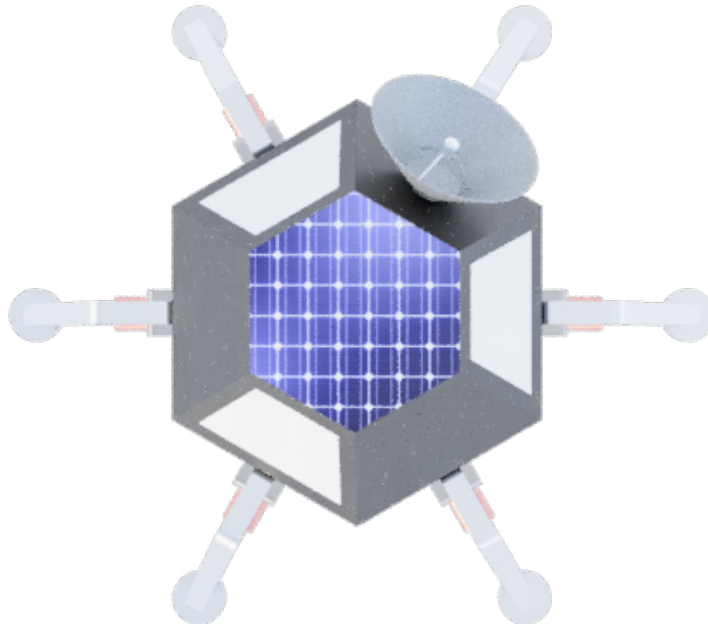

Fig. 6 Birdseye View of Conceptual Design

VII. Melt Duration

ARAGOG will release the melt probe once it has safely landed on Europa and after the lander has made an initial insertion. The probe itself will be 0.1 meters by 0.6 meters. The top of the probe will contain a small compartment where the tether from the lander will connect to the probe. This will be used to power the probe and send up all data gathered. Beneath this, there will be a compartment with all the necessary sensors to gather data. Present here will be cameras and other scientific instruments. Finally, the melting apparatus will be at the bottom of the probe.

This melting apparatus will be powered using radioactive decay, as previously stated. One kilogram of Plutonium 238 will decay roughly atoms every second, producing around mega electron volts every second [12]. This means there will be an energy production of 550 joules per second, equivalent to 550 watts of power.

A probe of a similar design by JPL was tested in the early 2000s. This probe was the first designed to melt through the ice off-world. Their probe was 1 meter long with a 12-centimeter diameter. This probe could melt through the ice at a speed of one meter per hour using one kilowatt of power.

Based on the data from JPL's probe, it is expected that with the available 550 watts of power, the Europa probe will have a melting speed of a little more than one meter every two hours. This means it will take a little less than 50,000 hours to melt through the ice, assuming the worst-case scenario of 25 kilometers of ice. This is just over five and a half years.

VIII. Satellite Integration

ARAGOG will be deployed by satellite. One key reason why satellite integration is so important is efficiency. This rover must melt through thousands of meters of solid ice at an extremely low temperature. If let's say the Europa Clipper uses its infrared spectrometer and magnetometer to, respectively, find the highest temperature and thinnest patch of ice. The rover would save a lot of time and energy. This process would be extremely difficult to program directly from Earth, so autonomous integration and communication with the Europa Clipper or another satellite are necessary. Also, a satellite armed with many of these rovers would be able to evaluate many different points of an ocean world at once. Time is crucial in this process, so a quick deployment with strategic positioning is key.

IX. Failure Analysis

The selection of materials for this rover is detrimental to mission success. Europa has a plethora of extreme conditions. Due to their proximity to Jupiter, they get hit with constant high-energy radiation [13]. The radiation is so extreme that NASA chose to orbit the Europa Clipper around Jupiter instead of Europa, as their electronic life expectancy was much higher [6]. To protect the rover and electronics, all surfaces should be treated with a radiation-resistant coating.

As mentioned, Europa has extremely low pressures and temperatures. This raises the concern of potential cryogenic to embrittle on the rover along with fractures due to thermal expansion. To counteract cryogenic embrittle, certain alloys should be used. These include stainless steel, copper, brass, and most aluminum alloys [14]. Now, to ensure that components do not fracture due to thermal expansion, materials with similar coefficients of thermal expansion should be used. This means that these materials will expand or shrink relatively the same amount at the same change of temperature, so they still interface properly.

X. Cost Analysis

NASA's Europa Clipper mission will cost $5 billion [15]. The deployment of the rover has two possible price points: traveling with the Europa Clipper or independently. The difference between these costs would simply be the cost to launch independently. Assuming a SpaceX Falcon Heavy is used, this will cost around $97 million [16]. The more expensive part is the manufacturing and mission operations. Congress granted NASA $195 million to develop a rover for their Europa mission [17]. Full development and deployment of this rover will cost around $300 million.

XI. Conclusion

Europa is one of many ocean worlds in our solar system. An extraterrestrial ocean has never been explored, so this simple yet efficient rover design sets a pathway for scientific breakthroughs. Water, heat, and certain elements are the building blocks of life. This makes these ocean worlds possible hosts to life outside of Earth. Our rover was designed around Europa because of the available and optimistic data obtained from the Galileo mission and another mission planned for Europa; NASA's Europa Clipper. The designed rover can land on treacherous terrain, melting through thousands of meters of ice to collect data from the ocean and finally transmitting this data back to Earth.

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