INEL-94/00023

Conf-950110--18

Log Nr 0000

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Prepared for:

Conference On Alternative Power From Space
Session C2: System, Key Technologies and Manufacturing
Sponsor: Institute for Space and Nuclear Power Studies
Date: 8 - 12 January, 1995
Location: Hilton Hotel, Albuquerque, New Mexico

Version / Date

"Lun-ice Ver 2.3," 17 October 1994

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Abstract

Recent Clementine bistatic radar data suggest that water ice may be present in a "forever shaded" depression or crater at the South Pole of the Moon. The ice is a feedstock for the electrolysis production of cryogenic oxygen and hydrogen rocket fuels for a transportation system on the moon and for leaving and descending on to the moon. The ice also provides a convective heat sink critical to the practical implementation of high throughput electric power generators and refrigerators that liquefy and cool the oxygen and hydrogen into cryogenic rocket fuel. This brief analysis shows that about a hundred tonnes of hardware delivered to the lunar surface can produce tens of thousands of tonnes of rocket fuel per year, on the moon. And it makes the point that if convective cooling is used instead of radiative cooling, then power and processing systems can be used that exist and have been tested already. This shortens the time by an order of magnitude to develop lunar operations. Quick deployment of a chemical cryofuel energy source is a key factor in the economics of lunar development.

INTRODUCTION

The possible discovery of water ice deep in a depression or crater at the Lunar South Pole may provide a heat sink, which is the key element needed to accelerate and jump start the development of the moon as resource. The moon could, for example, become a place to generate electricity for Earth.

Doing anything in space requires electricity, and the amount of electricity generated is directly proportional to the amount of heat the generator can dump to a heat sink. The vacuum of space is a bad heat sink, even though the night sky is at a very low, 3 Kelvin temperature. The vacuum can only accept heat by radiation, according to the Stefan-Boltzmann law. This fourth-power law constrains the radiative heat sink systems either to suffer at least an order of magnitude lower heat transfer rate than convective heat transfer, or to operate at a very high temperature. When we use freezing cold water as a heat sink, we accelerate the amount of work we can get out of a given amount of hardware launched to the moon by at least an order of magnitude over radiative systems at the same temperature. If we don't use a convective heat sink, then we must use very high temperature systems that require decade(s) of development. The cold water heat sink permits the use of heat management technology of the kind we now use on Earth, instead of specialized and very high temperature technologies designed to dump heat to a vacuum. This affects the economics because it cuts the time to reap a return on investment by an order of magnitude. This shortening of the time to reap a return on investment is the value and point of this analysis.

DATA AND ASSUMPTIONS

The Clementine mission in the first moon mission in two decades. It optically mapped the entire moon. And its bistatic radar circular polarization data from the lunar South Pole is consistent with perhaps several cubic kilometers, or several times 10^9 tonnes, of ice (Worden 94). We will assume that water ice or frozen mud will have been found close enough to the lunar surface for us to easily carve out as much of it as we need, and that we can extract coolant water from the frozen mud by heating it.

PROBLEM DEFINITION AND PLAN

The analysis estimates how much cryogenic rocket fuel we can generate on the Moon and how much of the rocket fuel we could deliver to (from) a Low Lunar Orbit (LLO). It uses as examples a radiatively cooled proposed system and a convectively cooled system based on existing, available technology. One measure of utility is the amount of

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rocket fuel created or payload delivered per year, for a given amount of hardware on the Moon. Another, perhaps more important measure, is how long it would take to develop and deploy the hardware to do so.

This analysis assumes that some infrastructure will exist on the Moon to chop, collect ice, and melt it. This is needed for either type of cryofuel production system. Auxiallry power will be needed, and something like an SP-100 derivative will do this. The cold water would also be used as coolant for a small (<30 MW), nuclear reactor heated, electric generator system, for a water electrolysis unit, and as a heat sink for the refrigerators that compress and liquefy the resulting hydrogen and oxygen. We will estimate the amount of ice needed for this, how much cryogenic rocket fuel this system can generate, and how much rocket fuel we can deliver each year to LLO. We will use existing studies or data to estimate the mass of essential hardware required.

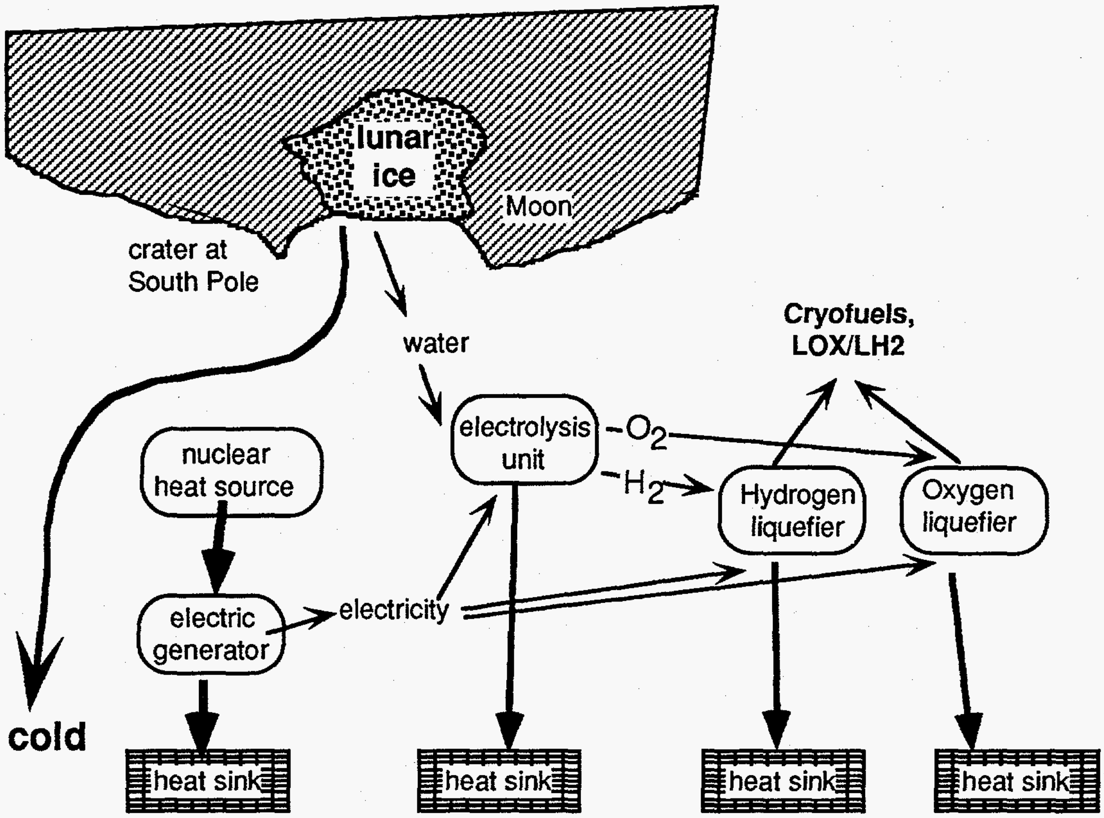

FIGURE 1. Energy, Heat Sink and Resource Elements for Cryofuel Production on the Moon

LOX/LH$_2$ PRODUCTION

We use a point design for a space electrolysis and liquefaction process which was performed as part of a 1990 International Space University project (ISU 1990). They designed for the thermal management in the vacuum of space. We delete their radiators to estimate the masses of the hardware appropriate for use of cold water coolants. We also use a small nuclear electric generator system taken from experiments and tests performed at the INEL.

Radiatively Cooled System

The ISU project calculated the masses and power consumption (or generation) of the electric generator, the electrolyzer and the liquefiers for a 5,970 tonne per year LOX/LH2 production system. Exerpts are given below in Table 1. The table was abstracted from the report and does not include the 18.5 tonnes of radiators the study specified.

The electrolysis part of the system scaled up to a mass of 100 tons would produce about 27,260 tonnes per year of cryofuels. It would require about 22.8 Megawatts of electricity. Scaling the electric generator up to 22.8 Megawatts would imply about 69 tonnes of electric power system.

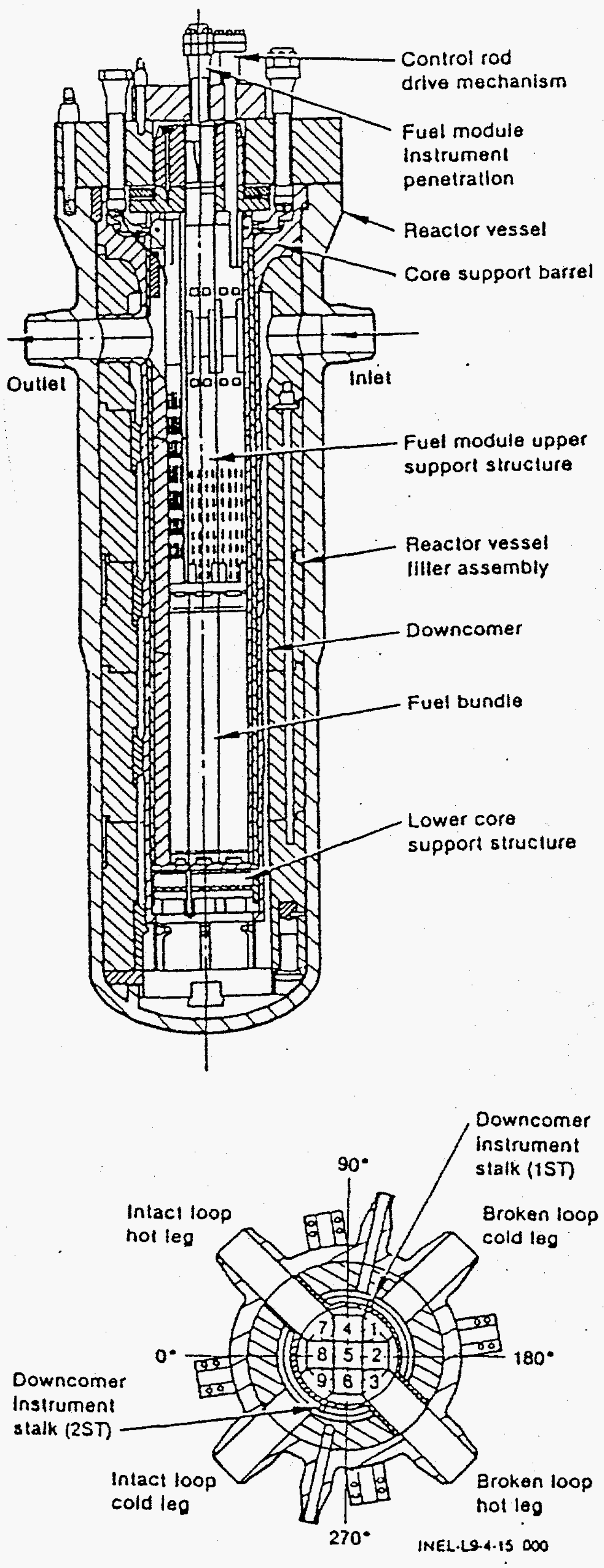

FIGURE 3. Cross Section of the LOFT Reactor

A small PWR system arranged in one or two primary coolant loops will use commercial UO2 fuel in zircaloy cladding in a typical generic PWR fuel assemblies and produce 60MW thermal (20MWe) power. The core will be designed to provide several years of operation without refueling. An ice condenser will be used as residual heat rejection system. Safety systems similar to those in current generation of commercial PWRs will be provided.

There is in the U.S. large design and operation experience base with small PWRs. The reactor and the coolant system can be modeled after the LOFT reactor operated at the Idaho National Engineering Laboratory for several years (the LOFT reactor system was used to demonstrate safety characteristics of commercial PWRs). Reeder (1978) and Fell and Modro (1990) describe such systems in detail. Figure 2. shows the operating loop of the LOFT system and Figure 3 the cross section of the reactor vessel.

We estimate a similar reactor system complete with safety systems, turbine-generator unit, condenser and all supporting and control systems will have a mass of less than 250 tons. The largest component will be about 1.7m in diameter and 6.5m long.

VOLUME OF THE ICE USED

To estimate an upper bound on the volume of ice used per year we use all the heat the system generates to convert ice to very cold water vapor. This double phase transition, from ice at 273 K to cold steam at 274 K (1 Celsius) and 690 Pa (5 mm Hg, or 0.1 psi), absorbs about 2.2 x 10^6 Joules per kg ice. This estimate is conservative because some of the energy is stored in the cryofuel, because the ice and the regolith around it is almost certainly at a 250 K (~-20) temperature, or lower, and because the heat sink system may result in much hotter output than 274 K..

A 22.8 MW electric generator operating at 35% efficiency dumps about 65.1 MW thermal to the heat sink. The total heat generated is less than about 89 MW. At this rate, we would use about 40 kg/s ice. This would amount to about 1.26 x 10^9 kg ice per year, which is about 1.38 x 10^9 m^3, or a cube about 111 meters on edge. If the ice on the moon is a like a deep lake, it will be a sphere several km across and contain about 1.4 x 10^{13} kg, or

TABLE 1 Mass and Power Requirements for a System designed for the vacuum of space to convert 0.1894 kg/s (5,970 Tonnes per Year) of Water into Cryofuels Liquid Oxygen And Liquid Hydrogen (LOX/LH2)

item	mass (tonnes)	power (Megawatts)	rates (kg/s)
electrolyzer	16.9	3.2 (input)	0.1894
LH2 liquefier	4	1.2	0.02111
LOX liquefier	1	0.6	0.16944
electric generator	38.6	12.7 (output)	

The drawbacks to using this example are that the reactor and metal vapor turbine does not exist as a real system. The authors claim that this "should be technically feasible within the next 10 years." It would opearate at 1550 K (2330 F) with lithium coolant. Its secondary, power conversion loop would produce potassium vapor to operate a turbine whose heat rejection side runs at 950 K. The heat sink is radiatively cooled.

If it should be feasible, then about 100 tonnes of electrolyzer/liquefier and 69 tonnes of electric generator would produce about 27,000 tonnes per year of cryofuels.

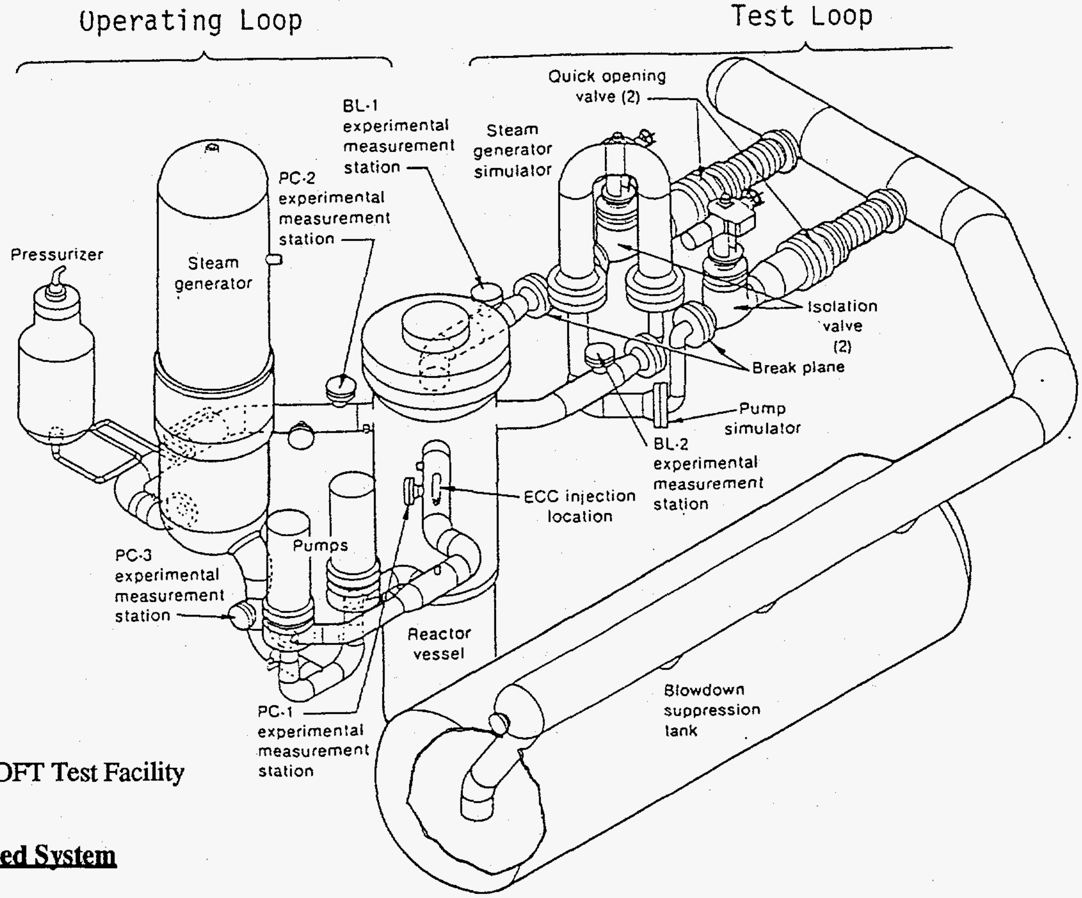

FIGURE 2. LOFT Test Facility

Convectively Cooled System

An alternative whose components exist today would use familiar systems that have been tested. We propose to utilize current Pressurized Water Reactor (PWR) technology to provide electric power for the water electrolysis unit.

about 10,000 such cubes. Even if we vented the vaporized water coming out of the heat sink system to the vacuum of space (a crime against Nature), we would dump only 0.01% per year of the resource.

To conserve very precious water we could dump vapor coming out of the heat sink into the sub-freezing lunar regolith The regolith would freeze most of the vaporized water and result in a much more dilute and warmer frozen mud than the ice we started with. This would at least not waste the water.

PAYLOAD INTO LOW LUNAR ORBIT

A launch system would use the LOX/LH2 to deliver payload to LLO. The payload mass delivered would be about the same as the mass of rocket fuel used to launch it. For example, a vertical launch system in a gravity field on Earth starts with about 40% more thrust than needed to hover the craft above the surface. The delta-V the launch system must achieve is about 20% more than the orbital velocity. A small final thrust circularizes the orbit. On the moon this translates to about 20% more than the 1678 m/s orbital velocity, or about 2014 m/s, and an additional 40 m/s to circularize at an orbit 5% higher than the radius of the moon. The total delta_V required is about 2054 m/s. The tanks, rocket engine and structure comprise a mass fraction of about 5% of the launch mass. This is also very much like that of current systems.

A LOX/LH2 rocket developing about 350 seconds Isp with 5% tankage and engine mass has a launch mass about 1.82 times the final mass in orbit. Conversely, the payload is about 52% of the liftoff mass.

Note that this Isp is lower than that of modern LOX/LH2 rockets, which develop about 460 s and use about 5.56 LOX per 1 LH2, instead of the stoichiometric 8 to 1. A stoichiometric LOX/LH2 rocket would only develop 350 seconds. But its thrust per pound would increase and would match the lunar liftoff conditions better than the higher Isp (~460 s) LOX/LH2 engines we use today.

OTHER OPTIONS CONSIDERED

The other options we considered were taken from the workshop held to evaluate the impact of the 1992 discovery of an ice-object in the space near Earth (Zuppero 1993). The object, comet Wilson-Harrington, comes anomalously close to Earth's orbit (about 0.004 A.U.) relatively often (every 4.3 years). This workshop evaluated many ways to process and use water ice in space.

Steam Rockets

We considered direct use of the water as propellant for a nuclear heated steam rocket. This would be an extremely simple use of the water. But it could deliver water, not rocket fuel, to LLO. Practical steam rockets, whose temperatures are lower than about 1500 K, have specific impulses less than about 230 seconds. Transportation missions to and from Earth orbits with this Isp consume between 10 and 50 times as much water as payload delivered. While this could be acceptable for the comet system, it was considered unacceptable here.

Furthermore, we found that we would need a very high power reactor (1000 MW) to launch relatively low masses (44.7 tonnes) from the moon. And the reactor would be in lunar orbit often. To deliver the same amount of mass to LLO as the cryosystem (~15,000 tonnes/yr), would require many hundreds of reactor liftoff episodes. A crash probability less than 1 in 100 would result in a 50-50 chance of a polluted moon.

Liquid Hydrogen Production

We also considered the production of LH2 alone, for use in solar thermal or nuclear thermal rockets. These can very reliably deliver Isp greater than 600 sec and, with development, could deliver up to 900 sec. The delivery of LH2 in massive quantities would be a very useful thing to do. Further, we could combine the 0.5% iron flakes found in the lunar regolith with 1500 K steam (no electricity required) to produce rust and pure hydrogen gas. We would then only need a hydrogen liquefier.

If all we needed were an electric generator and a hydrogen liquefier (and a 1500 K process heat source that needs no heat sink), then the data in Table 1 imply that 100 tonnes of equipment would only produce about 8,700 tonnes per year of LH2 -- not enough.

CONCLUSION:

Less than a few hundred tonnes of hardware can produce tens of thousands of tonnes of cryofuels per year on the lunar surface. A fleet of rockets can use these cryofuels to transport half of the fuels, or an equal mass of anything else, from the lunar surface to space.

This analysis dealt only in rough estimates. When, or if, the presence of water is verified, one can justify a more detailed analyses, including a most important analysis: one comparing the costs between using materials from Earth compared to using materials from the moon or space.

Although this approach would use nuclear systems, it keeps them deep in a hole in a permanently dark part of the moon. It never puts a live nuclear system into orbit. The "large" nuclear systems are relatively small, of the same kind and size found in submarines (~30 MW electric, water reactors). And the small electric power systems are exactly the same as the SP-100 class currently under development.

The nuclear systems it would use could be of the same the kind we use today, on Earth. The designs, components and parts for the nuclear electric system are chosen entirely from proven and tested examples familiar to those used at the INEL. The electrolysis and liquefaction systems could also be of the same kind we use on Earth. The key element permitting this is the thermal management afforded by cold water coolant. This accelerates the development and lowers the cost.

Acknowledgments

Work supported in part by the U.S. Department of Energy under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

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