Kilopower: Small Fission Power Systems for Mars and Beyond

Lee Mason

Principal Technologist for Power & Energy Storage
Space Technology Mission Directorate

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STMD Power Technology Needs

1) Power for Human Surface Missions

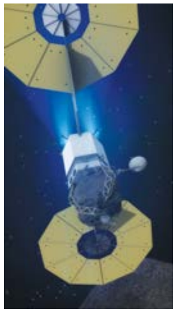
Stationary Power:
40 kW continuous power, day & night
High system specific power >5 W/kg
Nuclear fission or PV with energy storage
Human-rated (safety and fault tolerance)
Robotically-deployed (pre-crew arrival)
Survivable for multiple crew campaigns >10 yrs

Mobile Power:
6 to 10 kW rechargeable power, up to 120 kWh
Advanced batteries/fuel cells >300 Wh/kg, >200 cycles
Maximum commonality with other surface assets
Grid-compatible (with stationary power)

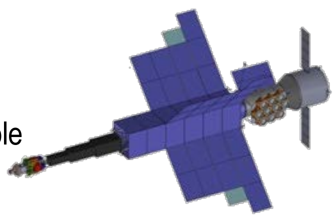
Both: Mars gravity, wind, dust, CO2, temperature, diurnal period

2) Power for Electric Propulsion

Near Earth Systems:
30 to 50 kW solar array wings >100 W/kg
Compact array stowage >40 kW/m3
High deployed strength >0.1g and frequency >0.1 Hz
High operating voltage >160V, PPU-compatible
Long life >7 yrs with reuse



Mars and Beyond:
100 to 300 kW solar array wings >150W/kg
Radiation tolerant solar cells
Compact array stowage >60 kW/m3
1 to 5 MW fission reactors <5 kg/kW
High operating voltage >300V, PPU-compatible
Long life >5 yrs (Earth to Mars)



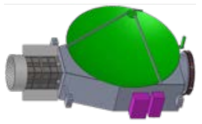
3) Power for Robotic Science Probes

Orbiters, Landers & Rovers:
Power levels from 100 to 600 W at EOM
Possibly kWs for ice melting, comm relays, EP
Very long life >10 yrs and high reliability
Low mass power systems >5 W/kg
High performance RPS/fission >15% eff.
Low intensity/low temperature PV >25% eff.
Advanced batteries >300 Wh/kg, >200 cycles
Extreme environments (low/high temperature, low/high solar intensity, high radiation)

4) Power for Small Spacecraft

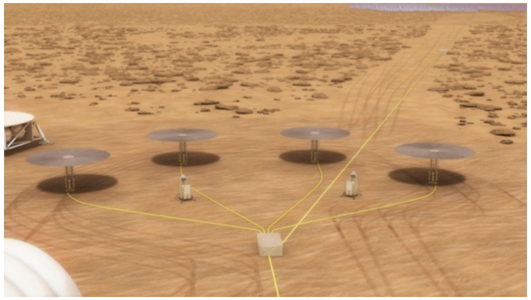
Near Earth Systems:
Power levels from 100 to 500W
Body-mounted or deployable solar arrays >200 W/kg
Advanced batteries >200 Wh/kg, >200 cycles
Compatible with 2U to 24U Cubesat platforms
Highly integrated systems with shared structure

Deep Space Systems:
Power levels from milliwatts up to 60W (nuclear)
Small RPS using multiple RHUs or single GPHS
Advanced conversion (TE, Stirling, Alpha/Beta-voltaic) >15% eff

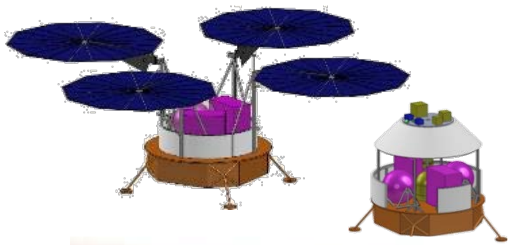


Power for Human Surface Missions

- **Primary Target is Mars, but extensibility to Moon desired**
  - Environment challenges include:
    - Mars gravity (0.38g), CO_2, dust, wind, temperature (170 to 270K), diurnal period (25 hrs)
    - Lunar gravity (0.16g), vacuum, dust, temperature (100 to 370K), diurnal period (29.5 days)



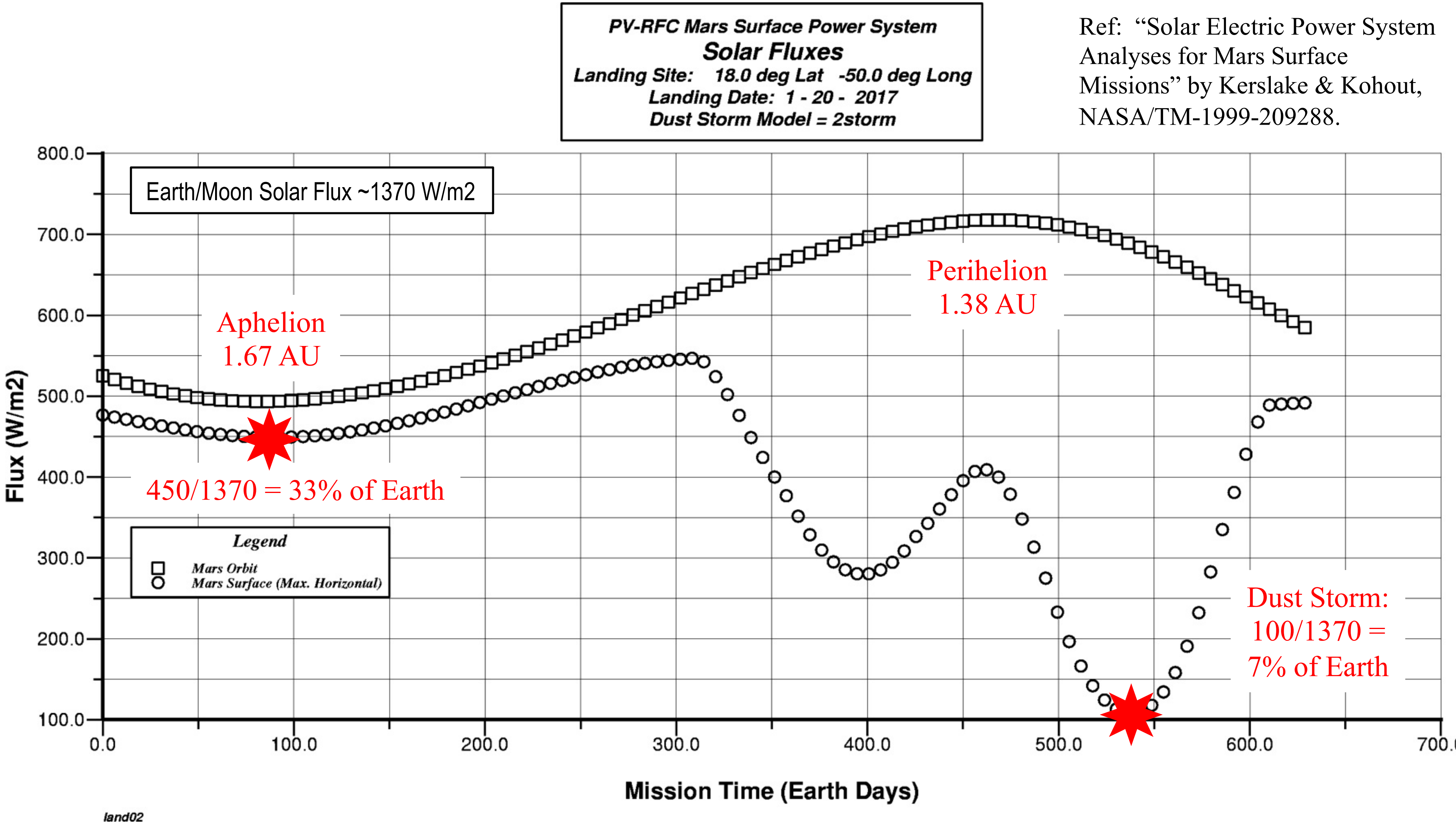
- **Stationary Power**
  - Need: Up to 40 kW day/night continuous power
  - Power for ISRU propellant production (pre-crew arrival)
  - Power for landers, habitats, life support, rover recharging (during crew operations)
  - Technology options: Nuclear Fission or PV with Energy Storage
  - Need compact stowage, robotic deployment, survivable for multiple crew campaigns (>10 yrs)
  - Potential EDL/ISRU/Power Demo (late 2020s) 5 to 10 kW on Single Lander w/ISRU



- **Mobile Power**
  - Need: Up to 120 kWh for rovers and construction equipment
  - Technology options: Batteries or Fuel Cells
  - Desire maximum commonality with other surface assets: multi-use, interchangeable components, shared reactants, grid-compatible

Mars Solar Flux

Ref: "Solar Electric Power System Analyses for Mars Surface Missions" by Kerslake & Kohout, NASA/TM-1999-209288.



Kilopower

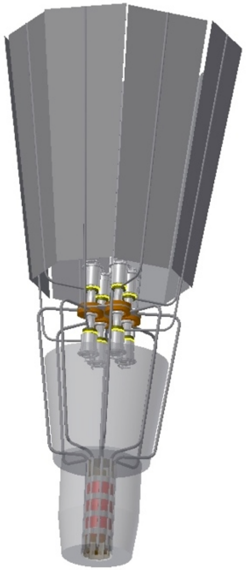
- **Compact fission electric power system with common design approach for Mars surface or deep space science applications**
  - 93% enriched cast UMo fuel, heat pipe reactor, Stirling power conversion
  - Baseline surface power option for Evolvable Mars Campaign
  - 2017 reactor ground test planned at Nevada National Security Site to demonstrate technology

- **Leverages existing DOE/NNSA nuclear materials, manufacturing capabilities, test facilities, and nuclear safety expertise (in which NASA is a minor user)**
  - U235 provided free-of-charge to NASA from large stockpile surplus
  - DOE/NNSA co-funding (~$5M) to complete nuclear prototype test

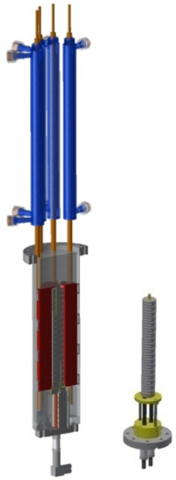
- **Provides pathway for NASA to transition from >$70M/yr Pu238 fuel production/ operations commitment (in which NASA is primary user)**

Kilopower was selected for a 2013 R&D 100 Award

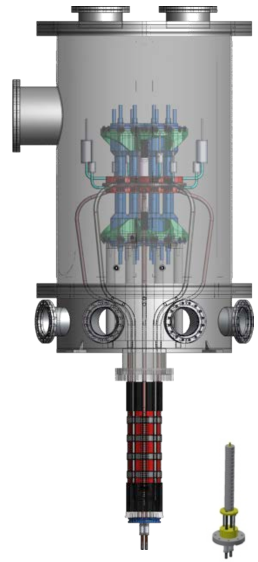
Kilowatt Reactor Using Stirling Technology (KRUSTY)



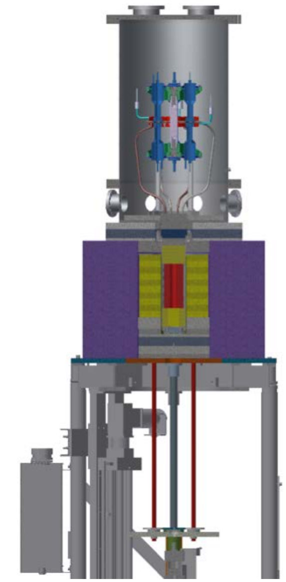
Notional Flight System Concept



Thermal Prototype & Materials Testing (Year 1)



Thermal-Vac System Test with Depleted Uranium Core at GRC (Year 2)



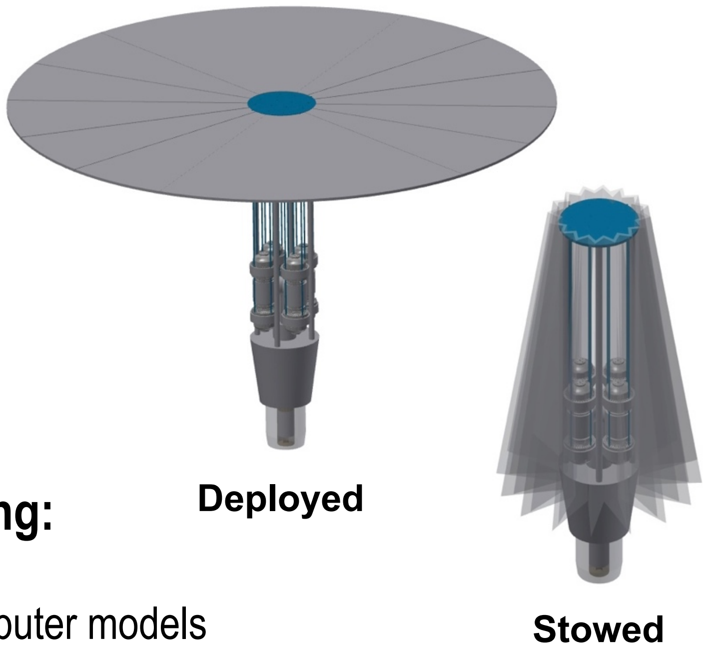
Reactor Prototype Test with Highly-Enriched Uranium Core at NNSS (Year 3)

- Verify system-level performance of flight-like U-Mo reactor core, sodium heat pipes, and Stirling power conversion at prototypic operating conditions (temperature, heat flux, power) in vacuum
- Establish technical foundation for 1 to 10 kWe-class fission power systems

NASA · NNSA National Nuclear Security Administration · Los Alamos National Laboratory EST. 1943 · Y-12 National Security Complex · NNSA Nevada National Security Site

Proposed Follow-on: Kilopower II

- **Proposed FY18 STMD New Start Project**
  - Possible candidate for TDM Ground Demo
  - Contingent on successful TRL5 KRUSTY test under GCD Project
- **Focus is on Surface Power for Mars**
  - Joint technology development with STMD/HEOMD as co-sponsors
  - Technology should be extensible to lunar surface and deep space science missions



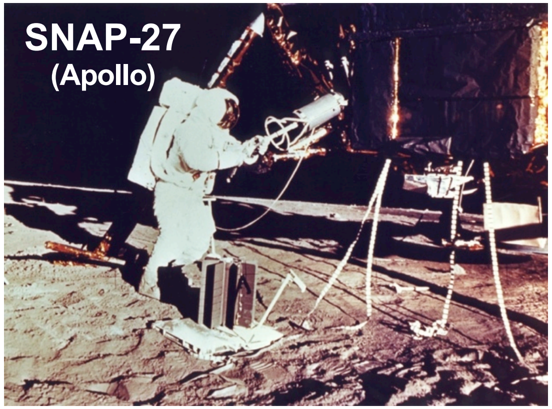
- **Potential Project content to include the following:**
  - Mars system scalability study (up to 10 kWe)
  - Detailed reactor design using KRUSTY validated computer models
  - Experiments to demonstrate in-core heat pipe integration
  - Contracts to design/build/test kilowatt-class power conversion units
  - Culminates in high-fidelity (non-nuclear) system ground test operated in simulated Mars surface environment (potentially in combination with an ISRU ground test)
  - Includes studies to evaluate nuclear launch safety and crew radiation safety
  - Includes option for possible nuclear flight demonstration on lunar or Mars precursor
- **NNSA remains as primary DOE partner assuring direct access to Los Alamos, Y12, and the Nevada National Security Site**

How Did We Get Here?

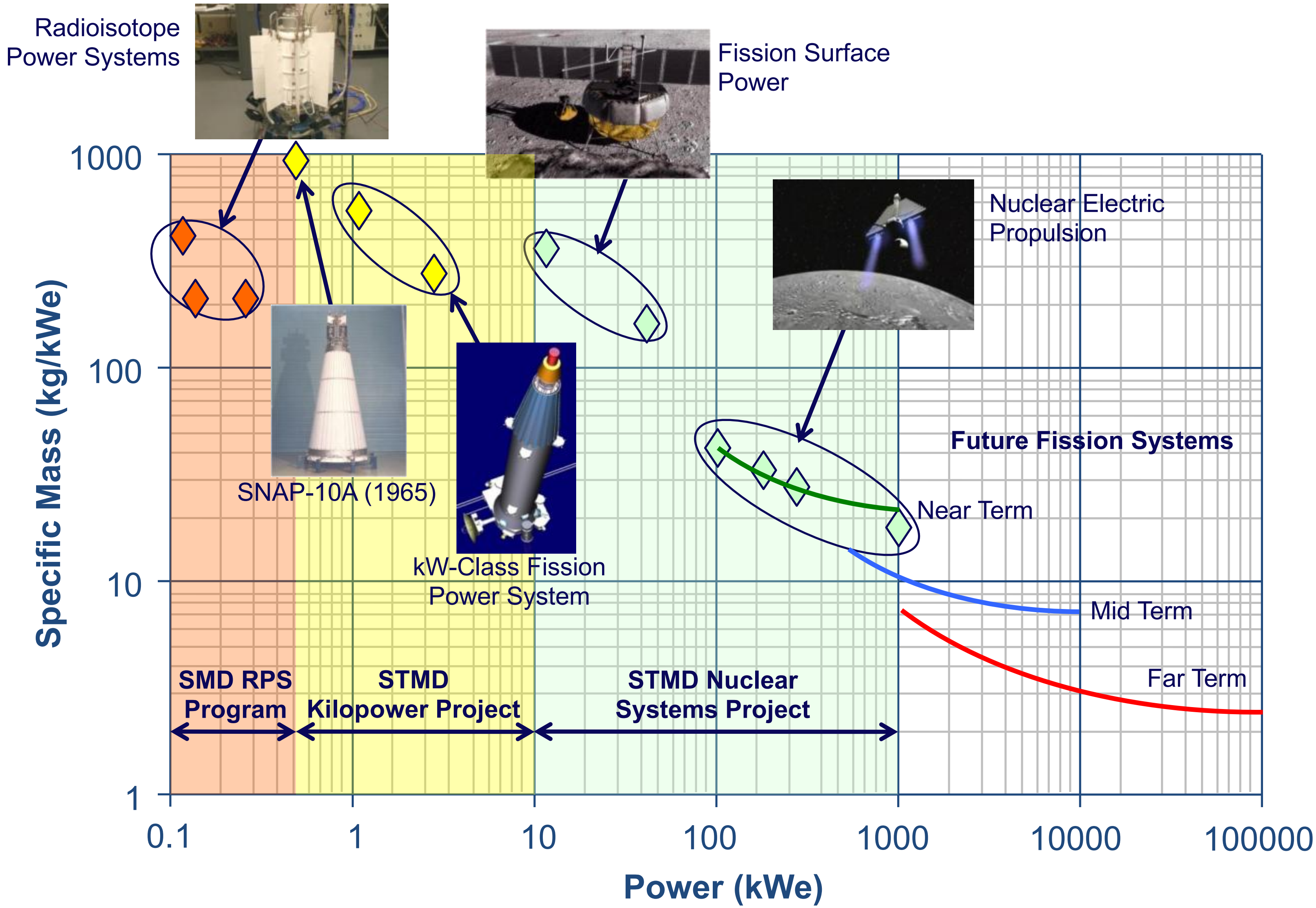
Space Nuclear Power History

- **Fission Power Systems**
  - SNAP-10A (launched 1965)
  - Soviet Space Reactors (1967-88)
  - SP-100 (1985-1992)
  - Jupiter Icy Moons Orbiter (2000-2005)
  - Fission Surface Power and KiloPower (Present)

- **Radioisotope Power Systems**
  - 45 Successful U.S. Radioisotope Thermoelectric Generators (RTG) Flown Since 1961, e.g.
    - » Apollo SNAP-27 (1969-72)
    - » Viking SNAP-19 (1975)
    - » Voyager MHW-RTGs (1977)
    - » Cassini GPHS-RTGs (1997)
    - » New Horizons GPHS-RTG (2005)
  - Multi-Mission RTG and Stirling Radioisotope Generators (Present)



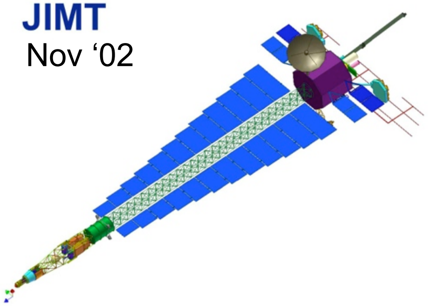
Nuclear Power Performance Regimes



JIMO/Prometheus Concepts

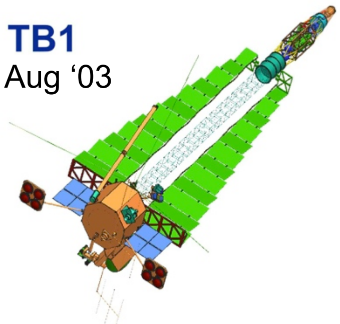
Government Team Designs

JIMT
Nov '02



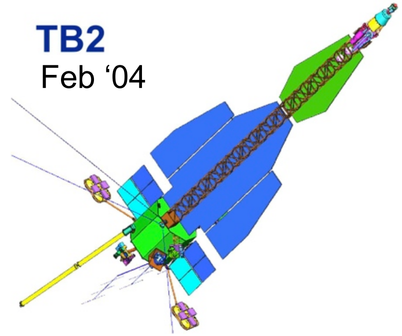
100 kWe Brayton
41 kg/kWe

TB1
Aug '03



100 kWe Brayton
44 kg/kWe

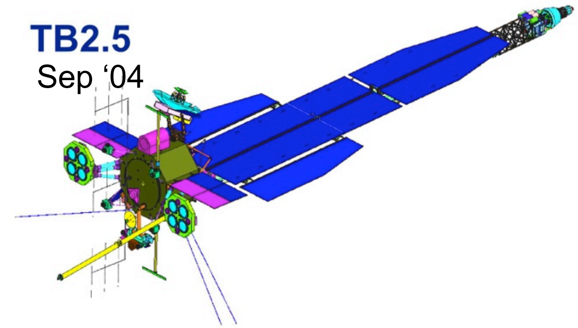
TB2
Feb '04



100 kWe Brayton
63 kg/kWe

80 kWe SiGe TE
81 kg/kWe

TB2.5
Sep '04

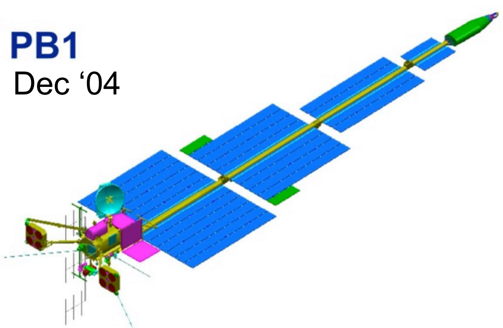


135 kWe Brayton
46 kg/kWe

135 kWe SiGe TE
57 kg/kWe

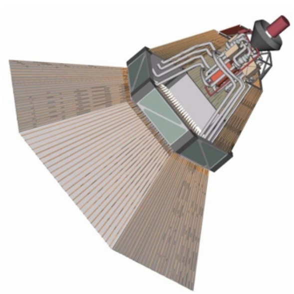
Contractor Designs

PB1
Dec '04

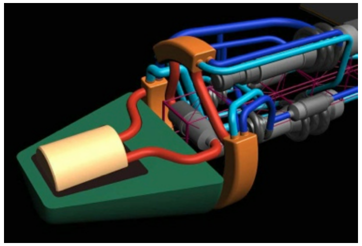


Northrup Grumman Brayton
200 kWe, 34 kg/kWe
(Gas-cooled Reactor)

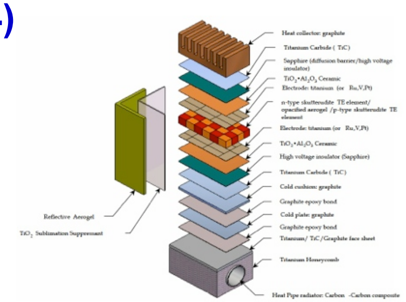
Prometheus NRAs (2004)



Boeing Brayton
100 kWe, 42 kg/kWe
250 kWe, 30 kg/kWe



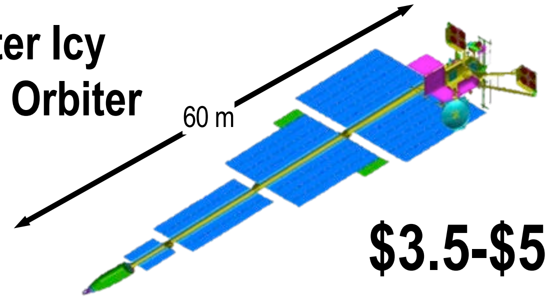
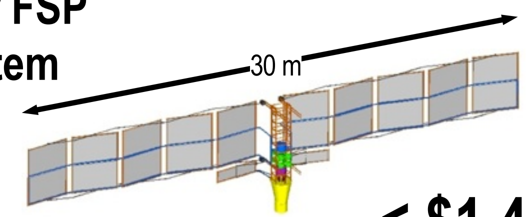
ORNL K-Rankine
100 kWe, 31 kg/kWe
250 kWe, 25 kg/kWe



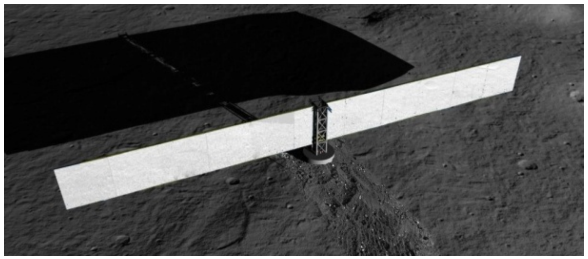
JPL Segmented TE
100 kWe, 47 kg/kWe
250 kWe, 39 kg/kWe

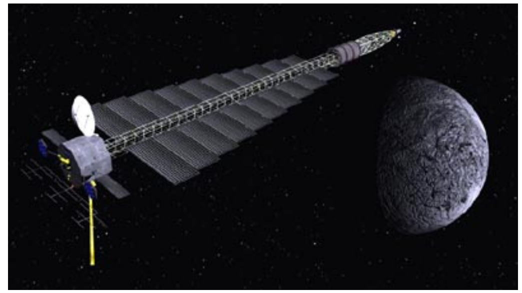
All specific mass values are based on overall power system including reactor, shield, power conversion, heat rejection, and PMAD.

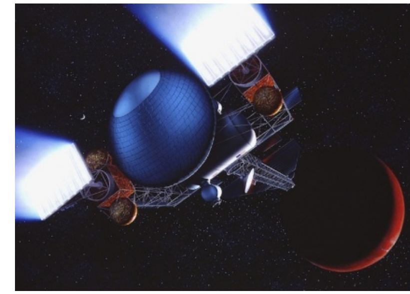
Affordable Fission Surface Power

	Jupiter Icy Moons Orbiter  $3.5-$5B	Lunar FSP System  < $1.4B
Power & Life	• 200 kWe, 15-20 years	• 40 kWe, 5-8 years
Design Approach	• 1300K gas-cooled reactor with UN fuel (no terrestrial design basis), 15 MWt-yrs • Direct 1150K Brayton conversion, ~100 kWe each • 500K water or liquid-metal radiators, >400 m2 • 400V transmission, 6000V bus for thrusters	• 900K liquid-metal cooled reactor with UO2 fuel (terrestrial design basis), 1 MWt-yrs • Indirect 850K Stirling conversion, ~10 kWe each • 400K water radiators (ISS-derived), <200 m2 • 400V transmission, 120V bus (ISS-derived) for loads
Technology Needs	• High temperature refractory alloys & joints • Reactor fuel development (life & burnup) • High power, high temperature Brayton converters • Integrated reactor-Brayton control verification • Rad-hard parts & thruster electrical load integration • End-to-end system performance test • Multiple, sustained, ground nuclear tests	• Liquid metal primary loop & Stirling hot-end interface • End-to-end system performance test (TDU) • Reactor criticality benchmarking tests
Launch & Startup	• Three launches, on-orbit assembly • Reactor startup after final stage Earth escape burn	• Single launch, up to (2) units in a single LSAM • Reactor startup after installation and crew inspection
Mission & Environment	• Sole power source; Full autonomy due to comm delays; Reactor shutdown results in mission failure • Jovian radiation, no solar heating, 120K sink, MMOD	• One of several power sources for crew and equipment; backup power and crew provide contingency options • Lunar day/night cycle, 50 to 350K sink, dust

An Evolutionary Development Path







Fission Surface Power

- 10 to 100 kWe
- 900 K Liquid metal (NaK) cooled reactor with UO_2 fuel and stainless steel structure
- Stirling or Brayton power conversion
- 400 K composite radiators with H_2O heat pipes

Moderate Power NEP

- 100 kWe to 1 MWe
- 1200 K Liquid metal (Li) cooled reactor with UN fuel and refractory alloy structure
- Brayton or Stirling power conversion
- 500 K composite radiators with H_2O heat pipes

High Power NEP

- Multi-Megawatt
- 1500 K Liquid metal (Li) cooled reactor with UN or other advanced fuel and refractory alloy structure
- Brayton or Rankine power conversion
- 600 K composite radiators with Na or K heat pipes

These mission classes share 3 basic building blocks that will be validated in the Fission Technology Demonstration Unit (TDU):

- ➢Liquid metal-cooled, fast-spectrum reactors with pin-type fuel
- ➢Dynamic power conversion with AC power mgmt & distribution
- ➢Large-scale, lightweight heat pipe radiator panels

FSP Technology Demonstration Unit

TDU Components:

- Reactor Simulator with Electrical Pin Heaters
- 850 K NaK Heat Transfer Loop with EM Pump
- 12 kWe Stirling Power Conversion Unit
- 400 Vac Stirling Electrical Controller
- 375 K H2O Heat Rejection Loop

TDU Timeline:

2008 – Initiated TDU development and completed SRR

2009 – Completed System Specification, PDR, and FDR

2010 – Developed DOE/NASA dynamic system model

2011 – Completed H2O cooling loop and buildup assembly platform; built and operated first of two 6 kWe Stirling engines

2012 – Completed reactor simulator testing at MSFC; built and operated 2nd 6 kWe Stirling engine

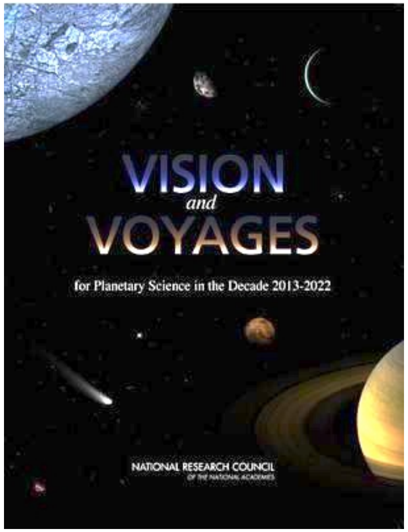
2013 – Completed flight-like structure and received reactor simulator from MSFC; operated dual opposed Stirling PCU at Sunpower

2014 – Completed final assembly of reactor simulator into flight-like structure and demonstrated NaK operations at GRC

2015 – Completed NaK heat exchanger, Stirling PCU integration, and system test – produced full power!

Small Fission Power

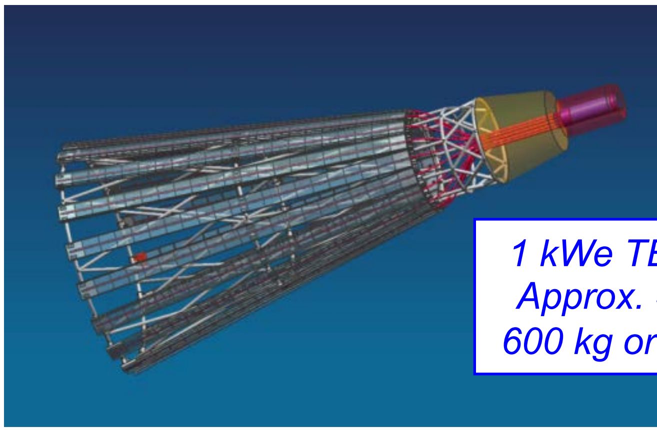
- **NRC Planetary Science Decadal Survey commissioned Small Fission Power System Feasibility Study in early 2010**
  - Results presented to Giant Planets Panel in Apr 2010
  - Final report delivered and appended to NRC Vision and Voyages Report
- **Follow-on informational briefings provided to SMD, HEOMD, and Office of Administrator**
- **Concept was refined and published at several IECEC and NETS technical conferences**



- **OCT initiated FY12 Formulation Study under the Game Changing Development Program, Nuclear Systems Project**
  - Concept development and small-scale component testing continued at GRC and MSFC
- **Los Alamos National Lab sponsored a nuclear-heated power generation proof-of-concept test at the DOE Nevada Test Site**
  - Test was completed in Sept 2012 using Flattop reactor and GRC Stirling engine assembly
- **Selected for FY15 New Start Project under STMD/GCD Program**
  - Three-year project to design, build, and test a 1 kW system with technology that is relevant for systems up to 10 kW

Decadal Study Concepts

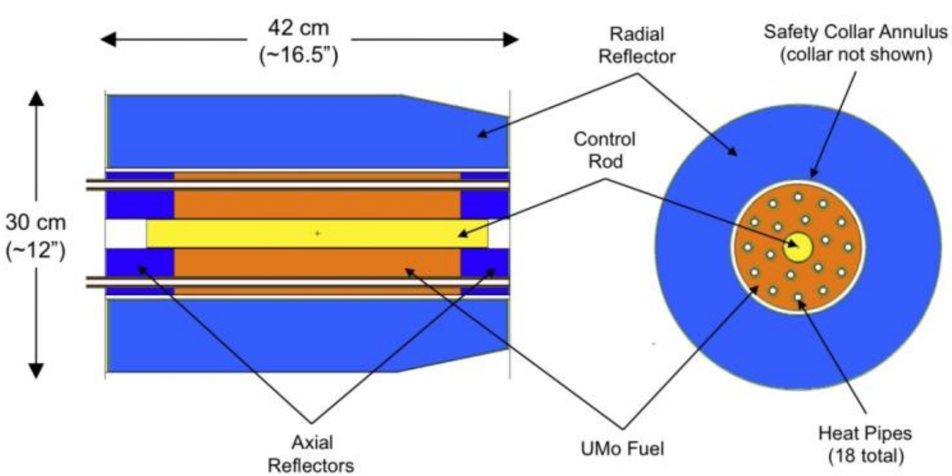
Ideally suited for flagship science missions or human exploration precursors with power requirements that exceed current radioisotope power system limits

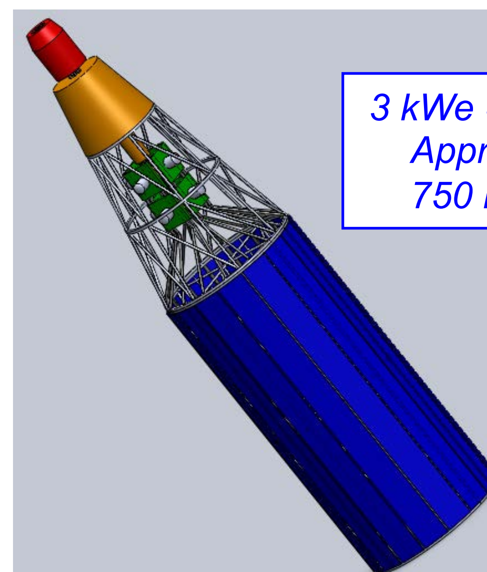


1 kWe TE System
Approx. 4 m long
600 kg or 1.7 W/kg

- **0.5 To 10 kWe; 10 Year Design Life**
- **Common Reactor Design with Solid Block U-Mo Core & Na Heat Pipe Cooling**
- **Thermoelectric (TE) or Stirling Power Conversion**
- **Aluminum Radiator and Truss**

Reactor Core and Reflector Assembly





3 kWe Stirling System
Approx. 5 m long
750 kg or 4 W/kg

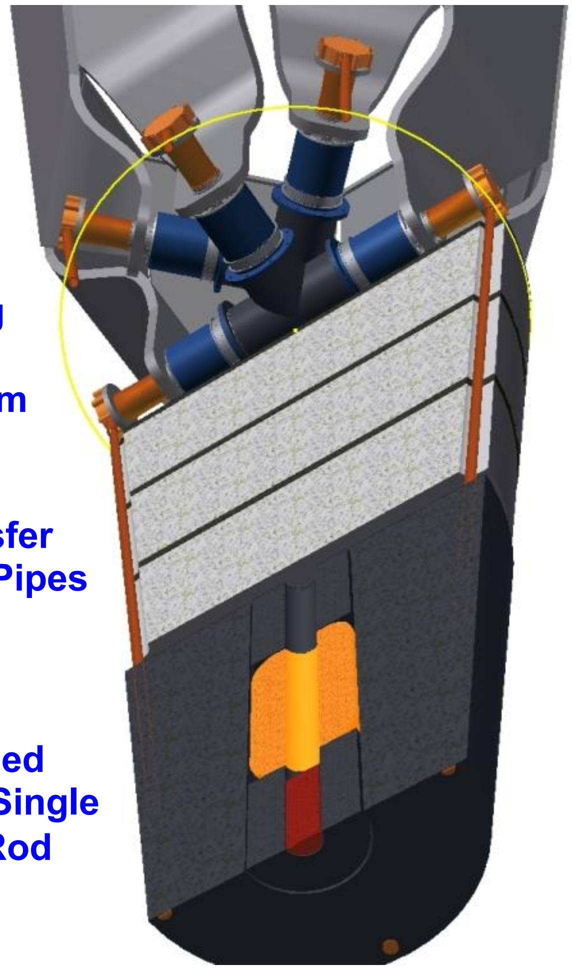
Even Smaller and Simpler…

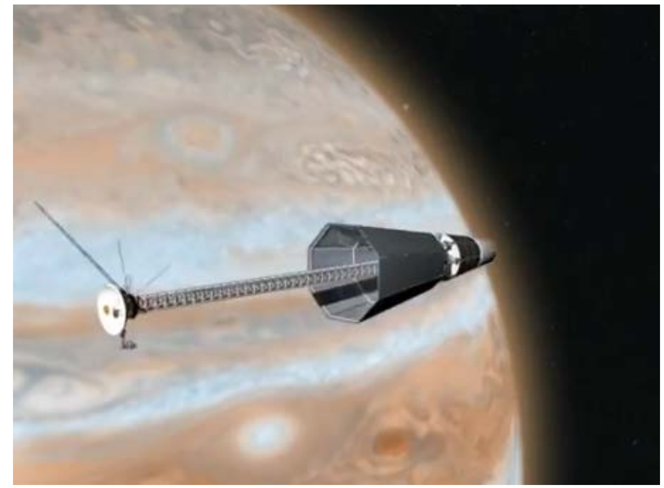
Radial Core Heat Spreaders and Ti-H2O Heat Pipe Radiators

Advanced Stirling Convertors from ASRG Flight System

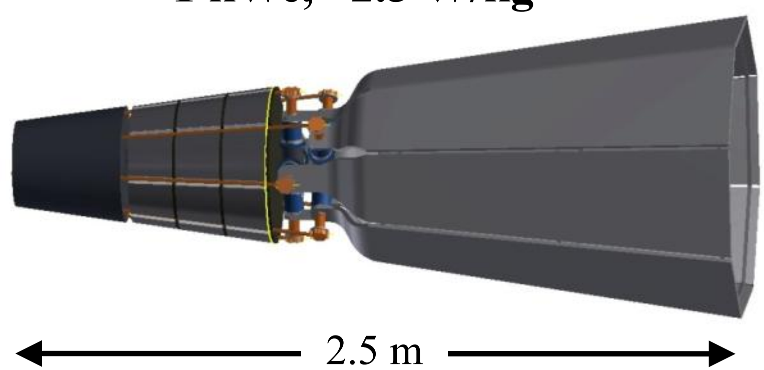
Reactor Heat Transfer via Ex-core Na Heat Pipes in Be Reflector

Highly-Enriched U-235 Core and Single B4C Control Rod





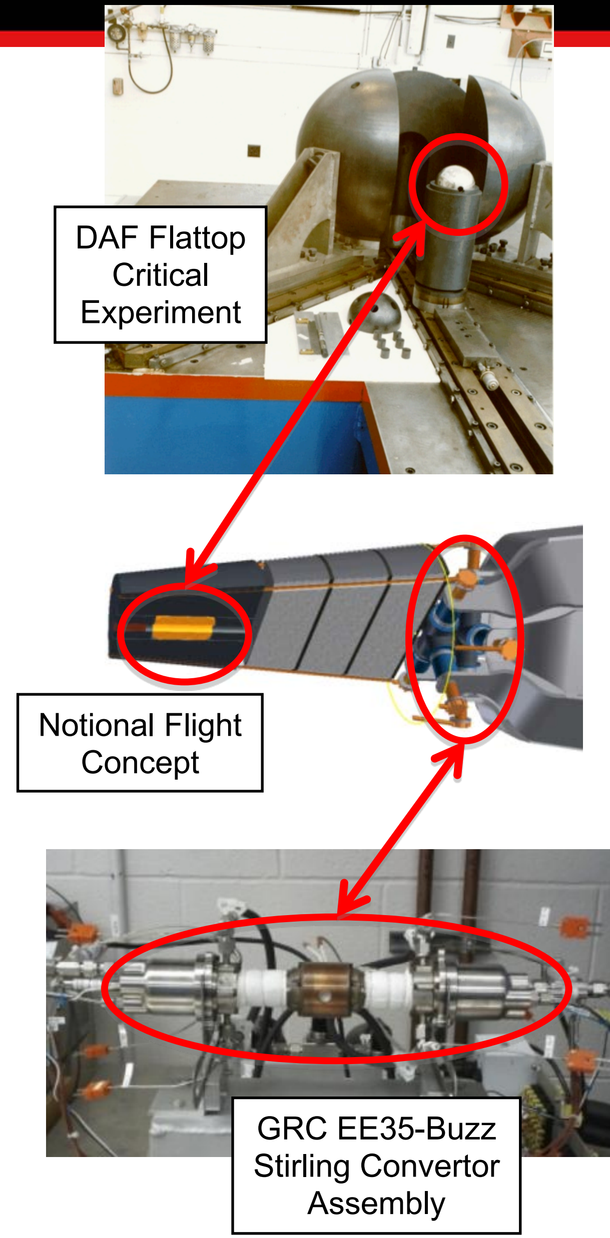
1 kWe, ~2.5 W/kg



A "Critical" Starting Point

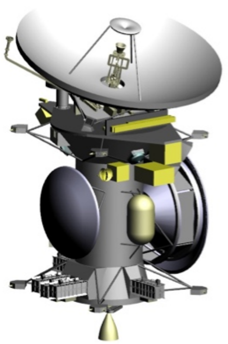
- **Proof-of-Concept Test**
  - LANL-sponsored test at DOE Nevada Test Site, Device Assembly Facility (DAF)
- **Test Configuration**
  - Highly enriched uranium core with central hole to accommodate heat pipe
  - Heat transfer via single water heat pipe
  - Power generation via two Stirling convertors developed during early phases of ASRG Project
- **Significance**
  - First-ever use of a heat pipe to extract thermal power from a fission reactor
  - First-ever use of a Stirling convertor to produce electric power with a fission heat source
  - Demonstration of nuclear reactivity feedback and dynamics with representative components

- **Sept 13, 2012: Success! 24 Watts produced**
  - Completed in less than 6 months with a total cost <$1M
  - Proof that a nuclear reactor ground test can be conducted quickly and affordably

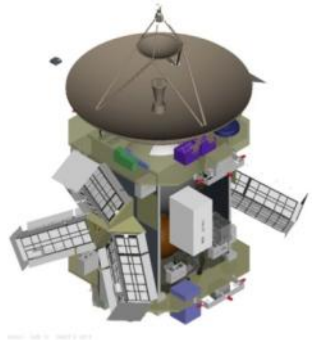


SMD Mission Pull for Small Fission

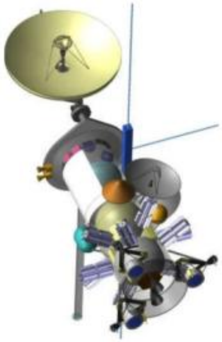
- **High power systems enable expanded science and new Decadal Survey missions (examples below)**
- **Potential benefits to SMD include:**
  - Orbiters instead of flybys, landers instead of orbiters, multiple targets
  - More instruments, bigger instruments, increased duty cycles
  - High rate communications, real time tele-operations, in-situ data analysis
  - Electric propulsion, lower launch mass, greater mission flexibility



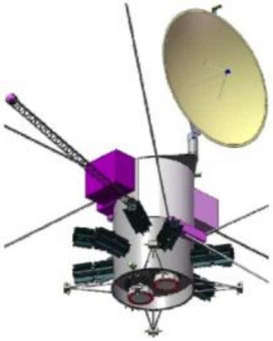
Titan Saturn System Mission ~600 We
5 MMRTGs
4 ASRGs
1 Small Fission System



Trojan Tour ~800 We
8 MMRTGs
6 ASRGs
1 Small Fission System



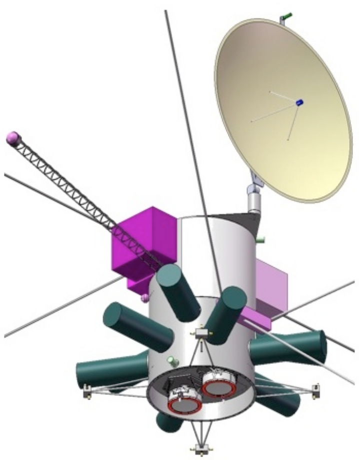
Neptune Systems Explorer ~3 kWe
28 MMRTGs
6 Large SRGs
1 Small Fission System

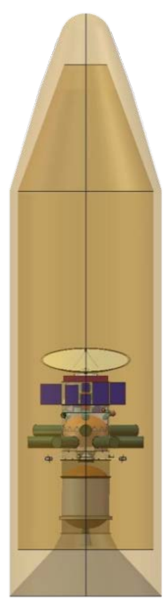


Kuiper Belt Object Orbiter ~4 kWe
36 MMRTGs
8 Large SRGs
1 Small Fission System

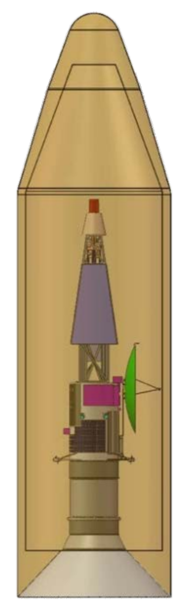
Kilopower NEP Example

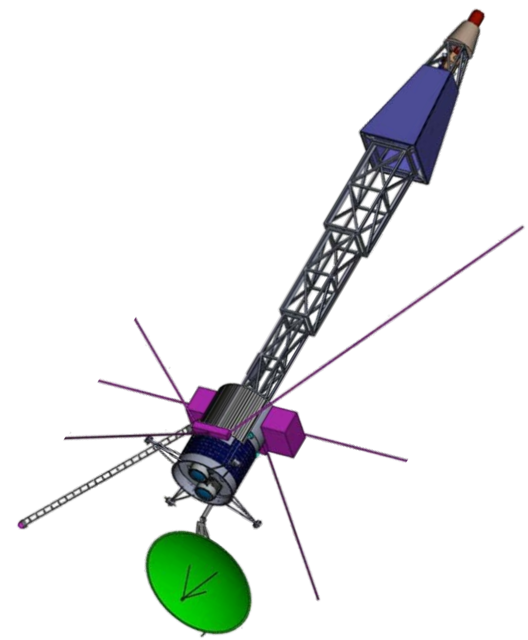
- **REP Kuiper Belt Object Orbiter with Advanced Stirling RPS**
  - 16 yr mission to Kuiper Belt Asteroid
  - 4 kWe; (9) 550W ASRG
  - 782 kg power system (5 We/kg)
  - 3000W NEXT ion propulsion
  - 27 kg Pu238





- **NEP Kuiper Belt Object Orbiter with Kilopower FPS**
  - Same mission
  - 8 kWe; (1) Reactor (8) Stirling convertors
  - 1162 kg power system (7 We/kg)
  - 7000W NEXT ion propulsion
  - 75 kg U235





2014 SMD Nuclear Power Assessment Study (NPAS)

- Current MMRTGs and planned Pu-238 production levels fulfill a subset of SMD mission needs, but with little margin
- Additional programmatic flexibility achieved through maturation of high efficiency advanced thermoelectric and Stirling conversion technologies
- SMD has no current requirements for a mission at the 1 kWe level or higher, and so no current requirement for a Fission Power System exists

Class	Type	Power (W_e BOL*)	Power (W_e EOM**)	Mass (kg)	Specific Power (W_e/kg BOL)	Specific Power (W_e/kg EOM)
Existing RPS	MHW-RTG	157	89***	38	4.1	2.3***
	GPHS-RTG	290	227	58	5.0	3.9
	MMRTG	115	55	45	2.6	1.2
RPS	eMMRTG	154	101	45	3.4	2.2
	6-GPHS SRG	370	297	47	7.9	6.3
	16-GPHS ARTG	456	347	54	8.4	6.4
FPS	1 kW_e Stirling FPS	1,000	1,000	406	2.5	2.5
	5 kW_e Stirling FPS	5,000	5,000	1,049	4.8	4.8
	10 kW_e Stirling FPS	10,000	10,000	1,559	6.4	6.4
	1 kW_e TE FPS	1,000	1,000	604	1.7	1.7

** BOL is Beginning of Life: when the unit is fuelled, typically 3 years before launch for RPS.*
*** EOM is End of Mission defined as 17 years after fueling, typically 14 years of operation for RPS.*
**** MHW-RTG values come from Voyager data at 34 years of operation, rather than 14 years of operation.*

Kilopower Reactor Scaling

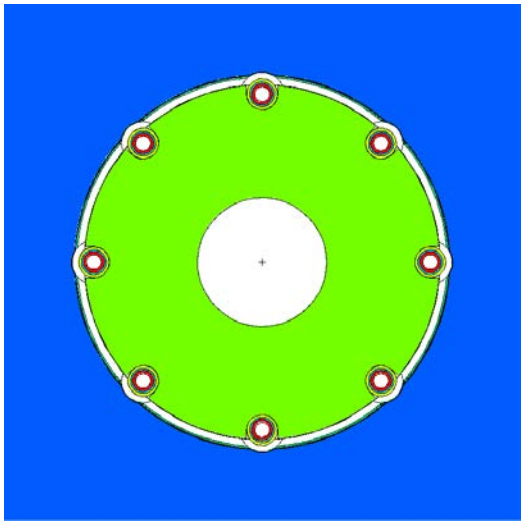
4.3 kWt, 1 kWe

11 cm Fuel OD

28.4 kg U235

0.09% Burnup

8X 3/8” HPs



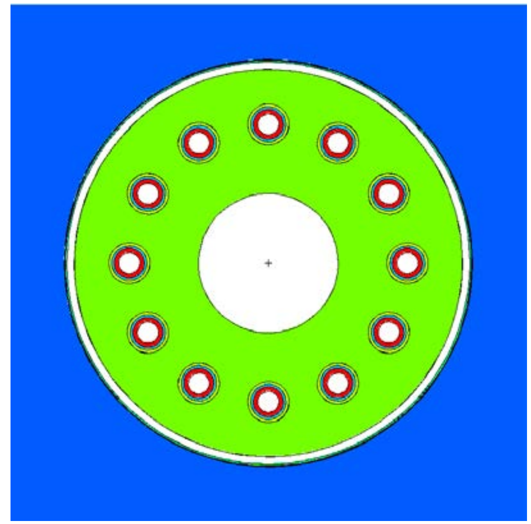
13 kWt, 3 kWe

12 cm Fuel OD

32.9 kg U235

0.22% Burnup

12X 1/2” HPs



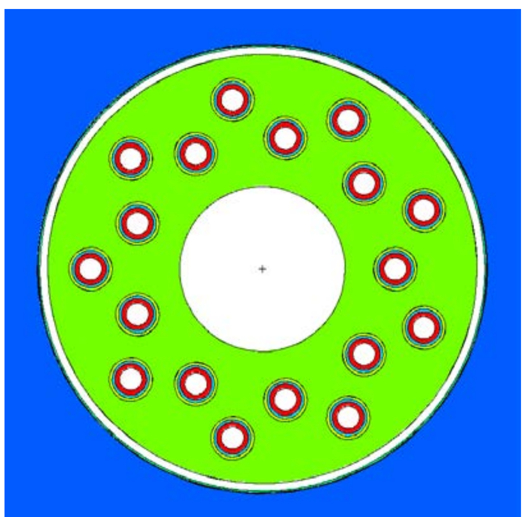
21.7 kWt, 5 kWe

13.2 cm Fuel OD

37.9 kg U235

0.32% Burnup

18X 0.525” HPs



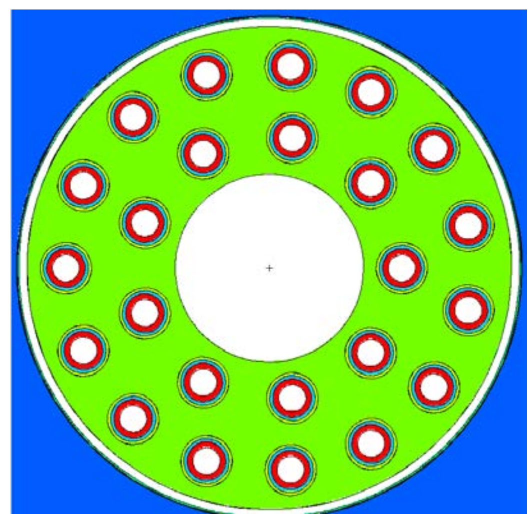
43.3 kWt, 10 kWe

15 cm Fuel OD

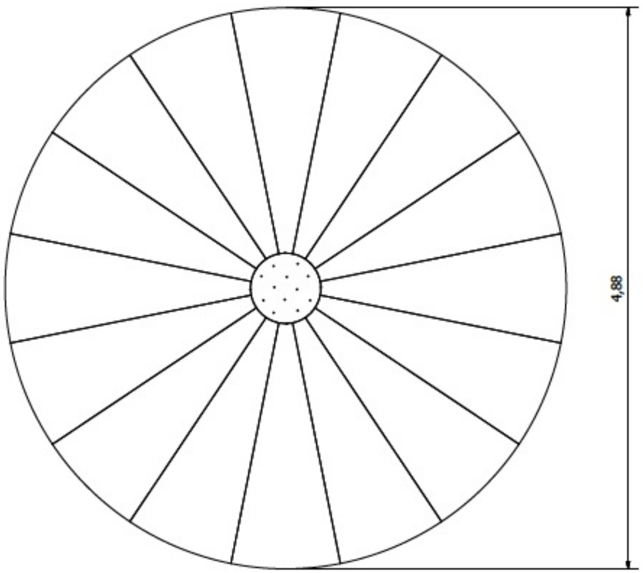
43.7 kg U235

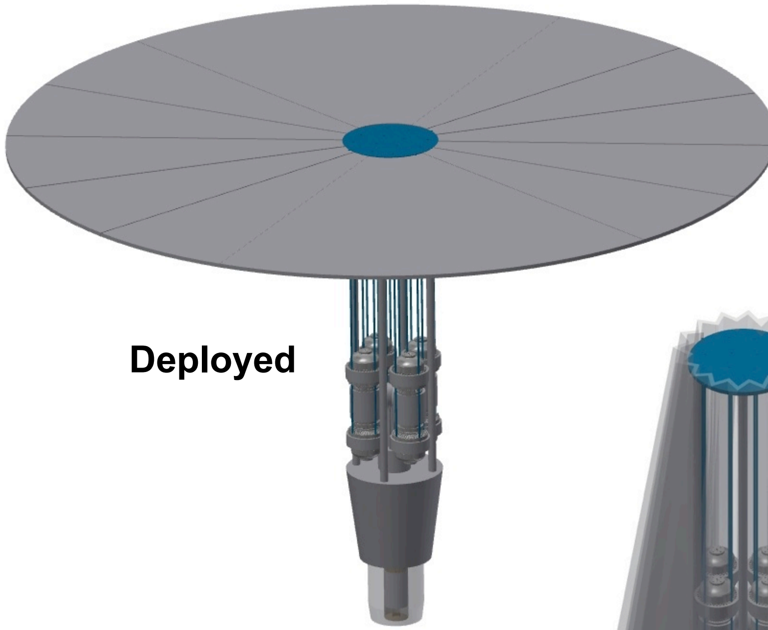
0.56% Burnup

24X 5/8” HPs

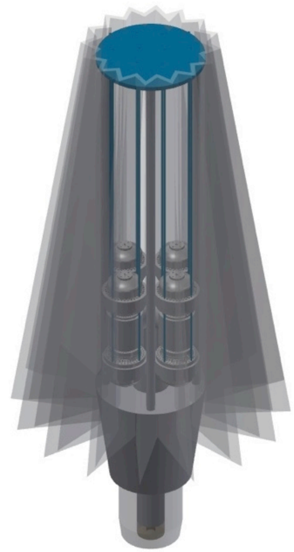


Preliminary 10 kWe Kilopower Concept for Surface Power Applications

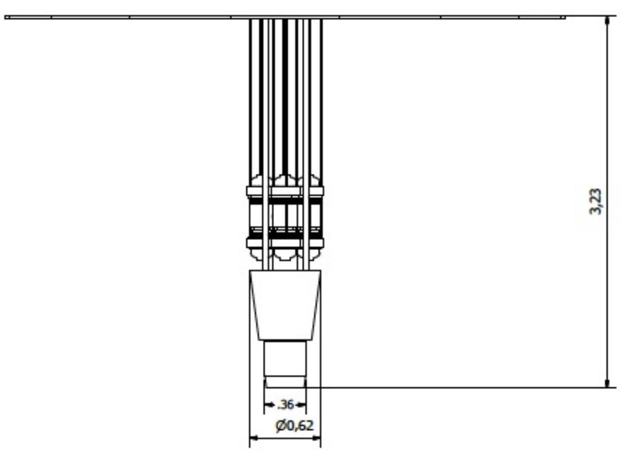


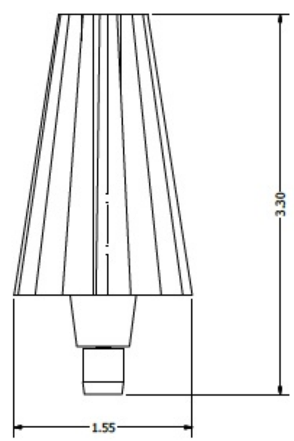


Deployed

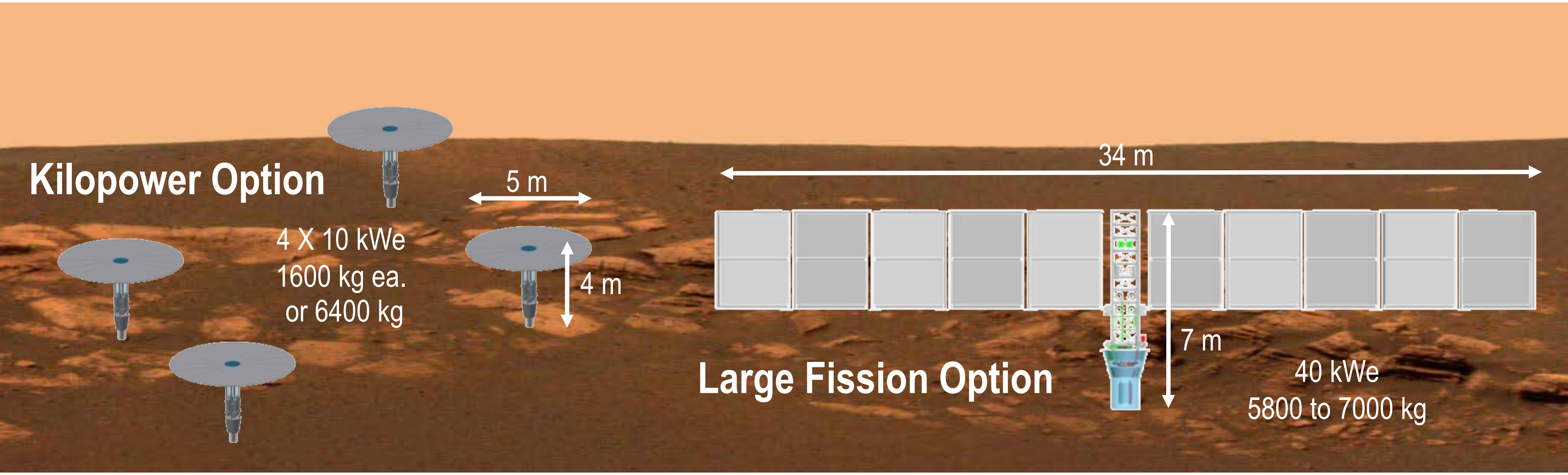


Stowed





HEOMD Mission Pull for Small Fission

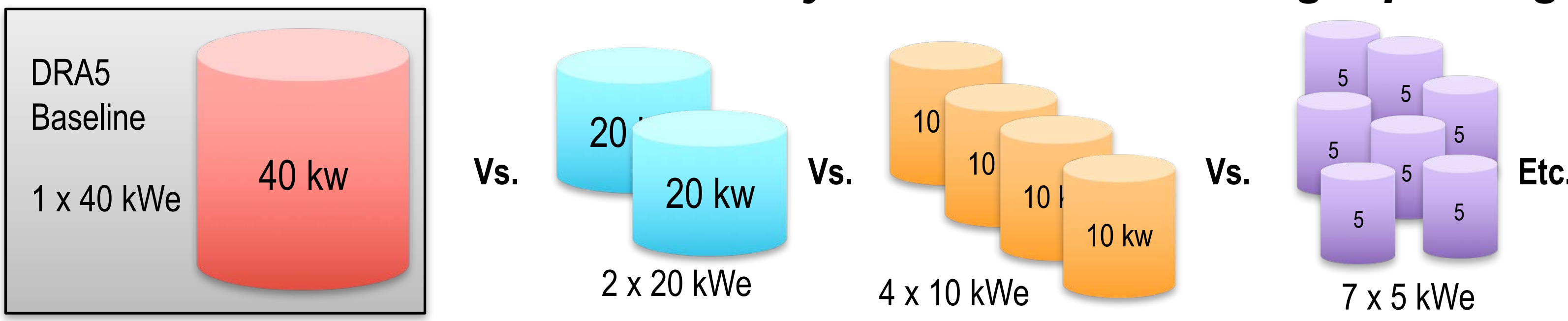


- **Kilopower systems can be used in multiples to address human surface missions as an alternative to a large single power plant**
  - Smaller unit size and mass permits easier packaging in surface landers and simplified startup process
  - Multiple units provide a greater level of redundancy and fault tolerance
  - Units can be deployed as needed in timeline for flexibility in buildup approach
  - Individual units can be shut down & relocated to address evolving mission needs; e.g. rover charging station to extend crew exploration radius

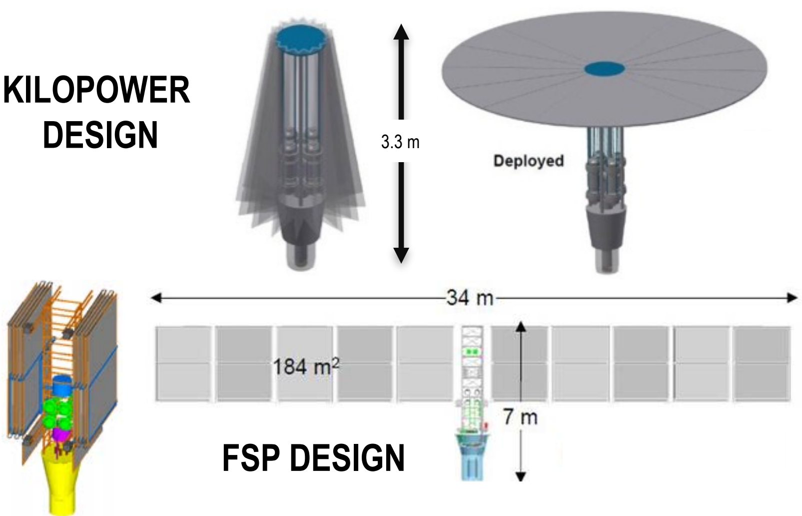
HAT Study: 40 kW Fission Surface Power vs. Multiple Kilopower Units

Mars surface mission needs ~40 kW of surface power

…but it doesn't necessarily have to be in a single package



"Kilopower" design is similar to the FSP, but with lower mass, less volume, easier logistics, and fewer moving parts



Type	Power (kWe)	Mass (kg)	Dimensions (m)		Radiators
			Dia.	Height	
KP	3	751	1.2	2.2	9.6 m^2
	5	1,017	1.3	2.7	13.5 m^2
	7	1,259	1.4	3.0	17 m^2
	10	1,572	1.5	3.3	20 m^2
FSP	10	3,300	1.0	7 m tall	37 m^2
	40	7,000	2.7	7 m tall	184 m^2

Kilopower Baseline for EMC

Assumptions Agreed to at January HAT TIF

1

1. *For the purpose of FY15 EMC studies*, **assume a crewed Mars mission will employ 10 kWe Kilopower systems for surface power**
   - Kilopower units have many advantages over the baseline FSP in a crewed surface mission scenario
   - Although 3, 5 or 7 kWe units would all work for the crewed surface mission, the 10 kWe option trades best for landed mass, stowed volume, and operational complexity
   - STMD's 10 kWe technology demonstrator will provide firm (not hypothetical) data for this option
2. *As a point of departure*, **assume 4 each 10 kWe Kilopower units to support a 4 crew, 500+ day surface mission with ISRU return propellant**
   - *Rationale*: Both DRA 5.0 and the integrated surface power study concluded that such a mission would require ~40 kWe surface power, but results could vary pending FY15 MAV deep dive analysis
3. *As a point of departure*, **assume 1 each spare 10 kWe Kilopower unit**
   - *Rationale*: Unlikely that all 4 primary units will fail, but it's prudent to have at least one spare, pending more detailed risk analysis
4. *As a point of departure*, **assume 4 each 10 kWe Kilopower units will be needed to extend rover traverse 250 km from the Landers/Habitat**
   - *Rationale*: Based on power study, which found co-located, daisy-chained units provide optimum traverse
     - Note: we don't have to use the power units in this way, but if our operations scenarios dictate this type of traverse, this is what we should assume for power

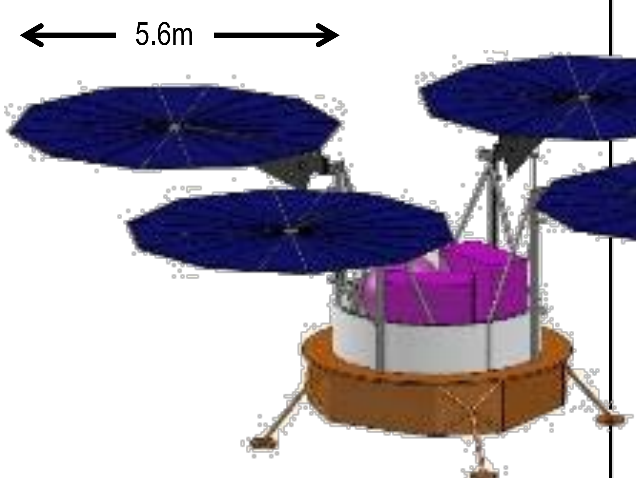
ISRU Demo Lander Study

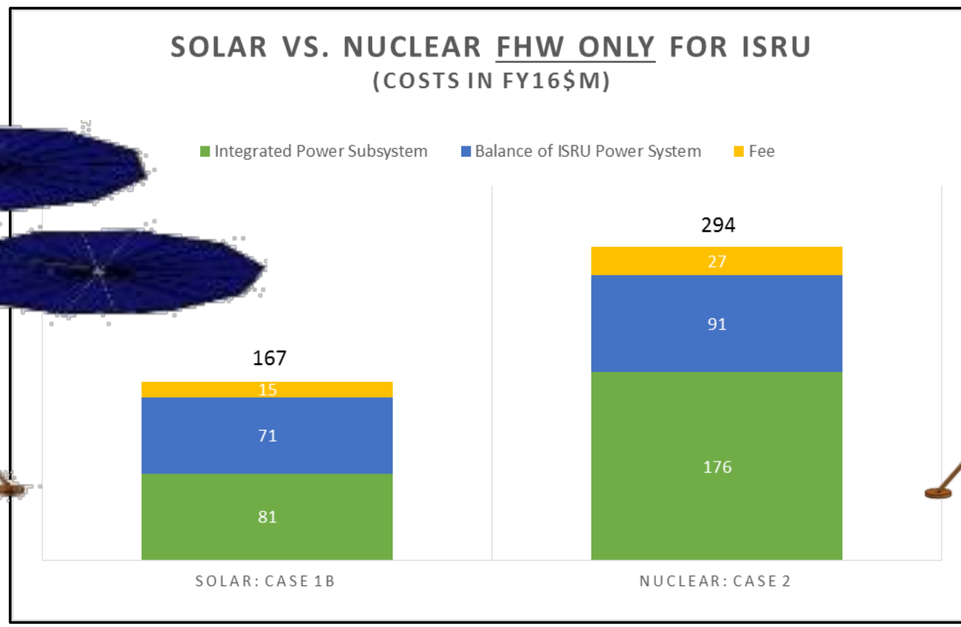
Solar version:

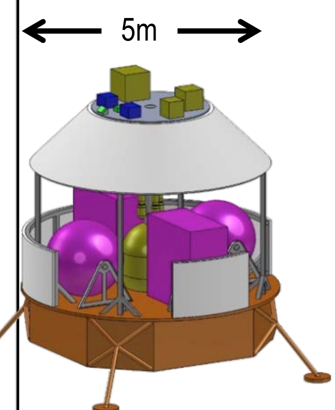
- 4X 5.6m Ultraflex arrays
- Daytime ISRU only (1098 days to produce 4400 kg LOX*)
- Requires 4X 7.5m arrays and 1100 kg Li batteries for day/night ISRU ops excluding dust storm (527 days to produce 4400 kg LOX*)

Nuclear version:

- 1X 10 kW Kilopower reactor operated at 70% power
- Continuous ISRU operations (407 days to produce 4400 kg LOX*)
- Co-located reactor results in elevated radiation levels for ISRU equipment on lander deck

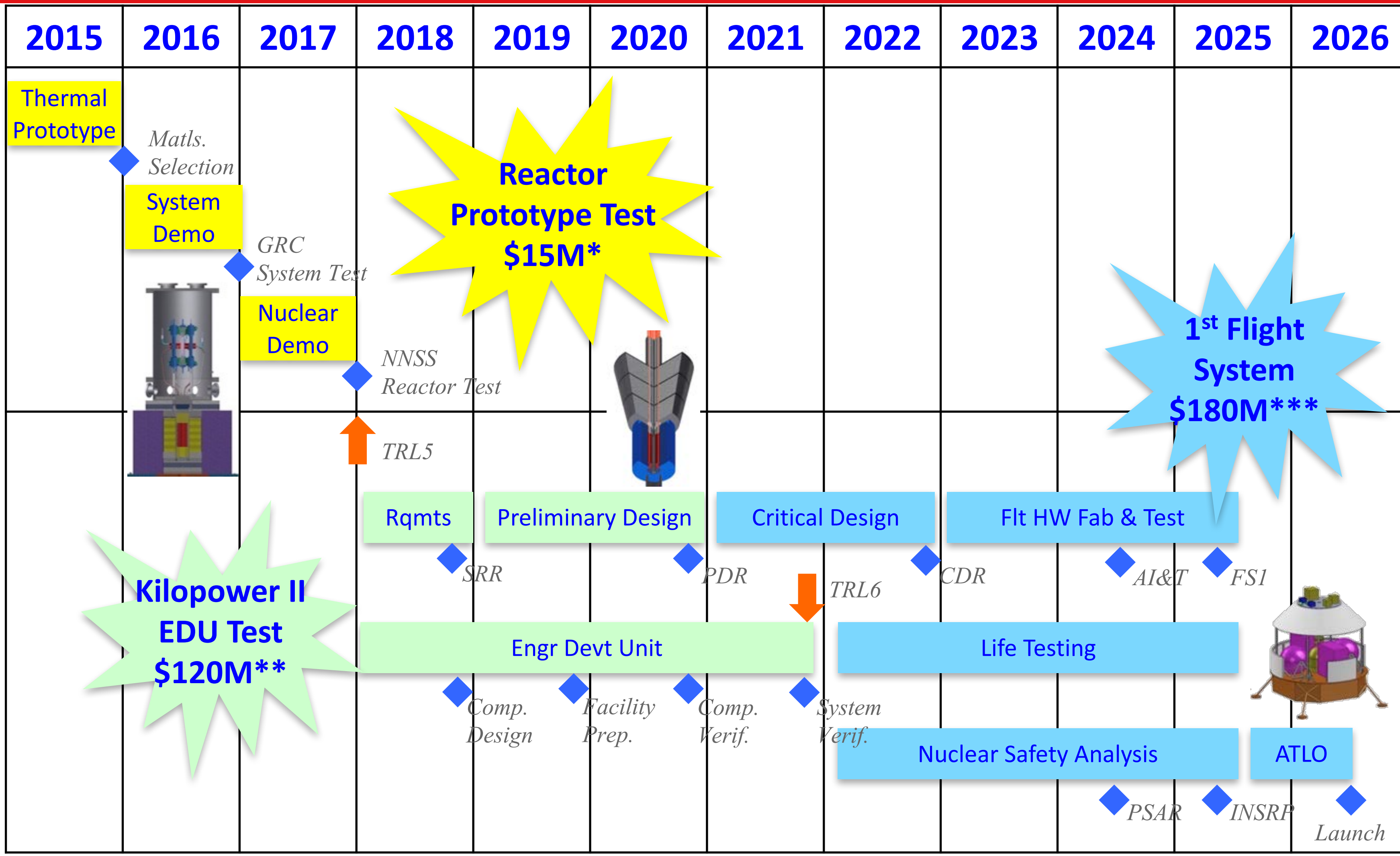






* 4400 kg LOX represents 1/5 total needed for crew ascent stage; deemed sufficient quantity to demo ISRU process for crewed mission.

Notional Flight Development Timeline

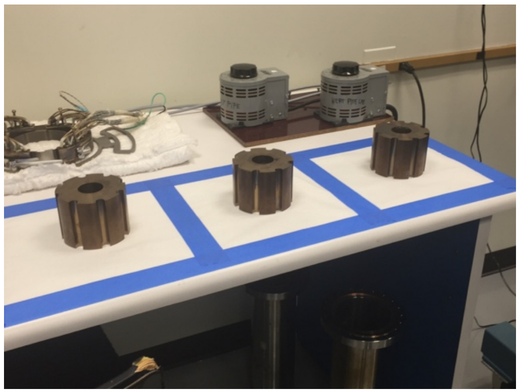


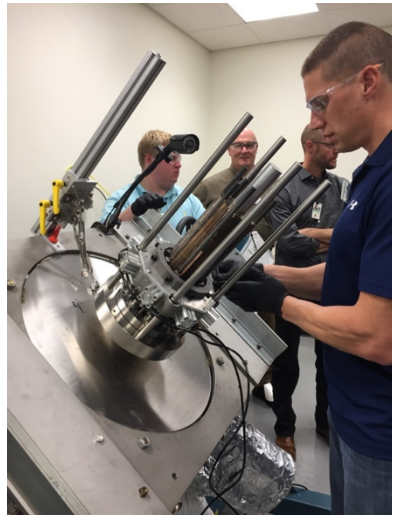
* Includes $5M funding from Department of Energy, National Nuclear Security Administration

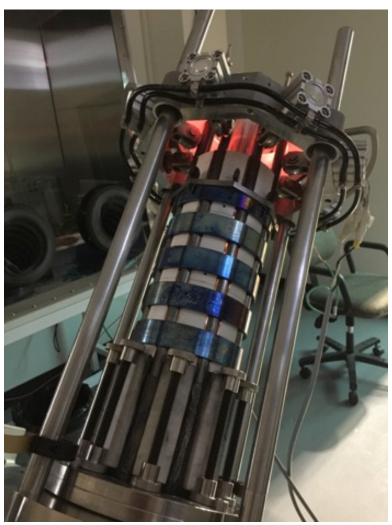
** Expected cost sharing between STMD and HEOMD for Mars-specific design and test

*** ROM costs based on preliminary estimates for Kilopower flight hardware on notional ISRU demo mission

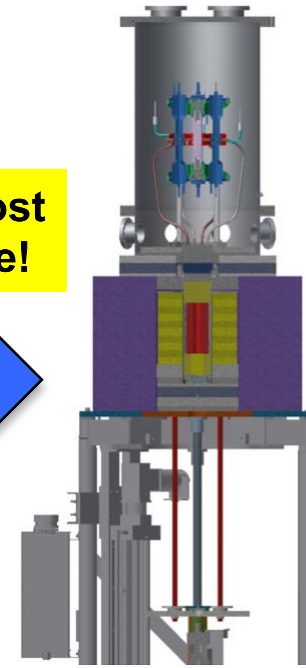
KRUSTY Dry Run with DU Cores (Dec. 2016)







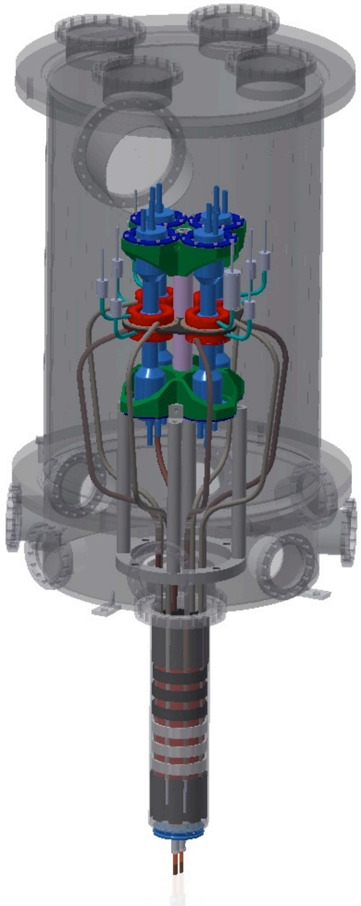
Almost There!



Reactor Prototype Test with Highly-Enriched Uranium Core at NNSS (Year 3)

Summary

- **Kilopower Technology Development on-going under STMD/GCD Program**
  - Fully-funded, 2017 Nuclear Ground Test at Nevada Test Site
  - Cost shared with DOE National Nuclear Security Administration
- **Scalable fission technology from 1-10 kWe for Science and Exploration**
- **New paradigm for space reactors with design based on affordability rather than performance**
- **Smaller and simpler than Constellation-era Fission Surface Power system concepts**
- **Leverages available materials and components; sized for existing ground test faciities**
- **Proposed high-fidelity EDU in simulated Mars environment**
- **Potential for flight test in less than 10 years**



Key Contributors

- GRC – Don Palac, Marc Gibson, Jim Sanzi, Max Briggs, Max Chaiken
- MSFC – Tom Godfroy, Kenny Webster, Mike Houts
- JSC – Michelle Rucker
- Los Alamos – Patrick McClure, Dave Poston
- Y12 – Chris Robinson, Jim Henkel, Hollie Longmire
- NNSA – Steve Clement, Angela Chambers, Jerry McKamy (ret.)
- NNSS – Chip Martin, Tim Beller, Rene Sanchez, David Hayes
- Sunpower, Inc. – Gary Wood
- Advanced Cooling Technologies, Inc. – Bill Anderson

- STMD – Lanetra Tate, Jeff Sheehy, Mary Beth Wusk & GCD Program
- HEOMD – Chris Moore, John Warren & AES Program
- SMD – David Schurr, Len Dudzinski, John Hamley & RPS Program