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# Kilopower–Nuclear Electric Propulsion for Outer Solar System Exploration (NEP Benefits Study)

## A Joint Study by Glenn Research Center, Jet Propulsion Laboratory, and Los Alamos National Laboratory

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## Preface

*Nuclear Electric Propulsion for Outer Solar System Missions* describes a new type of space fission reactor that, in combination with a spacecraft as described herein, would represent a game-changing capability for solar system exploration from Saturn to the Kuiper Belt, enabling missions that are otherwise not possible using solar or radioisotope power systems. Specifically, this report documents a study conceived to identify alternative mission uses for NASA Space Technology Mission Directorate's (STMD) Kilopower technology.

The Kilopower project is a near-term technology effort to develop preliminary concepts and technologies for use by the NASA Human Exploration and Operations Mission Directorate (HEOMD) as an affordable fission nuclear power system to enable long-duration stays on planetary surfaces. Kilopower technology has been in development since 2015; in March 2018, the Kilopower project completed a successful nuclear demonstration test at the Nevada National Security Site. The current mission focus for Kilopower is on surface power systems for the moon and Mars to support human exploration goals and their related robotic precursors. The Kilopower project is currently in a mission formulation phase that could be informed by other mission uses beyond the surface power application.

Glenn Research Center, Los Alamos National Laboratory, and Jet Propulsion Laboratory chartered a joint team to identify outer solar system alternative mission uses that could benefit from Kilopower. The resulting report concludes that the key adaptations required for the Kilopower technology to serve outer solar system needs—specifically, the number and size of the Stirling engines and the heat pipe configuration—are completely consistent with HEOMD needs to the extent that they can be defined at this early concept stage. Thus, both HEOMD and Science Mission Directorate can capitalize on the STMD investment in Kilopower developments for HEOMD; and, provided the Kilopower project accounts for them early in the HEOMD development phase, they will not drive additional technology development costs.

This report does not represent an endorsement by any of the contributing laboratories or a commitment to undertake any of the work described herein. The report identifies suggestions for further study but presents no recommendations regarding programmatic or project implementation. The authors and their supporting laboratories fully understand that such matters are the sole prerogative of the sponsoring agencies, i.e., National Aeronautics and Space Administration (NASA) and Department of Energy (DOE).

## Acknowledgments

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The content of this report is pre-decisional information and is provided for planning and discussion purposes only.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or JPL.

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# Executive Summary

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## *Purpose of the Study*

The objective of the study was to identify the generic and specific benefits of using NEP for the purpose of outer solar system exploration. Using COMPASS and Team X analysis protocols, the study team assessed two classes of missions: (1) **Enabled**: missions that are not possible using any other available power and propulsion system and (2) **Enhanced**: mission types using four example destinations studied previously by COMPASS or Team-X to show quantitatively the improvement possible with NEP. Participants from NASA Glenn Research Center (GRC), DOE Los Alamos National Laboratory (LANL), and Jet Propulsion Laboratory, California Institute of Technology (JPL) collaborated to define the mission scenarios and associated trajectories for both classes of missions.

## *Background*

### A Game-Changing Development in Space Program Power Sources

NASA's space program has long relied on only two sources of power for its multi-year planetary missions: radioisotope power systems (RPS) and the Sun. However, recent technology development efforts by NASA's Kilopower project have given rise to the viability of yet another power source for outer solar system missions: a small nuclear fission reactor that uses uranium-235 ($^{235}U$) to provide electrical power ranging from a few hundred watts to more than 10 kilowatts.

NASA's Kilopower project, which is jointly led by NASA Glenn Research Center (GRC) and Department of Energy (DOE) Los Alamos National Laboratory (LANL), has recently demonstrated the feasibility of a new and simple 1-kWe reactor design specifically for space application. A Kilopower reactor is a small, compact fission reactor in which heat pipes carry fission power from a solid block of uranium-metallic fuel[1] to the Stirling power converters. Kilopower reactors are designed to simplify reactor physics such that the reactor load-follows the thermal power demand of the power conversion system. The core uses inherent reactivity feedback to regulate itself to a temperature set point via thermal expansion/contraction of the fuel. The temperature set point is controlled by the position of a single control rod. Other than that, no motion of the control rod or reactivity control is required over the full operating range of the reactor, including the accidental full loss of heat removal from the power conversion system.

This small, simple Kilopower reactor uses existing technology and lends itself to quick and affordable development. The reactor is designed to passively load-follow the thermal demand from the power conversion system, thus eliminating the need for an active reactor control system during flight. This unique design feature was fully characterized both statically and dynamically over the full operational range of the reactor during the KRUSTY (Kilopower Reactor Using Stirling Technology) test program [Poston et al., 2019; Gibson et al., 2018].

[1] For this Kilopower–NEP report, fuel refers to the cast form of a highly enriched uranium-molybdenum (UMo) alloy currently in store at Y-12 National Security Complex.

KRUSTY completely and successfully validated all of the Kilopower nuclear design goals and objectives, including the claim that *future instantiations of the Kilopower design can be validated with zero power critical testing*[2] *only and will not require full power nuclear testing.* This is truly a game changing development, one that will drastically reduce the nuclear validation requirements and hence the cost of using and deploying small space reactors of the Kilopower ilk. The study team is well aware of the implications of this claim, and we therefore suggest that an independent group of experts be engaged to critically assess the Kilopower design and the KRUSTY results and claims. (A JASON-type[3] review comes to mind.)

### Context for Initiating the NEP Benefits Study

NASA's Human Exploration and Operations Mission Directorate (HEOMD) has been has been contemplating the use of nuclear power for sustained human presence on Mars as part of the human exploration program for over a decade. Lately, emphasis has evolved from a 40-kWe single unit to a modular architecture based on four modules of 10 kWe each as a more robust and flexible approach.

At the last decadal survey, the Outer Planet Subcommittee asked for a study to show how nuclear electric propulsion (NEP) could benefit outer planet exploration. GRC, LANL, Idaho National Laboratory (INL), and Jet Propulsion Laboratory (JPL) conducted the study. The results were impressive, but the Decadal committee consensus was that reactor power was not yet ready for use in space.

Meanwhile, the NASA Science Mission Directorate (SMD), having concluded that the best path forward would be to focus on 238Pu-fueled radioisotope systems, decided not to pursue NEP. The SMD Nuclear Power Assessment Study (NPAS) concluded that fission power was not an essential need for planetary science missions, but that SMD should consider using it if other mission directorates funded the development.

The NASA Space Technology Mission Directorate (STMD) did agree to fund the design, build, and test of a small prototype reactor led by GRC in collaboration with Department of Energy (DOE) National Nuclear Security Administration (NNSA). The project team included LANL, Y-12 National Security Complex, and Marshall Space Flight Center. The reactor was named Kilopower, and the test program was named KRUSTY.

With the March 2018 conclusion of KRUSTY by the Kilopower development project, STMD is now supporting NASA's interest in a technology demonstration project on the lunar surface leading to sustained presence on the Moon as a precursor to sustained presence on Mars. In order to identify other potential mission uses, the STMD Power Principal Technologist requested GRC and JPL to evaluate the possible mission benefits of a Kilopower-based NEP capability.

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[2] "Zero power critical is a condition of nuclear fission reactors that is useful for characterizing the reactor core. A reactor is in the zero power critical state if it is sustaining a stable fission chain reaction with no significant growth or decay in the reaction rate, and at a low enough level that thermal considerations are not important to the reaction." [DeForest, 2005] A zero power critical test determines at what point the reactor will go critical at room temperature when the reactor is not generating power. The test provides data that will enable designers to prevent the generation of hazardous fission products.

[3] JASON is an independent scientific advisory group of theoretical physicists, biologists, chemists, oceanographers, mathematicians, and computer scientists who provide defense science and technology consulting services to the U.S. government. The advisory panel was established in 1960, evolving from a 1958 military-issues physics summer study program named Project 137. JASON advisory panel activities are administratively run through the MITRE Corporation.

**Now What?**

NASA's latest charge—"Get boots on the Moon by 2024"—could establish the budget priorities for the next 5 years. However, sustained presence in terms of housekeeping and in situ resource utilization must follow closely, or boots on the Moon will be just a repeat of Apollo. NEP may not be a high priority in the near future; but if Kilopower is developed by NASA, it can be used directly as the power generator for a small NEP capability. Robotic missions would be a direct beneficiary of an NEP capability based on the HEOMD instantiation of Kilopower.

## *Why 10 kWe for NEP?*

NASA's HEOMD has been contemplating the development of a 10 kWe modular Mars surface power system; therefore, the team decided to look at that power level in the interest of minimizing new development activity for any mission (human or science) that elected to use a fission power system. Power levels as low as 5 to 6 kWe have been shown to be useful for NEP, with improved performance at higher powers. Greater power would yield greater benefits in terms of larger science payload mass and shorter flight times; but greater power would also approach diminishing returns given currently projected launch vehicle capabilities. Irrespective of the HEOMD-chosen power level, all the key nuclear design aspects can be identical for both human exploration and robotic mission applications.

## *NEP Benefits for Flagship-Class Missions*

A National Academies consensus study report on NASA's large strategic science missions describes the critical importance of flagship missions to NASA's Science Mission Directorate goals: "[Flagship-class missions] produce tremendous science returns and are a foundation of the global reputation of NASA and the U.S. space program. Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science…." [National Academies, 2017].However, ΔV requirements for outer solar system missions present a major challenge to chemical propulsion systems. For example, New Horizons flew by Pluto at 14 km/s, well beyond the ability of any existing chemical propulsion system to achieve orbit insertion. Electric propulsion provides fuel efficiency to achieve high ΔV; as an example, imparting 10 km/s to a vehicle with 400 kg dry mass (New Horizons–class) using a conventional bi-prop system (Isp~320s) would require 9300 kg of propellant, and this neglects the mass of the propulsion system. Imparting the same 10 km/s to the same mass vehicle using electric propulsion ion thrusters operating at an Isp of 4000 s would require just over 100 kg of propellant. Solar power is currently not practical at large solar ranges.Nuclear power is enabling for outer solar system missions. Advanced radioisotope power (~1 kWe) could be used to enable small spacecraft missions with limited payloads (New Horizons–class). Fission power (~10 kWe) enables flagship-class missions, including multi-body orbiters, large payload suites, and landers. Spacecraft using a 10 kWe reactor to power a nuclear electric propulsion (NEP) system would be capable of executing outer solar system exploration missions having a Cassini-class science payload (or larger) within short mission lifetimes (8 to 15 years), something simply not possible with any other power source. (Note that Cassini required 30 years to accomplish its mission using 33 kg of plutonium and radioisotope thermoelectric generators (RTGs) that no longer exist.)

Furthermore, a 10 kWe Kilopower reactor plus electric propulsion enables unique mission concepts that are not otherwise possible with current technology, such as

- A Neptune mission with enough performance to orbit Neptune's moon Triton and deliver a lander

- A spacecraft with enough propulsion capability to orbit two Centaur asteroids (including Chiron)
- A mission capable of orbiting Enceladus and then Titan (and delivering landers to both moons)

Note that all of these example missions are mentioned solely to illustrate the revolutionary capability of this class of NEP. The simplicity and projected technology readiness of the Kilopower system anticipated in the next few years suggest mission execution costs at or below typical flagship-class cost. This is a huge assertion, but within the realm of reason as suggested in the Notional Acquisition Strategy described in the report.

## *Study Overview*

For both enabled and enhanced missions, the study team assumed a 15-year mission lifetime requirement (discussed below). For the enhanced classes, they compared the missions with respect to power system, RTG or NEP, and figures of merit (FOMs).

### Enabled Mission Concepts

The enabled mission concepts were chosen from mission scenarios that were high priority in the 2013–2022 Planetary Science decadal survey[4] and are also expected to be high priority in the next decadal survey: ocean worlds, ice giants, and centaurs. The studies were based on a notional NEP flight system, defined by the team, that included fixed elements (e.g., structure, avionics, telecom system, electric propulsion components reactor, shielding, radiator) and some variable elements (e.g., the maximum propellant load required for the mission, the number of engines, and the tank(s) size). The available science payload mass and flight times were dependent variables and were calculated based on the mission design and residual propellant.

For each of the enabled missions, the team assessed the possibility of carrying a lander or a probe.

*Ocean Worlds: Titan/Enceladus*

Since the decadal survey was published, the Cassini mission has demonstrated that both Titan and Enceladus are ocean worlds. For Enceladus, the results of the Cassini mission also support the presence of hydrothermal activity at the ocean/rocky core interface, a process that exists at the terrestrial seafloor and where life has developed. The Cassini mission has made it clear that Titan and Enceladus are priority targets for understanding the habitability of solar system objects. It was therefore not surprising that NASA opened the fourth New Frontiers call to these two bodies. Ocean worlds in general are priority targets. As it is the case for the Neptune/Triton system, NEP would permit orbiting both Titan and Enceladus.

In this concept, a Falcon Heavy–class rocket launches the mission on a 9.75-year trajectory to Saturn with cruise science. This trajectory would arrive at Saturn with low enough energy that a Titan gravity-assist can capture the spacecraft into Saturn orbit. A Titan lander (with an aeroshell) could be released during this flyby. After capture, the spacecraft would use its NEP system to perform a 2.25-year $V_\infty$ leveraging[5] trajectory to reach Enceladus orbit. This trajectory would afford multiple opportunities for low-altitude, low-speed flybys of Saturn's icy moons. This tour would be

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[4] National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013–2022*, Washington, DC: The National Academies Press (2011).

[5] $V_\infty$ leveraging is a technique that uses maneuvers away from a flyby to change the flyby v-infinity (also known as hyperbolic excess velocity). This technique is an efficient way to change the spacecraft energy with respect to the flyby body, especially with low-thrust propulsion.

followed by a 6-month orbital mission at Enceladus where an Enceladus lander could be deployed. After the Enceladus orbital mission, a 2-year $V_\infty$ leveraging trajectory could then be used to reach Titan and enter orbit. There is then time for a 6-month orbital mission at Titan before the end of the 15-year prime mission. The total science payload mass would be 2550 kg, enough for several months for lander operations, and 100 kg for science.

*Ice Giants: Neptune/Triton*

There are several reasons to go to an ice giant. First, neither Uranus nor Neptune has had a dedicated orbiter. The decadal survey indicated Uranus was preferred over Neptune; however, the rationale was based primarily on the observation that Uranus would be easier to access than Neptune. While orbiters are possible with RTGs, the flight times are long and the science payload capability marginal and reliant on RTG technology development yet to be realized. Another reason to visit an ice giant is that the discovery of thousands of exoplanets, which has demonstrated that there is a peak in the number of planets the size of the ice giants. Understanding their interior structure, composition, and dynamics is therefore a strong science priority. Choosing Neptune/Triton, not possible with RTGs, provides a bonus Kuiper belt object, since the moon Triton is almost certainly a captured Kuiper belt object! Because Triton may also harbor a deep ocean, it makes the Neptune/Triton system a potentially high-priority science option, and NEP enables orbiting both in a single mission.

This mission concept would launch on a Falcon Heavy–class rocket and would use Earth and Jupiter flybys in concert with NEP thrusting to reach Neptune in 13 years. A chemical propulsion system (mono-prop in this example) would then be used for a 240 m/s maneuver to insert into Neptune orbit for a 1.4-year Neptune tour with 100 kg of orbiter science. After Neptune capture, the NEP system would provide 2.1 km/s of $\Delta V$ to reach the Triton orbit plane, perform a series of $V_\infty$ leveraging maneuvers (combined with Triton flybys) to reduce energy, and finally spiral down into low Triton orbit, over a period of 520 days. A 300 kg lander could then be deployed in orbit and use its own chemical propulsion system for the 1300 m/s required to land on Triton. Seven months would be available for the Triton orbiter with 100 kg of science and lander operations before the end of the 15 year prime mission. The total science payload mass would be 400 kg.

*Centaurs*

A third concept studied was a mission to orbit two centaurs. Centaurs are primitive objects that contain clues on the origin and early evolution of the solar system. Therefore, we also studied a mission concept that would first orbit a centaur and then orbit Chiron, which is believed to belong to the same family,

With NEP, the mission has enough $\Delta V$ capability to orbit two Centaurs, including Chiron; other Centaur pairings are also possible. A Falcon Heavy would launch a 5290 kg spacecraft, which would rendezvous with 2007 SA24 in 6 years. The 1-year orbital mission at 2007 SA24 would be followed by a 4.5-year cruise to Chiron for a 3.5-year orbital mission. The dual centaur mission would deliver a total science payload mass of 300 kg.

### Enhanced Mission Concepts

The team selected enhanced mission concepts from previously studied RTG missions—including Saturn, Uranus, Neptune, and Pluto orbiters. Previously studied missions were chosen in order to provide a reasonable basis for comparison with NEP. The comparisons were based on a few FOMs. In order to permit meaningful comparisons, the team used the same notional spacecraft that was used for the enabled missions. The available science payload mass and flight times were dependent variables and were calculated based on the mission design and residual propellant.

*Saturn and Uranus*

When compared to REP, NEP has the potential to reduce trip time, increase data rates, and massively increase the payload capability of a single Saturn or Uranus mission. Performance benefits could lead to a dramatic increase in the scientific return of a mission by returning more data in less time and carrying more capable science payloads. The maximum payload mass is above that which is required for the spacecraft and could be allocated to science instruments, atmospheric probes, landers, or additional propellant.

*Neptune and Pluto*

With NEP, the trajectory for a Neptune orbiter could deliver 875 kg to Neptune orbit for instruments and atmospheric probes. A 1-kW REP mission could deliver only 30 kg and would require 15 years. For the Pluto orbiter, an NEP spacecraft can deliver 67% more payload with 2.4 years shorter flight time (14.7 years) compared to REP option. Kilopower also enables greater than four times the data rate at Pluto than the REP option.

### *Mission Lifetime Considerations*

Mission lifetime is primarily determined by the allowable radiation dose to sensitive components. For the NEP study missions, we assumed a 15-year mission lifetime requirement, which primarily affects the design of the nuclear power system in two ways: the lifetime of the core itself and the mass of the shield and boom length required to limit integrated dose to electronics and other radiation-sensitive components.

The estimated <0.5% of core burnup (over the 15-year required lifetime) is extremely low and gives high confidence that the core lifetime will be met. This claim is based on the opinion of experts at Idaho National Laboratory that <1% presents no significant burnup-related lifetime issues for the fuel. This claim may also require independent assessment; the study team therefore suggests that an independent group of experts be engaged to evaluate it.

The design of the shield, in combination with the separation distance of the reactor from radiation-sensitive parts, controls the integrated dose the parts will receive over the specified mission lifetime. We picked 15 years as a reasonable lifetime requirement, but this can be changed easily by varying the boom length or even the shield mass.

Mission lifetime is also determined by engineering margins and the margins established for consumables. The lifetime of the power conversion system is mostly determined by the Stirling convertors. Two design features are used to gain high confidence in 15+ years of operation: large engineering margins, with an emphasis on reliability instead of high-efficiency performance; and considerable redundancy, such that full power can be delivered with two failed convertors and partial power can be provided with numerous failures.

The evidence that meeting mission lifetime is not a major obstacle given suitable derating and inspection practices is demonstrated by many missions flown in the past few decades: The Mars program, where orbiters and landers typically have lifetimes in excess of 15 years; the Voyager program, where two spacecraft have each operated successfully for over 42 years since launch; and Cassini, which operated without fail for over 20 years.

### *Commonality Between Human and Science Mission Applications*

NASA has been contemplating the development of a 10 kWe modular Moon surface power system; therefore, the team decided to look at that power level in the interest of minimizing new development activity for any mission (human or science) that elected to use a fission power system. Whatever the reactor's power level, the key nuclear design aspects can all be identical for both human exploration and science mission applications. As we believe we demonstrate in this report, outer solar system exploration science missions can be well served by Kilopower NEP reactors.

### *Conclusions*

- A 10 kWe NEP capability would enable a new class of outer solar system missions that would not otherwise be possible, and would significantly enhance a range of other deep-space mission concepts by increasing science payload mass, reducing flight time, increasing mission lifetime, and providing ample power for science instruments and/or increased data rates.
- This capability presents a breakthrough in science value beyond Cassini class, and would enable NASA to once again plan for large strategic missions to the outer solar system as recommended by the Space Studies Board in its report *Powering Science: NASA's Large Strategic Science Missions* [National Academies, 2017].

# 1. Introduction

## *Background: A Game-Changing Development in Space Program Power Sources*

NASA's space program has long relied on only two sources of power for its multi-year planetary missions: radioisotope power systems (RPS) and the Sun. RPS utilizes the heat generated by the natural radioactive decay of plutonium-238 ($^{238}Pu$) and has been successfully implemented on missions such as Galileo, Cassini and the twin Voyagers. Solar power systems have been successfully demonstrated out to Jupiter distances from the Sun and analysis has shown their viability for orbiters at Saturn. For outer solar system missions, defined here as extending from Saturn to the interstellar medium, the only existing power option that remains is RPS.

However, recent technology development efforts by NASA's Kilopower project have given rise to the viability of yet another power source for outer solar system missions: a small nuclear fission reactor that uses uranium-235 ($^{235}U$) to provide electrical power ranging from a few hundred watts to more than 10 kilowatts. The availability of a nuclear power system of this magnitude suddenly opens up the trade space to outer solar system missions that were previously unattainable. Nuclear electric propulsion (NEP) enables much shorter trip times and much larger payload capability to targets, more frequent and longer launch periods, and makes orbit insertion possible at all planets, moons and Kuiper Belt objects. While NEP allows for more flexible and efficient operations in operational tours, the reactor itself provides significant power at the destination for more power-intensive science operations and higher downlink data rates when not thrusting.

## *Kilopower Project Overview*

The Kilopower project was officially started in October 2014 to develop a family of fission reactor designs that could be scaled from 1 to 10 kWe and be applicable for both science and human exploration [Gibson et al., 2017]. Kilopower design followed the Demonstration Using Flattop Fission (DUFF) proof-of-concept nuclear test in 2012, which gave NASA confidence that performing nuclear ground testing could be done affordably when partnering with the National Nuclear Security Administration (NNSA) and using their existing facilities [Poston and McClure, 2013]. NASA Glenn Research Center (GRC) and DOE Los Alamos National Laboratories (LANL) have now designed, fabricated, and successfully tested a 1 kWe Kilopower reactor.

A Kilopower reactor is a small, compact fission reactor in which heat pipes carry fission power from a solid block of uranium-metallic fuel.[6] Kilopower reactors are designed to simplify reactor physics such that the reactor load-follows the thermal power demand of the power conversion system (PCS). The core uses inherent reactivity feedback to regulate itself to a temperature set point via thermal expansion/contraction of the fuel. The temperature set point is controlled by the position of a single control rod. Other than that, no motion of the control rod or reactivity control is required over the full operating range of the reactor, including full loss of heat removal from the power conversion system.

KRUSTY (Kilopower Reactor Using Stirling Technology) is the DOE name for a 5-month test program conducted at the Nevada National Security Site (formerly known as the Nevada Test Site), specifically designed to validate the Kilopower design concept. KRUSTY completely and successfully validated all of the Kilopower nuclear design goals and objectives, including the claim that *future*

[6] For this Kilopower–NEP report, fuel refers to the cast form of a highly enriched uranium-molybdenum (UMo) alloy currently in store at Y-12.

*instantiations of the Kilopower design can be validated with zero power critical testing*[7] *only and will not require full power nuclear testing.* This is truly a game changing development, one that will drastically reduce the nuclear validation requirements and hence the cost of using and deploying small space reactors of the Kilopower ilk. The study team is well aware of the implications of this claim, and we therefore suggest that an independent group of experts be engaged to critically assess the Kilopower design and the KRUSTY results and claims. (A JASON-type[8] review comes to mind.)

## Study Overview

The objective of this study was to identify generic and specific benefits of using NEP for outer solar system exploration. Using COMPASS and Team X analysis protocols, the team assessed a number of previously studied mission concepts using SEP and REP power systems and compared the ability to execute those missions using a 10 kWe NEP system based on a few of figures of merit (FOM).

In order to permit meaningful comparisons, the team defined a notional spacecraft for the NEP missions that included certain elements assumed to be fixed (e.g., structure, avionics, telecom system, electric propulsion components, reactor, shielding, radiator). The maximum propellant load required for each mission determined the number of engines and the propellant tank size. The available science payload mass was calculated as a dependent variable depending on mission design and residual propellant.

In order to make any comparison as close as possible, a number of unifying assumptions were made. All mission scenarios were analyzed using the notational spacecraft bus configuration. A maximum of 15 years from launch to end of mission was assumed. The maximum cumulative radiation dosage limit allowed at the dose plane and the mission lifetime determined the shield mass and boom length. Telecom rates were calculated assuming a standard 3m steerable high-gain antenna (HGA) with two 200 W Ka-band traveling wave tube amplifiers (TWTAs) and assumed receipt by a 34-m beam waveguide (BWG) Deep Space Network DSN antenna. NASA Evolutionary Xenon Thruster–Commercial (NEXT-C) electric propulsion thrusters were assumed.

The spacecraft bus configuration and the nuclear fission system—including possible assembly, test, and launch operations (ATLO) scenarios and system development schedules—are notional conveying just one possible implementation approach. They represent a point design, helpful to the team for assessing design closure and consistency with established regulatory requirements and practices for safety, reliability, ATLO and concept of operations. The point design is not a recommendation on implementation, other than it represents the thinking of the study team and could serve as useful guidance for a future implementation design agency. Likewise, a possible acquisition strategy for these notional descriptions based on the Asteroid Redirect Robotic Mission (ARRM) strategy approved by NASA illustrates a possible cost-effective approach.

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[7] "Zero power critical is a condition of nuclear fission reactors that is useful for characterizing the reactor core. A reactor is in the zero power critical state if it is sustaining a stable fission chain reaction with no significant growth or decay in the reaction rate, and at a low enough level that thermal considerations are not important to the reaction." [DeForest, 2005] A zero power critical test determines at what point the reactor will go critical at room temperature when the reactor is not generating power. The test provides data that will enable designers to prevent the generation of hazardous fission products.

[8] JASON is an independent scientific advisory group of theoretical physicists, biologists, chemists, oceanographers, mathematicians, and computer scientists who provide defense science and technology consulting services to the U.S. government. The advisory panel was established in 1960, evolving from a 1958 military-issues physics summer study program named Project 137. JASON advisory panel activities are administratively run through the MITRE Corporation.

We describe two classes of missions: missions enabled by NEP (and not possible using any other available power and propulsion system) and missions enhanced by NEP (mission types using four example destinations studied previously by COMPASS or Team-X to show quantitatively the improvement possible with NEP). We identify three mission scenarios enabled by the Kilopower concept, as well as four mission families, e.g., Saturn Orbiters, that are enhanced by the concept. The study team has identified suggestions for follow-on work to develop additional detail on the technical and programmatic issues raised.

Participants from Glenn Research Center (GRC), Jet Propulsion Laboratory, California Institute of Technology (JPL), and Los Alamos National Laboratory (LANL) collaborated to define the mission scenarios and associated trajectories, analyze the potential trajectories, and compare the missions with respect to power system and FOMs.

## 2. Notional Flight System Summary

### *Mission Lifetime Considerations*

Mission lifetime is primarily determined by the allowable radiation dose to sensitive components. For the NEP study missions, we assumed a 15-year mission lifetime requirement, which primarily affects the design of the nuclear power system in two ways: the lifetime of the core itself and the mass of the shield and boom length required to limit integrated dose to electronics and other radiation-sensitive components.

The estimated <0.5% of core burnup (over the 15-year required lifetime) is extremely low and gives high confidence that the core lifetime will be met. This claim is based on the opinion of experts at Idaho National Laboratory that <1% presents no significant burnup-related lifetime issues for the fuel. This claim may also require independent assessment; the study team therefore suggests that an independent group of experts be engaged to evaluate it.

The design of the shield, in combination with the separation distance of the reactor from radiation-sensitive parts, controls the integrated dose the parts will receive over the specified mission lifetime. We picked 15 years as a reasonable lifetime requirement, but this can be changed easily by varying the boom length or even the shield mass.

Mission lifetime is also determined by engineering margins and the margins established for consumables. The lifetime of the power conversion system is mostly determined by the Stirling convertors. Two design features are used to gain high confidence in 15+ years of operation: large engineering margins, with an emphasis on reliability instead of high-efficiency performance; and considerable redundancy, such that full power can be delivered with two failed convertors and partial power can be provided with numerous failures.

The evidence that meeting mission lifetime is not a major obstacle given suitable derating and inspection practices is demonstrated by many missions flown in the past few decades: The Mars program, where orbiters and landers typically have lifetimes in excess of 15 years; the Voyager program, where two spacecraft have each operated successfully for over 42 years since launch; and Cassini, which operated without fail for over 20 years.

### *Representative Flight System Configuration*

The spacecraft design used for our mission analyses is based on concepts developed by GRC's Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) team for earlier NEP mission studies. The philosophy for the design of the spacecraft is to maximize the use of standard subsystems and components in the bus, treating the fission power generator (FPG) as a "bolt-on" power source in a way similar way to how RPS units are used. While an operating fission power generator will emit significantly higher levels of radiation than an RPS, standard spacecraft bus parts and design can still be used. This is made possible by the requirements on the fission power generator, which stipulate an integrated radiation dose of <25 krad and neutron fluence of $5 \times 10^{11}$ n/cm$^2$ at a dose plane over a 15-year mission lifetime; the dose plane is defined to be 15 m from the spacecraft-facing end of the fission power generator shield. By separating the fission power generator from the spacecraft bus with a boom or other structure, this radiation requirement will allow the use of readily available subsystems and components without the need to resort to exceptionally rad-hard parts.

Figure 2-1 shows a representative configuration for the flight system. The major components of the fission power generator (described in detail in Section 6) include the core, radiation shield, Stirling energy converters, and radiators. In the configuration shown in Figure 2-1, the fission power generator is separated from the bus by an extensible boom that would be stowed to accommodate the launch vehicle fairing.

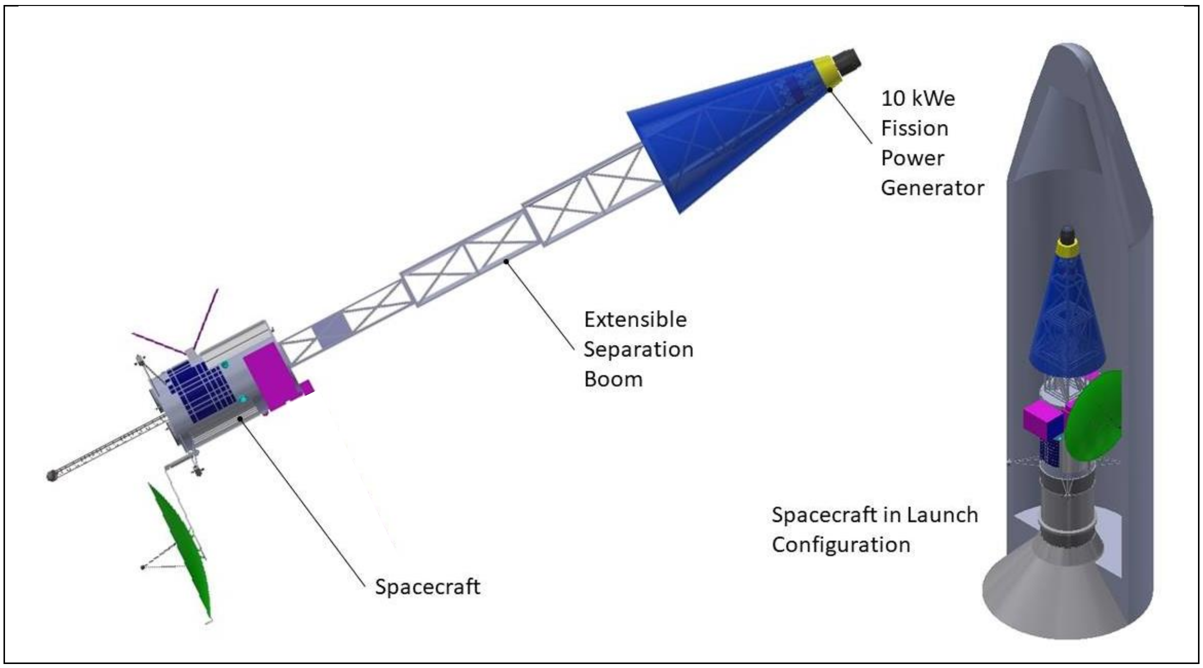


*Figure 2-1. Representative NEP flight system configuration. The science payload in this figure is shown at the front of the bus; in the text, we describe a different location for the science payload, aft of the tank. The actual locations will be largely at the discretion of the investigators provided they can accommodate the prevailing radiation effects at their preferred location within their existing mass allocations. Locations in the radiation shadow of the tank will experience lower radiation effects.*

The bus contains the Xenon fuel tank and power management and distribution electronics, mounted on the forward end of the bus. Spacecraft avionics and subsystems are mounted aft of the tank for additional radiation protection. Radiation-sensitive instruments may be mounted on the aft end of the bus, but those requiring specific fields of view may be mounted around the bus as required with appropriate attention to radiation protection. A number of NEXT ion thruster strings are mounted at the bottom of the bus, each with its own gimbal mechanism. The number can vary from two to as many as four, depending on Xenon throughput requirements imposed by each mission design. In all cases an additional single thruster string is provided for redundancy. A small hydrazine reaction control subsystem (RCS) is also included for attitude control and momentum unloading.

# 3. Nuclear Safety

## *Responsibilities and Observations*

The safety and security features of the Kilopower reactor for outer solar system exploration will mimic the NASA and DOE provisions for the Kilopower reactor for human exploration missions. Although nuclear safety is the responsibility of the agencies that execute the mission, we recognize that those responsibilities will be jointly shared by NASA and DOE; therefore, we respectfully submit the following observations for consideration by the respective implementing program officials.

On August 20, 2019, the White House released "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems" (NSPM-20), which updates the process for launches of spacecraft containing space nuclear systems, including fission reactors for power and propulsion. Specifically, NSPM-20 supersedes National Security Council Presidential Directive-25 (NSC/PD-25) of December 14, 1977 (as modified May 17, 1995, and May 8, 1996) and the section of the June 28, 2010, National Space Policy titled "Space Nuclear Power" and its corresponding section in Presidential Policy Directive–4. The Memorandum provides tiered launch authorization processes and quantitative safety guidelines for normal operating and accidental exposures to radiation, including probability-referenced dose limits to members of the public. The policy also tasks NASA, in coordination with the secretaries of Defense and Energy, to identify guidelines for safe non-terrestrial operation of nuclear fission reactors, including orbital and planetary surface activities. NASA has not yet completed its efforts with DOE and DOD to identify these safety guidelines, nor issued implementing requirements for NSPM-20. However, since NSPM-20 explicitly identifies nuclear safety analysis as "a critical step before any launch of a space nuclear system," we here provide observations indicative of the efforts and topics that will be involved in preparing safety analysis reports (SARs) for missions subject to the new policy.

The SAR will have a different focus than the current SARs developed for the launch of radioisotope systems. Inadvertent criticality accidents will require more attention than near-pad accidents involving blast, fragment and fire environments, since releases of $^{235}U$, relative to the $^{238}Pu$ used in NASA RPS missions, will involve relatively small amounts of radioactive material. The NASA databook will focus on identifying and specifying those anomalous commanding or operating scenarios and accidents that could result in system configurations that have the potential for inadvertent criticality within the Earth's biosphere. Additionally, since the Kilopower reactor will be activated shortly after launch (see Concept of Operations, Section 5), it will be operating before and after the first and last Earth flyby. The probability of inadvertent Earth entry will need to be calculated and shown to be consistent with the requirements of NSPM-20.

The SAR will focus on assessing the features of Kilopower (such as height-to-diameter ratio) that are intended to mitigate the risks of accidents and anomalous operating scenarios.

## *Kilopower Launch Safety*

An initial assessment by DOE, discussed below and in Appendix D, addressed the safety effects of a launch related accident.

### Explosions and Fires

Kilopower is designed to be safe for the worst-case explosion or fire. The launch safety analysis assumes the worst possible release occurs, which is the ENTIRE reactor core. The idea is that the core is essentially vaporized (or at least it changes phase to a vapor and a liquid). While in the air, the vapor and liquid form an aerosol. The aerosol forms a log normal distribution, of which about 20% of the material will be in the respirable range. The release values are based upon testing performed at the Nevada test site (project Roller Coaster) where plutonium was surrounded by high explosive and completely dispersed. The worst-case dose from a launch explosion accident to the maximally exposed individual at about 1 km is in the millirem to sub-millirem range. A millirem dose is equivalent to the dose to the average American in one day due to natural sources. This dose is one to two orders of magnitude below background and the legal limit for public exposure. Since the worst-case release is assumed, the type and size of the rocket does not matter. The analysis is rocket agnostic.

### Inadvertent Criticality

The second type of launch accidents for space reactors is the reactor inadvertently going critical from either landing in water or impacting the Earth's surface. Water immersion can add neutron moderation or reflection and increase the reactivity in the reactor. A land impact can deform the reactor causing a geometry that results in increased reactivity. An inadvertent criticality accident is not dependent on the type of rocket, it is a function of the reactor design.

Kilopower is designed such that criticality from land impact deformation or water immersion are either eliminated or greatly minimized. The Kilopower design has a high height to diameter ratio that prevents criticality when the reactor is submerged in water with all voids filled with water. Kilopower is also a highly reflected critical system. Small cracks in the reflector that leak neutrons will cause the reactor to be subcritical. Kilopower has a ceramic reflector and a ductile metal core. The reflector will break or crack causing neutron leakage in a deformed core. Figure 3-1 shows a cartoon sketch of a deformed core, reflector and control rod, with the cracked reactor leaking neutrons. The reactor core cannot go critical on impact unless the rod is ejected and the reflector remains intact with no large cracks, a very unlikely situation.

The dose for an inadvertent criticality accident to the maximally exposed individual at 1 km will be in the 1 to 10 millirem range. These doses are well within the limits established by NSPM-20. Only individuals within about 10 meters of the reactor, should it go critical, would be impacted. These individuals would receive life-threating doses of gamma rays and neutrons or would be severely injured by the falling debris.

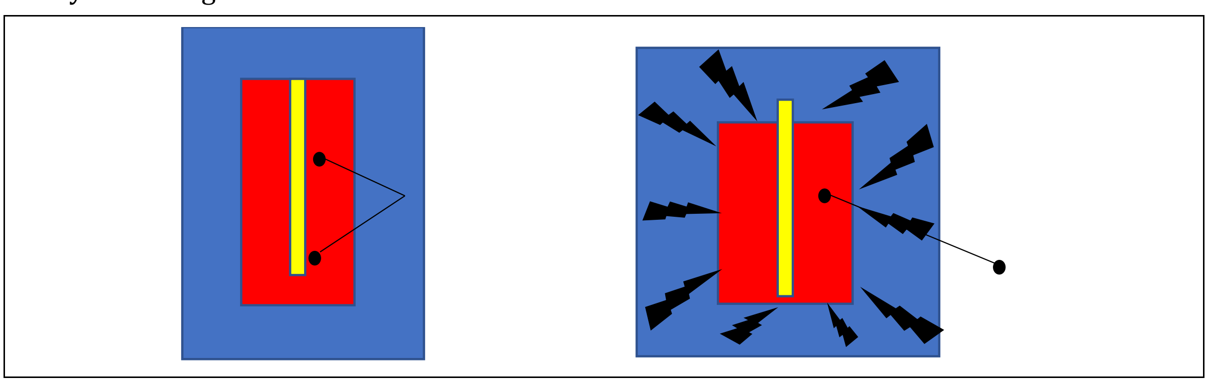

*Figure 3-1. Kilopower Core with Damage to Core Causing Neutron Leakage. Left: Intact core and reflector with rod in the center. Right: Damaged core (deformed) and cracked reflector.*

# 4. NEP Benefits for Outer Solar System Exploration

## *Overcoming Power and Propulsion Challenges*

A National Academies consensus study report on NASA's large strategic science missions describes the critical importance of flagship missions to NASA's Science Mission Directorate goals:

> These missions typically are billion-dollar-class missions, the most costly, the most complex, but also the most capable of the fleet of scientific spacecraft developed by NASA. They produce tremendous science returns and are a foundation of the global reputation of NASA and the U.S. space program. Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science because only the United States has the budget, technology, and trained personnel in multiple scientific fields to conduct missions that attract a range of international partners [National Academies, 2017].

Missions to the far outer solar system face challenges in both power and propulsion. ΔV requirements present a major challenge to chemical propulsion systems; for example, New Horizons flew by Pluto at 14 km/s, well beyond the ability of any existing chemical propulsion system to achieve orbit insertion. Electric propulsion provides fuel efficiency to achieve high ΔV. As an example, imparting 10 km/s to a vehicle with 400 kg dry mass (New Horizons–class) using a conventional bi-prop system (Isp ~320 s) would require 9300 kg of propellant, and this neglects the mass of the propulsion system. However, imparting the same 10 km/s to the same mass vehicle using electric propulsion ion thrusters operating at an Isp of 4000 s would require just over 100 kg of propellant.

With solar power not practical at large solar ranges, nuclear power is enabling for outer solar system missions. Advanced radioisotope power (~1 kWe) could be used to enable small spacecraft missions with limited payloads (New Horizons–class), and fission power (~10 kWe) enables flagship-class missions, including multi-body orbiters, large payload suites, and landers.

A NEP system with the Kilopower reactor is one way to overcome these challenges. The leading alternative approaches to NEP with near-term technology are solar electric propulsion (SEP) and radioisotope electric propulsion (REP).

SEP is fundamentally limited by the $1/r^2$ reduction in available solar radiation as distance from the Sun increases. However, recent advances in lightweight solar array technology have made solar power an option for missions as far out as Saturn. For these missions, SEP can be used in the Inner solar system to send more mass, more quickly and a chemical propulsion stage can be used for orbit insertion at the target. Current electric propulsion systems (with a useful amount of total impulse) require a minimum of 100 to 200 W to operate, and a spacecraft with large enough arrays and low enough bus power could use SEP at Jupiter or Saturn for orbit trim maneuvers. Larger power levels for electric propulsion (1 kW and higher) could allow all electric missions without a chemical stage.

Radioisotope thermoelectric generators (RTGs) could also be used to power an electric propulsion system. These REP missions need to achieve a thrust-to-weight ratio high enough to allow reasonable duration missions. A Pluto orbiter mission assessment in 2015 [Elliott, 2018] has found that the planned Next Generation RTG system with a New Horizons–sized spacecraft (~500 kg)could allow missions such as Centaur, Pluto, or Kuiper Belt objects. However, the total power for electric propulsion for REP spacecraft is likely limited to ~1 kW or less, which in turn limits these missions to 500 kg class spacecraft.

NEP with Kilopower could enhance previously studied SEP and REP missions by reducing flight times, delivering more mass, and increasing communication data rate. In addition, Kilopower NEP can enable new types of missions such as a Triton orbiter, a dual Centaur orbiter, and a dual Titan-Enceladus orbiter.

### Classes of Missions

Using COMPASS and Team X analysis protocols, the team characterized a range of outer solar system missions of interest to the science community. Two classes of missions were identified: those that are *enabled* by NEP and those that are *enhanced* with NEP.

A number of missions were identified that are uniquely enabled by the use of Kilopower NEP. These are missions that are not possible using any other available power and propulsion system. Three enabled missions are presented in detail below.

In addition, implementations using both REP and NEP were compared for four example destinations to identify how NEP could enhance these missions. The FOMs used to compare the results from the different systems were:

- Minimum Time of Flight (TOF) from launch to arrival at the target
- Maximum Payload Mass delivered to the target within the limitation of a 15 year mission
- The Communications Data Rate that could be achieved when not thrusting with NEP

### Mission Concepts Enabled by Kilopower NEP

We studied three example mission scenarios that came from the priorities of the 2013–2022 decadal survey[9] and that are also expected to be high priority in the next decadal survey: ocean worlds, ice giants, and centaurs.

We have identified three mission concepts in the outer solar system that are only possible with the power levels provided by a fission power system: (1) Ocean worlds: a Saturn system mission that orbits both Titan and Enceladus, (2) Ice giants: a Neptune system mission with a Triton orbiter and lander, and (3) a dual Centaur orbiter mission. A 10-kW reactor was assumed for these missions, but we have not identified the minimum power level needed for each mission. In general, lower power can be traded for reduced mass, longer flight time, or a combination of the two.

#### Ocean Worlds: Titan Orbiter/Lander–Enceladus Orbiter/Lander

Saturn missions, including a Titan orbiter are possible with chemical propulsion. The addition of SEP enables Enceladus orbiters. Kilopower NEP provides enough performance to enable orbiting Enceladus, delivering a lander, and then orbiting Titan within a 15 year prime mission.

Figure 4-1 shows a 9.75-year Kilopower NEP trajectory to Saturn with cruise science that launches on a Falcon Heavy class rocket. This trajectory would arrive at Saturn with low enough energy that a Titan gravity-assist can capture the spacecraft into Saturn orbit. A Titan lander (with an aeroshell) could be released during this flyby. After capture, the spacecraft would use its NEP system to perform a 2.25-year $V_\infty$ leveraging[10] trajectory to reach Enceladus orbit. This trajectory would

[9] National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013–2022*, Washington, DC: The National Academies Press (2011).

[10] $V_\infty$ leveraging is a technique that uses maneuvers away from a flyby to change the flyby v-infinity (also known as hyperbolic excess velocity). This technique is an efficient way to change the spacecraft energy with respect to the flyby body, especially with low-thrust propulsion.

afford multiple opportunities for low-altitude, low-speed flybys of Saturn's icy moons. This tour would be followed by a 6-month orbital mission at Enceladus where an Enceladus lander could be deployed. After the Enceladus orbital mission, a 2-year $V_\infty$ leveraging trajectory could then be used to reach Titan and enter orbit. There is then time for a 6-month orbital mission at Titan before the end of the 15-year prime mission. The total science payload mass would be 2550 kg, enough for several months for lander operations, and 100 kg for science.

Table 4-1 provides a summary of the mission ΔV and spacecraft mass at different stages of the mission. These masses assume no deployment of landers to Titan or Enceladus; but with final mass of 7229 kg, there is ample performance for the addition of such landers. Alternatively, some of this mass could be used for additional Xenon to reduce the flight time to Saturn. (Flight times to Saturn could be reduced as low as 5.5 years.)

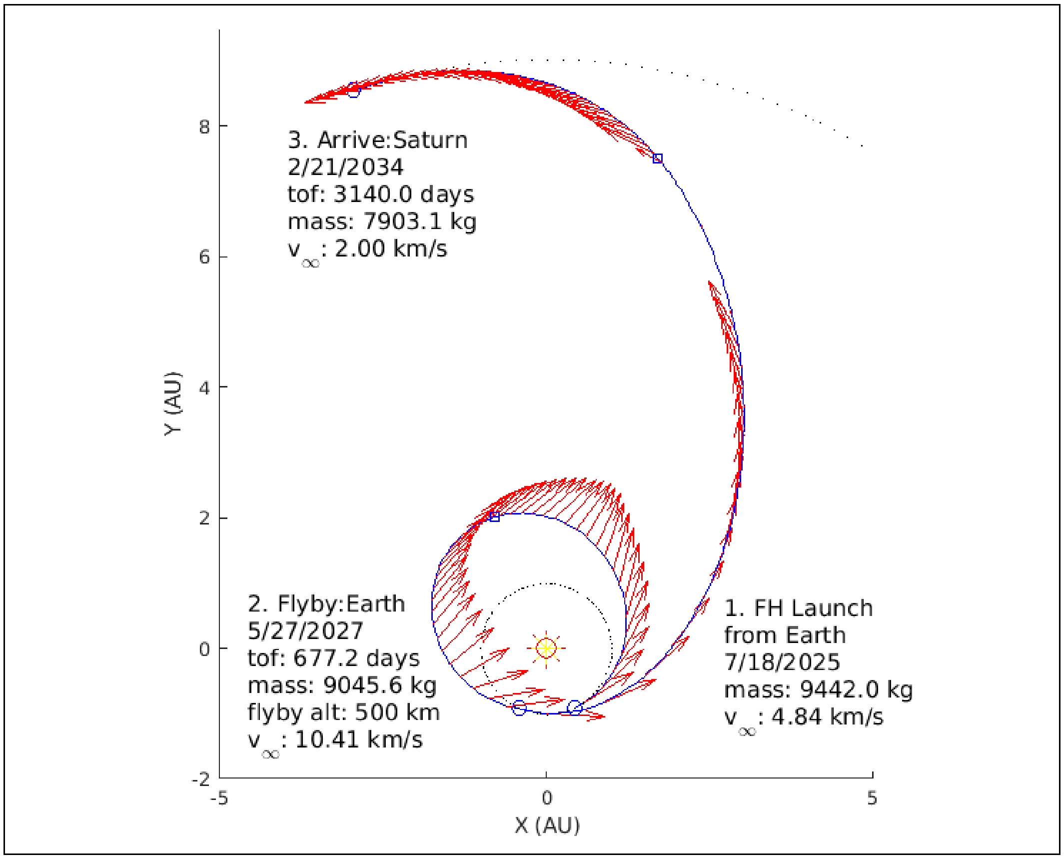


*Figure 4-1. A 9.75 Kilopower NEP trajectory to Saturn that launches on a Falcon Heavy class rocket (FH=Falcon Heavy)*

*Table 4-1. Summary of the mission ΔV and spacecraft mass at different stages of the Saturn mission concept*

| Event | Mass After Event |
|---|---|
| Launch, C3 = 22.66 $km^2/s^2$ | 9442 kg |
| Interplanetary ΔV to Saturn, 7.0 km/s | 7903 kg |
| ΔV to Enceladus & Enceladus Ops, 1.5 km/s | 7607 kg |
| ΔV to Titan & Titan Ops, 2.0 km/s | 7229 kg |

**Ice Giants: Neptune Orbiter–Triton Orbiter/Lander**

The Neptune Orbiter–Triton Orbiter/Lander mission concept uses an interplanetary trajectory found by the NASA Ice Giants Study [Hofstadter et al., 2017]. In that study, the trajectory was used by an REP Neptune orbiter mission that included several Triton flybys. The added performance from a Kilopower NEP system allows extending this mission into a Triton orbiter with enough performance to deliver a 300 kg lander to the surface of Triton.

This mission concept would launch on a Falcon Heavy (or equivalent performance) rocket and would use Earth and Jupiter flybys in concert with NEP thrusting to reach Neptune in 13 years (Figure 4-2 and Table 4-2). A chemical propulsion system (mono-prop in this example) would then be used for a 240 m/s maneuver to insert into Neptune orbit for a 1.4-year Neptune tour with 100 kg of orbiter science. After Neptune capture, the NEP system would provide 2.1 km/s of ΔV to reach the Triton orbit plane, perform a series of $V_\infty$ leveraging maneuvers (combined with Triton flybys) to reduce energy, and finally spiral down into low Triton orbit, over a period of 520 days. A 300 kg lander could then be deployed in orbit and use its own chemical propulsion system for the 1300 m/s required to land on Triton. Seven months would be available for the Triton orbiter with 100 kg of science and lander operations before the end of the 15-year prime mission. The total science payload mass would be 400 kg.

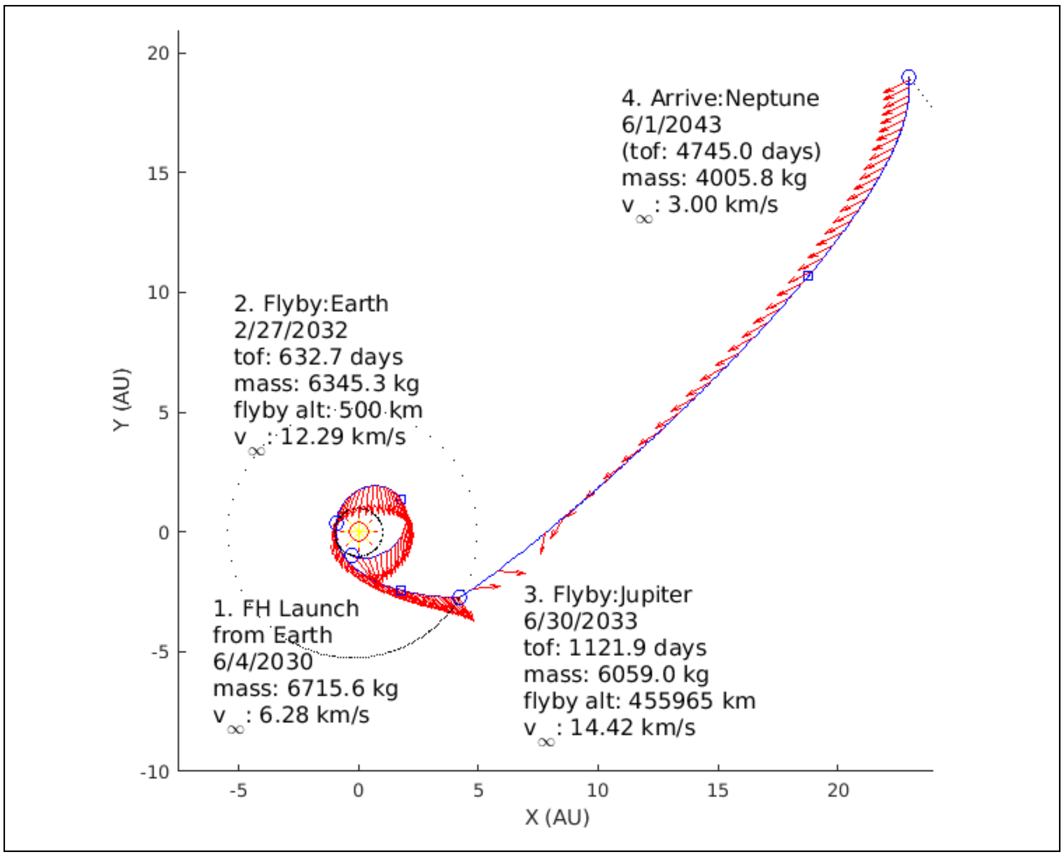


*Figure 4-2. Interplanetary trajectory for Neptune mission (FH=Falcon Heavy)*

*Table 4-2. Summary of the mission ΔV and spacecraft mass at different stages of the Neptune mission concept*

| Event | Mass After Event |
|---|---|
| Launch, C3 = 34.93 $km^2/s^2$ | 6716 kg |
| Interplanetary ΔV to Neptune, 20.2 km/s | 4006 kg |
| Neptune orbit Insertion, 240 m/s (chemical) | 3713 kg |
| Tour ΔV to Triton orbit, 2.1 km/s | 3520 kg |

### Dual Centaur Orbiter, including 95P/Chiron

Starting from a previous GRC COMPASS team REP trajectory to orbit 95P/Chiron [GRC COMPASS Team, 2012], Kilopower NEP enables an additional 1-year orbital mission at a second Centaur before arriving at 95P/Chiron. Figure 4-3 and Table 4-3 show a trajectory that includes one year in orbit at Centaur object 2007 SA24 on the way to 95P/Chiron. A variety of similar missions that orbit 2007 TB434, 2009 KE31, 2010 KG43, 2011 FS53, or 2011 GM96 before 95P/Chiron are also feasible in a similar timeframe.

This example mission would launch on a rocket with performance equivalent to a Falcon Heavy and begin returning science data from 2007 SA24 orbit just 5.9 years after launch without the use of planetary flybys. After a one-year orbital mission at this first Centaur, the spacecraft would depart for 95P/Chiron and arrive 11.5 years after launch, allowing for a 3.5-year orbital mission in a 15-year prime mission. A substantial 300 kg of instrument payload could be delivered to 95P/Chiron orbit with this trajectory.

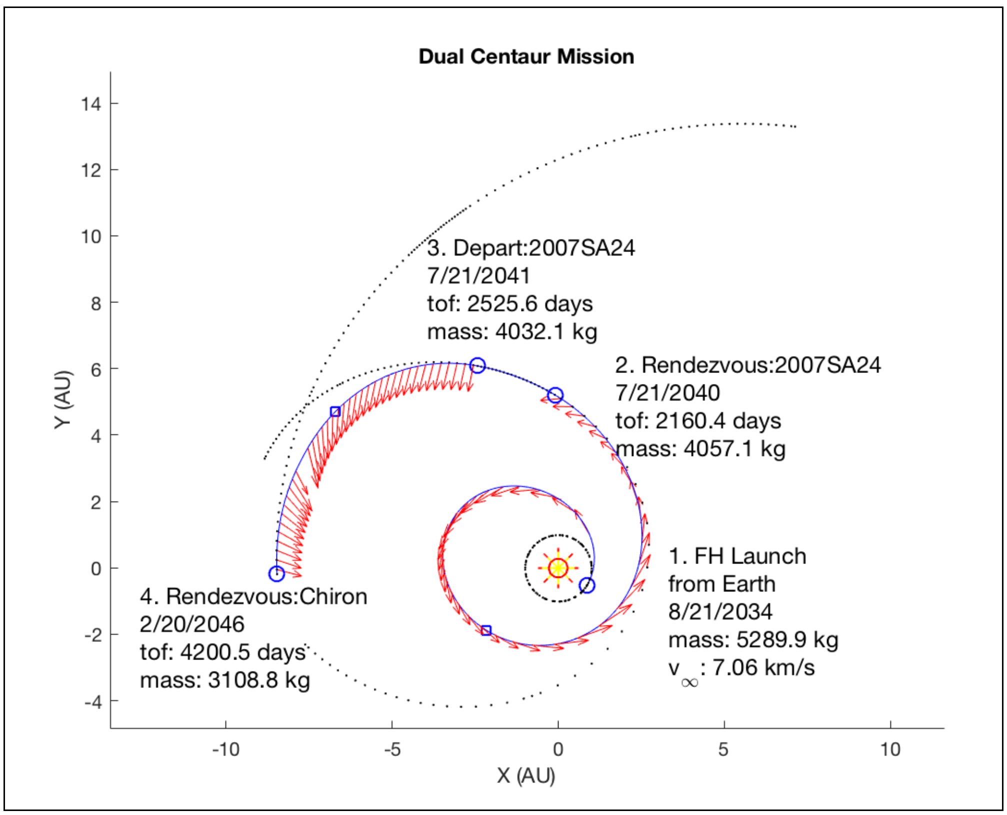


*Figure 4-3. Trajectory plot for example dual Centaur mission ( FH=Falcon Heavy)*

*Table 4-3.Summary of the mission ΔV and spacecraft mass at different stages of the dual Centaur mission concept*

| Event | Mass After Event |
|---|---|
| Launch, C3 = 49.84 $km^2/s^2$ | 5290 kg |
| Interplanetary ΔV to 2007 SA24, 10.42 km/s | 4057 kg |
| Orbiting 2007 SA24 ΔV, 0.250 km/s | 4032 kg |
| Interplanetary ΔV to Chiron, 10.22 km/s | 3108 kg |
| Orbiting Chiron ΔV, 0.250 km/s | 3088 kg |

## Mission Concepts Enhanced by Kilopower NEP

In addition to the above mission concepts enabled by NEP, several missions that would be possible with advanced RTGs are greatly enhanced by the power levels possible with the Kilopower reactor. These missions include outer planet orbiters as well as orbiter missions to Pluto and other Kuiper Belt objects that are not possible with SEP. The team selected enhanced missions from previously studied RTG missions—including Saturn, Uranus, Neptune, and Pluto Orbiters—in order to provide a reasonable basis for comparison with NEP.

### Saturn and Uranus Mission Concepts

For outer planet missions, gravity-assists with the inner planets can provide a significant performance increase, but finding good gravity assist combinations requires careful study on a per mission basis, especially for electric propulsion missions. Previous work has identified some of these gravity assist combinations for Kilopower NEP missions [McCarty et al., 2018]. However, for missions to Uranus distances or closer, this performance increase would be very similar for REP and NEP; and we can get a good idea of the relative performance advantages of each of these systems by limiting our trajectory search to just direct trajectories or those using Earth or Jupiter gravity assists (EGAs or JGAs). (Note that if nuclear safety ends up preventing Earth flybys (see Section 3), there are still many mostly-ballistic gravity assist trajectories available using other planets that have been identified [Petropoulos et al., 2000], and the addition of NEP enables even more trajectories).

Table 4-4 provides a comparison of simple REP and NEP orbiter missions to Saturn and Uranus as example cases. There are most likely higher performing missions to be found with each electric propulsion system, but this table provides an assessment of the relative performance of these systems given similar assumptions. Each trajectory assumes a Falcon Heavy equivalent launch vehicle and a minimum science payload mass of 30 kg for REP and 50 kg for NEP. The spacecraft mass and performance for the REP missions was based upon a previous JPL study [Elliott, 2018].

Table 4-4 shows that, compared to REP, NEP has the potential to reduce trip time, increase data rates, and massively increase the payload capability of a single mission. These performance benefits could lead to a dramatic increase in the scientific return of a mission by returning more data in less time and carrying more capable science payloads. The maximum payload mass shown is above that which is required for the spacecraft and could be allocated to science instruments, atmospheric probes, landers, or additional propellant.

*Table 4-4. Comparison of REP and NEP orbiter missions to Saturn and Uranus*

| Mission | Figure of Merit | 1-kW REP | 10-kW NEP |
|---|---|---|---|
| Saturn Orbiter | Minimum TOF (Years)* | 5.0 | 4.8 |
| | TOF for Maximum Payload Mass (years) | 13.0 | 12.6 |
| | Maximum Payload Mass (kg) | 1,095 | 7,840 |
| | Communications Data Rate (kpbs) | 120 | 530 |
| Uranus Orbiter | Minimum TOF (years)* | 11.7 | 10.2 |
| | TOF for Maximum Payload Mass (Years) | 14 | 14 |
| | Maximum Payload Mass (kg) | 175 | 3,320 |
| | Communications Data Rate (kpbs) | 30 | 130 |
| * to deliver a minimum science payload mass of 30 kg for REP or 50 kg for NEP | | | |

**Neptune and Pluto Missions Concepts**

Missions to Neptune and Pluto are not as straightforward to compare because realistic mission assumptions (launch vehicle, flyby sequences, orbit insertion) diverge for REP and NEP missions to these destinations. To enable a more realistic comparison, we looked at point-design mission concepts that make assumptions as needed for the design to close with each power system. Table 4-5 shows the results of this comparison.

For Neptune, the trajectory from the Triton orbiter mission presented earlier, if it were re-purposed for a Neptune orbiter, could deliver 875 kg to Neptune orbit for instruments and atmospheric probes. In comparison, a 1-kW REP mission could deliver only 30 kg and would require 15 years.

For a Pluto orbiter mission, the NEP mission delivers 67% more payload with 2.4 years shorter flight time compared to the REP option. The Kilopower NEP spacecraft can reach Pluto orbit in 14.7 years with a Falcon Heavy equivalent launch vehicle. Kilopower also enables over four times the data rate at Pluto than the REP option.

*Table 4-5. Comparison of REP and NEP orbiter missions to Neptune and Pluto*

| Mission | Figure of Merit | 1-kW REP | 10- kW NEP |
|---|---|---|---|
| Neptune Orbiter | TOF (years) | 15 | 13 |
| | Science Payload (kg) | 30 | 875 |
| | Communications Data Rate (kpbs) | 13 | 54 |
| | Flyby Sequence | Jupiter | Earth, Jupiter |
| | Launch Vehicle | Delta IV H + Star 63 | Falcon Heavy |
| Pluto Orbiter | TOF (years) | 17.1 | 14.7 |
| | Science Payload (kg) | 30 | 50 |
| | Communications Data Rate (kpbs) | 7 | 30 |
| | Flyby Sequence | Jupiter | Earth, Jupiter |
| | Launch Vehicle | Delta IV H + Star 63 | Falcon Heavy |

## 5. Concept of Operations

Nuclear power systems require a parallel path for hardware verification due to the special nuclear facilities required to test the fission power generator for flight. The safety and security requirements of the highly enriched uranium (HEU) fuel necessitate that certain facilities, such as the Device Assembly Facility (DAF), be used for reactor assembly and testing. Figure 5-1 shows the notional operations for the fission power generator running in parallel with notional operations for the spacecraft culminating with the delivery of the fission power generator to KSC, where it would be integrated with the spacecraft bus.

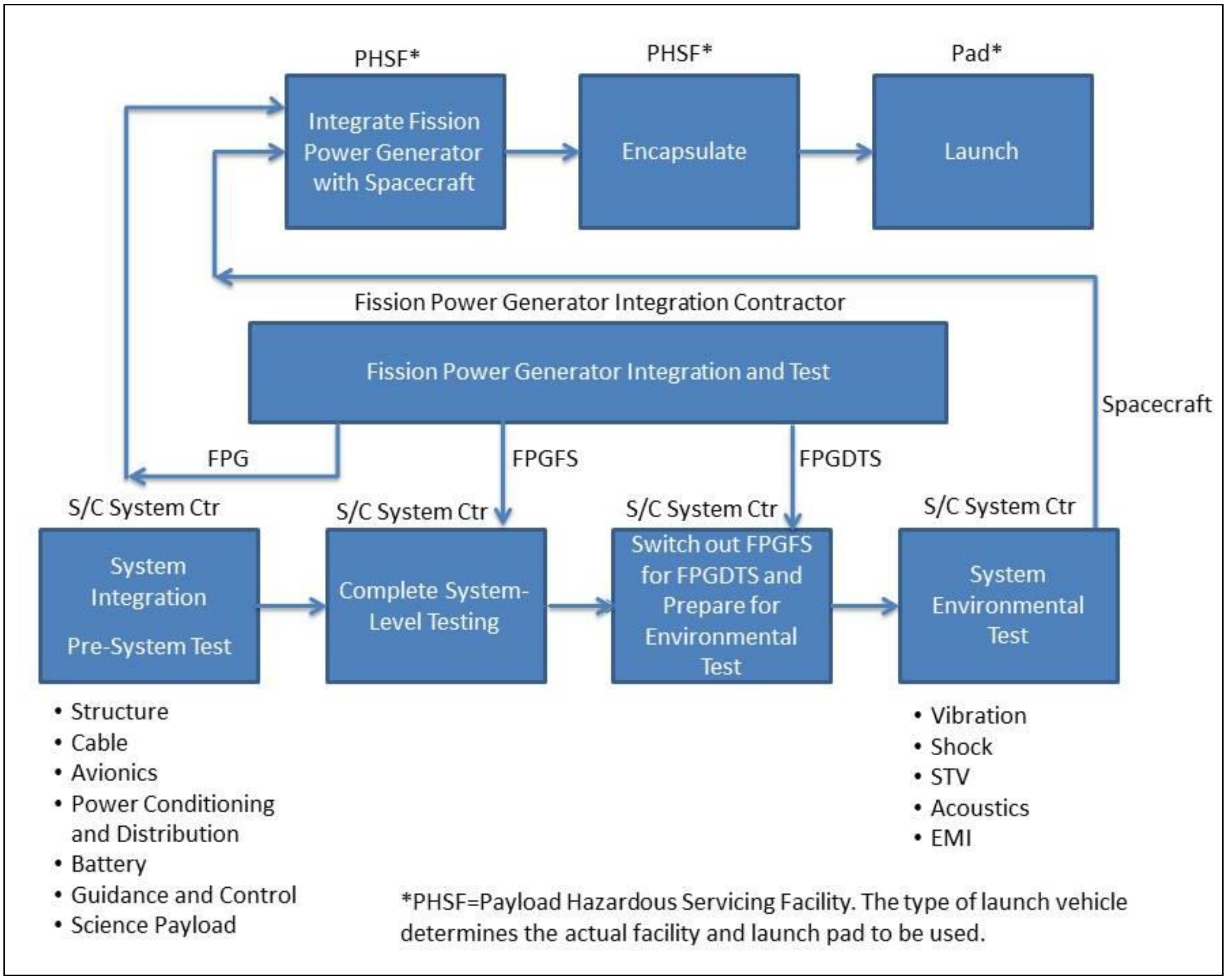


*Figure 5-1. Notional operations for fission power generator integration and test running in parallel with spacecraft integration and test.*

The fission power generator and the spacecraft bus each go through their own system integration and environmental test program, using simulators as surrogates to mimic the missing electrical and mechanical interfaces. This is highly analogous to what we have done on all prior RTG missions as well as the Galileo probe and the Huygens Probe on Cassini.

A fission system with $^{235}U$ presents no human or environmental risks before the reactor becomes critical (i.e., fissions.). A notional concept of operations includes subcritical tests, which will have been performed prior to fission power generator shipment to KSC. The radioactivity in the reactor core results from the naturally occurring elements present in the uranium. This will limit the core to a few curies of radioactivity.

The reactor, integrated with the rest of the fission power generator, would be shipped directly to the payload hazardous servicing facility (PHSF)[11], where DOE security would be in place for the integration into the spacecraft. It will be shipped as an integrated and environmentally tested and functionally verified unit. No disassembly or servicing of the FPG is contemplated after shipment to KSC, just a brief health check to verify survival of the shipping and handling processes.

During ATLO testing at the PHSF, the spacecraft would be operated with the FPGFS prior to integration with the flight fission power generator, after which the completed flight spacecraft will be moved to the pad.

During pre-launch operations on the pad, the spacecraft would be operated on batteries or external power. The Stirling engines will not be run on the pad because the reactor will not be operated until after launch and it is verified to be on a safe trajectory. After separation from the launch vehicle, the spacecraft would operate on battery and solar power until after the reactor is activated; nominally this would occur within the first two weeks after launch, allowing sufficient time to validate proper operation of the spacecraft. If the mission requires an Earth flyby, a Cassini-like strategy could be used to meet the Earth avoidance safety requirements. If a Cassini-like flyby analysis does not satisfy the safety criteria, the solar array could be augmented to permit operation on solar panels until the spacecraft is beyond the last Earth flyby, after which the reactor can be activated and the solar panels jettisoned.

- The launch approval process would be similar to the one in place for the launch of RTGs but will be simplified due to the differences in radioactivity levels and the streamlined launch approval process now being reengineered by DOE Office of Nuclear Energy (NE) and NASA.
- In-place and verified security capability would be used or the manufacture, transportation, test, and launch of the reactor system.
- In the event of launch failure, or failure to achieve stable orbit, the capability to retrieve and secure the fuel will be in place as required. The level of effort needed to prevent the fuel from falling into the wrong hands will depend on the ultimate launch trajectory, rocket failure modes, regulation and policy issues, and reentry analysis/testing of the spacecraft, reactor, and fuel.

### *Notional Flow for Fission Power Generator Assembly Operations*

A notional flow diagram of the fission power generator assembly operations (FPGAO) is shown in Figure 5-2. This flow diagram provides insight into how the nuclear and nonnuclear systems, the fission power generator functional simulator (FPGFS) and fission power generator dynamic/thermal simulator (FPGDTS), and the control systems will ultimately integrate into the spacecraft during ATLO.

The top half of the block diagram in Figure 5-2 shows that the core is fabricated at Y-12 according to NASA material specifications and manufacturing drawings. The HEU fuel is shipped to DAF by the

[11] A facility at KSC designed to accommodate a variety of NASA and NASA customer payloads; it can be used as a payload processing facility (PPF) or a hazardous processing facility (HPF). The type of launch vehicle determines the actual facility to be used. See Glossary for more information.

DOE Office of Secure Transportation (OST). After the flight spacecraft bus is mated with the flight fission power generator, integration and compatibility verification will be completed followed by encapsulation, followed by transport to the Pad and the normal preparation for launch.

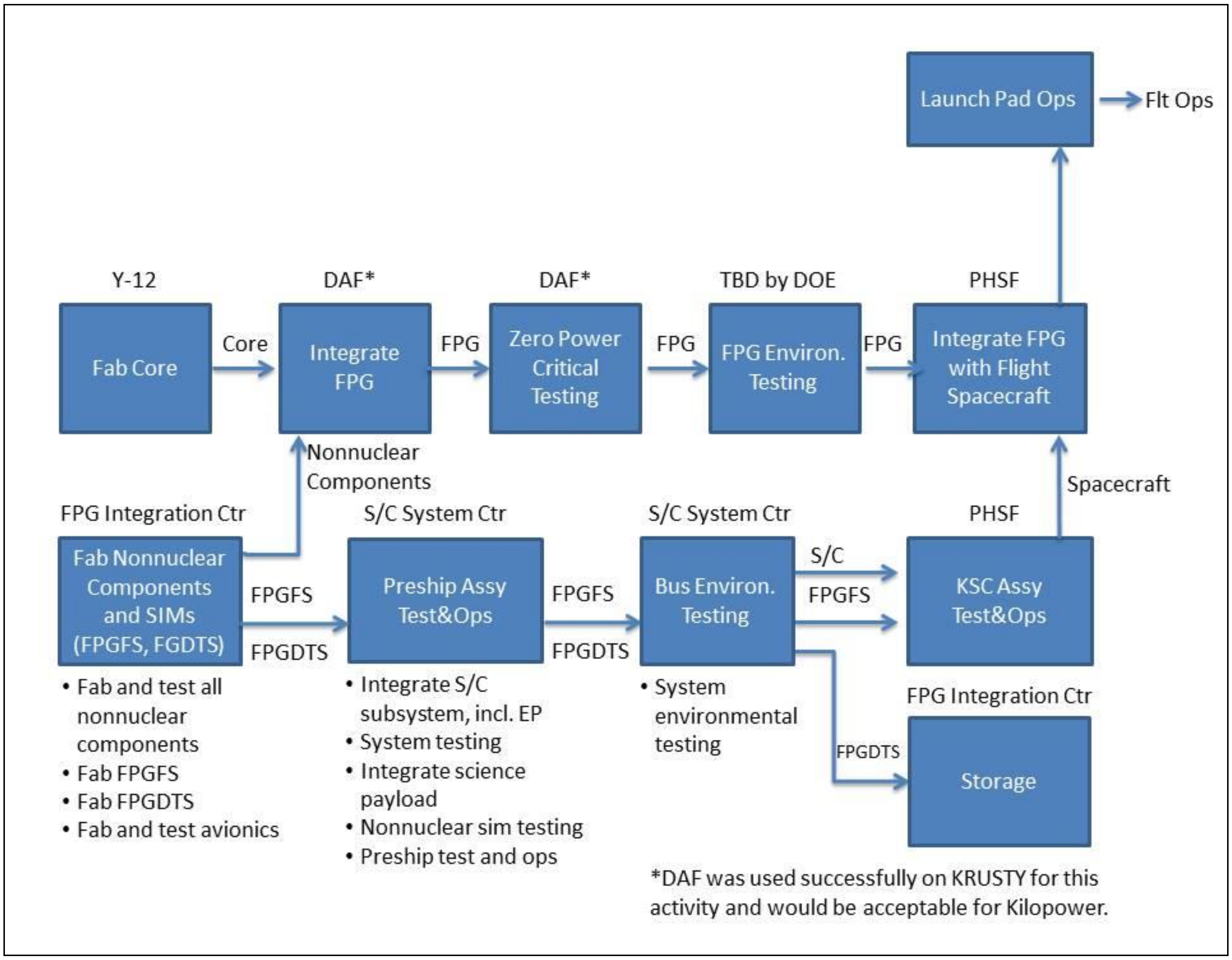


*Figure 5-2. Notional FPGAO Flow*

Nonnuclear components and subsystems will be acceptance tested at the fission power generator integration contractor prior to delivery to the integration facility. Once all the components have arrived, the reactor will be assembled. After assembly, the fission power generator will undergo zero power critical testing, which will include a complete flight control system and control rod. For additional safety, a process like that used in KRUSTY may be followed were the radial reflectors will be unbolted from the shield assembly and placed on a criticality machine platen (Comet or Planet) where the reactor will have several shutdown modes. Zero power critical and environmental testing may follow a process similar to that outlined below:

> Initially, the radial reflectors will be dropped so that the reactor cannot go critical while the control rod goes through several mission operations for final reactor sub-system acceptance testing.

Once the initial control rod testing has been performed, mechanical and electrical interlocks will be placed into the control rod assembly before the radial reflectors are lifted around the core and into their flight configuration.

Once the completed reactor assembly has been fully checked out and all interlocks have been removed, the test cell will be vacated for the zero power critical test. During this test, the flight control system will initiate reactor activation but only withdraw the control rod to the zero power location.

At completion of the zero power testing, the fission power generator will continue to environmental testing at a DOE Laboratory. This fully assembled fission power generator with HEU fuel will verify the system integrity during environmental mission conditions of launch, transit, possibly entry-descent-landing, and reactor activation.

The reactor will again be taken to a zero power critical state at the required mission startup temperatures.

The tests described above will require extensive review through DOE criticality safety operations before becoming finalized.

The control rod will be fully inserted with mechanical and electrical interlocks in place prior to shipment.

After the fission power generator performance and environmental testing is completed, the fission power generator will be inserted into the proper shipping container and await transport to the launch facility.

After the fission power generator has been delivered to the processing facility and integrated to the spacecraft, the entire package will be encapsulated in the launch vehicle fairing and moved to the launch pad for final launch operations.

The process depicted on the bottom half of Figure 5-2 starts with the fabrication of all nonnuclear components (including the FPGFS, FPGDTS, and avionics) at the fission power generator integration contractor, who is responsible for completing all component- and subsystem-level qualification and acceptance testing of the fission power generator and simulators. Flight components and controllers will then be shipped to the DAF for fission power generator assembly testing as described above.

Since the FPG cannot be powered up for spacecraft integration and checkouts, two separate simulators will need to be constructed. The functions of each are described below.

### *Fission Power Generator Functional Simulator*

The FPGFS is a programmable electrical bus controller that accepts input commands from the spacecraft, actively communicates system data and simulated health monitoring to the spacecraft, and outputs the appropriate electrical power to the spacecraft to simulate the Stirling engines and controllers. This simulator will be used in place of the FPG because the FPG cannot be operated for ground testing. The FPGFS will allow the spacecraft to operate and verify all data handling and control and power management associated with the FPG.

The FPGFS will initially be built and tested at the fission power generator integration contractor, who will perform several engineering-level verification tests prior to shipping the FPGFS to the spacecraft system contractor. A functional spacecraft simulator will be available at the fission power generator integration contractor to transmit and receive commands and information between a surrogate flight computer and the FPGFS.

After the FPGFS completes spacecraft integration and pre-ship assembly test and operations, it will continue through bus environmental testing. After completion of the environmental testing, the FPGFS will be shipped to the launch site for ATLO. The FPGFS will continue to support ATLO until the fueled FPG arrives and is integrated into the spacecraft.

### *Fission Power Generator Dynamic/Thermal Simulator*

The FPGDTS will be built to verify the structural and environmental integrity of the spacecraft using a geometrically accurate mass model of the FPG with appropriate surface heaters. The FPDGTS is meant only for dynamic and thermal simulation and does not produce electrical power. It will be built using a combination of component-level engineering units and mass/inertial equivalents. A depleted uranium core or mass-property equivalent will be used instead of the HEU core. This nonnuclear flight system will be bolted to the spacecraft to undergo system-level vibration and environmental testing to verify the mechanical and thermal integrity of the complete system without having to concern for criticality accidents and security of the HEU fuel. During vacuum environmental testing, the external heat fluxes measured from the FPG nonnuclear tests will be simulated using electrical heaters on the appropriate surfaces. This can be accomplished knowing that the FPG has a 15-m separation distance when running and that the thermal radiation can be easily simulated using surface heaters. Differences between the FPGDTS and the fission power generator will be verified through thermal and structural analysis with a high level of fidelity and certainty.

In preparation for the arrival of the fission power generator, the spacecraft will be fully verified using the FPGFS and FPGDTS at the spacecraft system contractor's facility. Both the FPGFS and FPGDTS are provided by the fission power generator integration contractor and will verify all system operations and spacecraft integration procedures prior to the assembly and testing of the fission power generator at DAF. Similar to the KRUSTY test, the fission power generator, FPGDTS, and FPGFS testing will allow all components, systems, and procedures to be verified prior to launch operations. The fission power generator criticality testing at DAF will verify that all reactor assembly and criticality procedures are fully vetted before environmental testing and shipment of the fission power generator to the launch site. Similarly, the FPGFS will allow all electrical power and communication systems to be verified through electrical simulation. The FPGDTS will verify that all structural and environmental testing, including system-level thermal-vacuum shock and vibration, have been completed without the presence of HEU. These three main assemblies and functional tests will provide the needed information for validation of the flight system.

The spacecraft will need to complete all checkouts and preparations prior to shipment of the fission power generator. Once the spacecraft is ready, the fission power generator will be shipped by OST to KSC for immediate integration with the spacecraft at the PHSF. After integration, the spacecraft and the fission power generator will be encapsulated into the launch vehicle fairing and delivered to the vehicle assembly building to be integrated to the launch vehicle. It is anticipated that security requirement will not permit removal of the interlocks before movement to the pad. Therefore, an access door will be required in the fairing where the control rod mechanical and electrical interlocks can be taken out prior to flight.

## 6. Fission Power Generator

The mission concepts we studied used a 10 kWe Kilopower fission power generator. The basic layout of a Kilopower system is shown in Figure 6-1, with a comparison to human height size shown in Figure 6-2. The components of a Kilopower system can be separated into three subsystems: the reactor core assembly, the power conversion assembly (PCA), and the heat rejection assembly (Figure 6-3). The reactor core assembly includes the core, heat pipes, neutron reflectors, radiation shield, and reactivity control. The power conversion assembly includes the Stirling converters, system control, and overarching structure.

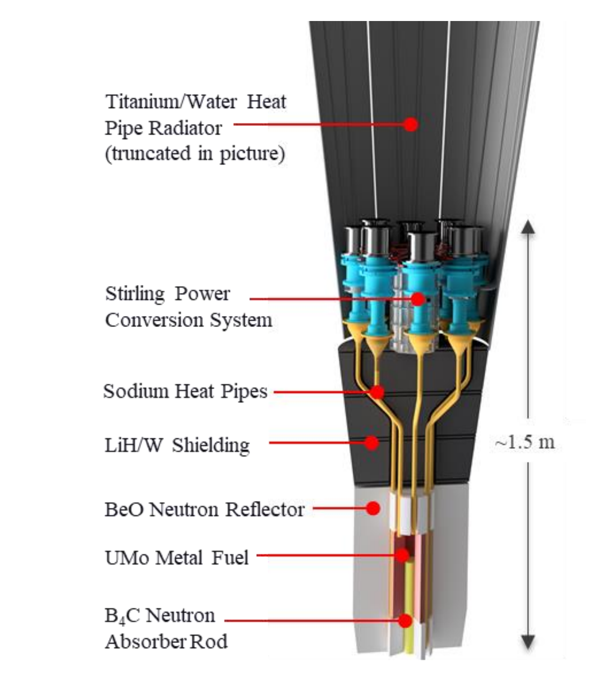


*Figure 6-1. Basic layout of an 8- engine 1 kWe Kilopower system. Note that the image is upside down with respect to the launch configuration.*

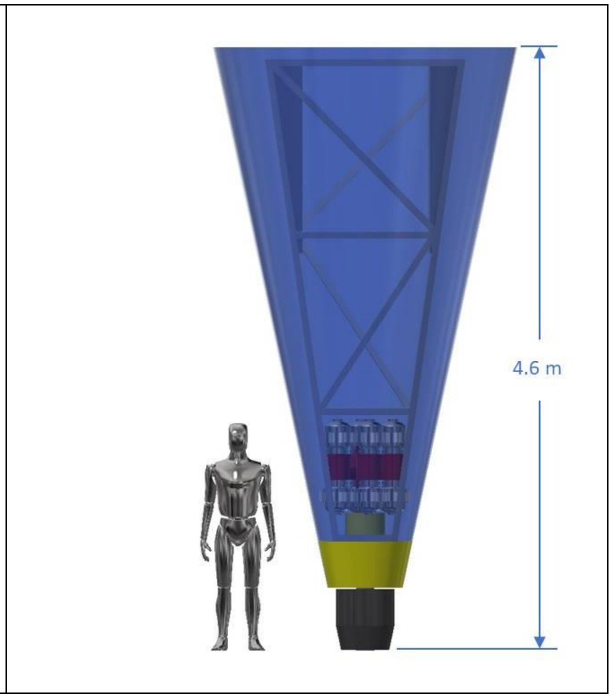


*Figure 6-2. Integrated fission power generator compared to average human height to demonstrate size. Note that the image is upside down with respect to the launch configuration.*

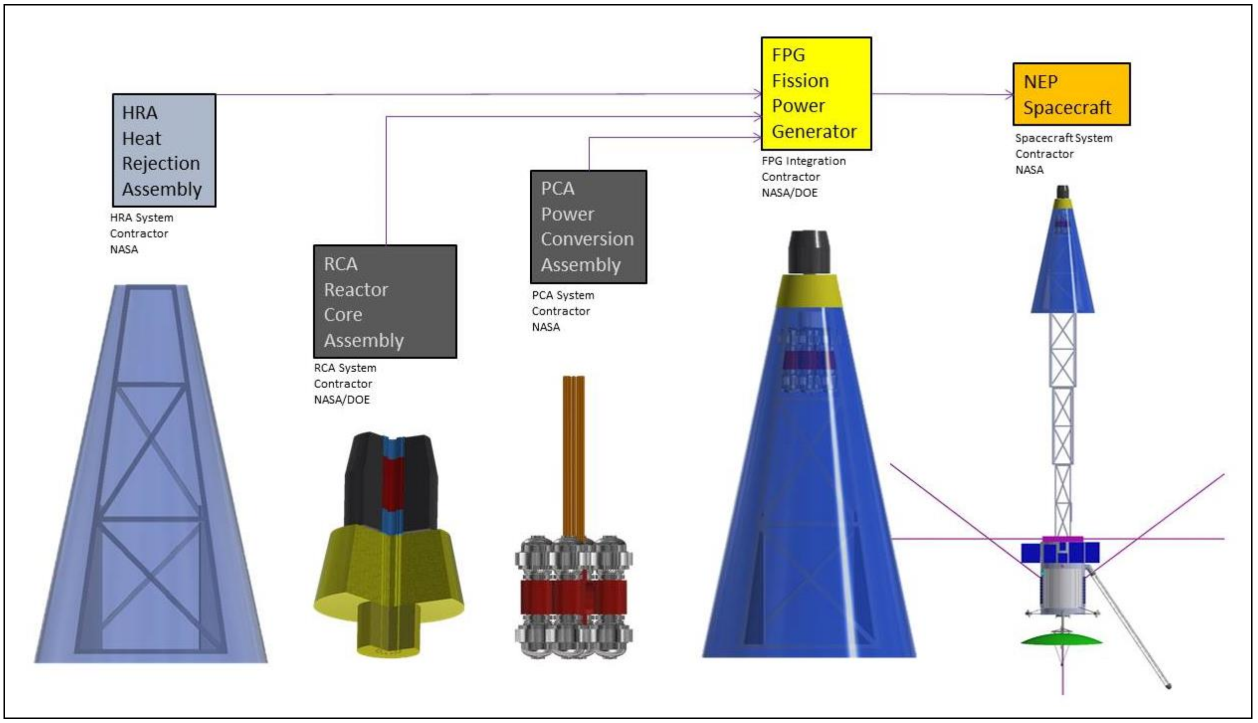


*Figure 6-3. Fission power generator system baseline components plus notional spacecraft for completeness*

The contemplated operational and reliability goals for the fission power generator include the following:

- 10 kWe, 50 kWth, system design with minimal fuel burnup.
- 15-year lifetime to be demonstrated by analysis and by previous deep space mission experience.
- Mass goal of 1000 g.
- 25 krad at 15 m aft of the shield.
- Use of existing and proven technology, or technology currently under development.
- Single point failure concerns in the heat pipes and heat exchanger eliminated by conservative de-rating and margin design as typically done with hydraulic and liquid plumbing systems using normal in process radiologic and other inspection techniques.
- Simplified start up and operation.
- Control rod actuator performance after activation is not required for safe operation, meaning system is fail safe and redundancy is not required.
- The load-following characteristic of the basic core design ensures reactor control during all load variations and spacecraft operating conditions. Ground operation of the control rod is provided only for long-term performance optimization over mission life time.
- Heat pipes and heat exchanger require startup and restart capability in zero gravity.

In March 2018, the KRUSTY nuclear test demonstrated the operation of a flight-like 1 kWe Kilopower system in vacuum at full power and temperature [Poston et al., 2019]. Figure 6-4 shows the actual components of the power system used for the KRUSTY test (fuel, axial reflectors, heat pipes, and Stirling convertors) prior to being inserted into the vacuum chamber. The KRUSTY test was highly prototypic of the Kilopower reactor; i.e., the fuel, heat pipes and reflector used the same materials, geometries, and operating conditions anticipated for a flight system. The KRUSTY power conversion system was less prototypic, but was designed to accurately mimic the heat removal from the reactor; i.e. the reactor–power conversion system interface reproduced the same steady and dynamic responses that a flight system would have. The most significant limitation of KRUSTY was that it used only two Stirling convertors (which were slightly undersized), and the rest of the power was drawn by Stirling simulators designed to mimic the thermodynamic behavior of the Stirling engines. Also, heat rejection was achieved via gaseous nitrogen ($GN_2$) flow, as opposed to the thermal radiator.

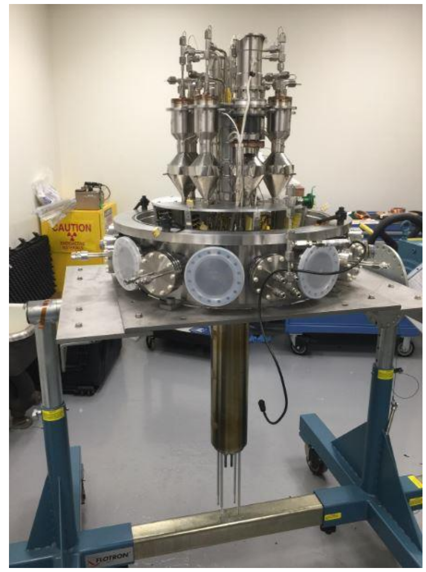

*Figure 6-4. KRUSTY test power system prior to being inserted into the vacuum chamber. This 1 kWe prototype power system used a 1-for-1 heat pipe to engine architecture for a total of 8 heat pipes and engines/thermal simulators. Note that the image is upside down with respect to the launch configuration.*

The KRUSTY nuclear system test also demonstrated the efficiency and robustness of system operation and that a new nuclear system could be designed, built, and tested affordably—the entire cost to fabricate the reactor and the heat pipes and the labor involved in assembling test article and the test setup was less than $20M. This obviously did not include the cost of the Stirling engines, or the full costs of using the NNSA facilities at Y-12 National Security Complex and the Nevada National Security Site (formerly known as the Nevada Test Site); however, the low $20M figure provides a basis of estimates for the work going forward and is reflective of the dedication and ingenuity of the small team that made it all happen.

### *Reactor Core Assembly*

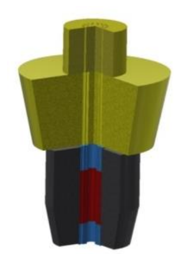

*Figure 6-5. 10 kWe reactor core assembly. Note that the image is upside down with respect to the launch configuration.*

The 10 kWe flight concept has the same basic components as any Kilopower design: fuel, heat pipes, control, reflector, and shield (Figure 6-5). The 10 kWe flight concept uses the same fuel composition that was actually fabricated and used in the KRUSTY test. The heat pipes are composed of Haynes 230, with a sodium (Na) coolant operating at 800°C, again the same as used in the KRUSTY test, although the internal heat pipe design (e.g., wick) will be redesigned and qualified to accommodate both space and surface missions. The beryllium-oxide neutron reflector and boron carbide control materials will also be the same as the KRUSTY test reactor. The 10 kWe concept has the same simplified reactor physics and heat removal characteristics as the 1 kWe concept (KRUSTY), which allows high confidence in reactor performance and operation (e.g., self-regulation and load following) without requiring a nuclear-powered system test. There is no hard limit where live reactor testing is needed vs zero power critical testing, but up to 50 kWth, live reactor testing would not eliminate any significant risk.

The KRUSTY test did not address potential lifetime issues of the reactor core, which includes the fuel, the heat pipes, and the interface between them. The high temperature of the Kilopower fuel, nominally ~800°C (up to 900°C in certain failure modes), is outside the range of most reactor irradiation testing. Several potential issues must be addressed to ensure structural and geometric integrity of the core throughout lifetime [Werner, 2014]. The existing UMo data, in concert with KRUSTY/Kilopower modeling and testing, give high confidence that these fuel risks can be adequately mitigated. The key feature of Kilopower reactors that mitigates lifetime risk is low fuel burnup (<0.5%). If the burnup is kept sufficiently low, then the properties of fresh, unburned fuel will be sufficiently close to irradiated fuel. This allows for core issues, such as mass-diffusion and creep, to be adequately tested in a nonnuclear fashion. It is also important to recognize that Kilopower reactors are not intended to operate on Earth and therefore do not require a rigorous fuel qualification process that might be required by a regulator (as opposed to KRUSTY and other potential ground tests, which must satisfy a regulator to gain permission to operate). Instead, Kilopower fuel, heat pipe, etc. “qualification” is the process of gaining confidence that the reliability risk of the core is in line with the other reliability risks of the overall power system—this is the focus of the Kilopower program.

The biggest difference between the Kilopower 10 kWe reactor and the Kilopower reactor used in the KRUSTY test is the thermal power. To produce 50 kWth, more heat pipes are required, and they must be placed within the fuel to keep the temperature gradients reasonable. As a result, a different heat-pipe-to-fuel bonding method will be needed than was used for KRUSTY (i.e., an interference-fit to create contact pressure). The 10 kWe reactor uses a diffusion bond to connect the heat pipes to the core.

The reactor mass is 187 kg: 45 kg fuel, 19 kg heat pipes, 98 kg reflector, 8 kg control rod and mechanism, and 17 kg structure. This is a best estimate mass, but is tied closely to the as-built KRUSTY test design, so there should be relatively little uncertainty in this estimate.

The shield for the 10 kWe concept is designed to provide a dose of 25 krad (silicon, Si) and neutron fluence of $5\times10^{11}$ n/cm$^2$ (>100 keV) to the payload region. The payload region is assumed to be 4 m in diameter, with 15 m of separation between the reactor and the dose plane. The dose is calculated assuming 10 full-power-years of operation, which could be any combination of full power and reduced power over a 15+ year period. The shield mass is 116 kg: 40 kg lithium hydride, 57 kg depleted uranium, and 19 kg of SS-316.

## *Power Conversion Assembly*

The power conversion assembly comprises the Stirling engines and the engine control electronics, described below.

### Stirling Engines

Stirling power conversion technology has shown significant technical achievements over the past decade (Figure 6-6). The efficiency, long life characteristics, and variable power capabilities are attractive to the NEP system in order to increase the specific power of the system, creating more mass budget for the science payload. Some engine designs have completed over 12 years of life testing in a lab environment with no degradation in power output. Although these power producing Stirlings have yet to fly in space, similar cryo-cooler designs have flight heritage. This technology, at the sub-100 W power levels, is close to being ready to fly and is expected to complete a flight readiness program in the next few years. Larger engines between 1 and 5 kWe have been developed for terrestrial applications with production of several thousand units. These systems are typically heavier and operate at lower temperatures but offer a baseline design for higher power flight systems.

| | Sunpower EE-35 | Infinia TDC | Sunpower ASC | Sunpower P2A | Sunpower GENSETS | AMSC GENSETS | Sunpower PCU |
|---|---|---|---|---|---|---|---|
| Nominal | 35 W | 55 W | 80 W | 1 kW | 1 kW | 1 kW | 6 kW |
| Range | 20 - 42 W | 50 - 60 W | 60 - 90 W | 0.5 - 1.4 kW | 0.4 - 1.1 kW | n/a | 4.5 - 7.2 kW |
| Thot | 650 °C | 650 °C | 760 °C | 550 °C | 650°C, 850C | 670 °C | 575 °C |
| Tcold | 80 °C | 120 °C | 90 °C | 50 °C | 20°C, 80C | 60 °C | 100 °C |
| Frequency | 105 hz | 80 hz | 102 hz | 50 hz | 60 hz | 58-62 hz | 60 hz |
| Piston Amp. | 4 mm | 5.6 mm | 4.5 mm | 10 mm | n/a | 12 mm | 16 mm |
| Approx. Mass | 1.4 kg | 4.5 kg | 2.5 kg | 35 kg | 23 kg (hermetic) | 56 kg | 100 kg |
| Bearings | Gas | Flexure | Gas | Gas | Gas | Flexure | Gas |
| Status | 6 units built for GRC | 16 units built for NASA/DOE, 4 remain on test at GRC | 29 units built for GRC, 13 on test at GRC | >10,000 units built by Microgen for residential CHP | Operational, Active projects, multiple applications | Prototype #1 Running on Natural Gas | 2 prototypes built at SP for 12 kW GRC technology demonstration |

- STC/ Infinia is now American Superconductor (AMSC)
- Sunpower now owned by Ametek, but retains name

*Figure 6-6. Scalability of Stirling convertor technologies*

The power level and number of engines for the 10 kWe NEP system is still under study but will be heavily linked to the reliability and technical risk associated with flight requirements (see Reliability discussion). Several concept power architectures are also being developed to further understand how the impacts of heat transfer, neutronics, and system dynamics affect the overall system reliability and success criteria. One power conversion concept using an intermediate heat exchanger and 8 engines is shown in Figure 6-7.

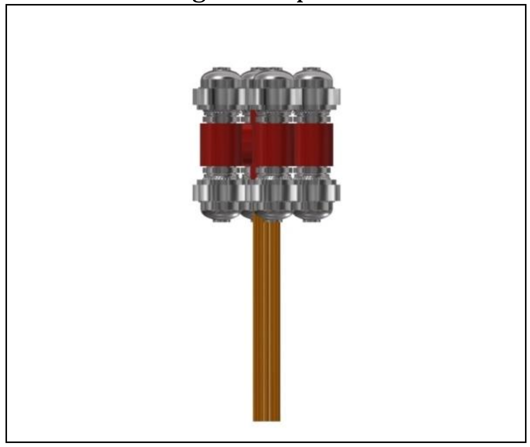

*Figure 6-7. Power conversion assembly. Note that the image is upside down with respect to the launch configuration.*

#### Engine Control Electronics

The engine control electronics (ECE) will be an avionics box with all the necessary electronics to start, stop, and maintain continued Stirling engine operations with a regulated output voltage of 120VDC. It will also have a communications port to allow the spacecraft to send commands and transmit information to and from the spacecraft controller. The engine control electronics architecture will have primary independent cards for each engine with backup cards for redundancy. These cards will control the amplitude and power level of each engine as well as provide power conditioning and distribution to the main bus. The engine control electronics will need input power from a battery prior to engine activation. Once the engines have started, the controller will run on power provided from the engines.

### *Heat Rejection Assembly*

The heat rejection assembly (Figure 6-8) will consist of an array of individual finned heat pipes that will bolt to each Stirling engine and the radiator support structure. These finned water heat pipes will remove heat from the Stirling engines and reject the waste heat to space. The radiator support structure will be bolted to the fission power generator once it arrives from the device assembly facility (DAF) to the PHSF. Once the support structure is in place, each individual radiator panel and heat pipe will be bolted to the cold end of the Stirling engines and to the support structure. Once all heat pipe panels are in place, the radiator assembly will be complete.

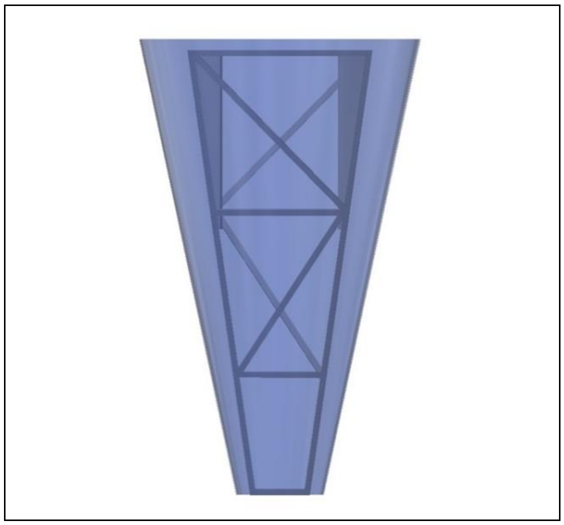

*Figure 6-8. 10 kWe heat rejection assembly. Note that the image is upside down with respect to the launch configuration.*

### *Control and Operation*

The Kilopower fission power generator concept is one of the simplest reactor concepts ever considered. Perhaps the most important “simplicity” of the system is in neutron kinetics. The kinetics of a compact, fast reactor are dominated by one factor—changes in material density or geometry (changes in neutron interaction rates, i.e. cross sections, have small effects). The Kilopower solid core eliminates potential movements of fuel rods or pieces relative to others, and the surrounding geometry is fixed (except for small potential relative movements due to thermal expansion), thus the only major reactivity effects are changes in neutron leakage/reallocation due to material expansion. This makes the startup and operational system dynamics easy to predict and verify.

During startup the control rod will be gradually withdrawn to achieve the desired reactor operating temperature—note that the rod controls temperature (via reactivity), not power. At this point the reactor power will be equal to the passive losses from the system at this temperature. Next the Stirling engines will be activated with reduced stroke (power) and the reactor will load-follow to match that power.

Very shortly thereafter, the power will be ramped to nominal power. It will take somewhere between a few hours to a few days to reach operating power. There is no requirement for a human operator to be in the loop during activation, but the plan is to have one because it greatly simplifies development and eliminates potential system failures.

After activation, the control rod will be exercised occasionally (weekly or monthly) to help maintain operability and will be withdrawn slightly every few months to boost the temperature of the reactor. All of these infrequent, and non-mandatory, control movements will be commanded manually from Earth.

Other than occasional ground commands to move the control rod, all system control is performed by providing commands to the Stirling convertor controllers. Once the control rod has been moved to the appropriate location and the reactor temperature is set, the Stirling controller will automatically turn the engines on in an orderly sequence when the engines are at 600°C.

The controller will operate on the spacecraft battery or solar array until the engines are operational and producing enough power to support a stable bus voltage. Over the next several hours of operation, the controller will gradually increase the engine amplitudes to the desired output power level set by the internal programming, spacecraft commands, or ground commands.

The Stirling controllers will have a communications port allowing it to receive and transmit data from the spacecraft for operational and health status. This allows the spacecraft to modify power output levels if desired and relay reactor status to the ground. Failsafe features will be employed in case spacecraft communications become faulty and the reactor needs to run on constant output power.

## *Reliability*

### Power Conversion Reliability

NASA guidelines do not specify a numerical reliability requirement for a spacecraft or its subsystems. However, studies have been performed which can give some guidance on how reliable both the spacecraft and spacecraft subsystems might be and suggest where redundancy may significantly enhance reliability. Power system reliability may be estimated by breaking down the individual reliability of its subcomponents through a failure mode, effects and criticality analysis (FMECA). Such an analysis was performed during the Advanced Stirling Radioisotope Generator (ASRG) program. Table 6-1 shows the probability of failure (POF) and accompanied reliability estimate of the advanced Stirling convertor (ASC), the advanced controller unit (ACU) and the generator housing assembly (GHA) from the FMECA.

In order to obtain a first cut estimate of the reliability of the Kilopower power conversion assembly, it was assumed that the Stirling convertor and controller reliabilities would be similar to those generated from the ASRG study. For those components that were not used in the ASRG, an attempt was made to estimate their reliabilities. As an example, the balancer reliability estimate was a combination of the alternator assembly and the controller from the ASRG FMECA. These were assumed as representative of an active balancer drive motor and moving mass as well as the accelerometer and control electronics. Because the design of the convertor is unknown, the advanced Stirling convertor FMECA was used to represent a gas-bearing Stirling convertor; for the flexure-based system, a second spring assembly was added and the gas bearing assembly was removed.

Heat pipe reliability was not readily available so the problem was bounded using a 0.2% POF (slightly higher POF than the housing) as a lower bound and a 1.0% POF failure as the worst case (similar to a single Stirling convertor POF). The results from this analysis show that the largest single differentiator was the addition of a redundant controller card for the Stirling convertor. The other subsystems, including the heat pipe and Stirling convertor type (gas bearings or flexures) in general make little difference in reliability.

*Table 6-1. Probability of failure and accompanied reliability estimate of the advanced Stirling convertor (ASC), the advanced controller unit (ACU) and the generator housing assembly (GHA) from the FMECA*

| | Probability of Failure | | | | | | |
|---|---|---|---|---|---|---|---|
| **Case** | Controller | Stirling Convertor(s) | GHA | Balancer + Controller | Heat Pipe | System POF | Reliabilit |
| **ASRG** | 1.30% | 1.76% | 0.07% | 0.00% | 0.00% | 3.1% | **96.9%** |
| **ASRG without Backup Card** | 5.91% | 1.76% | 0.07% | 0.00% | 0.00% | 7.7% | **92.3%** |
| **Single Stirling String + Heat Pipe** | 5.91% | 0.84% | 0.07% | 1.46% | 0.20% | 8.5% | **91.5%** |
| **Single Stirling String + Low Reliability Heat Pipe** | 5.91% | 0.84% | 0.07% | 1.46% | 1.00% | 9.3% | **90.7%** |
| **Single Stirling String with Heat Pipe and Backup Control Card** | 1.03% | 0.84% | 0.07% | 1.46% | 0.20% | 3.6% | **96.4%** |
| **Single Stirling String with Low Reliability Heat Pipe and Controller with Backup** | 1.03% | 0.84% | 0.07% | 1.46% | 1.00% | 4.4% | **95.6%** |
| **Dual Opposed Operation with Heat Pipe and Controller with Backup** | 1.30% | 1.76% | 0.07% | 0.00% | 0.20% | 3.3% | **96.7%** |
| **Dual Opposed Operation with Heat Pipe and Controller without Backup** | 5.91% | 1.76% | 0.07% | 0.00% | 0.20% | 7.9% | **92.1%** |
| **Dual Opposed Operation with Low Reliability Heat Pipe and Controller with Backup** | 1.30% | 1.76% | 0.07% | 0.00% | 1.00% | 4.1% | **95.9%** |

Table 6-1 shows the power system string combinations modeled. In general, those strings without backup controller cards have approximately 90% reliability, while those with backup cards have 96% reliability. These string reliabilities were then used to study the effects of the number of convertors necessary to meet various power conversion assembly reliability requirements. As an example, if the power conversion assembly needs to have 99.9% reliability, how many redundant strings are needed? For a 12-convertor Stirling convertor, heat pipe, and single-card controller string that has 90% reliability, we need to be able to produce full power with half of the convertors failed; therefore, each convertor's maximum power output is 1.9 kWe. Figure 6-6 shows the case when our single-string reliability is raised to 96% with the addition of a backup controller. This drops the number of full power strings allowed to fail to four and reduces the full power output from the convertors to 1.48 kWe. The addition of the backup controller allowed each Stirling convertor to be about 75% less massive than its 90%-reliability counterpart. Future work will look in more detail at both the string reliability assumptions, the requirements for the overall power system including the reactor as well as the number of convertors.

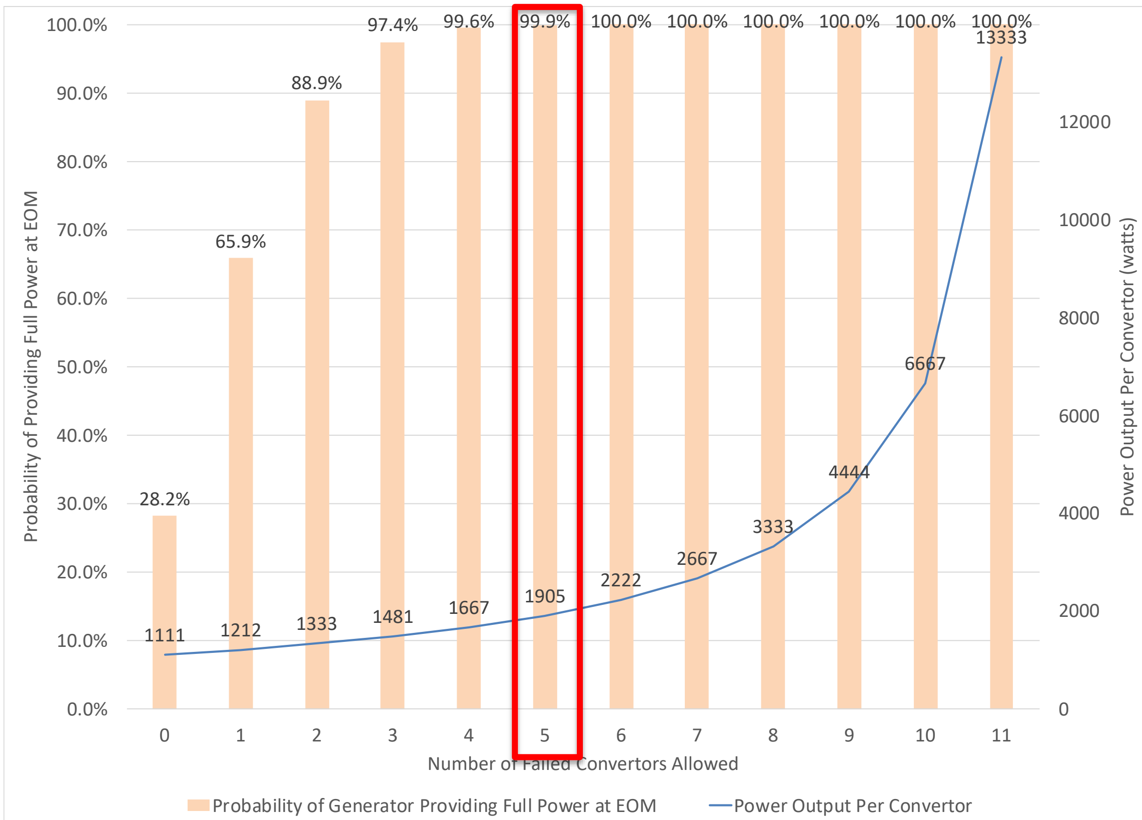


*Figure 6-6. Single-string reliability is raised to 96% with the addition of a backup controller*

### Reactor Reliability

Power system reliability is expected to be mostly a function of Stirling convertor reliability and the level of redundancy. The reactor itself is essentially solid-state, with the control rod being the only moving part. At all power levels, Kilopower reactors can survive worst case transients (e.g. loss of power conversion heat removal) without any control action. The lack of need for real-time reactor control greatly simplifies system control. The Stirling controller can independently control the system, without potential interference and interactions caused by a separate control feature associated with the reactor. The "reactor" control system only needs to move the rod at activation, and whenever a boost reactor temperature is desired – this could possibly be done remotely when deemed necessary by a ground engineer, and thus not require any automated control software.

Another system attribute that leads to high reliability is inherent redundancy in heat transport. Each heat pipe is an independent, highly reliable mechanism. In every Kilopower reactor, full power can be delivered even with several heat pipes or Stirling engines failed. If three heat pipes fail that are directly adjacent to each other, then power level may need to be reduced to avoid exceeding the fuel temperature limit, which requires that heat pipe failures can be diagnosed. The baseline Kilopower power conversion approach is to attach a single Stirling engine to a single heat pipe – referred to as the 1-for-1 approach. This was the configuration used in KRUSTY, which provides the simplest suite of technologies, the simplest system dynamics, and the highest efficiency (i.e., smallest temperature drop). The 1-for-1 configuration requires a large number of small engines, which may or may not be optimal from a cost and development perspective. One negative of this approach is that if a Stirling engine fails it effectively fails a heat pipe in the core, whereas an intermediate heat transfer mechanism would eliminate this problem. However, the 1-for-1 approach provides a reliable diagnostic of heat pipe failure, which will allow mitigation of worst case failure patterns if they indeed occur (noting that the probability of heat pipe failure will likely be much lower than that of a Stirling convertor).

Kilopower reactors should also be very reliable with respect to launch and landing loads. A solid block of fuel eliminates potential fuel-pin, grid plate movements. Heat pipes should also be less fragile than the alternative – coolant piping to and from the reactor, including connections to other loop components; plus, the piping and connections will likely provide a single point failure. The Kilopower project plans to continue to evaluate launch loads, and the system appears robust.

## 7. Kilopower Design: A Cost-Effective Solution for Human and Science Missions

The Kilopower project is designing the 1 kWe and the 10 kWe reactors to support both human and science missions for in-space power and propulsion as well as planetary surface power. This is being accomplished by designing a multi-mission architecture that uses modular components to support several missions. An example of this architecture is shown in Figure 7-1 and works on the principle that one fission power generator design can be used for in-space power, propulsion, or surface power by bolting it directly to the host spacecraft or a lander using an appropriate shield and radiator. Using this multi-mission architecture, the main fission power generator components will only have to go through the extensive development process one time.

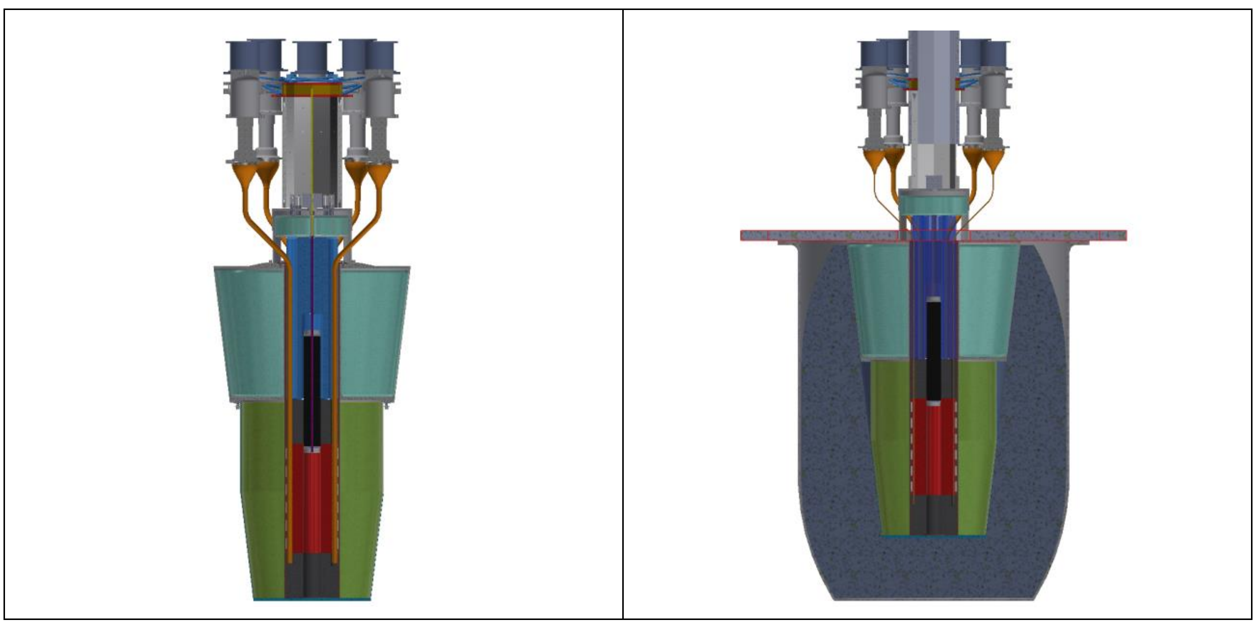

*Figure 7-1: Left: 1 kWe in-space fission power generator design with shadow shield. Right: Same in-space fission power generator design bolted into a 4 pi lunar lander shield. Note that the image is upside down with respect to the launch configuration.*

As an example, when the 10 kWe in-space fission power generator has been qualified and flown, a fission power generator with the exact same design can be used on a surface lander bolted into a

4-pi lander shield and used for surface power (Figure 7-2), or with a NEP system as described herein. The addition of the lander shield with attached fission power generator will require some minimal additional testing without having to change the base fission power generator design and thereby forego an entire new development program. This will ultimately reduce cost and development time by allowing multiple fission power generators to be fabricated at once to support several missions.

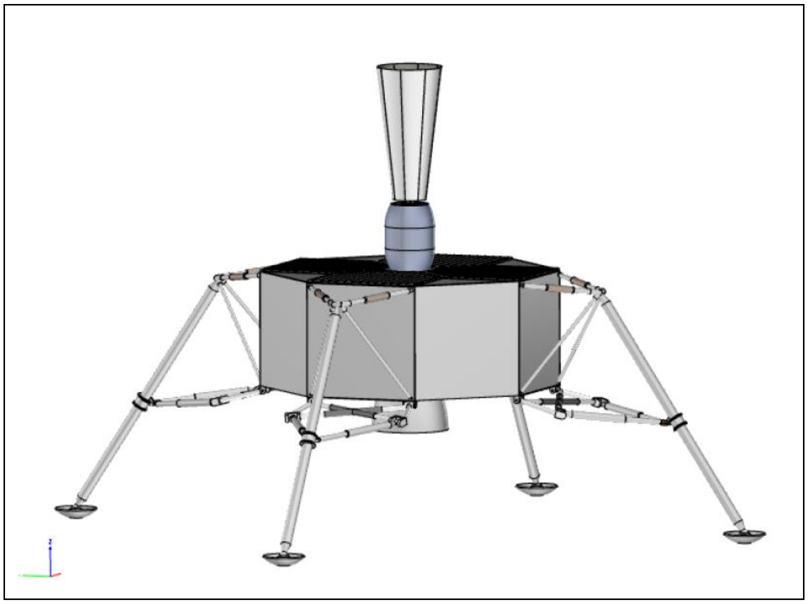

*Figure 7-2: 1 kWe Kilopower fission power generator on lunar lander. In-space fission power generator bolted into 4-pi shield for surface applications.*

The modular platform of the multi-mission design also provides a simplified evolution to higher power fission power generators. Using one fission power generator design at a designated power level to complete several missions provides significant flight experience, building confidence for the next generation of higher power designs. This database of flight experience can reduce the need for ground testing if the fission power generator power levels do not extend past one order of magnitude and the design evolves using realistic advancements. The Kilopower reactors followed this idea and were designed to fly the 1 kWe system to provide extended in-space nuclear testing before moving onto the 10 kWe system. This idea uses space as the testing ground for extended operations and life testing of the reactor instead of ground testing.

Extending this order of magnitude methodology to power grids, several 10 kWe reactors can be used to get to 100 kWe of total power making a fully redundant power grid. At that point, a 100 kWe system would be designed to make the next jump in power level and forego any significant nuclear ground testing due to confidence gained through the past flight experience of the 1 and 10 kWe Kilopower systems. The 100 kWe fission power generator will be expandable to 1 MWe using multiple 100 kWe systems. Approaching reactor development this way can reduce development time and cost and allow each reactor series to expand one order of magnitude in power level before developing a new design.

# 8. Notional Implementation

## *Notional Spacecraft Bus Design*

The notional spacecraft design used in the mission concepts studied in this report is meant to be flexible to accommodate a number of potential missions. To that end there are a number of subsystems and components that can retain the same design for any given mission, and some items that would be mission-specific. Fixed subsystems would include:

- Command and data handling (C&DH)

- Telecom
- Attitude control
- RCS propulsion
- Solar power system (small solar arrays to support reactor activation and commissioning)
- Bus structure
- Fission power generator

Items that may be varied based on mission requirements would include the following:

- Fission power system boom assembly
- Electric propulsion subsystem, primarily number of thrusters and tank size

Regarding the “fixed” subsystems, the conceptual mass equipment list (MEL) includes the following characteristics. Note that for all subsystems (and instruments) the design assumes a radiation hardness of 100 krad (behind 100 mils Al, including an RDM of 2). This flows from an assumption of no more than 25 krad environmental dose during the mission, which combines with the requirement of <25 krad maximum dose from the fission power generator to give a total mission dose of 50 krad at the dose plane. Adding a radiation design margin of 2 results in a required radiation hardness of 100 krad for subsystems and components.

**C&DH**: Single fault tolerant design using available “catalog” cards; e.g., RAD 750, would provide all the functionality required to support systems command, control, health management and science operations.

**Telecom**: The notional concept consists of a redundant Ka band system operating at 200 W RF output through a 3 m steerable HGA. This system should be able to return data at a rate of about 30 kbps to a 34 m DSN ground station even at a range of 38 AU, which is commensurate with operations in the Kuiper belt.

**Attitude Control**: The notional concept makes use of a full complement of standard sensors; redundant Galileo AA-STR star trackers, an internally redundant scalable inertial reference unit (SIRU), and sun sensors derived from the New Horizons design. Control is provided by a set of four Valley Forge Composite Technologies T-Rex reaction wheels, each with a momentum storage capability of 75 Nms.

**RCS (chemical) propulsion**: A small monopropellant hydrazine blowdown system is provided for momentum unloading and small maneuvers. This system comprises a pair of commercial, off-the-shelf (COTS) diaphragm tanks and 16 Aerojet MR 111c thrusters (4.4 N thrust each) mounted on four pods of four thrusters each, providing full control over three axes.

**Solar Power**: A solar power system will be required to provide bus power from launch through activation of the fission power generator. For the notional design this consists of body-mounted solar array producing ~500 W at 1 AU.

**Bus Structure**: The bus structure is a conventional aluminum design making use of a thrust tube and truss structure to bear operational loads. Aluminum honeycomb decks and secondary structure are provided for supporting equipment loads and mounting subsystems and science instruments. A forward deck of solid aluminum immediately aft of the fuel tank(s) provides an additional degree of shielding. This in addition to the separation distance provided by the boom provides a radiation-safe environment for100 krad parts without the need for a radiation vault.

As identified above, the notional spacecraft design describes a bus that can be used for a variety of potential mission concepts. However, the varying mission requirements among these concepts necessitate a degree of flexibility in certain areas of the design. Most notably this applies to the electric propulsion system and propellant tank(s). While the notional design assumes the use of NEXT thrusters, most mission designs are based on operation of a single thruster at a constant power level. The amount of ΔV required to execute the different mission concepts varies greatly, resulting in significant variations in the amount of xenon used in the trajectories.

Currently the NEXT thruster is qualified for a maximum throughput of 1,000 kg of xenon [Yim, 2019; Yim et al., 2019; Yim et al., 2017] for this sort of constant power mission profile. The notional spacecraft design includes three thruster strings, which allows the use of up to 2,000 kg of xenon with one thruster as a spare.

An additional area that would be left to the spacecraft designer is that of the boom assembly used to separate the fission power generator from the spacecraft bus. In the baseline as shown in Figure 2-1 this is depicted as a deployable solid truss assembly that would be stowed for launch and deployed prior to activating the fission power generator. The separation distance will be an important driver in spacecraft design, since the requirement for radiation from the fission power generator is set for a specific distance from the reactor and for a given assumption on the reactor full power run time. Lengthening the separation structure through deployable booms will have a direct impact on lowering the dose received at the bus for missions that need it, and conversely missions with reduced duration or lower dose contributions from the natural radiation environment may be able to take advantage of a lower separation distance to devise a simpler, more compact flight system.

Mass for the flight system was estimated based on conservative current best estimates (CBE) derived for each subsystem based on a detailed subsystem MEL. A maturity-based mass growth allowance was applied to each line item in the MEL per AIAA standards [AIAA, 2006]. Given the early nature of this design study, a further system-level margin was applied to the overall flight system mass to bring the total mass growth allowance to 43% over the CBE, in keeping with JPL and GRC design practices.

The mass for a version of the notional flight system sized for an example mission with a total ΔV requirement of ~11 km/s and a payload allocation of ~50 kg is shown in Table 8-1. This example includes three NEXT-C strings, two for throughput and one spare. For this example, which would be capable of several of the missions studied, the total fully margined dry mass is 2573 kg and the launch mass is 4343 kg.

### *A Notional Acquisition Strategy*

The acquisition strategy objective is to provide flagship-class science for substantially less than typical flagship mission–class cost. The study team recognizes that two separate acquisition strategies will be required for an NEP powered mission, one for the fission powered generator and one for the balance of the spacecraft.

Primary implementation elements include using a variation on a spacecraft system contractor's spacecraft bus, leveraging DOE experience, and an integrated science payload.

*Table 8-1. Example mass for mission with total ΔV ~11 km/s and payload allocation ~50 kg*

| Flight System | CBE Mass (kg) | Contingency (%) | Total Mass (kg) | Comments |
|---|---|---|---|---|
| Instruments | 50.0 | 30% | 65.0 | Allocation |
| C&DH | 35.0 | 25% | 43.8 | |
| Power | 993.0 | 21% | 1201.5 | Fission power generator without boom |
| Telecom | 50.0 | 29% | 64.5 | |
| Structures | 320.0 | 18% | 377.6 | Includes 200 kg for boom |
| Thermal | 75.0 | 0% | 75.0 | Bus thermal |
| EP Propulsion | 196.0 | 21% | 237.2 | Includes 3 strings NEXT and tank |
| RCS Propulsion | 50.0 | 6% | 53.0 | |
| GN&C | 25.0 | 5% | 26.3 | |
| **Flight System Total** | **1794.0** | **19%** | **2143.8** | |
| System Margin | 43% | 20% | 428.8 | To total 43% growth allowance |
| **Dry Mass Total** | | | **2572.5** | |
| Xenon Propellant | | | 1770.0 | Provides ~11 km/s DV |
| Hydrazine Propellant | | | 40.0 | For RCS |
| **Wet Mass Total** | | | **4342.5** | |

### Fission Power Generator

Acquisition of the fission power generator will likely require the use one or more of the existing DOE laboratories in order to ensure DOE indemnification. A commercial vendor may be an option, but indemnification would have to be negotiated. DOE provides indemnification under Public Law 85-804 for DOE and National Nuclear Security Administration contractors for nuclear risks resulting from activities that facilitate the national defense and relate to nonproliferation, weapons reduction, emergency response, anti-terrorism or other such national security activities.

The most likely path for acquiring the fission power generator would be through a DOE laboratory, but the path could be through other national laboratories. LANL is the leading candidate given their long-standing experience in space reactor design, their expertise in nuclear material assembly, their experience in zero power critical testing, and the collaborative working relationship with GRC on the Kilopower and KRUSTY developments.

The responsible DOE laboratory will contract with an outside contractor to be the integrator and delivery agent to the project. The integration contractor will conduct final assembly, quality assurance activities, flight acceptance testing, and delivery to Kennedy Space Center for subsequent integration with the spacecraft bus.

Implementation of fission power generator acquisition will require individual cooperative agreements between NASA and the DOE with the $^{235}$U fissionable fuel provider.

A key assumption is that nuclear development risks have been retired through KRUSTY, and that only nonnuclear standard engineering development risks remain. This claim will need validation by a broader segment of the reactor community, which is why a review for that purpose is one of our primary suggestions for follow-on work (Section 13). Retirement of the nuclear development risks enable a low-risk acquisition of the fission power generator.

### NEP Spacecraft

For the balance of the NEP spacecraft, opportunities for cost savings exist through judicious use of subcontracting with industry. The paragraphs below characterize an abbreviated contracting approach process.

The spacecraft system contractor will provide the spacecraft bus relying on an established system product line. Table 8-2 provides a summary-level comparison of successful missions using system contractors such as Lockheed Martin (LM), Ball Aerospace, and Orbital Sciences (now Northrop Grumman). The contracting type is (a) fixed price or (b) fixed price with a cost reimbursable contract for any design modifications.

As an example, NASA Psyche, a mission to investigate asteroid composition,[12] is at preliminary design review maturity using SEP with the SEP chassis design, integration, and test performed by Space System Loral (SSL) using a commercial bus and fixed price contract basis.

*Table 8-2. JPL Mission History*

| Project | MGS | Stardust | Mars Odyssey | Genesis | Deep Impact | MRO | Dawn | Juno | GRAIL (2 Spacecraft) |
|---|---|---|---|---|---|---|---|---|---|
| Target Body | Mars | Comet Wild-2 | Mars | Heliocentric orbiter sample collection | Impactor at 9P/ Tempel 1 | Mars | Rendezvous and orbit Vesta and Ceres (Ion Propulsion) | Jupiter | Map the structure of the lunar interior |
| Launch Date | 1/7/96 | 2/7/99 | 4/7/01 | 8/8/01 | 1/12/05 | 8/12/05 | 9/27/07 | 8/5/11 | 9/10/11 |
| Contractor | LM | LM | LM | LM | Ball Aerospace | LM | Orbital Sciences | LM | LM |

### Science Payload

The science payload can consist of a single integrated assembly of all, or a subset, of the science instruments and their related support equipment, such as cabling, secondary structure, computer and data handling, if required. The specific configuration of the science payload is a project decision, subject to fitting within the payload accommodation envelope, which is determined during the spacecraft bus preliminary design phase.

### Request for Information

A request for information (RFI) will be prepared to solicit industry responses to identify a spacecraft system contractor. Briefly, the RFI will include the following elements and any underlying assumptions:

[12] The NASA Psyche mission is led by Arizona State University. JPL is responsible for mission management, operations, and navigation. JPL is also doing the systems engineering and providing the avionics for the SSL bus. The spacecraft's solar-electric propulsion chassis will be built by SSL with a payload that includes an imager, magnetometer, and a gamma-ray spectrometer.

- A technical baseline with equipment list with mass and power estimates, performance requirements, development schedule.
- The spacecraft system contractor procures the fission power generator and associated avionics from the DOE integrating agency.
- Develop accommodation for the science payload and integrate instruments or, acquire an integrated instrument assembly.
- The contractor integrates the fission power generator simulators with the spacecraft bus at the contactors site for ATLO activities.
- The spacecraft system contractor ships spacecraft to Kennedy Space Center (KSC), receives the flight fission power generator at KSC, and integrates it with the rest of the spacecraft to the complete the launch-ready space flight system.
- The spacecraft system contractor completes the rest of the pre-flight launch operations and supports the launch.
- The RFI will request the industry contractors discuss their ability to use their own spacecraft bus.

The industry responses are assessed to scrutinize and compare contractor capabilities.

# 9. Commonality Between Human and Science Mission Applications

NASA HEOMD has been contemplating the development of a 10 kWe modular Moon surface power system; therefore, the team decided to look at that power level in the interest of minimizing new development activity for any mission (human or science) that elected to use a fission power system. It turned out that 10 kWe was a very good starting point for NEP. Greater power would yield greater benefits in terms of larger science payload mass and shorter flight times, but it would also approach diminishing returns given currently projected launch vehicle capabilities. The missions studied are all feasible with power limits less than 10 kWe, but to determine a lowest power level as an acceptable design point for the system would require further study. It seems not warranted at this time given no reason to doubt the attainability of a 10 kWe reactor.

Whatever the reactor's power level, the key nuclear design aspects (including the core, the reflectors, the control rod and mechanism, the number and size of the Stirling engines, the heat pipe configuration, and the control electronics) can all be identical for both human exploration and science mission applications. Only the shield, radiators, and the integrating structure will need to be different. As we believe we demonstrate in this report, outer solar system exploration science missions can be well served by Kilopower NEP reactors.

# 10. Development Risks

The KRUSTY nuclear system test eliminated most of the potential technical risk associated with nuclear development and operation. The physics of Kilopower reactors are configured to provide simple, robust, and predictable reactor operation, which the KRUSTY test confirmed. The steady and dynamic behavior of the fission power generator was nearly identical to the predictions of the design and pre-test models. The physics of the 1 kWe system are nearly identical to the 10 kWe system, which provides confidence that the latter will also perform as predicted. This claim needs to be verified with a panel of nuclear experts. The reactor was designed so that nuclear lifetime/aging effects are negligible, as confirmed by the existing database and experience; but this claim could be verified by a panel of experts. Although the physics of the reactor core seem to be known, this 10 kWe concept design assumes embedded heat pipes to the core. This technology, bonding, and thermal performance were not evaluated under KRUSTY and will require analysis and testing.

The development risk for the nonnuclear fission power generator components include risk associated with the Stirling Engines. The 10 kWe concept requires engines at higher power output than those used in KRUSTY. This component will require a technology development phase that may impact the overall project schedule and cost. However, the development cost for the fission power generator will be substantially lower than the $1B price tag associated with past, failed programs.

The nature of the fission power generator design is such that it is constructed of significantly less exotic materials than those required for radioisotope power systems. In fact, the cost driver for RPS lies in the $^{238}$Pu fuel. Cost of production and processing of this fuel has been estimated to be ~$10M per kg or more, meaning the total cost of the 4 kg of plutonium in a Multi-Mission RTG is roughly $40M. By contrast, the fission power generator fuel, cast uranium metal, is readily available from DOE stockpiles. One of the cost saving features of the KRUSTY-derived system is that by avoiding the more exotic fuels and refractory metals that might allow operation at higher temperatures, the design is simpler in every respect and fuel becomes a negligible contributor to system cost.

Design simplicity and production techniques for the fission power generator have been demonstrated in the KRUSTY test, which was executed for less than $20M. While KRUSTY was an initial prototype development of a lower power system than that required for the missions described in this report, it does pave the way and bodes well for a reasonably cost-effective development to bring a 10 kWe fission power generator to flight qualification. As with any new technology development, the initial flight unit would carry the significant cost of development and qualification. However, once qualified, the combination of a simple power system architecture; use of readily available, inexpensive fuel; avoidance of high-temperature operating regimes requiring exotic materials; and lack of significant radiation safety risks during ground handling and launch combine to indicate that subsequent flight units could be produced at low cost, allowing their use in New Frontiers– and possibly Discovery-level deep space missions.

## 11. Programmatic Risks: HEU vs LEU

The 10 kWe concept design assumes use of a HEU core, a configuration that reduces development risk since the fuel is readily available. The use of HEU is a major issue for the United States, and there is pressure to reduce the use of HEU in commercial reactors and research laboratories, including NASA. The primary concern has to do with terrorist interception of weapon-grade material, which is easier to safeguard against in the case of government users than it would be for commercial or university users. Possibly because of that, there does not yet seem to be the same focus on restricting government users or on specific uses, such as for space nuclear power, where HEU has specific advantages for both mass and size.

A decision to eliminate HEU would impact the benefits of Kilopower for both HEOMD and SMD uses. A major impact would be an increase in mass, which for NEP will reduce science payload mas and/or increase flight times. Low-enriched uranium (LEU) has not yet been evaluated for NEP; but an assessment of the impacts on surface power uses of propulsion, both nuclear thermal propulsion and NEP, would be valuable inputs to NASA's deliberations on the use of HEU.

The primary HEU-related risk is during an accidental reentry where under certain accident conditions the reactor could reenter anywhere in the world. The probability is low for these scenarios, and retrieving that material would be a major operation. The same concern is true for an

RTG—not because the $^{238}$Pu can be used for a nuclear weapon but rather it could be used for a dirty bomb. The United States is willing to take the risk to launch RTGs on a regular basis even with the knowledge that the diversion of the material would be a major incident; therefore the same should be true for a nuclear reactor.

## 12. Other Considerations

The following substantive considerations involve requirements, engineering, testing, and verification and will likely be driven by policy consideration affecting security, safety, and transportation.

Security is a good example of a cost uncertainty dealing with policy that at this stage of the project cannot be determined with any certainty. The Nuclear Power Assessment Study [APL/JHU, 2015] estimated that security cost at KSC would be approximately $70M. This estimate was based upon the worst-case time frame of nine months for a DOE security force at KSC.

In order to gain some insight and background on the info provided in the Nuclear Power Assessment Study, NASA GRC and Y-12 staff met with personnel from Peterson Air Force Base (PAFB). One point raised at the meeting was that there already exists a standing security force at the base, and the program should look into the possibility/feasibility of PAFB providing the required security for a lot less than standing up a new force just for a single operation.

The team recognizes that there are matters of policy and perhaps jurisdiction that would have to be resolved before this approach could be validated.

Similar issues exist for both safety and transportation. Safety for a space reactor has been estimated by LANL to be approximately a few millions of dollars and probably bounded by $10M. However, NASA is currently paying about $40M for safety analysis for the RTG program. Changes to the current process (as summarized in Section 3) are currently being developed into requirements and guidelines for use by NASA, DOE and DOD.

For transportation, a new container may be required for transporting the reactor to KSC after assembly. A new container may cost upwards of $10M. However, the FPG could be packed into two or more units, compatible with existing containers. This would require breakdown of the unit after environmental testing and reassembly at KSC. It may also be possible to get an exemption for using an existing container for a short-term, low-count operation such as a one-time launch of a space reactor. This would eliminate much of the cost for transportation. As a follow-on activity, the use of an exemption should be explored further before assuming this cost is certain.

## 13. Follow-on Work

The study team identified follow-on work suggestions that are intended to develop additional detail on the technical and programmatic issues raised in this report.

- Assess the impacts of using LEU for Lunar and Mars surface power and for NEP.
- Engage an independent group of experts (e.g., JASON-type review group) to critically assess the Kilopower design and the KRUSTY results and claims.
- Interface with HEOMD to preclude unnecessary divergence of requirements.
- Conduct a study on conceptual system architectures, the size and number of Stirling engines, and their effect on system reliability, performance, and mass.

- Do developmental testing as appropriate to support the choice of 1-to-1 or heat exchanger coupling to the Stirling engines.
- Conduct a flight system design study to further define spacecraft and interface design requirements and to inform cost estimates for mission concepts.
- Conduct additional trajectory design studies to identify and further refine NEP mission concepts of interest to the scientific community.
- Explore an exemption for using an existing transportation container for short-term, low-frequency use to support launch of a space reactor.
- Assess implications of powered Earth flybys. Evaluate approach for guaranteeing an acceptably low probability of Earth entry by analysis as was done for Cassini.
- Participate in the support of robotic mission objectives to the extent requested for NEP-enabled missions.
- Validate the conclusion that SMD requirements will be satisfied within the fission power generator configuration chosen for HEOMD such that the same reactor and converter configuration will serve the needs of both users.
- Obtain agreement on the fuel enrichment for the Kilopower system.
- Conduct an acquisition study to examine the feasibility of potential concepts for acquiring a NEP-type spacecraft for a typical outer solar system exploration mission.
- Conduct a fission power generator concept design study to develop a basis for estimating cost and mass.
- Some missions could be designed to require an Earth flyby. Assess the consequences of adding or augmenting the existing solar arrays for those missions, if a Cassini-like flyby analysis could not satisfy the safety criteria.
- Outline a safety analysis approach that satisfactorily complies with NASA's implementing requirements and guidelines for NSPM-20 (e.g., the interim update to NPR 8715.3 expected to be released in Summer 2020).
- Further investigate and establish arrangement between DOE, NASA (GRC and KSC), and the Air Force to provide security at KSC during a launch of a HEU space reactor, including retrieval efforts in the event of failed deployment.
- Participate in the development of science objectives to the extent requested for NEP-enabled missions.

# 14. Conclusions

- A 10 kWe NEP capability would enable a new class of outer solar system mission concepts that would not otherwise be possible, and would significantly enhance a range of other deep-space mission concepts by increasing science payload mass, reducing flight time, increasing mission lifetime, and providing ample power for science instruments and/or increased data rates (Section 4).
- This capability presents a breakthrough in science value beyond Cassini class, and would enable NASA to once again plan for large strategic missions to the outer solar system as recommended by the Space Studies Board in its report *Powering Science: NASA's Large Strategic Science Missions* [National Academies, 2017].

- The KRUSTY test of the Kilopower reactor system has paved the way for low-risk development of a fission power generator that could be cost-competitive with current RPS (adjusted for the cost that NASA is paying to achieve 1.5 kg per year), providing significantly higher power capabilities at a comparable price. (Section 10).
- Kilopower development is low cost and low risk.
  - Kilopower reactors are designed to keep the reactor physics simple such that the reactor behavior is analytically tractable and easily verifiable by zero power critical testing. (Section 1 and 6)
  - The core uses inherent reactivity feedback to regulate itself to a temperature set point via thermal expansion/contraction of the fuel, meaning the reactor follows the load without the need for any other reactivity control. (Section 6)
  - The temperature set point is controlled by the position of a single control rod. (Section 1)
  - The fuel burnup is estimated to be <0.5%, which means core lifetime is a non-issue. (Section 2)
- Developing the cost-competitive capability would require that NASA contract with system contractors who have existing avionic product lines.
- The first use of the 10 kWe NEP system would certainly occur after the launch of the first HEOMD mission. By coordinating with HEOMD planners, the NEP implementation can evolve in a way to permit the use of a HEOMD-developed reactor and power conversion system to be used virtually without change for the NEP application (Sections 7 and 9).
- Likewise, a spacecraft-configured clone of the 1 kWe fission power system being developed for the first HEOMD mission could be considered as an RPS backup for cost and schedule risks attendant to the $^{238}$Pu resupply project, or as a lower cost alternative (Section 7).
- The timing is right to develop the Kilopower 10 kWe capability given KRUSTY's success. Such a decision would enable several compelling HEOMD and SMD missions and serve as a pathfinder and risk reduction strategy for the larger needs of future HEOMD space power systems across the Moon–Mars system.

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## Appendix A. Glossary

| | |
|---|---|
| delivered mass | Total dry mass in orbit including science payload mass plus residual fuel mass after orbit insertion |
| dose plane | The dose plane is an imaginary plane, 5 m in diameter, centered on the Z-axis and located 15 m from the spacecraft-facing end of the FPG radiation shield. |
| DUFF | Demonstration Using Flattop Fissions, (DUFF), was a low cost experiment that used an existing nuclear critical assembly (i.e., small reactor) with a single heat pipe to a pair of Stirling engines to demonstrate the physics of the Kilopower reactor concept. The experiment was performed in 2012 by LANL and NASA. The experiment also demonstrated that low cost nuclear testing was possible. |
| flight system | The combination of the instruments (or science payload), the spacecraft bus (which includes the boom assembly), and the fission power generator |
| fuel (Kilopower projects) | Cast form of a highly enriched uranium-molybdenum (UMo) alloy currently in store at Y-12 |
| Kilopower | Kilopower is a space reactor concept for either deep space or planetary surface missions. It ranges in power from 1 kW electric to 10 kW electric and has variable shielding configurations depending on the mission. The reactor core and power conversion use a standardized technology consisting of a Uranium Moly alloy core, Sodium filled heat pipes, a Beryllium oxide reflector, Stirling Engines, a Boron Carbide start rod and Tungsten/Lithium Hydride shielding. |
| KRUSTY | The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) was a test program to demonstrate the 1 kW electric (4 kW thermal) Kilopower reactor concept. The test had a Y-12 manufactured HEU core, eight heat pipes, two Stirling engines, and six Stirling engine simulators in a vacuum that used nuclear heat to run the reactor at steady state and thru several transients to show fault tolerance. The test was the first demonstration of a new reactor concept in over forty years. The test was the basis for assigning a TRL 5 to the reactor. |
| PHSF: Payload Hazardous Servicing Facility | A facility at KSC designed to accommodate a variety of NASA and NASA customer payloads; it can be used as a payload processing facility (PPF) or a hazardous processing facility (HPF). When a payload uses the facility as a PPF, it is assembled, configured and checked out for launch. In its function as an HPF, the PHSF accommodates such payload activities as ordnance installation, loading of liquid propellants (hypergols, etc.), hazardous systems tests/checkout, buildup/mating of a payload to a solid propellant upper-stage motor, propellant leak tests and other potentially hazardous operations. |

| | |
|---|---|
| science instrument mass | Total mass of all instrument assemblies for a specific instrument including the instrument specific shielding mass required to accommodate the total mission dose at the mounting location |
| science payload mass | Total mass of all science instruments and their assemblies, including mass for all location-related shielding. |

# Appendix B. Acronyms and Abbreviations

| | |
|---|---|
| ACU | advanced controller unit |
| ARRM | Asteroid Redirect Robotic Mission |
| ASC | advanced Stirling converter |
| ASRG | Advanced Stirling Radioisotope Generator |
| ATLO | assembly, test, and launch operations |
| $B_4C$ | boron carbide |
| BeO | beryllium oxide, also known as beryllia |
| BWG | beam waveguide |
| C&DH | command and data handling |
| CBE | current best estimate |
| COMPASS | Collaborative Modeling for Parametric Assessment of Space Systems |
| COTS | commercial, off-the-shelf |
| CRE | control rod actuator electronics |
| DAF | Device Assembly Facility |
| DOE | Department of Energy |
| DU | depleted uranium |
| DUFF | Demonstration Using Flattop Fission |
| ECE | engine control electronics |
| EGA | Earth gravity assist |
| EMI | electromagnetic interference |
| eMMRTG | Enhanced Multi-Mission Radioisotope Thermoelectric Generator |
| EP | electric propulsion |
| ESA | European Space Agency |
| FH | Falcon Heavy |
| FMECA | failure mode, effects and criticality analysis |

| | |
|---|---|
| FOM | figure of merit |
| FPG | fission power generator |
| FPGAO | fission power generator assembly operations |
| FPGDTS | fission power generator dynamic/thermal simulator |
| FPGFS | fission power generator functional simulator |
| GHA | generator housing assembly |
| GN&C | guidance, navigation, and control |
| $GN_2$ | gaseous nitrogen |
| GRC | NASA Glenn Research Center |
| HEOMD | NASA Human Exploration and Operations Mission Directorate |
| HEU | highly enriched uranium (20% or higher concentration of $^{235}U$) |
| HGA | high-gain antenna |
| INL | Idaho National Laboratory |
| JGA | Jupiter gravity assist |
| JPL | Jet Propulsion Laboratory, California Institute of Technology |
| Kilopower | The Kilopower project, near-term technology effort to develop preliminary concepts and technologies that could be used for an affordable fission nuclear power system to enable long-duration stays on planetary surfaces. |
| KRUSTY | Kilopower Reactor Using Stirling Technology |
| KSC | NASA Kennedy Space Center |
| kWe | kilowatt-electric |
| kWth | kilowatt-thermal |
| LANL | DOE Los Alamos National Laboratory |
| LEU | low-enriched uranium |
| LiH/W | lithium hydride/tungsten |
| LM | Lockheed Martin |

| | |
|---|---|
| MEL | mass equipment list |
| Na | sodium |
| NASA | Nasa Aeronautics and Space Administration |
| NE | DOE Office of Nuclear Energy |
| NEP | nuclear electric propulsion |
| NEPA | National Environmental Protection Act |
| NEXT-C | NASA Evolutionary Xenon Thruster–Commercial |
| NNSA | National Nuclear Security Administration |
| OSS | Outer Solar System |
| OST | DOE Office of Secure Transportation |
| PAFB | Peterson Air Force Base |
| PCS | power conversion system |
| PHSF | Payload Hazardous Servicing Facility |
| POF | probability of failure |
| PPF | Payload Processing Facility |
| $^{238}$Pu | plutonium-238 |
| RAD | radiation hardened |
| RCS | reaction control subsystem |
| REP | radioisotope electric propulsion |
| RFI | request for information |
| RPS | radioisotope power system |
| RTG | radioisotope thermoelectric generator |
| SAR | safety analysis report |
| S/C | spacecraft |
| SEP | solar electric propulsion |

| | |
|---|---|
| SIRU | scalable inertial reference unit |
| SMD | NASA Science Mission Directorate |
| SNAP | Systems for Nuclear, Auxiliary Power |
| SSL | Space System Loral |
| STMD | NASA Space Technology Mission Directorate |
| TOF | time of flight |
| TWTA | traveling wave tube amplifier |
| $^{235}U$ | uranium-235 |
| UMo | uranium molybdenum |
| $\Delta V$ | delta velocity |
| Y-12 | Y-12 National Security Complex |

# Appendix C. Study Team

## Roles and Affiliations

| | | |
|---|---|---|
| *John R. Casani* | *Study Team Leader* | *JPL* |
| *Fred G. Doumani* | *Cost Modeling* | *JPL* |
| *John O. Elliott* | *System Engineering* | *JPL* |
| *Marc A. Gibson* | *Mechanical Engineering* | *GRC* |
| *Patrick J. Guske* | *Ground System Engineering* | *JPL* |
| *Dionne M Hernández-Lugo* | *Kilopower Project Manager* | *GRC* |
| *Steven L. McCarty* | *Trajectory Design* | *GRC* |
| *Patrick R. McClure* | *Reactor Test and Operations* | *LANL* |
| *Timothy P. McElrath* | *Trajectory Design* | *JPL* |
| *Steven R. Oleson* | *Mission Design* | *GRC* |
| *David I. Poston* | *Reactor Design* | *LANL* |
| *Paul C. Schmitz* | *Mechanical Engineering* | *GRC (Vantage Partners LLC)* |
| *Christophe J. Sotin* | *Science* | *JPL* |
| *Nathan J. Strange* | *Mission Design* | *JPL* |

## Biographies

**JOHN R. CASANI** (Study Team Leader, JPL) has decades of space program experience. He earned a Bachelor of Science degree in electrical engineering from the University of Pennsylvania in1955; after one year at Rome Air Development Center in Rome, New York, he continued his career at the Jet Propulsion Laboratory in 1956. His early career included development work as cognizant Accelerometer Engineer on the Sergeant Guided Missile and Integration Engineer on the CODORAC (coded Doppler radar command) Guidance System for the Jupiter intermediate-range ballistic missile (IRBM). He was a 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; and he has been involved with large cross–NASA center, inter-agency, international programs and projects. Dr. Casani was elected into the National Academy of Engineering in 1989 for pioneering systems engineering of planetary spacecraft, and he has served on several NAE committees as well as the Department of Energy National Nuclear Security Administration (NNSA) Advisory Panel. He also chaired a team jointly chartered by NASA and DOE to recommend a strategy for providing future space power systems; the report of this team was widely endorsed and formed the basis for NASA's Nuclear Systems Initiative. He is an honorary fellow of the AIAA and has received the AIAA von Kármán Lectureship in Astronautics Award. Dr. Casani has been recognized with many other prestigious awards, including the Smithsonian's National Air and Space Museum's Lifetime Achievement Award and three honorary doctorates: an honorary doctor of science degree from the University of Pennsylvania, Philadelphia; an honorary degree in aerospace engineering from the University of Rome La Sapienza for his work as project manager for NASA's Voyager, Galileo, and Cassini space missions; and an honorary degree from New York University.

**FRED G. DOUMANI** (Cost Modeling, JPL) has over 36 years of extensive cost estimating, pricing, and technical/contract/business management experience. Mr. Doumani is currently the manager of

Cost Estimation and Pricing at the Jet Propulsion Laboratory. Before this position, he was the manager of the Costing Office within JPL's Project Support Office, a position he held since coming to JPL in January of 2003. Prior to his career at JPL, Fred spent 20 years at Rockwell/Boeing working in engineering and finance. He held numerous management positions within the technical and financial organizations both in the military and commercial aircraft operations as well as their space segments and classified areas.

**JOHN O. ELLIOTT** (System Engineering, JPL) is a principal engineer in JPL's Mission Concept Systems Development group. He is currently leading studies in support of future outer planets exploration in addition to ongoing work in the development of concepts for robotic lunar exploration. He currently serves as lead architect and systems engineer for the Solar System Mission Formulation office and core flight systems engineer on JPL's A-Team for early mission concept development. His recent tasks have included serving as study lead for NASA's Ice Giants Pre-Decadal Survey Mission Study, and performing systems engineering and leadership roles on a number of recent Discovery and New Frontiers mission proposals. Mr. Elliott's past work has been strongly involved in missions enabled by nuclear power, including designs for cryobot missions to Mars' polar cap, an RPS-enabled Pluto orbiter, and systems engineering for the Prometheus Project, from the earliest preliminary mission studies through the eventual project deferment. He was also a member of John Casani's RPS Provisioning Strategy Team, which led to the development of the current MMRTG. With Master's and Bachelor's degrees in Nuclear Engineering from Purdue University, Mr. Elliott's past experience includes six years in the terrestrial nuclear power industry with Bechtel Corporation in addition to 28 years in aerospace systems at TRW and JPL.

**MARC A. GIBSON** (Mechanical Engineering, GRC) is the lead engineer for NASA's nuclear systems Kilopower project tasked with advancing the technology readiness of fission power systems for space. Mr. Gibson started his career at NASA in 2007 after working in the private sector for ten years as chief engineer for numerous commercial and government research projects. Since being at NASA, Marc has been responsible for the engineering and development of nuclear systems for in-space and planetary surface power in support of the Space Technology Mission Directorate. He received a bachelor's degree in Mechanical Engineering from the University of Akron and a Master's in Aerospace Engineering from the Case Western Reserve University.

**PATRICK J. GUSKE** (Ground System Engineering, JPL) began his time at JPL more than 25 years ago when he joined the Galileo Project as a Mission Planner. Since that time he has held senior System Engineering and Management positions during all phases of mission development and operations on a number of Deep Space and Earth Orbiting missions, including the roles of Mission Operations System Engineer, Mission Operations Manager and Project Manager for the Orbiting Carbon Observatory 2 (OCO-2) Project and Mission System Manager for the Asteroid Redirect Robotic Mission (ARRM). Mr. Guske received a B.S. in Aeronautical Engineering from Cal Poly, San Luis Obispo and an MSc in Astronautics and Space Engineering from the Cranfield Institute of Technology in Cranfield, England.

**DIONNE M. HERNÁNDEZ-LUGO** (Kilopower Project Manager, GRC) manages a multi-agency team (NASA and DOE) in the development of nuclear flight concepts for future NASA Moon and Mars missions. Currently she leads the pre-formulation under the Science Technology Mission Directorate (STMD) for the development of a 1-kWe Kilopower system for surface power on the Moon. Previous to joining the Kilopower project, she served as the technical and battery lead for the X-57 Maxwell all-electrified aircraft; in this role she was responsible of managing a multi-agency team in the development of a lithium-ion battery system as the main power source for this electrified aircraft. Her work within NASA targets the development of new innovative technology necessary to make the breakthrough gains in power systems for future space explorations. Dr.

Hernández-Lugo has been recognized across a number of forums for her outstanding leadership and meticulous research. In 2013, she received Crain's Cleveland Business 40 under 40 Club Award as a young Hispanic leader in the Cleveland community. In 2013, she was awarded the Women of Color STEM Leadership Award. NASA recognized Dr. Hernández-Lugo's commitment to STEM education and leadership with a 2012 NASA Ambassador award, a 2018 Aeronautics Research Mission Directorate (ARMD) Associate Administrator Award, and various NASA group awards. Dr. Hernández-Lugo holds a bachelor's degree in Industrial Chemistry and a Ph. D. in Physical Chemistry from the University of Puerto Rico.

**STEVEN L. MCCARTY** (Trajectory Design, GRC) is an Aerospace Engineer in the Mission Architecture and Analysis Branch at NASA Glenn Research Center. His work primarily focuses on low thrust mission design for Earth orbiting, cislunar, and interplanetary spacecraft. In addition to supporting regular mission concept studies, he is a member of the mission design team for NASA's Gateway and Power & Propulsion Element, and previously supported the Asteroid Redirect Robotic Mission. Steven graduated from the University of Michigan with a BSE in Aerospace Engineering and ME in Space Engineering.

**PATRICK R. MCCLURE** (Reactor Test and Operations, LANL) is the project lead for the Kilopower project at Los Alamos. He helped define the groundbreaking approach to reactor development for Kilopower and he was the regulatory lead for the project. Mr. McClure is a former line manager for the Nuclear System Design and Analysis Group. He has been at LANL for 24 years performing nuclear design for very small reactor systems and safety analysis for a variety of reactor concepts with an emphasis on severe nuclear accidents like Three Mile Island and Fukushima. Mr. McClure has a B.S. from the University of Oklahoma and a M.S. from the University of New Mexico.

**TIMOTHY P. MCELRATH** (Trajectory Design, JPL) has worked on navigation and mission design for numerous missions and mission concepts since arriving at JPL over 34 years ago. Most recently, he led the mission design and navigation team for the Europa Lander concept, and before that he worked on ARRM. His mission design experience spans both gravity-assist and low-thrust trajectories, and he has published papers in both areas. Mr. McElrath received a Bachelor of Science degree from MIT in 198, and a M.S. from USC in 1990, both in Aerospace Engineering.

**STEVEN R. OLESON** (Mission Design, GRC) has been at the NASA Glenn Research Center in Cleveland Ohio for the last 25 years. During that time he has performed low thrust mission design, developed and tested electric propulsion devices and created many advanced mission concepts. He is currently the Lead for the award-winning COMPASS Concurrent Engineering Team, which develops conceptual space system designs for many government and industry customers. Over the last ten years the COMPASS team has performed more than 150 innovative designs, such as the Asteroid Return Mission for the Keck Institute and the Venus Landsailer, Triton Hopper, and Titan Submarine for the NASA Innovative and Advanced Concepts Program. He was recently awarded the NASA Outstanding Leadership Medal for his leadership of the COMPASS team. His education includes a BSME from Ohio Northern University and a master's in Astronautical Engineering from the Air Force Institute of Technology.

**DAVID I. POSTON** (Reactor Design, LANL) is the leader of the Compact Fission Reactor Design Team at Los Alamos National Laboratory. This team is responsible for the design and development of nuclear fission reactors for civilian, NASA, and defense applications in space. Dr. Poston is the Chief Reactor Designer for the NASA Kilopower Project, including the DUFF and KRUSTY reactor experiments. Dr. Poston's 25 years of space reactor experience has been primarily been focused on near-term concepts for solar system exploration (including designs for missions to the Moon, Mars, Jupiter, Saturn, and Neptune). In addition, Dr. Poston has developed several Nuclear Thermal Rocket (NTR) design concepts for NASA, and numerous special purpose reactor concepts for commercial and defense applications. Prior to his experience at Los Alamos, Dr. Poston worked at GE Nuclear Energy for 4 years on advanced reactor design. Dr. Poston received a BS in Mechanical Engineering the University of Michigan, an MS in Mechanical Engineering from Stanford University, an MS in Nuclear Engineering from the University of California at Berkeley, and a PhD in Nuclear Engineering (thesis in Nuclear Thermal Propulsion) from the University of Michigan.

**PAUL C. SCHMITZ** (Mechanical Engineering, GRC/Vantage Partners LLC) is nuclear systems engineer at the NASA Glenn Research Center (GRC) currently focused on radioisotope power systems. He began working at GRC in 1989 and has worked on both the SP-100 program and Jupiter Icy Moons Orbiter. Beyond the early years focused on nuclear reactors he has worked on a wide range of projects as diverse as radioisotope power systems, high-altitude power IC engines for atmospheric science, and fuel cells for uninterruptible power supplies and long endurance aircraft. He is currently focused on analysis of dynamic radioisotope generators. He has a B.S. in Physics from Sam Houston State University, a M.S. Degree in Physics from Case Western Reserve University, and a M.S. in Nuclear Engineering from Texas A&M University.

**CHRISTOPHE J. SOTIN** (Science, JPL) received an Engineer's Degree in Geology and Geophysical Engineering from *Ecole Nationale Superieure de Geologie*, Nancy, France in 1981 and a *Doctorat es Sciences* from University of Paris VII in 1986. After a postdoctoral period at Brown University (Providence, RI), he created a laboratory in planetary geology and geophysics who is now located at the University of Nantes, France (period 1989–2007) where he was Professor. He mentored 18 PhD students, many of them being now involved in planetary missions in Europe. He moved to JPL in 2007 where he is presently Chief Scientist for Solar System Exploration. He has published more than 200 papers on the geology, interior structure, and dynamics of planets and moons. He determined the relationships between radius and mass of extrasolar terrestrial planets and ocean worlds. He has been Inter-Disciplinary Scientist on the Venus-Express mission, and Co-I of the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft, for which he implemented the Titan observations. He has worked on a number of mission concepts to the outer solar system. He was awarded the Runcorn-Florensky medal of the European Geoscience Union in 2008.

**NATHAN J. STRANGE** (Mission Design, JPL) is the Supervisor for the Mission Engineering and Planning Group (since 2017) in the JPL Mission Systems Engineering Section. Previously, he was the Mission Design Manager for NASA's Asteroid Redirection Robotic Mission (ARRM). He has supported numerous robotic and human mission concept studies in both mission design and systems engineering and has also spent 6 years on the Cassini-Huygens Mission Navigation Team as a gravity-assist tour designer. Dr. Strange holds a bachelor's degree in physics, and a master's and doctorate in Aerospace, Aeronautical, and Astronautical Engineering, all from Purdue University.

# Appendix D. Kilopower Launch Safety Estimate of Maximum Credible Accident Dose Calculations

**Patrick McClure, Los Alamos National Laboratory**

**Los Alamos Unlimited Release LA-UR-17-23520**

## *Introduction*

The KiloPower reactor concept is intended for both deep space and planetary surface missions. It must therefore be safe during each phase of launch until it is safely away from the Earth. Safe being defined in this study as minimal risk to the public (more on this later.) A design consideration of the system being that the reactor will not be turned on (fission occurring) until it reaches a safe distance away from the Earth. It is not the intent of the KiloPower program for the reactor to be used in Low-Earth-Orbit (LEO). Safety in LEO is a much more complicated matter for a reactor when there is any potential of the reactor re-entering the atmosphere after the reactor has been turned on and has a substantial fission product inventory.

This note presents the definition of the maximum credible accident and the analysis of very conservative estimates of the dose from such an accident as a function of distance in the immediate downwind direction. This dose would be used in determining the risk associated with these accidents for the launch of a KiloPower reactor and formulating a safety strategy for the design going forward.

## *Maximum Credible Accident*

In order to even have an offsite dose from an accident involving the KiloPower reactor, a portion of the fuel must be “aerosolized” during an accident and be transported offsite by atmospheric wind conditions. The two leading accidents capable of creating a large amount of aerosol would be a fire or an explosion. Other accidents, such as impact from a drop, may create an aerosol but the amount created would be trivial.

Of the fire and explosion accidents there are competing factors. First the size of the fire and size of the explosion are important in how they impact the nuclear material and how much becomes aerosolized. But this effect is offset by the fact that the explosion and fire both loft the plume and cause increased dispersion of the aerosol. For this study, the amount that becomes an aerosol will be set to the maximum value while plume lofting will be investigated.

For this study, several accidents will be examined, and include:

- A baseline point source release of the aerosol elevated to 200 ft. in the air (about the height of a rocket) and using the release values for a fire.
- A ground level explosion using 1000 lbs., 10,000 lbs. and 50,00 lbs. of explosive TNT equivalent.
- A ground level fire with 1 MW of peak output and a 10 MW peak output.

## *Reactor Core Assumptions*

The KiloPower reactor concept uses a Highly Enriched (93%) Uranium metal core with 8% Molybdenum. The weight of Uranium (excluding Moly) in the core varies from 23 kgs to 46 kgs for the 1 kWe to 10 kWe systems respectively. The uranium will have a maximum of 1% $U^{234}$ that accompanies the $U^{235}$ during enrichment, although actual material to date is about 0.7%. Using the largest core and maximum of $U^{234}$ the curie content of the reactor then is:

- 2.7 Ci of $U^{234}$
- 8.4E-2 Ci of $U^{235}$
- 8.5E-4 Ci of $U^{238}$

The uranium core may be accompanied by a neutron source that ensures neutrons are available for the start-up of the reactor. The use of a neutron source has not been decided given the abundance of neutrons in space. The neutron source will be either a Plutonium-Beryllium source or an Americium-Beryllium source. The curie content of the source could vary from sub-curies to as much as 0.5 curies. For this study, the maximum curie content will be used. Therefore, 0.5 Ci of $Am^{241}$ will be used as a parametric additive to the core radioactive inventory.

### *Release Fractions During an Accident*

Release fractions for the postulated accidents are based on the maximum values provided in DOE-HDBK-3010-94. DOE-HDBK-3010 is the DOE standard for accidental releases for nuclear material at DOE sites. The values used are the maximum values for both explosion and fire involving uranium metal. The values and the reasoning behind the values are discussed below.

Explosions on a launch pad would involve a large amount of fuel exploding and producing a large explosive force that could vary from 1000s of kgs TNT equivalent up to kiloton TNT equivalent (estimate of the Russian N1 rocket accident.) This force would cause a shock wave that would impact the reactor core in a violent manner with the most extreme case being vaporizing the reactor core.

For this study, the experimental work performed for accidental implosions of nuclear material during weapons testing is used a surrogate. The data was obtained during project “Roller Coaster” at the Nevada Test Site in the 1960s. The “Roller Coaster” data looks at an implosion device imparting a shock wave into the nuclear material and causing all the material to be an aerosol. The material in the air forms an aerosol distribution that has approximately a 20% fraction that is less than 10 microns Aerodynamic Equivalent Diameter (AED). 10 microns AED aerosol is the cutoff for material that can be lodged into the deep lung and contribute to radioactive dose. DOE-HNDB-3010 views the 20% of material released in the respirable range (Airborne Release Fraction, ARF x Respirable Fraction, RF) as the maximum for any explosive accident. Vaporizing the reactor core during the rocket explosion is seen as the worst-case event, thus, ARFxRF will be set to the maximum value of 0.20.

A large fire on the launch pad will most likely melt the reactor metal core and cause the metal to both oxidize and relocate simultaneously. The closest phenomena in DOE-HDNB-3010 is the spill and free fall of molten uranium which has an ARFxRF of 6E-3. To be conservative this value will be rounded up to 1.E-2.

The ARFxRF maximum values will be applied for all cases independent of the size explosion or fire. This is a conservative assumption, but does not accurately represent the real situation. Small explosions or fires would in actuality create smaller amounts of aerosols up to a maximum value that would not change. This effect is not captured in this study.

### Weather Assumptions

The NRC and DOE both use the 95% percentile worst-case weather conditions when examining the potential dose from accidental releases of nuclear material. Based upon experience with these types of calculations, the 95% percentile weather conditions occur under very stable weather conditions with very low winds speeds. These are conditions that tend to not disperse the aerosols and therefore produce the maximum offsite dose. These weather conditions are best represented by an F weather stability and a wind speed of 1 m/s in the direction of the nearest population center or the closest distance to public access.

### Other Assumptions

The standard breathing rate used by the NRC and DOE of 3.3E-4 $m^3/s$ will be used. Standard Gaussian plume modeling will be employed. The height of a rocket is estimated to be 200 ft. (~61 m).

### Computer Code – HotSpot

The HotSpot Health Physics Codes, or HotSpot program, provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. Lawrence Livermore National Laboratory created the HotSpot program to equip emergency response personnel and planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. HotSpot includes atmospheric dispersion models for plutonium in an explosion, fire, and resuspension; uranium in an explosion and fire; and a tritium release. Additional "General" programs address the release of any radionuclide or mixture in the HotSpot library. These models estimate the downwind radiological impact following the release of radioactive material resulting from a short-term release (less than a few hours), explosive release, fuel fire, or an area contamination event. HotSpot models explosions as input into a Gaussian model as shown in Figure 1.

The purpose of the model is to determine the height of the plume and the initial distribution of aerosol form the explosion.

Similarly, how fire plumes are modeled is as shown in Figure 2. The purpose of the fire modeling is to determine the height and size of the plume based on the size of the fire. Again this will feed into the initial conditions used in the Gaussian model.

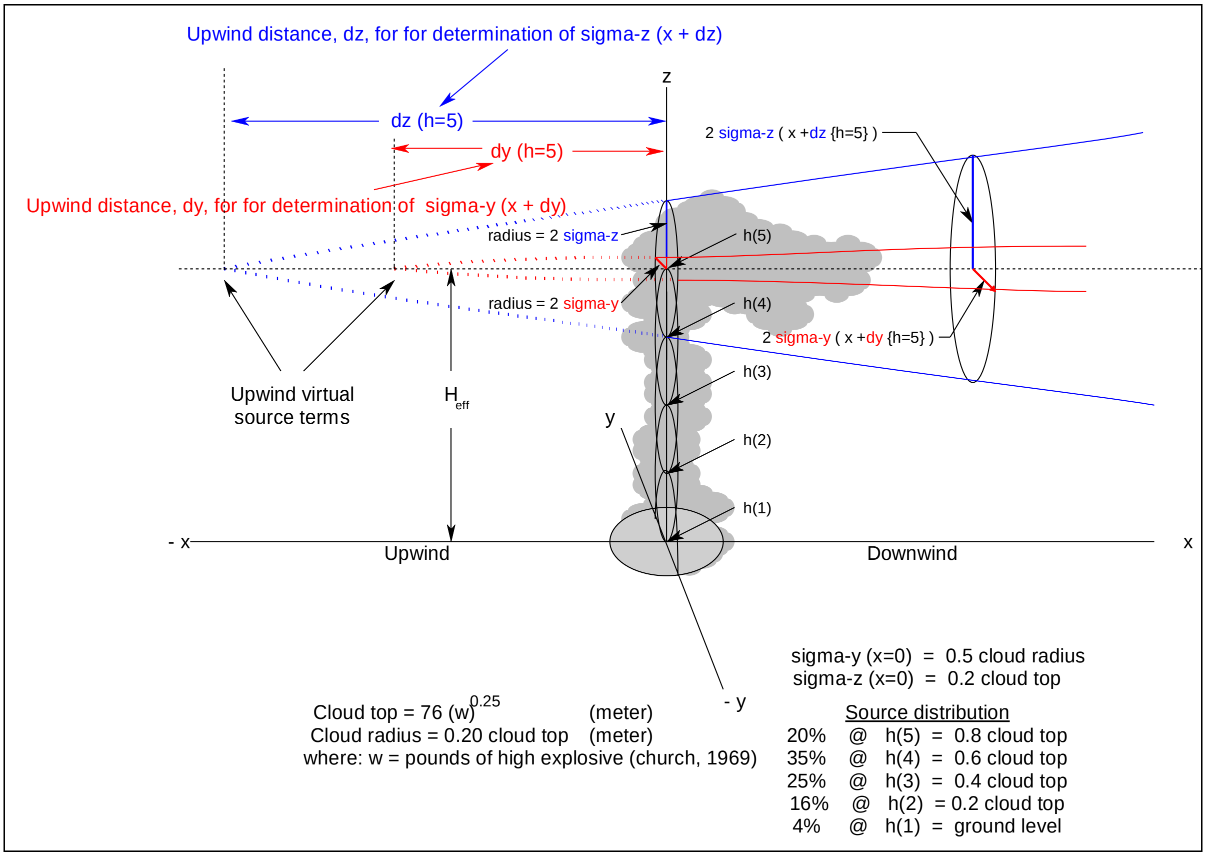


*Figure 1. HotSpot Model of Ground Level Explosive Plume*

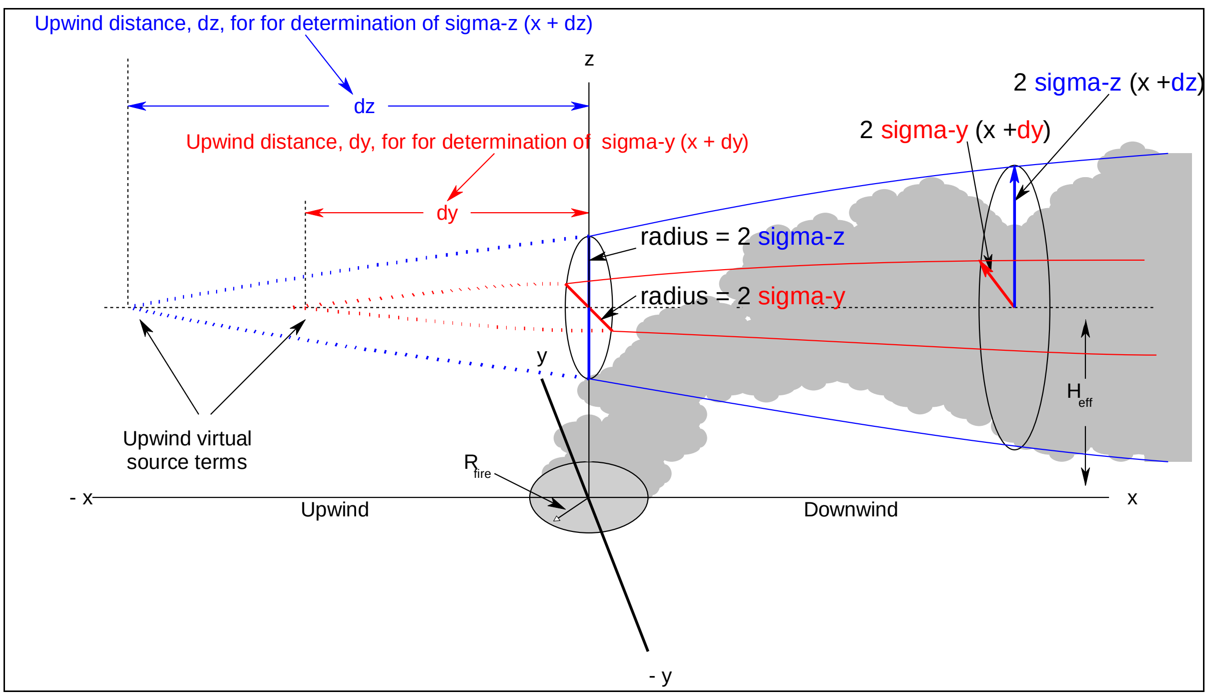


*Figure 2. Hotspot Model for a Fire Plume*

### *Dose Results for Explosion Events*

The dose for a range of explosions, a range of distances, with and without a neutron source are shown in Table 1.

*Table 1. Dose at Distance for Explosion Accidents Entire Core Vaporized*

| Distance in km | Dose in Rem (Total Dose Effective Equivalent) | | | | | |
|---|---|---|---|---|---|---|
| | Core Only – No Neutron Source | | | Core plus Neutron Source | | |
| | 1000 lbs TNT | 10,000 lbs TNT | 50,000 lbs TNT | 1000 lbs TNT | 10,000 lbs TNT | 50,000 lbs TNT |
| 1 | 1.3E-3 | 4.3E-4 | 5.7E-5 | 4.0E-2 | 1.3E-2 | 5.8E-3 |
| 2 | 8.3E-4 | 2.9E-4 | 4.3E-5 | 2.5E-2 | 9.0E-3 | 4.2E-3 |
| 4 | 5.0E-4 | 1.9E-4 | 3.1E-5 | 1.5E-2 | 5.7E-3 | 2.8E-3 |
| 6 | 3.6E-4 | 1.4E-4 | 2.5E-5 | 1.1E-2 | 4.3E-3 | 2.1E-3 |
| 8 | 2.9E-4 | 1.1E-4 | 2.1E-5 | 8.8E-3 | 3.5E-3 | 1.8E-3 |
| 10 | 2.4E-4 | 9.8E-5 | 1.9E-5 | 7.5E-3 | 3.0E-3 | 1.5E-3 |
| 20 | 1.4E-4 | 5.9E-5 | 1.2E-5 | 4.4E-3 | 1.8E-3 | 9.5E-4 |
| 40 | 8.6E-5 | 3.8E-5 | 8.1E-6 | 2.6E-3 | 1.2E-3 | 6.3E-4 |
| 60 | 6.4E-5 | 3.0E-5 | 6.5E-6 | 2.0E-3 | 9.2E-4 | 5.0E-4 |
| 80 | 5.2E-5 | 2.6E-5 | 5.6E-6 | 1.6E-3 | 7.8E-4 | 4.3E-4 |

The results show that all of the doses are in the low 1 to 10's millirem range for a 50-year dose from inhalation along the plume centerline. 1 millrem is about the maximum for the reactor core with no source. Approximately 40 millrem is the maximum with the neutron source included. The neutron source could be packaged to survive most explosions or it may not even be required. This issue would need further investigation.

As would be expected larger explosions loft the material higher, thereby lowering the dose. Given that all explosions are set to the maximum release this is not unexpected. In reality, small explosions would impact the material less.

### *Results from Fire and Point Source Release*

The results from the fire and point source release are shown in Table 2.

*Table 2. Dose at Distance for Fire Accidents and Point Source at 200 ft.*

| Distance in km | Dose in Rem (Total Dose Effective Equivalent) | | | | | |
|---|---|---|---|---|---|---|
| | Core Only – No Neutron Source | | | Core plus Neutron Source | | |
| | Point Source @200 ft | 1 MW fire | 10 MW Fire | Point Source @200 ft | 1 MW fire | 10 MW Fire |
| 1 | 3.4E-8 | 2.6E-5 | 2.5E-12 | 1.0E-6 | 7.9E-4 | 7.5E-11 |
| 2 | 2.0E-5 | 2.6E-4 | 3.7E-7 | 6.0E-4 | 7.9E-3 | 1.1E-5 |
| 4 | 8.2E-5 | 3.0E-4 | 1.1E-5 | 2.5E-3 | 9.2E-3 | 3.4E-4 |
| 6 | 9.0E-5 | 2.4E-4 | 2.0E-5 | 2.8E-3 | 7.2E-3 | 6.2E-4 |
| 8 | 8.5E-5 | 1.9E-4 | 2.4E-5 | 2.6E-3 | 5.9E-3 | 7.3E-4 |
| 10 | 7.8E-5 | 1.6E-4 | 2.5E-5 | 2.4E-3 | 4.9E-3 | 7.7E-4 |
| 20 | 4.9E-5 | 8.2E-5 | 2.1E-5 | 1.5E-3 | 2.5E-3 | 6.5E-4 |
| 40 | 2.7E-5 | 3.7E-5 | 1.5E-5 | 8.4E-4 | 1.1E-3 | 4.5E-4 |
| 60 | 1.8E-5 | 2.0E-5 | 1.1E-5 | 5.5E-4 | 6.3E-4 | 3.4E-4 |
| 80 | 1.3E-5 | 1.4E-5 | 8.9E-6 | 4.1E-4 | 4.2E-4 | 2.7E-4 |

The results show the typical pattern where the plume touches down at a distance one to several kilometers beyond the release point. The doses are largely in the low millirem range to sub millirem range. Given that explosions did not produce high doses it is no surprise that fires, which has a much lower amount of release, did not produce doses any greater than a few millirem with the source included.

### *Putting Risk/Doses in Perspective*

Safety can be achieved in a many ways, but the two of the most prominent are to either 1) prevent the hazardous material from being released; or 2) minimize or eliminate the hazard. For radioisotope systems, given the large magnitude of the hazard, the preferred method is to prevent the material from being released. This requires that the system be very robust and not fail during anticipated or even unlikely events like explosions or fires. For KiloPower, given the inherently low magnitude of the hazard (at least for material release), the preferred method of course is then to keep hazardous material low by not allowing fission to occur until the system is a long way from earth.

The risk to the public from the dispersal of the reactor core either from explosion of fire would be very low. The probability of a fire or explosion given any launch is probably on the order of 3 to 4% per launch and bounded by something like 10%. This would be combined with the inherently low dose to the public. What this note shows is that for these types of accidents (explosions or fires), doses on the order of a few microrem to 10's of millirem would be the largest anticipated dose at a point location. The doses also include the dose contribution from the neutron source. If the neutron source were not included (say because it is packaged robustly), then the largest dose is on the order of a single millirem. This dose would be a 50-year dose that a person at this point would receive over a lifetime assuming no medical procedures (such as chelation). This means that the yearly dose to an individual would be in the tens of microrem per year.

In addition, this is the maximum dose at this point. Other locations not on the centerline of the aerosol plume (down-wind dead center) will have doses that are one to several of orders of magnitude smaller. All these factors mean that actual public doses would be minimal and the calculations are extremely conservative.

To put these doses in perspective. The dose for a typical New York City-to-Los Angeles trip in a commercial airplane exposes a person to about 2 to 5 millirem (mrem) less than half the dose received from a chest X-ray (10 mrem). The EPA allows nuclear operations to provide 100 millirem to the public as a matter of routine operation. The background dose to the public is on the average about 200 to 300 millirem per year. So, a KiloPower accident dose would be orders of magnitude below background radiation.

So, in summary the dose to the public from an extremely conservative estimate of launch accidents involving KiloPower are minimal and below a level of concern. Even given the probability of a fire or explosion as being in the few percent range, the risk presented by reactor for material release is very low.