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NASA's Kilopower Reactor Development and the Path to Higher Power Missions

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Summary

The development of NASA's Kilopower fission reactor is taking large strides toward flight development with several successful tests completed during its technology demonstration trials. The Kilopower reactors are designed to provide 1 to 10 kW of electrical power to a spacecraft or lander, which could be used for additional science instruments, the ability to power electric propulsion systems, or support human exploration on another planet. Power-rich nuclear missions have been excluded from NASA mission proposals because of the lack of radioisotope fuel and the absence of a flight-qualified fission system. NASA has partnered with the Department of Energy's (DOE's) National Nuclear Security Administration to develop the Kilopower reactor using existing facilities and infrastructure to determine if the reactor design is suitable for flight development. The 3-year Kilopower project started in 2015 with a challenging goal of building and testing a full-scale-flight-prototypic nuclear reactor by the end of 2017. Initially, the power system will undergo several nonnuclear tests using an electrical heat source and a depleted uranium (DU) core to verify the complete nonnuclear system design prior to any nuclear testing. After successful completion of the DU test, the system will be shipped to the Nevada National Security Site where it will be fueled with the highly enriched uranium (HEU) core and re-tested using the nuclear heat source. At completion of the project, NASA will have a significant sum of experimental data with a flight-prototypic fission power system, greatly reducing the technical and programmatic risks associated with further flight development. To complement the hardware-rich development progress, a review of several higher power mission studies is included to emphasize the impact of having a flight-qualified fission reactor. The studies cover several science missions that offer nuclear electric propulsion (NEP) with the reactor supplying power to the spacecraft's propulsion system and the science instruments, enabling a new class of outer-planet missions. A solar versus nuclear trade for Mars surface power is also reviewed to compare the advantages of each system in support of ascent vehicle propellant production and human expeditions. These mission studies offer insight into some of the benefits that fission power has to offer, but still lacks a wider audience of influence. For example,

mission directorates will not include a fission power system in their solicitations until it is flight qualified, and scientists will not propose new missions that require more power than what is currently proven and available. An attempt to break this which came first effect has been ongoing with the Kilopower project with the goal of advancing the technology to a level that encourages a flight development program and allows scientists to propose new ideas for higher power missions.

Introduction

The U.S. space nuclear program has found considerable challenges in developing a flight-qualified fission reactor for NASA missions over the past half century. In fact, the 1960s Space Nuclear Auxiliary Power (SNAP) program was not only the last time the United States has flown a space reactor, the 1965 launch of SNAP 10A, but is also the last time that the United States has completed a nuclear-powered ground test for any space reactor. Without speculation, it is clear that a successful program will need to have clear advantages over current technologies, be affordable, and be efficiently executed by a qualified team. NASA has partnered with the Department of Energy's (DOE's) National Nuclear Security Administration to recruit specific talent in reactor design, fuel manufacturing, and criticality testing from the Los Alamos National Laboratory (LANL), the Y-12 National Security Complex, and the Nevada National Security Site. Hopefully, this Kilopower team will overcome the historical challenges and successfully complete a nuclear ground test in 2017 that will provide crucial information about the reactor neutronics and verify if the design can power the future of space exploration.

Nomenclature

ADL	Architecture Design Laboratory
ASRG	Advanced Stirling Radioisotope Generator
BeO	beryllium oxide
CBE	current best estimate
COMPASS	Collaborative Modeling for Parametric Assessment of Space Systems

DAF	Device Assembly Facility
DOE	Department of Energy
DRA	Design Reference Architecture
DU	depleted uranium
DUFF	Demonstrate Using Flattop Fissions
EOL	end of life
HEOMD	Human Exploration and Operations Mission Directorate
HEU	highly enriched uranium
HP	high power
ISRU	in situ resource utilization
JPL	Jet Propulsion Laboratory
KBO	Kuiper Belt Object
KBOO	Kuiper Belt Object Orbiter
KRUSTY	Kilopower Reactor Using Stirling TechnologY
LANL	Los Alamos National Laboratory
LEO	low-Earth orbit
MAV	Mars Ascent Vehicle
MMRTG	Multi-Mission Radioisotope Thermoelectric Generators
MTV	Mars Transfer Vehicle
NEP	nuclear electric propulsion
NEXT	NASA's Evolutionary Xenon Thruster
REP	radioisotope electric propulsion
RTG	Radioisotope Thermoelectric Generator
SEP	solar electric propulsion
SNAP	Space Nuclear Auxiliary Power
TBD	to be determined
TRL	technology readiness level
TSSM	Titan Saturn System Mission

Symbols

e	eccentricity
I_{sp}	specific impulse
k_{eff}	system reactivity

Technology Developments

After completion of the 2012 Demonstrate Using Flattop Fissions (DUFF) experiment (Refs. 1 and 2), the Kilopower team has been focused on the full-scale nuclear demonstration of the 1-kWe fission power system. NASA's Space Technology Mission Directorate officially started the Kilopower project in 2015 with the goal of maturing the fission reactor technology to technology readiness level (TRL) 5 by 2017. In order to complete the goal, the reactor is required to achieve steady-state operation at the nominal core design temperature and power of

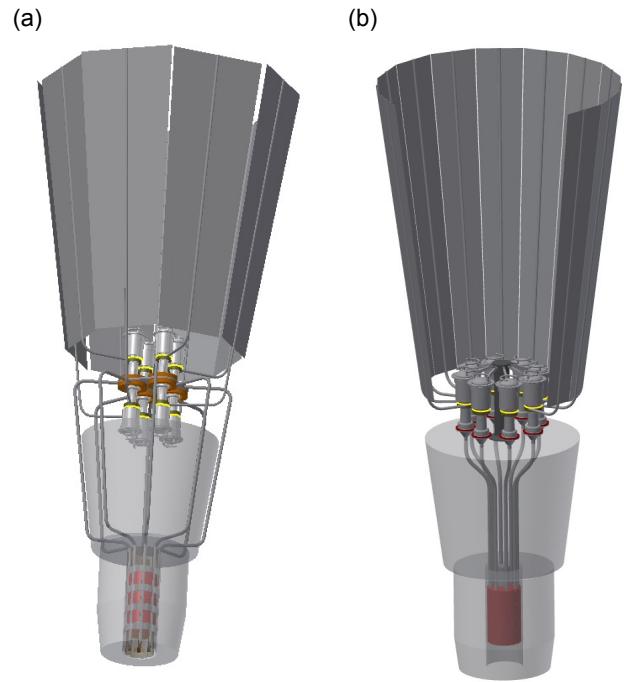


Figure 1.—Kilopower 1-kWe flight concepts. (a) Baseline dual opposed configuration with Haynes® 230® sodium heat pipes assembled around the shield. (b) Single engine configuration with sodium heat pipes passing through the shield.

800 °C and 4 kWt, respectively, within a space vacuum environment. Designing the reactor to reach these conditions requires extensive neutronic analysis that is heavily driven by material properties and design geometries. Additionally, the nuclear materials must be readily available and in production within the U.S. DOE and commercial complexes. Taking these facts into account and given the budget and schedule constraints, the Kilopower configuration was established in early 2015 during the conceptual design review. Early flight design concepts can be viewed in Figure 1.

Throughout 2015, several material tests were initiated to understand certain properties that were either unavailable or considered to be inconclusive based on past research data. Some of these tests included creep properties of the fuel, coefficient of thermal expansion of the fuel, and diffusion properties between the fuel and Haynes® 230® sodium heat pipes. In parallel with the material testing, subcomponent tests were initiated at the NASA Glenn Research Center to verify that the sodium heat pipes, as well as their connection to the reactor core, would sufficiently transfer heat from the reactor core to the power conversion system. Full-scale thermal prototype tests were conducted to study these effects using a stainless steel electrically heated surrogate core section. Figure 2 shows a picture of the thermal prototype testing conducted in 2015 with the sodium heat pipes transporting approximately 4 kW of thermal energy from the reactor core to the vacuum chamber over a distance of 1 m.



Figure 2.—Thermal prototype testing with Haynes® 230® sodium heat pipes radiating at over 800 °C to the vacuum chamber walls as seen through the chamber view port.

In 2016, major efforts were focused on completing the necessary nonnuclear-system-level tests at Glenn's VF71 facility to fully characterize the performance between the core and the thermal energy conversion process. These tests incorporated the surrogate stainless steel core, sodium heat pipes, and Stirling power conversion. Several power conversion concepts were evaluated and ultimately led to two Stirling convertor designs that moderately differed in their configuration. Both configurations baselined a total of eight 125-W Stirling convertors that would produce the required total electrical output of 1,000 W to the spacecraft bus. Funding was not available to purchase new convertors, so compromises were made to incorporate two of the existing 70-W convertors repurposed from the Advanced Stirling Radioisotope Generator (ASRG) project. With only two convertors, a Stirling thermal simulator was designed and fabricated to replace the remaining six convertor slots and balance the thermal load. The baseline design consisted of what is typically referred to as a dual convertor design in which the Stirling convertors are positioned opposing each other with the hot ends together. This allows the inertia forces from each convertor to be balanced through synchronous motion control. The second arrangement positioned all convertors, or thermal simulators, singularly, with the hot ends facing toward the reactor core. This configuration requires an active balancer connected to the backside of the convertor to balance the inertia forces from the moving convertor parts. The dual opposed baseline architecture can be seen in Figure 3.



Figure 3.—Balance of plant hardware showing eight Haynes® 230® sodium heat pipes attached to a conduction plate that supplies heat to two Stirling engines and six Stirling thermal simulators.

One of the major design considerations of the Kilopower reactors is the fueling process at the launch site. Use of highly enriched uranium (HEU) fuel requires increased levels of security, which have considerable costs. Integration between the reactor, spacecraft, and launch vehicle has a direct impact on the time required to fuel the reactor and complete payload assembly. At this point in the development process, the only task that can be addressed is the fueling process of the power system, as the spacecraft and launch vehicle are unknown at this time. Flight integration of the reactor will always position the reactor core and shield opposing the spacecraft to allow the shield to protect the spacecraft as designed. This allows the unfueled power system to be available at the far end of the total payload. In this architecture, the payload integration could be designed in a way that the reactor fueling could be one of the final steps in the assembly test and launch operations process. This would allow the HEU fuel to be shipped to the launch-processing facility close to the launch date and thus decreasing the number of days that the fuel would need to be secured.

The fueling process of a Kilopower flight system would start at the bottom of the shield with access to the heat pipe evaporators. The radial reflector assembly and control rod would be detached during fueling. The assembly tooling would attach to the lower shield plate and align the centerlines of the power system and core. The flight shield could not be included into the nuclear ground test due to geometric constraints within

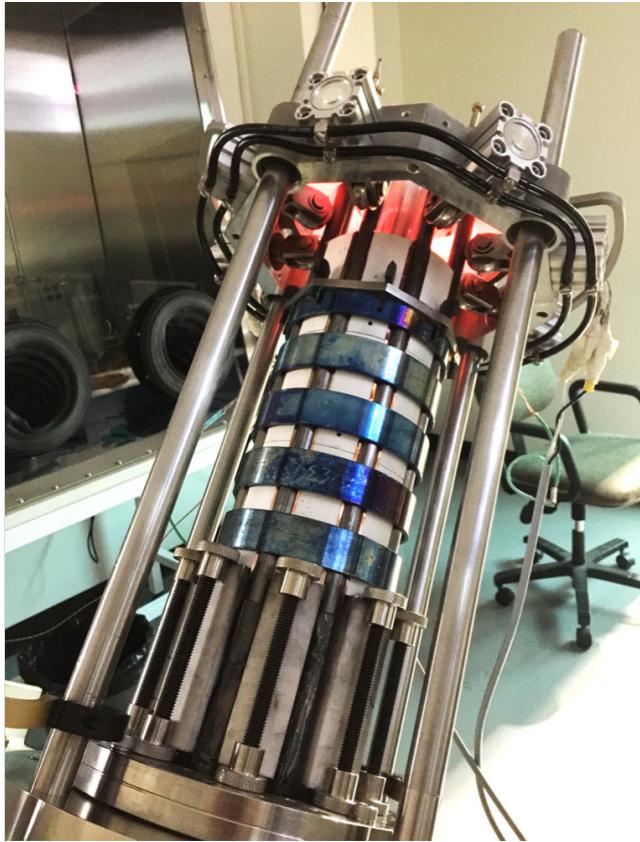


Figure 4.—Reactor fueling. Final ring clamp being heated to 800 °C before being inserted around the Haynes® 230® sodium heat pipes and core.

the criticality test cell, so the lower portion of the vacuum chamber service collar is used for the tooling fixture base. Several surrogate fuel assemblies were completed at Glenn during the development process and provided time durations for the process. It was determined that the reactor could be fueled, instrumented, insulated, and canned within 12 h. Additional time is required for assembling the control rod and radial reflector assembly, which is estimated to take an additional 8 h. A conservative estimate for the complete fueling process and reactor final assembly is determined to take no more than 4 working days. Figure 4 depicts the fuel assembly tooling and several ring clamps holding the heat pipes to the fuel.

Depleted Uranium (DU) Risk Reduction

The final risk-reduction effort before conducting the nuclear testing was an electrically heated system test using a DU core. This core was fabricated by Y-12 and provided them the opportunity to develop their fabrication processes in preparation for the HEU core needed for the 2017 nuclear testing. The DU core is exactly the same material as the HEU core with the major difference being the depletion of the Uranium-235 isotope. The DU core allowed the research team

to evaluate the mechanical and material interfaces to the heat pipes as well as any differences in thermal performance.

The DU material also provided a unique opportunity for the Kilopower team to perform training exercises regarding fueling the reactor. Team members from the Marshall Space Flight Center, LANL, and the Device Assembly Facility (DAF) visited Glenn to undertake the first Kilopower Reactor Using Stirling TechnologY (KRUSTY) dress rehearsal to perform the assembly process without the security and criticality requirements associated with the HEU material. This exercise allowed the processes to be evaluated and modified before moving into HEU operations at DAF for the KRUSTY test. The DU material is slightly radioactive and requires radiological work procedures for safe handling, making the training as close to the HEU process as possible. Anytime fissionable materials are being handled, criticality safety is a major concern to make absolutely sure that specific geometries and moderators cannot combine to make the material critical throughout the manufacturing, machining, and assembly processes. New designs, such as Kilopower, require additional efforts in criticality safety, and performing the procedures with DU ensures a well-prepared operation.

Once the power system was fueled with the DU core, it underwent the KRUSTY specific test protocols per the nuclear experiment plan. This allowed the thermal performance and power data to be benchmarked with the prior stainless steel surrogate core system testing as well as the nuclear-heated model predictions. This test marked the final key milestone required to progress into the nuclear test phase with the KRUSTY test.

Nuclear Ground Testing

All the preparations and testing are leading up to the long-sought return of a real U.S. space nuclear program starting with the Kilopower Reactor Using Stirling TechnologY (KRUSTY) Test. In the summer of 2017, the KRUSTY tests performed at the DAF will complete a number of key components to moving the Kilopower reactors toward further flight development.

Several zero-power critical tests will be completed to compare and verify neutronic modeling parameters. These nuclear data points will provide fundamental information that will be used to re-assess model results prior to performing experiments at power. In addition, one goal of the experiment is to try and get “clean” physics data for various materials and components. This data will be useful to the physics community at large, aid in future Kilopower reactor designs, and provide confidence in proceeding with KRUSTY experiments at power. Zero-power critical tests are performed for several configurations of the reactor in a stepwise fashion (by adding components) so as to characterize the entire system. Each zero-power critical determines the k_{eff} of a delayed-supercritical system (the reactivity of the system) from the slope of power increase measured for that system.

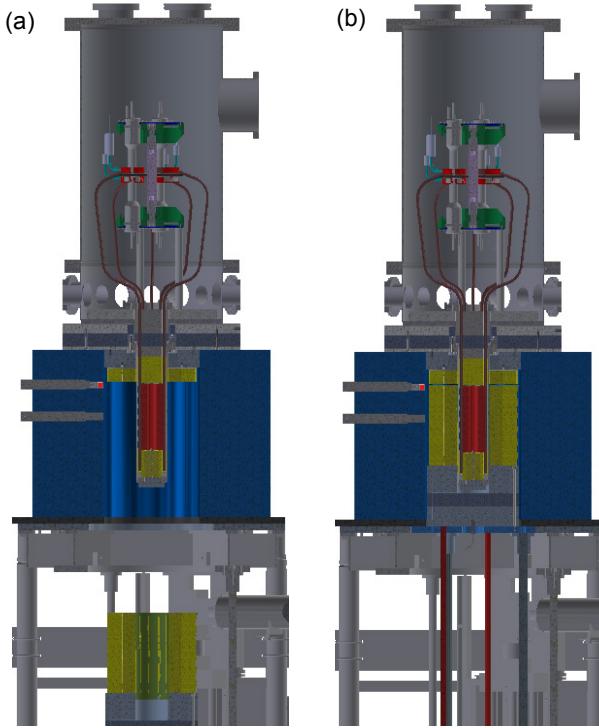


Figure 5.—Kilopower Reactor Using Stirling Technology (KRUSTY) test configuration. (a) Beryllium oxide (BeO) radial reflector (lower yellow cylinder) shown prior to reactor startup. (b) Radial reflector shown fully inserted around highly enriched uranium (HEU) core for full-power operation.

Several tests will be run at low temperature prior to testing at high temperature. Figure 5 illustrates the reactor startup by axially moving the beryllium oxide (BeO) radial reflector up around the reactor core. The amount of time the reflector spends at various axial locations determines the overall system power output and temperature obtained. For low-temperature testing, the runs will limit the excess reactivity in the system to less than \$0.80. Limiting the excess reactivity in the system to less than \$0.80 ensures the system is controlled by delayed neutrons and limits the temperature in the system. The first run will be a \$0.15 free run that inserts \$0.15 rapidly with no operator interactions after the insertion. This test will allow the analyst to correlate the neutron population measured in the experiment to the power in the reactor. The \$0.15 test will be followed by a test of \$0.30 and a test of \$0.60 in excess reactivity. These tests will begin with a \$0.15 free run and continue with steady-state power as the operator inserts reactivity in \$0.02 intervals until the desired amount of excess reactivity is inserted in the system. These tests will again be used to validate modeling of the system prior to testing at full operating temperature and power.

The final KRUSTY test will be a full-power run that will achieve the operating temperature of the reactor ($\sim 800^{\circ}\text{C}$ average core temperature). This test will require about \$1.70 in

excess reactivity to achieve operating temperature. The \$2.20 worth of excess reactivity will be loaded onto the machine in the form of more BeO radial reflector rings to cover any uncertainty in modeling or material measurements. The test will be run for approximately 28 h. The test will begin like the previous low-temperature runs—\$0.15 will be inserted at the start of the experiment and then bumped in regular intervals until the desired operating temperature is achieved. The system will be allowed to come to steady state for several hours. The first transient during this experiment will involve cutting the Stirling power removal by a factor of two and allowing the reactor to automatically adjust to the new power demand. After steady state is again achieved, the Stirlings will be brought back to maximum power removal, allowing the reactor to again compensate and load follow back to the original power level. After running at steady state for several hours, the power removal on one Stirling engine will be eliminated to simulate a failed heat pipe or Stirling engine. The reactor will be allowed to adjust to this new condition and temperature measurements will be compared to modeling. Finally, after returning to full-power steady state, all cooling to the reactor will be cut to simulate a full loss of cooling event. The reactor physics of this system are such that the temperature will rise to compensate and drop power to the level being dissipated by thermal losses to the environment. All runs will be compared to modeling of the full system for model validation.

The KRUSTY test will be the first flight prototypic nuclear test of a space reactor performed in decades. The results of the KRUSTY test will validate the computer models, methods, and data used in the reactor design. In addition, valuable experience in design, fabrication, startup, operation, transient behavior (load following based on reactor physics), and reactor shutdown will be obtained. The ultimate goal of the KRUSTY experiment is to show that a nuclear system can be designed, built, and nuclear tested and produce electricity via a power conversion system in a cost-effective manner.

Science Missions

Titan Saturn System Mission

In 2014, the Glenn’s Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) team completed a re-assessment study of the 2010 decadal survey Titan Saturn System Mission (TSSM) (Ref. 3) using a uranium fueled 1-kW electric nuclear reactor in place of the original plutonium fueled 500-W Stirling radioisotope system (Ref. 4). The TSSM goal was to explore Saturn’s moon Titan by incorporating an orbiter, lander, and Montgolfier balloon for a total of over 100 kg of science payload.

The mission was designed using several propulsion technologies. After reaching geosynchronous transfer orbit from the launch stages, a solar electric propulsion (SEP) stage would perform Earth and Venus flybys, with a jettison at the last Earth flyby, to obtain the necessary velocity for trans-Saturn

injection and the heliocentric cruise. Once at Saturn, a bipropellant chemical system would supply the deceleration and maneuvering required for Saturn orbit insertion where the 2-year science mission would begin. After 16 Titan flybys, release of the Montogolfier balloon and lander, 7 Enceladus flybys, Titan orbit insertion, and 200 Titan aerobrake maneuvers, a 1,500 km orbit would finally be achieved for a 20-month science operation. The mission duration for the fission system totaled 15 years and 3 months with the reactor starting after the SEP jettison and the last Earth flyby. Waiting to start up the reactor after the last Earth flyby extends the fission power system life and makes it much safer than the radioisotope system with respect to a reentry failure scenario.

The study concluded that the 1-kWe fission reactor with Stirling conversion could complete the mission with the advantages of operating all the science instruments simultaneously and providing higher data rate communications with a smaller antenna. The main disadvantage was that the reactor-powered spacecraft weighed 950 kg more than the ASRG version and took 2 more years to complete the Saturn mission. The study team recommended that the reactor power system increase to 10 kW electric to incorporate a nuclear electric propulsion (NEP) system in place of the SEP stage, which could reduce the chemical propellant and eliminate aerobraking. These modifications would simplify the spacecraft and potentially reduce the total mass, thus making the reactor-powered system an attractive option. Figure 6 shows the TSSM spacecraft and fission power system.

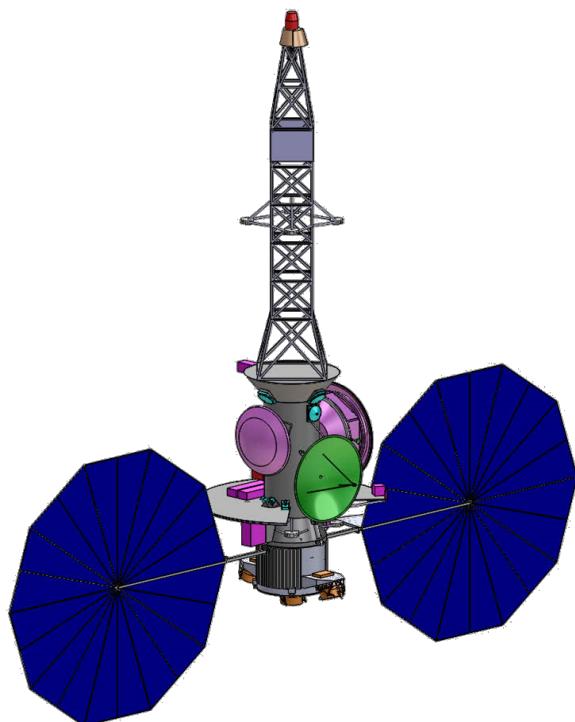


Figure 6.—Titan Saturn System Mission (TSSM) spacecraft with attached 1-kWe fission reactor.

Chiron Orbiter

The 2060 Chiron is a Centaur class object with a highly eccentric orbit, ranging from 8 to 19 au, in the Saturn Uranus system with perihelion just inside Saturn's orbit and aphelion near that of Uranus's orbit. This minor planet differs from many other Centaur objects in that it exhibits comet-like behavior that is visible near perihelion, making it an ideal candidate for primitive body research. In 2010, the NASA Goddard Space Flight Center Architecture Design Laboratory (ADL) and Glenn's COMPASS team partnered to study a Chiron Orbiter for the planetary science decadal survey steering committee and primitive bodies panel (Ref. 5). The purpose of the study was to evaluate power and propulsion strategies for putting 80 kg of science payload into a Chiron orbit at distances needed for 10-m imaging resolution. Guidelines for the study included a 10-year launch window between 2015 to 2025, New Frontier class cost cap of \$800 million, and a limit of two ASRG power sources, which was later modified for additional ASRG units.

The study looked at several propulsion architectures for the mission including all chemical, chemical/SEP, six ASRG radioisotope electric propulsion (REP), and two high-power (HP) ASRG REP. All the options used either the standard 134-We ASRG or the conceptual 550-W HP ASRGs to power the spacecraft throughout the mission. It was concluded that the ASRG REP missions could meet all the science requirements and deliver the most science payload (72 kg for six standard ASRG and 76 kg for two HP ASRG) to the Chiron orbit, but could not fit within the \$800 million cost cap of a New Frontier class mission.

In 2012, the COMPASS team re-opened the Chiron Orbiter mission to add a fission-powered NEP system to the trade (Ref. 6). The objective of this study was to design an equivalent NEP version of the decadal survey REP baseline, while using the same Atlas 551 launch vehicle, by scaling the power of the reactor and electric thrusters to offset the extra mass. It was found that an 8-kWe fission-powered NEP system could deliver the required science payload within the 13-year time period using 7,000-W ion engines (Figure 7). The increased capacity of the power and electric propulsion system allowed the NEP spacecraft to spiral out of Earth's gravity well on its own power without using the Star 48 payload assist module.

At first glance (Table I) it appears that the NEP version is excessively heavy compared to its REP counterpart, but in fact, the heavier mass of the reactor was offset by using the higher power and higher specific-impulse (I_{sp}) thrusters (and thus less propellant) than the REP version. Once in orbit around Chiron, all of the reactor power could then be used for the science mission, which would allow the use of HP science instruments and high data rate communications. This benefit has not been studied by the science community, but would likely provide a new evolution in science payloads and instruments. It should also be noted that REP and NEP are enabling for orbiting Chiron—no other way was found possible due to the lack of a substantial gravity well.

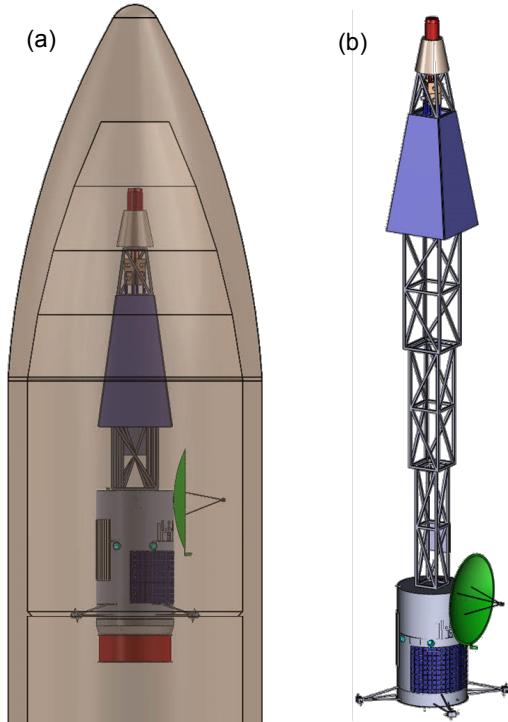


Figure 7.—Chiron Orbiter spacecraft with 8-kWe reactor and nuclear electric propulsion (NEP). (a) In launch vehicle. (b) Deployed.

TABLE I.—CHIRON ORBITER MISSION COMPARISON OF RADIOISOTOPE ELECTRIC PROPULSION (REP) AND REACTOR-POWERED NUCLEAR ELECTRIC PROPULSION (NEP)

Power system	REP	NEP
Science and trip time	44 kg CBE ^a /13 yr trip/1 yr science	44 kg CBE/13 yr trip/1 yr science
Launcher	Atlas 551/Star 48	Atlas 551
Launch mass, kg	1,300	4,000
Power level (EOL ^b)/mass α	Six, 150 W ASRG ^c , 900 We/189 kg (4.7 We/kg)	Single fast reactor, Stirling converters 8,000 We/1142 kg (7 We/kg)
Electric propulsion thrust/weight	Three 600 W Hall, ~450 kg Xe	Three 7,000 W Ion, ~1,600 kg Xe
Size, m deployed launch	2.2 4 (includes Star 48)	16 7
Nuclear material	~6 kg, Pu-238	~75 kg, 93 percent HEU ^d
Radioactivity at launch, Ci	91,840	4.8

^aCurrent best estimate.

^bEnd of life.

^cAdvanced Stirling Radioisotope Generator.

^dHighly enriched uranium.

Launch safety is greatly reduced using the fission reactor because the radioactivity at launch is several orders of magnitude lower. Radioactivity comparisons of 91,840 Ci for the radioisotope fuel to 5 Ci of the HEU fuel have a significant impact on launch safety analysis and overall public safety for fission-powered nuclear missions.

Kuiper Belt Object Orbiter (KBOO)

A similar design study from Glenn's COMPASS team and the Jet Propulsion Laboratory's (JPL's) Team X was performed in 2011 to evaluate several REP spacecraft for a Neptune Flagship Orbiter, studied by JPL, and a KBOO studied by Glenn. The KBOO spacecraft would launch in the 2030 timeframe and take 16 years of transit to support a 1-year science mission. This flagship class mission sported conceptual designs of either eleven 420-W advanced Radioisotope Thermoelectric Generators (RTGs) or nine 550-W ASRGs.

The trans-Neptunian Kuiper Belt Object (KBO) 2001 XH255 was chosen as the target with a slight eccentricity (e) of 0.07 with semi-major axis of 34.81 au and a perihelion of 32.28 au. These bodies are assumed to be composed of frozen methane, water, and ammonia, which due to their vast distance from the sun, have presumably never been thawed. The original REP study proposed using a Delta IV Heavy with a Star 63F upper stage to reach a C3 of $69.56 \text{ km}^2/\text{s}^2$ with 3180 kg of launch mass. The electric propulsion system would operate continuously after launch until a Jupiter gravity assist in 2037, followed by a long coast period, and finally deceleration and orbit insertion 16 years later. Once in orbit at KBO 2001 XH255, the 1-year science mission would begin.

In 2012, the COMPASS team compared the REP system to an NEP system to once again understand the differences between the two power systems and determine if a higher-power reactor could complete the mission at distances >32 au (Refs. 7 to 9). With a similar design and results from the Chiron Orbiter, it was found that an 8-kWe NEP system could complete the same mission as the 4-kWe REP system using the same launch vehicle, trip time, and science payload. Table II shows the results of the study with graphics in Figure 8.

The KBOO mission trade ended up with a better comparison between the REP and NEP systems, with little difference in the overall mass. The fission system provides 100 percent more power than the radioisotope system, with less than 20 percent extra mass. This is due to the constant specific power (5 We/kg) of the REP system and the growing specific power (7 We/kg) of the NEP system as power levels increase. Another important feature is the increasing specific impulse of the higher power ion thrusters. This decreases the amount of xenon propellant needed for the NEP mission with both REP and NEP systems requiring 1,200 kg of Xe. Radioactivity at launch provided another important parameter between the two systems, with the REP system having 413,260 Ci of radioactivity compared to the 5 Ci associated with the NEP system, again favoring the safer uranium fuel for launch failure analysis scenarios.

TABLE II.—KUIPER BELT OBJECT ORBITER (KBOO) COMPARISON OF RADIOISOTOPE ELECTRIC PROPULSION (REP) AND NUCLEAR ELECTRIC PROPULSION (NEP)

Power system	REP	NEP
Science and trip time	100 kg CBE ^a /16 yr trip/1 yr science	100 kg CBE/16 yr trip/1 yr science
Launcher	Delta IV Heavy/Star 63F	Delta IV Heavy/Star 63F
Launch mass, kg	3,100	3,700
Power level (EOL ^b)/mass alpha	Nine, 550 W ASRG ^c , 4,000 We/782 kg (5 We/kg)	Single fast reactor, Stirling converters 8,000 We/1162 kg (7 We/kg)
Electric propulsion thrust/weight	1+1 3,000 W NEXT ^d Ion, ~1,200 kg Xe	1+1 7,000 W NEXT Ion, direct drive, ~1,200 kg Xe
Height, m deployed launch	6 3	16 7
Nuclear material	~27 kg, Pu-238	~75 kg, 93 percent enriched
Radioactivity at launch, Ci	413,260	4.8

^aCurrent best estimate.

^bEnd of life.

^cAdvanced Stirling Radioisotope Generator.

^dNASA's Evolutionary Xenon Thruster.

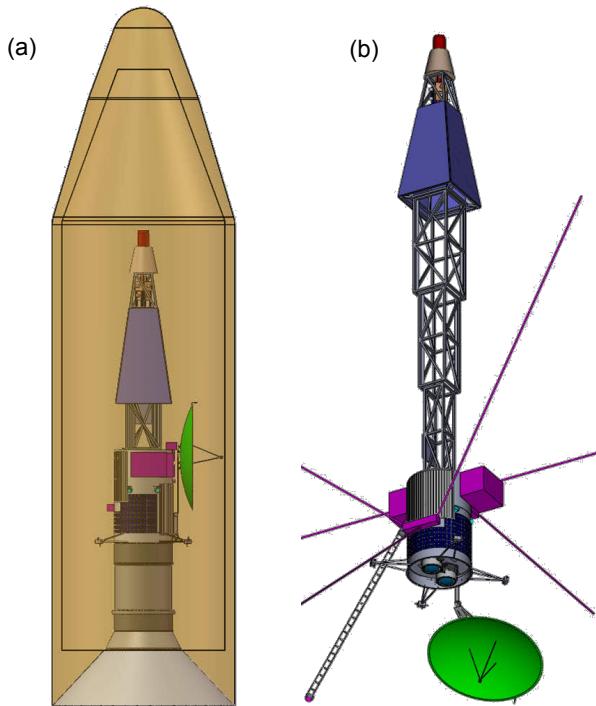


Figure 8.—Kuiper Belt Object Orbiter (KBOO) spacecraft with 8-kWe reactor and nuclear electric propulsion (NEP). (a) In launch vehicle. (b) Deployed.

According to the science mission studies, reactors could provide a higher power alternative to radioisotope systems, especially for missions requiring electric propulsion. The reactor technology could also enable new undefined missions,

outside the capabilities of current power systems, with instruments that may not yet be developed. The overall goal of the Kilopower project is to design a highly reliable reactor with low re-occurring launch costs that will enable scientists the ability to propose missions with several kilowatts of power. Exploring a paradigm shift may be best answered by asking the following question: If a flight-qualified 10-kWe reactor were sitting on the shelf with a life expectancy of 20 or more years (after it is started), how might the science proposals and missions be different?

Human Exploration Missions

NASA and its commercial partners are focused on putting humans on Mars within the following two decades as the next great step in human exploration. The Mars Design Reference Architecture (DRA 5.0) (Ref. 10) has baselined fission power as the primary power system for surface operations and has recently established the 10-kWe Kilopower reactor as the leading technology. There are two main phases of the Mars program that require new power system technology. Phase I requires a power system that will autonomously deploy and supply an in situ resource utilization (ISRU) plant. The ISRU plant will separate and cryogenically store the oxygen from the Martian atmosphere for ascent vehicle propellant. Phase II requires the same autonomous power system to support the human crew that arrives after completion of the necessary propellant phase. The power requirements for both phases are directly linked to the number of astronauts arriving and the science missions involved during the stay. NASA DRA studies have settled on 40 kWe as the required power level to support early Mars missions with a crew of four to six astronauts.

In 2016, the Human Exploration and Operations Mission Directorate (HEOMD) commissioned the COMPASS team to further evaluate the fission versus solar trades for Mars (Ref. 11). The study looked at the requirements for both the ISRU and crewed phases of the mission, with several different power architectures. Rucker et al. reported the results (Ref. 12) along with further evaluation on the subject. A brief summary is included here for discussion purposes.

Phase I—In Situ Resource Utilization (ISRU) Demonstrator

- Launch vehicle: Delta IV Heavy
- Payload mass to Mars surface: 7,500 kg
- Location: Jezero crater, 18°51'18"N 77°31'08"E
- Propellant production: 4,400 kg of liquid oxygen (1/5 scale)

The study took three different approaches to the solar architecture design including—1A, daylight-only operation at 1/5 production; 1B, around-the-clock operation at 1/5 production; and 1C, daylight-only operation at 2/5 production. All three designs used the ATK Ultraflex™ arrays that were

designed to operate at 120 Vdc, with a conversion efficiency of 33 percent. The arrays were mounted on a gimbal that would track the Sun and perform dust mitigation by sloping to 45°. Array and battery sizing changed with architecture options with contingencies for a 120-d global dust storm and an average of 10 h/sol of daylight. Lithium ion batteries were used for energy storage at 165 Wh/kg.

The fission option used a slightly oversized 10-kWe Kilopower unit with a permanent radiator attached to the top of the lander. The reactor operated 24 h a day at 6.5 kW (65 percent capacity) with no interruptions or power loss from dust storms or landing locations. Power conversion was performed by eight 1,250-We Stirling engines in the dual opposed configuration. Most lander subsystems were identical between the two power systems with some discrepancy in the

thermal control systems. Comparisons between the solar and fission power system ISRU demonstration mission are shown in Table III with conceptual drawings in Figure 9 and Figure 10.

The ISRU 1/5 scale demonstrator favors solar in terms of mass but requires more time to produce the needed liquid oxygen. Option 1C offers the best balance between propellant production time and mass given the study's assumptions, but does not adequately address the follow-on energy storage requirements of a crewed mission and cycles on and off every day. For this reason, option 1B is a better technology demonstrator as it fulfills the ISRU and crew phase needs with minimal start and stop cycles. Trading option 1B with fission provides a more apples to apples comparison with minor differences in mass and propellant production time.

TABLE III.—SOLAR VERSUS FISSION FOR IN SITU RESOURCE UTILIZATION (ISRU) DEMONSTRATION MISSION ON MARS SURFACE

Option	Solar 1A: 1/5 rate daytime only	Solar 1B: 1/5 rate around the clock	Solar 1C: 2/5 rate daytime only	Fission 2: 1/5 rate around the clock fission power
Total payload mass (including growth), kg	1,128	2,425	1,531	2,751
Electrical subsystem mass, kg	455	1,733	639	1,804
ISRU subsystem mass, kg	192	192	335	192
Power, kW	~8 daylight	~8 continuous (with 16 kW of arrays)	~16 daylight	~7 continuous
Solar arrays	4 each \times 5.6 m diam.	4 each \times 7.5 m diam.	4 each \times 7.5 m diam.	None
Night production	No	Yes	No	Yes
Liquid oxygen production, kg/sol	4.5	10.8	9.0	10.8
Time to produce 4,400 kg liquid oxygen, including 120-d dust storm outage, sol	1,098	527	609	407
ISRU On/Off cycles	1,098	<5	609	<5
Radiation tolerance	100 krd electronics and ISRU			300 krd electronics, 10 Mrd ISRU

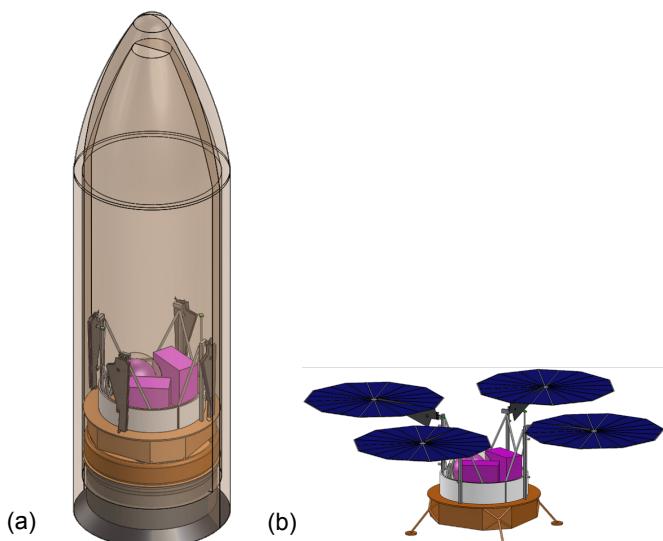


Figure 9.—Mars ISRU solar-powered lander concept.
(a) In launch vehicle. (b) Deployed on Martian surface.

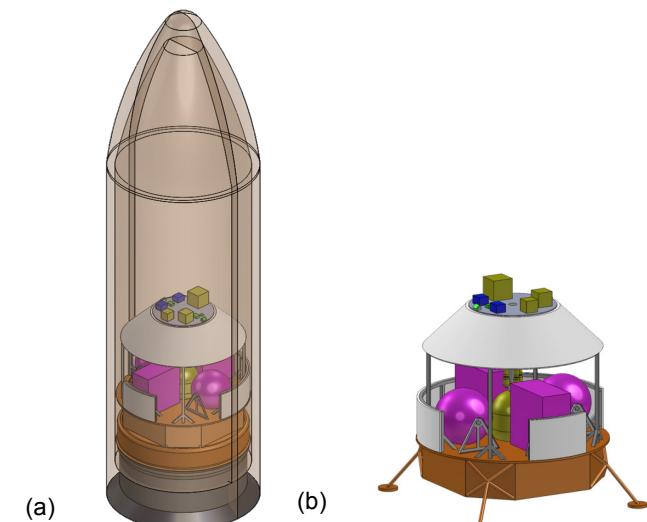


Figure 10.—Mars ISRU fission-powered lander concept.
(a) In launch vehicle. (b) Deployed on Martian surface.

Phase II—Crewed Mission

- Launch vehicle: Space Launch System
- Year: 2038
- Crew: four to six
- Landed mass: to be determined (TBD)
- Locations:
 - Jezero crater, 18°51'18"N 77°31'08"E
 - Columbus crater 29.8°S 166.1°W
- Propellant production: 23,000 kg of liquid oxygen

According to the NASA DRA 5.0 (Ref. 10), there will initially be three expeditions of four to six astronauts going to Mars for a stay of approximately 500 d for the conjunction class missions. Each expedition will land at a different location on Mars to adequately explore the diverse geological and environmental terrain. Each expedition will incorporate a pre-deploy mission architecture that allows a lower energy trajectory and larger payload masses with several key parts. First to arrive at the surface are the cargo landers, which house the autonomous power system, ISRU propellant production, and Mars Ascent Vehicle (MAV). The power system will initially be used to convert the Martian CO₂ atmosphere into oxygen where it will then be cryogenically cooled and stored in the MAV. After the required ascent propellant has been produced and stored in the MAV and the Mars orbiting habitat has been fully checked out, the crew will leave Earth, rendezvous with the Mars Transfer Vehicle (MTV) in low-Earth orbit (LEO), and begin the 175- to 225-day fast-transit trajectory to Mars. After arriving in Mars orbit, the crew will rendezvous with the habitat and begin the entry, descent, and landing to the pre-deployed cargo landers to start their surface mission.

Rucker et al. (Ref. 12) analyzed the ISRU COMPASS results to accommodate the crew phase logistics using the same technologies and general lander architectures to further evaluate the trade between solar and fission. The results in Table IV give a brief summary of the power system comparison with insight into the differences between the crewed and uncrewed ISRU portions of the mission. The 50-kWe fission system, four 10-kWe Kilopower units plus one spare unit, is delivered on the first lander and provides all three expeditions the required power with a design life of 12 years.

The reactors' performance would not change based on global location or dust storms, and could be permanently attached to the lander or offloaded for strategic arrangement. The major difference between the ISRU uncrewed mission and the crewed mission is the necessity for energy storage overnight and the additional requirements for crew to keep power alive during the global dust storms. This energy storage and power management addition can be seen in the mass of the first lander of each expedition and in the subsequent landers, closely matching option 1B from the ISRU study.

These initial results show that the fission system for crewed expeditions is roughly half the mass of a comparable solar system, even at favorable solar latitudes. The rarely debated advantage of using fission surface power systems on Mars is

TABLE IV.—SOLAR VERSUS FISSION MASS COMPARISON FOR THE THREE EXPEDITION ASTRONAUT CREW PHASE OF A MARS SURFACE MISSION

Crew expedition	Power generation/storage mass (kg)		
	Fission power	Solar power	
		Jezero crater	Columbus crater
Expedition 1	9,154	11,713	12,679
Lander 1	9,154	5,611	5,909
Lander 2	0	2,034	2,704 ^a
Lander 3	0	2,034	2,033
Lander 4	0	2,034	2,033
Expedition 2	0	6,102	6,770
Lander 1	0	2,034	2,704 ^a
Lander 2	0	2,034	2,033
Lander 3	0	2,034	2,033
Expedition 3	0	0	0
Lander 1	0	0	0
Lander 2	0	0	0
Lander 3	0	0	0
Three mission total (kg)	9,154	17,815	19,449

^aColumbus crater totals include additional in situ resource utilization (ISRU) strings on Mars Ascent Vehicle (MAV) landers.

their tolerance to dust storms and their ability to produce abundant power at any point on Mars. Another advantage that does not receive enough awareness is the potential for long power-producing lifetimes beyond mission requirements. The Kilopower reactor's thermal output in relation to the core's total fissionable energy is small, which reduces the fuel burnup significantly. With controlled reactivity insertion throughout the lifetime of the reactor, it is possible to achieve full power production for several decades. Although this advantage is attractive, it cannot be easily tested in ground demonstrations and will require an extended space mission to fully prove. The disadvantage of fission is the produced radiation, requiring shielding to protect equipment and crew. The mission architectures will likely have astronaut keep out zones and radiation safety protocols that would not be required with solar systems. For nonhuman rated systems such as the ISRU demo or other mechanical/electrical systems, radiation-hardened components will greatly reduce the amount of shielding required and thus lead to mass benefits.

Solar has these advantages—simplicity, redundancy, and flight heritage; all of which all been proven with many successful missions. The challenges for solar missions to Mars have remained numerous regarding dust accumulation on solar panels, limited solar insolation from dust storms, and available sunlight at northern and southern latitudes. These very reasons supported decisions to move away from solar-powered rovers such as Spirit and Opportunity and replace them with nuclear-powered Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) as seen on the Mars Science Laboratory.

Presumably, the ISRU demonstration slated to launch in the mid-2020s will determine the outcome of solar versus nuclear for near-term Mars missions. Regardless of the outcome, it is likely that both technologies will play a significant role in the Mars missions to come with more solar deployments in the

equatorial regions and nuclear expeditions in the polar regions. A combination of solar and fission will only add redundancy to the Mars missions and enable all possible expeditions.

Concluding Remarks

Science and human missions using fission power sources have been independently studied with positive results. Although scientists have been stifled about proposing kilowatt-class missions due to their nonexistence over the past 50 years, it is encouraging that the paradigm could be changing with the technology advancement of the Kilopower reactor. Specific interests in fission-based nuclear electric propulsion (NEP) have been acknowledged knowing that the power requirements are realistically outpacing the radioisotope fuel availability and production. Two decadal survey missions using NEP systems were studied by the Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) team with the goal of delivering an orbiter around the Centaur class object Chiron and a Kuiper Belt Object (KBO). Both studies were able to close the mission objectives with a 7- to 10-kWe Kilopower reactor. These missions are well suited for space reactors as the power levels are easily achieved with the abundance of uranium fuel. It is estimated that many of the decadal survey missions could be achieved and possibly enhanced with nuclear reactors and will be further studied as the Kilopower technology is further developed.

The human exploration of Mars will undoubtedly be the greatest achievement of the century and is quickly becoming a near-term reality. Many of the necessary technologies are already being developed and tested with nuclear power being no exception. The independent studies cited herein have pointed out some of the advantages of nuclear surface power and how the Kilopower reactor can reduce several risks associated with the Martian environment that has been inhospitable to the solar-powered missions. The study concluded that both the in situ resource utilization (ISRU) and crew phases of the early Mars missions were easily achieved with several 10-kWe Kilopower reactors. The Kilopower-based system won the mass and power trades for the crewed missions by a factor or two, even at solar-favorable sites, which provides additional support for nuclear systems when moving further from the equator.

The Kilopower reactor is well on its way to surpassing the technology barriers that have existed over the last half century. With a successful completion of the full-scale nuclear ground test nicknamed “KRUSTY” (Kilopower Reactor Using Stirling TechnologY), the technical and programmatic risks for space nuclear power will be significantly reduced in proving that nuclear technologies can be affordably developed and tested. The neutronic verification at full power and temperature for extended periods will provide the needed data for flight system development in the post KRUSTY years. Increased necessity

and advocacy for space nuclear power is expected as we expand our presence in the solar system and explore new worlds. It is more a matter of the perseverance required to fully develop a flight-qualified reactor and begin using it.

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