

Missions to Triton and Pluto using a Hopper Vehicle with In-Situ Refueling

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Abstract

The Triton Hopper is a NASA Innovative Advanced Concepts (NIAC) project to design a mission to not merely land, but repeatedly fly across the surface of Triton, utilizing the volatile surface ices (primarily nitrogen) as propellant for a radioisotope-heated thermal rocket engine to launch across the surface and explore all the moon's varied terrain. An engineering design study of the vehicle and mission was done. With a calculated range of 20 km per hop, equator-to-pole mobility can be achieved over a primary mission duration of 2 years. Using Nuclear Electric Propulsion for the transfer vehicle, the same concept can be applied for a mission to the surface of Pluto.

Keywords: Triton, Neptune, ISRU, hopper, radioisotope

Acronyms

I_{sp} : Specific impulse in seconds

GPHS: General Purpose Heat Source

NEP: Nuclear Electric Propulsion

1. Introduction

Neptune's moon Triton is a fascinating object, a dynamic moon with a highly varied surface, a thin atmosphere, and geysers [1]. Triton is unique of the moons in the outer solar system in that it is most likely a captured Kuiper belt object (KBO), a leftover building block of the solar system, of a size slightly larger than Pluto. At a temperature of 33 K, the surface is covered in ices made from nitrogen, water, and carbon dioxide, and shows surface deposits of tholins, organic compounds that may be precursor chemicals to the origin of life. At a distance of over 30 astronomical units, it would be by far the most distant object ever landed on by a spacecraft, and the first detailed visit to a Kuiper-belt object.

Experience with rovers on Mars shows that mobility is invaluable to exploring a planet (or moon). Triton, and its slightly smaller twin Pluto, are large and show a wide diversity of structure: one landing spot will barely scratch the surface. Triton's landforms are interesting from pole to equator. Mobility across the surface on a global scale is an indispensable requirement for full understanding of these bodies.

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(primarily nitrogen) as propellant for a radioisotope-heated thermal rocket engine to launch across the surface and explore all the moon's varied terrain [2,3]. We call this vehicle a "hopper" because it is capable of making multiple rocket-propelled ballistic "hops" across the surface, allowing long-distance mobility and the ability to examine multiple sites of scientific interest.

Using the in-situ resources of a body has been shown by many to be key to long-term exploration. The use of in-situ collection of surface volatiles as propellant for hopper's radioisotope thermal engine, will open up operations on not merely Triton and Pluto, but be an enabling technology for exploration of small bodies across the solar system

1.1 Phase I project

In the phase-I project, an initial engineering design of the spacecraft and mission was done, showing that the concept was feasible [4]. The Phase-I Triton Hopper design was lander capable of gathering nitrogen propellant from the Triton environment to enable rocket-propelled mobility across the surface after landing. The propellant collection for the Phase-I hopper was done from the thin (~1.4 Pa) atmosphere, using a 50-W cryocooler to freeze the atmosphere in the tank. The baseline acquisition rate was to collect approximately 100 kg of nitrogen over a period of 8 days. As a back-up, the sample arm could also be used as a scoop, collecting nitrogen snow or ice from the surface deposits. The frozen atmosphere was then heated to 300 °K and 14 MPa (2000 PSI) in about 11

days using 60 W of heaters. The compressed gas was then used in six 220-N cold-gas thrusters as primary propulsion for the hop. This allowed the vehicle to make a hop of up to 5 km approximately once per month. A two-year mission would allow the 300-kg vehicle to accomplish a traverse distance of about 150 km and visit 30 sites.

In the phase-I design, delivery of the vehicle was done using a solar-electric propulsion stage. A trajectory using Earth- and Jupiter- gravity assist maneuvers delivers the spacecraft to the Neptune system with a 12 year transfer time, requiring 2610 kg of Xe propellant. After arriving at Neptune, the spacecraft aerocaptures using the atmosphere of Neptune [6] into an elliptical Neptune orbit, and performs a series of aerobraking and propulsive maneuvers to insert into Triton orbit. The hopper vehicle then uses a chemical rocket burn to de-orbit at Triton for the landing, while the delivery vehicle continued on in Neptune orbit, serving as a communications relay.

The phase-I design is shown in Figure 1.



Figure 1. Artist's visualization of Triton Hopper on the surface of Triton.

1.2 Phase II project

Although the Phase-I results showed that the mission was possible, the design was capable of being improved. The phase-II project [7], presented here, analyzes improvements to the mission, utilizing a changed engine concept to improve performance to allow longer hops. This will achieve a goal of allowing pole-to-equator exploration while increasing the science payload. The phase-II analyses also improved the delivery system by incorporating a Nuclear Electric Propulsion (NEP) system utilizing the recently-developed "Kilopower" reactor [8] as a primary energy source, instead of the previously-baselined solar-electric propulsion system.

Triton is only one of many possible applications of the design of a vehicle able to use in-situ ices as fuel for

a radioisotope thermal engine. The use of an electric propulsion system energized by the Kilopower reactor means that the electric propulsion system is not limited to operation only in the inner solar system, and thus removes necessity for aerocapture to brake into orbit at the destination to deliver the vehicle. This allows the delivery vehicle to take the hopper vehicle to Pluto, bringing the possibility of a mission to the Pluto-Charon system into the range of feasible missions. Pluto, like Triton, has surface deposits of nitrogen ice, and the design for a Pluto-exploration hopper is very similar to the Triton Hopper design.

2. Advanced Mission and Vehicle Design

The phase-II design study improved the vehicle, and incorporated a number of trade-studies to optimize performance.

2.1. Radioisotope engine with thermal storage

The initial concept stored the energy for the rocket propulsion in the form of a heated gas. This concept has the advantage of simplicity, but the disadvantage is that since the specific impulse of the engine is proportional to the square root of the temperature of the gas, the tanks for storage of pressurized gas will heavy if a high specific impulse is required. The specific impulse (I_{sp}) of the nitrogen thruster for the Phase-I engine was about 65 seconds at the start of thrust, dropping down to about 45 seconds during the period of thrust as the gas in the tanks cools due to expansion.

In parallel with the initial design exercise, we had done did a top-level analysis of an alternate system, in which the thermal energy was stored in a separate thermal mass heated by the radioisotope [9]. Nitrogen is passed through thermal mass (via channels or pipes) to heat to exit temperature. This is shown in schematic in figure 2. The initial analysis [9] suggested that this heat storage system could significantly improve the performance over the thermal storage in the gas.

Several possible material to use for thermal storage were, both with and without phase-change. The materials which showed the greatest specific energy for heat storage were lithium, which is liquid over the temperature range of interest (melt temperature 180°C), and lithium fluoride, which incorporates a phase change from liquid to solid at 848°C, allowing some energy storage in the form of latent heat of fusion as well as the direct thermal storage as sensible heat. Due to its exceptionally high heat capacity, for the mission parameters used, the molten lithium had a slightly better specific energy; it also was superior in terms of its thermal conductivity, which is a factor in the transfer of heat from the thermal storage system to the propellant.

The lithium thermal storage mass is contained in a cylindrical containment vessel containing 25 kg of lithium. The nitrogen flows through 540 1.5-mm

diameter tubes, each 40 cm long, to three operating nozzles. Due to the reactivity of lithium at high temperature, the preferred alloys for the lithium heat pipes are molybdenum-based alloys [10], such as Titanium Zirconium Molybdenum (TZM), which has high melting point, a high thermal conductivity (110 W/mK at 1000°C), high strength, and is compatible with lithium at high temperatures.

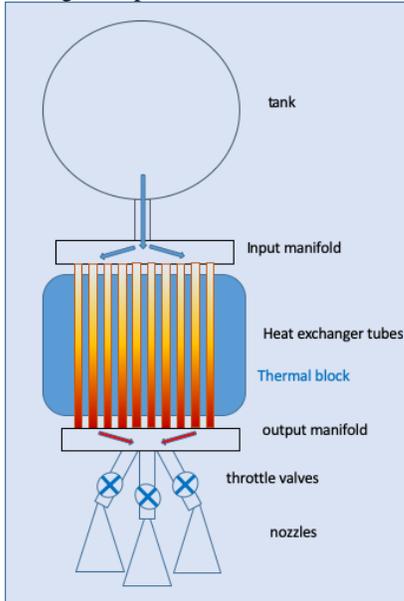


Figure 2. Schematic of tank and thermal block with heat exchangers. (Note that this is schematic only: for reasons of thermal configuration, in the final design the propellant tank was situated below the thermal block, rather than above).

In the center of the thermal block is a hollow in which four General Purpose Heat source (GPHS) bricks are inserted. The GPHS blocks contain the Pu-238 isotope, each one providing about 245 Watts from the radioactive decay of encapsulated plutonium oxide fuel, with a half-life of 87.7 years [11]. GPHS blocks are designed to be robust against mishaps ranging from launch failure to atmospheric entry, and have been used for missions ranging from Pioneer through the Mars Curiosity mission.

Initial optimization cases were run for thermal mass at 900°C, but the literature on the properties of the GPHS showed a maximum operating temperature of 1100°C [12,13], with 1500°C given as the maximum allowable, due to the reactivity of the Ir coating above this temperature (although the fuel elements themselves have been tested to survive 2360°C). From this data, we revised the maximum lithium block temperature to 1100°C.

Numerical simulations of the gas passage through the heat exchanger were run to calculate the performance, using GFSSP, Generalized Fluid System

Simulation Program, to analyze fluid flow parameters, and the ANSYS finite element model for fluid dynamics and heat transfer calculations.

The thrust is done in two segments, a first burn to loft the vehicle into its ballistic trajectory, followed by a coasting period, and then a second burn to bring the vehicle to a soft landing. Specific impulse achieved is about 161 seconds at the beginning of thrust, dropping down to about 108 seconds at the end of the second thrusting period, for an average specific impulse of 127.5 seconds.

2.2 Propellant collection

In the revised design, the propellant collection is done by collecting nitrogen from the surface deposits, rather than from compressing the atmosphere. The surface deposits on Triton may consist of either high-density ice, or of low-density snow. After some analysis of the properties of nitrogen ice, it was determined that ice cores could be obtained with a hollow-core drill, similar to the tools used to obtain glacial ice cores on Earth. The drill will thus do double-duty, serving also to produce scientific coring for stratigraphic studies of the ice. The ice cores produce can then be directly inserted into a cannister to load into the propellant tank.

Figure 3 shows the design of the hopper, with the coring drill shown at the front.

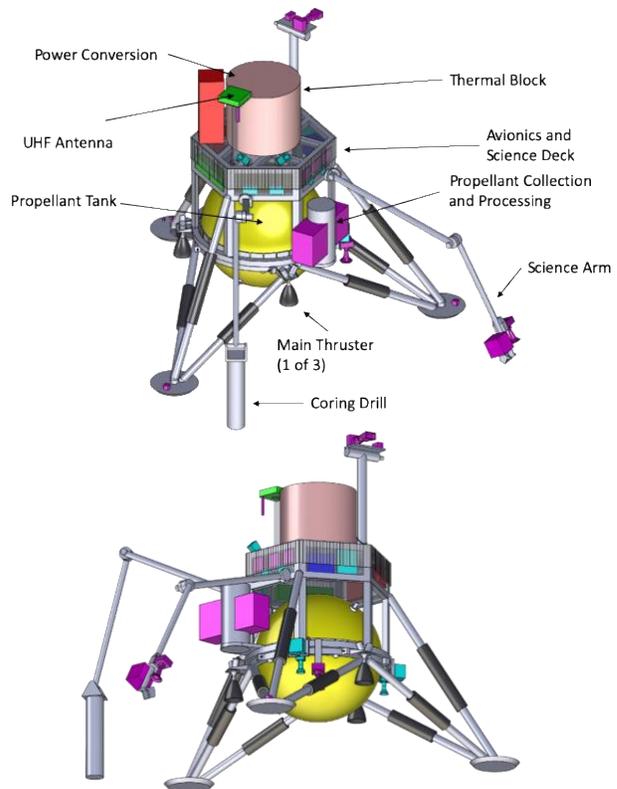


Figure 3. Solid model of the revised hopper design.

The revised design utilized a two-step process to fill the tank. This is shown in schematic in Figure 4. The ice core is inserted into the collection-chamber cannister, and the chamber then closed. The cannister is heated while maintaining a pressure sufficiently to liquify the nitrogen (~63K, >0.125 atm), at which point a pressure feed system drains liquid nitrogen into (low temperature) tank, where it is allowed to cool back into solid form. The process is then repeated as needed until the main tank fill reaches capacity. When the capacity is reached, the tank is then heated to the storage pressure and temperature.

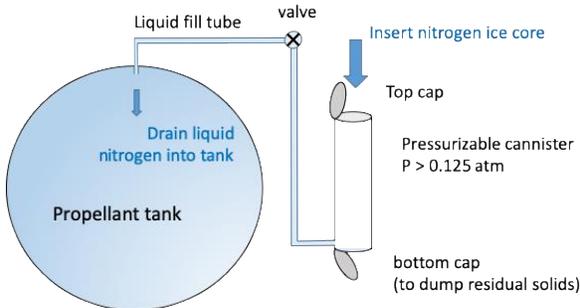


Figure 4. Propellant fill schematic.

Use of an intermediate liquid stage, instead of putting nitrogen ice directly into the tank, is incorporated for several reasons. This avoids mechanical problems of having a large door for nitrogen ice insertion into a tank that must be designed for both a high pressure and also for good thermal insulation. If the nitrogen is in a low-density form (“snow”), it avoids the problem of tank not being able to contain sufficient mass of nitrogen to bring it to the desired fill. And, finally, if the ice core contains solids, the residual solids entrained in the ice will not accumulate in the propellant tank, but are easily jettisoned.

The propellant in the tank is stored in the form of a pressurized gas. This simplifies the propellant feed, and avoids the difficulties of two-phase flow in the heat exchanger. As the propellant is exhausted, the drop in pressure and resultant expansion of the propellant remaining in the tank drops in temperature due to Joule-Thomson cooling. The point where the cooling reaches the liquidus point marks the end of the thrust period. This point depends on initial conditions. Higher initial tank pressures result in a smaller tank (and resultant lower thermal losses due to surface area), but propellant reaches the saturation line with a higher propellant mass fraction remaining in the tank when the liquidus point is reached (“residual”). Likewise, higher initial tank temperature decreases the residuals, but requires a larger and heavier tank. The optimum was determined to be around 21 MPa (3000 PSI) and 300K temperature, at which about 10% of the initial propellant load remains in the tank at the end of thrust.

This residual propellant can be re-heated and used for a second, short distance hop, if it is desirable to make a fine adjustment to the landed location.

2.3 Delivery

In the phase-II design, we replaced the solar electric propulsion with a nuclear electric propulsion for the Earth to Triton orbit insertion part of the trajectory. This is made possible by the development of the “Kilopower” reactor [8], a small nuclear reactor which was recently demonstrated with the “KRUSTY” experiment [14]. By incorporating a power system which continues to produce power in the outer solar system, energizing a high specific impulse electric propulsion system, the delivery vehicle can now use the primary propulsion system for the orbital entry, as well as for the heliocentric (Earth to Neptune) portion of the trajectory.

The delivery vehicle for the mission was adapted from an earlier design study of the use of electric propulsion using the Kilopower reactor for a Kuiper Belt Object mission [15].

The flight time and the payload mass allowable will depend on the launch date, since a Jupiter flyby will significantly improve the performance, but is only available for launch to Neptune during limited windows at intervals of about 12 years.

From Triton orbit, the surface is scouted to identify and verify the initial landing site. With the landing site identified, a solid rocket performs the de-orbit to initiate the descent of the hopper toward the surface. Figure 5 shows the hopper with the solid rocket motor attached. Following the de-orbit burn, the hopper vehicle then detaches from the solid rocket, and uses the radioisotope thermal engine to make the initial soft landing.

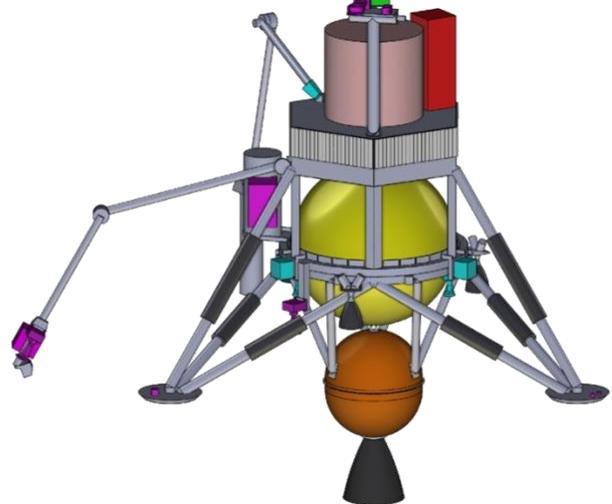


Figure 5. Solid model of the revised hopper design, showing attachment of the solid rocket motor for the initial descent toward Triton

3. Results

Table 1 shows the mass summary, showing both the hopper itself, and also the hopper with the solid-rocket stage for the initial descent of the vehicle from Triton orbit. (Note that the propellant load listed here is the propellant brought from Earth, which includes only the nitrogen required for the initial soft landing on Triton. This significantly less than the propellant which can be loaded for a hop.)

Basic dry mass of the vehicle, not including the solid rocket stage, is 440 kg; this rises to about 550 kg when a system-level growth allowance of 30% is assumed. This compares favorably to other similar landed systems; for example, the Mars Curiosity mission has a rover mass of roughly 900 kg. Including the descent stage, the mass delivered to Triton orbit by the transfer vehicle is about 900 kg, which again is very favorably compared to similar system, such as the Curiosity rover’s entry mass (with aeroshell and sky crane) of nearly 2000 kg.

Figure 5 shows the calculation of the distance achieved in a hop. In this image, the red curve, for the baseline vehicle, with no performance margin added and without the vehicle growth, shows that about 33 km can be achieved per hop. Incorporating margins and growth, the realistic distance achievable per hop is 21 km, which is still a considerable improvement over the 5 km baselined in the initial design.

MEL Summary: Case 3 Triton Hopper CD-2019-12			
	Hopper	Solid Stage	TOTAL
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Science	31.6	0.0	31.6
Attitude Determination and Control	8.2	0.0	8.2
Command & Data Handling	11.5	0.0	11.5
Communications and Tracking	6.5	0.0	6.5
Electrical Power Subsystem	23.3	0.0	23.3
Thermal Control (Non-Propellant)	41.5	0.0	41.5
Propulsion (Chemical Hardware)	154.3	51.6	205.9
Propellant (Chemical)	79.4	265.3	344.7
Propulsion (EP Hardware)	0.0	0.0	0.0
Propellant (EP)	0.0	0.0	0.0
Structures and Mechanisms	83.7	12.9	96.6
Element Total	440.1	329.7	769.8
Element Dry Mass (no prop,consum)	360.7	64.5	425.1
Element Propellant	79.4	265.3	344.7
Element Mass Growth Allowance (Aggregate)	65.0	6.4	71.4
Additional System Level Growth (For 30% tot)	43.2	12.9	56.2
Total Wet Mass w/ 30% Growth	548.3	349.1	897.3

Table 1. Mass summary

2.4 Operations (Conops)

The core drilling and fueling process takes about 3 days, not including margin. This allows a hop once per Triton day (141 hours, about every 6 Earth days).

Since the transfer vehicle remains in orbit, a high-resolution camera is used to plan each jump. This planning is used to ensure that the landing spot for each hop is smooth, level, and free of large (>50 cm) boulders. Infrared spectroscopy will verify that surface deposits of nitrogen ice (or snow) are available for refueling. The orbital imagery will also give geological context for the science, and will be used to search for targets of special interest, such as nitrogen geysers,

which may give clues as to the deeper interior of the moon.

In the case that the hopper lands at a location that does not have nitrogen ice available on the surface, the residual propellant in the tank can be used to make a secondary hop to a more suitable location for propellant harvesting.

At the maximum hop distance of 20 km, the desired mission criteria of 2400 km (*i.e.*, Triton pole to equator) is achieved in the nominal prime mission duration of 2 years.

A mission to the surface of Triton is likely to be flown as part of a mission to observe Neptune [1]. Following the 2-year primary mission of the hopper, the level of detail of the surface observation viewed from orbit will be sufficient that the NEP transfer vehicle will no longer be required for close support of continued operation of the hopper vehicle in an extended mission. The NEP vehicle is then free to leave Triton orbit, and can be used as a vehicle to study Neptune and its ring system, as well as making fly-bys of other satellites.

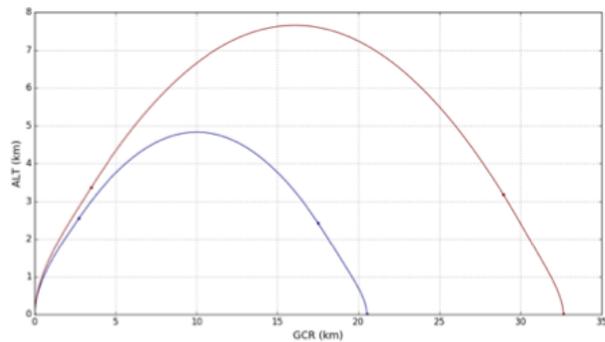


Figure 6. Calculated hop trajectory. The red curve shows the distance travelled for the case where no growth or margin is assumed; the blue curve shows the calculated trajectory with mass growth and margin incorporated.

4. Conclusions

The design study improved the design of the mission, allowing a much longer hop with a larger complement of science instruments. The revised design is capable of global (pole to equator) coverage of the surface within a primary mission span of two years.

Use of the Nuclear Electric Propulsion for the transfer vehicle means that the same vehicle concept can be used for a hopper vehicle to explore Pluto.

Acknowledgements

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