Kilopower Technology Demonstration – Overall Objectives & Elements

• **Innovation:**
  – A compact, low cost, scalable fission power system for science and exploration
  – Novel integration of available U235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors

• **Impact:**
  – Provides Modular Option for HEOMD Mars Surface Missions
  – Bridges the gap between Radioisotope Power Systems (RPS) and 40 kW_e class fission power technology
  – Enables SMD Decadal Survey Missions
  – Reduces NASA dependence on Pu238

• **Goals:**
  – **Nuclear-heated system-level test of prototype U235 reactor core coupled to flight-like Stirling convertors**
  – Detailed design concept that verifies scalability to 10 kW_e for Mars

1 to 10 kWe Kilopower Technology

Full-scale nuclear test of reactor core, sodium heat pipes, and Stirling convertors at prototypic operating conditions

- 10X the power of current RPS
- Available component technologies
- Tested in existing facilities
Why Kilopower?

• The Kilopower technology demonstration is the practical and affordable first step to getting a reactor power system in space
  - Executing nuclear testing in existing DOE facilities is crucial to affordable technology development and demonstration
    - Small physical size of hardware and low power level allows use of existing facility within current regulatory authority
  - The reactor core can be fabricated and shipped with existing assets
  - The same equipment used to test pre-nuclear prototypes can be transported to the DOE facility and used in the nuclear test
  - *Keeping it small means keeping it affordable*

• Kilopower enables larger power systems and nuclear propulsion
  - The path from technology maturation to flight qualification of a larger power system will not be trivial; smaller and simpler is better
  - Qualification and programmatic risks will be substantially retired so that larger reactor systems requiring more fuel and engineering complexity can be developed
Kilopower-Enabled Concepts Family

- **Common Design Features include:**
  - 0.5 to 10 kWe; >10 year design life
  - Utilize available UMo reactor fuel from DOE
  - Minimize thermal power to simplify reactor design and control
  - Incorporate passive Na heat pipes for reactor heat transport
  - Leverage power conversion technologies from RPS Program (TE, Stirling)
  - Design system so that it can be tested in existing DOE nuclear facilities

- **1 kW Thermoelectric**
  - Approx. 4 m long
  - 600 kg or 1.7 W/kg

- **800 W Stirling**
  - Approx. 2.5 m long
  - 400 kg or 2 W/kg

- **3 kW Stirling**
  - Approx. 5 m long
  - 750 kg or 4 W/kg

- **10 kW Stirling**
  - Approx. 4 m tall
  - 1800 kg or 5 W/kg

**1 kWe-class Technology Demonstration establishes foundation for range of systems and capabilities**
<table>
<thead>
<tr>
<th>Task</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
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</thead>
<tbody>
<tr>
<td>Kilopower Prototype Test</td>
<td>Finalize system design and assemble components</td>
<td>Perform non-nuclear system verification test at GRC</td>
<td>Install reactor core and perform nuclear test at Nevada Nuclear Security Site</td>
<td>Initiate modifications for Mars surface power 10 kW&lt;sub&gt;e&lt;/sub&gt; technology demo</td>
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<tr>
<td>Mars Kilopower System Concept and Scalability from Prototype</td>
<td>Develop 10 kW&lt;sub&gt;e&lt;/sub&gt;-class power system concept for Mars surface missions</td>
<td>Mars Kilopower detailed conceptual design</td>
<td>Demonstrate in-core heat pipe heat transfer, determine power conversion adaptation scope, and deliver system technology demonstration plan</td>
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Kilowatt Reactor Using Stirling Technology (KRUSTy)

- 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
Kilopower Thermal Prototype

- Kilopower Thermal Prototype is first of three steps to a nuclear ground demonstration
  - Non-nuclear functional prototype with steel simulated reactor core
  - Non-nuclear prototype with depleted uranium simulated core
  - Nuclear demonstration with uranium reactor core

- Thermal prototype validates core geometry and heat pipe attachment method prior to build of depleted uranium simulated core
  - Steel core thermal properties are close enough to uranium to validate heat pipe attachment method under thermal load, and segmentation of core
  - First of two electrically heated trials of heat pipe attachment methods tested at temperature in vacuum

Stainless Steel Thermal Prototype  Vacuum Tank Integration  Integrated Assembly  Test
Latest Configuration of 1 kW$_e$ Krusty Nuclear Demonstration
• Small fission technology enables 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

<table>
<thead>
<tr>
<th>Mission</th>
<th>Power</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter Europa Orbiter</td>
<td>~600 We</td>
<td>6 MMRTGs, 4 ASRGs, 1 Small Fission System</td>
</tr>
<tr>
<td>Neptune Systems Explorer</td>
<td>~3 kWe</td>
<td>28 MMRTGs, 6 Large SRGs, 1 Small Fission System</td>
</tr>
<tr>
<td>Kuiper Belt Object Orbiter</td>
<td>~4 kWe</td>
<td>36 MMRTGs, 8 Large SRGs, 1 Small Fission System</td>
</tr>
<tr>
<td>Trojan Tour</td>
<td>~800 W</td>
<td>8 MMRTGs, 6 ASRGs, 1 Small Fission System</td>
</tr>
</tbody>
</table>
The Evolvable Mars Campaign has found that 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
- Multiple units provide a greater level of redundancy and fault tolerance
- Units can be deployed as needed in timeline for flexibility in buildup approach
- Human missions can benefit from first user’s establishment of nuclear infrastructure (material handling, testing, safeguards) and launch approval process
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

<table>
<thead>
<tr>
<th>Type</th>
<th>Power (kWe)</th>
<th>Mass (kg)</th>
<th>Dimensions (m)</th>
<th>Radiators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dia</td>
<td>Height</td>
</tr>
<tr>
<td>KP</td>
<td>3</td>
<td>751</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1,011</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1,246</td>
<td>1.4</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1,544</td>
<td>1.5</td>
<td>3.3</td>
</tr>
<tr>
<td>FSP</td>
<td>10</td>
<td>3,300</td>
<td>1.0</td>
<td>7 m tall</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>7,000</td>
<td>2.7</td>
<td>7 m tall</td>
</tr>
</tbody>
</table>
• **DOE/National Nuclear Security Administration**
  - Nevada Nuclear Security Site Device Assembly Facility is being provided without cost to NASA
  - NNSA will own, keep, and dispose of Kilopower demonstration reactor core
  - *NNSA is a funding partner in FY16 & 17 to Kilopower*

• **HEOMD**
  - Kilopower is the assumed surface power technology for Evolvable Mars Campaign architecture trades
  - Providing time of Human Spaceflight Architecture Team (HAT) members for Mars Kilopower Concept Development
  - Possible Kilopower use on 2024-26 Mars In Situ Resource Utilization Surface Demo

• **Other Government Agencies: ARPA-E**
  - Contracts awarded for 1 kWe residential power: GENerators for Small Electrical and Thermal Systems (GENSETS)
  - Two Stirling technology contracts could have direct benefit to Kilopower (Infinia, Sunpower)
• Existing NNSA nuclear test facilities operated within current safety constraints
• Available high-enrichment U235 fuel and other nuclear materials from Y-12
• Existing, benchmarked LANL reactor design codes
• Four SBIRs producing plug-in ready test hardware
  • Phase II contracts for Na heat pipes, radiators, and alternate (Brayton) power conversion
  • Phase IIE in negotiation for Na heat pipes to be used in nuclear test at NNSS
• Existing Advanced Stirling Convertors and design expertise from RPS Program
• Stirling cold-end heat pipes from Flight Opportunities Program & RPS
• Extensive MSFC experience-base in reactor thermal simulators and custom electric resistance heaters

Existing facilities, expertise, and equipment provide a uniquely timed level of affordability
Cross-cutting Experience Gained Through 1 kW\textsubscript{e} Test

- Experience gained and infrastructure established during the 1 kW\textsubscript{e} test will reduce risk of any future reactor development
  - Common nuclear fuel form that is scalable to 10 kW\textsubscript{e}
  - Fabrication of reactor core to NASA specifications
  - Shipping and handling of reactor core in specialized cask
  - NNSS familiarization with NASA test practices
  - NASA familiarization with NNSS nuclear safety & contingencies
  - Reactor assembly with combination of NNSS and NASA personnel
  - Reliable instrumentation, data acquisition, and data storage
  - Reactor operator experience for startup, steady-state, transient, & shutdown
  - Reactor cool down, disassembly, and core disposal

These capabilities translate across a wide range of space nuclear applications and power levels
## Stirling Industry Base Supports Full Range of Kilopower Systems

<table>
<thead>
<tr>
<th></th>
<th>Sunpower EE-35</th>
<th>Infinia TDC</th>
<th>Sunpower ASC</th>
<th>Sunpower P2A</th>
<th>Qnergy QB-3500</th>
<th>Sunpower PCU</th>
<th>Qnergy QB-7500</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal</strong></td>
<td>35 W</td>
<td>55 W</td>
<td>80 W</td>
<td>1 kW</td>
<td>3.5 kW</td>
<td>6 kW</td>
<td>7.5 kW</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>20 - 42 W</td>
<td>50 - 60 W</td>
<td>60 - 90 W</td>
<td>0.5 - 1.4 kW</td>
<td>4.5 - 7.2 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thot</strong></td>
<td>650 °C</td>
<td>650 °C</td>
<td>760 °C</td>
<td>550 °C</td>
<td>575 °C</td>
<td></td>
<td>Qnergy I.P.</td>
</tr>
<tr>
<td><strong>Tcold</strong></td>
<td>80 °C</td>
<td>120 °C</td>
<td>90 °C</td>
<td>50 °C</td>
<td>100 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>105 hz</td>
<td>80 hz</td>
<td>102 hz</td>
<td>50 hz</td>
<td>60 hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Piston Amp.</strong></td>
<td>4 mm</td>
<td>5.6 mm</td>
<td>4.5 mm</td>
<td>10 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Approx. Mass</strong></td>
<td>1.4 kg</td>
<td>4.5 kg</td>
<td>2.5 kg</td>
<td>35 kg</td>
<td>67 kg</td>
<td>100 kg</td>
<td>103 kg</td>
</tr>
<tr>
<td><strong>Bearings</strong></td>
<td>Gas</td>
<td>Flexure</td>
<td>Gas</td>
<td>Gas</td>
<td>Flexure</td>
<td>Gas</td>
<td>Flexure</td>
</tr>
<tr>
<td><strong>Status</strong></td>
<td>6 units built for GRC</td>
<td>16 units built, 4 remain on test at GRC</td>
<td>29 units built for GRC, 13 on test at GRC</td>
<td>&gt;10,000 units built by Microgen for CHP</td>
<td>430 solar Powerdish units on field trial at Tooele</td>
<td>2 units built at SP for GRC TDU</td>
<td>&gt;100 production units built for CHP</td>
</tr>
</tbody>
</table>
1 kW_e Kilopower Test Retires Many Challenges for 10 kW_e Fission Systems

- Existing Comet test stand at NNSS
- External heat pipe channels
- 8 perimeter, clamped heat pipes
- Single HP-to-Stirling thermal interface
- Existing Stirling units from RPS

- Prototypic reactor core
- Material properties & compatibility
- UMo fuel casting, machining & inspection
- BeO reflector material & configuration
- Facility controlled reactivity insertion/removal
- Reactivity feedback control
- System performance – start, run, stop, restart
- Nuclear test safety and contingencies
- Nuclear performance code validation

**Common Elements**

**Greater complexity**
- New test stand at NNSS
- Internal heat pipe channels
- 24 brazed or liquid-metal bonded heat pipes
- Shared HP-to-Stirling thermal bus
- Larger, commercial-adapted Stirling units

**Wait for more specific Mission reqmts**
- Fuel irradiation studies
- Prototypic reactor control
- Prototypic radiation shielding

**TRL 5 for 1 kW_e**

**TRL 5 for 10 kW_e**

- End-to-end system
- Environmental testing
- Nuclear launch safety

**TRL 6**
Summary

• We have the team

• We have available, leveraged infrastructure and experience

• We have mission pull from HEOMD and willingness to use the technology from SMD

• We have an NASA-wide directive on a role to fulfill

• We are making progress today with successful technology development accomplishments

We’re seizing the opportunity to demonstrate system-level technology readiness of space fission power