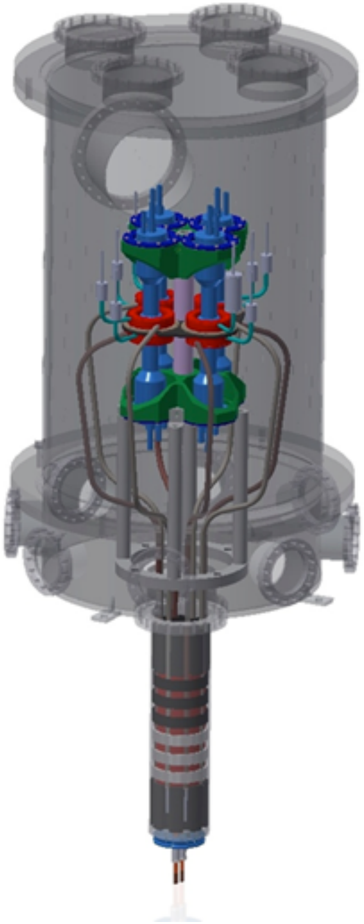
Lee Mason, NASA
Kilopower overview and mission applications

Kilopower Project

- **Innovation**
  - A compact, low cost, fission reactor for exploration and science, scalable from 1 kW to 10 kW electric
  - Novel integration of available U-235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors
  - Would provide about 10x more power than the Multi-Mission Radioisotope Thermoelectric Generator
- **Impact**
  - Could be scaled up to provide modular option for human exploration missions to the Mars/Lunar surface
  - Potentially enables Decadal Survey Planetary Science missions without reliance on limited plutonium dioxide fuel
- **Goals**
  - Full-scale nuclear system-level test of prototype U-235 reactor core coupled to flight-like Stirling convertors at relevant operating conditions
  - Design concepts that show scalability to 10 kWe for Mars surface power
- **Leveraging**
  - Leverages existing DOE/NNSA nuclear materials, manufacturing capabilities, test facilities, nuclear safety expertise, and DOE/NNSA co-funding

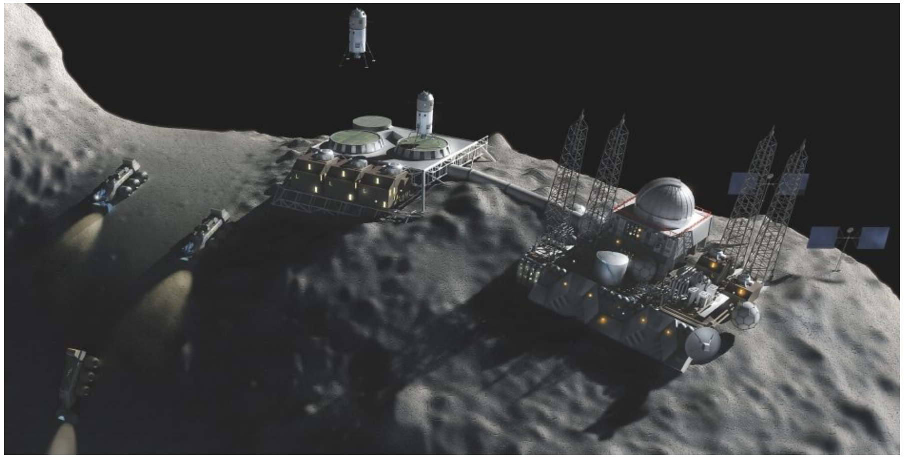


Potential Applications

- **Government Missions**
  - Human Mars surface missions
  - Deep Space Gateway: lunar surface operations
  - Planetary orbiters and landers: Europa, Titan, Enceladus, Neptune, Pluto, etc.
  - Planetary nuclear electric propulsion: Small Bodies, Ocean Worlds, Interstellar, etc.

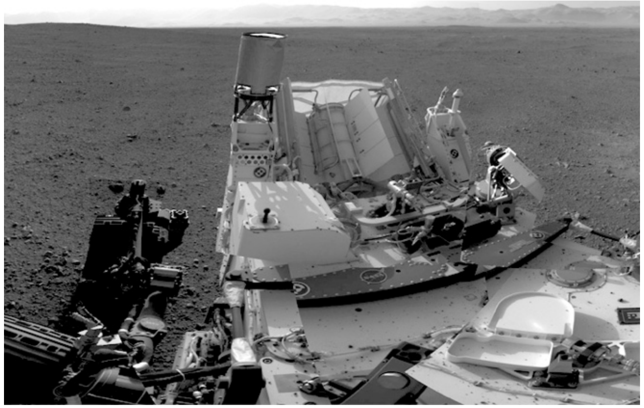
- **Commercial Missions**
  - Space power utility (pay-for-service)
  - Asteroid/space mining
  - Lunar/Mars settlements

- **Terrestrial Adaptations**
  - Military Forward Operating Bases
  - Unmanned Underwater Vehicles

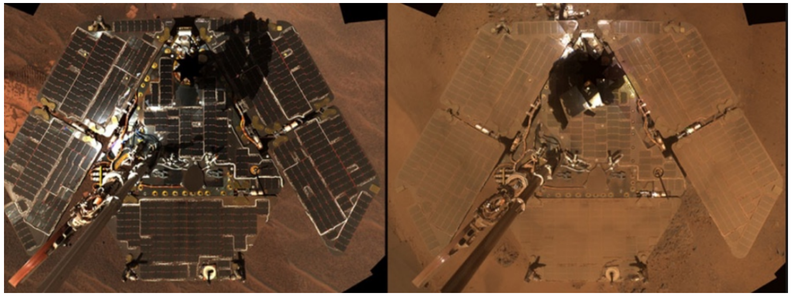


- **Power uses:** drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging,…

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
  - Power for In-situ Resource Utilization propellant production (pre-crew arrival)
  - 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**
  - CO2 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

Patrick McClure, Los Alamos
Reactor overview and development history

The Road to Kilopower

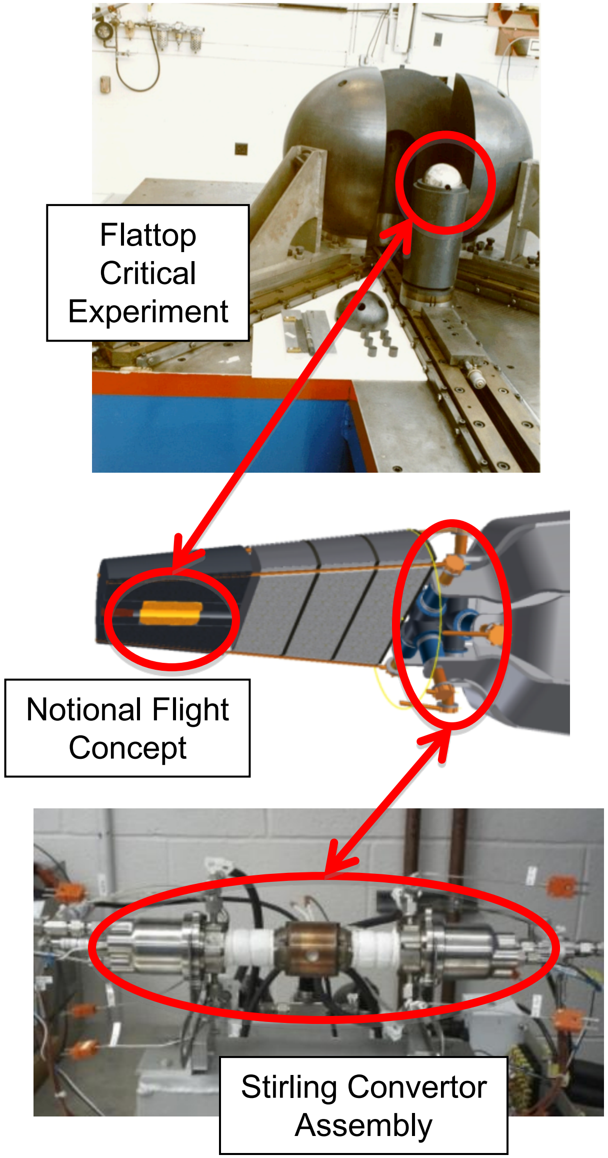
- **1970-2010: Many NASA/DOE space reactor programs attempted with limited success and NO flight missions**
  - Too complicated and costly
  - Too dependent on new materials and processes
  - Too long to develop, usually longer than the mission can wait
  - Too much optimism for out-of-the-box system performance

- **2010 Planetary Science Decadal Survey:** Technology assessment study to determine if fission reactors can provide an alternative to radioisotope systems
- **2012 Proof-of-Concept Test:** Demonstration Using Flattop Fissions; 24 watts produced in test that took less than 6 months and cost less than $1M
- **2014 NASA Nuclear Power Assessment Study:** Small fission option examined for Titan Saturn System Mission and Uranus Orbiter Probe
- **2014 NASA Evolvable Mars Campaign:** Small fission power baselined for pre-crew propellant production and post-landing crew operations
- **2015 Kilopower Project starts under STMD Game Changing Development Program:** 3 years and <$20M to design, build, and test a prototype reactor

Demonstration Using Flattop Fissions

- **Proof-of-Concept Test**
  - Los Alamos sponsored test at DOE Nevada National Security Site, Device Assembly Facility (DAF)
- **Test Configuration**
  - Highly enriched uranium core with central hole to accommodate a single heat pipe
  - Heat transfer via the water based heat pipe
  - Power generation via two Stirling convertors
- **Significance**
  - First-ever use of a heat pipe to extract thermal power from a fission reactor
  - First-ever use of a Stirling convertor to produce electric power with a fission heat source
  - Demonstration of nuclear reactivity feedback and dynamics with representative components

- **Sept 13, 2012: Success! 24 Watts produced**
  - Completed in less than 6 months with a total cost <$1M
  - Proof that a nuclear reactor ground test can be conducted quickly and affordably



Kilopower Safety

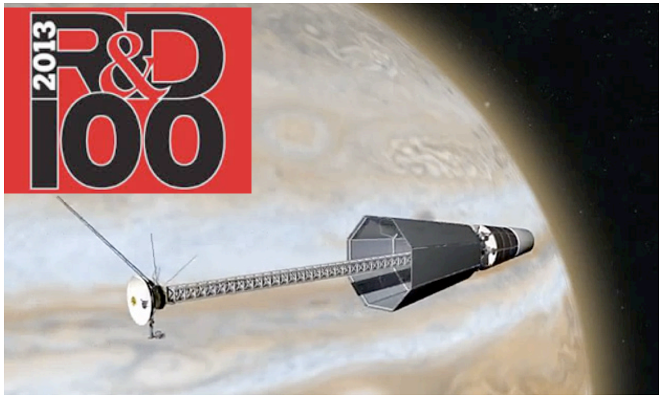
Safety is a top priority of NASA and the Department of Energy

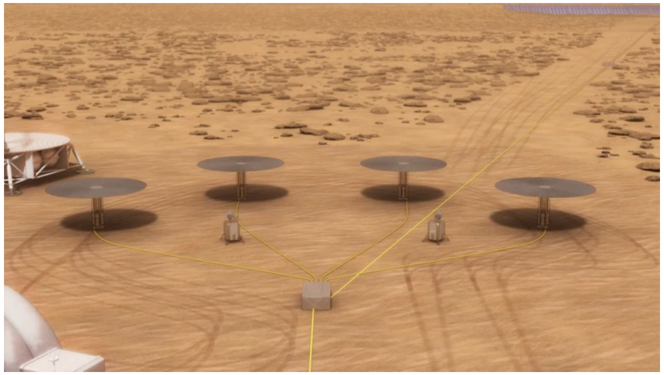
- **The KRUSTY experiment adheres to all Federal and Department of Energy regulations for safe operations,** including 10CFR830, “DOE’s Nuclear Safety Management”
- **This test and any future testing will comply with National Environmental Policy Act (NEPA) processes** to assess possible adverse environmental impacts and allow for public comment & engagement
- **A NEPA review would be completed before NASA decides to proceed to a flight mission**, and potential launch and operational hazards would be analyzed by an independent interagency nuclear safety review panel
- **Several factors inherent in space fission power contribute to launch and operational safety,** including
  - At launch, the radiological hazard would be limited to the naturally occurring radioactivity present in the uranium reactor core (<5 curies)
  - The reactor would not be operated until reaching the surface of a planet or being placed on a trajectory leaving Earth
  - During planetary surface operations, the reactor would have sufficient radiation shielding to protect crew members and prevent damage to sensitive equipment
  - The reactor design includes inherent fault tolerance, so that loss of cooling would result in an automatic reduction in fission power that prevents uncontrolled scenarios

Marc Gibson, NASA Glenn
Kilopower system design and overall test plan

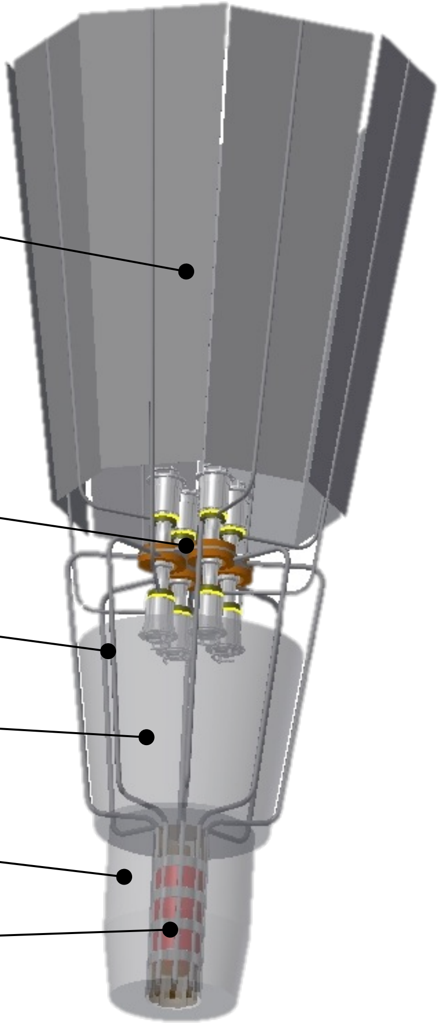
Kilopower System Design

Possible Mission Configurations





(Artist's Concepts)



Titanium/Water Heat Pipe Radiator

Stirling Power Conversion System

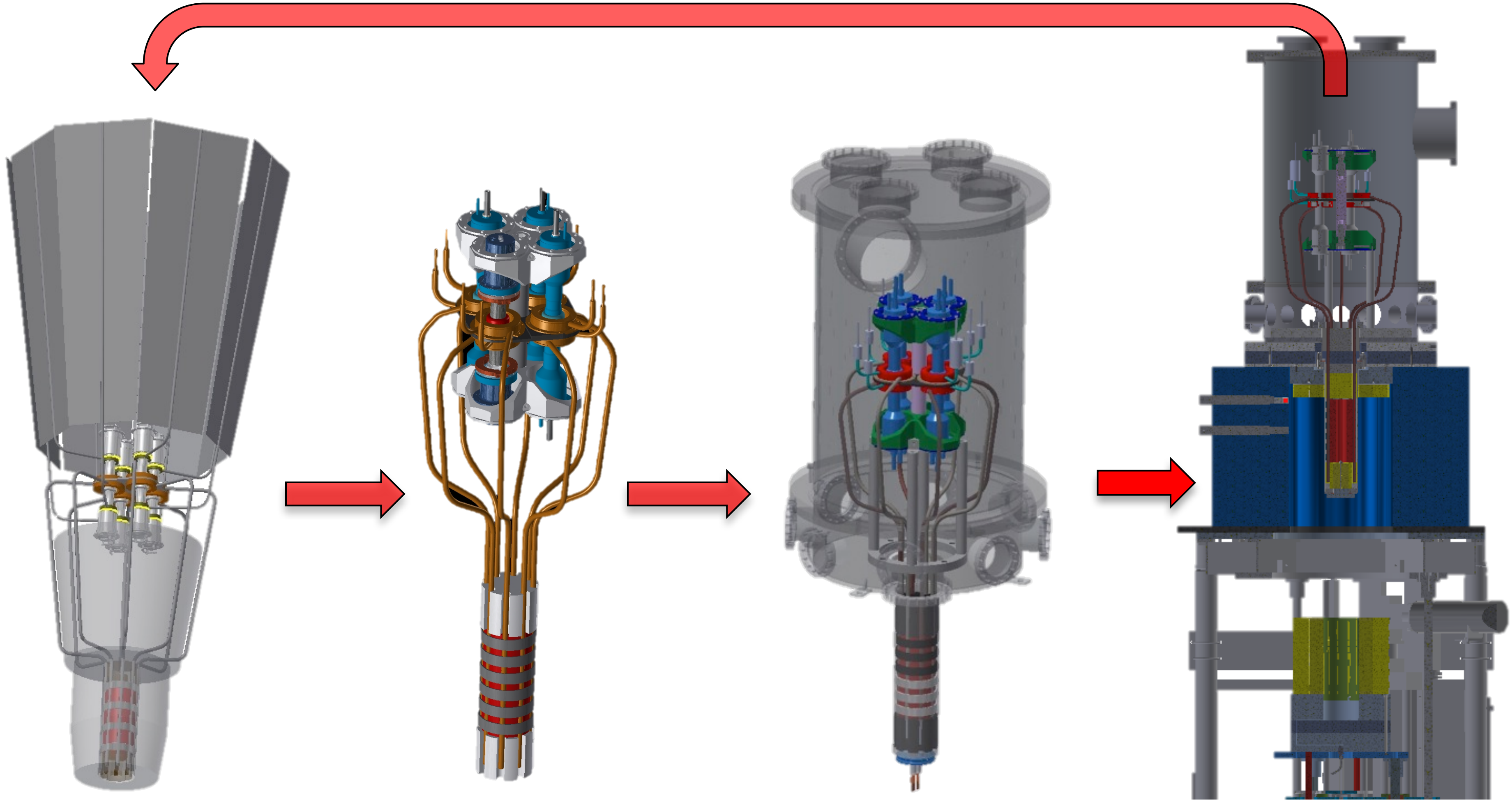
Haynes 230/Sodium Heat Pipes

Lithium Hydride/Tungsten Shielding

Beryllium Oxide Neutron Reflector

Uranium Molybdenum Cast Metal Fuel

Kilopower Technology Development



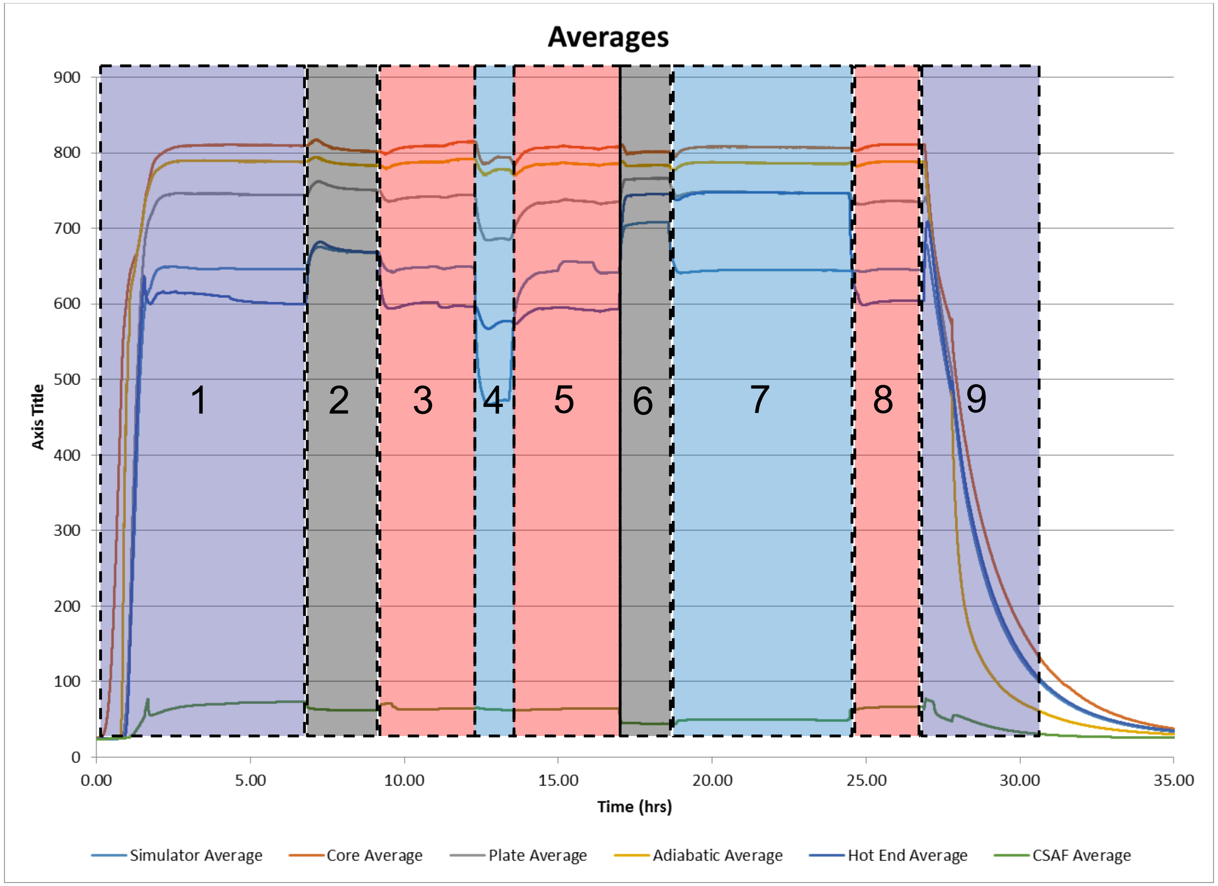
Flight Concept

Flight-prototypic Power Pack

Electrically Heated System Test with Depleted Uranium Core (NASA GRC)

Reactor Experiment with Highly Enriched Uranium Core (DOE NNSS)

System Test Profile: Expected Operating Temperatures



1. Heat up and steady state Operation, simulators set to match Stirling heat input
2. Half power Stirling operation
3. Return to steady state
4. Full thermal power
5. Return to steady state
6. Turn off Stirling engines and cooling (Simulators), adjust core power to simulate temperature feedback
7. Add additional cooling to Simulators, up core power, engines still off
8. Turn Stirling engines back on, return to steady state
9. Cut core power, GN2 backfill to chamber

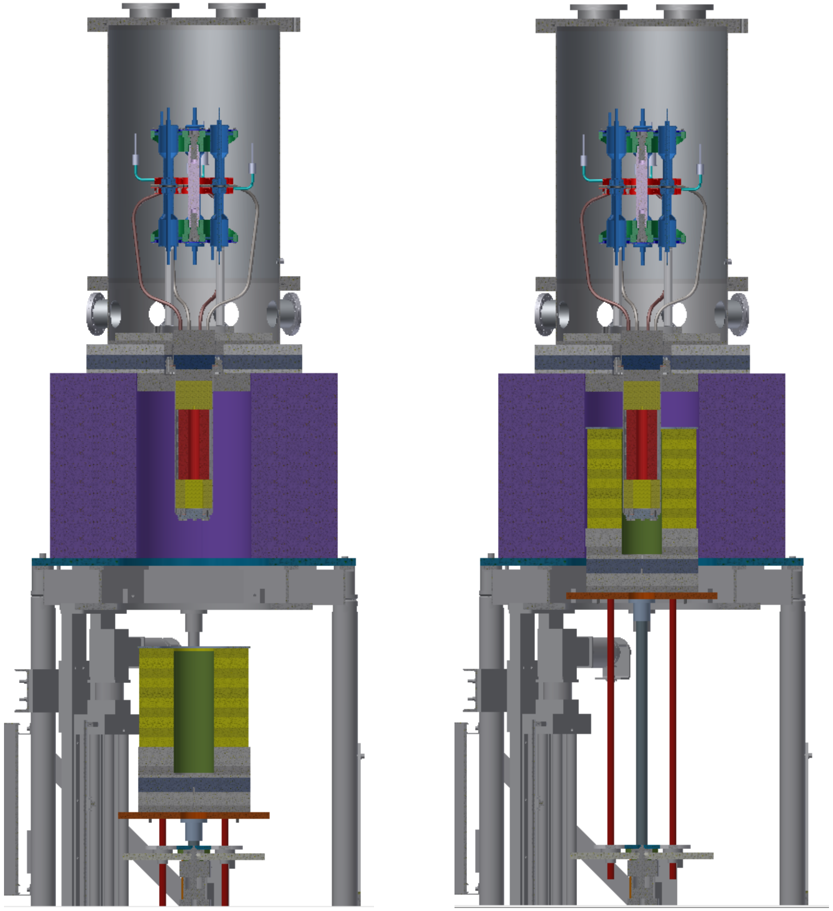
This test profile has been performed numerous times with the surrogate Depleted Uranium core using an electrical heater. It will be repeated, with the Highly Enriched Uranium core at NNSS.

Dave Poston, Los Alamos

Nuclear design and benefits of completing the test

Kilopower Reactor Using Stirling TechnologY = KRUSTY

- **Designed with flight-like components**
  - Uranium core, neutron reflector, heat pipes, Stirling engines
- **Integrated into flight-like power system**
  - Realistic configuration and interfaces
- **Tested at flight-like conditions**
  - Vacuum environment
  - Thermal power and operating temperature
  - System dynamics
- **Exercising flight-like infrastructure**
  - Analytical modeling
  - Nuclear test operations
  - Ground safety issues
  - Transport and assembly issues
  - Interagency cooperation

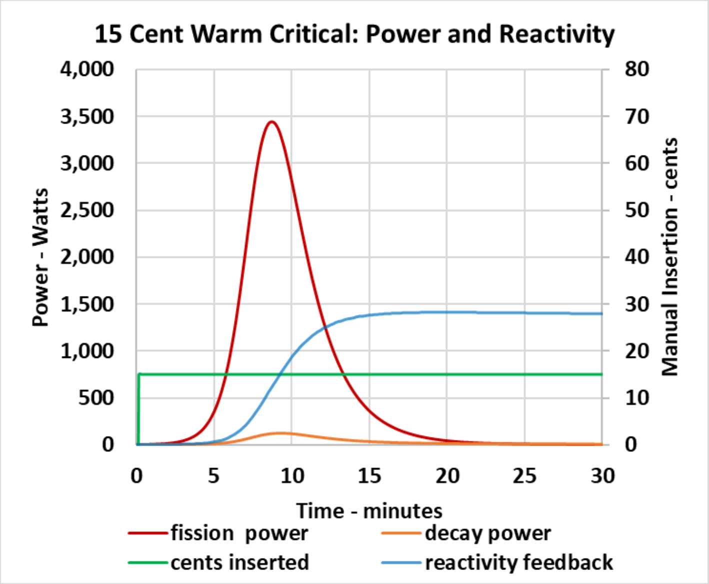


Key things missing from KRUSTY: radiator, full suite of Stirlings, startup-rod, zero-g, launch approval, flight hardware, launch loads, flight qualification, lifetime effects, spacecraft integration.

KRUSTY: Summary of Nuclear Experiments

The **KRUSTY Test** is being conducted in four phases over 3 to 5 months beginning November 2017, with fission reaction levels iteratively increased during each test phase to validate models and gain confidence

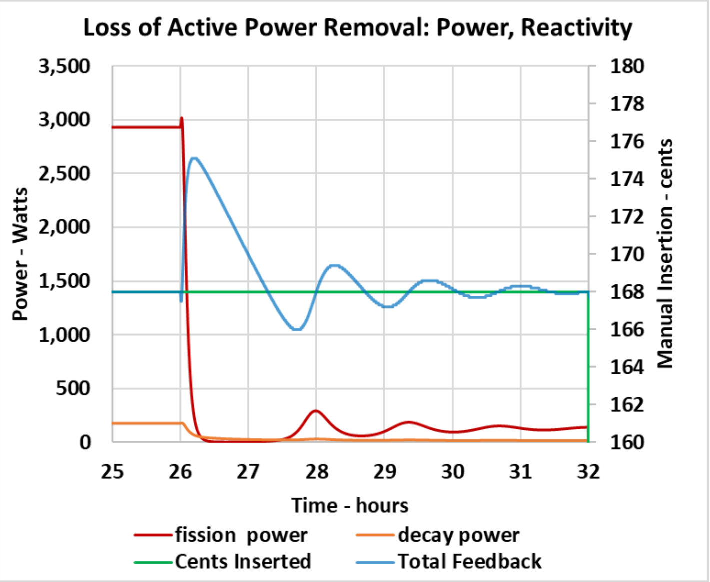
- **Component Criticals:** The reactor core, neutron reflector, and startup rod are tested alone to measure reactivity.
- **Cold Criticals:** Heat pipes and power conversion are added, and reactivity is gradually added until the system is critical but no heat is produced.
- **Warm Criticals:** Reactivity is increased until full reactor power (4 kilowatts thermal) is achieved at moderate temperatures of about 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.

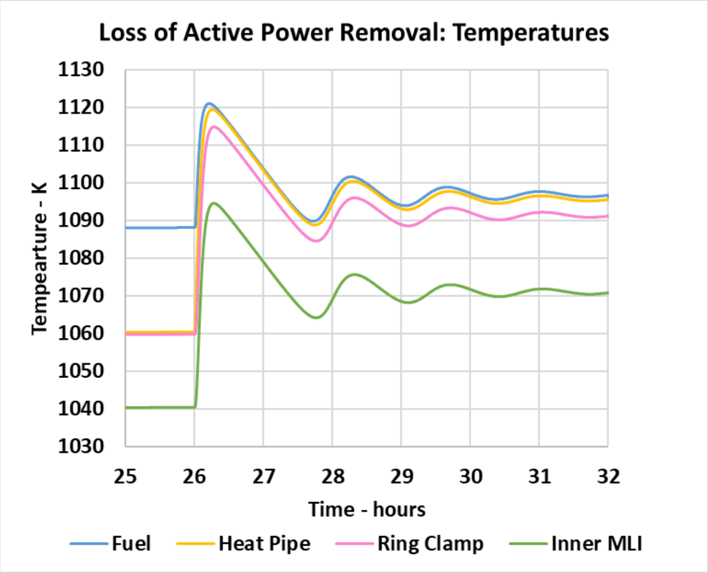


KRUSTY Full-Power Run

- **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 load-following ability.**
  - 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).**

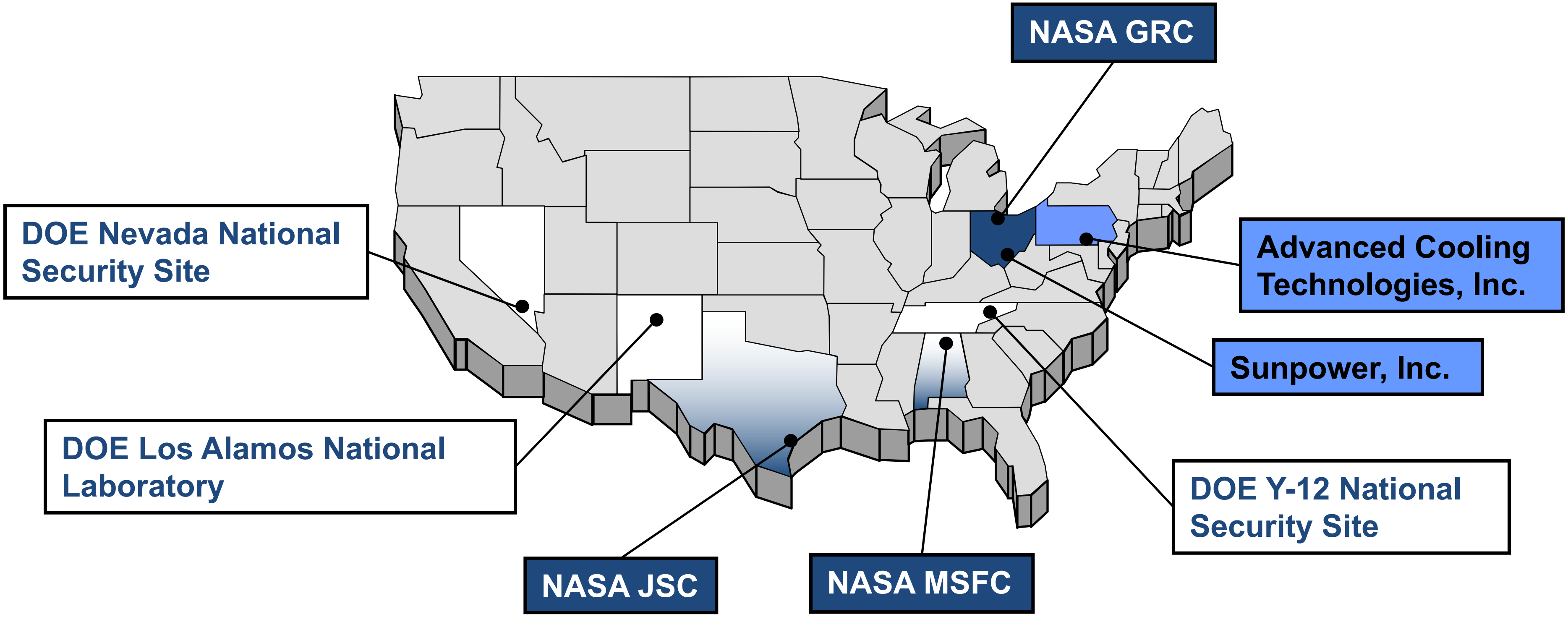
The nuclear operation and dynamics of KRUSTY are similar to any proposed Kilopower flight reactor (from 500 We to 10 kWe) – even if technologies and materials change, the coupled thermal-neutronic behavior is essentially the same.





Walk-off Slide

Project Participants



NASA GRC

DOE Nevada National Security Site

Advanced Cooling Technologies, Inc.

Sunpower, Inc.

DOE Los Alamos National Laboratory

DOE Y-12 National Security Site

NASA JSC

NASA MSFC