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Selection of an Effective Architecture for A Precursor Mission to Callisto

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ABSTRACT

One startling realization that's come from NASA's explorations of the satellites of Jupiter and Saturn is that the so-called "habitable zone" around our Sun may not be restricted to Earth's vicinity. The Galileo mission found conditions that might support life on two Jovian moons-Europa & Callisto. This raises the possibility of habitable zones elsewhere near the outer planets.

Consideration of human missions beyond Mars, likely to occur sometime beyond the year 2040, exceeds the horizon of even the most advanced planning activities within NASA. During the next 25 to 30 years, robotic spacecraft are envisioned to explore several moons of outer planets, especially Europa and Titan. Since Callisto lies well outside Jupiter's radiation belt, and there is evidence of water ice there is a compelling rationale to send human explorers to that Jovian moon.

Human exploration of Callisto would most certainly require breakthroughs in the technologies of propulsion and power; in situ resource utilization, radiation protection; artificial gravity; vehicle reliability, and extreme autonomy. Well-planned, robust precursor mission(s) will be required to not only demonstrate such breakthroughs, but to also establish supporting infrastructure at Callisto to enable safe and efficient human operations on its surface.

This paper delineates an efficient and effective potential precursor mission architecture for making critical science measurements, and establishing sufficient infrastructure to facilitate human landing on Callisto. For orbiting, landing, and exploring the Callisto surface, the study addresses the problem of determining the tradeoff space in terms of hardware choices: monolithic, a large number of small, dexterous robotic, and their judicious combinations.

INTRODUCTION

As a part of NASA's Revolutionary Aerospace Systems Concepts (RASC) Program, a multi-center team conducted a study of Human Outer Planet Exploration (HOPE)[1]. The RASC Program seeks to develop aerospace systems concepts and technology requirements to enable future NASA missions, which hopefully will include crewed journeys beyond Mars. This RASC work involved identifying new mission approaches and defining the technology required for the accomplishment of those missions. The HOPE study, in line with the RASC philosophy, attempted to envision concepts for a human mission to the outer planets and to identify the technology needs for the success of such a mission, which would take place circa 2045 A.D. An important aspect of the HOPE study is the issue of defining an appropriate architecture for precursor missions to enable humans stay on the *surface* of an outer solar system body. To narrow its focus, the HOPE team chose Callisto as its specific target in the outer solar system. Callisto is an icy and rocky moon of Jupiter, orbiting at a distance of 1,882,700 km, outside of Jupiter's radiation belt. With a diameter of 4820 km and a mass of 1.076×10^{23} kg, Callisto has $^1/_8$ the gravity of Earth. It is composed of a mixture of water ice and rock, in a ratio of about 55:45 water ice to rock. Because it has a relatively low albedo, it is possible that an abundance of the non-ice materials resides on its surface[2]. This paper focuses on delineating a feasible precursor mission to Callisto.

Implicit in the HOPE study was the basic assumption that precursor missions will have acquired all the scientific knowledge about Callisto necessary to send humans to its surface. The precursor phase is defined by the period of time before any humans land, and spends time on the surface of Callisto. As shown in Table 1, the mission requirements dictate that this phase must perform required science measurements, install necessary infrastructure to not only validate needed technologies, but also to support establishing a landing site for human landing. To approach the problem of defining precursor mission architectures, three top-level questions were posed. What science related tasks would need to be completed on Callisto's surface? How would the tasks be distributed among mobile and stationary platforms? What surface infrastructure systems will likely exist during, and after the precursor mission phase to enable subsequent human landing and operations? Answers to these questions produced a precursor mission architecture, sub-system level designs, technology trade-offs, required science measurements, and requirements for technology developments.

TABLE 1. Precursor Mission Objectives

<u>Callisto Precursor Missions Overall Objectives and Strategy</u>

- Focus on demonstrations to reduce cost and risk of human missions
- Also demonstrate and/or develop infrastructure for human base
- Establish safety and acceptability of Callisto's surface for humans
- Determine nature of potential material resources
- Demonstrate resource extraction and utilization systems
- Demonstrate key elements of human missions (e.g., precision landing)
- Determine robustness of Callisto's surface to human activities
- Conduct hardware construction/maintenance demonstrations
- Demonstrate elements of human-robotic operational systems
- Demonstrate sensing systems for scientific and environmental analysis
- Demonstrate deep space robotic outpost capabilities

Callisto

Callisto is about the size of the planet Mercury and it is the most heavily cratered place in the solar system. The craters come from asteroids and meteorites that have crashed into the moon since the solar system was formed billions of years ago. All those old craters are still there because there is no wind, weather, volcanoes or earthquakes to erase them. However, scientists have noticed that the smallest craters seem to be somewhat erased. What is causing these smaller craters to disappear? Scientists have noticed that Callisto's magnetic fields drift about in a pattern that matches Jupiter's spinning. This means that there could be a salty ocean of rocky slush under the moon's surface. Callisto is a chilly but fascinating moon. An ozone ionosphere on Callisto is generated by ultraviolet light striking the surface and splitting oxygen from the hydrogen in the ice molecules. Together, these provide protection to shelter life from UV radiation and solar particles as they do on our world.

As shown in Figure 1, Callisto has been imaged by the Galileo spacecraft on 10 orbits, half of which involved close flybys, producing images with resolutions as high as 15m/pixel. Callisto's density of ~1.86 gm/cm^3 shows the surface materials are an aerial mixture of intimately mixed water ice and rock. Surface temperatures on Callisto range between 96 K and 128 K, but are generally near ~ 100K. The ice and rock mixture is also thought to have volatiles such as H_2S, CO_2, and SO_2. The total radiation exposure of a mission depends on the overall trajectory (duration) in Jupiter vicinity. Its main characteristics are:

- Third Largest Satellite in the Solar System
- Has the oldest landscape in the solar system ~ 4 Billion years
- Outermost Galilean Moon, and orbits beyond Jupiter's main radiation belts.
- Exposure to normal galactic radiation on surface.
- Has the lowest density of the Galilean satellites.
- Inner rock core surrounded by thick icy mantle.
- A very tenuous atmosphere composed of carbon dioxide.
- Complete absence of any geologic activity on its surface
- No large mountains on the surface.
- Large number of shallow craters
- Evidence of a weak magnetic field
- Diameter (km): 4806
- Surface Gravity (Earth = 1): 0.127
- Mean Distance from Jupiter (km): 1,883,000
- Mean Distance from Sun (AU): 5.203
- Orbital period (days): 16.68902
- Rotational period (days): 16.68902
- Density (gm/cm3): 1.86
- Escape velocity (km/sec): 2.45

- Visual Albedo: 0.19
- Equatorial Subsurface Temperature (K): 126

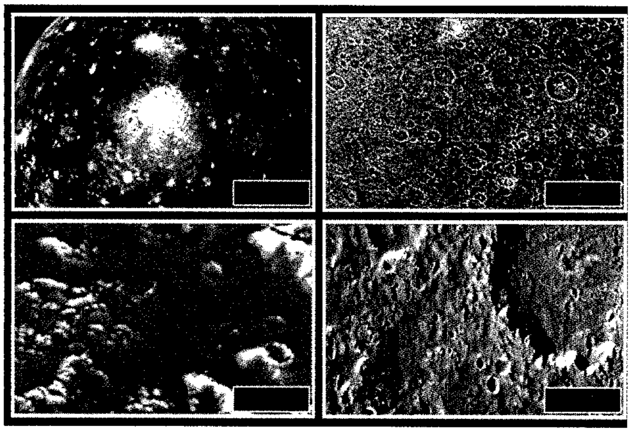


FIGURE 1. Callisto Surface Features

PRECURSOR MISSIONS

Precursor missions can be the backbone of a Callisto scientific program, and, in their development of robotic technologies, can complement future human exploration. The automated missions should be considered as an important part of an integrated Callisto science, technology, and human mission development program. Their dual role is not only desirable, but also essential to ensure that the effort and expense of getting to Callisto yields valuable scientific results and reduces the risk and cost of human exploration. Robotic precursor missions can also establish the degree to which human presence is a requirement for a more efficient and elaborate study of Callisto, and what role automation might be called upon to play in assisting human exploration. The following precursor mission strategy is delineated in Table 2.

TABLE 2. Precursor Missions: The Split Mission Strategy

✷ A significant attribute that allows cargo to be sent to Callisto without a crew on low energy transfers longer transit time trajectories and long before, the crew to be sent on a required higher energy, shorter transit time trajectory.

1. Break the mission elements into pieces that can be launched from Earth-Moon L1.
2. Develop power, propulsion, communication, placement and mobility and integration of major elements in a timely manner for deployment in orbit around Callisto and on its surface to allow needed infrastructure facilities, hardware, habitats, and ISRU facilities. Three robotic precursor missions are proposed:
3. The first precursor missions will gather information about Callisto that will be used to determine what landing sites are best for specific crew activities. For optimum mission performance, it will be necessary to pick a landing site based primarily on its ability to achieve HOPE Mission objectives. The site must be consistent with operational considerations, such as landing and surface operational safety. Detailed maps of candidate landing sites built from data gathered by precursor robotic missions will define the safety and operational hazards of the sites, as well as confirm whether access to scientifically interesting locations is possible by humans or robotic vehicles. To satisfy the human habitation objectives in particular, it would be highly desirable to locate the outpost site where water can be readily extracted from minerals or from subsurface ice deposits. Such a determination may only be possible from data collected by a robotic surface mission.
4. The second precursor mission is to determine the feasibilities of operation on Callisto surface and key technologies required for the HOPE Mission.
5. The third precursor mission is to land, deploy, operate, and maintain a significant portion of the surface systems prior to the human arrival.

DEFINITION OF PRECURSOR ACTIVITIES

There are two basic categories of precursor activities: those for performing science and those for establishing an appropriate infrastructure to facilitate human exploration of the callisto surface. With reference to the human exploration part, there are four classes of precursory activities, where we define "precursors" as relating to knowledge and experience necessary prior to human activities at a given destination. For science, there are the same four classes of engineering precursor activities, plus science precursor activities that are necessary in pursuing a given scientific objective. Opportunities for merging these precursor activities can result in a higher return on investment than if done independently.

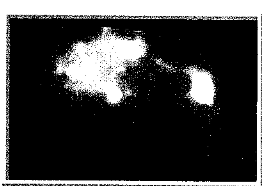
ENGINEERING PRECURSOR ACTIVITIES

(A) Knowledge capture -- environmental information necessary to design systems that will allow humans to conduct activities at the given destination. This includes: all relevant engineering data required to enable necessary human capabilities, including at least limited mobility, some form of subsurface access (i.e., either physical or remotely sensed); safe human adaptation to the environment and its changing nature (i.e., temperature, pressure, chemistry, dust, space weather and radiation, micrometeoroid flux, etc.); power systems; and safe return to Earth (via powered ascent).

(B) Emplacement of required Infrastructure -- This includes: telecommunications (bandwidth, access time, etc.); geolocation control (for precision landing and knowledge of local position in the vicinity of the destination); pre-deployed power and other systems for safe human adaptation; pre-deployed consumables including fuel, water, etc.; in situ resource utilization as required for at minimum life support (O2 extraction, water recovery, etc.); and others.

(C) Operational verification and experience – systems and procedures that will be used to support human trips that must be tested either in situ (i.e., at the given destination of choice) or in an analogue space environment.

Near geologic features of interest to science community. Slope and terrain roughness compatible with available landing technology area large enough to accommodate multiple landings with worst case landing error. Offers excellent opportunities for ISRU demonstrations, infrastructure buildups, and human habitats.



Likely Landing Site: Asgard Impact Structure on Callisto, centered at 30 degrees north, 142 degrees west, is approximately 1700 km across and exhibits a greater abundance of water ice compared with the surrounding region.

FIGURE 2 : Callisto Precursor Mission

(D) Technology/System demonstrations – space flight demonstrations of multiple technologies that form the basis for future systems to be used to support human space flight. Typically, these demos will bring technologies from TRL 4 to TRL 7. Space flight demonstrations for individual technologies are not considered precursor activities, but are considered part of the technology roadmaps.

To satisfy the human habitation objectives in particular, it would be highly desirable to locate the outpost site where water can be readily extracted from minerals or from surface ice deposits. A likely candidate site based on Galileo images is shown in Figure 2. However, such a determination may only be possible from data collected by a robotic surface mission. The second phase, utilizing probes and landers, will perform in-situ science measurements and gather data to assure landing and feasibility of surface operations on Callisto. A lander (including a mini-rover) capable of determining the mineralogy/ chemistry of silicates and organics, and other ices will need to follow the orbiter mission. Observations of geological, physical and mechanical properties of materials around the landing site will require the lander to be equipped with high resolution imaging capabilities. The lander can also be utilized to test some ISRU technologies and measure the radiation environment.

In the first phase, orbiter spacecraft will gather information about Callisto that will be used to determine what landing sites are best for specific crew activities. For optimum mission performance, it will be necessary to pick a landing site based primarily on the ability to achieve HOPE mission objectives. The site must be consistent with operational considerations, such as landing and surface operational safety. Detailed maps of candidate landing sites built from data gathered by precursor robotic missions will define the safety and operational hazards of the sites, as well as confirm whether access to scientifically interesting locations is possible by humans or robotic vehicles. It was determined that the orbiter will require high resolution imaging (including 1 m/pixel coverage for selected targets and global comprehensive coverage at 50 m/pixel in stereo); an IR spectrometer with coverage out to 4.5 microns, with high spectral and spatial resolution and high Signal to Noise Ratio (SNR). A laser altimeter and a Synthetic Aperture Radar (SAR) with a 25m/pixel resolution will also be required. The orbiter will need to be equipped with high volume and high data rate communication capabilities.

Robotic Precursor missions to Callisto will be severely constrained by the large energy requirements of the interplanetary trajectories and the inherent ΔV limitations of chemical propulsion. Missions using gravitational assists from Earth or

Venus or Mars to achieve high-energy trajectories are possible, but with limitations on payload masses and for longer flight times. A nuclear thermal propulsion engine design using a nuclear reactor, called MITEE[5] has been proposed for outer planet exploration. This engine would have over twice the ΔV capability of H_2/O_2 rockets enabling unique precursor missions that are difficult to accomplish with conventional chemical propulsion. MITEE with its small size (~ 0.5m diameter, and low mass ~200 kg), and high specific impulse (~1000 sec), as shown in Figure 3, could be used to drive a Nuclear Thermal Rocket (NTR) using hydrogen as the propellant to cruise and land on Callisto, and also generate electric power using the in-situ water/ice on Callisto.

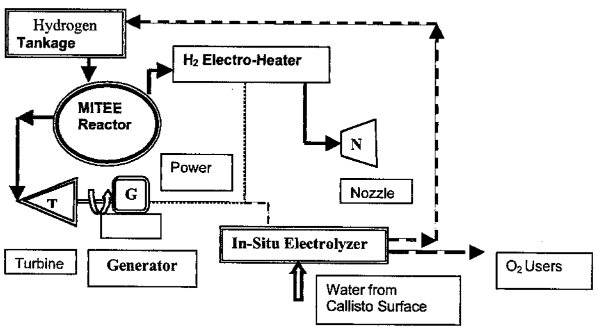


FIGURE 3. MITEE Nuclear Reactor System for Propulsion & Power

In order to impact the technologies and functionalities associated with the crewed Callisto surface systems, the precursor missions will need to be launched at least 15 years before the crewed missions are to occur. Assuming a 2025 launch date, a bimodal nuclear thermal propulsion system coupled with an orbiter/lander combination could be launched on a Delta IV class launch vehicle from Earth and reach Callisto four years later. The bimodal system would allow 5 kW of electrical power during the cruise phase and up to 20 kW or power for surface operations (such as ISRU processing experiments). Results of the mission launched in 2025 could lead to another set of precursors in 2030 that still would provide data that could be utilized to support planning and design of the crewed mission. The precursor mission strategy as shown in Table 2 and the supporting mission scenarios in Figure 4 will enable us accomplish these objectives in an effective manner.

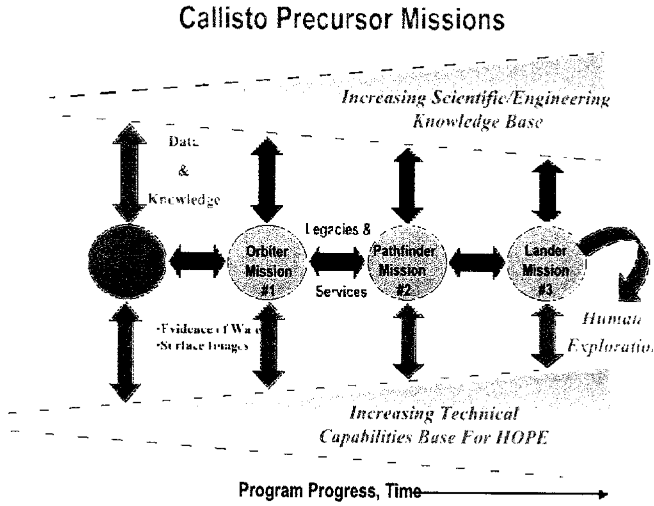


FIGURE 4. Scenarios for Precursor Missions

The objectives of each precursor mission are delineated in Table 3.

TABLE 3 . Callisto Precursor Missions: Objectives

- ***Mission #1: Callisto Orbiter (CO)***

  High resolution imaging (including 1 m/pixel coverage for selected targets and global comprehensive coverage at 50 m/pixel in Stereo); an IR Spectrometer with coverage out to 4.5 microns, with high Spectral and Spatial Resolution and high Signal to Noise Ratio (SNR); Laser Altimeter; Synthetic Aperture Radar (SAR) with 25 m/pixel. Equipped with high volume and high data range communication capabilities.

- ***Mission #2: Callisto Pathfinder Lander (CPL)***

  A lander (including a rover) capable of determining the mineralogy/chemistry of silicates, organics, and other ices. Observations of geological, physical and mechanical properties of materials around the landing site. Equipped with high resolution imaging capabilities.

- ***Mission #3: Callisto Lander (CL)***

  A lander (including autonomous rovers) capable of establishing a Callisto base for in-situ resource utilization, launch facilities, human habitats, robotic outposts for scientific observations, measurements, and telerobotics of any hardware on other Jovian moons. Communication Network.

The mission design representing the proposed architecture, scenario, and strategies is depicted in Figure 5, along with a proposed trajectory in Figure 6. The results of our study concerning technologies needed, assessments of hardware trade space, and technology development roadmap are summarized below in Figures 7 & 8, and Tables 4 & 5.

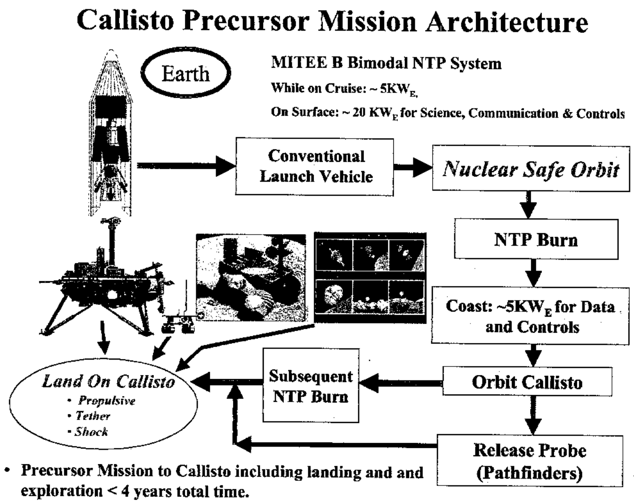


FIGURE 5. Proposed Mission Design

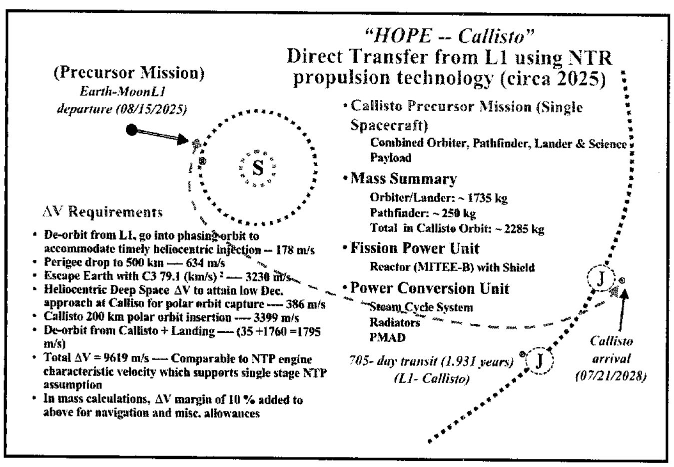


FIGURE 4. Precursor Mission Trajectory

TABLE 4. Micro/Macro/Nano-Robot Roles in Callisto Precursor Mission(s)

- Relative strengths of Independent/large or small robots in performing a wide variety of tasks is well-established CONCEPTUALLY
- Guided or Nearly autonomous, and independent robots on Earth are proven in a variety of science and engineering situations
- Robust, self-contained robots are good in hostile and high-risk service
- Design of Power, Mobility, & Communication systems of moderate and large size robots are well understood even for Space Applications
- Independent, small/medium-size robots have gone to "worse-than-hell" places (Venus, Jupiter), and "less hostile" Mars
- There is no EXPERIENCE to validate advantages and feasibilities of Swarm/Ant Robots even on Earth! Hardware technical problems include
- Autonomous/Polling decision-making in hostile environment.
- Providing power, communication network, and task control/integration for extended periods of reliable operations
- Systematic comparisons that delineate AI needs, Minimum number of survival for essential mission Reliability, etc are not available as yet nor fully investigated for a wide range of envisioned surface operations
- Need standardized METRICS to quantify performance
- Need rigorously defined criteria to EVALUATE relative performance

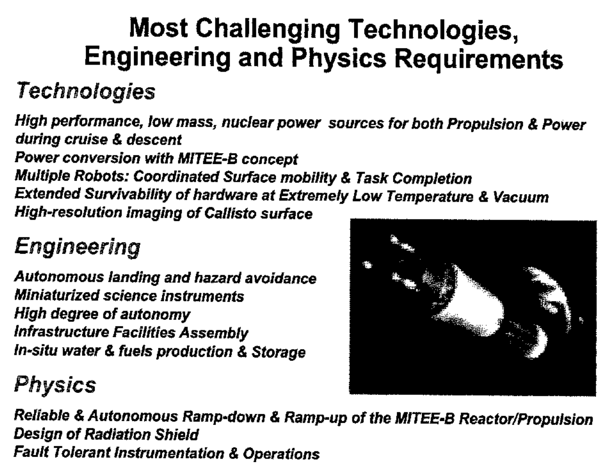


FIGURE 7. Technology Challenges for the Callisto Precursor Mission

TECHNOLOGY IDENTIFICATION AND DEVELOPMENT

This surface scenario depends on several technology advancements. Without the development of these technologies, the surface mission that has been described is not plausible.

Table 5 summarizes the technology development requirements for the Callisto surface mission.

Precursor Mission Trade-Space Assessments

System Complexities, Reliabilities, & Mission Compatibilities

Lander Type	Power & Life	Propulsion For Landing	Comm-unications	Thermal Control	Autonomy & Control	Precursor Mission Compatibility
Ant-Robot Swarm	Highly Complex	Highly Complex	Highly Complex	Highly Complex	Highly Complex	Doubtful
Micro-rovers	Moderately Complex	Moderately Complex	Moderately Complex	Highly Complex	Highly Complex	Moderately High
Mini-rovers	Feasible	Complex	Complex	Complex	Feasible	Highest
Static	Feasible	SOA	SOA	Feasible	SOA	High

➢ *Conclusions: Combinations of Orbiter/Static & Mini-rovers is the best approach for accomplishing the Precursor Mission(s) objectives*

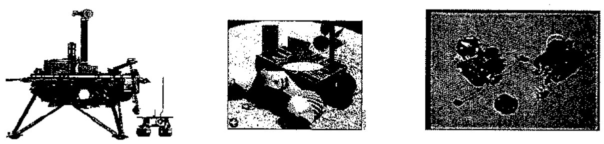


FIGURE 8. Summary of the Callisto Precursor

TABLE 5. Surface Mission Technology

Technology	Summary Description of Desired Technology and Key Performance Metrics	Applications of the Technology Other Than HOPE
Precision Landing	Ability to reach landing target within 30 meters	Lunar and Martian landing
Cryogenic Mass Transfer	Transfer of liquid cryogen over 30+ meters with less than 25% loss	Liquid cryogen transfer for spacecraft propulsion
Super-Cold Metals	Support of mechanisms at 100 K	Any environment down to -235 C
Super-Cold Composites	Structural support as well as flexibility, at 100 K, to enable inflatable surface habitat design	Other super-cold environments
Super-Cold Lubrication	Prevention of locking of mechanisms at 100 K	Other super-cold environments
Brayton Nuclear Reactor Power System	Delivery of 250 kWe power at a mass of 12,000 kg or less	Advanced propulsion spacecraft, planetary surface missions
Mobile Power Plants	Power to give vehicles and robotic systems a range of several kilometers	Planetary rovers, interplanetary spacecraft

CONCLUSION

The HOPE study has shown that a crewed mission to Callisto in the 2045 era is possible given advances in life support, propulsion and power generation technologies. Common components, reusable systems, in-situ resource utilization and innovative vehicle design can enable humans to explore a destination that is 8 times as far away as Mars.

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