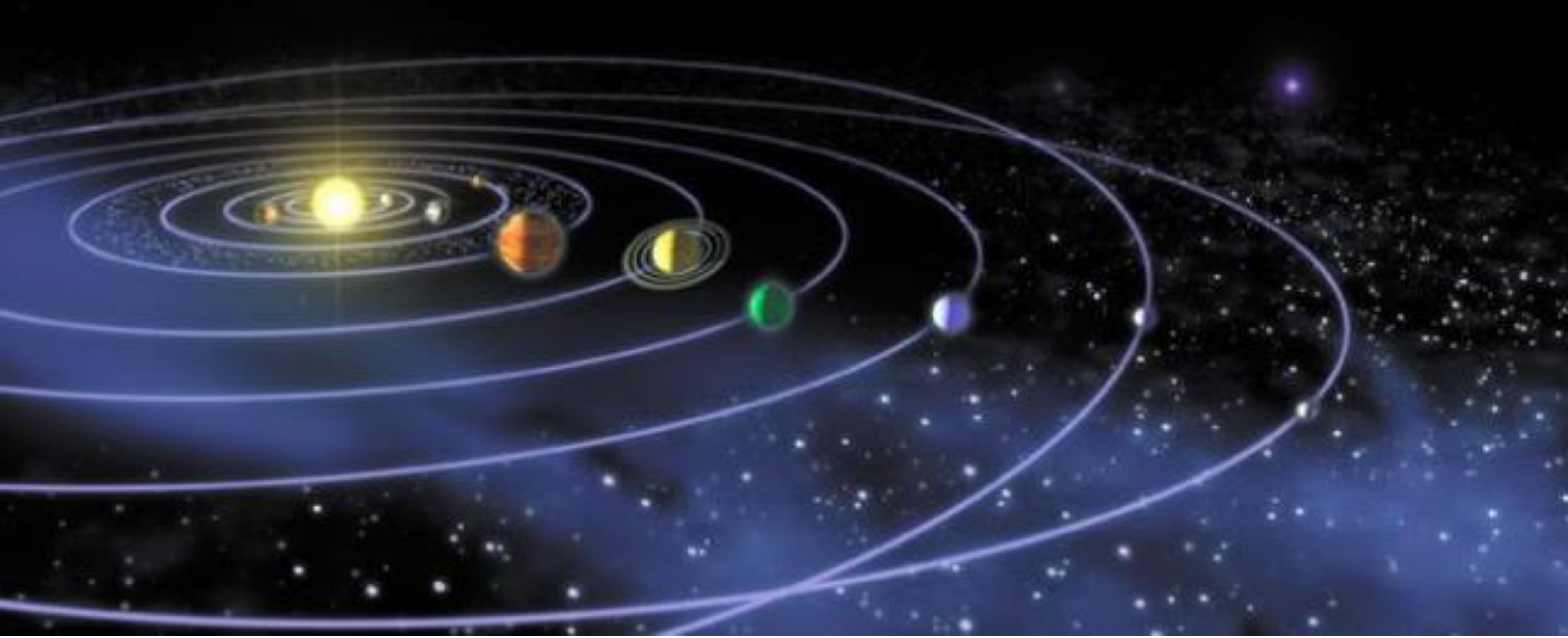

Kilopower–Nuclear Electric Propulsion for Outer Solar System Exploration

A Study for the NASA Space Technology Mission Directorate by Glenn Research Center, Jet Propulsion Laboratory, California Institute of Technology, and Los Alamos National Laboratory

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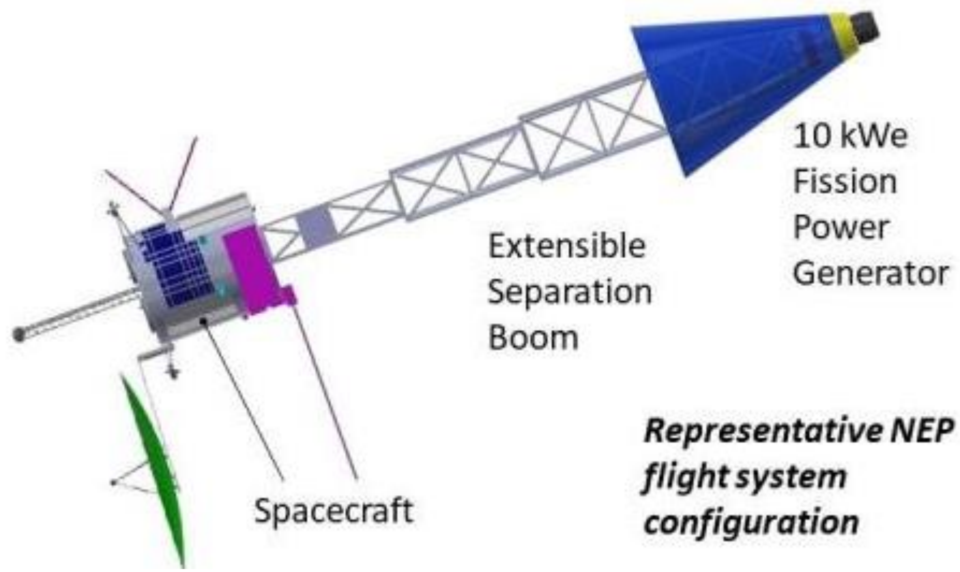
Purpose of Study

- The study objective was to identify generic and specific benefits of using NEP for outer solar system exploration.
- Two classes of mission concepts were studied:
  - **Enabled:** Missions that are not possible using any other available power and propulsion system.
  - **Enhanced:** Mission types using four example destinations studied previously by COMPASS or Team-X to show quantitatively the improvement possible with NEP.



This presentation also includes examples of Interstellar Medium (ISM) mission enhancements possible with NEP.

NEP Benefits Outer Solar System Exploration

- ΔV requirements for outer solar system missions present a major challenge to chemical propulsion systems.
  - New Horizons flew by Pluto at 14 km/s, well beyond the ability of any existing chemical propulsion system to achieve orbit insertion.
  - 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 9,300 kg of propellant, clearly not possible with a 400 kg dry mass.
  - Accounting for the tankage and structure mass for the propellant, would require more than 40,000 kg of wet mass.
- Electric propulsion provides fuel efficiency to achieve high ΔV
  - Imparting the same 10 km/s to the same 400 kg dry mass vehicle using EP ion thrusters operating at an Isp of 4000 s would require just over 100 kg of propellant.
- Nuclear power is enabling for outer solar system missions.
  - Solar power is currently not practical at large solar ranges.
  - 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.

SMD Can Benefit From Boots On the Moon

- NASA’s latest charge, “Get boots on the Moon by 2024,” could establish the budget priorities for the next five years.
- Sustained presence in terms of housekeeping and in-situ resource utilization must follow closely, or boots on the Moon will be viewed as just “Apollo on Steroids.”
- Therefore HEOMD will likely seek to develop Kilopower as a necessary component for Moon to Mars.
- If NASA does develop a 10k We Kilopower for Moon and Mars surface, it could be used directly as the power generator for NEP, and
- SMD would be the beneficiary of a low-cost NEP capability for robotic missions — provided NASA
  - Retains control of the Kilopower high-level requirements and holds to its stated strategy of demonstrating the technology needed for Mars on the Moon first
  - Doesn't develop capability for the Moon that is not extensible to Mars.

Titan/Enceladus Enabled

A mission that can orbit Enceladus and then Titan, and deliver landers to both

- Falcon Heavy launch
- Launch mass 9442 kg
- 9.75 years to Saturn with cruise science
- 2.25-year tour of icy moons with remote sensing science
- 0.5-year Enceladus orbit with remote sensing science + one or more landers
- 2-year tour to Titan with science + one or more landers
- 0.5-year Titan orbit with science
- Total science payload mass = 2550 kg (e.g., multiple Titan and Enceladus landers)

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

Neptune/Triton Enabled

Enough performance to orbit Neptune and Triton and deliver a lander

- Falcon Heavy launch
- Launch mass 6716 kg
- 13 years to Neptune with cruise science
- 1.4-year Neptune tour with 100 kg of orbiter science
- 0.6-year Triton orbit with 100 kg of science
- 300-kg Triton lander and lander ops
- Total science payload mass = 400 kg

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 Enabled

With enough ΔV capability to orbit two Centaurs (including Chiron)

- Falcon Heavy launch
- Launch mass 5290 kg
- 6 years to rendezvous with 2007 SA24
- 1-year orbital mission at 2007 SA24
- 4.5 years to Chiron rendezvous
- 3.5-year orbital mission
- Total science payload mass = 300 kg instrument
- Other Centaur pairings possible

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

Saturn and Uranus Orbiter Missions Enhanced

- When compared to REP, NEP has the potential to reduce trip time, increase data rates, and massively increase the payload capability of a single 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.

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			

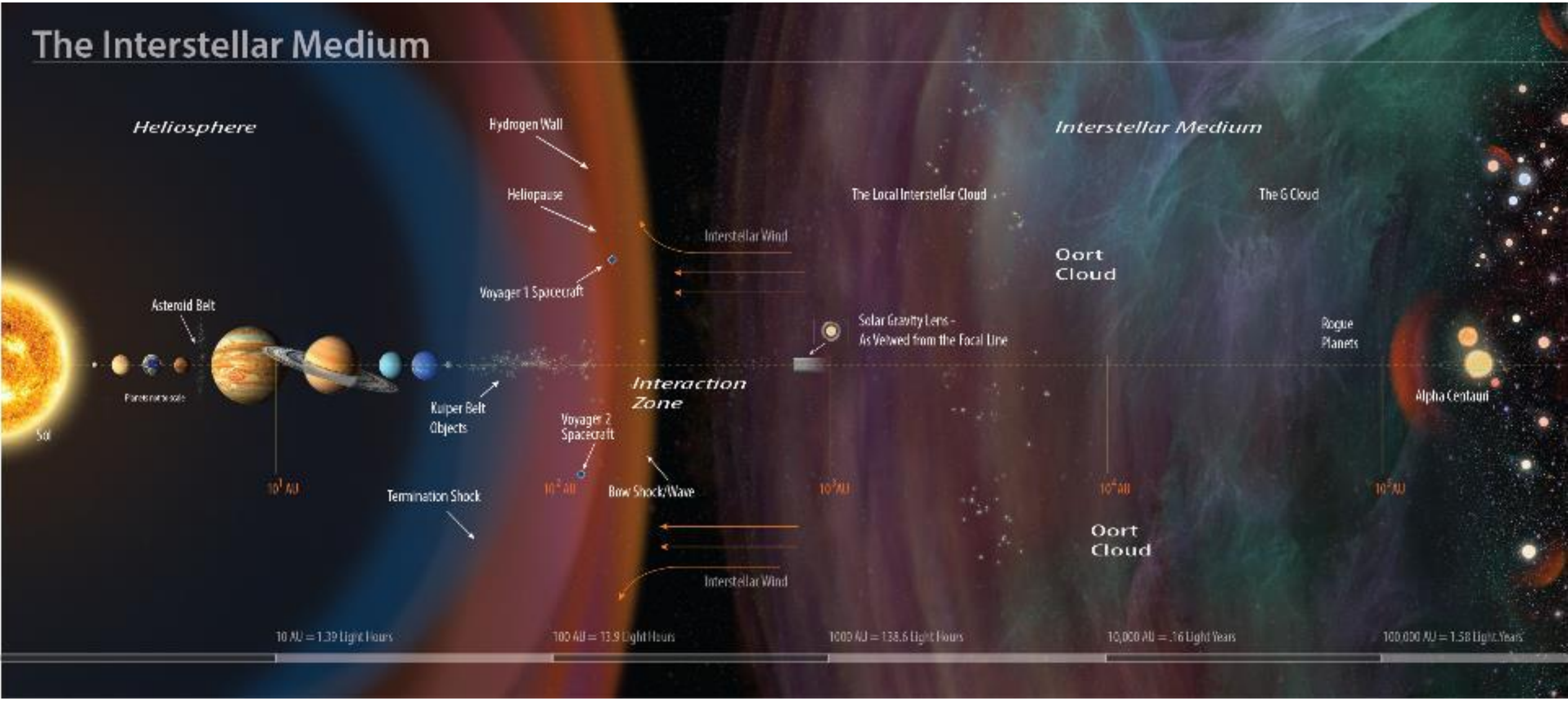
Neptune and Pluto Orbiter Missions Enhanced

- With NEP, the trajectory for a Neptune orbiter concept 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 concept, 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 >4× the data rate at Pluto than the REP option.

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

Interstellar Medium (ISM) Mission Concepts

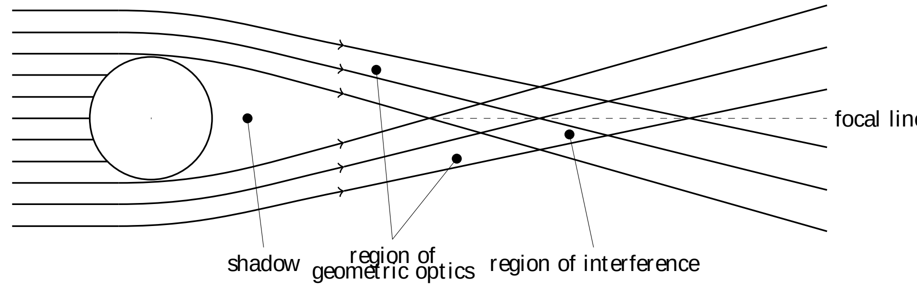


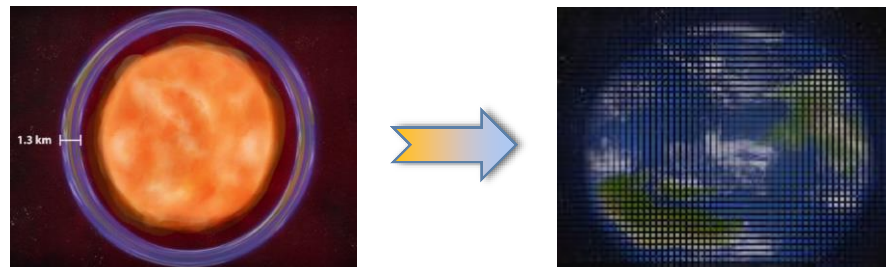
- 2013/2014 KISS Workshop Led by E. Stone, L. Alkalai explored ISM missions and needed technologies. Was followed by studies at JPL, MSFC, and APL.
- JPL concept used a low perihelion with Solar Thermal Propulsion (STP) and NEP to achieve high escape speeds.*

* Results presented by L. Alkalai at STMD/NEP Workshop on Interstellar Probes, September 11-12, 2019

Solar Gravity Lens Focus Concept

- Starting at ~600 AU, the Sun's gravity could be used as a lens to image exoplanets.*
- The focal line extends to infinity and the spacecraft could move about the line to image all exoplanets in a star system.
- The image would be constructed for each exoplanet by deconvolving multiple Einstein rings imaged over 6-12 months from different locations along the focal line.
- The resulting image could be up to 10 km/pixel resolution (for an exoplanet 30 parsecs away).

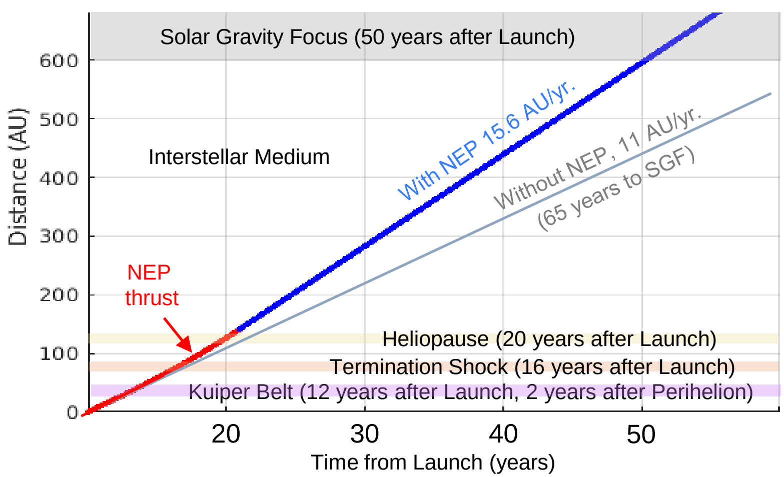


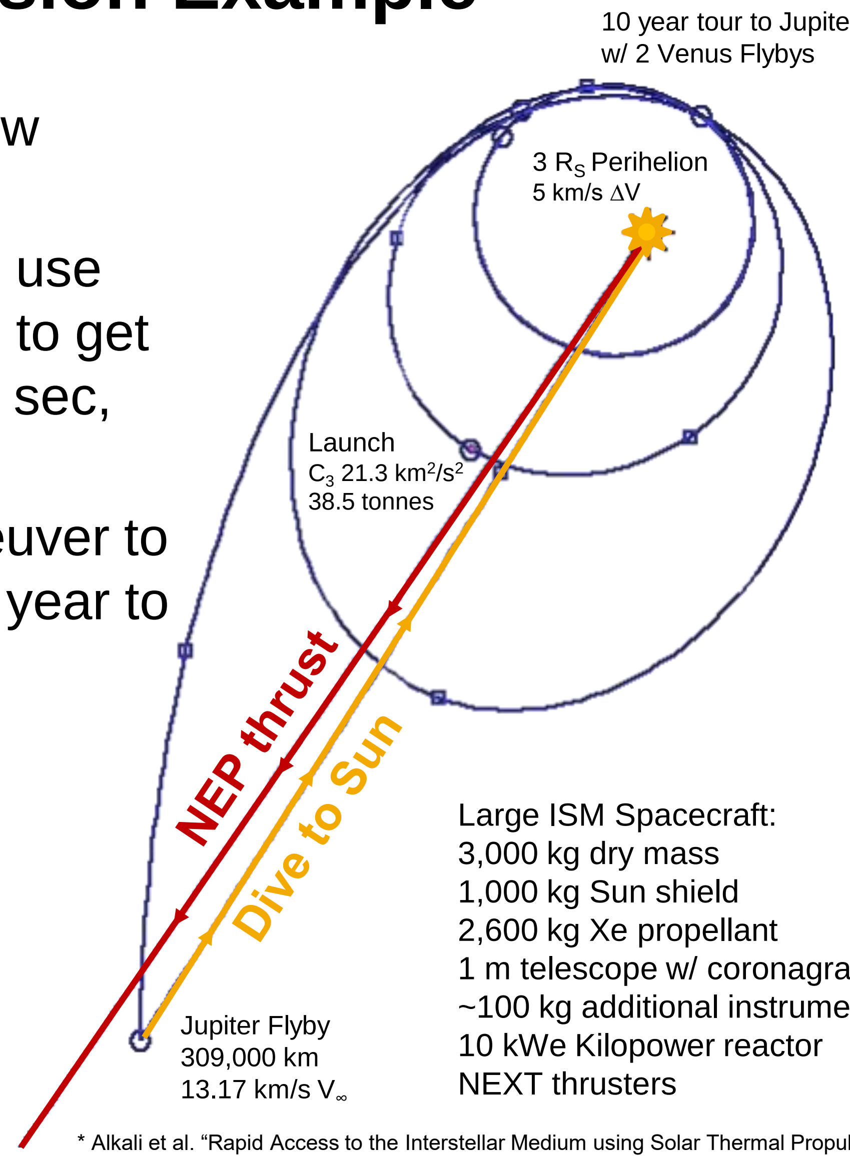


* Turyshev et al. "Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Mission," Final Report for the NASA's Innovative Advanced Concepts (NIAC) Phase I

ISM / SGLF Mission Example

- A Jupiter flyby (with a 6.3 yr. tour, SLS launch) would be used to get a very low perihelion (3 R_S).*
- Solar Thermal Propulsion (STP) could use Hydrogen from cooling the heat shield to get very high specific impulse (1077-1283 sec, depending on Solar distance)
- STP would be used for a 5 km/s maneuver to get an escape speed of 11 AU/yr. (< 1 year to Saturn).





Large ISM Spacecraft:
3,000 kg dry mass
1,000 kg Sun shield
2,600 kg Xe propellant
1 m telescope w/ coronagraph
~100 kg additional instruments
10 kWe Kilopower reactor
NEXT thrusters

* Alkali et al. "Rapid Access to the Interstellar Medium using Solar Thermal Propulsion: A Feasibility Study" *JPL White Paper to be released September 2019*

Mission Lifetime Considerations

- Mission lifetime is primarily determined by the allowable radiation dose to sensitive components.
- Mission lifetime requirement affects the design of the nuclear power system in two ways:
  - Lifetime of the core itself
    - Very low core burnup of <0.5%. (Based on Idaho National Laboratory expert opinion that <1% presents no significant burnup-related lifetime issues for the fuel*)
  - Mass of the shield and boom length
    - Required to meet allowable limit integrated dose to electronics and other radiation-sensitive components.
- A 15-year lifetime requirement was selected as a reasonable balance among science instrument mass, boom length, radiation hardness for parts. (Mission lifetime can be changed easily by varying the boom length.)

*May also require assessment by an independent group of experts.

Mission Lifetime Considerations (cont.)

- Mission lifetime is also determined by engineering margins and the margins established for consumables.
- Lifetime of the power conversion system is mostly determined by the Stirling convertors. Design features include:
  - Large engineering margins, with an emphasis on reliability instead of high-efficiency performance.
  - Redundancy (full power can be delivered with two failed convertors and partial power can be provided with numerous failures).
- Evidence that meeting mission lifetime is not a major obstacle, given suitable derating and inspection practices, is given by
  - Mars program, where orbiters and landers typically have lifetimes in excess of 15 years.
  - Voyager program, where two spacecraft have each operated successfully for over 42 years since launch.
  - Cassini, which operated without fail for over 20 years.

Risks and Considerations

- **Development risks**
  - In-core heat pipes to the core: Technology, bonding, and thermal performance were not evaluated under KRUSTY and will require analysis and testing.
  - Higher power output Stirling engines: Will require continuation of the technology development phase focused on cost and reliability rather than the earlier ASRG objectives of high efficiency and low mass required by ^{238}Pu applications for small spacecraft.
- **Policy Considerations**
  - Security, safety, and transportation issues would be handled in a risk-accepted way by the existing DOE regulations and practices that recognize the distinction between government usage and commercial usage.
  - HEOMD usage would precede Kilopower usage, and thus will be the pathfinder for NEP in the realm of security, safety, and transportation.

Earth Gravity Assist Flyby Risks

- Kilopower reactor would be activated and operating shortly after launch. Many mission concepts of interest include EGA flybys as part of their mission design.
- The reactor would be operating before and after the Earth flyby. The probability of inadvertent Earth entry and associated dose/risk effects will need to be evaluated and shown to be consistent with the requirements of NSPM-20.
- In the event that the safety criteria for a reactor-powered Earth flyby cannot be adequately addressed, it is possible to execute the missions (with some potential loss in payload mass and time of flight) by substituting Venus and/or Mars gravity assists in place of EGAs.
- As an alternative, it is possible to add more solar arrays to provide power for electric propulsion so that reactor start-up could be delayed until after the final EGA. After the reactor is activated, the solar arrays would be jettisoned, and the remainder of the mission completed on nuclear power.

Accidental Reentry Risk

- Primary risk is during an accidental reentry. 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. Emergency retrieval is already established as part of the planning for the launch of an RTG.
- The United States has successfully managed this risk for over 50 years with RTG applications and would continue similar risk management practices for nuclear reactor mission applications.

HEU vs LEU Risk

- Use of HEU is a major issue for the United States, and there is pressure to reduce the use of HEU.
- The primary concern has to do with terrorist interception of weapon-grade material. Security and safeguards are well established for the governmental use of HEU, but implementation across the broader spectrum of commercial and university facilities may well represent a greater security risk.
- The reactor would be under DOE established security provisions continuously throughout the system preparation and launch; thus, the possibility of diversion should be as low as the US Government can make it.
- The governmental use of HEU is justifiable where the benefits out-weigh the risks for specific missions by providing significantly lower mass and size.
- A decision to eliminate HEU would impact Kilopower benefits for both HEOMD and SMD use.

Conclusions

- A 10k We NEP capability would
  - Enable a new class of outer solar system missions that would not otherwise be possible.
  - Significantly enhance a range of other deep-space mission concepts, including ISM, 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 represents a break through in science value beyond Cassini class, enabling NASA to 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*.
- KRUSTY validated all of the Kilopower nuclear design goals and objectives, including the claim that future instantiations of the Kilopower design will not require full power nuclear testing, i.e., nuclear validation requires only zero power critical testing.

Key Take-Aways on NEP

- A 10k We NEP capability would enable a new class of outer solar system missions that would not otherwise be possible.
- It would significantly enhance a range of other deep-space mission concepts, including ISM, 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 would represent a breakthrough in science value beyond Cassini class, enabling NASA to 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*.
- KRUSTY test of the Kilopower reactor system paved the way for low-risk development of a 1k We fission power generator that would be cost-competitive with current RPS systems.
- By coordinating with HEOMD planners, NEP can evolve in a way to permit the use of the HEO-developed reactor and power conversion system to be used virtually without change for the NEP application.

Back Up

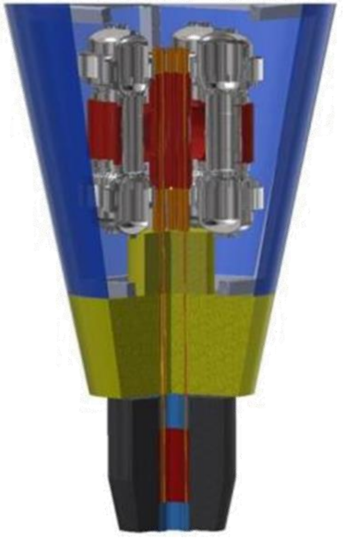
- Context for Initiating Study
- Why 10 kWe
- Fission Power Generator and Flight System Configuration
- ATLO and Concept of Operations
- Nuclear Safety
- Follow-on Work
- Key Take-Aways on Kilopower
- Fuel Selection
- Acquisition Strategy
- Disclaimer

Context for Initiating the Study

- NASA has been has been contemplating the use of nuclear power for sustained human presence on the Moon 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 10k We each as a more robust and flexible approach.
- At the last Decadal Survey, the Outer Planet Subcommittee asked for a study to show how NEP could benefit outer planet exploration. GRC, LANL, INL, and 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, SMD, having concluded that the best path forward would be to focus on ^{238}Pu-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 SMD should consider using it if other mission directorates funded the development.
- STMD agreed to fund the design, build, and test of a small prototype reactor led by GRC in collaboration with DOE/NNSA. The project team included LANL, Y-12, and MSFC.
- The reactor was named Kilopower; 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 evaluate the possible mission benefits of a Kilopower-based NEP capability.

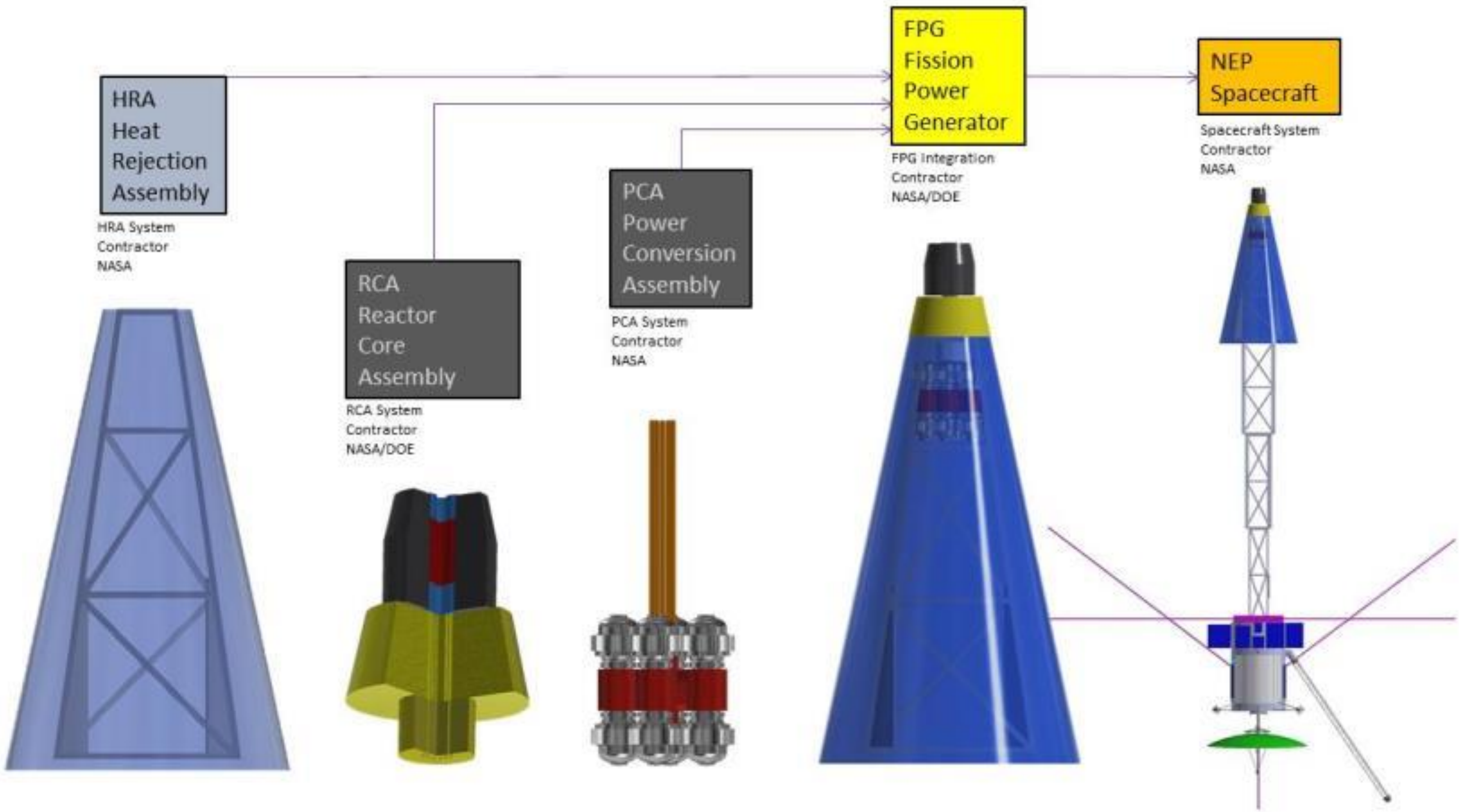
Why 10k We for NEP?

- The short answer is because NASA has been contemplating a 10k We modular Mars surface power system
- Power levels a low as 5 to 6k We have been shown to be useful for NEP, but 10k We is enabling for many high priority missions.
- The team selected the 10k We power level to capitalize on the ongoing NASA development activity and to benefit any other mission (human or robotic) that should choose to use an NEP system.
- Irrespective of the chosen power level, all the key nuclear design aspects can be identical for both human exploration and robotic mission applications.

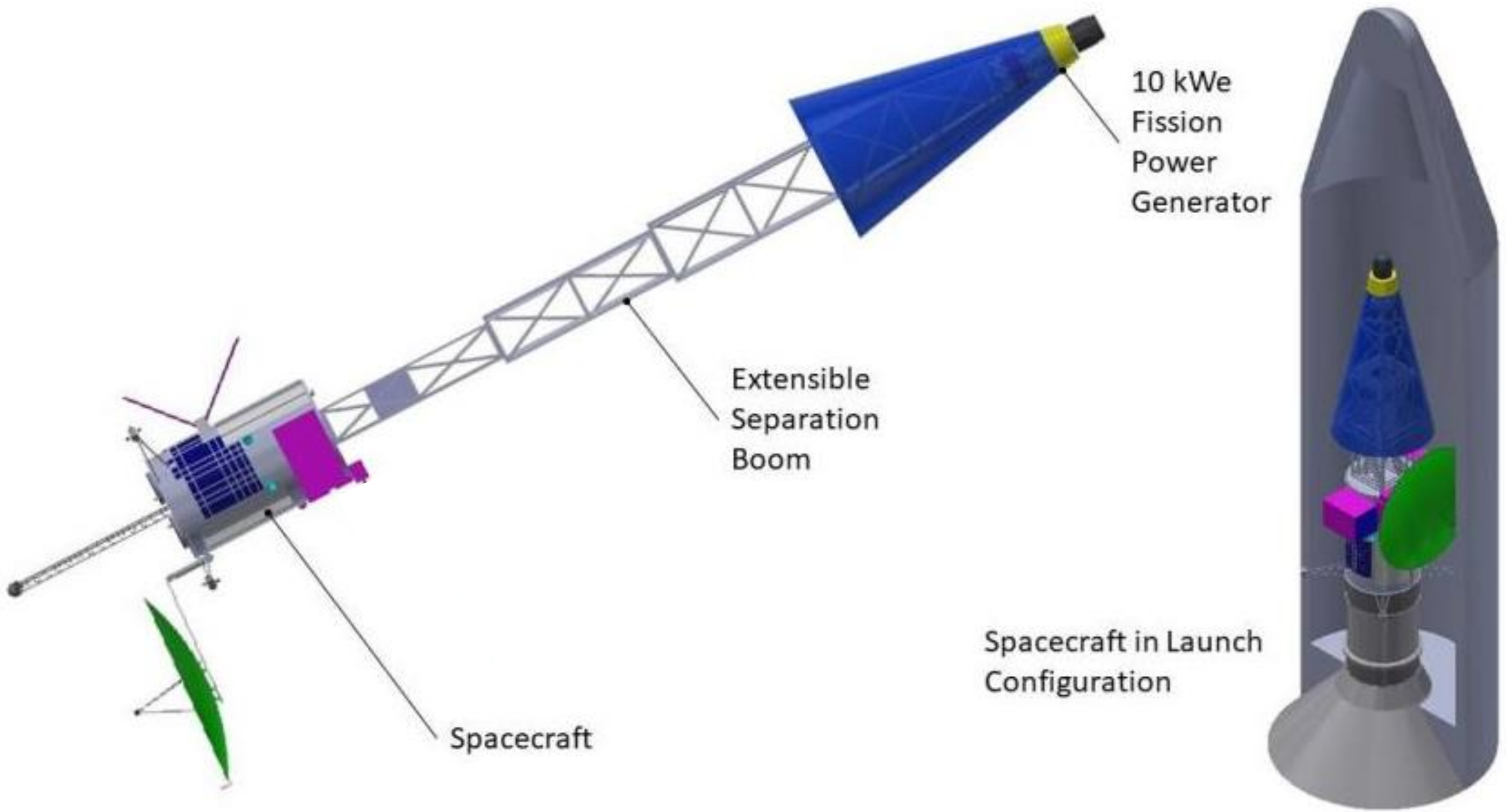


Integrated fission power generator concept

Fission Power Generator Baseline Design

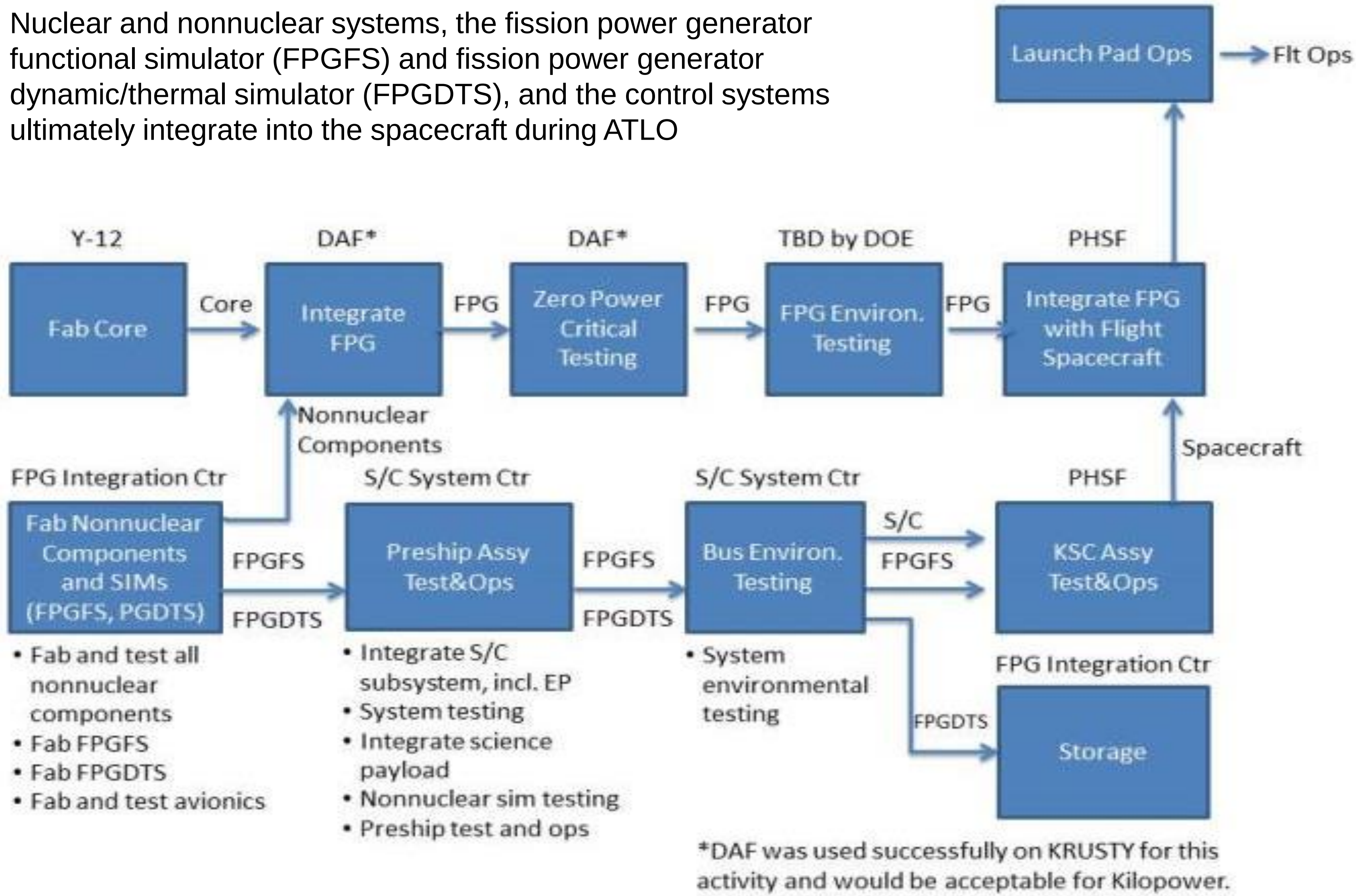


Notional Flight System Configuration



Notional Flow for Fission Power Generator Assembly Operations

Nuclear and nonnuclear systems, the fission power generator functional simulator (FPGFS) and fission power generator dynamic/thermal simulator (FPGDTS), and the control systems ultimately integrate into the spacecraft during ATLO

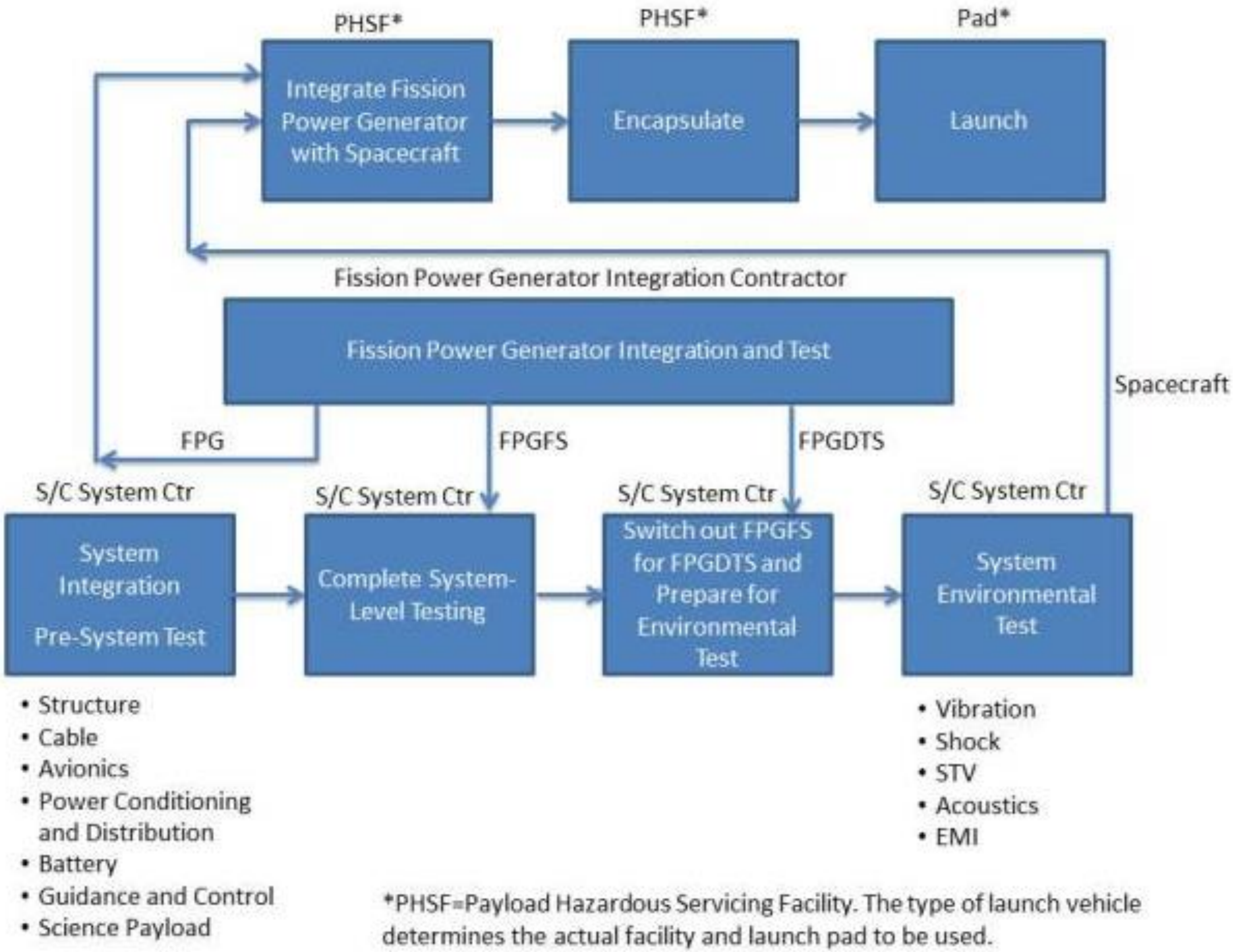


Concept of Operations

- 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.

Concept of Operations (cont.)

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.



Proposed Nuclear Safety Framework

- The safety and security features of the Kilopower reactor for outer solar system exploration would mimic the NASA and DOE provisions for the Kilopower reactor for human exploration missions.
- Launch must comply with requirements of the 2019 National Security Presidential Memorandum-20 and the National Environmental Policy Act of 1969 (NEPA).
- Nuclear safety responsibilities will be jointly shared by NASA and DOE
  - NASA implements NSPM-20 through NASA General Safety Program Requirements, NPR 8715.3.
  - DOE plays a key role in the development and review of a safety analysis report (SAR) developed both for input to NSPM-20 and as input to NEPA.

Safety Analysis Report

- Kilopower would be the first implementation of a reactor SAR because SNAP-10A (1965) predated the current process and did not require one.
- A reactor SAR would have a different focus from SARs for launch of radioisotope systems. NEP mission SARs would have a section on launch fires and explosions that is bounding.
  - Low amount of radioactivity (~2.5 curies, much lower than 60,000 curies planned for eMMRTG); therefore, fires and explosions in the early launch phase will have minimal impact to the public (millirem range or less), and extreme bounding conditions can be assumed.
  - Role of the data book for the launch vehicle can be minimal and just cover a bounding range of insults.
- Main section of the SAR would focus on inadvertent criticality during the launch phase (the probability that the reactor could go critical during an accident).
  - The focus would be on geometry changes and increased reactor moderation from impacts on land and water.
  - The goal would be to demonstrate the features of Kilopower (such as height-to-diameter ratio) that make these scenarios low risk.
- Missions involving EGAs would require additional analysis.
- A SAR could be developed rapidly for a Kilopower reactor given that experimental safety testing would be minimal and likely relegated to one or two confirmatory zero power critical tests.

Consultations on Fuel Selection for Kilopower

1st fuel meeting for NPAS, July and August 2014

Attendees: Steve Herring, INL; Abe Weitzburg, Consultant; John Creasy, Y-12: Chris Robinson, Y-12; Bob Magevicius, LANL; Pat McClure, LANL. Steve Herring is a UMo fuel expert from INL (Lab fellow); John Creasy, Y-12, is a uranium expert; Bob Magevicius is a uranium expert. All are metallurgists.

Focus was phases of U, fuel swelling, fission gas release, creep, diffusion, ratcheting of fuel by multiple start and stops. Biggest issues were creep and diffusion. This led to Glenn studies on both. Creep issue has been resolved. Diffusion has many solutions.

2nd time talking fuels, March or April 2018

Attendees: Steve Johnson, Brad Kirkwood, Mitch Meyer all INL along with Pat McClure and Dave Poston, LANL

Focus on UMo density and thermal expansion, but also conversations on fission gas swelling and release. Density and thermal expansion is now well known, based on KRUSTY test.

Overall summary. The data we have show that the fuel should perform as advertised. There should be no issues for the time, temperature, and burnup we are proposing. However, there is always some uncertainty. Is it large? NO. But there are people who would choose to expend resources to remove even a small amount of uncertainty.

Acquisition Strategy

- The acquisition strategy objective is to provide flagship-class missions for substantially less than typical flagship mission–class cost.
  - Two separate acquisition strategies would be required for an NEP powered mission: one for the fission powered generator and one for the balance of the spacecraft.
- Spacecraft bus
  - Primary implementation elements include using a variation on a spacecraft system contractor’s spacecraft bus, e.g., Psyche, and an integrated science payload.
- Fission power generator acquisition
  - Requires the use of one or more of the existing DOE laboratories in order to provide space reactor capability and DOE indemnification.
    - LANL is the preferred candidate given their long-standing experience in space reactor design, expertise in nuclear material assembly, experience in zero power critical testing, and the collaborative working relationship with GRC on the Kilopower and KRUSTY developments.
  - Acquisition of the unfueled fission power system, including all nonnuclear components and their integration, would be accomplished using a commercial system integration contractor hired by the lead DOE laboratory.

Follow-on Work

Suggestions intended to develop additional detail on the technical and programmatic issues raised in the study.

- 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 HEO 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.

Key Take-Aways on Kilopower

- 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.
- 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.
- The temperature set point is controlled by the position of a single control rod.
- The estimated fuel burnup is <0.5%, which means core lifetime is a non-issue.
- The timing is right to develop the Kilopower 10k We capability given KRUSTY's success to enable several compelling HEO and SMD missions and serve as a pathfinder and risk reduction strategy for the larger needs of future HEO space power systems across the Moon–Mars system.

Disclaimer

NOTE: 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 NASA.