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EXPLORING TRITON WITH MULTIPLE LANDERS

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ABSTRACT

In our pathway for Outer Planetary Exploration several mission concepts were considered, based on the proposed JIMO mission architecture. This paper describes a JIMO follow-on mission concept to Neptunes largest moon. Triton is a target of interest for outer solar system studies. It has a highly inclined retrograde orbit, suggesting that it may have been a Kuiper Belt object captured by Neptune. Given this assumption its composition, which may include organic materials, would be of significant scientific interest. The present concept considers a surface mission architecture with two landers, each powered by a standard multi-mission radioisotope thermoelectric generator (MMRTG). The landers would operate on the surface for several years providing science data, thus expanding our understanding of the environment, the dynamic surface and atmospheric processes, and some of the seasonal variations. A JIMO class orbiter would provide telecommunication link between the landers and Earth, and would be instrumented to observe both Triton and Neptune. In this paper all key aspects of the mission architecture are addressed, including the science instruments, the main subsystems, trade options for the power system and a conceptual design for the landers.

INTRODUCTION

The Vision for Space Exploration [1] identifies three major exploration pathways, targeting Mars, the Moon and the Outer Planets. Within this roadmap the first planned science mission to the Outer Planets was the Jupiter Icy Moons Orbiter (JIMO) mission. Potential JIMO follow-on missions were envisioned to target other outer planetary destinations, such as Saturn, Neptune or Pluto. This paper describes a landed mission concept to Neptune's largest moon, Triton, with the aim of expanding our incomplete knowledge of the Neptunian system, which is based on the August 25, 1989 flyby of the Voyager 2 spacecraft and on more recent Earth and space-based observations.

Since the completion of this study, the JIMO mission has been deferred. Although this Triton lander concept baselined a JIMO follow-on architecture, alternatives were also addressed. Thus, this generic lander concept is not dependent on JIMO follow-on architectures and could be considered as a "black box" concept for other Neptune/Triton exploration missions.

SCIENCE AND MISSION GOALS

Triton is a target of great interest for outer solar system studies. Thus, potential *science objectives* for a Triton lander mission would include a more complete characterization of the composition and circulation of the atmosphere; investigation of the physical processes responsible for plume formation; surface composition measurements; and geophysical monitoring. In particular, seismological measurements could potentially refine our knowledge of the physics of plume eruptions, and could detect Triton-quakes, if such are occurring at the present time. A pair of landers, one located in the summer hemisphere and the other in the winter hemisphere, could collect complementary information

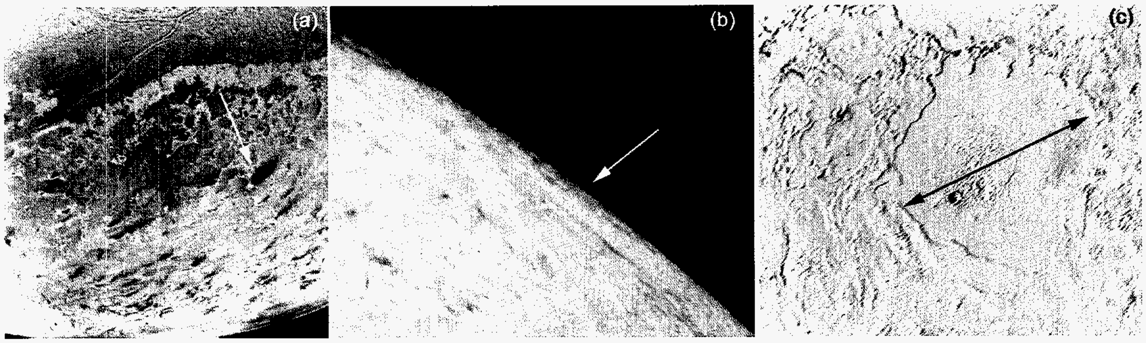

Figure 1: Triton images: (a) South Pole; (b) Tenuous Clouds; (c) Icy-slurry filled crater.

on atmospheric processes and on the interior structure. It would be very desirable to land atop one of the dark streaks (Figure 1(a)), in order to perform in-situ compositional analyses. This information would help constrain models of the physics of plume eruptions (Figure 1(b)) on this exceedingly cold, icy body.

The complement of instruments for such a landed mission could include a sophisticated weather station (pressure, wind, and temperature measurements), along with an imaging system and a micro-seismometer system. Remote or contact instruments for determining the compositions of surface materials would also have high priority. Last but not least, a separate instrument for determining the atmospheric composition (a mass spectrometer of some type) should be included.

Although not described here in detail, the accompanying orbiter should likewise carry instrumentation to measure the magnetic field (if any) and to determine the internal structure through gravity measurements. (The latter would be a radio science investigation employing the communications signal from the spacecraft to the Earth). Imaging, remote sensing of surface composition, and fields and particles instruments appropriate for Neptune's magnetospheric environment should also be considered. Remote measurements of surface composition may be difficult due to the extremely low surface temperature; active illumination of the surface might be required. Further details on Triton can be found in [2].

The *mission goals* for this Triton lander mission would include a successful landing of one but preferably two spacecraft on the surface followed by a long duration surface science operation (measured in years) to characterize the environment and to extend our knowledge base on the Neptunian system. Measurements would be taken to identify mineral composition in the vicinity of the landing site. Seismic activity and geyser eruptions would be monitored as well. Visual observations would be taken and local meteorological conditions could be monitored over a long duty cycle in order to characterize seasonal changes through a small portion of a Neptunian year.

MISSION ARCHITECTURE OVERVIEW AND ASSUMPTIONS

The primary architecture assumes a JIMO follow-on configuration utilizing a low thrust nuclear electric propulsion (NEP) system, with the mission referred to as the Neptune Icy Moon Orbiter or NIMO. The NIMO spacecraft, just as its predecessor, would require a heavy launch capability, which does not exists at this time. The various launch options could include a number of Delta IV-H LVs and in orbit assembly or a single heavy LV with a Saturn LV capability. Although this study will focus on this primary configuration, a second high thrust trajectory based architecture will be also mentioned for comparison purposes. The various mission architecture options are summarized in Table 1.

Option	Comments
Baseline (NIMO)	300 kWe fission reactor; Low thrust through all stages; Payload: ~3000 kg; Trip time: ~15 years to Neptune (+ 3 years orbit transfer to Triton)
Chemical / SEP (Low C3 / High mass)	C3=12.1 km^2/s^2; SEP: 50 kWe; Payload: ~1940 kg; Trip time: ~12.5 years
Chemical / SEP (High C3 / Low mass)	C3=18.4 km^2/s^2; SEP: 30 kWe; Payload: ~790 kg; Trip time: ~10.25 years
JIMO class launcher for the baseline option	(a) multiple launches plus in orbit assembly (b) Saturn class launch vehicle

Table 1: Mission architecture options for a Triton lander mission.

Baseline Architecture

It is assumed that a 300 kWe nuclear reactor would power NIMO, built upon the 100 kWe JIMO heritage. NEP enables the highest mass delivery, but results in the longest transfer time when compared against high thrust trajectories. Venus and Jupiter gravity assists could further reduce the trip time to Neptune. A NEP enabled mission to Neptune would take about 15 years, which includes spiraling out of Earth and spiraling in to Neptune. It would take an additional 3 years to reach orbit around Triton. JIMO's currently proposed payload allocation is 1500 kg. Since the NIMO spacecraft would only pass Jupiter during a gravity assist flyby, the high radiation environment of the Jovian system would not have a significant effect on it. Thus the mass allocated on JIMO for shielding could, in part, be reallocated as payload on NIMO. (Note that mass differences will in part be a function of the size of the power system, and more importantly will reflect differences in the propellant needs to account for traveling about 6 times farther from the Sun to Neptune than JIMO's journey to Jupiter.) Increasing the payload envelope to as high as 3000 kg could be assumed for the present mission, effectively supporting two landers on Triton and still allowing for additional science instruments on the orbiter for remote sensing / mapping of Triton and for observing Neptune from Triton's orbit. Since the present mission concept focuses on the landers, it is assumed that NIMO is already in a 1500 km circular orbit around Triton with a suitable payload allocation for two landers. Therefore, details of the NEP enabled low thrust trajectory from launch to arrival are not addressed due to the limited scope of this study.

According to the primary mission configuration, NIMO would achieve a 1500 km circular orbit around Triton and spend the first weeks mapping the surface. The returned data would enable the science team on Earth to select suitable landing locations for the two landers for a "stop-and-drop" type landing. Each lander would de-orbit to the surface using the lander's own propulsion system. An initial 137 m/s small de-orbit burn would lower the lander's periapsis to about 20 km, where a large 1200 m/s burn would remove the horizontal velocity. Soft landing would re-quire a small 195 m/s throttled burn from the bi-propellant system, assisted further by a sky-crane, which would be based on 2009 Mars Science Laboratory (MSL) concept. Lowering the landing platform from a skycrane could help with minimizing surface contamination from the impinging exhaust of the thrusters. Once the lander was released, the skycrane platform would disengage and crash land at a safe distance from the payload base. Soft landing was selected for two reasons. First, when landing on an airless body the option for an aeroshell and parachutes is not feasible, thus all or at least most of the velocity must be removed through propulsive means. (From the aspects of descent and landing, Triton, with its very thin atmosphere, can be considered an airless body.) Further to this, the fuel mass saving from cutting off the engine at a few kilometer altitude, free falling

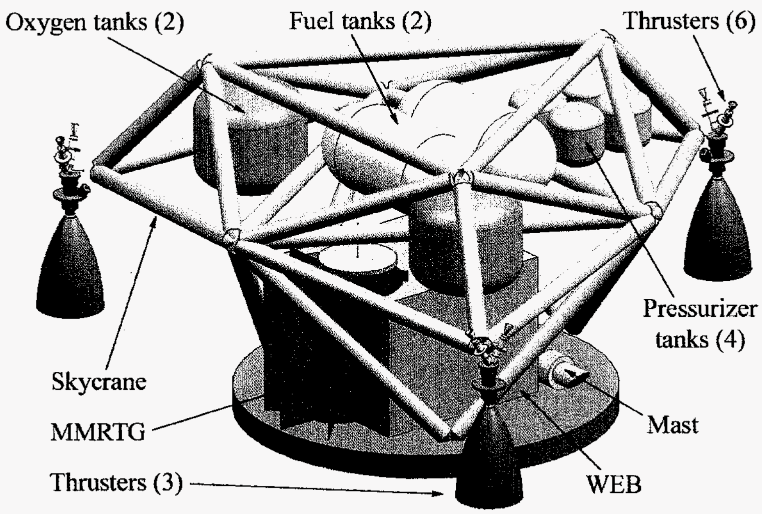

Figure 2: Triton lander with a skycrane platform

and landing with airbags is significantly less than the additional mass required for an second landing system, such as airbags for hard landing or crushable mate-rials for rough landing. Therefore, as demonstrated by Balint [3] adding a second landing system, such as airbags similar to the landing configuration of the Mars Exploration Rovers [4], or crushable materials such as proposed for the Mars Net Landers [5] would decrease the landed payload mass. Second, the power source proposed for this mission, a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), is designed for a maximum acceleration load tolerance of about 40g. Therefore, on Triton soft landing presents the only viable mass effective landing configuration with the given power source. A conceptual design of the Triton lander with the skycrane, thrusters and propulsion system is shown in Figure 2.

As discussed above the first lander would touch down on the illuminated side of Triton, such as the South Pole shown in Figure 1(a). The landing location could be either inside or outside of the dark streaks. Another potential landing location could be inside the remains of an ancient impact crater that is thought to be filled with ice, probably formed by eruptions of water or water-ammonia slurry (Figure 1(c)).

The second lander would touch down on the opposite side of the moon, which would allow for studying atmospheric processes such as potential migration of atmospheric constituents from the illuminated side to the dark side of Triton.

The environment on the surface of Triton is harsh. Therefore, the lander concepts are designed with the philosophy of simplicity and reliability in mind to meet mission lifetime requirements using an appropriate combination of high-reliability components and dual-string design. The very long 18 years cruise phase combined with the 38K surface temperature makes mobility with a rover or even with a robotic arm undesirable. Thermal cycling or freezing could cause an early end to a long awaited mission. Upon arrival to the surface, the lander would initiate the investigations of science targets. First it would deploy its only mobile component, the mast, on which the panoramic camera (Pan Cam) and remote sensing instruments (Raman Spectrometer / Laser Induced Breakdown Spectrometer or LIBS) are located. Good contact with the surface would allow for seismic measurements. A meteorology sensor suite would monitor the temperature and pressure changes in the atmosphere, while a Gas Chromatograph / Mass Spectrometer (GCMS) would make compositional measurements. Details on the instruments and their operations are given in the relevant sections below. To minimize risk, the lander design would use as much design and flight mission heritage as possible from previous outer planets orbiters and landers.

Additional Architectures

In comparison with the baseline concept using NEP, a chemical propulsion system combined with a 30 kWe solar electric propulsion (SEP) system, could reduce the trip time from ~15 years to ~10.25 years. Due to the distance between Earth and Neptune, the trajectory would require a high C3. Since Triton's gravity is very small, Neptune's gravity field would be used to capture the spacecraft. From there the orbit would be changed to an orbit around Triton, still with the propulsion system of the mother spacecraft. Such a mission is expected to utilize a significantly sized propulsion system for the orbiter/mother spacecraft. For this baseline trajectory the spacecraft would be launched on a C3 of 18.4 km^2/s^2, followed by a Venus and a Jupiter Gravity Assist (VJGA). The inertial entry velocity for a Neptune aerocapture, in the range of 28-30 km/s, would offer the best combination of highest delivered mass to a Neptunian orbit with the lowest entry heating. Although this second option would cut trip time by about a third and would be achievable with available Delta IV-H or Atlas V launch vehicles, the deliverable total mass to Neptune's orbit would be only around 790 kg [6] [7]. This mass is not sufficient for a Neptune-to-Triton orbit transfer while still supporting an orbiter and a lander at Triton. With the reduction of C3 velocity from 18.4 km^2/s^2 to 12.1 km^2/s^2 (with V_{inf}=12.8 km/s) and scaling up to a 50 kWe SEP stage (with 2800 kg wet mass), about 3330 kg could be inserted into Neptune's orbit on a 2017 launch opportunity. This is based on a Delta IV-H launch vehicle with a 7250 kg payload mass inserted to a C3 of 12.1 km^2/s^2; a 12.5-year VJGA trajectory; and an advanced aerocapture vehicle (<1250 kg). (Note that for this C3 the maximum payload on a Delta IV 4050-H launch vehicle is 7510 kg [8].) Following an orbit transfer to Triton the total mass of the spacecraft would be around 1940 kg. Assuming an approximately 900 kg lander the spacecraft in orbit could only support one lander and an approximately 1000 kg orbiter. This configuration would not fully satisfy the science goals of the mission. Although this option was not selected, the velocity and propellant mass calculations for the lander shown in Table 2 would be the same as for the primary mission configuration.

Note that this second mission architecture would be more power limited. Due to an average 30 AU distance from Triton to Earth, telecommunication would present a significant challenge, requiring power in the multi hundred-watt range. For example 3 MMRTGs could provide about 250 We power to the orbiter after 18 years. In summary, this second architecture would require 4 MMRTGs, between the orbiter and a single lander.

A summary of the various mission architectures is provided in Table 1. For the chemical / SEP options the SEP stage would be ejected at Jupiter and the S/C would utilize aerocapture at Neptune. The baseline option would require one of the launcher options, while the chemical/SEP options would use a single Delta IV-H launch vehicle.

SCIENCE INSTRUMENTS

The lander concept shown in Figure 2 was designed to fulfill the key science objectives of the mission. Potential instruments on the lander can be broken down to three categories, such as remote sensing, contact and analytical suites. Remote sensing instruments are located on the mast and include a panoramic camera (Pan Cam), and sensors for a Raman spectrometer and a Laser Induced Breakdown Spectrometer (LIBS). Contact instruments are the seismometer and, to a certain extent, the meteorology station. The Gas Chromatograph & Mass Spectrometer (GC/MS) is an analytical instrument. All of these instruments must have sufficient sensitivity to measure the relevant environmental conditions. After describing the instruments shown in the Triton lander concept drawing (Figure 3), additional potential instruments will be considered. These might be placed either on the lander or NIMO on the orbiter.

The imaging system, a MER derivative panoramic camera, is located at the top of the

Item	Delta V (m/s)	Required Mass (kg)	Total Mass (kg)
Initial payload mass at launch to C3	⊗	⊗	**7250**
Mass to place into Neptune orbit	⊗	**3460**	**3790**
SEP module (wet mass)	n/a	2800	⊗
(ejected before aerocapture)			⊗
Cruise propellant	25	70	⊗
Neptune aerocapture aeroshell / TPS	n/a	400	⊗
(discarded after aeropassage)			⊗
Aerocapture control	30	40	⊗
Neptune Perineps Raise to 4000 km	110	120	⊗
(including 3% gravity loss)			⊗
Neptune Aponeps Correction	40	30	⊗
(358,000 km Neptune orbit)			⊗
From Neptune orbit to Triton orbit			
Insert to 1500 km circular Triton orbit	2800	**1850**	**1940**
Orbiter mass at lander-orbiter separation & mass available for lander	n/a	**1000**	**940**
From Triton Orbit to surface (propellant only to land 300 kg payload, including the propulsion system dry mass for tanks, thrusters etc., and 30% contingency)			
Lander de-orbit burn	137	37	⊗
(to a 1500 km by 20 km orbit)			⊗
Triton Pericenter Burn	1200	241	⊗
(including 2% gravity loss)			⊗
Soft landing (incl. 10% gravity loss)	195	28	⊗
Attitude Control Allotment (total)	n/a	15	⊗
Propulsion system dry mass	n/a	97	⊗

Table 2: Mass allocation and Delta V requirements for a Chemical / SEP system. [9]

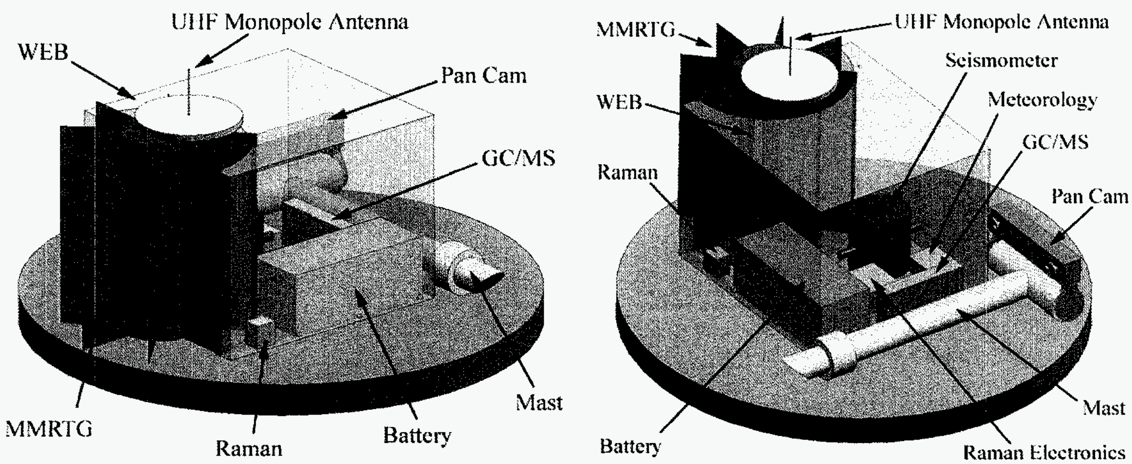

Figure 3: Triton Lander Instrumentation

mast. The high-resolution stereoscopic camera provides needed context and aids in characterizing the geomorphology of the surface through the generation of terrain maps, slope maps and ranging. It can generate 360° panoramas and multi-spectral images of the surface, which helps to characterize the nature of the materials sampled with other instruments. Thus in effect the Pan Cam would work in conjunction with the Raman spectrometer and with the LIBS. The Pan Cam camera is at TRL9.

The combined Raman spectrometer and LIBS system could measure elemental abundance and mineralogy of surface materials. By actively stimulating the target these instruments avoid the negative consequences of the low surface temperature that reduce the capabilities of TES and other IR-sensitive instruments. The Raman spectrometer fulfills the astrobiology driven science goals by performing mineral characterization and assisting in the detection of water, organic and inorganic forms of carbon. It identifies many major, minor and trace minerals and their relative proportions (i.e., Mg/Fe ratios), and carbon ratios. Sharp Raman spectral features and statistical point counting help identify minerals in complex mixtures and morphologies. LIBS would use a higher energy excitation of the surface than Raman, consequently ablating the studied surface. Compositional information would be drawn from spectral analysis of the resulting plasma. The instrument is based on the Mars Microbeam Raman Spectrometer, currently at TRL4. LIBS is proposed for upcoming Mars missions and is at TRL5.

The lander would be equipped with a two-component seismometer measuring both high and low frequencies. The 2-axis very broadband seismometer would capture tidal and long period motions up to 10 Hz. The 3-axis short period micro-seismometer would measure high frequency movements from 1 Hz to 50 Hz. The two sets of seismometers would achieve the highest sensitivity in an ultra broad band from 5×10-5 Hz to 50 Hz. In addition, a partial redundancy would be achieved due to their significant overlap in frequency band. Triton's geysers produce plumes rising several kilometers in height. Like geysers on Earth, these must produce seismic waves within crustal materials, which could be measured with this seismometer. Detection and analysis of seismic energy can provide information on the eruptive processes (their energy, frequency, time evolution) and on the properties of crustal materials traversed by the waves. This proposed seismometer is currently at TRL4.

Triton is one of two satellites in the solar system with an appreciable atmosphere, beside Saturn's moon Titan. Every aspect of this frigid atmosphere is of scientific interest: its composition, its circulation, its exchange processes with the surface, its evolution with time. A pair of sophisticated weather stations situated in opposite hemispheres could yield a very significant science return. The very cold environment and thin atmosphere requires significant modifications to the sensitivity of existing weather monitoring equipment. Such instruments are at TRL5.

The gas chromatograph & mass spectrometer (GC/MS) measures isotopic gas ratios of trace atmospheric components. If a sampling mechanism were implemented, the GC/MS could be used to identify the presence of organics as well as mass spectra and isotopic ratios of evolved gas constituents from rock and soil samples. The instrument is proposed for upcoming Mars missions and is currently at TRL5/TRL6.

Although not included in this concept, additional instruments on the lander and orbiter could also be considered. For example on the lander a small sampling mechanism in the form of a robotic arm with a scoop could be used to position the contact instruments (Raman, LIBS) closer to the target objects. If a sample acquisition (scoop) is included, then the collected sample could be analyzed by a Thermal and Evolved Gas Analyzer (TEGA). TEGA offers a more complete characterization of the volatile component of surface materials than is possible with Raman and LIBS. However, TEGA is heavier and more complex than a simple oven to heat the samples and analyze them by the GC/MS. Sample handling introduces additional complexities especially in a cold environment as Triton, hence this is not included in the present concept. Beside LIBS, a heat lamp or conducting fins could warm the surface near the lander. Heating or thawing the surface could potentially initiate small geyser-like eruptions after creating a sub-surface greenhouse effect.

On the orbiter, an Ion and Neutral Mass Spectrometer (INMS) could directly sample the tenuous atmosphere surrounding Triton. It could confirm the presence of the major gases and could detect others (not yet known to be present) in the atmosphere. The orbiter should carry additional atmospheric remote sensing instruments to fully characterize the composition of the atmosphere, such as (LIDAR) radar; ground penetrating radar; cameras; and a Thermal Emission Spectrometer (TES). (Note that thermal emissions at 38K are very low, compared to the ~150K on Mars. Therefore, TES at Triton may not have the sensitivity to perform meaningful measurements.)

POWER SOURCE SELECTION

This section discusses power source trade options, radioisotope power system characteristics used for the baseline configuration and describes alternative RPS options.

Power Source Trade Study

Insolation decreases with one over distance squared from the Sun. In fact, at Neptune (30 AU from the Sun) solar radiation is only about 0.1% of that at Earth. It has been shown in [10] that beyond ~3-4 AU solar power generation with current technology is less mass efficient than power generation with RPSs. Low Intensity Low Temperature, or LILT, solar panel technology – which is planned for the Juno spacecraft to Jupiter – could potentially work at 5 AU, but beyond that it could be mass prohibitive and likely not feasible. Consequently, missions to Jupiter and beyond (such as to the Neptunian system) require a different kind of power source, independent from the Sun. Batteries may support limited duration mission operations, however, longer missions require nuclear fission or radioisotope decay-based power systems. Beside an MMRTG, a lander mission to the Neptunian system could utilize a Stirling Radioisotope Generator (SRG) or a small fission reactor. SRG-110 is a 110 W (BOL) Stirling system under development with a TRL9 target date of 2009. It is based on two GPHS modules and two pistons positioned head-to-head, resulting in a significantly lower Pu^{238} fuel requirement than the 8 module based MMRTG. With fewer GPHS modules the thermal output of the SRG would also be reduced by 75%, to about 500 Wt (BOL). However, with an MMRTG more waste heat would be available to heat the spacecraft, which is more desirable on the present mission. It should be also noted that both the MMRTG and the SRG have the same 14 years life-time requirement [11] [12], while the proposed Triton mission would have a mission life over 18 years. Outer planets missions should address and resolve mission lifetime issues in this context. Small fission reactors, for example a HOMER type reactor, could generate ~3 kWe of power. A small 3 kWe surface reactor with Stirling power converter could weight about 775 kg [13]. This power and mass configuration is beyond the power requirements and mass limits of a Triton lander mission. Therefore, fission reactors are not considered as power source alternatives. (Note that, a fission reactor can remain inactive until the beginning of the surface operation. During the inactive "cold" phase the system produces negligible radiation and is not affected by the long cruise phase.)

Although not the focus of this study and therefore not discussed in detail, the NIMO orbiter would perform remote sensing measurements to characterize Triton and Neptune. On NIMO, the onboard 300 We nuclear reactor would power the science instruments. Other subsystems such as telecom and command and data handling would also be supported. Thus, the baseline mission architecture would rely on a nuclear reactor on the NIMO orbiter and two MMRTGs on the two landers.

RPS Characteristics

Each lander would use a single MMRTG. It is required that the power system should operate continuously during the entire mission, which includes ~15 years of cruise phase to Neptune and about 3 additional years to reach Triton's orbit. During these 18 years the power generated by the MMRTG would degrade by about 1.6% per year. Half of it is due to natural decay of the plutonium fuel and the other half is to degradation of the thermoelectrics. Thus at the beginning of the science mission, defined by landing on Triton, the generated electrical and thermal power would be only ~82.6 We and ~1735 Wt, respectively. During surface operation, the power would continue to decrease at a rate of about 1.2 We/year. Soft landing on Triton would impart acceleration loads on the MMRTG within design limits. Waste heat would be utilized through radiation from the MMRTG to a hot plate of the warm electronic box (WEB), and through conduction along the MMRTG fins and thermal straps from the power source to the WEB. Consequently, the present design would benefit from two of the advantages of an RPS, namely continuous electrical power generation and utilization of its excess heat.

Alternative RPS Power System

Small radioisotope power systems with TE conversion, in a modular configuration, could be considered for a Triton lander mission. However, the minimum number of small-RPSs required to support a Triton lander mission would be close to the number of GPHS modules in an MMRTG.. The mission could also consider SRGs, providing the same electric power output as the MMRTG. However, an MMRTG would generate four times more heat than an SRG,, providing an advantage at the cold Triton environment through waste heat utilization. Therefore, an MMRTG is considered the best choice for a Triton lander mission in order to reduce complexity and potentially lower cost through the use of a single system.

OPERATIONS AND ENVIRONMENTS

This sections discusses operational issues, such as power requirements, data collection and communications, and thermal and radiation environments.

Power Issues

Each lander would utilize an MMRTG for electrical power. In addition, a 25 Ahr Li-Ion battery would provide backup during high power operating modes, such as during telecom opportunities. Power calculations for a 3-day repeatable mission scenario with an 82 We continuous power source demonstrated that the present hybrid system would provide sufficient power to the lander and would keep the secondary battery power positive. This would permit a repeatable cycle lander operations through the whole mission lifetime. In the power analysis three operational modes were considered. In high power mode all science instruments and support subsystems would work simultaneously. In low power mode, some of the instruments would not be operated, such as the Raman spectrometer, LIBS and the GC/MS. In telecom mode the UHF transmitter would operate in conjunction with the power, electronics and thermal subsystems. Science instruments designated as "Always on// would be also operational throughout all three modes, as shown in Table 3. The electronics subsystem would provide permanent support to the instruments, by processing the collected information, storing it and sending it to NIMO through the telecom system (10.4 We). The power subsystem would use 15.4 We to power the peripheral control unit (PCU), the power distribution unit (PDU), the battery control, the universal switch and the shunt limiter. Thermal heaters would also be used continuously (5.9 We) to keep the Pan Cam and the warm electronics box above survival temperature. The telecom system would use 52 We of power but only during the telecom opportunities.
The power analysis confirmed that an MMRTG enabled lander to Triton would be feasible.

Data and Communications Issues

The command and data handling system, assumed to be a dual string Harris RH3000 electronics unit with radiation tolerance over 100 kRad, is sized by the data collected from the science instruments and communicated to NIMO during the telecom opportunities. The highest data volume would be generated by the seismometer, which would collect up to 16.6 kbits/sec and would operate continuously. The collected data would include both high and low frequency measurements. This data volume could be significantly reduced by data compression and by stand-by monitoring of the activi-

Instrument/Subsystem	Power	Duty cycle
Panoramic Camera	5.6 We	1 hour on demand
Raman Spectrometer	23.4 We	2-3 hours
LIBS	23.4 We	2-3 hours
Seismometer	3.5 We	Always on
Meteorology sensors	1.4 We	Always on
GC/MS	11 We	8 hours total
Harris Electronics	10.4 We	Always on
Power subsystem	15.4 We	Always on
Telecom	52 We	1 hr / day (max)
Thermal heaters	5.9 We	Always on

Table 3: Power requirements (with 30% contingency).

Instrument/Subsystem	Data rate
Panoramic Camera	50.4 Mbits/frame raw. Average compression ~3:1; 12 frames required for a full panorama
Raman Spectrometer	17 kbit / spectra (raw), 50 Raman spectra per hour
LIBS	Similar to Raman
Seismometer	16.6 kbits/sec
Meteorology sensors	Few kbits / hour
GC/MS	~10 kbits per mass spectra (MS); ~200 kbits per evolved gas sample (GC)

Table 4: Data rate.

Systems	CBE Mass (kg)	CBE Mass + 30% cont. (kg)
Propulsion System	321.5	418
Structures & Mechanisms	135.0	175.5
Power System	77.1	100.2
Thermal System	7.9	10.3
Avionics	2.2	2.9
Telecom	8.3	10.8
Science Instruments	12.4	16.2
Total	564.5	733.8

Table 5: Triton Lander mass Breakdown.

ties. For time periods without seismic activity the data handling system would simply discard the data. In case of an activity, a memory loop would retain the immediate time period prior to the event and record throughout the activity. The Pan Cam would take 12 frames for a full panorama, where each frame would use 50.4 Mbits of raw data. This data could be compressed at a ratio of 3 to 1. Following the initial 360° panorama taking, the Pan Cam would be on standby mode until a seismic activity, which could allow to capture geyser events in the vicinity of the lander. The Raman spectrometer and LIBS would each generate less than 1 Mbits of data per measurement. The GC/MS would perform only a limited number of measurements; therefore, the data obtained by these instruments would not have an impact on the C&DH system. (see Table 4)

The lander operation would include two modes, based on operation time frames. The initial mode, following the landing, would include a full set of measurements. The second mode would switch most of the instruments into standby mode, keeping only the seismometer and meteorology sensors operational. This second mode would generate only a small amount of data, which would reduce data transfer from the surface to NIMO and back to Earth. For the second mode only a reduced staff would be required to operate the orbiter and landers, and to analyze the data.

The distance of Neptune from the Sun is 30 AU, therefore, direct to Earth (DTE) communication from the landers is not likely. Because of the limited power availability from the MMRTG and potential visibility issues, the data to Earth would nominally be relayed through NIMO. Each lander would utilize redundant ElectraLite UHF radios with a 5 W transmitter to communicate with NIMO. This telecom system would support a data rate up to 500 kbps. (The UHF system could transfer data at rates between 1 kbps and 2048 kbps, while the receive data rate would correspond to a range between 1 kbps and 8 kbps.) Based on the telecom opportunities for an assumed 1500 km orbit the daily data volume could be over 200 Mbits, transmitted through the lander's monopole antenna. The ElectraLite UHF radio would be placed inside the warm electronics box, while the base plate of the UHF monopole antenna would be positioned above the MMRTG, utilizing its waste heat through conduction and radiation to prevent the antenna from freezing (see Figure 3).

Thermal Issues

Thermal design of the landers requires maintaining them at an appropriate operating temperature during all phases of the missions. It would be desirable also to reduce and potentially eliminate the number of moving components on the landers in order to minimize the potential for thermal-mechanical failures. For this, the thermal environment could be sustained by utilizing waste heat from the MMRTG.

Thermal control for the Triton landers would be accomplished by a combination of passive and active components. Both landers would have the same thermal design. The Pan Cam camera would require a 2.5 W resistance heater. To maintain the electronics box warm, two possible options could be considered, either by covering each of the exposed surfaces with a 1/16 inch layer of Aerogel (a high performance, lightweight insulator) or by covering them with MLI in addition to two 2 W resistance heaters to compensate for a less efficient thermal blanket design. An MMRTG would generate about 1735 W of thermal heat, a portion of which would be dissipated radiatively through the fins. The remaining heat (~520 Wt assuming a 70% efficient fin) would need to be conducted to the warm electronics box (WEB) using a high performance thermal strap (such as a K1000 heat strap). A doubler plate could also be used to help remove a portion of the heat and to minimize the hot spots located along the mounting plate. It was found that waste heat utilization with the present thermal management strategy would be sufficient to keep the warm electronics box continuously with its operating temperature range, while the MMRTG would provide enough power to allow for resistance heating of components outside of the WEB (e.g., Pan Cam).

Radiation Issues

During the total mission lifetime the NIMO spacecraft and the landers would be exposed to various radiation sources. These are the Van Allen radiation belts near Earth, cosmic radiation through the cruise phase, Jupiter's radiation during the flyby, and radiation from the NIMO reactor and from the MMRTGs. A calculation was performed comparing the radiation environment for this mission against the preliminary calculations for the JIMO mission. The calculations assumed 100 mil of aluminum shielding to protect NIMO and its landers. During the spiraling out phase from an 1000 km Earth orbit the Van Allen radiation belts would expose both NIMO and the landers to about 100 kRad of total ionizing dose (TID) radiation. The Jupiter flyby could add about 40 to 60 kRad, based on the flyby distance (the above values assumed 10 and 6 Jupiter radii at 0° inclination). The NIMO reactor would add ~40 kRad TID. Radiation from the MMRTG would be dependent on the distance from the radiation source and was extrapolated from calculations performed for the Mars Science Laboratory mission [14]. The resulting TID for an 18-year cruise phase is estimated to be below ~250 kRad. The natural radiation environment at Neptune results in an additional 0.003 kRad/year, which is negligible. It is evident that such a mission does not require the amount of shielding seen on JIMO. Since the shield mass per unit area for 100 mils of Al is 0.686 gm/cm^2, the mass savings due to shielding could be significant, accommodating an equally larger payload. The currently projected JIMO payload allocation envelope is 1500 kg. The JIMO follow-on spacecraft assumed for this Triton lander mission could accommodate a payload in the 2000 to 3000 kg range.

MASS ALLOCATION

It is assumed that NIMO could deliver up to 3000 kg of payload mass to Triton's orbit. The payload allocation on the NIMO orbiter is higher than that of JIMO due to two factors. First, the 300 kWe NIMO reactor would allow for larger electric propulsion thrusters, thus increasing the deliverable mass to the Neptunian system. Second, Neptune's radiation environment is benign compared to that of Jupiter. Thus, the shielding requirement is much lower, resulting in a mass savings, which can be re-assigned to the payload fraction. The larger mass in effect allows for up to two landers in addition to science instruments allocated on the orbiter for remote sensing and data relay. The mass breakdown is shown in Table 5. The mass of the propulsion system accounts for about 57% of the lander mass at the time it detaches from the orbiter. This includes the propellant wet mass (bi-propellant and pressurant) and the propulsion system dry mass (thrusters, tanks, valves). The structures and mechanisms, about 24% of the total mass, account for the lander base plate, WEB housing, mast, skycrane and miscellaneous items such as cabling. The power system is almost 14% of the total mass, and includes the MMRTG power source, the batteries and other components such as PCU, PDU, shunt limiter and battery control boards. The thermal, avionics and telecom systems account for less than 3.3% of the mass. Finally, the science instruments utilize about 2.2% of the total lander mass. With 30% mass margin, required by design principles for conceptual designs, the Triton lander mass at the time it detaches from NIMO would be about 733.8 kg, while two landers would be less than 1500 kg, leaving half of NIMO's assumed payload for orbital science instruments.

CONCLUSIONS

A study has been performed to demonstrate the feasibility of a landed mission to Neptune's moon Triton with two landers, deployed from a JIMO follow -on fission reactor powered orbiter (NIMO). Each lander was designed to use a standard MMRTG as its power source. At BOL an MMRTG would generate 2000 Wt and 110 We, however, due to natural decay of the plutonium power source, and degradation of the TE converters, the power would drop to about 1735 Wt and 82.6 We after the 18 years transfer from Earth to Triton. Since Triton is considered to be the coldest place in our solar system with a mean surface temperature of -235°C, the lander was de-signed with no moving parts (beside the panoramic camera), and with arrangements to utilize the excess heat from the MMRTG. An MMRTG would provide sufficient electric power to support science instruments fulfilling the science objectives outlined above. It can also be concluded that radioisotope based power systems provide the best solution for a landed mission to Triton, since solar energy at this distance is inefficient and mass prohibitive for power generation and fission reactors would be oversized for this type of missions.

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