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CURRENT STATUS AND FUTURE OF SPACE NUCLEAR POWER

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ABSTRACT

Deep space missions require thermal and electric power to support both in-space and surface functions. To support these functions, most deep-space or planetary science missions have used a combination of solar power, fuel cells, and radioisotope power systems (RPS). Future missions may involve more complex or long-term activities such as mining or in situ resource utilization on the moon, or a human journey to the moon or Mars, and will require larger and more reliable sources of power than currently exist. In this paper, we present findings related to the status of and challenges facing the U.S. space nuclear power enterprise, as well as observations on how to ensure the availability of adequate nuclear power capabilities for emerging missions in the next 10-25 years.

I. ROLE OF SPACE NUCLEAR POWER IN THE SPACE EXPLORATION ENTERPRISE

Deep space missions require thermal and electric power to support in-space functions such as onboard processing, remote data collection, propulsion, downlinking acquired data, and surface activities such as roving. To support these functions, most deep-space or planetary science missions have used a combination of solar power, fuel cells, and radioisotope power systems (RPS). Future missions may involve more complex or long-term activities such as mining or in situ resource utilization (ISRU) on the moon, or human exploration of Mars, and will require larger and more reliable sources of power than currently exist.

By investigating ten future missions proposed by NASA, the National Academy of Sciences, and other authoritative sources, we have found that future deep-space operations have a range of power requirements depending on their function; location, whether inner or outer solar system and beyond; and whether the operations will be human or robotic. The table below summarizes mission requirements, and highlights their enormous range, from tens of watts for housekeeping functions such as thermal management, to thousands of watts for remote science and surface sampling, to hundreds of thousands of watts for sustained surface operations. The analysis showed that nuclear power is essential especially for two classes of scientific or exploration missions:

Table 1: Stated Power Requirements for Space Operations in the 10-25 Year Timeframe

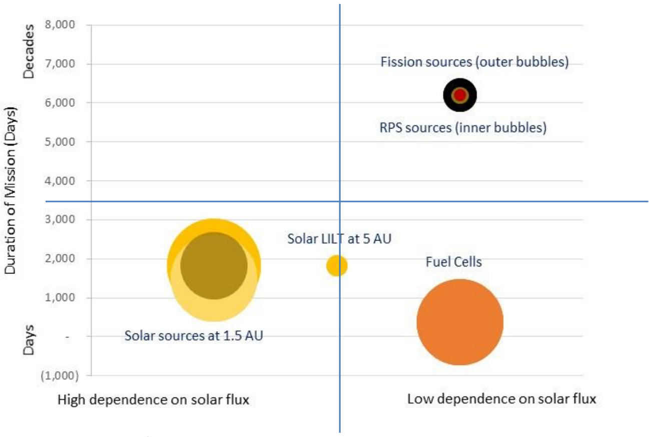
	Inner Solar System		Outer Solar System	
Function	Human	Robotic	Human	Robotic
Propulsion*	N/A	N/A	N/A	N/A
Remote Science and Surface Sampling	N/A	20 W–1 kW		30–650 W
Sustained Surface Operations**	28–50 kW	45 W–1 MW		N/A
Life Support for Crewed Missions	13–30 kW	N/A		N/A
Near Earth Object (NEO) Deflection/Disruption	N/A	700 W–70 kW		N/A
“Housekeeping”/In-Space Infrastructure	7–22 kW	15 W–1 kW		90–740 W

* Propulsion systems have a range of power needs depending on the particular technology; however, for comparison, a consistent metric for propulsion technology is specific impulse (ISP). The following specific impulses for a reference manned mission to Mars have been noted: chemical, 465 s; solar electric, 4000 s; nuclear electric, 1800–4000 s; and nuclear thermal, 900 s.

** Shackleton Energy Company’s architecture for mining on the moon, from which the 1 MW number is drawn, has humans in the loop. However, it is classified here as a robotic mission since the driver for the high power requirement is the mining operations, rather than human life-support (better exemplified by the 28–50 kW power requirement from the reference manned Mars mission architecture).

- ***The first includes missions where high levels of power are required for a sustained length of time, and the use of other high-power but low-lifetime sources such as fuel cells is not feasible.*** Examples include surface power for human and robotic activity on the moon or Mars, or propulsion for human space flight missions where it is important to reduce transit time to minimize human exposure to galactic cosmic radiation. High power is also desirable when the architecture of a space mission needs to remain flexible after launch. For example, the trajectory of a spacecraft needing to make contact with a Near-Earth object (NEO) may need to be altered after launch for scientific or other reasons. Such missions typically call for fission power.
- ***The second includes missions where solar flux is too low and durations of the mission long, and therefore the use of other power sources, such as solar power and fuel cells, is not feasible.*** This category includes missions in deep space and the outer solar system where environmental conditions are too harsh for solar power to be considered (high temperature, corrosive and high pressure atmospheres, high g-load, dust, etc). Missions too close to the sun may also need fission power if they have to operate in shadows (e.g., lunar poles or craters) or during nighttime to avoid extreme temperatures and radiation exposure. Such missions typically call for radioisotope systems, especially if power levels required are low (under 1 kW_e).

As Figure 1 illustrates, nuclear power may be especially relevant when all critical dimensions of interest—long lifetime, independence from solar flux, and high power level—are simultaneously important.



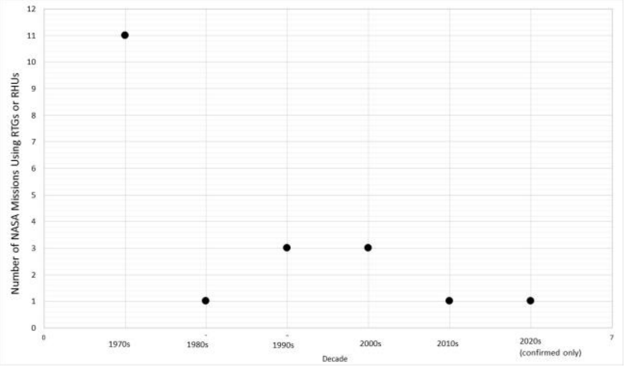
Note: The area of each bubble is roughly proportional to the actual or estimated specific power of the source

Figure 1. Power Sources Compared on Key Metrics.

II. STATUS

A. Radioisotope Systems

Figure 2 shows the cadence of the use of RTGs and RHUs (radioisotope heating units) in NASA missions, and shows that of the hundreds of NASA missions listed on the NASA website, only about 20 have used an RTG or an RHU in the last five decades. After the end of the Apollo program in the 1970s, the cadence of RTG launch has been 1 to 2 per decade.



Source: Discussions with NASA

Fig. 2. Cadence of NASA's Use of Radioisotope Systems.

In the near-term, for radioisotope systems there is currently only one available choice, the multi-mission radioisotope thermoelectric generator (MMRTG). Because it is not optimized for vacuum operations, MMRTG is not ideally-suited for in-space missions. There are alternatives under development (the eMMRTG [enhanced MMRTG which uses new, high-efficiency thermocouples] and SMRTG [segmented modular radioisotope thermoelectric generator] which would provide higher levels of power for in-space missions), but they will not be ready for many more years. In the foreseeable future, the one-size-must-fit-all system, the MMRTG, is all we have.

There is also no good source for estimating the cost of an MMRTG. The New Frontiers-4 announcement provides a sense of its *price* to users (it is unclear if the price of a MMRTG is the same as the marginal cost of producing one). The announcement suggests that an MMRTG would cost a mission over $130M for manufacturing, safety procedures, launch approval and other related processes. In other words, the user must assign 20% of more of the mission cost to the use of nuclear power. It is also noteworthy that the price today remain at levels comparable to those of systems developed over forty years ago (according to DOD documents, the Multi-Hundred Watt RTG developed in 1975 cost about $110M in 2015 dollars).

Mission planners are keenly aware of the trade-offs associated with RPS. In addition to the high cost, the nature of the power source (radioactive decay of Plutonium-238) and the complex production process makes RPS a schedule risk; there is no starting or stopping the alpha particle decay of the plutonium source, and power degrades monotonically. Any changes in the schedule of a mission necessitates redesign of systems to compensate for the lower available power. In the power trade study for the Europa Clipper mission, for example, the MMRTG option received top scores in the technical and reliability categories, but scored lower for cost, schedule, and risk, the latter two relating to perceptions of delays in plutonium production. Stakeholders interviewed also note that they have less influence over the RPS option than over solar, and therefore prefer solar as a power source where feasible.

From the supplier's (Department of Energy) perspective, the challenge is no easier. Plutonium-238, a highly radioactive and toxic element, is produced in a very expensive, complex, multi-site Department of Energy (DOE) laboratory system at high cost [1]. According to publicly available documents, the annual cost of production is approximately $15M for producing the fuel and $55M for maintaining the infrastructure. A 2013 joint NASA-DOE report suggested that DOE may need about $200M in infrastructure upgrades [2].

B. Fission Power and Propulsion Systems

The US government has flown one fission powered system, the SNAP 10A, in 1965, and there have been no fission systems flown since then. Today, fission power is not at a high enough TRL yet for flight—at either the component or system level. With a lack of mission pull, investment in the past few decades has been low. The one option under development, Kilopower, receives less than $10M annually in direct and indirect funds from NASA and the Department of Energy (DOE), but making steady progress [3].

After significant investment in the 1960s and 70s, fission propulsion has fluctuated recently, and uncertainty in funding remains high. NASA's human exploration directorate (HEOMD) funded nuclear thermal propulsion (NTP) at about $10M a year until the program moved to the space technology mission directorate (STMD) where it is being funded at about $20M a year under Congressional direction. With growing interest in a human mission to Mars, nuclear thermal propulsion has seen resurging interest, and there is renewed discussion within the community, particularly with regard to thrust levels, testing approaches, the choice between low and highly enriched uranium fuel, and the most promising type of fuel form.

III. ORGANIZATION AND MANAGEMENT

In the domain of space nuclear power, there appears to be a historically complex relationship between NASA and DOE. By statute and policy, DOE has ultimate responsibility for any nuclear fuel and fueled systems, and NASA is responsible for providing overall planning priorities that govern DOE's systems development for space applications, providing the requirements, specifications, and schedules for any systems needed. NASA is also responsible for providing the funding for DOE's RTG-related R&D and production. Annually, NASA spends approximately $105M on RPS systems, about two thirds of which flows to DOE, and a third is used for developing next generation systems. In addition, tens of millions of dollars (given few launches, the amount changes for every mission) are spent to certify each launch that carries an RPS. This "user pays" approach, which was mandated by Congress in 2013, has created interagency challenges that are being addressed.

In sum, NASA's RPS enterprise is currently locked into a monopsonic-monopoly structure, meaning a single user (NASA) is procuring a product from a single provider (DOE) in a highly risk-averse environment due to the need for provision of a complex product that needs to be operationally robust in extreme environments. This structure may enable incremental technological innovation, but does not incentivize cost or other systemic innovation. The fission enterprise suffers from similar structural issues, but also low levels of funding, has made little progress, and is not considered ready for deployment on any planned near- or mid-term missions. As a result, there is only one nuclear power source available for all high power or deep space applications, and it is a relatively low power (120W) one-size-fits-all type of radioisotope system.

IV. DISCUSSION

If the existing system continues without change, nuclear power will likely remain expensive and underutilized, limiting capabilities of both human and robotic missions. We believe that the root cause of the high cost of the system can at least partially be traced to the little-to-no *demand* for space nuclear power. In this section, we discuss how to address this challenge. Given differences between radioisotope and fission systems, we discuss them separately.

A. Radioisotope Systems

The cadence of the use of RTGs (1-2 per decade) is predicted to continue going forward. In the 2020s, there is likely to be a New Horizons mission that would use an RTG, and possibly an RTG on a potential Europa Lander. Low demand exacerbates the production challenge, making both total and unit cost of production high, which further discourages use, creating a vicious cycle. Were the demand for nuclear systems higher, there would likely be incentives to reduce the cost of production, and certainly pressure to bring down the per unit cost of an MMRTG (and perhaps develop, at a faster rate, alternatives and upgrades to the MMRTG).

There are two principal categories of reasons this demand is low. First is the obvious one: the cost of an RPS. To PIs, as mentioned above, an RTG costs about $130M. To NASA, the cost is about $100 million annually to maintain production, no matter how often or whether an RTG is actually used. There is no publicly available number on the cost to DOE (likely also in the hundreds of millions of dollars especially in infrastructure maintenance), again no matter how often or whether an RTG is actually used.

There are other challenges that make PIs avoid using RPS. In addition to high cost, PIs see RTGs as a schedule risk—because of aging infrastructure and a lengthy testing/certification process, delivery dates are unreliable. Also, because DOE "owns" an RTG for life, PIs also believe that they have less control over radioisotope systems than if they were using other power sources (solar, for example). In some cases, the planetary protection guidelines disincentivize use. And last, launch vehicles must be certified specifically for launching nuclear material, which is expensive. The SLS rocket, for example, has not been certified to launch nuclear material.

Despite the demand being low, NASA and DOE spend a large and steady amount every year to maintain a capability deemed important, and yet that capability is not used at levels remotely comparable to those in the past. Many stakeholders therefore question the price of this production enterprise given that it does not get amortized over many missions each decade (RTGs were referred to some interviewed by the team as "the billion dollar battery”). The problem is recognized—the RPS enterprise has been “under review” for decades, the most recent one coming in 2017 by the General Accounting Office. Most reviews make the mistake of focusing only on production rather than looking holistically at the system, including the demand side and cost of production and use. But more importantly, most reviews come up with the same conclusions, that Pu-238 production is important, will remain expensive, and the system is working as well it can, and needs only tweaks.

Going forward, NASA could simply continue to pay the approximately $100 million spent annually to keep the capability. NASA could also move away from RTGs, and instead invest in alternatives such as longer lasting low-weight batteries or smaller space-qualified fission reactors. Both scenarios are less than ideal. The second one is perilous as it presents a real risk of permanently losing an important national strategic capability.

A third alternative requires creative thinking about increasing use of RPS through a combination of strategies related to either growing the use of RPS (demand side approaches), or reducing the cost of producing an RPS (supply side approaches).

Demand side approaches. NASA could incentivize RPS use by making them free or subsidizing them further by potentially moving the cost from each individual mission tto SMD overhead (or elsewhere in NASA). NASA could also incentivize RPS use by specifying RTG-only competitions. For example, if 15 kg of Pu-238 is produced per decade (as is currently planned), NASA could make sure that 2-3 RPS are flown per decade via RPS only New Frontiers competitions. NASA could also support efforts to modify planetary protection rules so they do not disincentivize the use of nuclear material. Lastly, Congress could allocate RTG production funds directly to DOE, and NASA missions could receive the power supplies at no additional cost – as used to be the case in the 1970s. This last approach may also ameliorate interagency conflict.

With growing space investment around the world, the US government could also consider increasing the user base to organizations other than NASA and national security agencies. Over fifty years of operation has ensured that MMRTGs do not carry significant safety and security risk (the RTG on Apollo 13 is still resting without leaks at the bottom of the Indian Ocean). It might be worthwhile to examine if the US government could lease MMRTGs to allied government agencies engaged in scientific missions both terrestrially and in space. Increasing the number of users for MMRTGs would distribute the cost of production to a larger number of users, potentially resulting in a lower per-unit cost. Indeed, the 2010 National Space Policy identified space nuclear power as an area for potential international cooperation [5].

Supply side approaches. On the supply side, it would be useful to seriously examine if the cost of production of an RPS could be brought down. NASA and DOE could (as they already are doing) explore ways to reduce cost within the current system. However, reductions using incremental approaches would be minimal; the zero based report, for example, showed that the system is working well. The government could also continue to explore ways to reduce cost by producing device or fuel differently (e.g., as presented in previous NETS conferences, produce Pu-238 in the commercial sector). Proposals have also been made to consider alternative fuels such as Am-241. While there is no evidence that this would be a good technical substitute or even cheaper, all analyses need to be publicly accessible and explored with an intent to reduce overall system costs.

B. Fission Power Systems

To date, fission power systems suffer from a lack of specific mission pull. In other words, there are no missions to-date where there aren’t less expensive and less risky ways to achieve mission objectives. As more ambitious missions are developed for which there are not less expensive options (e.g., ISRU on Mars), the trades may shift toward fission systems. The lack of mission pull can also be tracked to a combination of low levels of technology readiness and relatively (and perceived) high cost of development. Lack of demand and funding levels are mutually reinforcing factors: lack of mission pull inhibits investment to raise TRLs, and low TRLs prevent missions from asking for fission power.

In the case of fission power, because of the association of fission with nuclear weapons, technical maturity alone will not ensure use. Leadership at the White House level would be needed for fission systems to be included in future missions.

C. Fission Propulsion Systems

Similar to surface power, the lack of demand for nuclear propulsion systems stems from a combination of low levels of technology readiness, and high cost of development. And as with surface power, there are public policy challenges to the use of fission-based propulsion. With growing space capabilities in the private sector [4], NASA is beginning to identify strategic capabilities such as NTP that may not attract significant private investment (though it is clear from current trends that the private sector is willing to co-invest in areas traditionally considered the province of government). The government would be well advised to invest in these strategic areas rather than replicating capabilities that are developing at a rapid pace in the private sector. Having Presidential, NASA, and congressional leadership would be critical to ensuring appropriate levels of investment in fission-based propulsion systems.

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