KiloPower

A very small nuclear reactor for space applications

A presentation to:

The National Academies of Sciences, Engineering, and Medicine
Committee on Biological and Physical Sciences in Space

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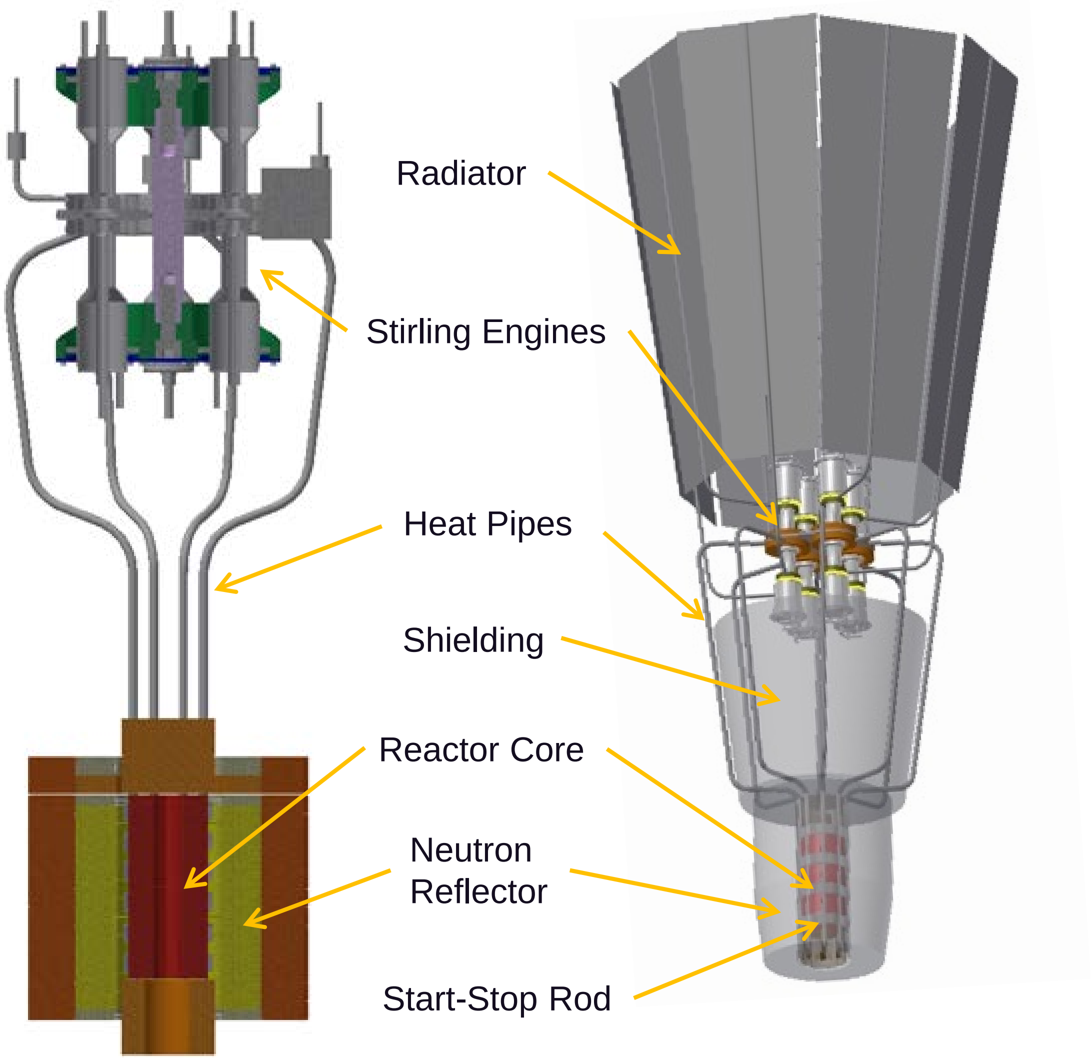
KiloPower – Reactor Concept



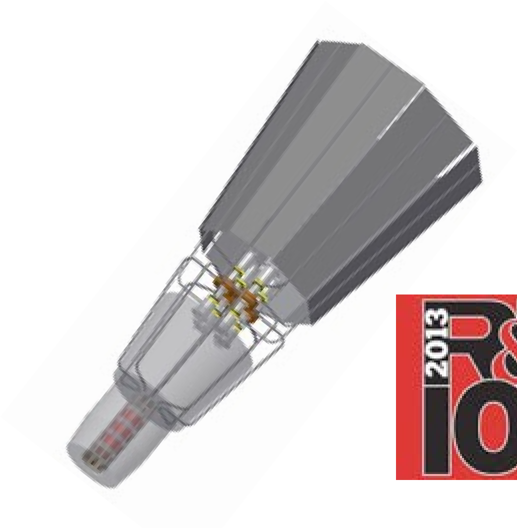
Test Unit

Space Flight Concept

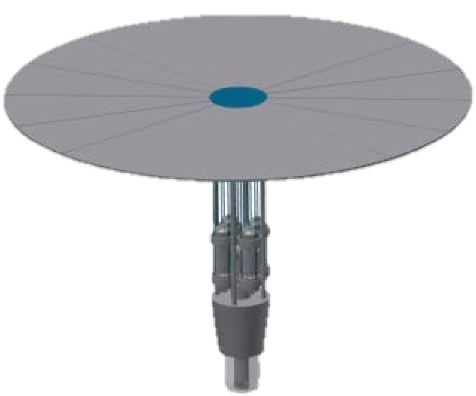
7 COMPENENTS

- 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



Deep Space Version



Surface Power Version

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

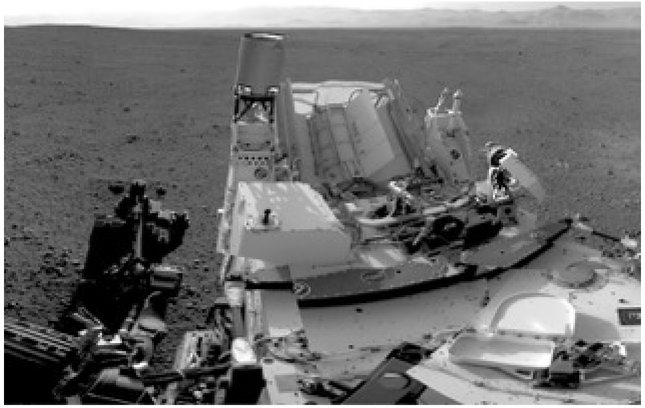
Potential Applications

- **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

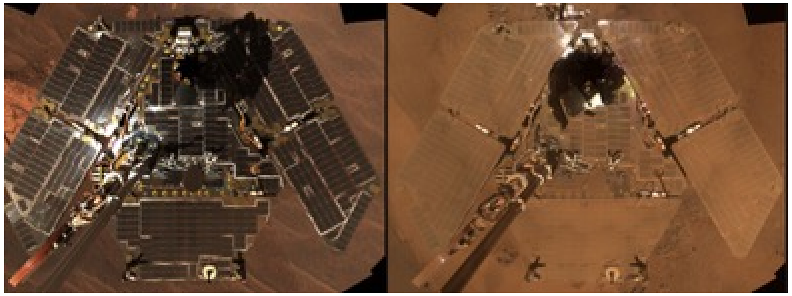
- **Power uses**
  - drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging

Mars Surface Power

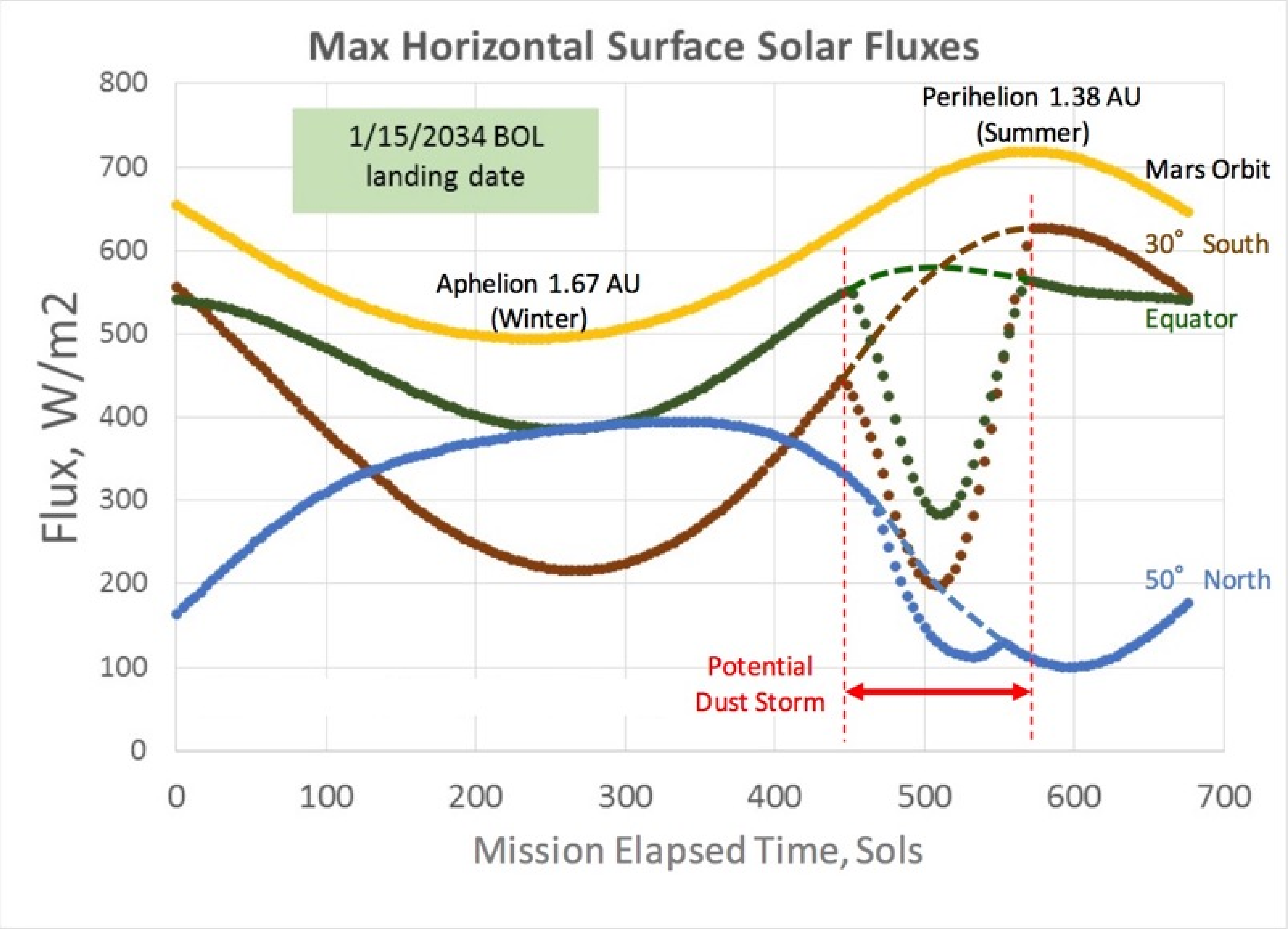
- **No off-the-shelf options exist to power long-term human surface missions on Mars**
  - Power systems used on previous robotic missions (e.g. Spirit/Opportunity, Phoenix, Curiosity) do not provide sufficient power: all less than 200 W



- **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, 3/8th gravity, 1/3rd solar flux of Earth orbit, >12 hour night
  - Large seasonal and geographical solar flux variations, long-term dust storms, high winds



Mars Solar Flux

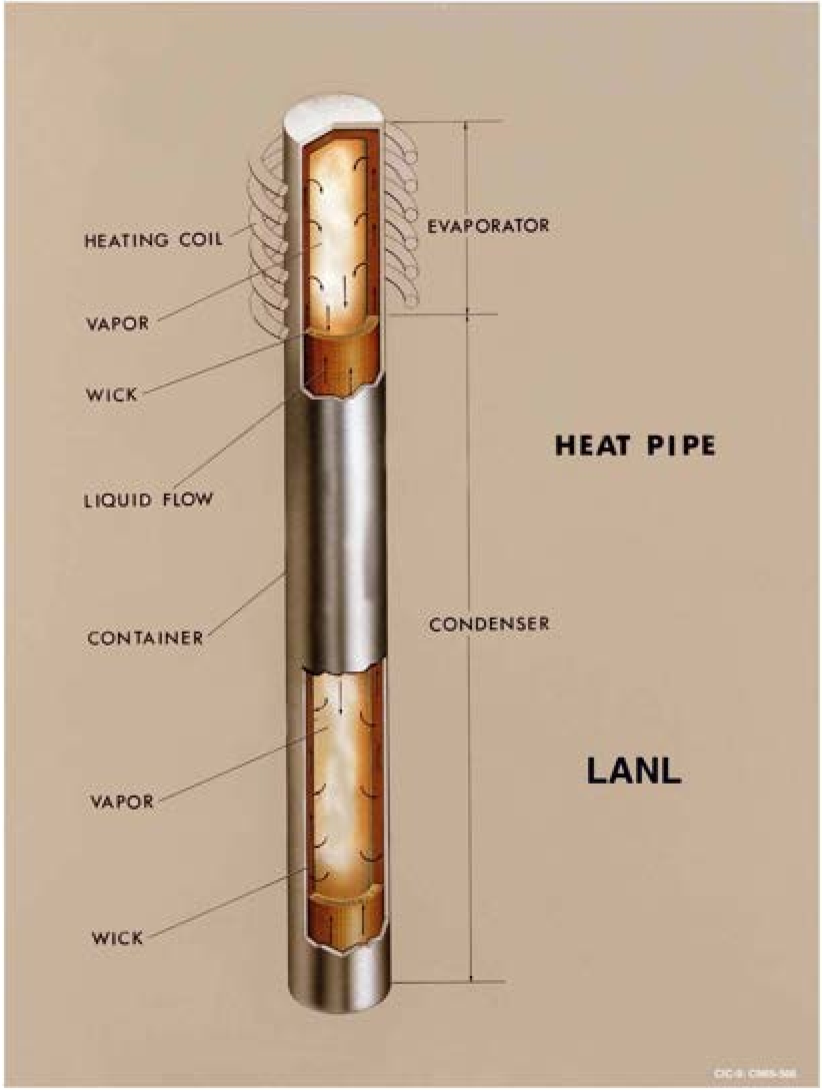


Why this reactor design?

- **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

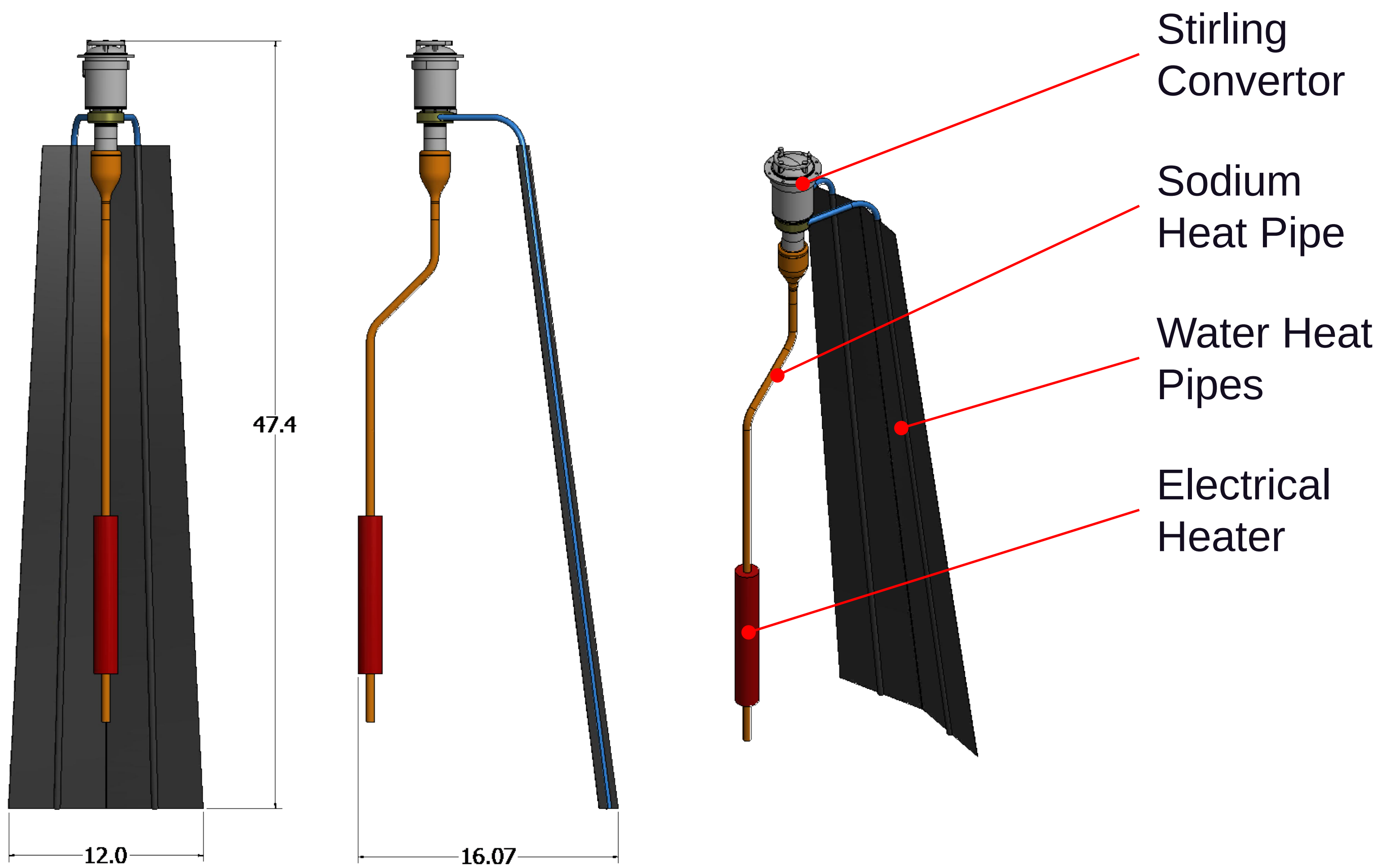
- A heat pipe is a sealed tube with a small amount of liquid that boils at the hot end, the vapor travels to the cold end where it condenses back to a liquid.
- A wick is used to bring the fluid back to the hot end
- A heat pipe works in any direction - even against gravity
- Heat pipe are a very efficient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

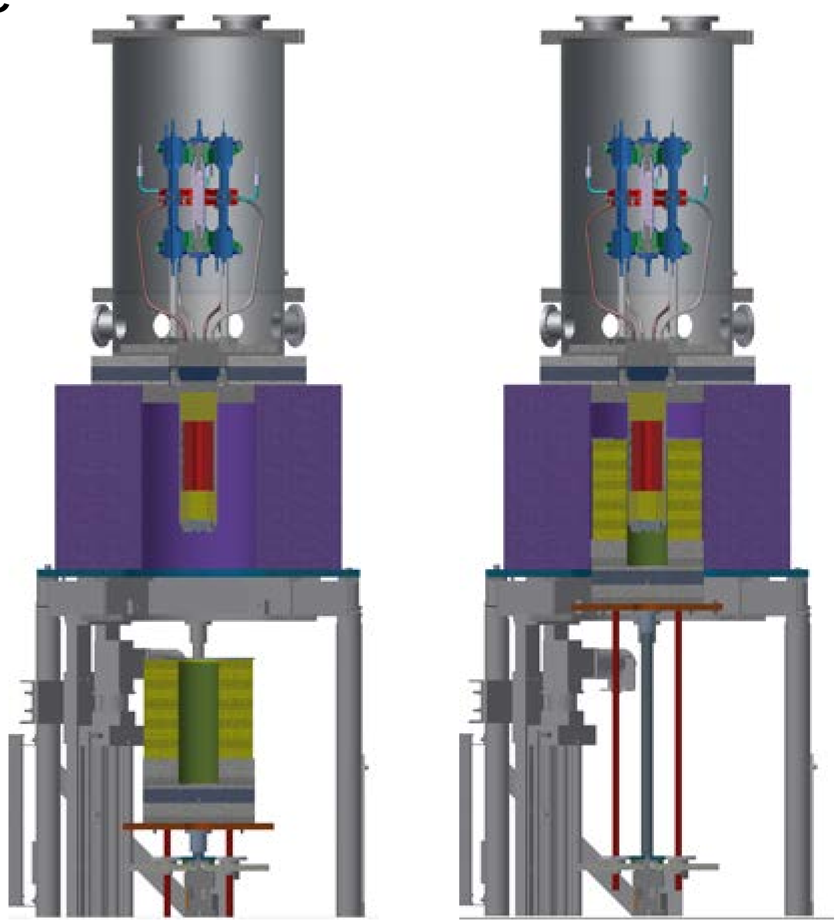


Other Design Issues

- **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

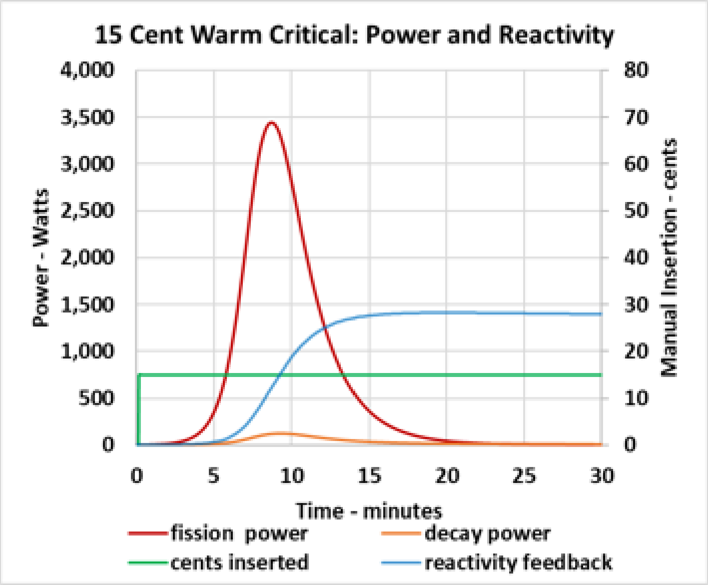
- Designed with space flight-like components
  - Uranium core, neutron reflector, heat pipes, Stirling engines
- Tested at flight-like conditions
  - In a vacuum
  - Design thermal power
  - Design temperature
  - Design system dynamics
- Performs tasks needed for space flight
  - Computer modeling
  - Nuclear test operations
  - Ground safety
  - Transport and assembly



KRUSTY: Summary of Nuclear Experiments

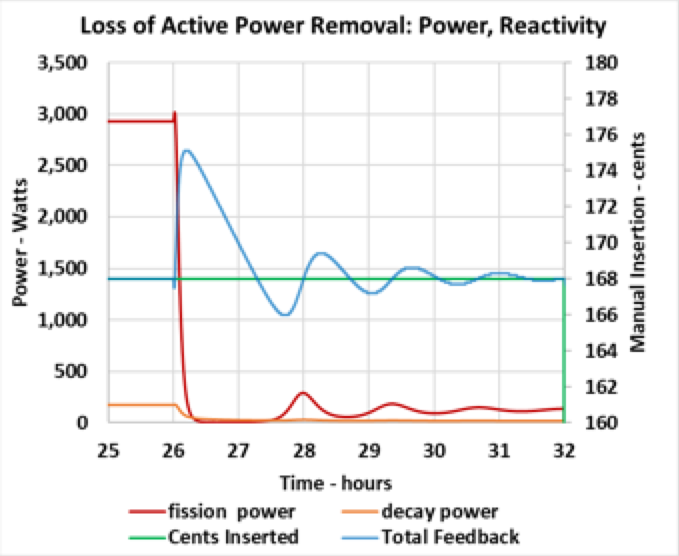
The **KRUSTY Test** was conducted in four phases over 5 months and started in November 2017 and finishing in March 2018.

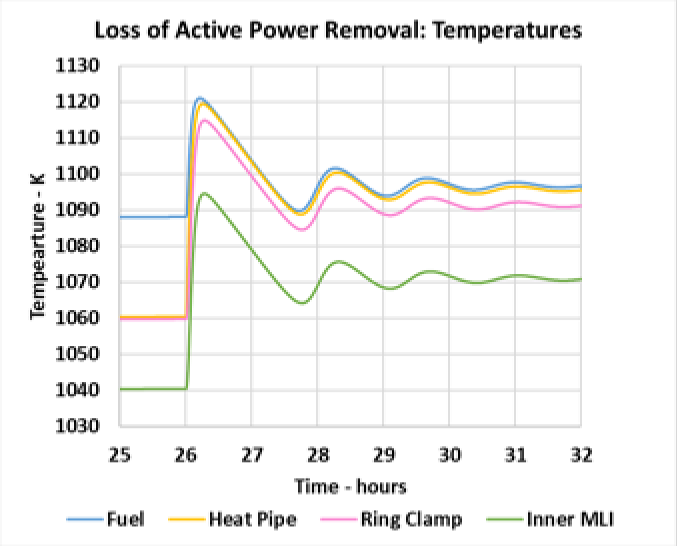
- **Component Criticals:** The reactor core, neutron reflector, and startup rod are tested alone to measure reactivity.
- **Cold Criticals:** Heat pipes and power conversion are added, and reactivity is gradually added until the system is critical but no heat is produced.
- **Warm Criticals:** Reactivity 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

Picture – NASA Glenn Research