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Propulsion to Moons of Jupiter Using Heat and Water Without Electrolysis Or Cryogenics

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Abstract. Exploration of the inner solar system during the last 20 years revealed the existence of many water objects. They include hydrated minerals in the near earth asteroids, ice on Earth's moon, water ice moons, and ice lakes on planets and moons. Examination of the composition and hardness properties of the objects revealed that the use of heat alone, at temperatures well below the melting point of rock, would release water vapor or water. Research dating from the 1960's demonstrated the technology to use water as the coolant in nuclear reactors at temperatures up to 1100 Kelvin without significant wear or erosion of the nuclear system. In a nuclear rocket, nuclear heated coolants flow directly from the reactor core into a rocket nozzle bolted on the reactor. The coolants boil to vapor and propell the rocket. The combination of these elements permitted use of the water from space as a propellant for inner solar system exploration.

Two mission options were compared. Each would deliver a net 10,000 tons of useful space ship payload to Callisto, a moon of Jupiter. The H2O option uses water as propellant and only thermal processes. The other, cryogenic option uses liquid hydrogen (LH2) as propellant and electricity to split water and for cryo systems. Both systems get all their water from space. The hardware mass for a heater to release water from ice or regolith is estimated. For the LH2 option, additional mass is needed for an electrolysis unit to split the water, for cryogenic liquefiers to condense hydrogen gas into LH2 and for the electric power needed to run them. The H2O NTR option is shown to use less mass and only thermal processes..

1. Introduction

During the period from 1991 thru 1998 a nuclear propulsion group at the United States Department of Energy in Idaho examined options to transport massive payloads from Earth orbits to accessible objects in the solar system. One objective included delivering human habitat supplies for missions to Mars. The required payloads would exceed tens of kilotons.

During that same period it became clear that the accessible inner solar system contained at least hundreds and possibly thousands of objects containing water. The amount of water seemed to be huge relative to anything we had previously encountered. Data from the Lunar Prospector suggested our own moon contained ~300 Megatons of water in thin permafrost or hydrated alkali layers at the bottom of forever dark lunar craters at the North and South pole One could release the water by heating the regolith/permafrost (Zuppero et al. 1998)

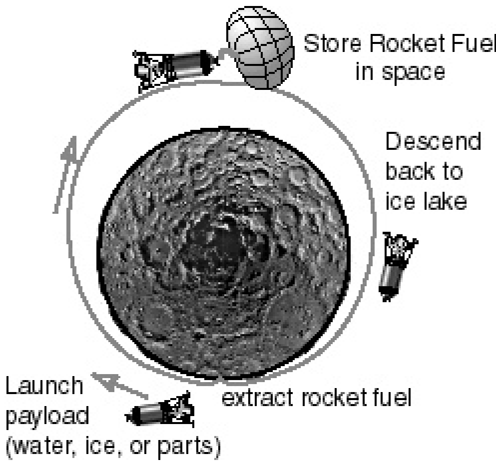

Figure 1 Lunar South Pole, reported site of water bearing regolith, shown with proposed water extraction systems. The object could also be one of at least several tens of NEAs with delta_V to access them similar to the escape velocity of the moon, ~ 2300 m/s. The object could also be any of the more than 20 ice moons of the solar system, whose escape velocities are similar to or less than that of the moon.

During the same period, a formation of near earth asteroids (NEA's) was discovered to populate a region in the ecliptic plane approximately between Venus and Mars, as shown in Figure 2. As many as 40% of the NEA's consist of a form of rather soft, hydrated silicate. The water content, typically ~15%, would vary between ~5% and 25% of the silicate as a hydrated mineral of the form M * n-H2O. The hardness of the NEA dirt has been measured to be about like that of dried mud, unlike the sidewalk-like hardness of the rock and metal asteroids that survive reentry to the Earth's surface. Most of the water could be released by cooking the dirt at kitchen oven temperatures (~450 F). For example, a 2 km NEA would contain ~ 10,000 to 20,000 megatons of dirt. Cooking the dirt would dehydrate it, releasing ~10% of it, 1000 megatons, as water. At the time of the early studies, mid 1990's, there appeared to be at least tens of NEA's at least as accessible as the surface of the moon.

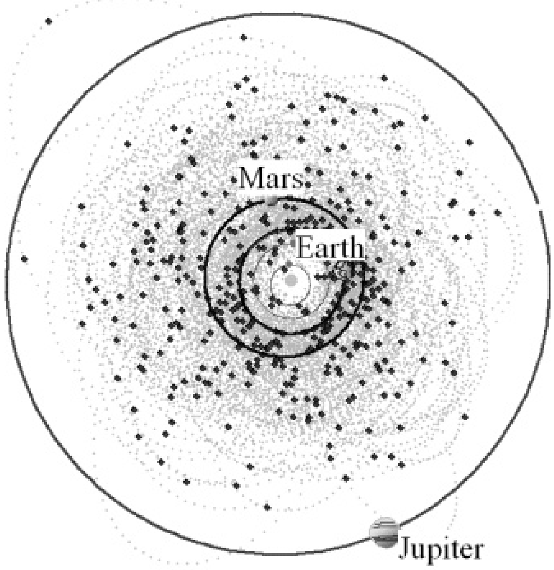

Figure 2 Near Earth Asteroids (NEA's) rather densely populate a region in the ecliptic plane, near Earth. Up to 40% are reported to contain hydrated clay-like minerals with a variable 5 - 25% water content. Diamond points are NEA position projected on to ecliptic. Dotted orbit points are equi-spaced in time so that density of orbit points approximates NEA density, as of 6 Oct 1996 (Whitman et al. 1997).

During that same period European missions to Halleys comet, Figure 3, discovered that comets contain roughly equal parts water ice, a form of dirty oil shale, clay-like silicates, and also possibly ~1% amines. A little known formation of about 150 comets populate the region of the ecliptic between Mars and Jupiter, as shown in Figure 4 (Whitman, Pat, 1997). About 10 are as accessible as moons of Jupiter. The size of these comets is about 3 - 5 km. At 10% ice content, a 5 km comet would yield ~10 Gigatons water. One would ignore or discard the additional 10 Gigatons of oil-like material.

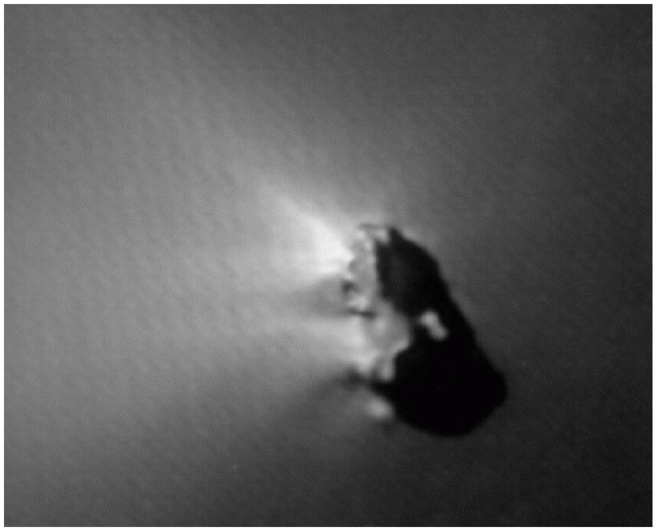

Figure 3. Halley's comet, an almost inaccessible water ice object in the formation of near earth comets.

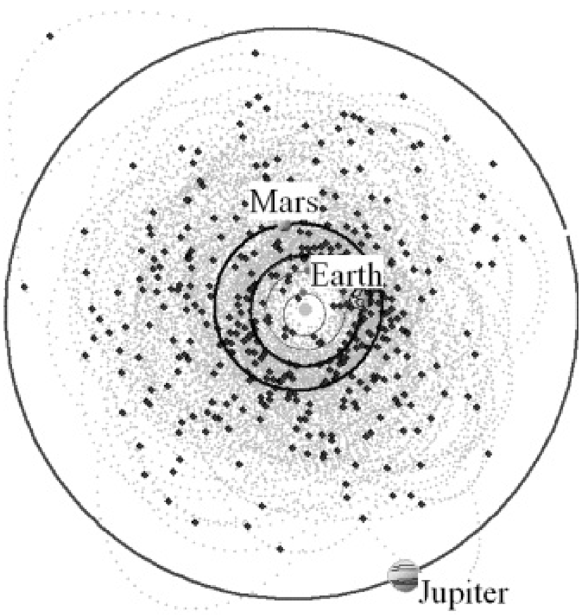

Figure 4. The "periodic comets" also known as "Jupiter family comets" as of 6 Oct 1996. Diamond points are comet positions projected on to ecliptic. Dotted orbit points are equi-spaced in time so that density of orbit points approximates comet density.

For the manned Mars missions, nuclear thermal rockets (NTR's) were being proposed and designed that would use liquid hydrogen (LH2) as propellant. Water (H_2O) propellant NTR's were also evaluated, as in Figure 5.

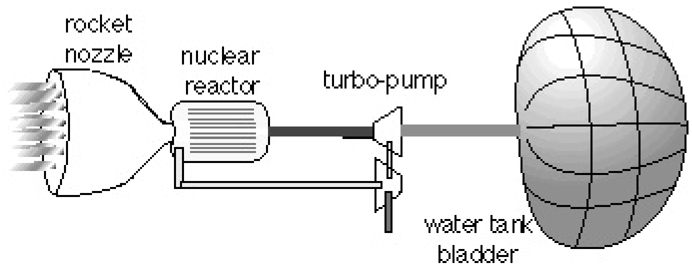

Figure 5. Nuclear Thermal Rocket (NTR) uses nuclear reactor to heat propellant (water or liquid hydrogen, LH2). Rocket nozzle is bolted directly on to reactor. Bleed gas turbo pump forces propellant into reactor. LH2 NTR's would deliver 800 - 900 seconds specific impulse and run at power densities ~ 300 megawatts per ton of rocket.

What would be the best way to use the water for propelling massive payloads. "Massive" would mean "like a submarine holding 100 people". It was obvious that one should split the water, condense the hydrogen to cryogenic, liquid hydrogen (LH2), dump the oxygen and use just the liquid hydrogen for the obviously superior nuclear thermal rockets.

During the Star Wars program 5 Megawatt electric generators for use in space were designed for weapon and propulsion power supplies. One could use the 5 megawatt Star Wars electric generator to split the water and liquefy hydrogen.

The system includes space ship, its propellant tank, armor for the tank, a nuclear thermal rocket energy source, and propellant. The system also includes whatever hardware it takes to extract the propellant from the space resource and prepare it for use in the rocket.

2. Nominal Payload

The nominal payload must be like that of a medium sized nuclear submarine. It must spin to create synthetic gravity. It must be shielded with ~ 1 meter H_2O or equivalent mass to attenuate the deadly radiation in space and around Jupiter and in space to 5 Rads or less per year. The nominal ship is a torus (like the inner tube of a bicycle tire) 160 meters diameter at the outer edge. The torus tube is 7 meters inner diameter with 1 meter thick walls for radiation shielding and structure. Almost all the mass is in the 1 meter wall. Such a vehicle will rotate at 3.34 revolutions per minute (18 seconds period) to achieve 1 G centripetal acceleration. The interior shielded volume is equivalent to 77 homes each with 1100 square feet of 8 foot high floor space, not counting structures. This would house ~100 astronauts comfortably, something more spacious but similar to the ~120 sailors on a nuclear submarine. This nominal vehicle is characterized entirely by its mass, "10,000 tons."

3. Mission to Callisto

A mission from the vicinity of Earth to Callisto, an ice moon of Jupiter, is defined by the total delta-V accumulated for each segment. Once at Callisto, both Ganymede and Europa become readily accessible. The sequence of maneuvers for going to Callisto includes:

1. refuel using water derived from Earth's moon, comets or NEAs
2. at Earth perigee, transfer from nearly-escaped, highly elliptic orbit around earth to minimum energy trajectory to Jupiter;
3. capture at Jupiter to high elliptic Jupiter orbit
4. at Jupiter orbit apoapsis, change periapsis to intersect Callisto orbit
5. at Callisto closest approach, capture into High Elliptic Callisto orbit
6. use shuttles to descend to Low Callsito Orbit or to Callisto surface
7. refuel using water derived from Callisto surface ice

The first step assumes one can obtain up to 1 megaton of water. It can come from the Earth's moon or from NEA's. Extracting water from the moon demands a rocket to transport through the lunar ~ 2300 m/s escape velocity. With this ~ 2300 m/s, one way delta V budget, many tens of NEA's are good candidates for the water. If the moon doesn't work, NEAs will work. Since the propellant for this is "free," it does not count against the mission launched mass.

To make a rocket change from a circular orbit around the Sun at Earth's distance to an elliptic orbit tangent to Jupiter's orbit around the sun, the vehicle must increase its velocity by approximately 8850 meters / second higher than the velocity of Earth around the sun. To do this, the vehicle starts in a high elliptic earth orbit (HEEO) with apogee at twice the distance to the Moon, 120 earth radii, and with perigee just outside the debris and junk zone close to Earth at 1.3 earth radii. This orbit is chosen to have approximately the same period as a lunar orbit. During the closest approach to Earth, deepest in the gravity well, one performs a thrust. A peculiar result of doing this is that a thrust adding just 3456 m/s to the vehicle at closest earth approach results in a velocity far from Earth in excess of escape velocity by 8850 m/s (V_infinity). The thrusting must in principle be delivered at the very lowest point in the gravitational potential well. In practice, one may need to take 1 hour do to this, because the rockets have a limited power. The rocket power required is inversly proportional to the thrust time used. Since the rocket spends significant time away from the lowest gravity potential, simulations showed that a 1 hour thrusting would incur a gravity loss equivalent to increasing the total mission delta V by a factor of about 1.18, or about 4219 m/s delta V for this maneuver.

The trip to Jupiter lasts about 2.8 years. A vehicle in the transfer orbit tangent to Jupiter is going to slow at Jupiter by about 5650 m/s to rendezvous with Jupiter If Jupiter happens to be there and if we perform an accelerating thrust as deep in the Jupiter gravity well as possible, for example, at 1.1 Jupiter radii, we need only 312 m/s of delta V at periapsis to achieve a 5650 m/s increase in speed. With this mere 312 m/s we will not only speed up to rendezvous with Jupiter but we will become captured in an orbit with apoapsis (high point) 1000 Jupiter radii and periapsis 1.1 Jupiter radii.

The vehicle then takes 0.43 years to reach the apoapsis, the high point in the Jupiter orbit. At apoapsis the next thrust of 239 m/s raises periapsis up from just skimming Jupiter at 1.1 R_J to skimming the Callisto orbit at 26.37 R_J. The orbit now has 1000 x 26.373 R_J orbit parameters. The descent to Callisto lasts about 0.476 year.

When the vehicle reaches periapsis it meets Callisto but is moving too fast by about 3250 m/s to stay there. A thrust of 1622 m/s at the deepest point of the Callisto gravity well places the vehicle into a captured Callisto orbit with ~ 1 Callisto radius periapsis and 30 Callisto radii apoapsis. The vehicle meets Callisto once per orbit.

Shuttle vehicles will need a thrust of 715 m/s to drop into a very low Callisto orbit and another 1,730 m/s to slow down and land on Callisto. Shuttles would extract water from Callisto ice in a manner similar to extracting water from Earth's moon. The gravity of Callisto is similar to that of our moon, so the water harvesting is essentially the same for both. This scheme was analyzed in prior work .

Water tank shuttles can fully refuel the vehicle at Callisto or at any of the known water moons of the solar system. Traveling to Europa and Ganymede takes much less than 6800 m/s delta V the vehicle is capable of and less than a week of travel.

The entire mission to Callisto would take about 6800 m/s delta V, including gravity losses.

4. Propulsion Requirements

All propulsion options must achieve a mission delta V of 6800 m/s with 10,000 ton net useful payload, not including basic vehicle. The required propulsion is a function of total vehicle mass. Basic vehicle mass includes the propellant tanks, tank armoring, the nuclear reactor engines (either steam or hydrogen propellant). All options requrie water-extraction mass, which includes the nuclear reactor heater to fry regolith or melt ice (both yielding water), hardware to handle the reactor, and hardware to handle the regoliths or permafrosts. For the LH2 NTR option, additional extra mass is needed for the water splitter, for a refrigerator / compressor to convert gaseous hydrogen to cryogenic liquid, plus the associated electric power supplies.

The maneuver which determines the minimum NTR power is the thrust at

Earth perigee. The thrust adds about 4219 m/s delta_V in about 1 hour, which is an acceleration of about 0.12 G. Since most of the propellant is exhausted during this maneuver, one can approximate the power required by assuming all the propellant is expended at the given specific velocity (Isp * Go) in 3600 seconds (1 hour) at 95% energy efficiency. One also needs the acceleration to calculate tank mass fraction, which is a direct function of the hydrostatic load on the propellant tank. The tank mass fraction is then used (iteratively) in the rocket equation to determine the amount of propellant needed for the mission.

Tanks would be made using PolyBenzOxazole (PBO) because of its high tensile strength (700 Ksi), as per work by Joe Lewis, formerly of TRW tank group, and more recently with JPL (Zuppero and Lewis 1998). A safety factor of 2 was assumed for the tank. Water has density 1 gram / cc and vapor pressure 0.1 psi at temperature 275 Kelvin. Liquid Hydrogen has a density of 0.09 gram / cc and vapor pressure ~ 20 psi at 20 Kelvin.

5. H2O NTR Option

The rocket equation for a 6800 m/s delta V H2O NTR mission, including a tank factor 0.000 280 tons tank per ton propellant and specific impulse 198 seconds gives a water requirement of 32.55 tons propellant per ton of gross payload. This means the 10,000 ton payload needs a vehicle with 325,500 tons of water.

A calculation shows that a water bladder holding 325,000 tons of water in a 0.12 maximum G load need only weigh 0.000 280 tons per ton of water. Liquid water needs a tank to hold 0.1 psi vapor pressure at 274 Kelvin (1 Celsius). Most (99%) of the tank tensile strength is required to hold a hydrostatic load. The 86 meter diameter (bladder) tank would weigh about 92 tons.

All tanks must be armored in space against micrometeorites. As a conceptual description, one can armor the tank by enclosing it in another bladder tank of 1 cm larger dimension. The space between the two can be filled with space dirt, or water which is allowed to freeze to ice (Lewis and Zuppero 1998). We assumed we use one tank of 92 tons as the propellant tank and then enclose it inside 2 more tanks, each slightly larger and filled with ice. The armoring therefore adds about 183 tons.

A power of 181 Gigawatts thermal is needed to expel 325,500 tons of water in 1 hour at a specific impulse of 195 seconds and 95% thermal efficiency. The NERVA NTR demonstrated a power density of 300 Megawatts per ton, which implies 597 tons of engines are needed.

6. Water Extraction Hardware

Prior studies calculated the heater needed raise the temperature of lunar crater ice at ~ 50 Kelvin to water at 274 Kelvin ((Schnitzler et al 1997, Larson et al. 1999). A 1 Megawatt heater running 5 days per week, 24 hours per day for 48 weeks, will produce 6900 tons of water per year. To liberate 326,000 tons of water per year requires about 47 Megawatts of heat, and without electricity. This can be supplied using one ton of reactor (which could operate at a maximum of 300 Megawatts). Estimates suggest that 10 tons of hardware are required to handle the reactor with its heat distributors, and that 100 tons of hardware are required to handle the regolith and spent permafrost material. For scaling purposes, we are assuming that 1 ton reactor, 10 tons "heat" hardware and 100 tons "material" hardware produces 326,000 tons water in one year.

Estimates indicate that liberating water from hydrated silicates requires about the same heat and mass handling as liberating water from hyper-cold ice. This means if the ship can take water from ice on a moon, a device of the same mass can take water from an NEA.

The 10,000 ton useful payload used in the rocket equation is therefore diminished by 111 tons water extraction and processing hardware, 190 tons of water bladder armoring and 598 tons of engines. The net useful payload is therefore 9102 tons instead of 10,000 tons.

If we scale this entire system up so that the net payload is 10,000 tons, we can estimate the final space vehicle masses and configuration

Final Configuration: H_2O NTR Option

- 10,000 tons Net payload
- 358,000 tons water propellant
- 104 tons water bladder
- 208 tons water bladder tank armoring
- 656 tons Nuclear Thermal Rocket engines

- 122 tons water extractor

7. Liquid Hydrogen / NTR Option

The rocket equation for a 6800 m/s delta V mission using LH_2 NTR, with tank factor 0.01 tons tank per ton propellant and specific impulse 830 seconds gives a LH_2 requirement of 13,200 tons. Note this is more than 25 times lower propellant mass than that of the H_2O NTR. The 1 hour thrusting time to expel 13,200 tons of LH2 implies a reactor engine power of 121 e9 watts thermal, or 404 tons of engines. Note that this is only 2/3 the NTR power compared to the H_2O NTR.

Students at Utah State during 1998 calculated the mass of a fully armored and insulated tank holding between 10,000 tons and 100,000 tons LH_2 . The LH_2

tank needs enough strength to hold 20 psi pressure at 20 Kelvin temperature. They obtained the tank factor ~0.01 tons tank per ton LH_2 propellant. The same tank holding only 100 tons would need a tank about 10 times heavier. Calculations show that about 1/4 the mass of the tank is needed for insulation and containing the vapor pressure of 20 psi. Another 1/4 is for hydrostatic load and structure and the remainder is for armoring. The 66 meter diameter tank is about 78 tons and armoring is 54 tons.

Since 18 grams of H_2O contains 2 grams of hydrogen, one needs 9 tons of water to yield 1 ton of hydrogen. Therefore the LN2 rocket needs 118,800 tons of water. Scaling the previous water extraction device, one needs 41 tons of hardware to yield the water.

Estimates indicate that extracting H_2 using electrolysis requires 286 kilojoules per mole H_2. To extract 13,200 tons of hydrogen from water requires 2.2 e15 joules, or 69.8 megawatts of electricity for a year.

The Star Wars program and the NASA electric propulsion programs designed nuclear electric generators for use in space. The larger systems, though never actually built, were expected to deliver 1 kilowatt of electricity for about 8.3 kilograms of generator. Realistic, near-term systems would require beyond 45 kilograms per kilowatt. This 60 Megawatts then implies between 479 and 2691 tons of electric generator for electrolysis.

Kittell of NASA Ames provided the specifications for a cryolizer (Kittel 1997)). The mass and power varies dramatically with the heat sink available. To condense 1000 tons of hydrogen per year into LH2 requires 67 kilowatts of cooling. With a 300 Kelvin heat sink, a 20-30% efficient Carnot refrigerator will require 45 - 70 Watts input per watt of cooling. The hardware will have a mass between 4.5 tons and 100 tons. This implies we need between 59.4 and 1320 tons of cryolizer mass and between 40 and 62 Megawatts of electricity. The power requirement implies we will need between 319 and 2786 tons of electric generator to operate the cryolizer.

The 10,000 tons payload is therefore diminished by 41 tons of water extraction hardware, 479 to 2691 tons to generate electricity for electrolysis, 60 to 1320 tons for cryolizer hardware and 319 to 2786 tons for cryolizer electric power, and 408 tons of engines.

This leaves a net payload between 8565 tons and 2626 tons. The lower payload corresponds to 45 kg / kilowatt electric generators and a higher mass for cryolizers, as could be implemented with certainty in the next 15 years. The higher payload corresponds to optimum engineering available "someday."

Final Configuration: LH2 NTR Option

Scaling the entire system so that the net payload is 10,000 tons gives

- 10,000 tons useful payload
- (138,000 to 453,000 tons water for LH2)
- 15,400 tons to 50,300 tons LH2 propellant
- 154 tons to 503 tons armored LH2 tanks
- 472 to 1536 tons of LH2 NTR engines

- 48 - 156 tons to extract water
- 559 to 10248 tons for electricity for electrolysis
- 70 to 5027 tons for cryolizer hardware
- 372 to 10609 tons for electricity for cryolizer

8. Comparative Mass Budget Analysis

Summary

H_2O NTR doable now	LH2 NTR doable someday	LH2 NTR doable now	tons launched
10,000	10,000	10,000	tons useful payload
1,090	1,675	28,072	tons non-payload

Details

H_2O NTR doable now	LH2 NTR doable someday	LH2 NTR doable now	
10,000	10,000	10,000	tons net useful payload
[358,000]	[139,000]	[452,000]	tons water needed from space resources
358,000	15,400	50,300	tons propellant used
312	154	503	tons armored tanks
656	472	1538	tons Nuclear Thermal Rocket engines
122	48	156	tons hardware to extract water
0	559	10,248	tons electric generator for electrolysis
0	70	5,027	tons for cryolizer
0	372	10,600	tons electric generator for cryolizer

Since all that we pay for is the launched hardware, we should look at the payload part of the ship compared to the non-payload part. Most of the 10,000 tons payload is wall shielding and could be a non-launched part.

The H_2O NTR option requires only heat and water. The LH2 NTR option requires less heat and less water by at least a factor of 2, or more heat and more water by at least a factor of 2, depending on whether the technology can be achieved in 15 years or "someday." The H_2O NTR basic vehicle comprises about 11% more mass than the useful payload, and the "someday" LH2 NTR is 16.5%. In this sense, the two options are equal. However, if we had to make the LH2 NTR in the next decade, the LH2 NTR could incur a mass penalty of 280% of payload.

The advantage of an LH2 NTR system is that one has about 100 Megawatts of excess electric power available. Further, the LH2 NTR system can supply high speed, 830 second Isp, LH2 propelled shuttles using a few of the many NTR engines, and, relative to the needs of a shuttle, "unlimited" LH2 propellant.

The bulk of the system mass lies in the mass of the hardware needed to supply the electricity for the processes that separates H2 from water H_2O and the mass of the refrigerator / compressor needed to liquefy the gasses into LH2.

The advantage of the H_2O NTR system is its dramatic simplicity. It uses only heat. It does not require massive space electric power nor electrolyzers, compressors or refrigerators to make LH2. The H_2O NTR system can also use the H_2O propellants promptly and directly, without the 1 year processing delay to split the water.

Getting water from space dramatically changes the system costs. All transport schemes are ultimately judged on cost. We could eliminate the cost of launching the propellant and instead launch empty tanks and the system needed to extract and prepare propellants to fill them. This is completely different from familiar propulsion systems.

9. Summary

This work shows that a H_2O NTR propulsion system can propel massive payloads between near-Earth and the ice moons of Jupiter. The additional hardware to use water from space in the H_2O NTR propulsion requires only heat, not electricity. It is also shown to be far simpler than more massive and far more complex hardware needed for the cryogenic propellant, LH2 NTR alternative.

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