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/

SPACE FISSION POWER: NASA'S BEST BET TO CONTINUE TO EXPLORE THE OUTER SOLAR SYSTEM

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Implementation of balanced, cost-efficient programs to develop power technologies would enable future Voyager- and Cassini-class missions at the outermost planets; open up subsurface missions at Europa, Enceladus, and Titan; and facilitate orbiter and lander missions at Neptune and Triton. A rebalancing of the NASA power technology portfolio could establish the option of using fission power in space. The timing is right for the development of a small nuclear reactor design (such as KRUSTY) that can provide power for multi-year robotic missions and serve as a pathfinder and risk reduction strategy for the larger needs of future human exploration space power systems. *

I. HISTORICAL PERSPECTIVE

NASA's space program has long had only two sources to power multi-year missions: the Sun and radioisotope power systems (RPS), which use heat generated by the natural radioactive decay of plutonium-238 (^{238}Pu). Under President Eisenhower's Atoms for Peace, Systems for Nuclear Auxiliary Power (SNAP) explored the use of radioisotope thermoelectric generators (RTGs) and space nuclear reactors for use on Earth and in space.

During the 1960s and 1970s, ^{238}Pu was relatively inexpensive ($600/thermal W, or $336k/kg), and the Atomic Energy Commission (later the Department of Energy, DOE) funded all RTG costs; for example, NASA was not charged for six Voyager RTGs. In 1988, the United States suspended ^{238}Pu production, creating a criticality of supply and tripling the cost to $1M/kg. DOE continued to fund RTG design, development, test, and evaluation but began to transition recurring costs to users, with NASA's Galileo mission paying $33M each for two RTGs. By 1997, as ^{238}Pu costs tripled again to $3M/kg, DOE transitioned all costs to the user. NASA's Cassini mission paid $38M each for three RTGs.

Cost was not the only issue. Participants at the 1980 International Atomic Energy Agency Plasma Physics and Controlled Nuclear Fusion Research Conference in Brussels agreed that space nuclear power presented a seemingly unresolvable "Catch 22" situation: Space reactor power systems take longer to incubate than do the missions that could use them. Therefore, mission planners will not plan them and technology funders will not fund them. To solve the conundrum, NASA needed either a technology funder with a vision for the future or a high-priority mission that would take longer to incubate (and cost more to develop) than the space nuclear power system it would need.

A solution seemed in reach in 2002, with then-new NASA Administrator Sean O'Keefe. He was convinced that the next breakthrough in space exploration would require space fission power; and he understood that without it, space exploration could progress only incrementally. Without help from the science community, O'Keefe led an effort to name, select, and design a mission to establish the capability to develop a 200-kWe fission power system and safely deploy it in space for robotic exploration. NASA would

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then use the resulting capability and infrastructure as a stepping stone to nuclear thermal propulsion (NTP) and higher power systems for human exploration. Thus, Prometheus was born.

In 2002, the Administration and Congress supported the strategy of landing humans on Mars before returning to the Moon. NASA's Constellation program emerged as the high-priority mission set that would use NTP to get to Mars and fission power on the surface: Specifically, the mission needed NTP to reduce the number of launches and flight time for each sortie to Mars and a 40-kWe surface power system to support humans on Mars. Prometheus was thus the technology pathway to space fission and to human exploration of Mars. Or so it seemed.

II. A FLIGHT PROJECT MANAGER PERSPECTIVE†

In 2005, Administrator Michael Griffin determined that the Prometheus development was ill-timed, given that NASA would need NTP (to launch) before NEP (to support humans on the surface). He redirected funding for Prometheus to Constellation. Four years later, the Presidential Review of U.S. Human Space Flight Plans Committee (aka Augustine Commission) found that Constellation, too, was ill-timed given the Administration's funding constraints. NASA's fiscal 2011 budget included no funding for Constellation. Returning to the Moon had become the renewed pathway to Mars.

Meanwhile, NASA advised Congress and the Administration to fund DOE to restart ^{238}Pu production without having (in retrospect) a full accounting estimate of the cost. NASA also urged funding for dynamic conversion systems technology to maximize efficiency in order to reduce ^{238}Pu mass and cost, with two results: NASA now "owns" the cost of the ^{238}Pu infrastructure at DOE, and the technology push for lower mass has been reduced due to escalating costs and lower-than-expected results. The results imply

- NASA's plan for re-establishing a ^{238}Pu production line for planetary spacecraft was not tempered with a realistic understanding of the infrastructure required to produce it. Since ^{238}Pu had previously been available only as a by-product of weapons production, the real cost was inseparable from the cost of producing the weapons-grade material. DOE's yearly facility maintenance costs after 2025 remain unclear.
- The primary cost for new ^{238}Pu will be dominated by the annual cost of maintaining the new infrastructure and will largely be insensitive to quantity for amounts less than 3 kg/year.
- Absent a new source of neutrons or new hot cells, production rates greater than 3 kg/year are not possible.
- Claims by the NASA RPS Program Office that ^{238}Pu production is on track or that other sources of neutrons are available may face increasing scrutiny (see U.S. Government Accounting Office (GAO) findings and schedule).[1]

However, a former user of ^{238}Pu has recently acknowledged the existence of several kilograms of ^{238}Pu in DOE storage as of 2013. That ^{238}Pu is available to NASA, but it does not meet current specifications and will need to be mixed with newly produced ^{238}Pu to emit sufficient heat. The cost for reprocessing is ~$8M/kg, the DOE currently quoted cost for ^{238}Pu.[2]

Now, NASA may be considering foregoing future outer planet Flagship missions based on

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† This perspective is built on decades of space program experience as system engineer on early Rangers and Mariners; project manager of the successful Voyager, Galileo, and Cassini missions and the ill-fated Prometheus–Icy Moons Orbiter; involvement with large cross–NASA center, inter-agency, international programs and projects; and service on several National Academy of Engineering committees and the National Nuclear Security Administration (NNSA) Advisory Panel.

two compelling arguments: (1) Cassini required 33 kg of ^{238}Pu, which would take 22 years to produce at the rate of 1.5 kg/year. (2) The opportunity cost of deleting one Flagship mission per decade will permit a robust program of Discovery- and New Frontier–class missions, which are lighter and less expensive because they use advanced-technology RTGs (using skutterudite and multi-layer thermoelectrics) with less ^{238}Pu. History (such as the 1970s' decision to discontinue expendable launch vehicles in favor of the Space Shuttle) has shown that cost-related trade-offs are sometimes ill-considered.[3]

NASA's ability to meet its 1.5 kg/year production goal is also at risk.[1] The goal assumed that the Advanced Stirling Radioisotope Generator (ASRG) converter would be available to reduce the earlier stated need of 5 kg/year by a factor of 4. However, the ASRG program was canceled in 2013 for cost overruns and lack of sufficient technical progress. DOE production has fallen behind expected progress. Making up the schedule will require significant additional workforce and training. There are other potential obstacles to meeting the 1.5 kg/year goal. NASA's ^{238}Pu allocation could be reassigned to a national security user, should the need arise. Without a demonstrated understanding of the cost and technical issues involved in dynamic RPS or a clear plan to address them, NASA is not likely to fly such hardware. NASA Glenn Research Center (GRC) seeks to fund advanced power conversion technology at $10M/year to overcome the ASRG shortfall, but the success of any technology thrust cannot be counted on in advance. Furthermore, any increase in the 1.5 kg/year production rate will require a commensurate increase in neutrons and additional hot boxes and will be very expensive. At the end of the day, NASA is not likely to be able to afford the cost and risk of staying solely dependent on ^{238}Pu.

III. AN ALTERNATIVE

RPSs are not the only option for space nuclear power. A small nuclear fission reactor that uses uranium-235 (^{235}U) could provide power ranging from a few hundred watts to 10 or more kilowatts. At the lower end, reactor-based systems are workable substitutes for RTGs. At the upper end, 10-kWe systems permit use of electric propulsion that increases science payload mass, reduces flight time, increases mission lifetime, and provides power for science instruments and/or increased data rate when not thrusting.

What changed the game? The impossible happened. SpaceX demonstrated the capability to reliably put mass in orbit for much lower cost than anyone (with the possible exception of Elon Musk) believed possible 10 years ago.[1] Since then, GRC and LANL have designed, fabricated, and successfully tested a reactor in near-spaceflight configuration: KRUSTY (aka Kilopower Reactor Using Stirling Technology), a 1-kWe fission power system that fully validated the nuclear design approach for a 1- to 10-kWe space power system.

NEP benefits for outer solar system missions include larger specific power and power output; much shorter trip times and much larger payload capability; and more frequent and longer launch periods. Orbital insertion and landers are possible at all planets, moons, and Kuiper Belt Objects. NEP allows more flexible and efficient operations in orbital tours as well as additional power at destination for more power-intensive science and data operations. NEP fuel characteristics and use of Stirling engine technology give it several advantages over RTGs, as follows:

Uranium fuel is readily available, with a large existing inventory of highly enriched uranium (HEU) (≥20% ^{235}U). Production is already paid for, with a near-zero cost to NASA. Handling and processing are well developed and low risk. HEU, while highly desirable for space reactors, is in low demand for Earth-based usage, with few users.[‡] **Plutonium fuel** is expensive

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‡ DOE Nuclear Energy (NE) does receive HEU usage requests, which, when allocated, reduce supplies. NE tracks the usage requests, but NNSA is the decision maker.

(~$8M/kg today); future costs are unknown. NASA is paying ~$1B to develop infrastructure to produce 1.5 kg/year. Development cost and cost risk is high. Sustaining costs are unstated, but likely $25M–$90M/year, which would be the annualized full cost of 1.5 kg of ^{238}Pu. Plutonium is difficult to manufacture and process, with high schedule risk. The short ^{238}Pu half-life complicates inventory and manufacturing schedules and limits mission lifetimes. ^{238}Pu is in high demand with only two users, NASA and a national security user with higher priority. Continuous processing requires fuel blending and loading constraints on generator fueling.

Stirling technology used with fission reactors: Conversion efficiency is not critical since the core is rich with thermal power. While low converter mass is desirable, it is not a driver given the ever-decreasing cost of launch services. Therefore, technology development can be focused on reliability, manufacturing simplicity, reproducibility, and low cost. The converters need not be qualified for operation in the launch environment, since they cannot operate before reactor startup. Power changes in flight do not need control rod adjustment or other means of reactivity control, since the core is designed to run at a constant temperature, independent of the load. This was fully demonstrated over the full dynamic range of the reactor during the KRUSTY tests. Multiple converters can be used as spares, simplifying redundancy implementation.

IV. WHAT CAN A 10-KWE NEP SYSTEM DO?[§]

The National Academy of Sciences 2013–2022 Decadal Survey[4] identified ten RPS-powered mission concepts that could be performed using 1-kWe or 10-kWe NEP. For 1–1.5 times the cost of a New Frontiers mission, an NEP system for these missions would support an increased science payload mass, increased communications rate, and shorter flight times. With a lesser increase of science payload mass, an NEP system could also support >40-year mission lifetime. A 10-kWe NEP system can provide the power for multi-year outer solar system robotic missions, such as the following examples:

Neptune+Triton Orbiter: A 10-kWe reactor with a Falcon Heavy launch could get a 3700-kg spacecraft into Neptune orbit with 13 years flight time. With a 1.5-year Neptune tour, the system could then get 3500 kg into Triton orbit. This would allow a 6-month orbital mission; delta-velocity studies indicate that it would also support Triton landers.[5] This mission concept uses the same trajectory as the Ice Giants (a 2030 launch opportunity with Jupiter flyby), but with NEP instead of solar electric propulsion (SEP), which was only able to deliver half as much mass into Neptune orbit and would not be able to get the spacecraft into Triton orbit.

Chiron Orbiter: Work is pending on using an existing Chiron mission study design for a Stirling-powered electric propulsion mission from the 2003 decadal survey.[6] With 10-kWe power, it is possible to orbit two Centaur objects with a Dawn spacecraft–like double orbiter.

Titan+Enceladus Orbiter: A 10-kWe NEP can put 7200 kg in Enceladus orbit 10.5 years after launch or reduce flight time to 7 years with 3000 kg in orbit. A 10-kW reactor with Falcon Heavy launch could get a 4000-kg spacecraft to orbit both Titan and Enceladus (1 year at each moon) with a <14-year mission. The system can provide 50 kb/s data rate to ground and 5 kWe to spacecraft when not thrusting, and 1 kWe to spacecraft when thrusting. Results are similar for Titan and faster for Europa missions. Saturn NEP launch opportunities recur every year.

Pluto Orbiter: A 10-kWe reactor with a Space Launch System (SLS) launch could get a 2600 kg spacecraft into Pluto orbit with a 14-year flight time.

[§] The missions discussed here are documented in GRC COMPASS and JPL Team-X studies and reports; they will be referenced in a report supporting these claims that is due out the end of February 2019.

V. WHAT COULD HAPPEN?

NASA could reevaluate its dependence on radioisotope systems in view of the following considerations:[1] (1) Cost and cost risk of "owning" part of the DOE NE infrastructure for ^{238}Pu, and NASA's challenges in modulating its cost outlays to product delivery. (2) Schedule risk for achieving production rates of 1.5 kg/year and the impact of delivery uncertainty on mission selections and project development schedules. (3) Management complexity due to DOE's having adopted a continuous product rate approach to manage their ^{238}Pu production process, with new reporting and coordination requirements.[1]

NASA could take the following steps to reduce cost and schedule risk for space-based power systems: (1) Develop a 200- to 1000-We fission-based backup for RTGs as a hedge against ^{238}Pu cost and schedule risks.[1] (2) Require the Human Exploration and Operations (HEO) and Science Mission directorates to select a common-size core such that first-generation reactors can be built and delivered based on KRUSTY results (needing only subcritical testing). (3) Assess, evaluate, and select the right size Stirling engine to serve both human and outer solar system exploration. (4) Devise a strategy to acquire a 10-kWe NEP–based standard bus that would match the New Frontier–class constraints. (5) In coordination with DOE, determine whether NE or NNSA should be the supplier of fission-based space power systems given the infrastructure ownership and interests of the two organizations.

VI. CONCLUSIONS

(1) A 10-kWe NEP capability would enable Cassini-class missions to the outer solar system in the New Frontier cost range. Developing the capability would require that NASA establish contracts with system contractors who have existing avionic product lines. (2) A 1-kWe fission power system could be exploited as a backup for cost and schedule risk attendant to ^{238}Pu resupplying. (3) The timing is right to develop the 10-kWe NEP capability given KRUSTY's success. Such a decision would enable several compelling missions and serve as a pathfinder and risk reduction strategy for the larger needs of future HEO space power systems across the Moon–Mars system.

ACKNOWLEDGMENTS

Views rely in part on GRC and LANL work and on GAO findings. Space here does not permit me to address many thoughtful comments raised by John Hamley, NASA RPS Program Manager, which will be fully addressed in a report due out in February 2019.

REFERENCES

1. U.S. General Accounting Office, *Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium238 and Radioisotope Power Systems Production Challenges*, GAO-17-673 (September 2017).
2. Oregon State School of Nuclear Engineering, "Rebuilding the Supply of Pu-238," https://ne.oregonstate.edu/rebuilding-supply-pu-238. Cited in Seth Auginstein, "Plutonium-238, Nearly Out of Reach for 30 Years, Now in Competition," *Laboratory Equipment* (December 23, 2015).
3. J. M. LOGSDON, "The Space Shuttle Program: A Policy Failure?" *Science* 232, 4754, pp. 1099–1105 (1986).
4. National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013–2022*, Washington, DC: The National Academies Press (2011).
5. N. STRANGE, "Triton Orbiter DV Budget," JPL internal correspondence (December 2018).
6. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*. Washington, DC: The National Academies Press (2003).