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Lunar South Pole Space Water Extraction and Trucking System

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This concept proposes to use thermal processes alone to extract water from the lunar South Pole and launch payloads to low lunar orbit. Thermal steam rockets would use water propellant for space transportation. The estimated mass of a space water tanker powered by a nuclear heated steam rocket suggests it can be designed for launch in the Space Shuttle bay. The performance depends on the feasibility of a nuclear reactor rocket engine producing steam at 1100 degrees Kelvin, with a power density of 150 Megawatts per ton of rocket, and operating for thousands of 20 minute cycles. An example uses reject heat from a small nuclear electric power supply to melt 17,800 tons per year of lunar ice. A nuclear heated steam rocket would use the propellant water to launch and deliver 3,800 tons of water per year to a 100 km low lunar orbit.

INTRODUCTION

Anticipating that the Lunar Prospector will find abundant ice at the permanently dark lunar South Pole, we examined the simplest architecture in the literature (Zuppero et al 1997) to deliver ice or water to near-earth space. Thermal processes provide the simplest architectures for rocket propellant production and delivery. A compact nuclear reactor could provide the thermal process heat to melt ice. Distillation would purify the ice, removing solids and salts. Nuclear or solar thermal rockets could use the water as propellant.

Currently available materials limit the specific impulse (Isp) of steam rockets to less than about 200 seconds. The corresponding temperature at the rocket throat is about 1100 K. This Isp is 2 to 5 times lower than competing propulsion options. However,

numerous authors showed how nuclear-heated steam rocket (NSR) propulsion would outperform otherwise superior alternatives (Landis 1991; Zuppero 1991, Aug 1992, Sept 1992, Jan 1993, March 1993, Whitman 1993, Taylor 1994). The NSR would deliver between 10 and 100 times more payload per launched hardware than either chemical rockets using liquid oxygen and liquid hydrogen, with Isp 450 sec, or nuclear rockets using liquid hydrogen propellant, with Isp up to 950 sec. The conditions for NSR performance are 1) a limited system energy, 2) abundant propellant in space, and 3) a mission delta V less than about 6500 m/s. The steam rocket uses far more propellant mass (water) than alternatives. However, water is now known to be plentiful in the Solar System, from planet Mercury on out (Fanale et. al 1982, 1989, 1991; Huebner 1990, Salvail 1994, Slade 1992, Butler 1993, Luu 1994 and 1996, Nozette 1996, Zuppero 1996, Jewitt 97). Absolutely key to this performance claim is the availability of abundant water propellant in space.

This analysis estimated the infrastructure mass and size and the payload delivered by systems considered feasible using existing engineering practices. The analysis also identified key nuclear reactor issues.

MISSION DESCRIPTION

A space water truck would ferry a water payload from a storage tank at the Lunar South Pole (LSP) to a water holding tank at low lunar orbit, as shown in Figure 1. Several crater basins at the LSP are permanently shadowed and at a temperature of about 90 degress Kelvin. A small nuclear reactor system would generate about 100 kilowatts of electricity for operations (e.g. lights and computers). This generator would incidentally reject about 2.4 Megawatts of heat. This otherwise-wasted reject heat will melt and boil lunar permafrost/ice. The steam would condense in a still cooled by the 90 K environment. We assume thie results in pure water, free of salts and solids, filling a storage tank at the launch site.

The water truck would use water as propellant for its NSR. It would launch itself and its payload to a low lunar orbit. It docks with a holding tank facility in orbit. It decants its payload, preferably water, to the holding facility. The water truck then returns to LSP to repeat the process.

Deliberate Mission Conservatism

The architecture we chose is not balanced in the sense that the water truck sits idle for about 40 hours, waiting for the water collector to provide enough propellant and payload for another trip. A balanced system would specify enough water heaters, purifiers and collectors to keep the water truck busy.
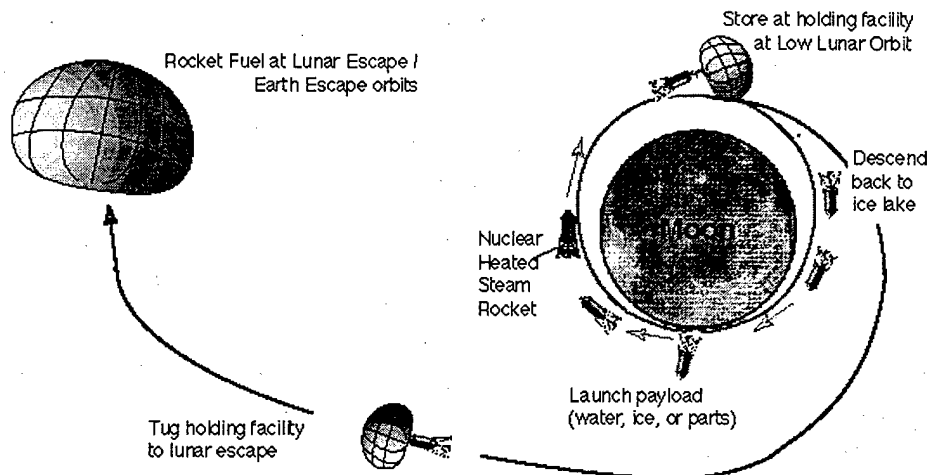
Figure 1. Space Water Truck Concept A space water truck hauls water payload from the lunar South Pole to a holding tank in low lunar orbit. Using water as propellant in its nuclear heated steam rocket, the truck returns to the lunar South Pole and repeats the process. Either nuclear or solar heated steam rockets can use some of the water to deliver the holding tank to lunar escape, which is an ideal starting location for interplanetary missions or for delivery of payloads around or in the vicinity of Earth.

This architecture is not regenerative. A regenerative architecture would use some of the water delivered to space to deliver more hardware. This would increase production capacity but only incur incremental cost. For example, the estimated cost of each additional space water truck (~$100 M) and water melter hardware (~$100 M) is far less than the operations cost ($2B to $10 B over 5 years).

SYSTEM DESCRIPTION AND REQUIREMENTS

The system consists of an ice mining, melting, collecting and water purification subsystem, and a lunar space water truck. The water truck rocket must develop sufficient peak power to launch against lunar gravity. All subsystems must have sufficiently low system masses to permit delivery to lunar surface and satisfy nuclear safety and reliability constraints

Water Extraction Subsystem

The principal issues in the basin of an extremely cold and permanently dark lunar crater are the heating needed to extract the water and the electricity for illumination and computers.

Bennett et. al (1991 and 1992) proposed an SP-100 derivative, modular reactor for lunar and planetary base service to provide both 100 kilowatts of electricity and about 2.4 megawatts of heat. The system is composed of six power modules, each connected to a waste heat radiator module. Each module produces about 17 kWe and sheds about 400 kWt of moderate temperature waste heat. System dimension is approximately 1 meter diameter and estimated mass less than 10 tons.

The 2.4 megawatts of rejected heat, at temperatures between 400 and 800 K, is sufficient to melt and boil approximately 0.7 kg per second of lunar ice from a starting point of 90 K. Operated continuously, this would provide 21,600 metric tons per year of water. This in turn would provide the 92 tons of propellant and 20 tons of payload for about 192 launches per year, or one launch every 42 hours.

Collecting water from an ice/permafrost medium will be easier and simpler than collecting trace hydrogen from lunar regolith. We refer to Wittenberg, just one of many suggestions, where he provides an in-situ, pneumatic structure system to collect and evolve solar wind gasses from the lunar regolith. Our analysis provides the heat for a process like his, but would collect water vapor in a permafrost basin.

Water Purity Considerations
We expect the distilled water from this process to be free of dissolved of solids and salt contaminants. The reactor will not produce radioactive, neutron activated contaminants with pure water. Some contaminant hydrocarbons do not completely separate from the water upon distillation. This uncertaintly can only be resolved by sampling the lunar ice.

When the water is derived from near earth comet resources (Zuppero, June 1996), we expect that hydrocarbon contamination will be a serious consideration. We also expect that distillation will be more difficult because of the low gravity of comets.

Launch System
The launch system must provide sufficient thrust to lift payloads against lunar gravity. This results in a rocket engine minimum power per mass ratio in excess of 150 megawatts per ton of rocket engine, and a minimum specific impulse of at least 150 seconds, whether is it nuclear, chemical or other (Zuppero et. al. 1997). Figure 2 shows this launch system, with our calculated masses indicated.
This conservative design used an aluminum tank pressurized to 1.1e5 Pa (15 psi). The tank is singled out because the literature suggests water propellant tanks can consist of bladders, and that the vapor pressure of water at just above freezing, 790 Pa (6 mm Hg), is so low that the bladders need not weigh very much. Claims suggest a 1 ton bladder can contain between 100 and 5000 tons of water, in space.

Table 1 shows the water truck parameters. This design favors lowest development cost and least risk and does not incorporate optimizations such as advanced materials or methods. A launch delta V of 1859 m/s (6100 fps) and a lift off thrust equal to 1.5 times lunar gravity at launch provides an 11% margin against gravity loss. The landing system of 681 kg (1,500 lbs) permits folding for stowage in the Shuttle bay, but is otherwise of the "fixed" type. The guidance package of 454 kg (1000 lbs) is sufficiently massive to permit some shielding of radiation sensitive electronics and is located at the top of the vehicle to provide as much distance from the reactor as

possible. The primary and secondary structure mass of 1818 kg (4000 lbs) is specified for low cost rather than high performance as the driving criteria. Thrust structure and feed lines of 909 kg (2000 lbs) support the tank and anchor the nuclear reactor. A 25% growth factor of 2090 kg (4600 lbs) provides a standard margin to accommodate design changes appropriate for minimizing development costs.

Mass Budget		Water Truck Mass Breakdown	
10.3 tons	structure	.45 tons	guidance package (1000 lbs)
92.6 tons	propellant water	1.6 tons	tank (3500 lbs)
75. 7 tons	up propellant	.91 tons	thrust structure and feed lines (2000 lbs)
16.9 tons	down propellant	1.82 tons	primary and secondary structure (4000 lbs)
20 tons	payload	.68 tons	landing system (1500 lbs)
123 tons	lift off	2.09 tons	25% growth factor (4600 lbs)
		1.82 tons	reactor (4000 lbs)
Dimensions		.23 tons	turbopumps and rocket nozzles (500 lbs)
3.38 m	diameter (11.1)	.68 tons	reaction control nozzles (1500 lbs)
8.5 m	tank barrel length (27.7 ft)		
11.9 m	total length (39 ft)		

Table 1. Total Mass, dimensions, and mass breakdown of launch vehicle.

The calculated tank mass of 1590 kg (3500 lbs) would be constructed from 3.17 mm (1/8 inch) aluminum, would be pressurized to 1.1E5 Pa (15 psi) to keep it structurally rigid, and would hold 58 tons of water per ton tank. Ullage (propellant remaining in tank at end of mission) is 3%. An advanced system, which this is not, would reduce this ullage through use of an internal gas bladder and optimally shaped bladder tank. Experience with rockets using liquid hydrocarbon fuels indicates propellant sloshing will not be a problem. The reactor supplies between 4 and 120 kWt to maintain an un-insulated, un-armored tank of water at 15 psi and 373.7 K.

Small reaction control jets that bleed some of the steam to side-pointing thrusters perform thrust vector control. This increases mass but permits fixed, non-gimbaled rocket engine, and simplifies the design.

NUCLEAR ROCKET

The nuclear reactor mass of 1818 kg (4000 lbs) is considered 50% more than minimum. The reactor must deliver 292 megawatts to the steam at a mixed mean

outlet temperature of 1100 K with propellant flow of 155 kg/s. A rocket nozzle area ratio of 200:1 will deliver a specific impulse of 198 seconds.
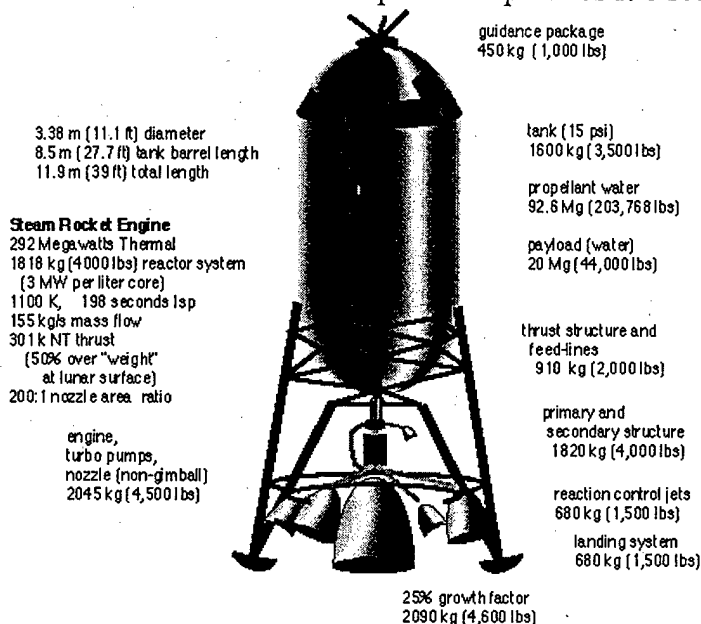
guidance package
450 kg (1,000 lbs)

3.38 m (11.1 ft) diameter
8.5 m (27.7 ft) tank barrel length
11.9 m (39 ft) total length

tank (15 psi)
1600 kg (3,500 lbs)

propellant water
92.6 Mg (203,768 lbs)

Steam Rocket Engine
292 Megawatts Thermal
1818 kg (4000 lbs) reactor system
  (3 MW per liter core)
1100 K, 198 seconds Isp
155 kg/s mass flow
301 k NT thrust
  (50% over "weight"
  at lunar surface)
200:1 nozzle area ratio

payload (water)
20 Mg (44,000 lbs)

thrust structure and
feed-lines
  910 kg (2,000 lbs)

engine,
turbo pumps,
nozzle (non-gimball)
2045 kg (4,500 lbs)

primary and
secondary structure
1820 kg (4,000 lbs)

reaction control jets
680 kg (1,500 lbs)

landing system
680 kg (1,500 lbs)

25% growth factor
2090 kg (4,600 lbs)

Figure 2. Lunar South Pole, Space Water Truck uses nuclear reactor to heat rocket propellant water into steam. This design traded system weight to get lower cost.

The turbopump and rocket nozzle assembly is assigned 227 kg (500 lbs). A turbo-pump to pressurize the propellant bleeds less than 1% of output steam through a turbine-turbopump assembly. Figure 3 shows this simplified nuclear thermal rocket reactor scheme.
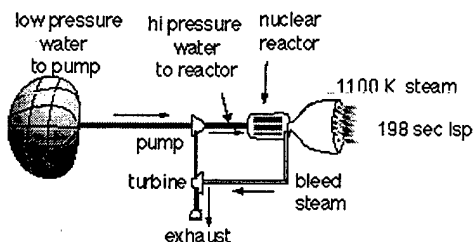
low pressure   hi pressure   nuclear
water   water   reactor
to pump   to reactor

1100 K steam

198 sec Isp

pump

turbine   bleed
                 steam

exhaust

Figure 3. Nuclear Heated Steam Rocket A nuclear reactor produces steam and directs it directly into a rocket nozzle. A turbine-turbopump assembly pressurizes the water and feeds it into the reactor using bleed steam.

REACTOR ISSUES
Operating Pressure and Condition

This reactor is a boiling water reactor, similar to commercial reactors and is operationally very similar. A reactor core with mass of 1000 kg would imply a core power density between 1 and 3 megawatts per liter. This required power density at 1100 Kelvin is less than that achieved during the Nerva program (4 Megawatts per liter) with hydrogen propellant at temperatures in excess of 2500 K. .

Nuclear Fuel Cladding

The nuclear fuel elements require a cladding (encapsulation material) that resists pitting and corrosion attack by the 1100 K steam. Data suggests several candidates for testing that may provide the required performance. An experimental study (Berry) of samples in steam containing up to 20 ppm oxygen and 1 percent moisture, at temperatures to 1005 K, velocities to 91 m/s (200 ft/s) and with irradiation of 1E22 nvt (>1 MeV), suggests Incoloy 800, Inconel 600 (at low stresses) and Hastelloy X will survive years of reactor operation. Another experiment (Uhlig) showed Inconel 625 lost only 6.2e-3 mm (0.246 mills) at 1089 K steam during a 2667 hour test. Other tests of several sample steels "12 Cr, 18-8 and 18-8 CB" (chrome-nickel) in contact with steam at approximately 1018 K for 300 hours showed erosion or penetration less than 0.02 millimeters.

Multiple Cycles

The water truck must deliver water once every 42 hours, using a 20 minute thrusting cycle. This will require about 192 cycles, from cold to full thrust. This is an operating condition of the kind not experienced in conventional reactor operations, so it must be addressed.

Neutronics

The nickel-chrome steel cladding materials will require highly enriched uranium fuel to maintain reactivity. Designs exist to render this reactor safe upon an ocean immersion launch accident.

Decay Heat

Within 200 seconds of reactor shut down the power drops to less than 0.95% of full power. A reactor operated for 3 intervals of 20 minutes every day for a year may release enough decay heat to consume 3.8 tons of water per trip. When the reactor is docked in orbit, the thrust produced by decay heated steam can be used efficiently to raise the docking station orbit, which is desirable. When the reactor returns to the lunar surface, it returns to a location where water is plentiful. The operational issue is that of a reactor that must be cooled and is radioactive.

Fuel Burnup

The nuclear rocket will burn about 0.7 kg of uranium to develop 292 megawatts in 20 minute thrust intervals and totaling about 240 hours per year. A tanker making 3 trips per day for a year will burn less than 5 kg Uranium.

The period of a 100 km orbit is approximately 2 hours, so a water truck launch and return trip that consumes a day (24 hours) would result in a the water truck spending most of its time waiting for the water extractor to provide water.

CONCLUSION

This analysis included all critical elements of a system to extract water from ice at the lunar South Pole and deliver it to a low lunar orbit. A deliberately conservative, perhaps unimaginative design estimated the upper limit of water truck mass to be less than 11 tons and a lower limit of payload to be 20 tons.

This architecture focused on infrastructure and operational simplicity, at the expense of a system mass and space resources (water). System details considered to be solvable but not on critical path were not analyzed. We provided data suggesting key issues could be resolved. These issues included:
- nuclear heated rocket with sufficient thrust
- general thermodynamic cycles involved
- nuclear safety issues

Analysis suggests that the engineering systems required are feasible and can be developed without extreme cost, risk or schedule penalty. The key requirement is a nuclear rocket delivering greater than 150 megawatts per ton at 198 sec Isp. This system could deliver 3800 tons per year to lunar orbit.

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