Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting
Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/

Small Modular Fission Reactors for Space Applications

Enabling an Affordable, Commercially Developed Power Architecture for the Moon and Beyond

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Introduction

The National Aeronautics and Space Administration (NASA), other international space agencies, industry, and private entrepreneurs have plans to robotically explore planetary bodies and to return humans to the Moon within the next decade, followed by human visits to Mars. Performing these activities via public/private partnerships is highly advantageous, offering NASA and industry the opportunity to share both the risk and rewards.

Planned Future Human and Robotic Mission Activities

- Characterization of planetary surface morphology, geology, and geochemistry, including detailed mapping of mineral deposits and in situ resources;
- Exploration of surface and subsurface locations, including craters, lava tubes, and perhaps subsurface oceans;
- Collection, return, and analysis of samples from the lunar, asteroidal and Martian surfaces and interiors;
- In situ resource utilization (ISRU) for construction, life support, and propellant production;
- Prospecting and mining of lunar and asteroidal resources for utilization in space and/or possible return to Earth; and
- Construction of outposts, settlements, habitats, and other infrastructure.

Common to all these robotic and human activities is the need for abundant and reliable electrical power. More capable robotic exploration, ISRU, and sustained human presence will require electrical power in the 40 kW to 150 kW range that is continuously available throughout the entire day/night cycles of the planetary body being explored. In the case of the Moon, a power plant capable of meeting this need would form the basis for establishing commercial electrical utility services on the lunar surface. Such services will jump-start the exploration, resource mapping, commercial exploitation, and colonization of the Moon by a broad mix of public and private users that include space agencies, industries, adventurers, and entrepreneurs.

To address the challenges and opportunities of establishing in-space commercial electrical utilities, Universities Space Research Association (USRA) recently began an internal research and development (IRAD) project to perform a concept study of a new small modular fission reactor (SMFR) targeted for use on the Moon. SMFRs have significant advantages over other potential power sources being considered for the Moon.

While photovoltaic systems will play an important role in future space power architectures, their inability to generate power during the long lunar night (which can last for up to 14 Earth days) or in shadowed regions places significant limitations for most applications envisioned on the Moon.

Photovoltaic systems become impractical when accounting for the mass of the energy storage components (batteries, flywheels, etc.) required to provide electrical power through the long lunar night. On Mars, photovoltaic systems are also limited by solar intensity and atmospheric dust.

Similarly, radioisotope thermoelectric generators (RTGs), like the one shown in Figure 1, have significant limitations for planetary and deep space robotic and human missions. RTGs, which operate using exotic Pu-238 fuel, typically provide only a few hundred watts of electric power. The production of Pu-238 has only recently restarted in the United States in response to the need for deep space power sources for robotic missions. However, production is very expensive and slow, so missions requiring multiple RTGs are generally not feasible. Thus, while RTGs are suitable for the modest power requirements of many robotic missions, they are inadequate for the requirements of more demanding robotic missions and sustained human exploration.

USRA's SMFR IRAD Project Design Characteristics

- Uses NASA's Kilopower design as the starting point;
- Delivers 40-150kWe on the lunar surface;
- Operates for a minimum of 20 years unattended; and
- Uses Low Enriched Uranium (LEU: <20% U-235) U-Mo fuel.

Using a variety of possible energy conversion techniques, SMFRs can provide both the heat and electricity needed for human and robotic activities, including outposts, habitats, fleets of exploration rovers, ISRU systems, and excavation/mining operations. The study will also examine what aspects of the SMFR design are applicable for use on Mars and other deep space missions.

This white paper describes the concept study that USRA is performing that could lead to development of an SMFR for use on the Moon by 2028, or sooner, if properly resourced.

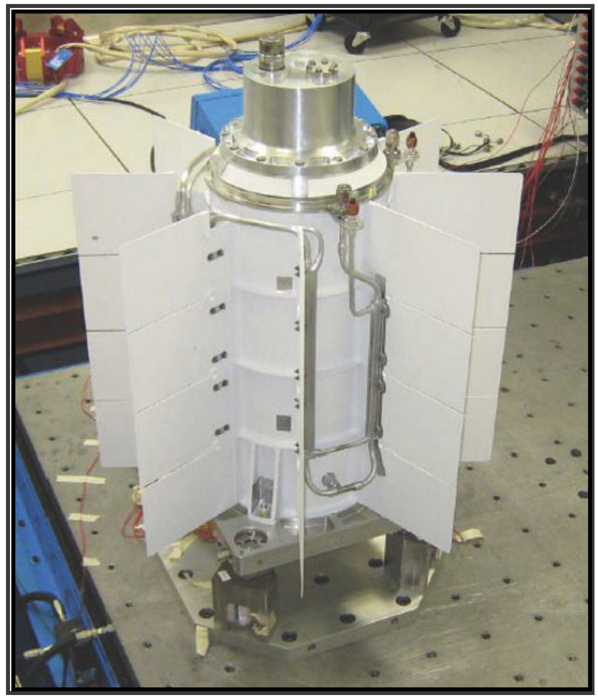

Figure 1: ***The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the Curiosity Rover Mission to Mars prior to assembly into the rover. Source: NASA***

State of Technology Readiness for Small Modular Fission Reactors

Large, high power fission reactors utilize mature technology that is currently in use throughout the world in power and naval propulsion applications. However, because of their size, these existing reactors are not feasible for use in space. There is a concerted effort on the part of Department of Energy (DOE) to develop SMFRs for terrestrial applications, with an output of 300 MWe or less. The general motivations for the development of SMFRs have been to address the evolution of market demand for electric power with smaller, modular additions rather than introducing a massive step in capacity of 1000 to 1600 MWe. Smaller units also are more amenable to factory fabrication of standardized modules such that the engineering and tooling costs are spread over a production run of dozens (or perhaps hundreds) of plants.

NASA is currently performing research and development on SMFR technologies for space applications as part of the Kilopower project. Kilopower is focused on showing the proof-of-concept of a fission reactor using highly enriched uranium (HEU) (>20% U-235) with an initial output of 1 kWe and the potential to scale up to 10 kWe.

USRA's SMFR IRAD project is to study the requirements to build upon Kilopower's successful 1 kWe proof-of-concept experiment to build a cost-effective, commercially developed SMFR that could deliver the electric power levels needed (40k-150kWe) on the lunar surface to perform extensive exploration, resource prospecting, and ISRU activities.

Use of Low Enriched Uranium

A significant difference between USRA's SMFR IRAD project and NASA's Kilopower project is that USRA is focused on developing an SMFR that uses low enriched uranium (LEU, < 20% U-235) as its heat source. While HEU has several advantages over LEU (it requires a smaller mass of nuclear fuel, allows the use of a wider range of materials, and reduces the need for a moderator), there are significant problems associated with HEU that are insurmountable from a commercial perspective.

HEU has sufficient U-235 to be usable for nuclear weapons. The manufacturing, security, and safety costs associated with the production, transportation, storage, and use of HEU make it commercially impractical. HEU by its very nature is the property of the U.S. federal government and must remain in the government's control throughout the entire life cycle of the fuel. Use of HEU essentially eliminates the possibility of commercially owned and operated reactors, either in space or on Earth.

Conversely, LEU is much more difficult to use for nuclear weapons and has significantly fewer restrictions associated with its use. The cost and availability of LEU make it a good candidate fuel for SMFRs. The reactor design challenges associated with using LEU fuel will be thoroughly addressed in the concept study.

The use of LEU fuel will require a larger mass of fuel for criticality. A tactic to reduce the mass disadvantage of LEU is to analyze the isotopes resulting in parasitic neutron absorption and to evaluate the feasibility of removing those isotopes.

There will probably be other structures near the reactor, either for storage or as a shield, to protect nearby humans from cosmic and reactor radiation. The clever multiple use of materials moderator, neutron reflector and radiation shield could reduce the mass penalty in using LEU. The radiating surfaces needed by the heat sink might also act as a neutron reflector.

Initial Results of the SMFR Study

USRA asserts that the mass penalty associated with an LEU-based SMFR for the lunar surface system, compared to an HEU-based system, is acceptable when the total cost, logistical complexity, and security implications of HEU are fully taken in account. To verify this assertion, USRA's initial step in the SMFR study was to develop mass estimates for LEU and HEU systems of equal power output.

A comparison of the masses of two sizes (1kWe and 10kWe) of fission reactors for space applications was performed in 2017 by Poston and McClure[1] of Los Alamos National Laboratory. Using this report as a baseline point of reference, USRA analyzed the seven main components of the reactor and scaled them to the higher power levels that will be required to power significant exploration, prospecting, ISRU, and habitation activities on the lunar surface.

The various components of a surface-power reactor scale quite differently with respect to the output power. For instance, once a critical configuration is achieved, the fuel mass of the reactor increases slowly with respect to power, primarily to compensate for the insertion of additional heat pipes into the core. On the other hand, the mass of the heat rejection system scales slightly less than linearly with power, since the radiator area required scales linearly with power, while the piping and structures needed increase less rapidly.

In order to assess the trends shown in the LANL White Paper, USRA compared the two conceptual reactor designs at 1 kWe and 10 kWe using Uranium 7 wt% molybdenum high enrichment uranium fuel and the two designs using the same fuel alloy containing low enrichment (i.e. 19.75%) uranium.

Making the assumption that the masses of individual components can be scaled with output power by the equation,

$$m_{i_2} = \left(\frac{P_2}{P_1}\right)^{y_i} m_{i_1} \quad (1)$$

where P_1 and P_2 are 1 kWe and 10 kWe and m_{i1} and m_{i2} are the masses of the *i*th component (e.g. Heat Rejection, Gamma Shield, etc) at P_1 and P_2. The masses for each of the components are shown in Figures 1 and 2 of Poston and McClure (Ref. 1) are shown in Table 2 highlighted in green. Rewriting equation (1), the scaling exponents, y_i, are therefore

$$y_i = \frac{\ln\left(\frac{m_{i_2}}{m_{i_1}}\right)}{\ln\left(\frac{P_2}{P_1}\right)} \quad (2)$$

The scaling exponents, y_i, for each of the components are tabulated in Table 1 using equation (2).

Table 1. Scaling Exponents

Scaling Exponents for various components, based on 1 kWe and 10 kWe designs			
i	Component	yi	
		HEU	LEU
1	Fuel	0.06	0.06
2	BeO	0.30	0.03
3	Reactor Components	0.38	0.11
4	Neutron Shield	0.30	0.18
5	Gamma Shield	0.64	0.56
6	Power Conversion	0.60	0.64
7	Heat Rejection	0.90	0.90

The scaling exponents appear to be logical in that core mass is nearly independent of output power: once a critical configuration has been achieved, the output power is dependent on heat removal capability rather than the amount of fissile material. On the other hand, for a given heat sink temperature, the radiator area needed is directly proportional to the output power.

Using the scaling exponents shown in Table 1, the component masses, m_{ik}, at another output power, P_k, can be estimated using equation 3,

$$m_{i_k} = \left(\frac{P_k}{P_1}\right)^{y_i} m_{i_1} \quad (3)$$

as shown in Table 2.

Extrapolation by an order of magnitude beyond the 10 kWe design considered by Poston and McClure should be viewed with caution, though the trends in each of the components seem logical. Nevertheless, the comparison indicates that the relative mass advantage of HEU is significantly reduced at the 40kWe to 150 kWe range that is needed for large bases on the Moon or for ISRU.

Four points can be drawn from these comparisons:

1. At 40 kWe the mass difference is approximately 33%, and at 150 kWe the difference is down to just 15%.
2. The mass difference remains at about 900 kg throughout the range of powers.
3. The mass of the fuel itself is nearly constant from 1 kWe to 150 kWe.
4. About half of the numerical mass difference is in the fuel itself and the remainder is in the gamma and neutron shielding.

These estimates based on Poston and McClure's calculations show that HEU has its best advantage at low powers, as Poston and McClure qualitatively state in their conclusion. Given the industrial, political and security incentives for using LEU and the decreasing relative mass difference at output powers that are required for lunar and Martian bases

Table 2: Scaling of SMFR components for specific output power levels of the system.

	Fuel		BeO		Reactor Components		Neutron Shield		Gamma Shield		Power Conversion		Heat Rejection		System-Level Total		Difference		Specific Power (We/kg)	
	HEU	LEU	HEU	LEU	HEU	LEU	HEU	LEU	HEU	LEU	HEU	LEU	HEU	LEU	HEU	LEU	(kg)	%		
Exponent, yi	0.06	0.06	0.30	0.03	0.38	0.11	0.30	0.18	0.64	0.56	0.60	0.64	0.90	0.90					HEU	LEU
Power (kWe)																				
1	35	350	75	360	25	100	60	120	25	55	90	85	35	35	345	1105	760	220%	2.90	0.90
5	38	388	122	377	46	120	97	159	70	136	237	238	150	148	761	1565	804	106%	6.57	3.19
10	40	405	150	385	60	130	120	180	110	200	360	370	280	275	1120	1945	825	74%	8.93	5.14
20	42	423	185	393	78	141	148	203	172	295	546	576	524	511	1694	2543	848	50%	11.80	7.87
40	43	442	228	401	102	152	182	230	268	435	829	897	979	951	2632	3509	877	33%	15.20	11.40
60	44	454	257	406	119	159	206	247	348	546	1059	1162	1412	1368	3445	4342	896	26%	17.41	13.82
80	45	462	281	409	132	165	224	260	419	642	1259	1397	1831	1769	4192	5103	912	22%	19.09	15.68
100	46	469	300	412	144	169	240	270	484	727	1440	1611	2240	2161	4894	5818	924	19%	20.43	17.19
150	47	481	339	417	168	177	271	290	628	913	1838	2087	3231	3106	6522	7470	949	15%	23.00	20.08
Ref: LA-UR-17-27226																				

as well as for ISRU, USRA believes that further research on a LEU-based SMFR is definitely warranted.

Next Steps in the SMFR Study

Given the number of parameters in the optimization of an SMFR for use on the lunar surface and the desire to minimize challenges to implementation of space reactor capabilities on planetary missions, a more thorough study is needed to evaluate design choices that will lead to a viable strategy within the coming decade. This more detailed study, scheduled for completion in June 2019, will focus on three areas of the SMFR design.

One of the important components of the study will be the modeling of the depletion of the U-235 content and the *in-situ* breeding of Pu-239 over the long, relatively low power, operating life. Table 3 shows the consumption of U-235 after 20 years for various power levels if no breeding is included.

Table 3. Uranium Consumption

Uranium Consumption in Surface Power Reactors					
Thermal to Electric Conversion Efficiency		25%			
Planned mission		20	years		
Power (kWe)	**kg fisssioned**	**decrease in enrichment, percentage pts (no breeding)**		**Burnup (MWth-d/kg)**	
		HEU	**LEU**	**HEU**	**LEU**
1	0.031	0.089%	0.009%	0.835	0.083
5	0.156	0.406%	0.040%	3.802	0.377
10	0.312	0.779%	0.077%	7.305	0.721
20	0.624	1.498%	0.147%	14.034	1.381
40	1.247	2.877%	0.282%	26.963	2.643
60	1.871	4.215%	0.412%	39.504	3.864
80	2.494	5.527%	0.540%	51.801	5.059
100	3.118	6.820%	0.665%	63.919	6.235
150	4.677	9.993%	0.973%	93.650	9.115

Selection of Fuel Cladding and Structural Materials:

The choice of fuel cladding and structural materials might also be made to achieve better neutron economy, especially if certain isotopes are removed. For instance, in the design of an LEU nuclear thermal propulsion reactor, Patel et al. (2016)[2] found that the removal of W-186 in the W-uranium dioxide (UO_2) fuel was necessary The use of N-15 (0.4% of natural nitrogen) in high-density, high-temperature uranium mononitride (UN) fuel both avoids (n, p) reactions by N-14 and greatly reduces the production of radioactive C-14. Likewise, the removal of Mo-95 from high-temperature structural reactor components reduces neutron absorption. This portion of the study will focus on material selections that best meet SMFR design objectives.

Thermal Control Approach:

In the overall systems engineering of the reactor power system, the need for effective heat sinks is also a challenge. While terrestrial power plants can use a convenient lake or river as a heat sink, orbiting reactors have to rely on blackbody radiation to the 4 K background of space. As a rough comparison, a surface at 300 K radiates 460 W/m^2 to space, while a vertical surface in still water at 300 K dissipates 14 kW/m^2 - a factor of 30 greater. A blackbody radiator would have to be at 700 K to dissipate heat at 14 kW/m^2. Thus, the careful design of the heat sink for any orbital electrical generating system is critical.

The Kilopower reactor, which uses HEU, is cooled using liquid sodium heat pipes clamped to the outside of the solid metal core. Larger reactors would require heat pipes in the interior of the core in order to reduce temperature peaking.

The Jupiter Icy Moons Orbiter (JIMO) program proposed a 200 kWe gas-cooled Brayton cycle reactor for the 20-year mission. The Naval Reactors branch of DOE conducted the design study from 2003 to 2005. The JIMO reactor design will serve as a valuable reference point in the trade study.

A reactor on the lunar (or Martian) surface might use subsurface deposits of ice in high latitude craters as a heat sink. The walls of the craters shade the interior of the craters from direct solar exposure. Movable shades over the radiating surfaces might allow the heat sinks to be more effective during times of solar exposure.

Specific Design Choices for Study by USRA's SMFR Team

- Selection of fuel cladding and structural materials;
- Thermal control approach; and
- Reactor configuration options.

Reactor Configuration Options:
The Kilopower design is compact, with the core itself about the size of a roll of paper towels and the heat removed to the energy conversion system via heat pipes containing counter-flowing sodium liquid and vapor and a central wick. This study would consider similar configurations using an LEU core with a surrounding beryllium reflector. The beryllium reflector returns neutrons back toward the core with a minimum loss due to absorption.

Since the LEU core is >80% U-238, it is important that absorption by the U-238 resonance at 6.7 eV be minimized. One technique is to use thick sections of metal fuel and little moderation such that the neutron flux near 6.7 eV was depleted at the surface of the fuel and the flux in the interior of the sphere was not further depleted by the 6.7 eV resonance since uranium is a poor moderator. Thus, the annular configuration of the Kilopower core could be retained, though the LEU core would have a significantly higher mass than the HEU design.

Higher power versions would require more heat pipes, predominately on the periphery with only a few in the interior of the core. Component dimensions and the moderator material of choice will be the major configuration options in this study. Though beryllium is the probable material of choice for the reflector, graphite will be considered.

Study Deliverables
(Scheduled for Completion by June 2019)

- Design concept(s) for one or more configurations;
- Mass and volume estimates; and
- Cost estimates.

Conclusion
Exploration of the solar system, whether by robots or humans, is highly constrained by the need for adequate sustained power-generation systems to operate instruments, maintain appropriate thermal environments for equipment or humans, and enable resource extraction and processing to sustain the mission. Even robotic missions, which can generally operate using solar electric power out to Jupiter and maybe farther, become seriously power-limited in instrumental capability and survivability in the outer solar system and in regions with extended periods of no or little solar radiation, like the two-week night on the Moon or the dark side of Mercury.

Space nuclear reactors for power and propulsion have been studied for three decades, with significant progress in developing the capability. Various prototypes have been developed but then abandoned because of lack of continued funding (e.g., the SP-100 space reactor power system). The most recent advancement in space reactor development has been the Kilopower project, which has seen significant development in the past few years.

In our IRAD project, USRA is addressing the design issues for an SMFR for use on the lunar surface that can be developed commercially, thus enabling greater industry participation in current and future initiatives for the exploration, habitation, and exploitation of the Moon. Our study will build upon the progress made by NASA's Kilopower project and make use of the DOE's experience in the development of compact reactor systems.

REFERENCES

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