KiloPower

A very small nuclear reactor for space applications

A presentation to:

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KiloPower – Reactor Concept

7 COMPONENTS

- Core of uranium metal fuel
- Beryllium oxide neutron reflector
- Sodium heat pipes
- Radiation shielding
- Boron-carbide start-stop rod
- Stirling engine convertors
- Radiator to remove excess heat
KiloPower – Key Features

Attributes:
• 1 to 10 kW of electricity generated
• Reliable passive heat transfer
• Efficient Stirling engine heat to electricity conversion
• Solid Uranium metal fuel can be made easily
• Nuclear effects are low, so testing is minimized
• Low startup power in space – battery only
• Reactor can be started, stopped and restarted
• Reactor self regulates using simple physics

Benefits:
• Low reoccurring costs for each reactor
• Reactor is safe to launch (minor radioactivity in fuel)
• Reactor will not be started until at destination
• Allows for higher power missions
• Reactor works in extreme environments
• Reactor could be used for electric propulsion
Potential Applications

• **Government Missions**
  – Human Mars surface missions
  – Lunar (moon) surface missions
  – Planetary orbiters and landers:
    • Europa, Titan, Enceladus, Neptune, Pluto, etc.

• **Commercial Missions**
  – Space power utility
  – Asteroid/space mining
  – Lunar/Mars settlements

• **Power uses**
  – drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging
Mars Surface Power

- No off-the-shelf options exist to power long-term human surface missions on Mars
  - Power systems used on previous robotic missions (e.g. Spirit/Opportunity, Phoenix, Curiosity) do not provide sufficient power: all less than 200 W

- Projected human exploration power needs...
  - Up to 40 kW day/night continuous power
  - In-situ Resource Utilization (make oxygen and propellant before crew arrives)
  - Power for landers, habitats, life support, rover recharging (during crew operations)
  - Technology options: Nuclear Fission or Solar Photovoltaic & Energy Storage
  - Desire compact stowage, robotic deployment, survivable for multiple crew campaigns (>10 yrs), lunar extensibility

- Mars surface presents major challenges
  - CO$_2$ atmosphere, 3/8$^{th}$ gravity, 1/3$^{rd}$ solar flux of Earth orbit, >12 hour night
  - Large seasonal and geographical solar flux variations, long-term dust storms, high winds
Mars Solar Flux

Max Horizontal Surface Solar Fluxes

1/15/2034 BOL landing date

Perihelion 1.38 AU (Summer)

Aphelion 1.67 AU (Winter)

Mars Orbit

30° South

Equator

50° North

Potential Dust Storm
Why this reactor design?

• Very simple, reliable design
  – Self-regulating design using simple reactor physics
  – The power is so low there should be no measurable nuclear effects
  – Low power allows small temperature gradients and stresses, and high tolerance to any potential transient

• Available fuel with existing Infrastructure

• Heat pipe reactors are simple, reliable, and robust
  – Eliminates components associated with pumped loops; simplifies integration
  – Fault tolerant power and heat transport system
  – The only reactor startup action is to withdraw reactivity control

• Systems use existing thermoelectric or Stirling engine technology and design

• Low cost testing and demonstration
  – Non-nuclear system demonstration requires very little infrastructure and power.
  – Nuclear demonstration accommodated in existing facility, the thermal power and physical size fits within current activities at the Nevada National Security Site.
Heat Pipe

- A heat pipe is a sealed tube with a small amount of liquid that boils at the hot end, the vapor travels to the cold end where it condenses back to a liquid.
- A wick is used to bring the fluid back to the hot end
- A heat pipe works in any direction - even against gravity
- Heat pipes are a very efficient way to move heat
Full Scale, 1/12 Power ISS Demo

• One Haynes 230/sodium heat pipe
  – Transfers heat from reactor core (heater) to Stirling engine
  – TRL 5

• One Stirling convertor
  – Converts approximately 200 Wt to 80 We
  – The convertor was designed for a radioisotope generator which is why only 80 We is generated vs. the 125 We needed for Kilopower
  – TRL 5

• Two titanium/water heat pipes
  – Rejects 120 Wt to space environment
  – TRL 6
Heat Pipe Demo Concept

Stirling Convertor
Sodium Heat Pipe
Water Heat Pipes
Electrical Heater
Other Design Issues

• **Impact of Dust and Debris**
  – Core has one moving part (start up rod)
    • Will be in a sealed housing (to be designed)
  – Stirling Engine Convertors
    • Sealed units protect moving parts

• **Temperature issues**
  – No issues with freeze-thaw cycle for heat pipes
    • Startup from frozen sodium done routinely
  – No other temperature issues are anticipated

• **Low Pressure or vacuum – Not an issue**
Kilopower Reactor Using Stirling Technology = KRUSTY

- Designed with space flight-like components
  - Uranium core, neutron reflector, heat pipes, Stirling engines
- Tested at flight-like conditions
  - In a vacuum
  - Design thermal power
  - Design temperature
  - Design system dynamics
- Performs tasks needed for space flight
  - Computer modeling
  - Nuclear test operations
  - Ground safety
  - Transport and assembly
The **KRUSTY Test** was conducted in four phases over 5 months and started in November 2017 and finishing in March 2018.

- **Component Criticals:** The reactor core, neutron reflector, and startup rod are tested alone to measure reactivity.

- **Cold Criticals:** Heat pipes and power conversion are added, and reactivity is gradually added until the system is critical but no heat is produced.

- **Warm Criticals:** Reactivity is increased until full reactor power (4 kilowatts thermal) is achieved at moderate temperatures of less than 400 C.

- **Full Power Run:** A notional mission profile is simulated including reactor start up, ramp up to full power, steady state operation at about 800 C, several operational transients, and shut down.
**KRUSTY Full-Power Run**

- **Demonstrate start-up, stability, and steady-state performance.**
  - Start the same way as warm criticals, but continue to add reactivity until an average fuel temperature of 800°C is reached.
  - Turn on Stirling engines when temperature reaches 650°C.

- **Demonstrate reactor self regulation**
  - Increase and decrease power removed by Stirling engines/simulators, with no reactor control action.

- **Demonstrate reactor fault tolerance**
  - Simulate a failed heat-pipe or engine by halting power removal from a Stirling simulator, with no reactor control action.

- **Demonstrate ability of reactor to remain operational after acute failure of all active heat removal (at end of ~24 hour run).**
Reactors on Mars – NASA Concept