NUCLEAR FISSION AND FUSION MICROREACTORS FOR LUNAR AND PLANETARY TUNNELING APPLICATIONS.

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Introduction: Lunar and deep space missions and the successful development of the solar system and beyond will require power-intensive bases, mining, and construction activities. Becoming a space faring species is not an option for humanity. It is an evolutionary necessity, which opens our development to the "open economy" of space.[1] Mankind's future successful development requires the bold, new advancement of thermonuclear "peacetime" technologies, rather than seeking thermonuclear warfare. [2]

Development of the near Solar System and beyond is not merely a matter of efficient mining of *in-situ* space resources and maximizing monetary profit. "Profit" from successful space development lies in increasing the power of labor employed in space through scientific and technological breakthroughs, applied through good engineering, that increases the potential population density of settlements, and then cities and even sovereign republics, on the Moon, Mars and beyond. [3] *Simple seeking of monetary profit, and maintaining control of space markets through hybrid warfare, will lead to the rapid failure of development efforts.* Development means building physical infrastructure as well as research, industrial, educational, habitation, recreational, agro-industrial, and cultural facilities. The Moon is an excellent place to begin this development, as it is relatively close to the Earth.

Construction of subsurface facilities has been proposed to mitigate harsh surface conditions on the Moon and Mars. [4] Tunnel-boring machines modified for planetary environments may be good choices for building lunar subsurface habilitation, research, industrial and recreational facilities, providing straightforward protection from harsh surface solar radiation, near vacuum, micrometeorites and meteorites, and wide diurnal temperature swings. Facilities could be made by improving or connecting existing lava tubes [5] Tunneling operations will require lightweight, energy dense, dependable, reliable, and resilient power supplies. [6] Nuclear fission and fusion microreactors are a good choice for this mission.

US Microreactor Designs, 1950's through 2000's: For design purposes, assume a tunnel boring machine requiring one MWe of power. Various earlier microreactor designs could not produce that much, but design work was critical for ultimately reaching that power goal.

U. S. Army ML-1: The Army's ML-1 modular reactor was built, reached criticality and field tested in the early 1960's. It produced 500 kWe, 2400/4160 VAC, at ambient temperatures between -65°F and 100°F. Cycle efficiency was 13.3%. The entire package weight 40 short tons, broken down into 3 packages that weighed a maximum of 15 tons and were 150" tall, for loading onto C-124, C-130, C-133, ship, barge, railroad flat car, or standard Army trailer. It required 6 hours to prepare for loading onto an aircraft, and 12 hours for field installation. Estimated power density was estimated at 700kW/ft^3. It contained a heterogeneous, water moderated, enriched UO_2 core in 61 fuel-bearing pressure tubes.

Successfully field tested, the program was shut down by Vietnam War budgets and the beginnings of cultural pessimism following Kennedy's assassination. Not suitable for planetary applications, ML-1 kicked off a long series of planetary application microreactors.[7]

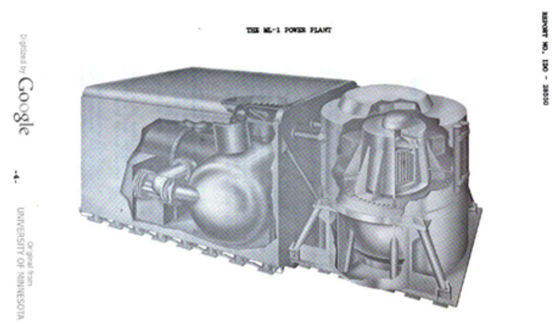

Figure 1: Sketch of ML-1 Microreactor

SNAP (Systems for Nuclear Auxiliary Power) Reactor Development and Deployment: The Atomic Energy Commission began two parallel SNAP projects lines in 1955, in conjunction with private industry and other Agencies. Odd-numbered SNAP 1 through 19 for various satellites led to the current MMRTG aboard *Curiosity* and *Perseverance* Mars rovers. Reactors varied in size from small weather buoy to rovers, using fuels including ^{144}Ce, ^{90}Sr, ^{242}Cm, and ^{238}Pu.

Even-numbered SNAP projects were compact nuclear power thermal generation projects intended for long-term space and planetary missions. SNAP-2, for example, was developed and tested by North American Aviation between April 1961 and December 1962. Multiple versions using UZrH fuel were tested up to 10,000 hours, producing 55 kWt. It was intended for powering manned spacecraft and shielded by LiH. [8] SNAP-10A, a 500 W Be-reflected, liquid NaK cooled reactor, powered the Agena-D satellite for 43 days in 1965 before a faulty command receiver shut it down. [9].

Project Prometheus. Project Prometheus designed a spacecraft powered by a 200 kWe Brayton cycle converter powering ion propulsors and Hall thrusters, using a SNAP reactor, for a 20 year long unmanned mission to the Jovian moons scheduled to begin in 2017. It was designed to reduce travel time to Mars to 8 weeks but was cancelled in 2006. [10]

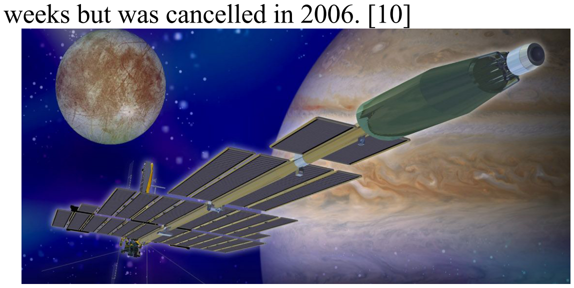

Figure 2: Artist's rendition of Project Prometheus

Some Current Designs: The US is beginning to restore capabilities lost when SNAP programs were cancelled, nearly 50 years ago. Bottlenecks continue in production, qualified labor, and funding. Only some designs can be covered here.

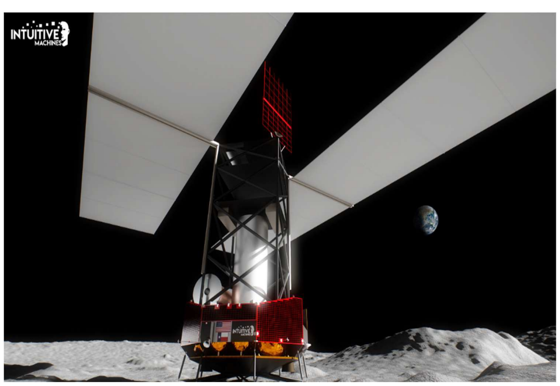

Figure 3: Artist's conception, potential IX Joint Venture , 40 kWe lunar nuclear power plant

Intuitive Machines and X-Energy Team for Fission Surface Power. In 2023 NASA awarded IX, a joint venture between Intuitive Machines and X-Energy, which also included Maxar and Boeing, to deliver a 40 kWe nuclear power system to the lunar surface by 2028. [11] The contract specifies 40 kWe continuous output for 10 years, withstanding launching loads, fitting in a 4-meter cylinder 6 meters long in stowed launch configuration, a mass less than 6,000 kg, and readily scaled up to produce 1 MWe. Three joint ventures are in the second design phase. [12]

Basic Tunnel Boring Machine (TBM) Concepts: A TBM consists of a large metal cylinder, or *shield*, and support mechanisms trailing behind. The shield protects the system from variable ground conditions or seismic effects ("moonquakes") and is pushed forward by hydraulic jacks that press against the walls. An erector rotating system behind the shield installs precast concrete segments to line the tunnel on terrestrial TBM's. It may be possible to line a lunar tunnel with sintered regolith panels, or coat the walls, to allow tunnel pressurization and atmospheric control.

At the front of the shield is a rotating cutting face. It can be pressurized or unpressurized.[13]

TBM's for lunar deployment (LTBM) will depend upon ground conditions. They would have to withstand launching loads, vacuum, and potentially high levels of radiation during transport. Large scale orbiting industrial space stations could manufacture the LTBM's, mitigating some of these environmental challenges.

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