• **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 kWₑ 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 kWₑ for Mars

1 to 10 kWₑ 
Kilopower Technology

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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

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

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

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

1 kWe-class Technology Demonstration establishes foundation for range of systems and capabilities
## Approved Kilopower Project Plan by Element

<table>
<thead>
<tr>
<th>Task</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
</tr>
</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>
</tr>
<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>
<td></td>
</tr>
</tbody>
</table>
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 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
Latest Configuration of 1 kW$_e$ Krusty Nuclear Demonstration
SMD Mission Pull for Small Fission

- **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 (kWe)</th>
<th>MMRTGs</th>
<th>ASRGs</th>
<th>Large SRGs</th>
<th>Small Fission System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter Europa Orbiter</td>
<td>~600</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neptune Systems Explorer</td>
<td>~3</td>
<td>28</td>
<td></td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Kuiper Belt Object Orbiter</td>
<td>~4</td>
<td>36</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Trojan Tour</td>
<td>~800</td>
<td>8</td>
<td>6</td>
<td>1</td>
<td></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>
Partner Organizations Investing in Kilopower

• **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)
Extensive Project Leveraging

- 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$_e$ Test

- Experience gained and infrastructure established during the 1 kW$_e$ test will reduce risk of any future reactor development
  - Common nuclear fuel form that is scalable to 10 kW$_e$
  - 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>
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</thead>
<tbody>
<tr>
<td>Nominal</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>Range</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>575 °C</td>
<td>100 °C</td>
</tr>
<tr>
<td>Thot</td>
<td>650 °C</td>
<td>650 °C</td>
<td>760 °C</td>
<td>550 °C</td>
<td>Qnergy I.P.</td>
<td>50 °C</td>
<td>100 °C</td>
</tr>
<tr>
<td>Tcold</td>
<td>80 °C</td>
<td>120 °C</td>
<td>90 °C</td>
<td>50 °C</td>
<td></td>
<td>60 °C</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>105 hz</td>
<td>80 hz</td>
<td>102 hz</td>
<td>50 hz</td>
<td></td>
<td></td>
<td>Qnergy I.P.</td>
</tr>
<tr>
<td>Piston Amp.</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>Approx. Mass</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>Bearings</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>Status</td>
<td>6 units built</td>
<td>16 units</td>
<td>29 units</td>
<td>&gt;10,000 units</td>
<td>430 solar</td>
<td>2 units built</td>
<td>&gt;100 production</td>
</tr>
<tr>
<td></td>
<td>for GRC</td>
<td>built, 4</td>
<td>built for</td>
<td>built by</td>
<td>Powerdish</td>
<td>at SP for</td>
<td>units built</td>
</tr>
<tr>
<td></td>
<td></td>
<td>remain on</td>
<td>GRC, 13 on</td>
<td>Microgen</td>
<td>units on</td>
<td>GRC TDU</td>
<td>for CHP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>test at GRC</td>
<td>test at GRC</td>
<td>for CHP</td>
<td>field trial at</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tooele</td>
<td></td>
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</tr>
</tbody>
</table>

*Qnergy I.P.* indicates production units.
1 kW<sub>e</sub> Kilopower Test Retires Many Challenges for 10 kW<sub>e</sub> 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

TRL 5 for 1 kW<sub>e</sub>

- 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

TRL 5 for 10 kW<sub>e</sub>

- 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

Greater complexity

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

TRL 6

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