Origin Of How Steam Rockets Can Reduce Space Transport Cost By Orders Of Magnitude

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Abstract. A brief sketch shows the origin of why and how thermal rocket propulsion has the unique potential to dramatically reduce the cost of space transportation for most inner solar system missions of interest. Orders of magnitude reduction in cost are apparently possible when compared to all processes requiring electrolysis for the production of rocket fuels or propellants and to all electric propulsion systems. An order of magnitude advantage can be attributed to rocket propellant tank factors associated with storing water propellant, compared to cryogenic liquids. An order of magnitude can also be attributed to the simplicity of the extraction and processing of ice on the lunar surface, into an easily stored, non-cryogenic rocket propellant (water). A nuclear heated thermal rocket can deliver thousands of times its mass to Low Earth Orbit from the Lunar surface, providing the equivalent to orders of magnitude drop in launch cost for mass in Earth orbit. Mass includes water ice. These cost reductions depend (exponentially) on the mission delta-v requirements being less than about 6 km/s, or about 3 times the specific velocity of steam rockets (2 km/s, from Isp 200 sec). Such missions include: from the lunar surface to Low Lunar Orbit, (LLO), from LLO to lunar escape, from Low Earth Orbit (LEO) to Geosynchronous Orbit (GEO), from LEO to Earth Escape, from LEO to Mars Transfer Orbit, from LLO to GEO, missions returning payloads from about 10% of the periodic comets using propulsive capture to orbits around Earth itself, and fast, 100 day missions from Lunar Escape to Mars. All the assertions depend entirely and completely on the existence of abundant, nearly pure ice at the permanently dark North and South Poles of the Moon.

INTRODUCTION

The Lunar Prospector has recently returned data consistent with multi-billion ton, pure veins of water ice at the forever dark poles of the moon (Binder 1998; Feldman, 1998). Public statements asserting the value of this water specify splitting it, using electrolysis, to make liquid oxygen (LOX) and liquid hydrogen (LH2). The moon would be a rocket fuel station, as in Figure 1. LOX and LH2 make a premier performance rocket fuel, and LH2 is an exceptionally premier performance, thermal-rocket propellant.

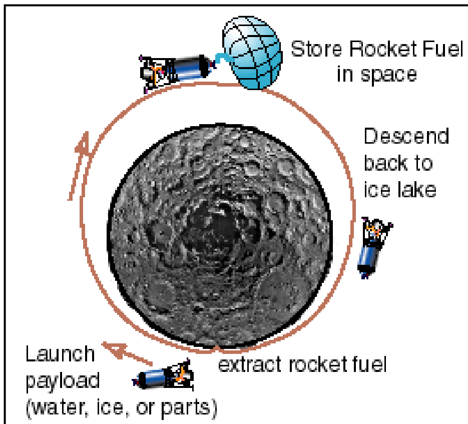

FIGURE 1: Water ice would provide rocket fuel for operations in space. Shown is South Pole of the Moon, taken by the DOD Clementine Mission., 1994.

The Idaho National Engineering and Environmental Laboratory (INEEL), a United States Department of Energy (DOE) national laboratory, had proposed an alternative, direct use of the water as propellant for steam rocket space transportation (Zuppero, 1998; Zuppero, 1997). A steam rocket delivers payload by using a heat source such as a nuclear reactor to convectively heat water to steam, and produces thrust by expanding the steam in a rocket nozzle, as in figure 2.

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A nuclear heated steam rocket (NSR) would launch payloads from the lunar surface to low lunar orbit (LLO). The rocket would then return to the surface to launch more payloads. A separate facility located at an ice formation on the moon would use a nuclear heater to melt ice, as in Figure 3. The facility would condense pure water for the NSR to use in its rocket propellant tank.

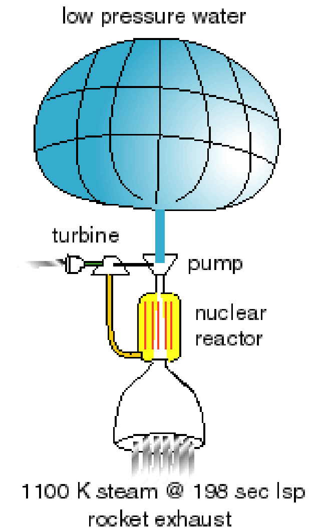

FIGURE 2. A nuclear heated steam rocket uses water as propellant. A nuclear reactor heats the water to steam, expels it in a rocket nozzle, and produces thrust.

Some of the payload delivered to LLO would be water, for use as propellant for steam rockets. Either a solar-heated or nuclear-heated steam rocket (see Figure 4.) would take the payloads from LLO to a Lunar Escape Orbit, which is a nearly ideal location. Note that a payload at lunar escape can be lowered to Low Earth Orbit (LEO) by an incremental aerobraking and orbit decay, which consumes only a small fraction of the propellant.

Every known paper involving steam rockets showed performances that seemed to exceed that of competing architectures by orders of magnitude (Landis, 1991; Zuppero, 1991; Zuppero, 1992-a; Zuppero, 1993-a; Zuppero, 1993-b; Powell, 1993). One estimate (Zuppero, 1997) suggested a single space water truck would be able to deliver about 14,400 tons per year to lunar escape. The proposed architecture would use less than 10's of tons of space hardware to so do, including a single, many-ton water truck. The authors also estimated how much hardware a LOX/LH2, chemical propulsion system would need to deliver the same yearly payload. The LOX/LH2 architecture required between 1000 and 12,000 tons of tanks and hardware, depending on the proposed maturity level of hardware. The "orders of magnitude" difference was noted.

Analyses (Zuppero, 1991; Zuppero, 1993-b) showed how tankage factors permitted nuclear heated steam rocket engine-tank-structure assemblies with tens of tons mass to propel payloads with masses between 1,000 and 10,000 tons.

The findings contradicted well-established interpretations of the rocket equation. The steam rocket has the lowest specific impulse compared to alternatives. The LOX/LH2 rocket has double the specific impulse. An LH2 thermal rocket, either solar or nuclear heated, may show 5 times the specific impulse. Electric rockets have demonstrated orders of magnitude higher specific impulse. The rocket equation shows performance degrades exponentially with a decrease in specific impulse. High specific impulse is the performance objective. However, cost per launched hardware dominates the practical performance objectives.

The cost of a space system rises sharply with the number of systems that must operate in a sequence and with extreme reliability. The chemical propulsion option has many such elements, contrasting the few elements for the steam option.

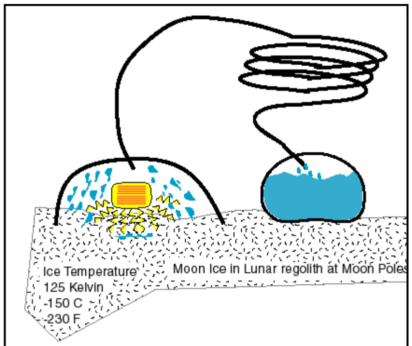

FIGURE 3 A refrigerator-sized nuclear heater can melt and vaporize 100,000 tons ice per year. A steam rocket uses the condensed water directly as propellant.

Other analysis revealed a high relative hardware mass required to produce electricity for the competitors to the steam rocket, to produce the cryofuels LOX and LH2 from water. Closer examination revealed a fundamental issue: radiative heat transfer to the vacuum of space limits the electric power produced per unit hardware mass. The available electric power limits the LOX/LH2 production rate. The rate is orders of magnitude lower than that of the steam rocket architecture.

The results of these analyses suggest there may be a fundamental reason for the disparity in cost between splitting water and using it directly. Examination of Figure 5 shows that systems where electricity provides the energy for propulsion all have a common step: they must reject heat radiatively to space.

SCOPE OF ORDERS OF MAGNITUDE CLAIM

The "orders of magnitude" appear both in absolute and relative senses. Relative to alternatives, steam propulsion can offer clear advantage when the alternatives meet two conditions: 1. the energy in the rocket exhaust is derived entirely from electricity; 2. the mission delta_V is less than about 6 km/s, or about 3 times the specific velocity of steam rocket exhaust (~2 km/s). All architectures using LH2 and those using LOX, derived from electrolysis of water, satisfy the first condition. These include chemical fueled rockets and also liquid hydrogen propellant, nuclear thermal rockets or solar thermal rockets. All architectures using electricity to accelerate masses also satisfy the first condition. These include all ion engines, spark jets, arc jets and electric thrusters. These also include rail guns launching mass off the surface of the moon or asteroids. Missions from the lunar surface to LLO, from LEO to GEO, from LLO to lunar escape, from Lunar Escape to GEO, missions returning payloads from about 10% of the periodic comets using propulsive capture to orbits around Earth itself, and 100 day missions from Lunar Escape to Mars all satisfy the second condition (mission delta_V less than about 6000 m/s). The first and second conditions are satisfied for most missions between Venus and Jupiter.

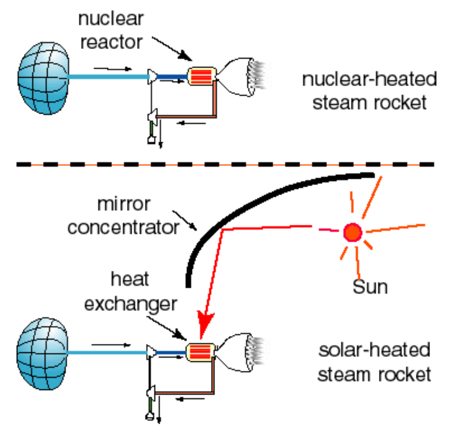

FIGURE 4 Either a solar heated or a nuclear heated thermal steam rocket can take payloads from low lunar orbit to lunar

Architectural simplicity

Architectural simplicity provides a relative advantage. Figure 5 shows the relative simplicity of the steam rocket architecture compared to that of alternative. The steam architecture must extract pure water from ice and store it in a tank. Its principal disadvantage is that it must typically use 3 times as much water as the alternative.

The alternative must generate heat, convert the heat to electricity, dump waste heat doing so, operate an electrolysis unit to split water, manage separate oxygen and hydrogen gas streams, operate mechanical refrigerator-compressor systems to liquefy oxygen and hydrogen gasses, reject heat for these processes, operate separate storage and transfer systems for cryogenic liquids. Rejecting heat to the vacuum of space requires relatively massive radiators, because the vacuum of space provides an environment like that of a thermos jar. The tanks for the cryogenic liquids must contain approximately one atmosphere and must be insulated and refrigerated to cryogenic temperatures.

Reference for comparison

The reference system, based on work presented at the 1997 Joint Propulsion Conference, used 6 tons of steam rocket hardware to deliver 14,400 tons per year to lunar escape. A more conservative, recent analysis (Zuppero, 1998) estimated 20 tons would represent a more conservative system mass estimate. The system included the launch rocket to deliver payloads.

The cryo system needed to do the same job and deliver the same 14,400 tons per year to lunar escape required between 1080 and 8100 tons of electric generators, depending on the mass efficiencies of the generator and the compressor efficiency of the liquid hydrogen cryo-cooler. The water splitters and liquefiers required between 420 and 4,400 tons. The total mass for the electrolysis system is between 1,480 tons and 12,500 tons (totals for upper and lower limits). This chemical fueled system would require 100 to 1000 times more hardware mass on the lunar surface than the steam system delivering the same yearly payload.

DETAILS FOR "ORDERS OF MAGNITUDE"

The origin of the orders of magnitude lies mostly in the Second Law of Thermodynamics and in the Stephan Boltzman relation. The generation of electricity in space depends entirely on the ability to reject heat to space (Stephan Boltzman). And all engines must reject heat (Second Law). The practicality lies entirely in the discovery of massive quantities (~6 billion tons) of pure ice veins at the poles of the Moon.

Practicality

One needs both a nearly limitless sources of ice and people to man the operations. Only missions short enough for humans to endure and using hardware we can afford are candidates for practicality. Moon missions were practical 3 decades ago in affordability (~$20 Billion or less) and duration (~days). In contrast, the steam rocket and the asteroid resource utilization literature has claimed that missions to a comet or asteroid are practical (Lewis 1987). The rocket delta_V to bring back payloads from a significant fraction of earth-approaching, periodic comets and earth-orbit crossing asteroids can indeed be within the scope of steam rocket propulsion. However, the duration of the minimum mission is of order 4 or more years, like that for Mars's missions. Only the moon offers sufficiently short manned round trip times.

Electricity: Thermal Electric Generators

Electric generators in space suffer from the Second Law of Thermodynamics because they must reject heat to generate electricity. All known space electric generators have a thermal efficiency less than 20%. This means reject at least 5 times more energy to space, radiatively, than electricity generated.

Space electric generators can only reject heat by radiation to space, unless they are in contact with a thermal heat sink. The Stephan-Boltzman relation (fourth power of temperature law) limits the heat loss rate for practical radiators. Further, All radiators in space must be armored to mitigate the effects of micro-meteors. For example, a radiator operating at 1100 Kelvin with an emissivity of 0.5 using a 2 mill thick membrane to contain zero grams of thermal conducting fluid (extremely conservative), with structure and armor of 20 mills of radiating material, with density 3 (ceramic), and operating as a heat dump for a 20% efficient electric generator would achieve no more than 5.5 Megawatts per ton (0.18 kg/kw). Compare this to a steam rocket with effective power of 200 Megawatts per ton.

Space electric generators are characterized by the system mass in kilograms to generate one kilowatt of power, expressed as the reciprocal of megawatts per ton. The most optimistic electric generator proposed to be practical was quoted at 7.8 kg/kw (0.12 Megawatts per ton) (Gilland, 1992). Typical space electric generators can not do better than 15 to 200 kg/kw. (0.066 to 0.005 MW/ton).

Solar Electric generators

Solar electric generators must remain well below 200 Celsius, or they become resistors instead of electric generators. They are typically less than 15% efficient. Thus 85% of the input solar energy must be radiated to space, and a major fraction at less than 200 C. Commercial, unarmored solar photovoltaic materials designed for use in orbit have achieved nearly 300 watts per kilogram, at beginning of life (Sanyo, 1994). This is an upper limit power factor of 0.3 Megawatts per ton. Compare to NSR 200 MW/ton.

Tank Mass Fractions

Lower tankage mass fraction provides an absolute advantage. The tanks for a steam rocket can be at least an order of magnitude less massive than tanks for cryogenic fluids such as liquid oxygen , liquid hydrogen and liquid methane. The water vapor pressure is about 10 kPa (1/100 atmosphere, 7 mm Hg) and at 1 Celsius, which is about 100 times lower than that of the cryogenic liquids. The water could be heated by just the waste heat from small electric generator. Joe Lewis at Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, suggested that a collapsible water propellant bladder tank could be made from 5 mill Polybenzoxazole (Zuppero, 98-b). Such a tank would hold hundreds tons of water per ton of tank, which is at least an order of magnitude more than the best tanks for cryogenic liquids. A tank in orbit designed to contain water during a 100 milli-G acceleration maneuver could in principle hold thousands of times its mass in propellant.

Mass in Space

Mass already in space provides an absolute advantage. The cost to launch payload into LEO from Earth is diminished by the payback factor. The lunar ice / nuclear heated steam rocket architecture has the unique potential to provide high payback. Estimates suggest 20 to 100 tons of mass for this architecture, launched from earth, would be able to return 14,000 tons per year, and 140,000 tons of mass to LEO during the operational lifetime (Zuppero, 1997; Zuppero, 1998) . That is, a mass payback of about 1000 times the launched mass appears to be possible. This is equivalent to orders of magnitude drop in the cost of rocket propellant and mass in space. In sharp contrast, calculations suggest a water-splitting system would deliver a mass payback to LEO of 3 to 10 per year from the lunar surface, or less than 100 times its mass during operational lifetime.

Thermal Heat Sinks

A thermal heat sink may be available at the lunar poles and on the surface of ice moons such as Callisto, Ganymede and Europa. A thermal heat sink can be the 90 Kelvin, permanently dark lunar crater basin containing the ice formation. An electric generator would exhaust vapor directly into space at that crater. In so doing, the system would not loose the water because almost all will condense back on the crater. With this heat sink, a minimum mass electric generator would consist of a turbine, a dynamo and a heat source. Based on system masses of similar terrestrial turbine-dynamo combinations, such generators may achieve 2 Megawatts per ton. A nuclear heat source would, in principle, achieve 200 Megawatts per ton and be a small relative fraction of the system mass.

The convective thermal heat sink properties of ice fields of moons may offer a way to produce LOX and LH2 competitive with steam rocket systems. The resulting increase in specific impulse (400 sec for LOX/LH2 systems, 800 sec for LH2 nuclear heated thermal rockets) could open the entire solar system to human exploration.

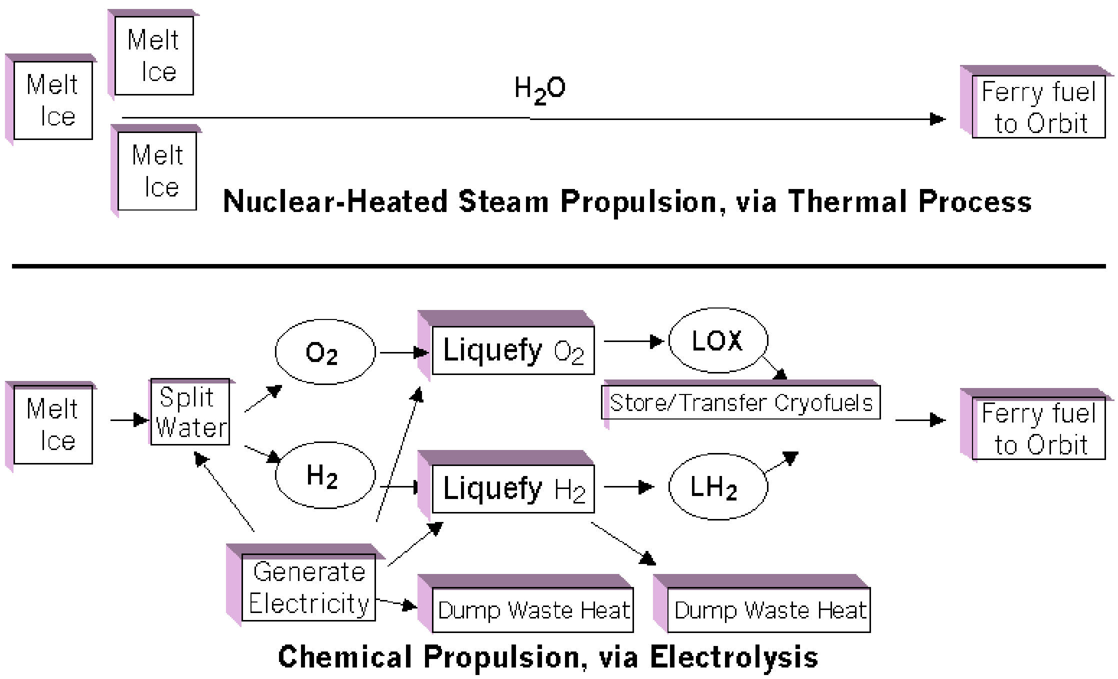

FIGURE 5 An architecture based on a nuclear-heated steam rocket is compared to an architecture that splits water for its hydrogen and oxygen. Simplicity and thermodynamics can dramatically lower cost for the steam system.

CONCLUSION

The discovery of abundant, pure veins of ice in permanently dark crates of the moon offers new degree of freedom in the design of space transportation architectures. Comparison of two competing schemes, a nuclear heated steam rocket and a chemical propulsion rocket, both using water as the raw material, showed that the one that traditionally should be much worse in fact performed orders of magnitude better. The result could be a dramatic drop in the cost of space transportation for missions around Earth itself and to nearby objects such as the Moon, Mars, earth-crossing asteroids and near-earth objects.

The origin of the "orders of magnitude" lies predominantly in the hardware needed for electrolysis to split the water. The steam rocket architecture could in principle operate entirely without electricity. All other architectures derive all the energy for the rocket from electricity. Electrolysis of water and refrigeration of the resulting gases into Liquid Oxygen and/or Liquid Hydrogen caused a requirement for a massive electric generator. The hardware mass to produce electricity and manufacture LOX and LH2 requires about 1000 times heavier systems than the steam rocket system (1,400 to 12,000 tons for the electric system, Vs tens of tons for the steam system).

Other factors also provide potentially dramatic performance gains. The tank to hold water can be collapsible bladder that can hold between hundreds and thousands of times its mass in propellant, compared to tanks for cryogenic fluids such as LH2 and LOX, which hold at most only tens of times their mass in rocket fluids. The complexity of the electrolysis system relative to the steam system has a dramatic effect on the reliability required for the space hardware. Reliability in complex systems increases cost exponentially.

The cost of rocket fuel and other mass in space can drop by orders of magnitude because Earth can launch "pumps." A pump delivers orders of magnitude more mass than its own mass. Like a pump, each ton of hardware sent to space to operate a steam rocket architecture can return between 10,000 and 100,000 times its mass in rocket fuel at Low Earth Orbit. This is completely equivalent to orders of magnitude drop in costs. A chemical architecture would only return 100's of times its mass.

The analysis showed that the radiative heat sink is the issue, and that the ice formations themselves at places like the moon and the ice moons of Jupiter can be a solution, and provide orders of magnitude drop in cost for both LOX and LH2. Conversely, if abundant, nearly pure ice veins are not present on the lunar surface, then dramatic, orders of magnitude cost reductions will not be possible.

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