Exploring Europa with a Surface Lander Powered by a Small Radioisotope Power System (RPS)

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Europa is a high-priority target for future exploration because of the possibility that it may possess a subsurface liquid ocean that could sustain life. Exploring the surface of this Galilean moon, however, represents a formidable technical challenge due to the great distances involved, the high ambient radiation, and the extremely low surface temperatures. A design concept is presented for a Europa Lander Mission (ELM) powered by a small radioisotope power system (RPS) that could fly aboard the proposed Jupiter Icy Moons Orbiter (JIMO). The ELM would perform in-situ science measurements for a minimum of 30 Earth days. The primary science goals for the Europa lander would include astrobiology and geophysics experiments and determination of surface composition. Science measurements would include visual imagery, microseismometry, Raman spectroscopy, Laser Induced Breakdown Spectroscopy (LIBS), and measurements of surface temperature and radiation levels. The ELM spacecraft would be transported to Europa via the JIMO spacecraft as an auxiliary payload with an extended duration cruise phase (up to 13 years). After arriving at Europa, ELM would separate from JIMO and land on the moon's surface to conduct the nominal science mission. In addition to transportation, the JIMO mothership would be used to relay all lander data back to Earth, thus reducing the size and power requirement of the lander communications system. Conventional power sources were evaluated and found to be impractical for this mission due to the extended duration, low level of solar insolation (~3.7% of Earth's), the low surface temperatures (as low as 85K), and the 1.75 days of eclipse every Europa day. In contrast, a small-RPS would enable the ELM mission by powering the lander and keeping all key instrumentation and subsystems warm during the cruise and landed phases of the mission. The conceptual small-RPS is based on the existing General Purpose Heat Source (GPHS) module using thermoelectric conversion. This would generate 225 Wt (thermal) and 10.1 We (electric) at the end of the mission, and would provide a 145% energy margin. A small rechargeable lithium-ion battery would be used to handle peak load demands during the short-duration communication events and while using the higher-power instrumentation (LIBS and Raman). In summary, small-RPS technology could enable an exciting, scientifically valuable Europa lander mission designed to verify the existence of a subsurface ocean, and to search for signs of past or present life.

1. INTRODUCTION

This paper describes a conceptual landed mission to the Jovian satellite Europa using a small-RPS powered lander that would ride piggyback on the proposed Jupiter Icy Moons Orbiter (JIMO). This mission study was performed to assess the feasibility of landing a realistic science-driven payload using a conceptual small radioisotope power system (RPS) to provide electrical and thermal power during the extended duration cruise phase (up to 13 years) and the nominal 30 day surface science mission. This paper includes individual sections that describe the key science goals, the mission architecture, and the conceptual design of the Europa Lander Mission (ELM) spacecraft.

2. SCIENCE GOALS

Europa is recognized as a high-priority target for future exploration because of the possibility that it may possess environments suitable for life [1]. The primary science goals for ELM, as recommended by the JIMO Science Definition Team [2], are to perform *astrobiology* investigations, *geophysical* investigations, and *geological-composition* investigations.

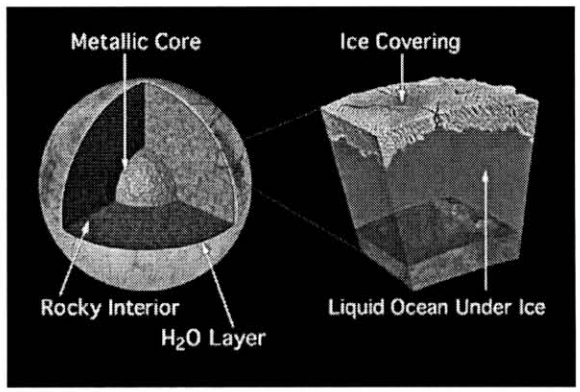

Figure 1. Europa's Predicted Internal Structure and Composition

The *astrobiology* goal would be to search for signs of past or present life, and to characterize the habitability of the Jovian moons. To meet this objective, ELM instruments would be designed to search for organic materials and to determine their composition. In-situ experiments would be conducted to reveal chemical patterns that might be indicative of biological origin, and measurements would be taken of local temperature and radiation intensity. The *geophysics* goal would be to determine the local thickness and characteristics of the icy crust, and determine the location of liquid water beneath Europa's icy crust (Fig. 1). This knowledge would lead to a better understanding of the interior structure and crustal dynamics of Europa. ELM would perform in-situ seismometry experiments to achieve this objective. The *geological-composition* goal would be to determine the evolution and present state of the Galilean satellite surface and subsurface, and to investiage the processes affecting them. Lander experiments would be performed to determine the elemental and mineralogical composition of surface ice and non-ice materials. Imaging, radiation and temperature measurements would also contribute to achieving the *geological-composition* goal. The ELM mission would, in addition, provide ground truth for remote measurements of temperature, composition, and radiation levels obtained by the JIMO spacecraft.

3. MISSION ARCHITECTURE OVERVIEW

The ELM is derived from the Europa Pathfinder (EPF) study [3] and takes advantage of RPS technology to enable a 30-day surface mission (the EPF mission duration was battery-limited at 3.5 days). ELM (Fig. 2) would ride as payload on the aft section of JIMO as shown in Figure 3. The launch date of the JIMO space craft is assumed to be 2015 for the purposes of this study. The nominal JIMO transit time to Europa is not yet defined, but is conservatively assumed to be ~13 years (in order to bound the RPS lifetime), with a 65-day spiral-in period, a 30-day science period, and a 6-day spiral out period [4].

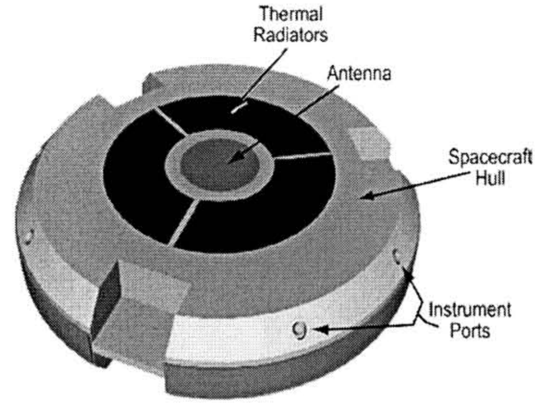

Figure 2. Configuration of the Europa Lander Mission (ELM) Surface Lander

The Europa landing site would be determined during the 65-day JIMO spiral-in phase where detailed Europan surface mapping could be performed by JIMO, assisting the science and engineering communities in choosing the landing location that maximizes science returns and minimizes landing risk.

JIMO would enter a nominal 100 km (altitude) circular orbit about Europa at an inclination of 45°. The JIMO orbital inclination constrains the maximum possible landing latitudes to between ±45° for this mission design. Upon reaching this orbit, the ELM spacecraft would separate from JIMO and would perform a series of maneuvers, known as "Stop and Drop," to prepare for landing.

After separation, the ELM spacecraft would be spun-up using small solid rockets in preparation for two subsequent descent burns. The first descent burn would impart a velocity change (Delta V) of 22 m/s opposite the direction of travel, which would alter the original 100 km circular orbit to an elliptical orbit with a 1.5 km periapse and 100 km apoapse (Fig. 4). The second descent burn would be performed at periapse, and would impart a Delta V of 1458 m/s opposite to the direction of travel. This would null out all forward motion, resulting in the lander "falling" into Europa under the force of gravity. The total Delta V requirement to perform the "Stop and Drop" maneuver would be 1480 m/s.

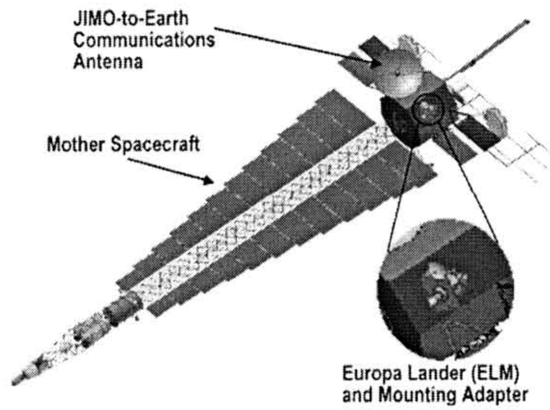

Figure 3. Artist's Concept of the ELM Spacecraft Riding the Aft Section of the JIMO Mothership (Preliminary Version) During 13-Year Cruise Phase

Following the second descent burn, the ELM lander would separate from its propulsion stages (Fig. 5) and inflate its airbags in preparation for surface impact. The free-fall time would be ~48 seconds based on a periapse altitude of 1.5 km, and the resulting impact velocity would be 63 m/s. As Europa has a negligible atmosphere, aeroshells and parachutes are ineffective. Thus, airbags and a low periapse are the key design techniques to control the impact acceleration, with a resulting maximum landing acceleration of <600 g. Upon landing, the pressurized airbags would be released and would bounce away, allowing the ELM lander to make direct contact with the Europan surface.

During the surface mission, ELM would communicate with JIMO using omni-directional antennas onboard the lander and a JIMO-mounted parabolic antenna. The JIMO High Gain Antenna (HGA) would then be used to relay the ELM science and engineering data to Earth.

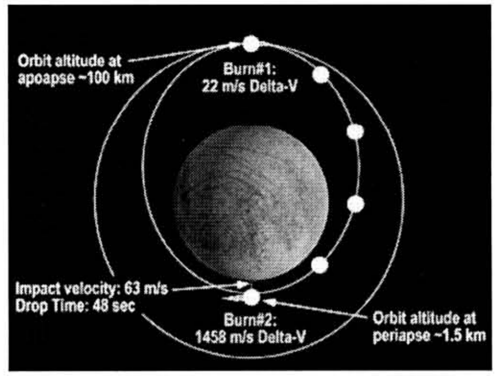

Figure 4. Orbital Maneuvers Performed by the ELM Spacecraft During the Entry and Landing Phases

4. POWER SOURCE TRADE STUDY

Trade studies were performed on three different potential power systems for the ELM spacecraft, including solar arrays, primary batteries and RPS. The critical driving factors were 1) the high-latitude landing requirement ($\pm 45^{\circ}$), 2) distance of Europa from the Sun (~5 AU) and the resulting low insolation levels, 3) Europa's long rotation period (85.2 hrs), and 4) the extremely low surface temperatures. Europa receives only 3.7% of Earth's insolation, corresponding to an average diurnal solar flux of less than 15 W/m^2 at 45° latitude (Fig. 6). The long rotational period means that the ELM lander would see 42.6 hrs of shadow per Europa day. Additionally, the average surface temperature approaches a frigid 103 K, (and the nighttime surface temperature can drop even further to ~85 K. Thus, significant thermal power and energy would be required to maintain operating temperatures during both the proposed multi-year cruise phase (on JIMO) and during the nominal Europan surface mission. Lastly, due to the

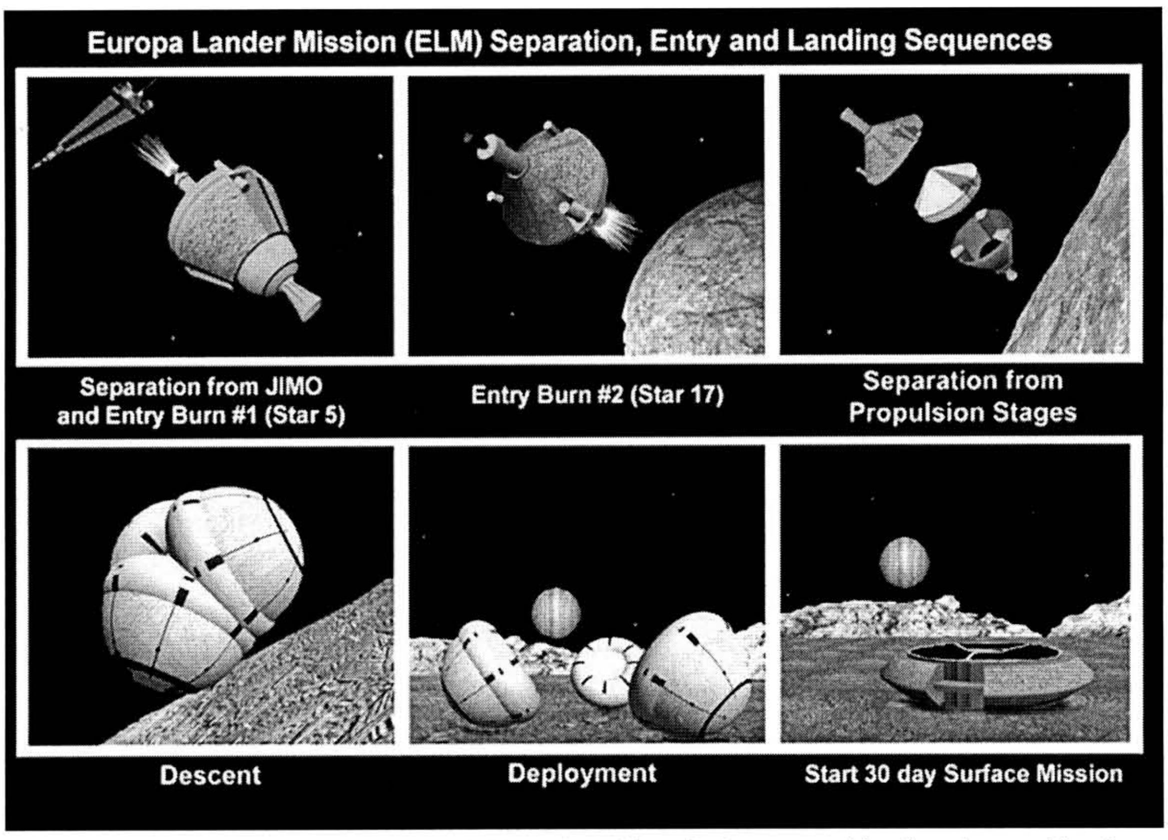

Figure 5. Illustrations of the separation, orbital-insertion, airbag deployment and landing phases of the Europa Lander Mission (ELM) spacecraft. Original picture courtesy of the EPF Team [3]

rough surface topography, ELM would be designed to operate in any landing orientation, including right-side up and up-side down; thus, power generation must be possible in any landing orientation. The baseline total energy requirement for the surface mission was estimated at 6620 W-hrs including a 5-W heater budget. This is assumed to be the minimum required thermal power necessary to maintain operating temperatures in addition to any RHUs.

For a solar array power system to be employed on ELM, a number of technological challenges would have to be overcome. First of all, as the ELM lander would see 42.6 hrs of shadow per Europan day, a large energy storage system (e.g., rechargeable batteries) would be required to permit operations and maintain operating temperatures during the long periods of eclipse. Secondly, as the specific landing orientation of the spacecraft could not be guaranteed apriori, the solar array system would need to be capable of generating enough power regardless of landing configuration, i.e., it would need solar panels on both the top and bottom surfaces of the lander and/or a method of solar array (SA) articulation (adding complexity) to maximize the amount of incident insolation. Thirdly, the ELM spacecraft would need an additional power system or umbilical to JIMO during the proposed multi-year cruise phase, as the solar arrays would be shrouded within the entry system (i.e., retrorockets and airbags) and would not be capable of generating any power to perform health and status checks and maintain operating temperatures.

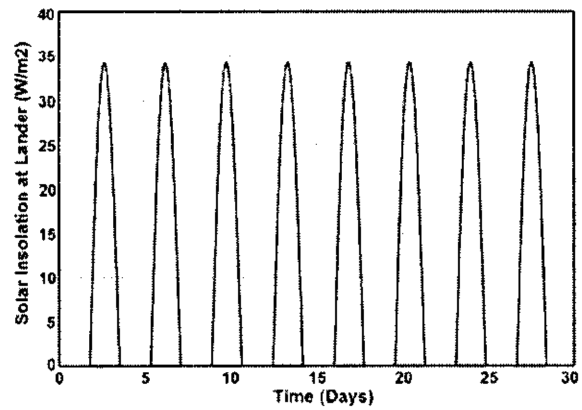

Figure 6. Incident Solar Flux at Surface of Europa at 45° Latitude Over 30 Earth Days

Lastly, solar array technology would need to be developed to operate at the low solar insolation levels specified above, in a high natural radiation environment (multi-MRads), and in the extreme cold. Analyses were conducted on the solar array size and total mass (array and batteries) required to meet the energy requirements of the surface mission – the effects of radiation and the need for an auxiliary power system during cruise were ignored in this study. The results are presented in Table 1 and indicate that 27 m^2 of solar panels (13.5 m^2 on each surface) would be needed to meet the total energy requirement for the surface mission. This would correspond to a solar array mass of ~68 kg, and a battery mass of ~10 kg in order to permit continuous operations and maintain operational temperature during the long Europan nights. Considering that the conceptual ELM spacecraft would have a diameter of ~1 m, and a mass of ~30 kg (without power system), it is clear that the solar option is not practical from either a size or mass perspective.

Table 1. Solar Array Trade Study Parameters for the ELM Mission

Parameter	Value
Total power reqt for surface mission (W-hr)	6624
SA Power Conversion Efficiency (EOL)	15%
Total Solar Energy Flux Received over suface mission (W-hr/m^2)	7270
Eclipse period per Europa day (%)	50%
Battery Charging Efficiency (%)	90%
Required SA Area (m^2) - Single Surface	13.5
Required SA Area (m^2) - Both Surfaces	27
Solar Array mass density (kg/m^2)	2.5
Required Solar Array mass (kg)	67.5
Max Shadow Period per Europa day (hrs)	42.8
Power Used During Shadow (W-hr)	393
Battery Depth of Discharge (%)	33%
Battery Energy Requirement (W-hr)	1192
Battery Energy Density (W-hr/kg)	120
Reqt Battery Mass (kg)	9.9
Total Mass (Not including cables, etc.)	77

The use of primary batteries was also analyzed, and issues similar to those for solar arrays were discovered. Namely, in order to maintain the batteries at their operational temperature (typically above -40°C), a significant amount of thermal power would be required to heat them as well as sensitive electronics and systems. The resulting power requirement would result in a battery mass and volume significantly larger than that required for an equivalent RPS. Additionally, an auxiliary power source or umbilical to JIMO would be required to power the lander and keep it warm during its cruise phase.

The use of a small-RPS was analyzed and found to have significant advantages that would enable the ELM mission from a power system perspective. These advantages include long-life (the small-RPS could operate for decades), generation of excess heat that could be used to maintain operating temperatures, and a relatively high energy density averaged over the mission duration The GPHS module with thermoelectric converters was assumed for this trade study based on the long flight heritage of the individual technologies. The RPS trade study assumptions are provided in Table 2 [5, 6]. Due to the excess heat generated by the GPHS, the total energy requirement for the 30-day mission would be less than that for solar or batteries, and was calculated estimated at ~3000 W-hr (Section 10). The total RPS electrical output for the surface mission would be 7300 W-hr (based on 13-year EOL performance), resulting in the RPS system having a total energy margin of ~145%. To meet the peak power demands of all the instruments and communications equipment, a small rechargeable battery would be utilized. An additional advantage of RPS is that it would permit the ELM spacecraft to be a self-contained system, eliminating the need for external recharging or alternate power connectivity with the JIMO spacecraft during the cruise phase. In summary, RPS technology would enable the ELM mission by providing a small, long-lived, low mass power source that would produce valuable excess heat to keep the spacecraft warm during the entire mission.

Table 2. RPS Trade Study Assumptions for the ELM Mission

Parameters	Value
RPS Heat Source Type	GPHS
Thermal Power Ouput @ BOL, (W)	250
Operating Life (Years)	13
Pu^{238} Decay Rate / year (%)	0.8%
Thermal Power Output @ EOL, (W)	225.2
Thermoelectric Degradation Rate / year	0.8%
Power Conversion Efficiency	5%
Electrical Power Output @ EOL, (W)	**10.1**

5. SMALL-RPS CHARACTERISTICS

The small-RPS power system utilized for the ELM mission is a conceptual design based on a single GPHS module utilizing thermoelectric (TE) conversion, and assumed to possess a total system efficiency of ~5% at Beginning of Life (BOL). This RPS system is based on individual components (heat source, TEs and insulation) that all currently exist and have been flight proven. Conservative estimates of power system performance were assumed in the RPS and battery sizing calculations. The existing GPHS module produces a nominal 250 Wt at BOL, and its thermal output degrades by ~0.8%/year due to the radioactive decay of the Pu^{238} fuel ($T_{1/2}$ = 87.8 years). Degradation of the TE material would result in an additional ~0.8%/year reduction in electrical output. Thus, the power output from the small RPS is estimated as 225 Wt and 10.1 We at EOL (13 years).

This RPS thermoelectric converter is assumed to be comprised of PbTe–TAGS, operating with a cold shoe temperature of ~155°C. The TEs are oriented normal to each of the four sides of the GPHS module (Fig. 7a), and Min-K thermal insulation would provide the structural support for the TEs and heat source. The RPS assembly would be packaged in a cylindrical container that allows venting of the Pu^{238} decay products (helium) to the ambient environment through vents penetrating the Min-K and external RPS canister. The RPS would be centrally located within the body of the ELM spacecraft (Fig. 7b), permitting efficient channeling of the excess GPHS heat to the surrounding electronics, subsystems and radiators via conduction straps. The RPS is assumed to be capable of surviving the 600g maximum spacecraft landing loads without damage. The maximum extrapolated mass of the RPS is 10 kg based on existing detailed RPS designs [7] reinforced to handle the expected acceleration load.

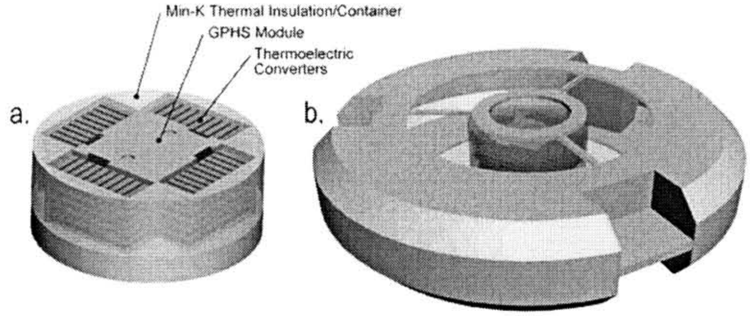

Figure 7. (a) Small-RPS (with Top Removed) and (b) ELM Spacecraft with Small-RPS Installed (Radiator panels and internal systems removed for clarity.)

6. SCIENCE INSTRUMENTS

The proposed ELM spacecraft would carry a complement of six science instruments specifically chosed to meet the science objectives of the mission (Table 3). Of these, the temperature and radiation sensors would provide information on surface conditions relevant to the *Astrobiology* goal (determining the habitability of the subsurface) and to the *Geological-Composition* goal of determining the physical state and mechanical properties of the surface. These relatively simple sensors would be installed on the top and bottom surfaces of the lander.

The imaging system would view the surface through a set of transparent ports that are distributed over the outer surface of the lander. All of the ports would convey their information to a centralized imaging system via fiber optic leads. Some ports would be optimized for far-field views to image the surroundings, while others ould be optimized for near field views to resolve small-scale features of surface ice that may be in close proximity to the port. The imaging system addresses the *Geological-Composition* goal.

The Raman spectrometer and the LIBS are sophisticated instruments that would obtain information on surface compositions in complementary ways. Both would utilize laser light to illuminate a target, and both would employ fiber optic leads to stimulate the target and measure the resulting emissions. The Raman spectrometer would nondestructively excite the molecules of the target surface, with the resulting emissions being diagnostic of mineralogical composition. The LIBS would break down the molecules of the surface materials, and would determine the elemental compositions by recording and analyzing the emission lines of the resulting short-lived plasma. Both organic and inorganic materials are characterized by each of these instruments, making them directly relevant to the *Astrobiology* goal and the *Geological-Composition* goal.

The microseismometer would directly address the *Geophysics* goal, as this instrument would be designed to enable researchers to determine both the mechanical properties of the icy crust and its thickness. This would be crucial information with respect to the question of whether or not Europa possesses an ocean beneath its icy crust.

Table 3. Science Payload and Instrument Description for the Proposed ELM Spacecraft

Instrument	What it does	Science Objective Addressed
1. Imager	Obtains near-field and far-field images through viewports.	Characterizes the surface characteristics and surface geology of the landing site.
2. Microseismometer	*Detects and records ground motions (icequakes).*	Determines the internal structure of Europa.
3. Raman Spectrometer	Measures backscattered laser light to determine composition and concentration of minerals and chemical species present, including organics.	Searches for signatures of biological activity. Characterizes the chemical and physical habitability. Describes the composition of non-ice materials.
4. LIBS	Pulsed laser focused on surface ice produces an ionized plasma whose emissions are diagnostic of the elemental composition of surface materials (Complementary to the Raman instrument).	Searches for signatures of biological activity. Characterizes the chemical and physical habitability. Describes the composition of non-ice materials.
5. Temperature Sensor	Measures ambient temperature at the landing site.	Provides ground truth for remote observations. Characterizes the thermal properties of the surface through measurements over the diurnal cycle.
6. Radiation Sensor	Measures levels of ion and electron irradiation at the landing site.	Characterizes surface habitability. Provides ground truth for models of surface radiation levels based on orbiter data.

7. Data

Mission data would be generated from the nine scientific instruments and from other sensors designed to assess the health and status of the spacecraft. Each science instrument would operate at its own data rate and data-taking frequency that would be dependent upon the phenomena or object being measured, the desired temporal resolution, and the rate at which the measurement would be expected to vary (Table 4). All lander data would be uplinked to JIMO during the communications events described in Section 8 for transmission to Earth.

The total volume of data obtained over the course of a Europa day is estimated at 1160 Mbits, with the data stream comprised primarily of microseismometer data (79%) and high-resolution images (19%). Communication from ELM to JIMO would occur only during limited windows of opportunity; thus, a solid-state data recorder (SSR) with 1400 Mbit capacity would be used to store all measurement data until the next communication cycle. Due to the quantity of stored data and short duration communication windows, a 1.4 Mbit/s bandwidth would be used to transmit all stored data and any newly generated data to JIMO during each window. To allow for uncertainties and limited future growth, both the SSR storage requirement and communications bandwidth requirement include ample margin (20% and ~200%, respectively). Additionally, data compression algorithms could be used to significantly decrease the accumulated data volume, especially from the microseismometer, by 4:1 or greater. The resulting data margin could then be allocated to new higher-bandwidth instruments (e.g., increased imaging resolution and sampling frequency, etc.) or used to simplify the communications and data storage systems by permitting the use of smaller antennas, transmitter and SSR.

Table 4. Data Rates, Uplink Rates and Data Storage Requirements for the ELM Spacecraft

Instruments	Data Rate (kbps/ msmt)	# of Instruments	#Measure mts per Europa Day	Measuremt Frequency (#/Earth Hr)	Accumulated Data Volume per Europa Day (kbits)	Accumulated Data Volume per Europa Day (Mbits)
Imager	2600	16	85	1	220532	221
Microseismometer	1	3	305352	3600	916056	916
Raman Spectrometer	10	1	85	1	848	0.85
LIBS	10	1	42	1	424	0.42
Temperature Sensors	0.016	16	170	2	43	0.04
Radiation Sensors	0.016	4	305352	3600	19543	20
Engineering Data	0.100	1	5089	60	509	0.51

Total Accumulated Data Volume / Europa Day (Mbits)	1160
Uplink Capability / Europa Day (Mbits)	3410
Required Uplink Rate (Mbit/s)	0.48
Available Uplink Rate (Mbit/s)	1.40
Margin in Uplink Capability (Includes a 3 dB Link Margin)	194%
Data Storage Reqt Based on Longest Eclipse (Mbits)	1160
Design Data Storage including 20% Margin (Mbits)	1400

8. COMMUNICATIONS

The ELM communications architecture would be designed to allow the lander to transmit all of its science and engineering data to JIMO for any landing latitude between $\pm 45^{\circ}$ (Fig. 8) and in any landing orientation (right-side up, upside-down, and in-between). The lander would utilize a pair of omni-directional antennas (one on each surface), to communicate with JIMO, and an SSR to buffer all data when JIMO is out of sight of the lander.

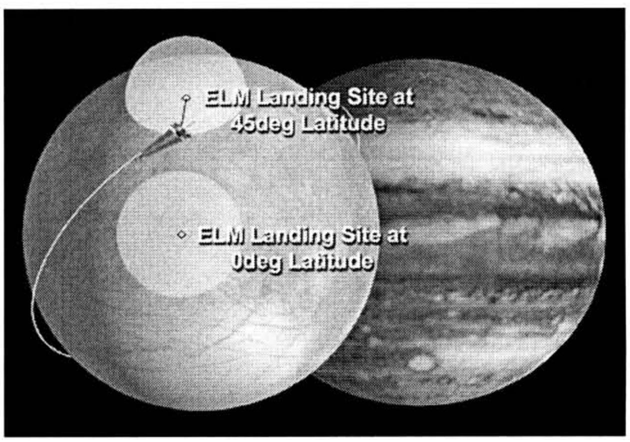

Figure 8. Communications Event Between ELM (at 45° latitude) and JIMO

Due to the orbital and geometric parameters of the mission, ELM-JIMO communication events would occur in groups (called cycles) of 5 to 14 (dependent upon landing latitude) and would take place over a relatively short duration (hours) as illustrated in Figure 9. These cycles would repeat with a period that is determined by the landing latitude, and range from 0.5 to 1 Europa day. The communications architecture would be designed such that all data generated between successive cycles would be uplinked to JIMO prior to the next interval.

The frequency and duration of communications events would be highly dependent upon the ELM landing latitude. As the latitude is decreased (towards 0°), the total number of JIMO over-flights of the landing vicinity would decrease, as illustrated in Figure 9. Quantitatively, there would be 10 possible ELM-JIMO communication opportunities per Europan day at 0° landing latitude, whereas there would be 14 possible opportunities at 45° latitude, assuming a minimum 5° line-of-sight (LOS) angle is required to close the link (Table 5 and Figure 9). Additionally, as the landing latitude is decreased, the average duration of the communications window would also decrease. The result is that the total amount of communications time during the surface mission would be lowest at the equator (710 minutes), and highest at 45° (1050 minutes). As the rate of data generation would be independent of latitude, the 0° latitude case represents the most stressing case from a data uplink perspective, and drives the minimum bandwidth requirement for the lander.

Table 5. Frequency and Duration of Comm. Events Versus Landing Latitude for the ELM Mission

	Lander Latitude	
Communication Parameter	**0 deg**	**45 deg**
# Comm. Cycles (Total Mission)	~17	~8
# Comm. Periods / Europa Day	10	14
# Comm. Periods (Total)	83	111
Comm. Duration (Total)	710 min.	1050 min.
Comm. Duration per Cycle (Avg)	43 min.	130 min.
Eclipse Duration per Cycle	43	84

Conversely, as the landing latitude was increased (to a maximum of 45°), the duration between successive communications cycles (called the eclipse period) would increase significantly (Fig. 9). Analyses show that a lander at 0° latitude would experience ~43 hours of eclipse, whereas 84 hours would be observed at 45° latitude. The 45° latitude case is the most stressing in terms of the volume of generated data, and thus would drive the solid-state recorder memory requirement.

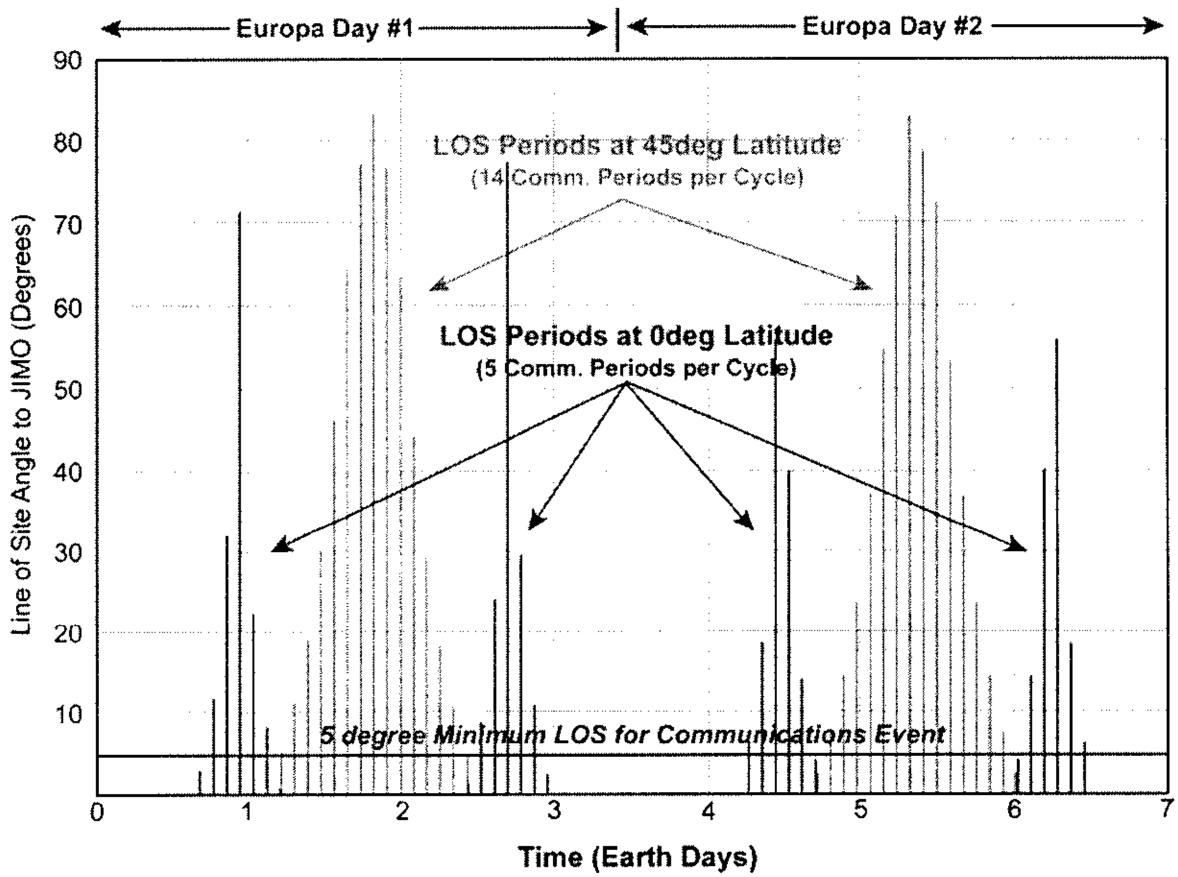

Figure 9. Elevation Line of Site (LOS) Angle between ELM and JIMO as a Function of Latitude and Time

9. THERMAL

A significant amount of thermal power would be required to maintain operational and survival temperatures during cruise and on the surface of Europa where the nighttime temperatures can drop to 85 K. The source of this thermal power would be the GPHS RPS that produces 225 Wt at EOL, and has a thermoelectric cold-shoe temperature of 155°C. Thermal control would be accomplished via a combination of conduction straps and thermal switches designed to keep critical electronics, batteries and subsystems warm. Heat rejection from the spacecraft would be performed via variable-emissivity radiators [8–10] whose emissivity could be actively varied between ~0.3 and 0.7 to maintain the desired temperature profile. The radiators would be mounted on both surfaces of the lander to ensure functionality regardless of landing orientation (Fig. 2). Heat rejection to the Europan surface would be made via conduction between the surface and lander structure, and thermal switches would manage the heat flow.

10. POWER

The proposed ELM would use a combination of RPS and secondary (rechargeable) batteries to supply power to the spacecraft during the mission. The power requirements, duty cycle, and operating duration of each system is presented in Table 6. To manage the spacecraft power draw, five distinct operating modes would be defined that correspond to specific sets of activities. The baseline modes would be *Standby*, *Basic Measurement*, *Raman Operation*, *LIBS Operation* and *Communications*. Each mode would have its own average and peak power draw and operating duration (Table 7 and Fig. 10).

The spacecraft power system would be sized to meet the demands of all modes, and would be driven by peak power requirements of the *Communications* mode (17.8 We), *Raman Measurement* mode (17.3 We) and *LIBS Measurement* mode (17.3 We). Because peak power utilization occurs infrequently, the total energy usage would be very modest and is estimated at ~3000 W-hr for the surface mission (Table 7). This corresponds to an average power level of 4.2 We that would be adequately supplied by a single-module GPHS RPS with 10.1 We (EOL) output.

Table 6. Proposed ELM System Power Levels, Duty Cycles and Operating Durations

System	Quantity	Power Draw (W/unit)	Power Draw All Units (W)	Duty Cycle	Avg Power Draw per Europa Day (W)	Operating Time per Europa Day (hrs)
Command Data and Handling						
System Flight computer	1	2.60	2.60	0.30	0.78	85.20
Peripheral Subsystem Interface	1	1.00	1.00	0.30	0.30	85.20
Power Distribution						
DC/DC Converter Card	1	3.00	3.00	0.30	0.90	85.20
Power Distribution Slice	1	2.20	2.20	0.30	0.66	85.20
Science Instruments						
Imager	1	0.20	0.20	1.00	0.20	0.24
Microseismometer	3	0.14	0.42	1.00	0.42	84.52
Raman Spectrometer	1	5.00	5.00	1.00	5.00	2.83
LIBS	1	5.00	5.00	1.00	5.00	2.83
Temperature Sensors	16	0.10	1.60	1.00	1.60	0.47
Radiation Sensors	4	0.10	0.40	1.00	0.40	84.52
Comm. Subsystem (JIMO Link)						
Transceiver (33% Efficient)	1	6.00	6.00	1.00	6.00	0.68
Data Storage						
Data Storage (SSR)	1	3.00	3.00	0.30	0.90	85.20

To handle the peak power demands, a small lithium-ion battery with a minimum 2.7 W-hr capacity would be used. The battery would discharge only during the transient periods where total load exceeds the RPS output; otherwise, the battery would be continually recharged by the RPS. The total energy margin using a single GPHS RPS would be 140%, which allows for uncertainty and limited future enhancements.

Table 7. ELM Operating Modes and Total Energy Requirement

Mode	Peak Power Draw (W)	Max GPHS Output Power (W)	Avg Power Draw (W)	Duration of Mode / Europa Day (hr)	Total Power Used During Mode (W-hr)
1: Standby	11.80	10.14	1.50	0.00	0.00
2: Basic Measurements	12.34	10.14	4.12	84.42	347.83
3: Raman Measurements	17.34	10.14	9.12	0.03	0.30
4. LIBS Measurements	17.34	10.14	9.12	0.07	0.61
5: Communications	17.80	10.14	7.50	0.68	5.07
Max (Peak Power Draw) (W)	**17.80**	**Energy Req'd / Europa Day (W-hr)**			**354**
Avg Power Draw (W)	**4.2**	**Total Energy Req'd (30 Earth Days)**			**2990**
GPHS Power Output (W)	**10.14**	**Total GPHS Energy Margin (%)**			**140%**

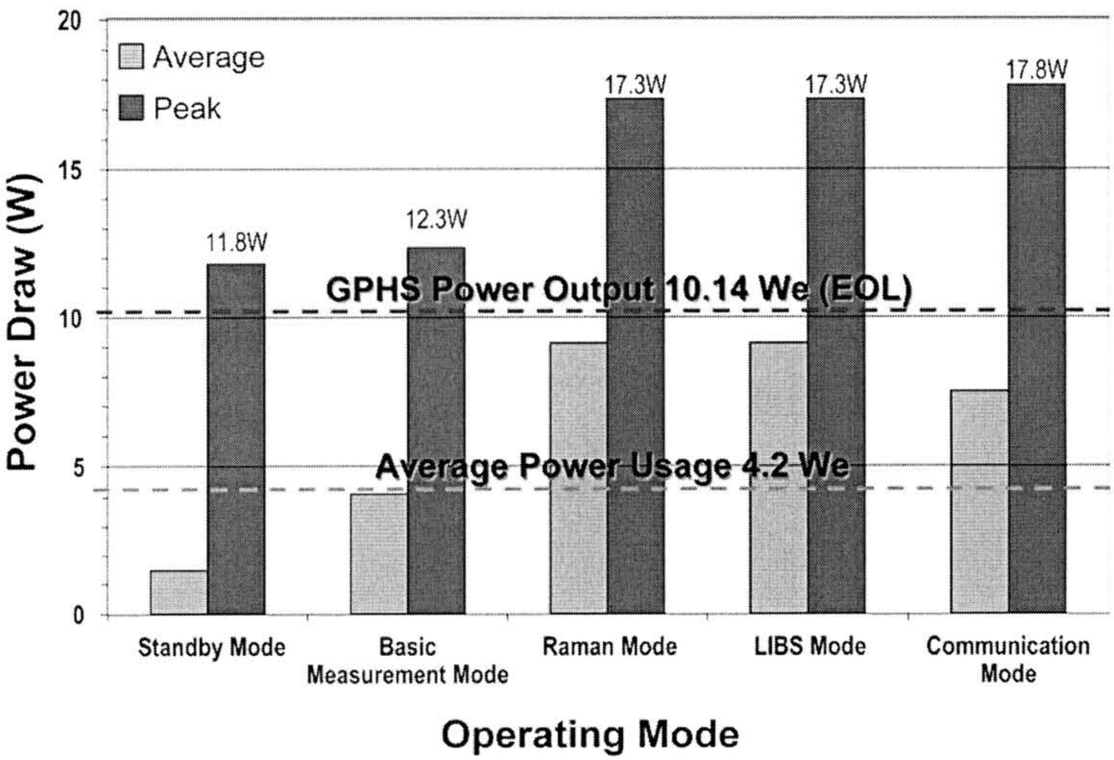

Figure 10. ELM Power Requirements (Peak and Average) for Each Operating Mode

11. MASS

The total mass of the ELM spacecraft would be ~230 kg, and includes the lander, dual propulsion stages, landing system (airbags, etc.), JIMO attachment system, and JIMO- mounted communications equipment (Table 8). The mass of the lander is estimated at ~40 kg, constituting 17% of the total spacecraft weight. The RPS power system is assumed to weigh 10 kg, and is extrapolated from conceptual RPS designs [7] upgraded to handle the expected landing loads. The total instrument mass allocation is 9.3 kg, and the heaviest instruments are the imagers, Raman spectroscope and LIBS.

Table 8. Mass Breakout of the ELM Spacecraft Systems and Subsystems*

Item	Qty	CBE (Kg)	Uncertainty (Kg)	Total CBE
Lander Payload				38.3
Command Data and Handling				**1.84**
System Flight Computer	1	0.50	0.08	0.58
Peripheral Subsystem Interface (PSI)	1	0.10	0.02	0.12
Bus	1	1.00	0.15	1.15
Power Distribution				**1.64**
Power Distribution Slice	1	0.49	0.05	0.54
DC/DC Converter Card	1	1.00	0.10	1.10
Power Generation and Storage				**10.77**
GPHS RPS	1	5.00	5.00	10.00
Batteries	1	0.10	0.01	0.11
Packaging	1	0.63	0.03	0.66
Pyro and Valve Control				**0.87**
Battery Charge Control	1	0.30	0.03	0.33
Prop Drive	1	0.49	0.05	0.54
Science Instruments				**9.30**
Seismometer	3	0.05	0.01	0.18
Imagers	16	0.20	0.04	3.84
Raman Spectrometer	1	2.00	0.40	2.40
LIBS	1	2.00	0.40	2.40
Radiation Sensor	4	0.10	0.02	0.48
Temp sensors	16	0.01	0.00	0.17
Telecom Subsystem				**3.30**
Transceiver	1	0.30	0.03	0.33
S-Band Antenna	6	0.25	0.03	1.65
Packaging	1	0.30	0.03	0.33
Coax Cables to antennas	6	0.15	0.02	0.99
G & C Sensors				**0.21**
Accelerometers	3	0.05	0.00	0.16
3-axis gyroscope	1	0.05	0.00	0.05
Thermal				**1.26**
Heater Elements	10	0.02	0.00	0.21
Insulation	1	1.00	0.05	1.05
Mechanical Systems				**10.00**
Structure	1	3.60	0.36	3.96
Covers	6	0.10	0.01	0.66
Misc (fasteners)	1	0.72	0.03	0.75
Cabling	1	0.60	0.03	0.63
Radiation Shielding	1	2.00	2.00	4.00

Item	Qty	CBE* (Kg)	Uncertainty (Kg)	Total CBE
Propulsion				**111.4**
Upper Desent Stage				13.7
Support and Separation Mechanism	3	1.00	0.05	3.15
Support structure	1	2.54	0.25	2.79
ARC Solid KS40B Thrusters (spin-up)	2	0.38	0.02	0.80
ARC Solid PAC-3 Thrusters (spin-down)	2	0.16	0.01	0.34
Hydrazine trim system	1	1.80	0.09	1.89
Star 5 rocket motor	1	4.50	0.23	4.73
Lower Desent Stage				97.7
Support and Separation Mechanism	3	1.00	0.05	3.15
Support Structure	1	5.70	0.57	6.27
Star 17 Motor	1	84.10	4.21	88.31
Thermal				**2.2**
Thermal Blankets	1	1.00	0.05	1.05
Temp sensors	10	0.01	0.00	0.11
Misc	1	1.00	0.05	1.05
Mechanical Systems				**13.9**
JIMO Attachment System	1	5.00	3.00	8.00
Ballest	1	5.00	0.50	5.50
Fasteners	1	0.40	0.01	0.41
Landing System				**61.0**
NSI - Gas Generator	3	1.00	0.05	3.15
Airbags	3	16.06	3.21	57.82
JIMO-Based Comm.system				**5.5**
Antenna	1	3.00	1.00	4.00
Gimbal	1	1.00	0.50	1.50
Net Spacecraft (EPF)*				**232.2**
Lander Mass (Total)				**38.3**
Propulsion Mass (Total)				**111.4**
Thermal Mass (Total)				**2.2**
Mechanical Systems Mass (Total)				**13.9**
Landing System Mass (Total)				**61.0**
JIMO-Based Comm. System				**5.5**

** The total spacecraft mass includes an effective 30% margin. This is because the mass estimates of the rocket motors and airbags used herein are for the previous heavier models of these two systems, whereas the new lighter models (using composite casings, etc.) would be used in an actual flight system [11]. The resultant mass savings could then be reallocated to increase the mass margins of the remaining subsystems.*

The dual propulsion stages (upper descent and lower descent) make up the bulk of the spacecraft mass at 111.4 kg, or 48%. The Star 17 solid rocket motor within the lower descent stage has the single greatest component mass at 88.3 kg due to the large delta V (1458 m/s) required at periapse (Section 3). The landing system, comprised of airbags and gas generators, has a total mass of 61 kg (26% of S/C total). The three air bags dominate the landing system mass, cumulatively weighing 57.8 kg.

The JIMO attachment system would include the struts and structure used to mount the ELM spacecraft to the JIMO mothership during the cruise phase. The mass of this system is estimated at approximately 14 kg. A supplemental JIMO-mounted communications system would be used to allow JIMO to exchange commands and data with the lander during descent orbital insertion (DOI) and during the surface science mission. This communications system would include a gimbaled parabolic antenna, transceiver electronics, mounting brackets, and all necessary power and data interfaces to the JIMO spacecraft. The mass of this communications system is estimated at 5.5 kg.

12. RADIATION

The ELM spacecraft would be required to operate in a range of extreme radiation environments that include externally produced (natural) and internally produced gammas, neutrons, and other high-energy particles (alphas, betas, etc.). Key sources of natural radiation include the Van Allen radiation belts traversed during the Earth spiral-out phase, cosmic radiation received during the multi-year cruise phase, radiation that would be generated by the JIMO reactor, and the intense radiation environment around Jupiter's inner moons. Internal radiation would be generated from the decay of the plutonium fuel within the GPHS module and from resulting secondary fission reactions that occur due to fuel impurities. The lifetime dose of the ELM spacecraft from natural radiation would be ~6 MRad, and assumes 100 mils of aluminum shielding [12]. The majority of this radiation would be received in proximity to Jupiter's moons, particularly during Europa spiral-in, where Jupiter's radiation field is very strong (Fig. 11). Once landed on Europa, ELM would benefit from the shielding properties of this moon and would receive a marginal ~400 kRad during the surface mission. To mitigate the effects of natural radiation, potential strategies include housing ELM in a JIMO-mounted radiation shelter (thus reducing the received natural dose), using localized spot shielding around critical components, and employing radiation hardened electronics that can tolerate doses up to 1 MRad. The use of a radiation shelter and spot shielding could potentially

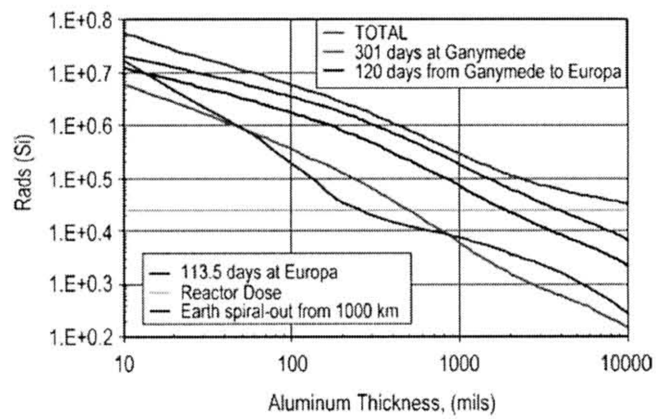

Figure 11. Natural Radiation Dose (4-Pi) Received by the JIMO Spacecraft Versus Shielding Thickness [12]

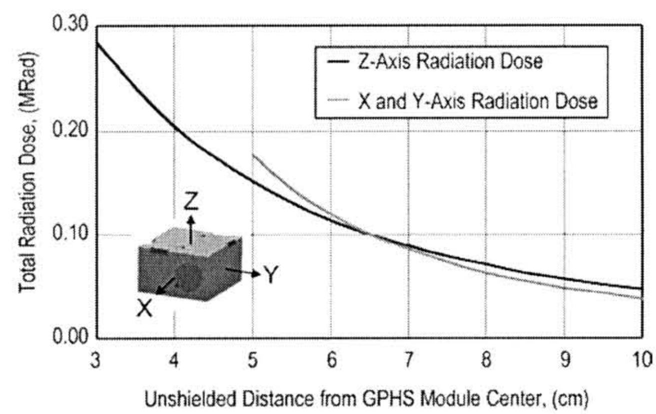

Figure 12. Lifetime (13-year) Radiation Dose Generated by a GPHS Module Versus Distance [13]

reduce the ELM lifetime external dose to <1 MRad, making the mission potentially feasible with radiation-hardened parts. ELM would capitalize on the JIMO radiation technology currently being studied, and would utilize similar mitigation schemes as appropriate.

The magnitude of the internally generated GPHS radiation dose would be significantly lower than that received from natural sources (by more than an order of magnitude), and would be highly dependent upon the distance between the GPHS and the "target" component [13]. The intensity of the dose falls off quickly with distance from the GPHS module due to geometric attenuation (Fig. 12) and structural attenuation through the spacecraft. With judicious placement of sensitive subsystems and components, the total lifetime internal dose could be reduced to <100 kRad

13. ALTERNATE RPS POWER SYSTEMS

The baseline ELM design would be powered by a single GPHS-based RPS with PbTe–TAGS thermoelectric conversion, which is assumed capable of generating 10.1 We at EOL. A small supplemental battery would be used to meet peak power demands (maximum of 17.8 We) during LIBS, Raman spectrometry and communication events. In addition to this baseline design, three alternate RPS concepts were considered that could generate enough power to eliminate the need for a battery.

The first concept would use two GPHS-based RPSs with PbTe–TAGS thermoelectrics, and would generate 20.2 We at BOL. This RPS configuration would meet all ELM power requirements without the need for a supplementary battery; however, this larger RPS system would require a redesigned spacecraft that is larger in both size and mass. Additionally, the ability to reject the increased amount of waste heat could pose a significant challenge to the ELM thermal control system.

The second concept would use a single GPHS-based RPS with higher-efficiency (9%) thermoelectric converters (e.g., segmented PbTe–TAGS/BiTe). This RPS configuration could generate ~18 We (EOL) which would be sufficient to meet all power requirements without a battery. Studies have been performed by the DOE [14] that suggest this RPS configuration may be attainable in the near future.

The third concept uses a fractional GPHS-based RPS with a conceptual high-efficiency Stirling convertor (20%). This RPS could produce 18 We (EOL) using just two GPHS fuel capsules. However, the Stirling convertor would need to be sufficiently vibration-free to prevent interference with microseismometer measurements, and the fractional GPHS (with a redesigned aeroshell) would need to be developed.

14. ADDITIONAL RPS-ENABLED LANDER MISSIONS

The design of the ELM spacecraft and its small-RPS power source is somewhat generic and could potentially be utilized for missions to other planetary bodies with minimal modification. Examples include missions to the outer Galilean satellites Callisto and Ganymede, using either the JIMO spacecraft as transport and communications relay to Earth, or a dedicated orbiting satellite that would perform an analogous function. One preliminary version of the JIMO mission could include a nominal 60 day science orbit around Callisto and a 120 day science orbit around Ganymede [4]. A variant of the ELM spacecraft, with its long-lived small-RPS power source, would be sufficiently capable of performing the analogous surface science mission on either of these moons, both of which are of high scientific interest.

Other lander-class missions potentially enabled by small-RPS technology include landers for outer solar system planetary bodies, including moons, Pluto, asteroids and comets. These missions could have different science payloads using similar power requirements as the ELM mission. Lunar human-precursor missions could also be enabled by a small-RPS, with its ability to operate continuously, independent of solar insolation, at the lunar poles and in craters that are permanently shadowed. Mars network landers, Scout-class rough landers, and Mars human precursor landers are additional missions that could potentially benefit from small-RPS technology.

15. SUMMARY AND CONCLUSIONS

Europa is a high-priority target for future space exploration, as it may possess a subsurface liquid ocean that could sustain life. The ELM mission is designed to land on Europa and take in-situ measurements for a nominal period of 30 Earth days, in order to meet the science objectives defined by the JIMO Science Definition Team [2]. Due to Europa's vast distance from the Sun, long cruise phase and surface mission duration, small-RPS would provide unique capabilities not possible with conventional power sources.

The small-RPS used in the ELM concept is a conceptual design based on a single GPHS module using thermoelectric conversion with 5% system efficiency to produce 10.1 We at end of life. This RPS configuration would provide a 140% energy margin, and employ a small Li-Ion battery to carry the peak loads during high-power operations, i.e., communications events, Raman spectrometry and LIBS. The small-RPS would need to be designed to withstand the 600-g acceleration load incurred by the spacecraft during landing.

In conclusion, ELM is a high-value science mission that could potentially be enabled by small-RPS technology.

ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors wish to acknowledge the efforts and contributions of the following individuals:

JPL Europa Pathfinder Team (JPL)
Wayne Zimmerman (JPL)
Jacklyn Green (JPL)
Bob Carpenter (JPL)
Insoo Jun (JPL)
Ellis Miner (JPL)
John Elliott (JPL)
Tom Spilker (JPL)
Erik Nilsen (JPL)
Bill Nesmith (JPL)
Rao Surampudi (JPL)

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