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Kilowatt-Class Fission Power Systems for Science and Human Precursor Missions

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Abstract. Nuclear power provides an enabling capability for NASA missions that might otherwise be constrained by power availability, mission duration, or operational robustness. NASA and the Department of Energy (DOE) are developing fission power technology to serve a wide range of future space uses. Advantages include lower mass, longer life, and greater mission flexibility than competing power system options. Kilowatt-class fission systems, designated "Kilopower," were conceived to address the need for systems to fill the gap above the current 100-W-class radioisotope power systems being developed for science missions and below the typical 100-kWe-class reactor power systems being developed for human exploration missions. This paper reviews the current fission technology project and examines some Kilopower concepts that could be used to support future science missions or human precursors.

FISSION TECHNOLOGY DEVELOPMENT

NASA and the Department of Energy (DOE) are collaborating on fission power technology development to enable future space power systems for science and exploration. Project participants include the NASA Glenn Research Center, NASA Marshall Space Flight Center, Jet Propulsion Laboratory (JPL), and DOE National Laboratories at Idaho, Los Alamos, Oak Ridge, and Sandia. The present work effort resides under the Space Technology Mission Directorate, Game Changing Development (GCD) Program as the Nuclear Systems Project. The team has been in place since the end of the Prometheus Program performing analysis and hardware testing to establish technology readiness.

The Nuclear Systems Project has been addressing the typical fission power design regime aimed at larger fission power systems (FPSs) for human exploration missions in the 10 to 100 kWe range with extensibility into the megawatt class. The current focus is a nonnuclear Technology Demonstration Unit (TDU) that will be tested in thermal vacuum to demonstrate integrated system performance (Refs. 1 and 2). The TDU test assembly, which includes a NaK-cooled reactor simulator and one 12-kWe Stirling convertor, serves as an important hardware foundation for large-scale FPSs to verify technology readiness and support mission application studies. The TDU test configuration is based predominantly on a lunar or Mars surface power system (Refs. 3 and 4). Fission surface power (FSP) systems for the Moon and Mars could produce between 10 and 100 kWe. Emphasis is on low risk, operational robustness, and affordability. The reactor design leverages terrestrial technology with fast-spectrum UO_2 pin-type fuel, stainless steel construction, and NaK coolant. This approach allows for operating temperatures up to 900 K, well suited for Stirling power conversion.

The TDU also has broader applicability to moderate- or high-power nuclear electric propulsion (NEP) vehicles for near-Earth objects (NEOs) or Mars missions (Refs. 5 and 6). Initial NEP power systems might produce between 100 kWe and 1 MWe. Low system specific mass (kg/kWe) is crucial to mission performance, and higher reactor operating temperatures are the key to low specific mass. Extensibility from the FSP-class is maintained through the use of the liquid-metal-cooled, fast-spectrum reactor technology and pin-type fuel. Substituting UN fuel, refractory alloy construction, and Li coolant permits an increase in reactor operating temperature to at least 1200 K. The higher power levels are better accommodated by closed Brayton cycle power conversion and the reactor temperature is well matched to heritage Brayton designs using superalloy construction. Farther term, high-power NEP power systems might produce several MWe or more, and low specific mass is essential. A further increase in reactor temperature to 1500 K would require an improved UN fuel or other advanced fuel form and improved refractory alloy materials. Since the reactor is an evolutionary step from the moderate power NEP-class, the primary technical challenge resides in developing the high-power, high-temperature power conversion technology. The high power levels and high reactor temperatures necessitate the use of advanced refractory alloy Brayton or potassium Rankine power conversion.

KILOPOWER

In examining the potential uses of FPS technology, the extensibility to high-power applications was evident. However, very little effort was expended in examining FPS technology for low-power (<10 kWe) systems to support potential planetary science or human precursor missions. In order to address the gap above current radioisotope power systems (RPSs) and below the conventional large-scale FPSs, the NASA/DOE team began pursuit of kilowatt-class FPS design options, designated “Kilopower,” which could scale to the lower power levels while being mass and cost competitive with RPSs.

Mission Pull and System Benefits

Science missions are pushing for more power and greater spacecraft capabilities. Several Decadal Survey mission studies identified kilowatt-class NEP as enabling. The potential benefits of NEP-based planetary science include launch flexibility, expanded science orbits, and multiple mission targets. The larger power systems that accompany NEP also benefit spacecraft functionality and science return. Greater power allows for more capable instruments, increased instrument duty cycles, onboard scientific analysis, higher data-rate communications, and smaller antennas. Kilopower provides an approximate 10X power increase over current RPSs. This permits a single optimized power source rather than a large number of low-power units that could complicate the spacecraft. The result is less complex spacecraft integration and operations as well as easier accommodation for body mounting science instruments and instrument field of view.

A long-life, uninterruptible, and environment-tolerant power source is also needed for exploration precursors. Potential mission uses include collecting site engineering data to design crew systems, conducting in situ resource utilization (ISRU) experiments, establishing communication networks for Earth-based teleoperations, powering remote science packages, or recharging rovers that perform site reconnaissance. The Kilopower systems could be utilized on Mars orbiters or pre-crew surface stations on Mars or its moons, Phobos and Deimos. The compact size and constant power output make it ideal for precursor ISRU demonstration plants. An early Mars technology demonstration mission combining fission power and ISRU to demonstrate local propellant production would validate methods that could be scaled to support subsequent human missions.

The current radioisotope Pu-238 fuel supply is very limited. The National Research Council Decadal Survey Report (Ref. 7) stated, “The committee is alarmed at the status of Pu-238 availability for planetary exploration. Without a restart of Pu-238 production, it will be impossible for the United States, or any other country, to conduct certain important types of planetary missions after this decade.” The U.S. Pu-238 stockpiles are extremely low and production restart has been delayed. Foreign-supplied Pu-238 has become prohibitively expensive and difficult to obtain. A Kilopower capability could reduce our dependence on the limited Pu-238 fuel supply, permitting its continued use at lower levels for smaller science missions. Replacement of an RPS with a Kilopower FPS for large planetary science missions could save as much as 28 kg of Pu-238 per kWe of spacecraft power.

Fission-based power systems could simplify launch and mission operations relative to other nuclear power systems. Reactors are launched cold with essentially no radioactive hazards. In the case of the Kilopower concept, a single control action is required for reactor startup after orbit insertion. Once started, the reactor automatically responds to thermal load changes and maintains safe operating temperatures based on negative temperature reactivity feedback. The load following characteristic assures a safe response to power plant transients where the reactor would revert to a lower thermal power to avoid an over-temperature condition. This feature also minimizes power degradation over mission life since the reactor can compensate for some performance degradation effects through thermal power increases.

The Kilopower system should offer high projected reliability and fault tolerance. The expected fuel form is well characterized based on terrestrial reactor applications and is operated within established limits. The design provides high levels of redundancy in both the heat transport and power conversion subsystems. The low reactor power reduces thermal stresses and provides tolerance to potential damaging transients. The low fuel burnup minimizes fission products that would cause adverse radiation effects on reactor materials and spacecraft components.

Decadal Survey Study

The Kilopower concept was initially conceived through a study performed for the National Research Council Planetary Science Decadal Survey and the NASA Science Mission Directorate (Ref. 8). The purpose was to evaluate the feasibility of FPSs for kilowatt-class science missions as an alternative to RPSs, given the limited availability of the Pu-238 fuel source. The goal was to minimize development risk and cost, with system mass that was comparable to multi-unit RPSs. The Decadal Study evaluated numerous design options and alternatives before selecting the reference reactor concept. The selected reactor concept uses 93 percent enriched uranium-molybdenum (UMo) fuel in a solid casting surrounded by a beryllium reflector with a single, centered boron-carbide control rod. The compact, fast-spectrum core is 12.9 cm in diameter by 30 cm long and is cooled by 18 sodium heat pipes. The reactor supplies 13 kWt to the power conversion at an average fuel temperature of 1200 K and a heat pipe condenser temperature of 1100 K. A conical LiH/W shadow shield provides electronics-rated radiation protection at the science payload, assumed to be 10 m from the core.

The reactor could be combined with thermoelectric (TE) power conversion, as shown in Figure 1, to produce 1 kWe. This concept utilizes segmented TE materials with a combination of Zintl, $La_{3-x}Te_4$, and Skutterudites that provide 8 percent system efficiency at 1050 K hot-end and 525 K cold-end temperatures. The TE elements are distributed along the heat pipe condenser and coupled directly to aluminum radiator fins, with a total radiator surface area of 5 m^2. The system mass is about 600 kg, or 1.7 W/kg, and the overall length is about 4 m (Ref. 8). The same 13-kWt reactor could be combined with Stirling power conversion, as shown in Figure 2, to produce 3 kWe. This concept uses eight 400-W Stirling convertors that provide 23 percent system efficiency at 950 K hot-end and 475 K cold-end temperatures. The Stirling option assumes water heat pipes on the cold end coupled to a cylindrical aluminum radiator, with a total radiator surface area of 9.6 m^2. The system mass is about 750 kg, or 4 W/kg, and the overall length is about 5 m (Ref. 9).

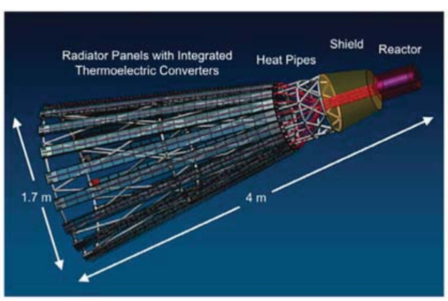


Figure 1.—Thermoelectric-based Kilopower system (1-kWe).

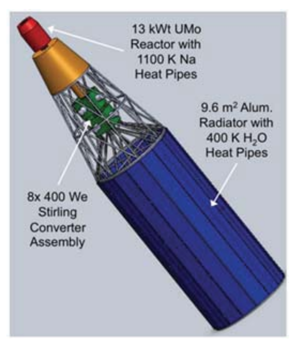
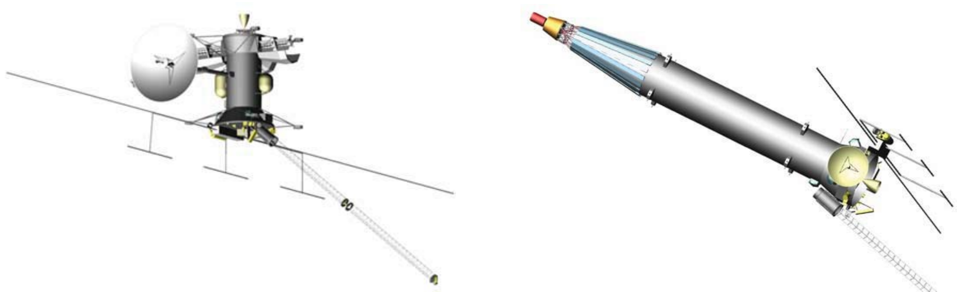


Figure 2.—Stirling-based Kilopower system (3-kWe).

The Decadal Study also included a preliminary assessment of Kilopower schedule and cost based on a “grass-roots” estimate by the design team. The proposed 10-year flight system program was organized into three phases: Development, Engineering, and Flight Qualification. Key tests during the development phase included a zero-power critical reactor mockup test and an electrically heated single-element power generation test. During the engineering phase, a full-size reactor prototype would be characterized in a series of zero-power critical tests, and a full-scale electrically heated engineering model system would be tested to verify performance in the expected operational environments (e.g., launch, transit, and destination) and validate control software. The Flight Qualification phase would include delivery of one fueled system from DOE for launch and an electrically heated qualification test unit. Within each phase, best-guess engineering estimates were made related to NASA and DOE labor costs, government support costs (e.g., materials, facilities, and ground equipment), and system contractor costs. The result of the Rough-Order-of-Magnitude (ROM) cost estimate was $690 million for the first flight system and $145 million for recurring systems.

Potential Mission Applications

Several mission studies were performed using the Kilopower systems as a reference. At the conclusion of the Decadal Study, a quick-turnaround assessment was made by JPL on a fission-based Jupiter Europa Orbiter (JEO) spacecraft, shown in Figure 3. The baseline JEO spacecraft included five Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) with a total mass of about 240 kg providing about 500 W while using 20 kg of Pu-238. Alternatively, a 1-kWe Kilopower system using TE power conversion could provide twice the power output with a mass increase of about 360 kg and no plutonium required. The power increase with the FPS permits a decrease in the size of the high gain antenna from 3 to 1.2 m in diameter and a corresponding mass decrease. Overall, the FPS-based JEO spacecraft is heavier than the MMRTG version, but still fits easily in the Atlas 5 launch vehicle fairing with adequate mass margin.



(a) (b)

Figure 3.—Jupiter Europa Orbiter (JEO). (a) JEO with five Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) (0.5 kWe). (b) JEO with single Kilopower system (1-kWe)

More recently, NASA Glenn conducted several science mission studies using the Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) Team. The studies were performed to compare radioisotope electric propulsion (REP) and small fission-based NEP for future space science missions. Two previously studied REP missions were evaluated: Kuiper Belt Object Orbiter (KBOO) and Chiron Orbiter. The objective was to compare mission parameters and spacecraft complexity between the two power source options. Figure 4 shows two variations of the KBOO spacecraft that could be launched on a Delta IV and perform the Kuiper Belt mission in about 16 years. The REP version uses nine large (550 W) Advanced Stirling Radioisotope Generators (ASRGs) providing a net power of about 4 kWe with 27 kg of Pu-238. A single 8-kWe Kilopower system with a UMo heat-pipe-cooled reactor and eight 1-kWe Stirling convertors was required to achieve the same mission trip time. The power system specific power improved from 5 W/kg for the high-power ASRGs to 8 W/kg for the Kilopower system. The Chiron Orbiter REP mission uses an Atlas 551 launch vehicle and six standard (150-W) ASRGs providing a net power of 1 kWe with 6 kg of Pu-238 to complete the 13-year trip. The same mission could be performed using the 8-kWe Kilopower system while eliminating the Star 63 upper stage. In both mission studies, the spacecraft are significantly simplified by using a single power source. The added power provided by the fission systems could also enhance spacecraft capabilities, although that was not evaluated in the COMPASS studies.

(a) (b)

Figure 4.—Kuiper Belt Object Orbiter (KBOO). (a) KBOO with nine large Advanced Stirling Radioisotope Generators (ASRGs) (4-kWe). (b) KBOO with single Kilopower system (8-kWe).

Even Smaller and Simpler

The Kilopower concept has continued to evolve from the original Decadal Study configurations with an emphasis on smaller size and lower development cost. Los Alamos National Laboratory has developed reactor concepts that move the heat pipes to the outside perimeter of the core and replace the UMo core with a smaller monolithic uranium block. The smaller core and external heat pipes greatly simplify fabrication and testing. The reactor thermal power is reduced from 13 kWt in the original concept to approximately 4 kWt. This power level should allow full-scale ground nuclear testing in existing DOE test facilities such as those available at the Nevada National Security Site, Device Assembly Facility (DAF). The lower thermal power allows the practical use of available Advanced Stirling Convertors (ASCs) that are in flight development for the ASRG. Figure 5 shows a modified Kilopower concept using the smaller core and eight ASCs to produce 800 W of electric power. The overall system is approximately 2.5 m long and weighs about 400 kg (2 W/kg). The simplified design and the ability to test the system in existing nuclear facilities could reduce development cost from the original Decadal Study estimate of $690 million down into the $300 to $500 million range.

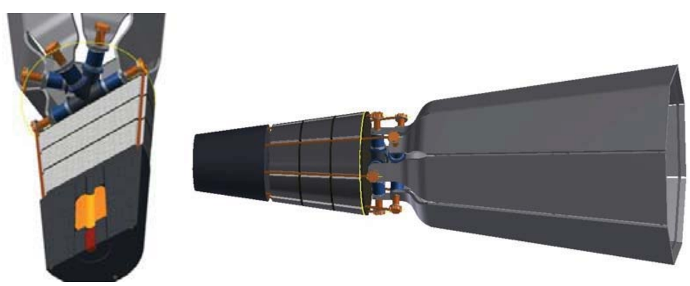


Figure 5.—Modified Kilopower system with eight Advanced Stirling Convertors (ASCs) (800-W).

Demonstration Using Flattop Fissions

In order to demonstrate the fundamental operation of a small heat-pipe-cooled reactor with Stirling power conversion, Los Alamos conducted a proof-of-concept test. The Demonstration Using Flattop Fissions (DUFF) test was performed at the DAF using the “Flattop” Criticality Experiment (Ref. 10). The test was conceived in April 2012 and completed in about 6 months for less than $1 million by leveraging resources from the National Nuclear Security Administration, Los Alamos, and NASA. Flattop includes a 12.7-cm spherical U-235 core on a pedestal surrounded by a spherical reflector as shown in Figure 6. NASA Glenn supplied the power generation test assembly that included a single hot-end heat pipe coupled to two small Stirling convertors (Ref. 11). The 60-cm-long by 1.27-cm-diameter water-filled heat pipe was inserted into an existing instrumentation port in the Flattop core to allow thermal energy transfer to the Stirling convertors. On Sept. 13, 2012, nuclear criticality was achieved with excess reactivity to heat the Stirling convertors via the heat pipe. Upon achieving a suitable temperature ratio, the Stirling convertors were successfully started and operated up to a total electric power output of 24 W. The test represents the first-ever attempt at using a heat pipe to extract thermal power from a reactor and the first-ever use of a Stirling convertor to produce electric power with a fission heat source. The successful test serves as a significant milestone for space reactors and paves the way for additional development of small FPSs.

(a) (b)

Figure 6.—Demonstration Using Flattop Fissions (DUFF). (a) Flattop criticality experiment at Device Assembly Facility (DAF). (b) Inserting heat pipe through reflector into U-235 core.

NUCLEAR SYSTEM OPTIONS

The Kilopower systems fit nicely into the space nuclear power performance map, shown in Figure 7, between RPSs and larger FSP systems addressing what would otherwise be a gap in NASA’s power portfolio. Performance is presented in terms of power system specific mass versus power level. The graphic shows various space nuclear power system designs (designated by diamond markers) and groupings that represent general classes. At the low end are RPSs including MMRTG, ASRG, and the General Purpose Heat Source (GPHS) RTGs that were flown on missions such as Cassini and Pluto New Horizons. Those systems are either flight proven or ready for flight based on current support from the Science Mission Directorate (SMD) RPS Program. At the far end are very large FPSs that would require significant technology development in order to achieve the projected power levels and specific mass. The region occupied between 10 and 1000 kWe and is currently being addressed by the GCD Nuclear Systems Project. The basic building block technologies including liquid-metal-cooled pin-fuel reactors, dynamic power conversion, alternating current power transmission, and large heat pipe radiators are crosscutting for both FSP and near-term NEP applications. Kilopower clearly addresses the gap between the RPS Program and the Nuclear Systems Project. The systems shown in the Kilopower region have heritage to the 500-We Systems for Nuclear Auxiliary Power Program (SNAP)–10A system, the only U.S. space reactor ever operated in space. The proposed design approach offers performance improvements relative to SNAP–10A while maintaining simplicity and robustness. While the specific mass is not considerably better than the RPS, Kilopower offers significantly greater power levels and does not detract from the limited Pu-238 fuel inventory.

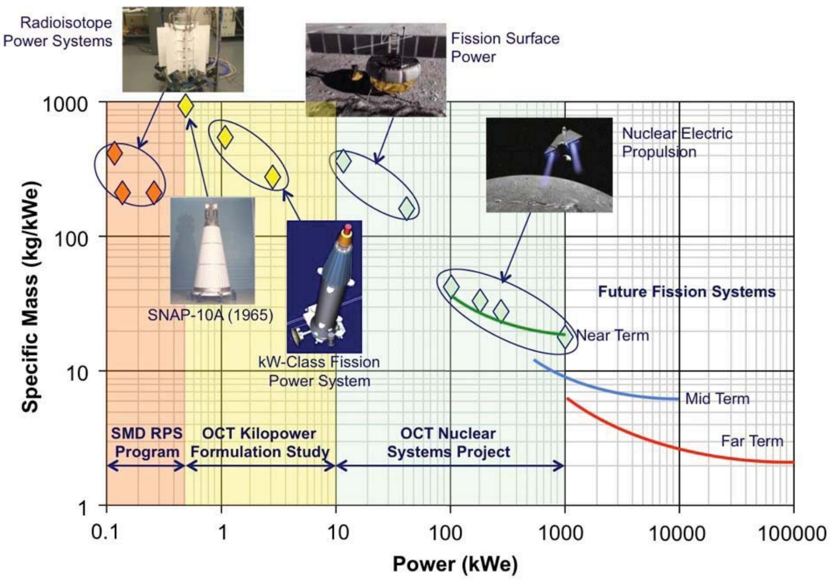


Figure 7.—Space nuclear power performance map.

CONCLUSION

Under NASA's Nuclear Systems Project, NASA and the Department of Energy (DOE) are developing fission power technology to serve a wide range of future space uses. More-conventional fission power systems employing liquid-metal-cooled pin-fuel reactors and dynamic power conversion are well suited for lunar and Mars surface power or nuclear electric propulsion (NEP) vehicles. Kilopower is a new class of fission power technology intended to address robotic science and human precursor applications. Several design configurations have been developed for power levels between 0.5 and 10 kWe. The concepts use a solid, cast uranium core and liquid metal heat pipes to transfer fission heat to either thermoelectric or Stirling power conversion. Performance is competitive with current radioisotope power systems (RPSs) providing between 2 and 8 W/kg, and the fission-based systems would not detract from the limited Pu-238 fuel supply. Mission studies have shown that the Kilopower concept can be used for planetary science probes such as Jupiter Europa Orbiter or robotic NEP missions such as Kuiper Belt Object Orbiter. Los Alamos National Laboratory and NASA Glenn Research Center completed a proof-of-concept test at the Nevada National Security Site in 2012 using the Flattop reactor and two small Stirling convertors to produce 24 W. That test provides a foundation for further system development and future Kilopower flight systems.

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