Kilopower

A very small nuclear reactor for space applications

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The Future?

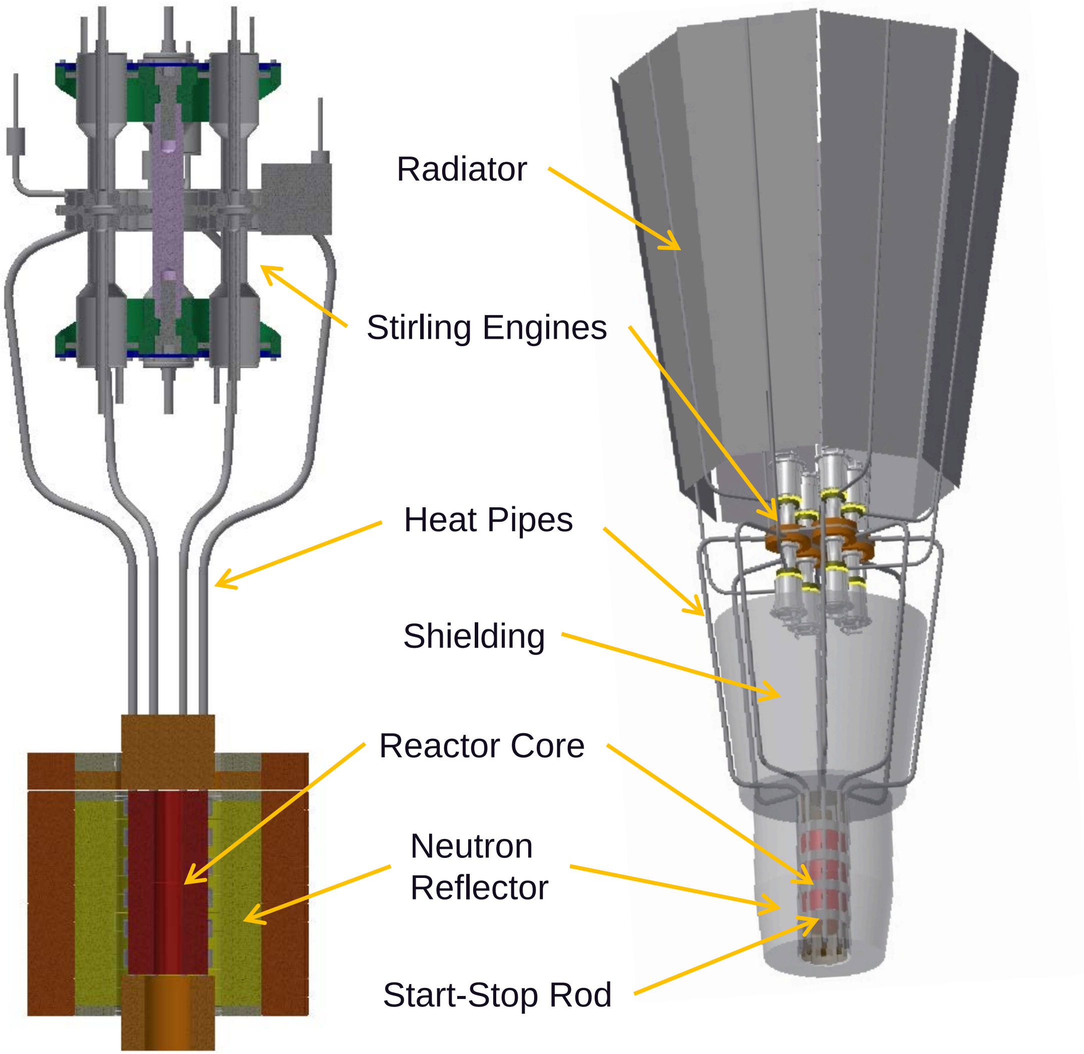
Reactors on Mars – NASA Concept

Picture – NASA Glenn Research

Video of Kilopower Reactor

Animation – NASA Langley

Kilopower – Reactor Concept



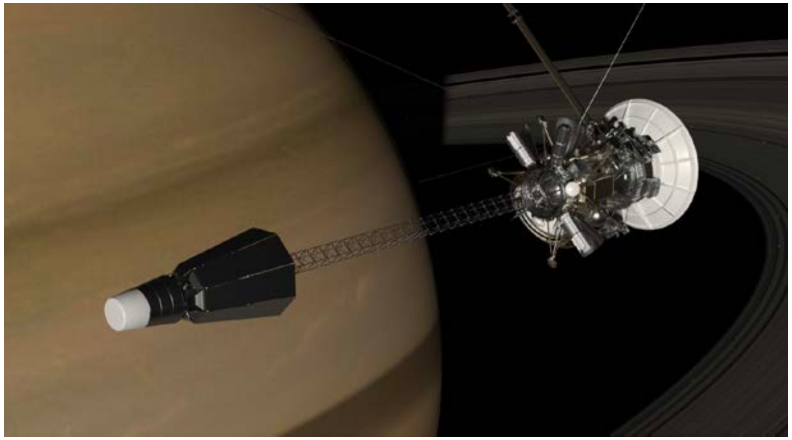
Test Unit

Space Flight Concept

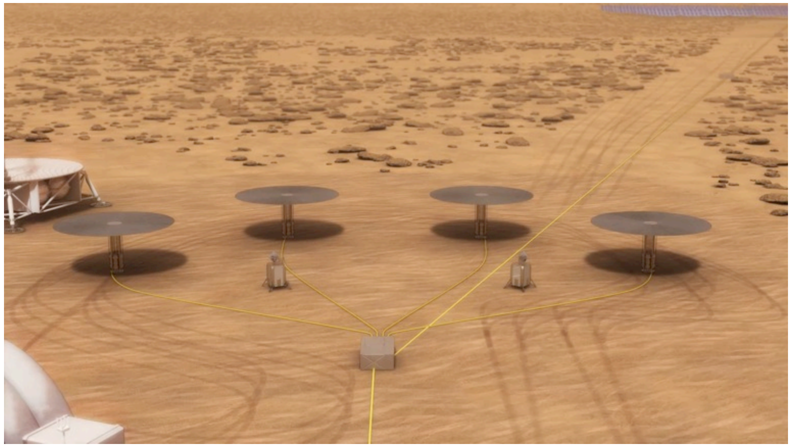
<u>7 COMPENENTS</u>

- 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 is designed to deliver 1 to 10 kilowatts of electric power



Deep Space Mission Power



Planetary Surface Power

1 kW

5 kW

10 kW

Toaster ~ 1 kW

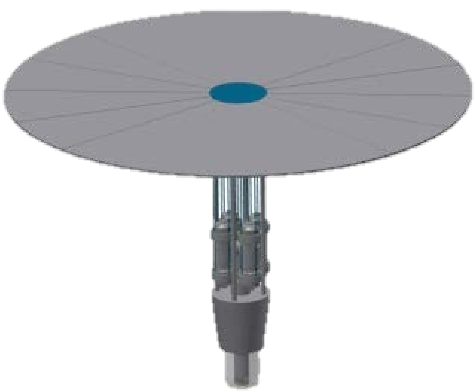
Peak use at home ~ 5 kW

Power for multiple houses ~ 10 kW

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

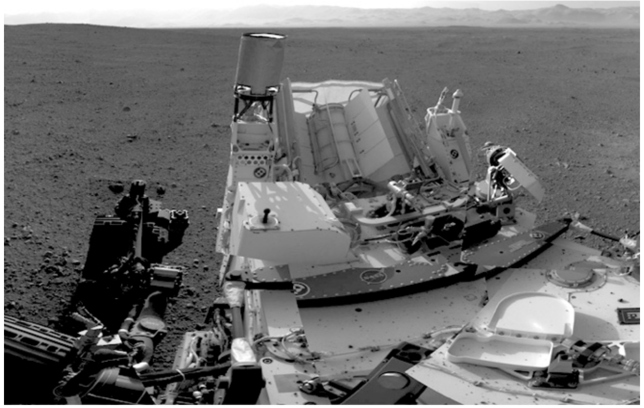
Potential Applications

- **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

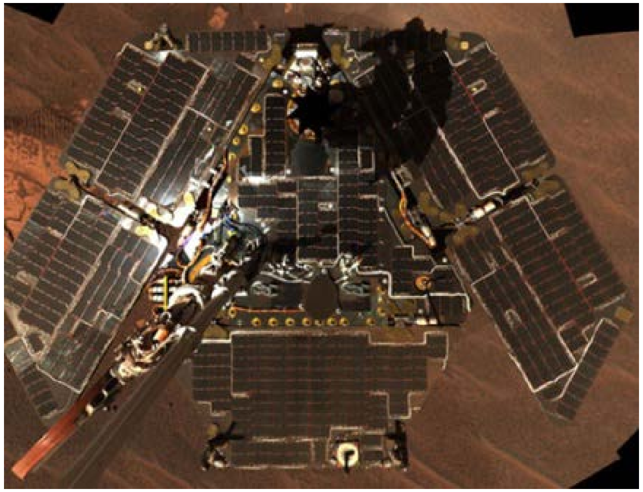
- **Power uses**
  - drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging

Mars Surface Power

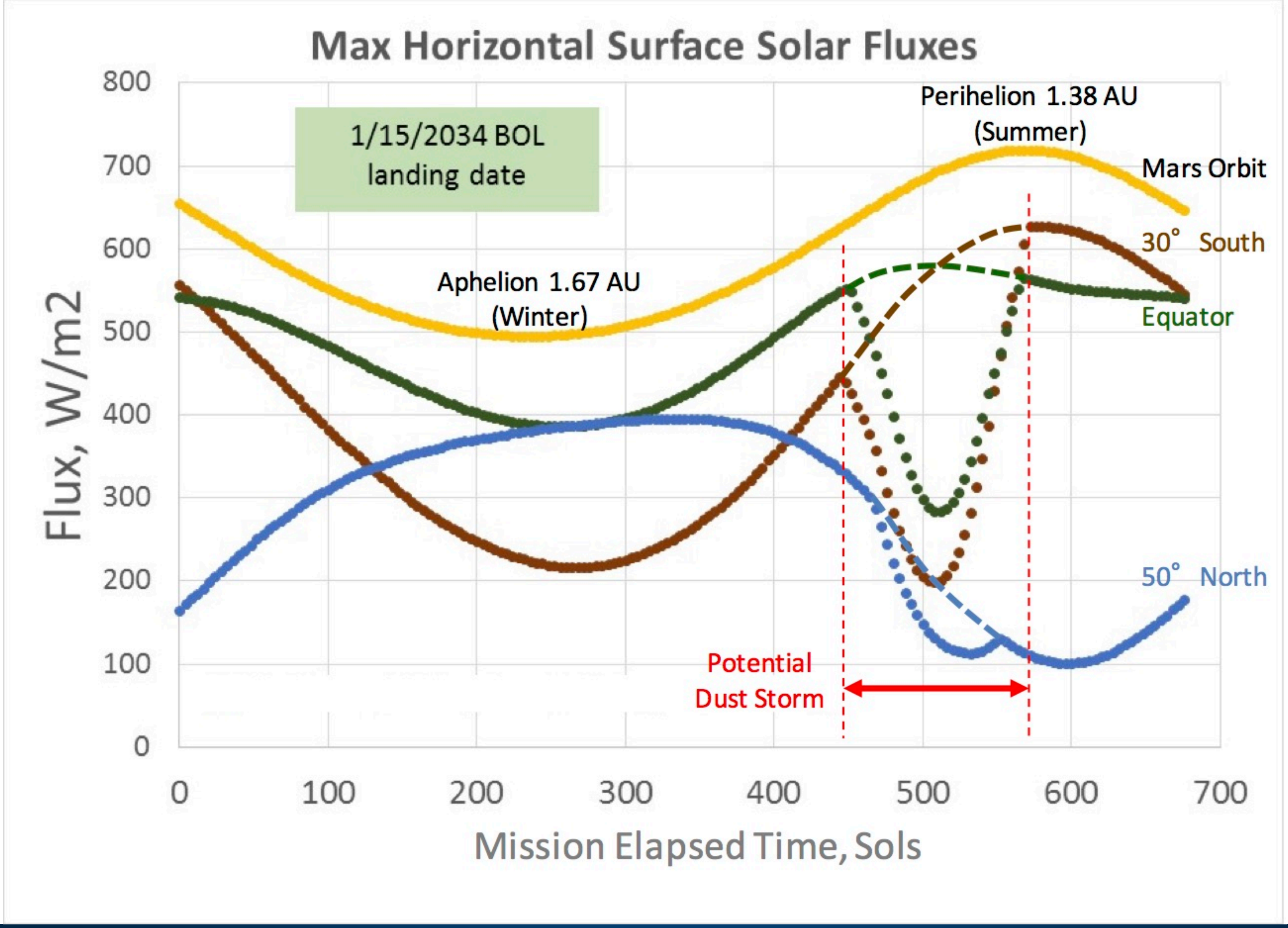
- **Human missions on Mars**
  - Previous robotic missions (Spirit/Opportunity, Phoenix, Curiosity) used either solar or radioisotope system that produced ~100 W
- **Projected human exploration power needs is:**
  - Up to 40 kW day/night continuous power
  - Four to Five Kilopower reactors
- **Mars surface presents major challenges**
  - 1/3rd solar flux of Earth
  - Greater than 12 hour nights (need batteries)
  - Variations in solar energy by geography
  - Long-term dust storms (years in length)



NASA

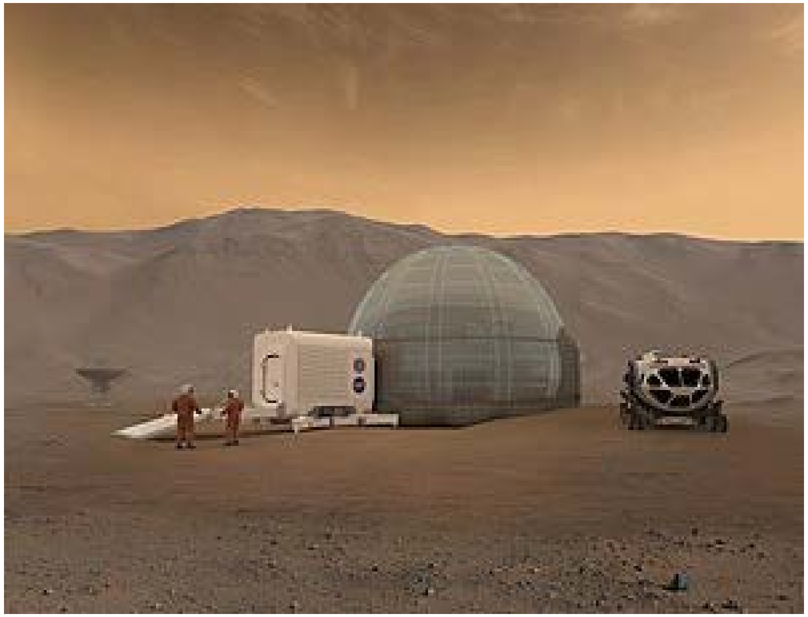


Mars Solar Flux



What is needed for Humans to go to Mars

- **Electricity would be used to make:**
  - Propellant to get back to Mars orbit
    - Liquid Oxygen
    - Methane



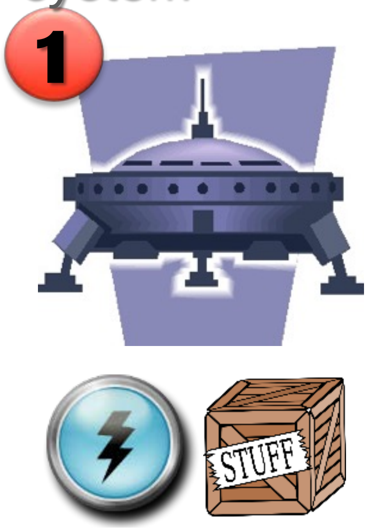
Mars Base Camp – NASA Langley

International Mars Research Station – Shaun Moss

- **Electricity is needed for:**
  - Oxygen for astronauts
  - Purify water
  - Power of habitat and rover

Notional Mars Field Station Concept

FIRST send cargo, including a surface power system



Power System + Cargo

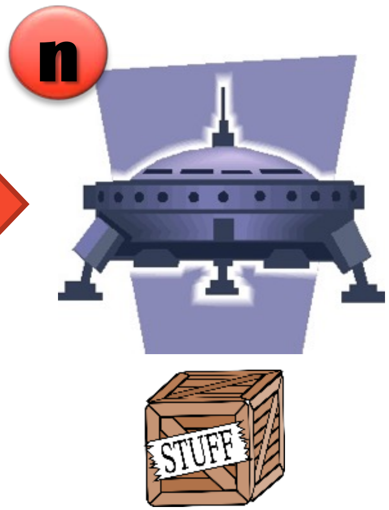
THEN send Ascent Vehicle and ISRU to fill empty prop tanks

Ascent Vehicle + Propellant Manufacturing

WHEN tanks are full, crew lands and begins surface mission

Habitat + Crew + Cargo

SUBSEQUENT crews land at same site, use infrastructure



Additional Crew + Ascent Vehicles + Cargo

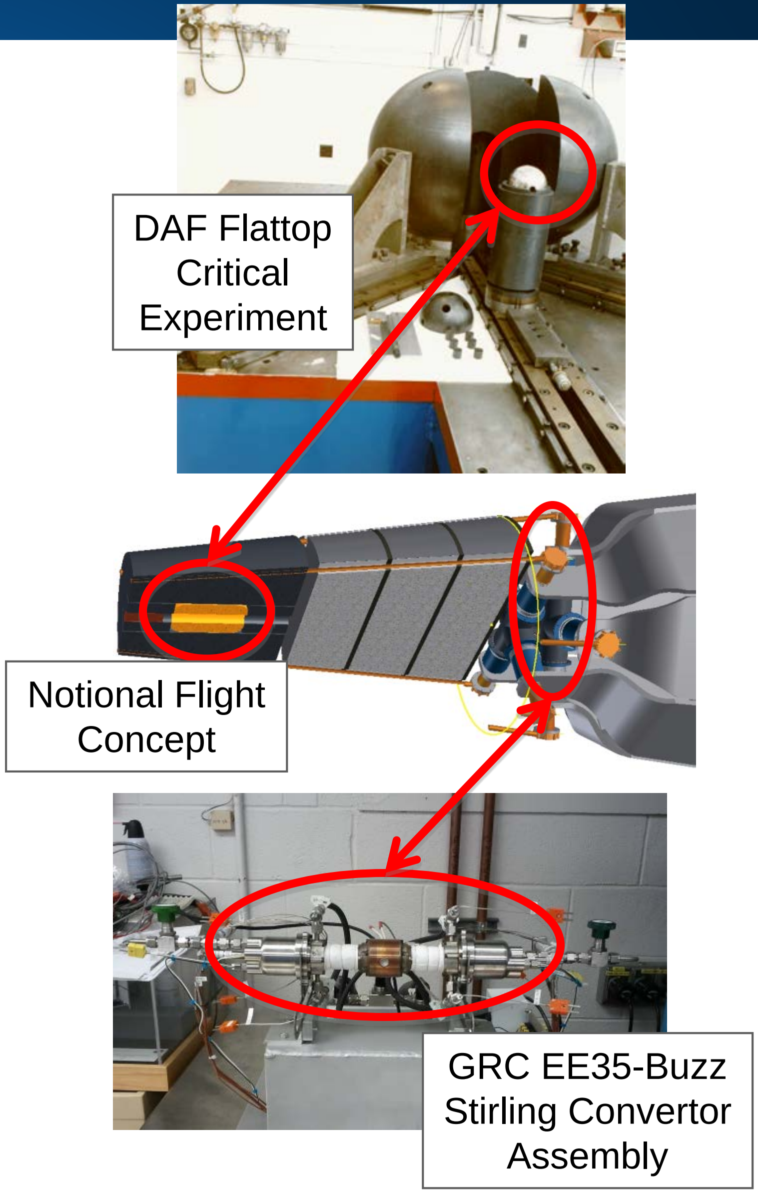
Power system is robotically set up before crew arrive

The Road to Kilopower

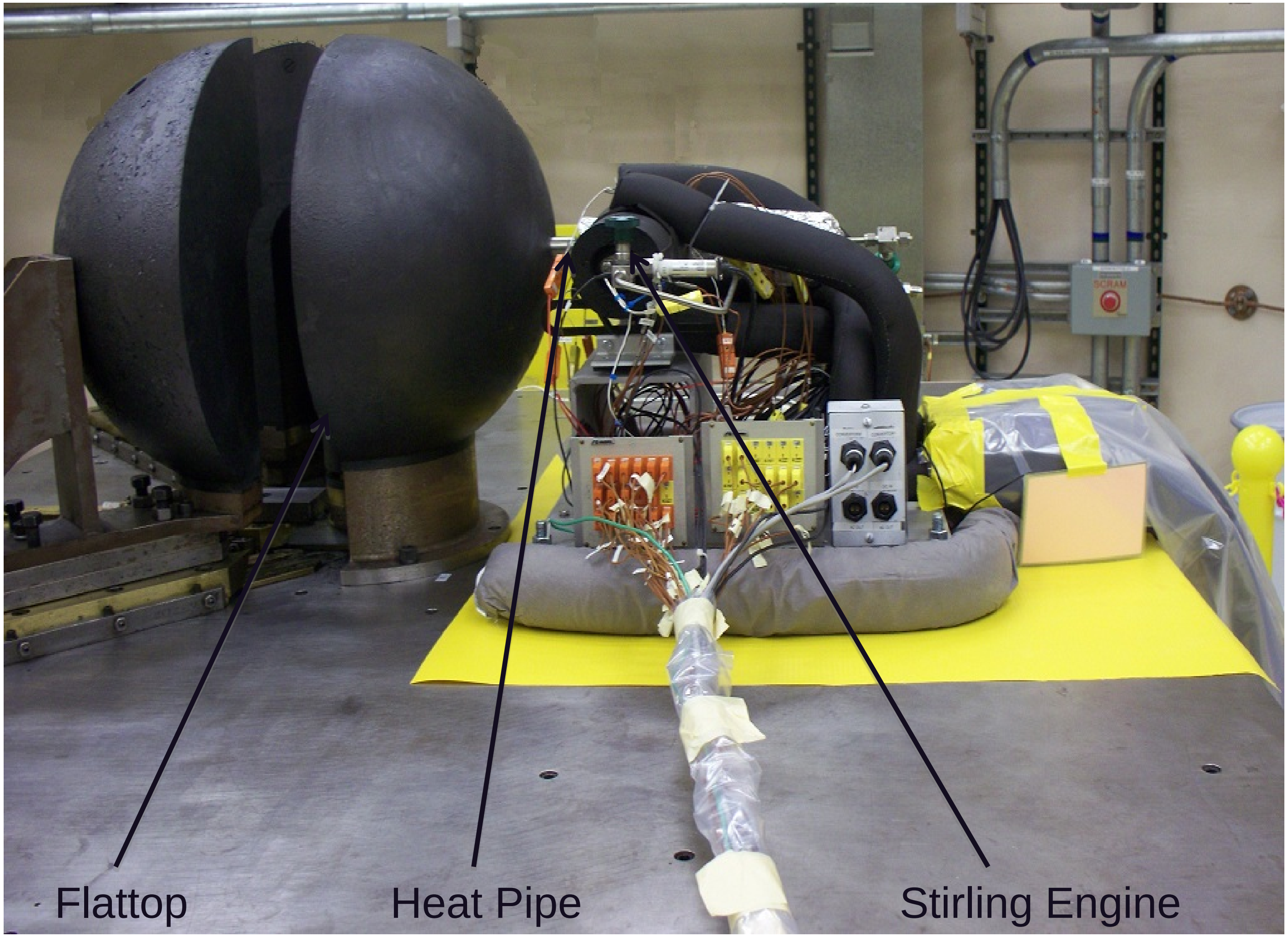
- **1965: SNAP program**
- **1970-2010: Multiple NASA/DOE space reactor programs**
  - –Limited success, but NO nuclear heated tests and NO flight missions
- **2010: Planetary Science Decadal Survey**
  - –Designs for simple low power reactor concept proposed
- **2012: Demonstration Using Flattop Fissions (DUFF)**
  - –Proof-of-Concept test
- **2014: NASA Mars Campaign:**
  - –Small fission power baselined for potential Mars missions
- **2015: Kilopower Project leading to KRUSTY experiment:**
  - –Effort to design, build, and test a prototype reactor

DUFF: A "Critical" Starting Point

- **Proof-of-Concept Test**
- **Test Configuration**
  - Highly Enriched Uranium core with central hole to accommodate heat pipe
  - Heat transfer via single water heat pipe
  - Power generation via two opposed free-piston Stirling Engines
- **Significance**
  - First-ever heat pipe cooled fission experiment
  - First-ever Stirling engine operation with fission heat
  - Demonstration of nuclear reactivity feedback with prototype components
- **Test Objectives**
  - Use electric power generated from nuclear heat to power a load (light panel)
  - Demonstrate that basic reactor physics was well characterized and predictable using current analytic tools



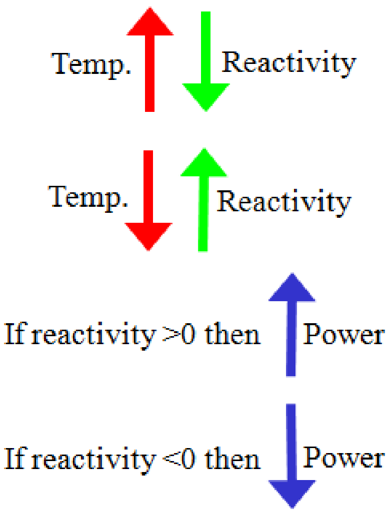
DUFF -- Complete Experimental Setup

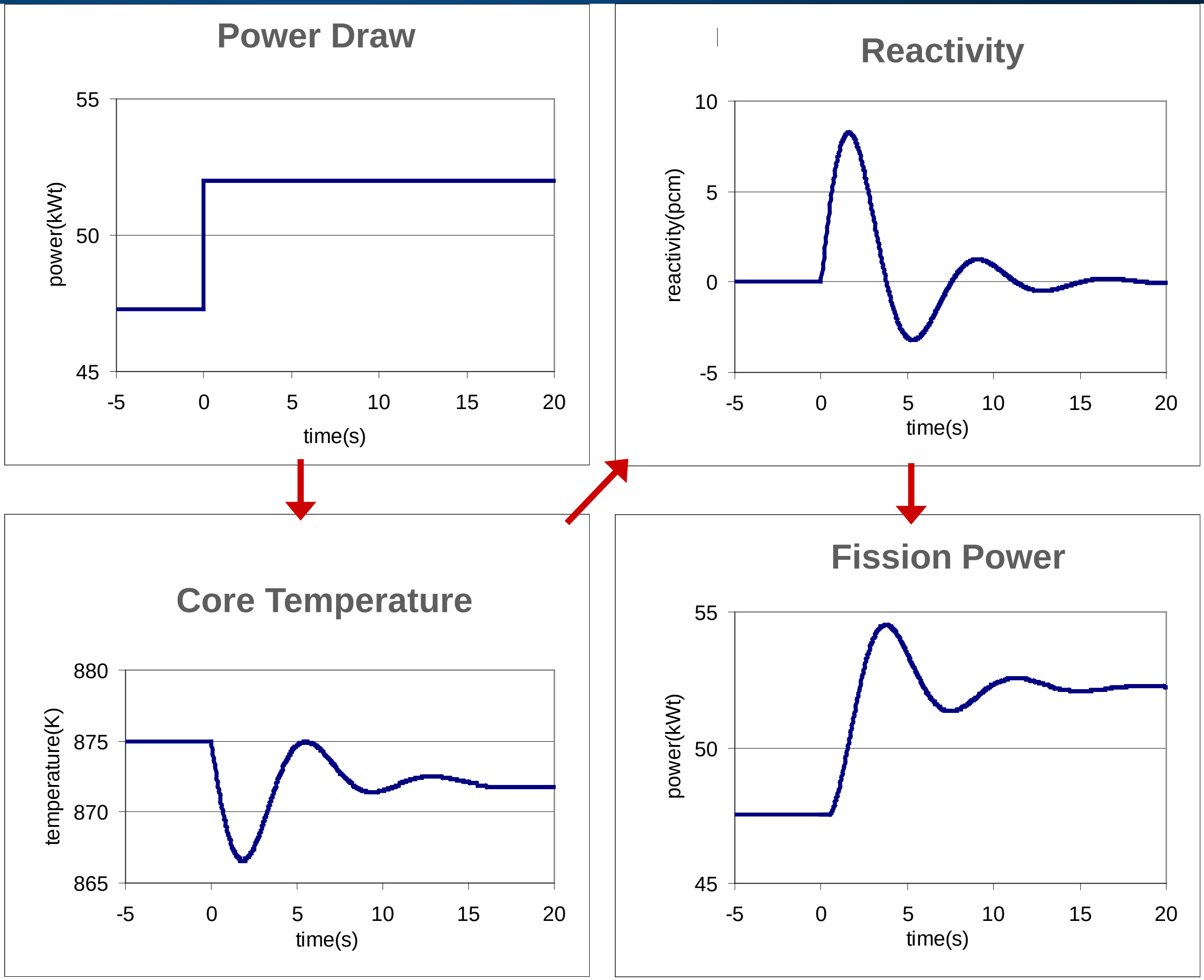


Reactor load following example…

10% increase in thermal power removal

This scenario assumes an immediate 10% increase in power draw by the power conversion system. No reactor control action is simulated. No secondary feedback from the PCS is modeled.





Note: this reactor has 2 components, core and reflector. In this scenario, the increased power causes an increase in reflector temperature, which creates a small net reactivity drop, thus the core settles at a lower temperature to compensate.

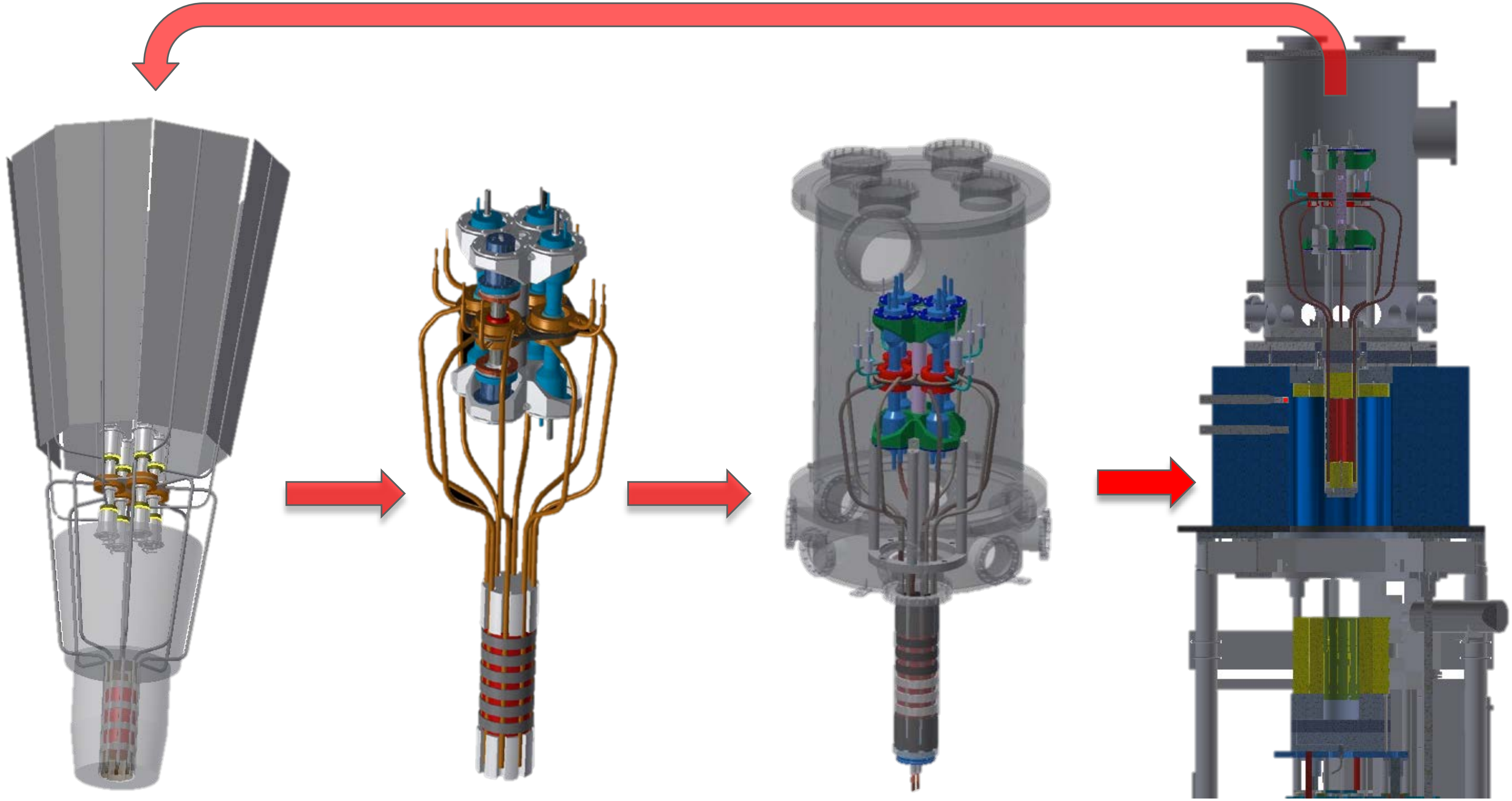
Why this reactor design?

- **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.

Space Reactor Safety

- **A reactor that has not undergone fission, (been turned on), has very very low safety concerns. It will have from 1 to 10’s of curies of naturally occurring radioactivity**
- **This is 1,000s to 10,000s times lower radioactivity than in current radioisotope systems already flown in space**
- **Launch accidents will have consequences <u>100’s of times less</u> than background radiation or radiation from a commercial plane flight**
- **After the reactor has fissioned, it will become radioactive**
  - Reactors would only be used in deep space, very high Earth orbit (long term decay) and on other planets.

Kilopower Technology Development



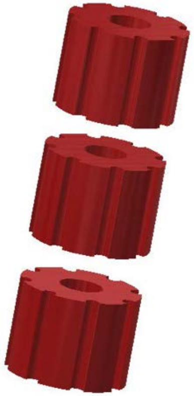
Flight Concept

Flight-prototypic Power Pack

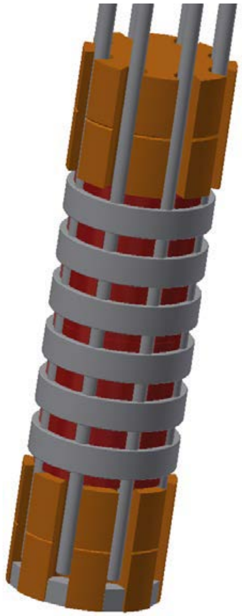
Electrically Heated Test with Depleted Uranium Core

Reactor Experiment with Uranium Core

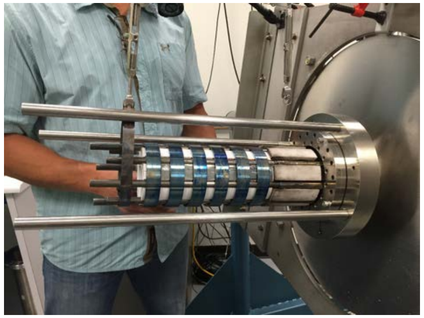
Key Subsystems

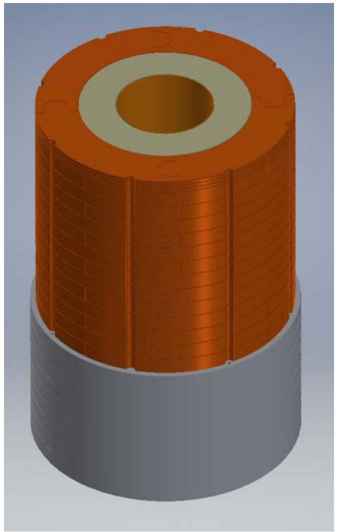


Uranium Core Segments

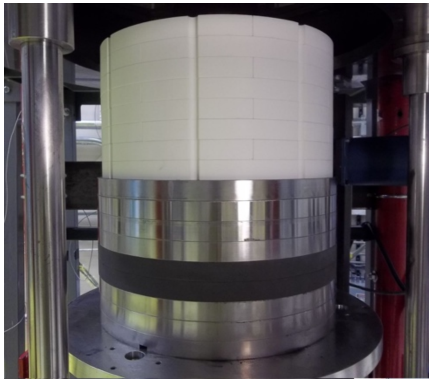


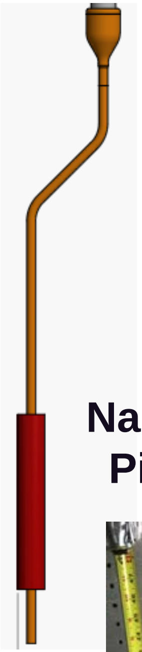
Reactor Assembly



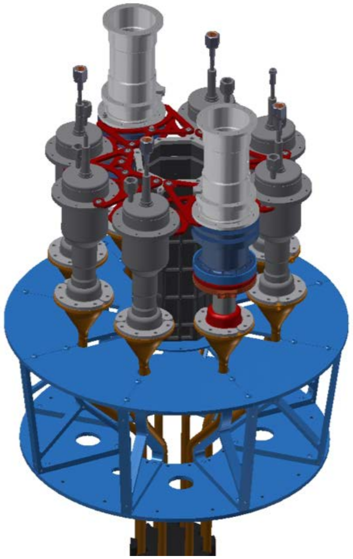


Beryllium Oxide Neutron Reflector

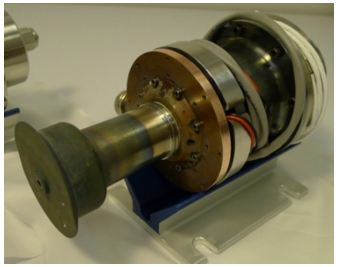




Na Heat Pipes



Stirling Engines & Simulators

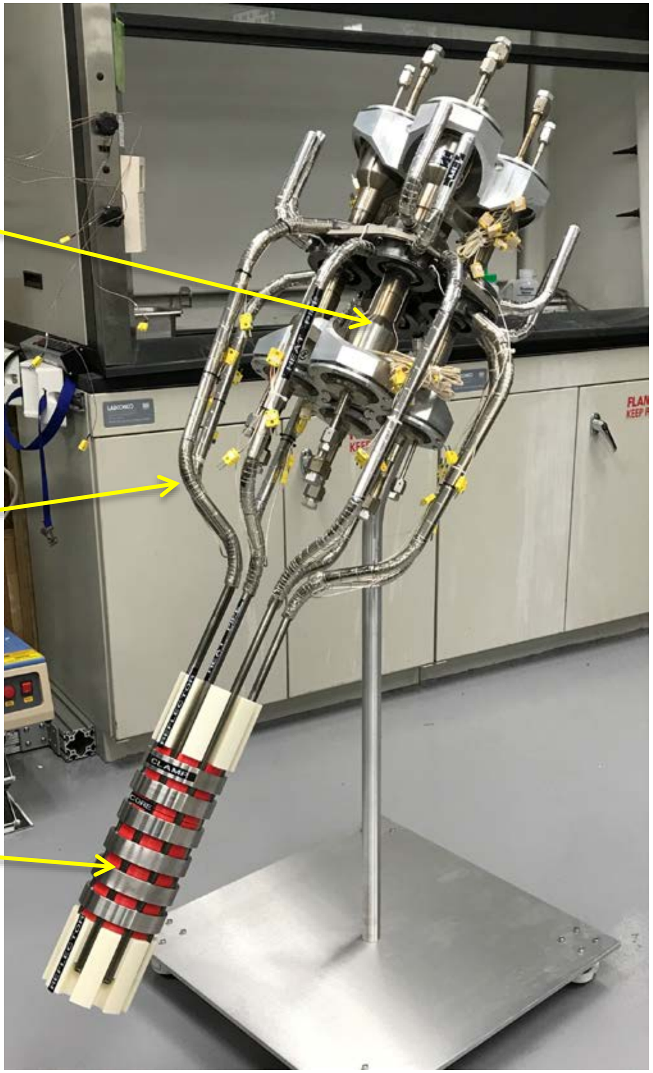


Mock Up of Assembled Power System

Stirling Engines

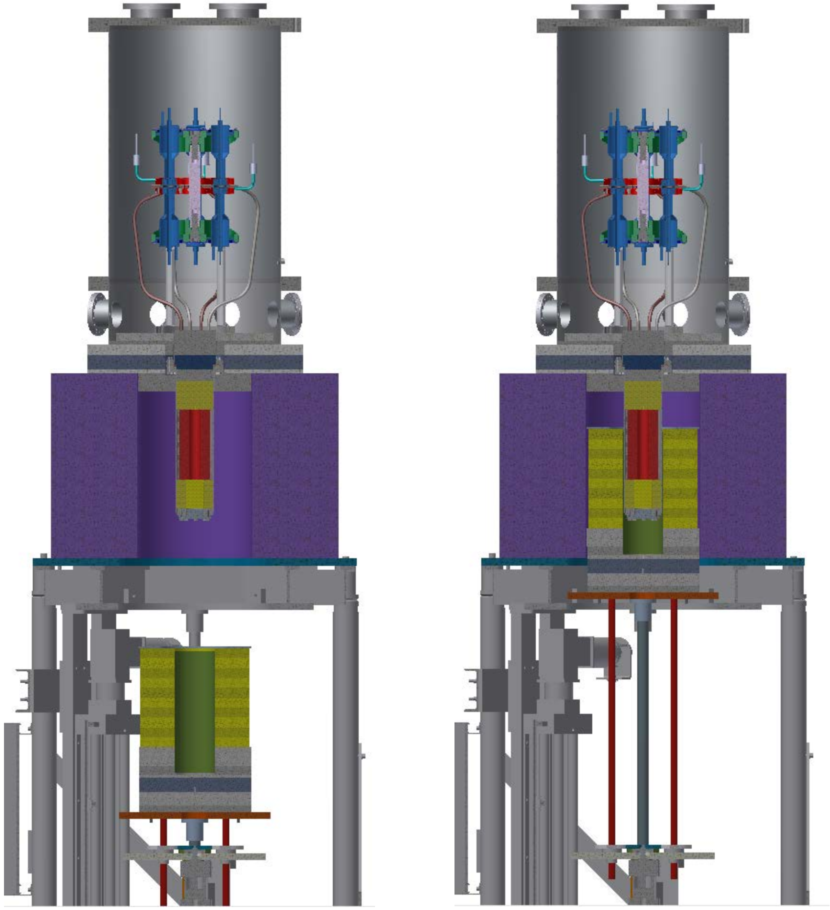
Heat Pipes

Core



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

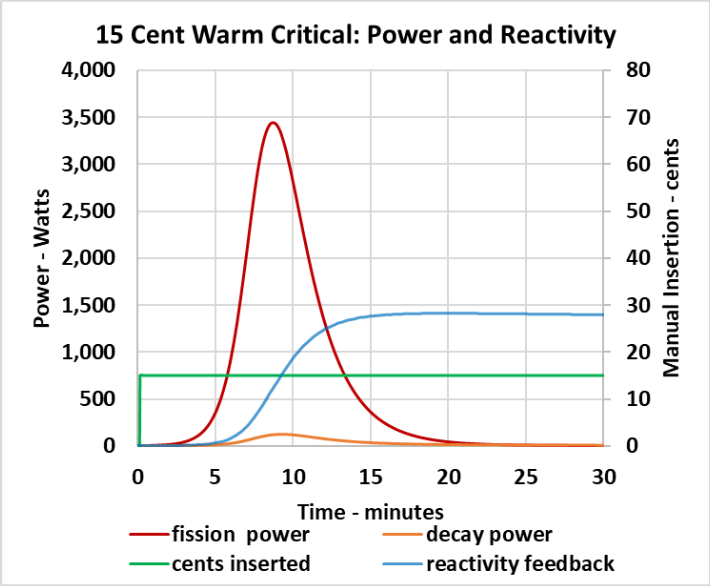


Los Alamos and NASA – Test Prep

KRUSTY: Summary of Nuclear Experiments

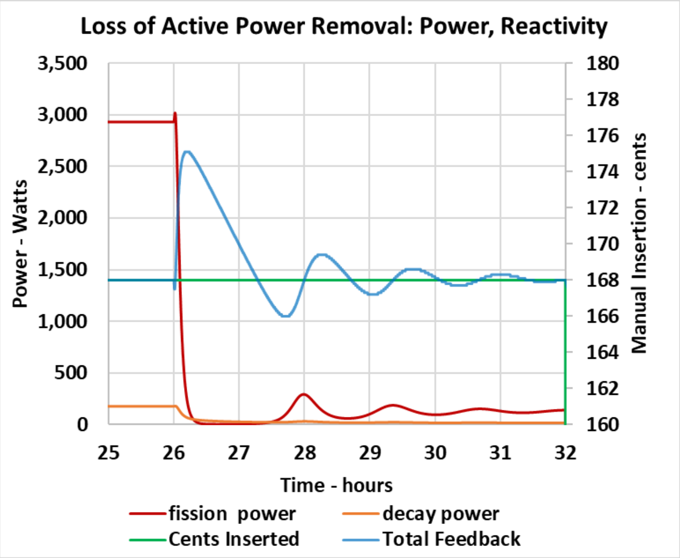
The **KRUSTY Test** was conducted in four phases over 5 months and started in November 2017 and finishing in March 2018.

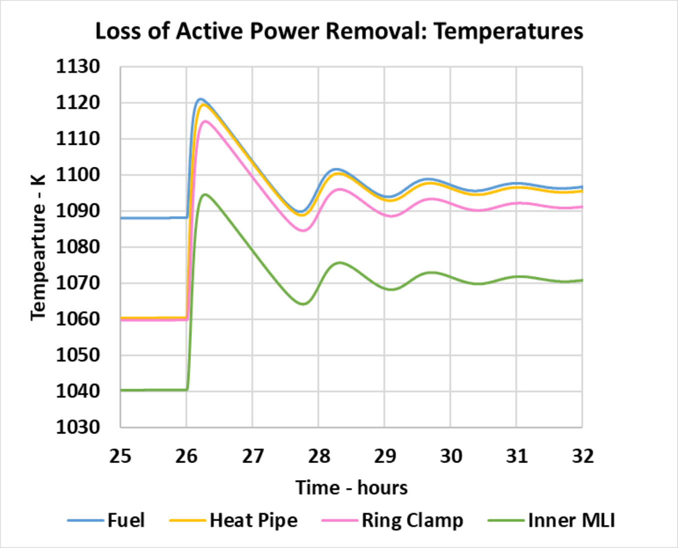
- **Component Criticals:** The reactor core, neutron reflector, and startup rod are tested alone to measure reactivity.
- **Cold Criticals:** Heat pipes and power conversion are added, and reactivity is gradually added until the system is critical but no heat is produced.
- **Warm Criticals:** Reactivity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





Okay, what's next

- **Project needs a <u>technology demonstration mission</u>**
  - Work on mission begins in 2020
  - Leading candidate is to land a reactor on the moon
- **Mission would include several new task such as:**
  - Design and testing of startup-rod mechanism
  - Formal safety analysis of launch,
  - Building space flight hardware
  - Testing for launch loads,
  - Study lifetime effects,
  - Integration of reactor with spacecraft

Could Kilopower soon power a moon base?

European Space Agency