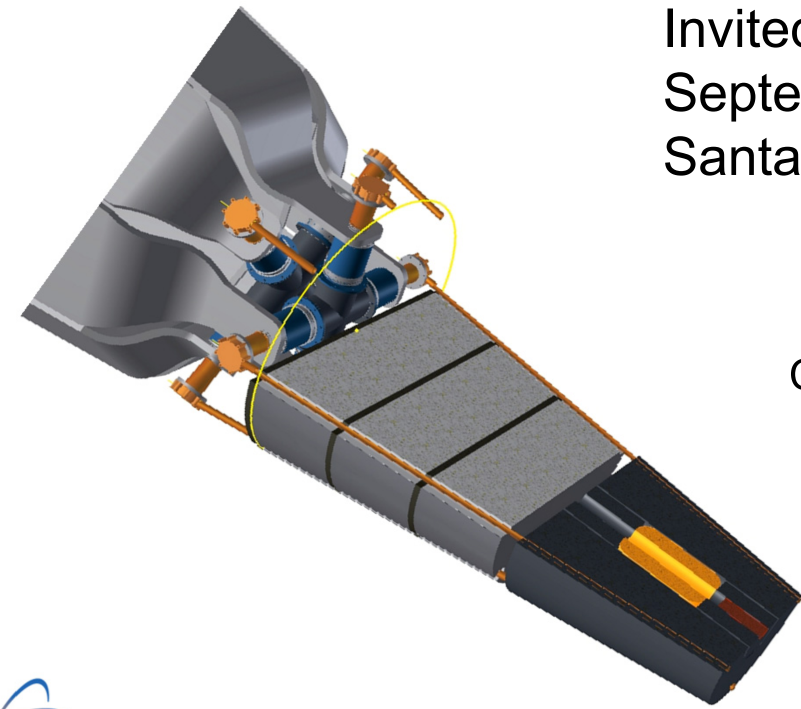
Design and Testing of Small Nuclear Reactors for Defense and Space Applications



Invited Talk to ANS Trinity Section
September 20th, 2013
Santa Fe, NM

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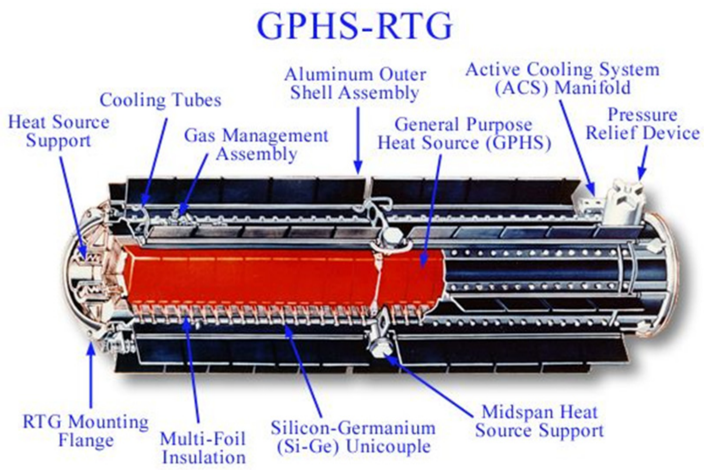
Los Alamos National Laboratory

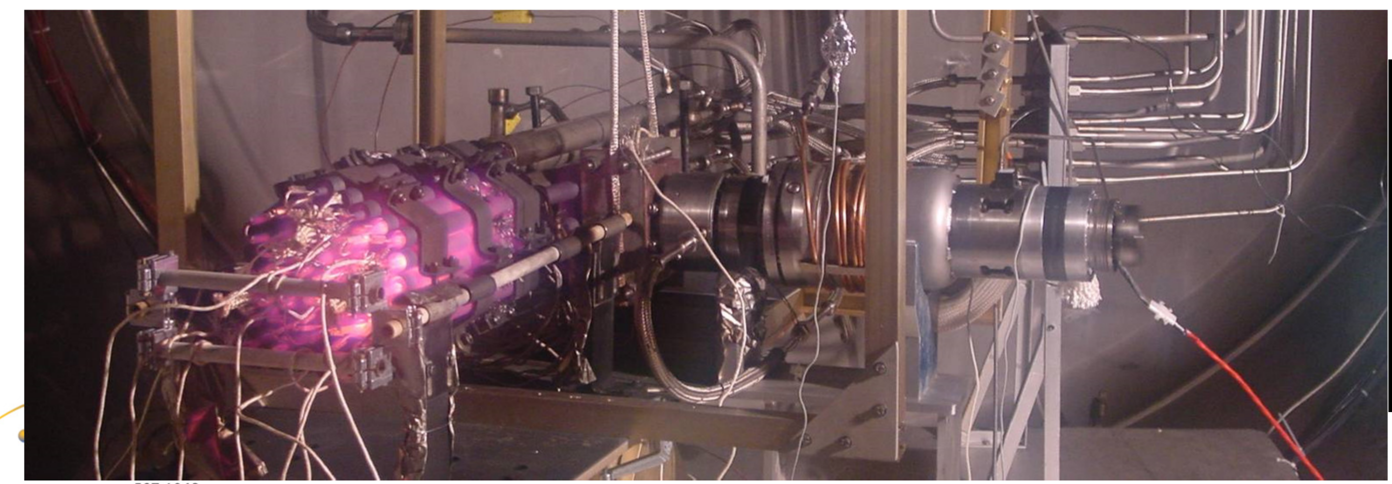
LA-UR-13-27054

Near-Term Applications of Space Nuclear Power

- Radioisotope Power Systems
  - Power via decay of radioactive atoms
  - Well established space technology base



- Fission Power Systems
  - Power via splitting of atoms, very high energy density
  - Well established terrestrial technology base - limited space experience



Non-nuclear breadboard test of a nuclear-electric propulsion system: heat-pipe cooled reactor coupled with Stirling engine powering an ion thruster (in separate chamber).

Why is NASA Interested in Space Reactors?

= 50 x

Fissioning 12 fl oz (341 ml) of Uranium yields 50 times the energy contained in a Space Shuttle External Tank

Energy Density: 82 billion joules per gram

- Fission is the only near-term technology that can provide long-duration, reliable high power at low mass for a large variety of missions.
  - Conventional chemical systems.
    - Very near their theoretical performance limit, low energy density.
  - Solar power.
    - Dependent on orientation, radiation field, eclipses, debris, etc.
    - Large spacecraft profile (vulnerability – random debris or hostile).
  - Radioisotope power.
    - Energy density is many orders of magnitude below fission.
    - Future sources of Pu-238 or other radioisotopes unknown.

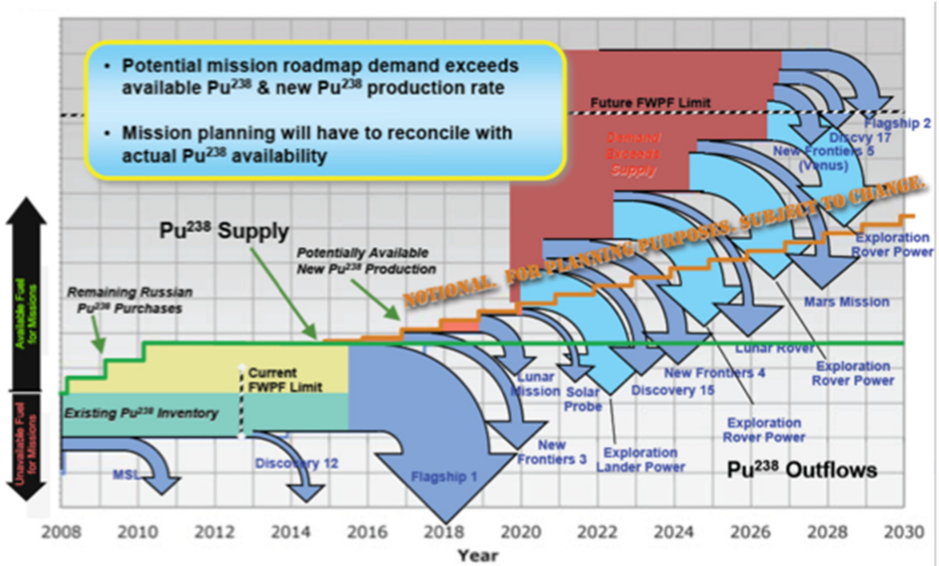
- Recent technology advances in power conversion systems, radiators, spacecraft design, electronics, etc., put less burden on the reactor.
  - Development of Stirling engine techonology for radioisotope power is very mature and allows for a much lower power reactor.

Benefits of Space Fission Power Systems

- Space Fission Power can enable or contribute to many national and global missions
  - **Ambitious space science and exploration.**
    - Outer-planet mission power (e.g. Kilopower)
    - Mars/lunar surface power (robotic and human).
    - Outer-planet propulsion (e.g. Jupiter Icy Moons Orbiter)
    - Propulsion in support of human missions (cargo/crew).
    - Interstellar precursor or solar missions.
  - **Enhanced national and planetary defense.**
    - High power and enhanced mobility for defense applications.
    - Potential use for comet/asteroid orbit alteration.
    - Synergy with advanced terrestrial and airborne defense systems.
  - **Future commercial value in space.**
    - Satellite power, mobility, maintenance, retrieval.
    - Space tourism (orbital, lunar, ?).
  - **Revitalizing the nation's nuclear power infrastructure and capabilities**
    - Space fission programs inspire students and young professionals to pursue nuclear engineering
    - Many technologies developed could be used for advanced terrestrial power reactors

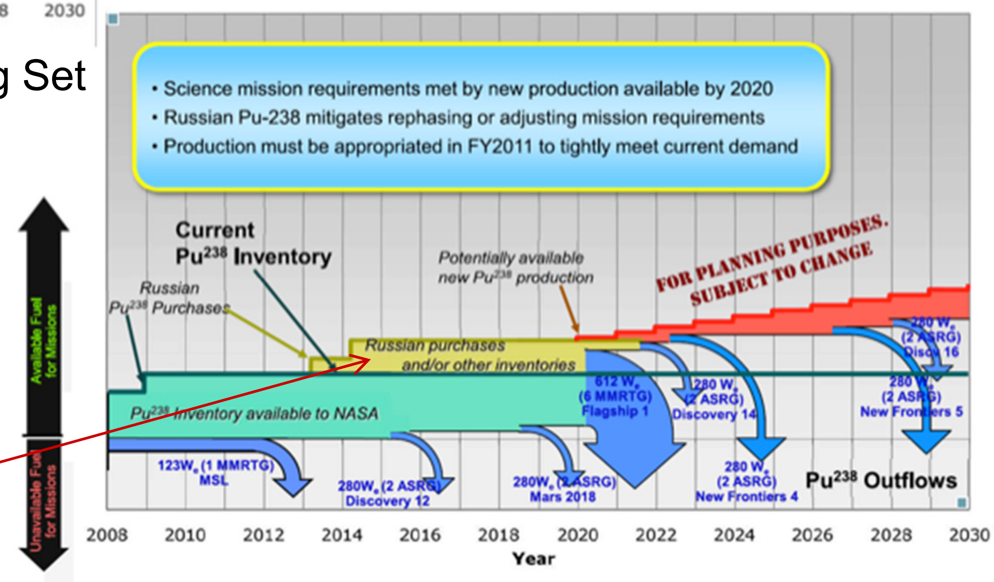
- Furthermore, for new and enabling technologies the majority of applications are often not thought of until the technology is proven and in hand.

Recent Motivation - ^{238}Pu Supply Issues



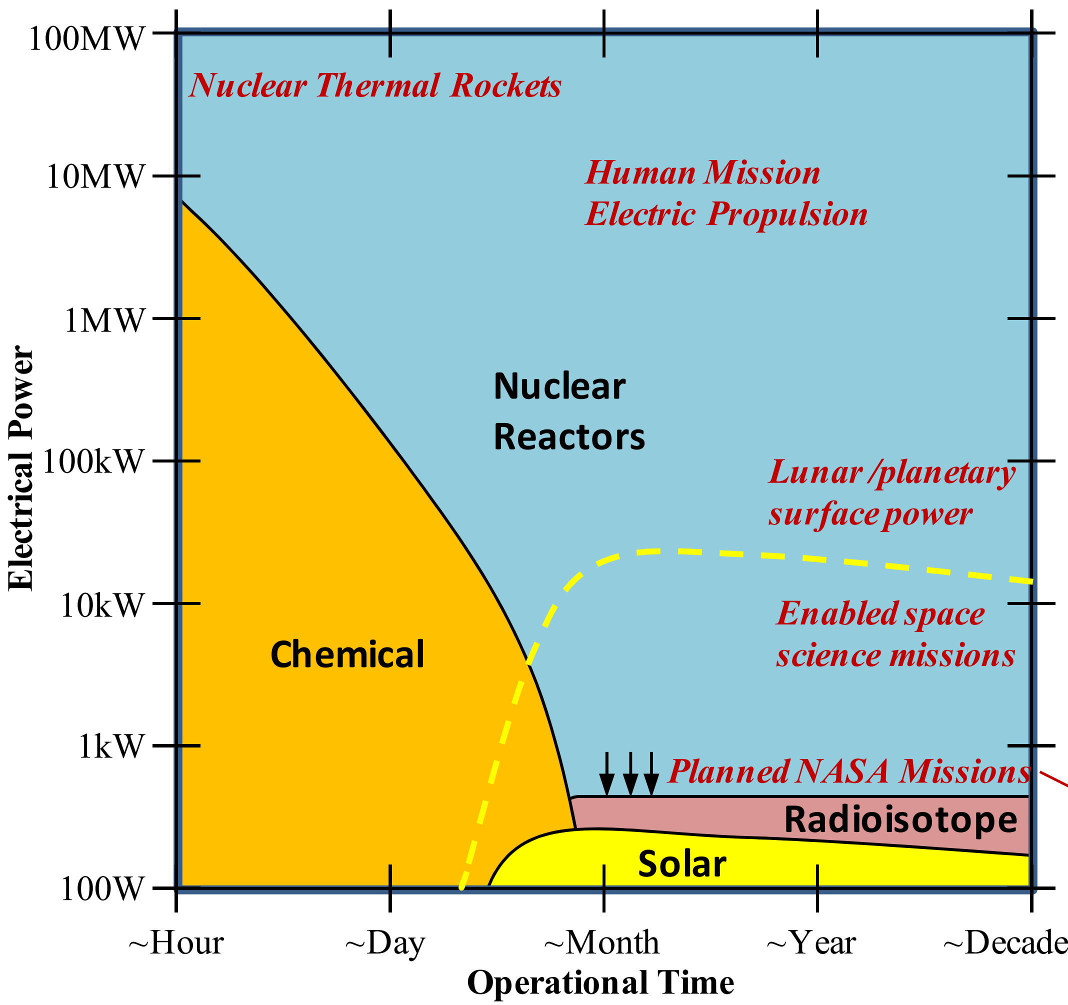
March 31, 2008 SMD RPS Mission Planning Set

Nov. 30, 2010 SMD RPS Mission Planning Set



Russian purchases not likely to happen

Potential NASA Power Sources



This chart includes estimates of mass, practicality and utility of each power source.

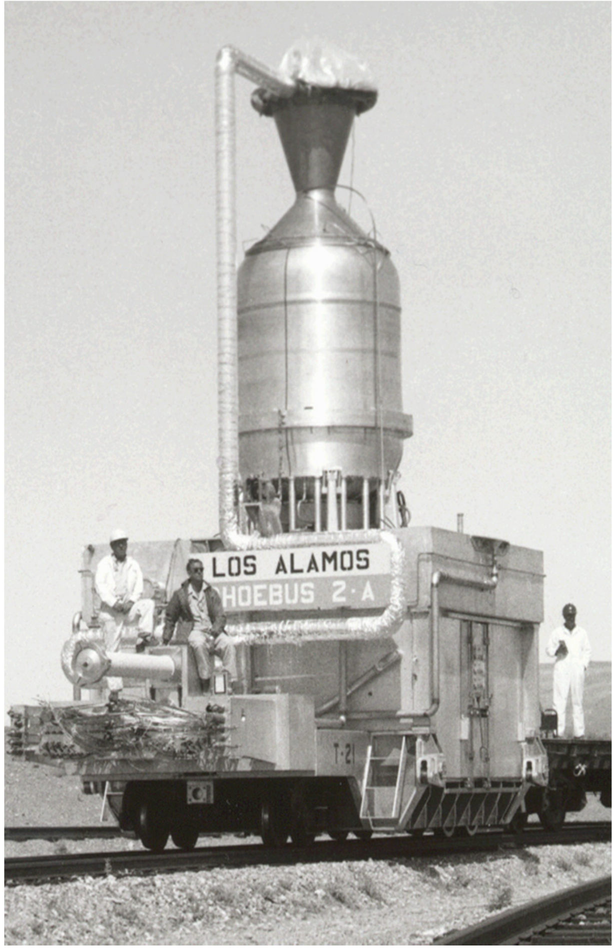
The utility of solar power is obviously dependent on distance from sun and/or possibility of day-night cycle.

Yellow curve is estimate of utility at 10 AU, dotted yellow line is estimate at 1 AU (no eclipse application).

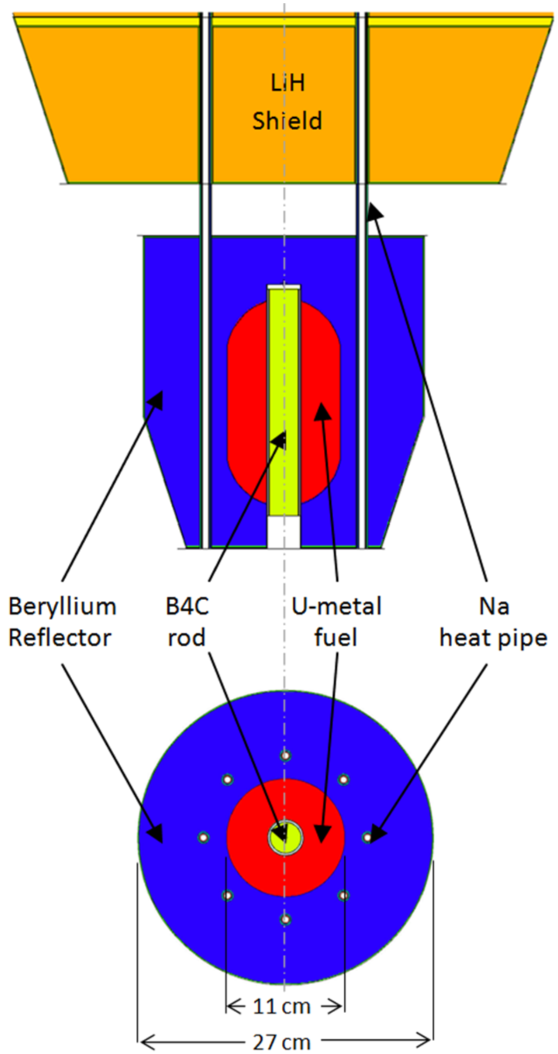
Limited ^{238}Pu supply has lowered the threshold for entry-level fission systems.

Nuclear Thermal Rockets: Not Currently Affordable

- A Nuclear Thermal Rocket (NTR) is a reactor in which the propellant flows directly through the core and out through a nozzle.
- There was an amazing amount of progress in developing Nuclear Thermal Rockets in the 60s and early 70s.
  - Dozens of nuclear tests continually got us closer to a flight reactor – but still a ways to go.
  - However, the glory days of unencumbered nuclear testing are gone, as well as the infrastructure and facilities they used.
- How realistic in today's environment is it to develop a reactor with….
  - temperatures above most materials melt (>2800 K)
  - world-record levels of power and power density
  - cooled by nature's most reactive substance (H).
    - For this effort you'd expect a warp drive, but in reality you get a factor of 2 performance gain over conventional chemical rockets.



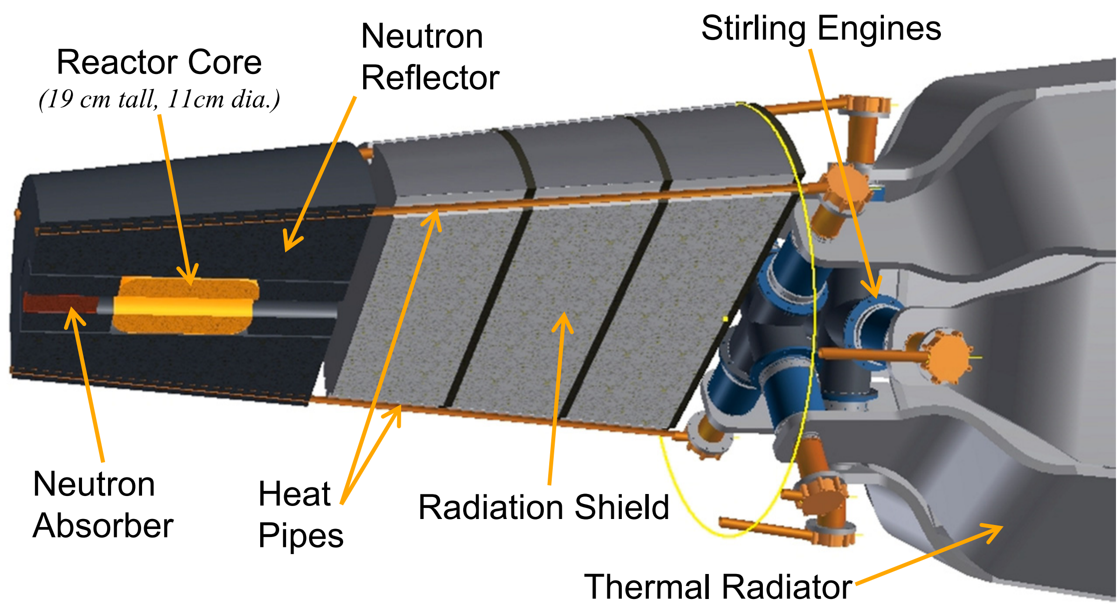
Our basic reactor concept



1000 W electric, 4000 W thermal

6 SYSTEM COMPENENTS

- block of U-metal fuel
- beryllium reflector
- sodium heat pipes
- lithium-hydride/DU shield
- boron-carbide safety rod system
- ASC-derived Stirling engines



DUFF - Demonstration Using Flattop Fissions

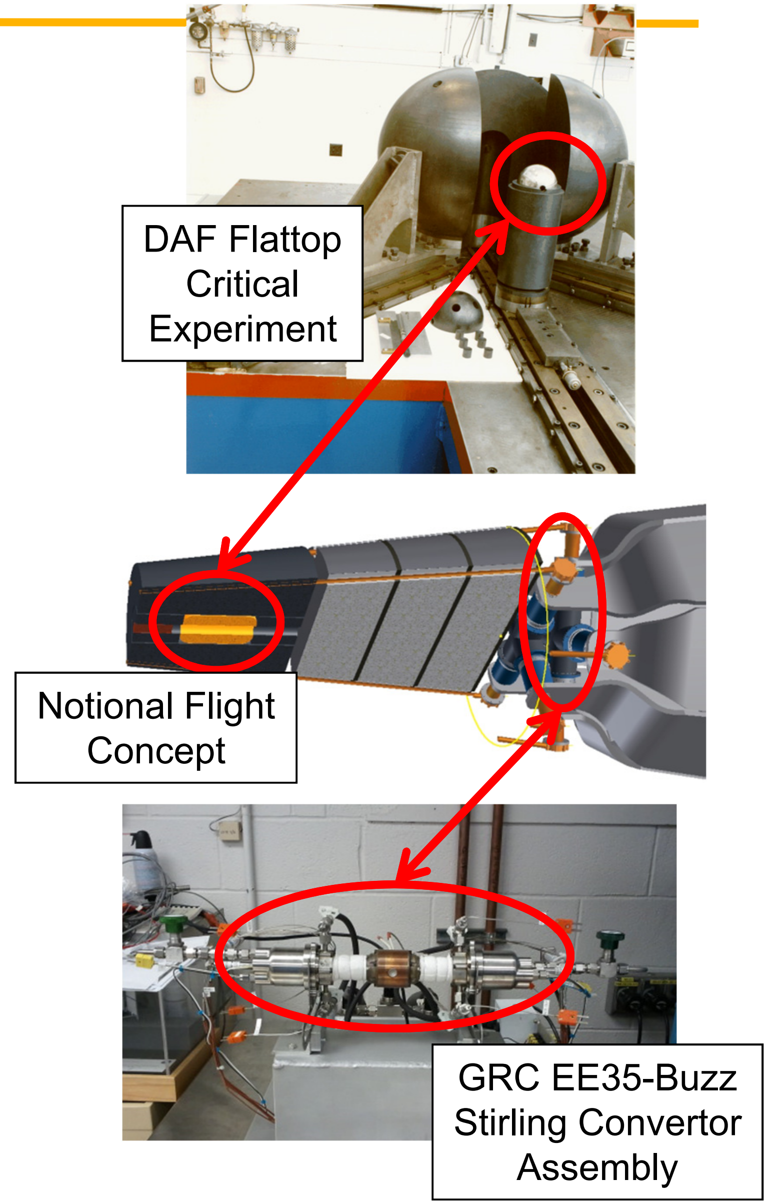
- LANL had an idea for a new, low power reactor with heat pipe cooling and Stirling engine power conversion (<u>Previous Slide)</u>
- We believed a nuclear-powered demonstration could be performed with minimal effort
  - Basic Idea: Insert a heat pipe connected to a Stirling engine into an existing critical experiment machine.
    - Make nuclear material go critical, heat up, drive heat from heat pipe to Stirling engine, make electricity.
  - LANL has several critical experiment machines at the Nevada Nuclear Security Site (NNSS) Device Assembly Facility (DAF)
    - Flattop critical experiment chosen for DUFF
      - Most similar to flight concept, easiest for heat pipe integration
  - Test was not prototypic
    - Lower temperatures than proposed reactor concept (300 C vs 800 C)
    - Water heat pipe not Sodium (required by lower temperature)
    - Different reflector material (natural uranium vs beryllium)
- While a more prototypic test might be nice, it was not considered immediately necessary.
  - Completing the test demonstrates reactor concept is sound*<u>, and that affordable nuclear testing is possible</u>*

Why this reactor design for first system?

- Very simple, reliable design
  - The power is so low there are no measurable nuclear effects
    - No fuel burnup issues, fission gas production, or swelling
    - Negligible reactivity loss, minimal decay heat
    - No irradiation damage to any component
  - Low power allows small temperature gradients and stresses, and high tolerance to any potential transient
- Heat pipe reactors are simple, reliable, and robust
  - Eliminates components associated with pumped loops; simplifies integration
  - Fault tolerant power and heat transport system
  - 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 NCERC within the DAF.

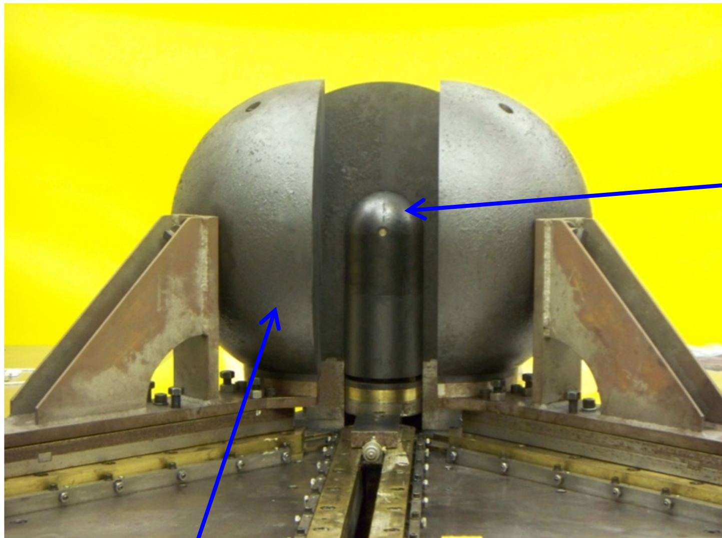
DUFF: A "Critical" Starting Point

- 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
    - Similar to Advanced Stirling Convertors
- 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

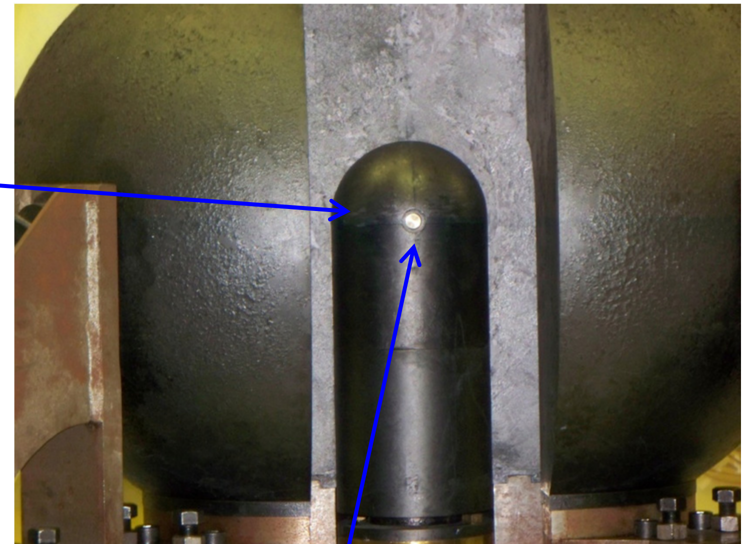


DUFF Experimental Setup - Core

Flattop core on pedestal with reflector



Close up picture of core

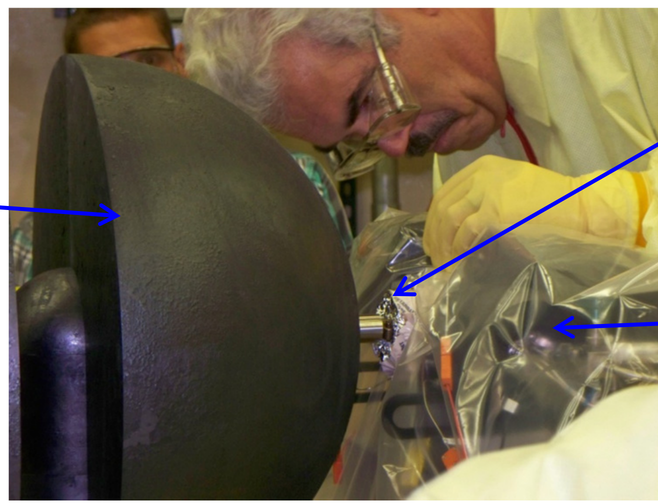


Core

Heat pipe

Reflector

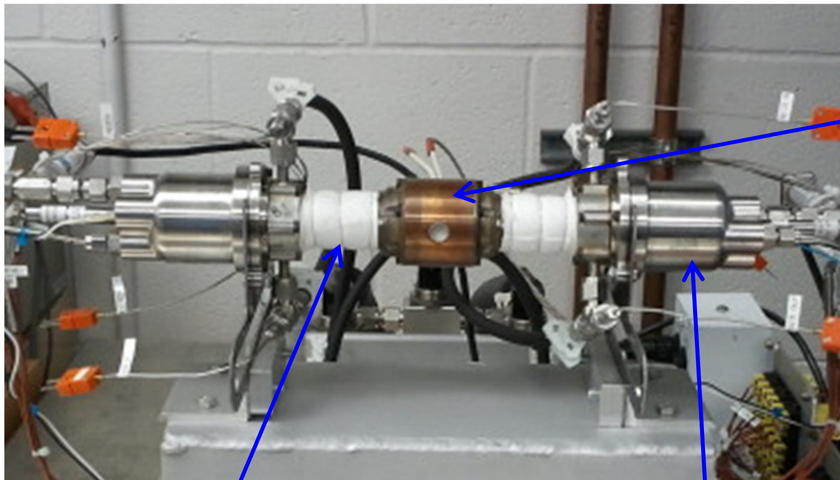
Stirling Engine



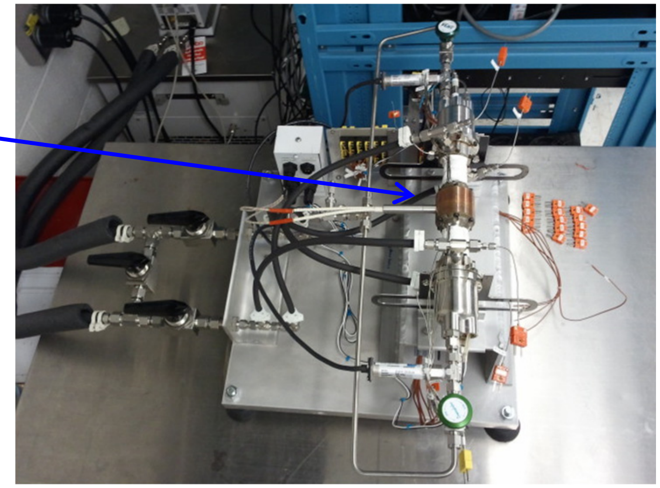
Core with heat pipe emerging from reflector

DUFF Experimental Setup – Stirling Engine

Dual Stirling engines connected by copper block



Stirling engines looking down from above



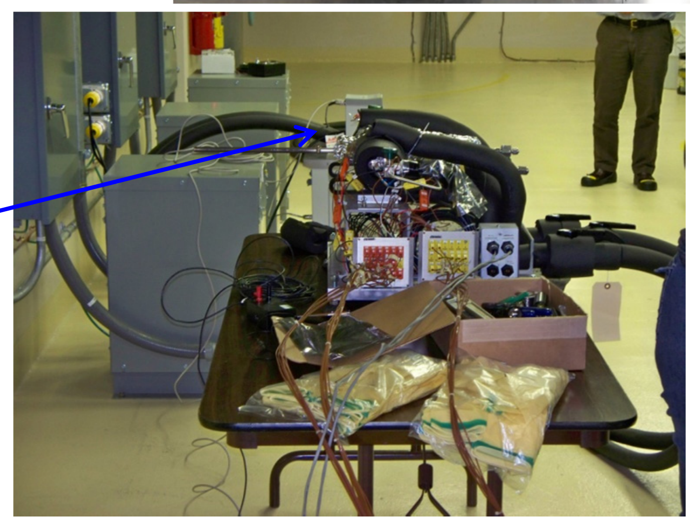
Copper block

Piston

Alternator

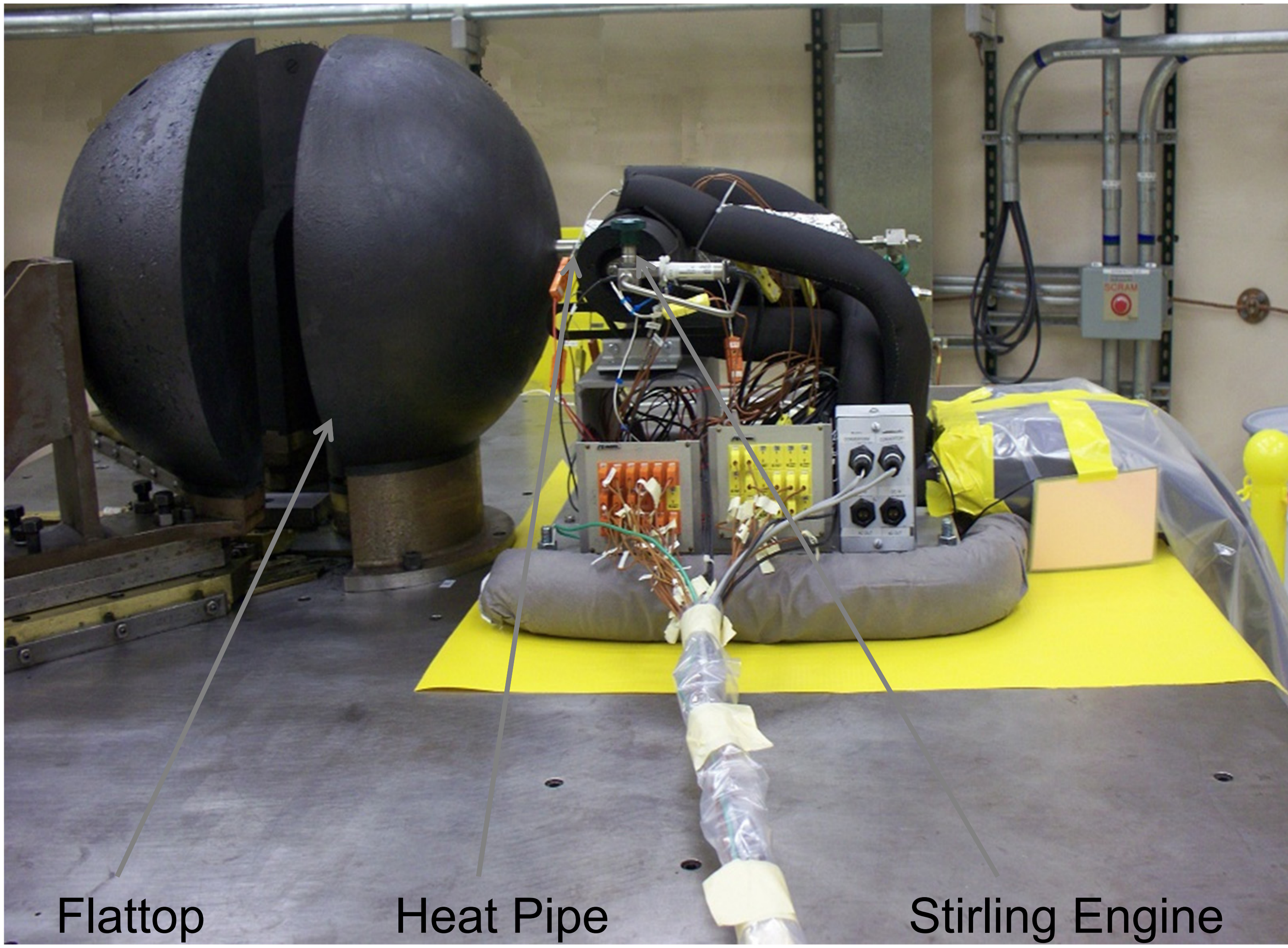
This hardware provided by the NASA Glenn Research Center.

Chiller



Stirlings connected to chiller with controllers prior to insertion into Flattop

DUFF -- Complete Experimental Setup

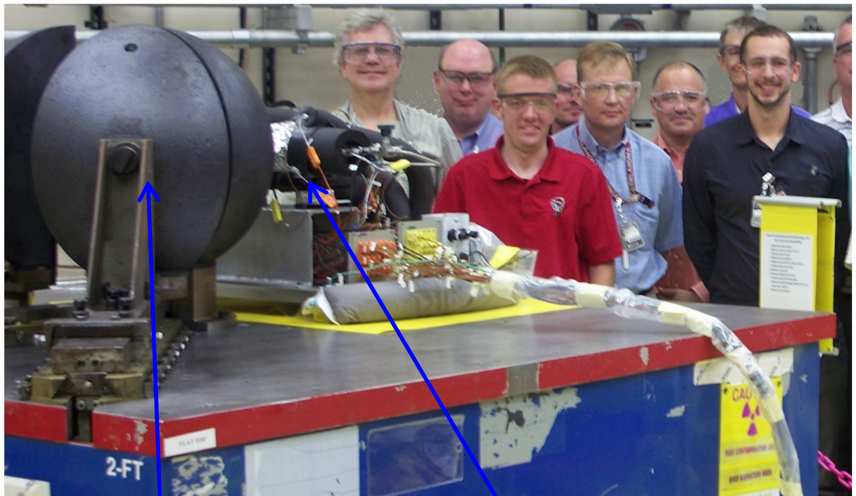


Pre-Modeling of the Test Very Important

- Would we have enough reactivity?
  - It was possible that the configuration would not go critical – Flattop had never been in a configuration like this before.
- Would we have too much reactivity?
  - The authorization to run the experiment hinged on the requirement that we had less than 80 cents positive reactivity – if it was >$0.80 when we fired it up the experiment would have been terminated and we/management/etc. would have been in big trouble.
- Would transient response be fast enough to get engine started before our ~1 hour time limit reflector heated up?
  - If we had poor thermal coupling or excess thermal inertia, then we might never get the engine hot enough to operate.
    - We were limited to 1 hour per run, because of room activation concerns, plus we would lose all of our reactivity if the reflector fully heated.
- Would transient response be slow enough to satisfy the safety review panel that nothing bad could happen?
  - We had to show the safety review panel our expected results: not only did the results have to show that the test was safe, we also had to convince them that we knew what we were talking about and the results were reasonably accurate.

Running the DUFF Test

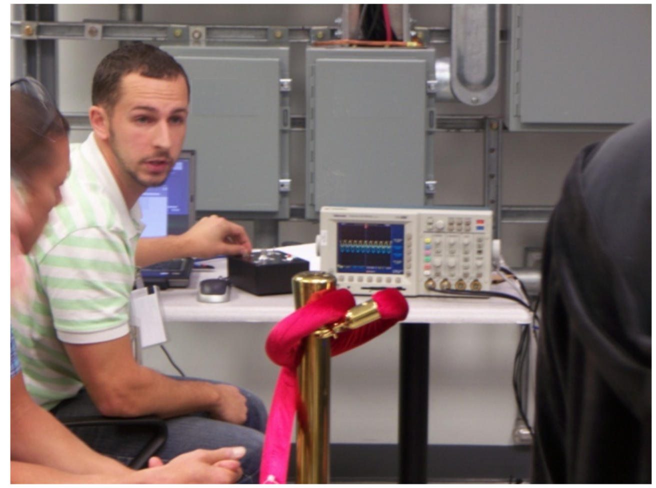
Pre-test: Flattop on its table with Stirling engines



Core and reflector

Stirlings

Switch to kick-start Stirling engines



Ready to go!!

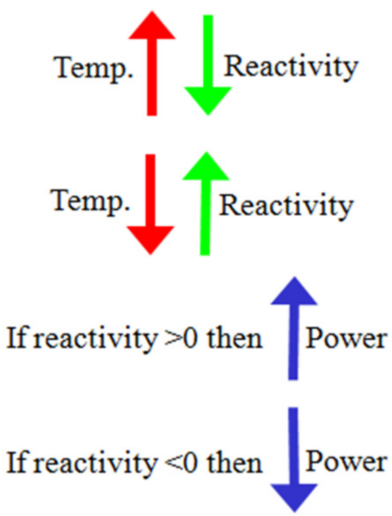
Control room for operating Flattop

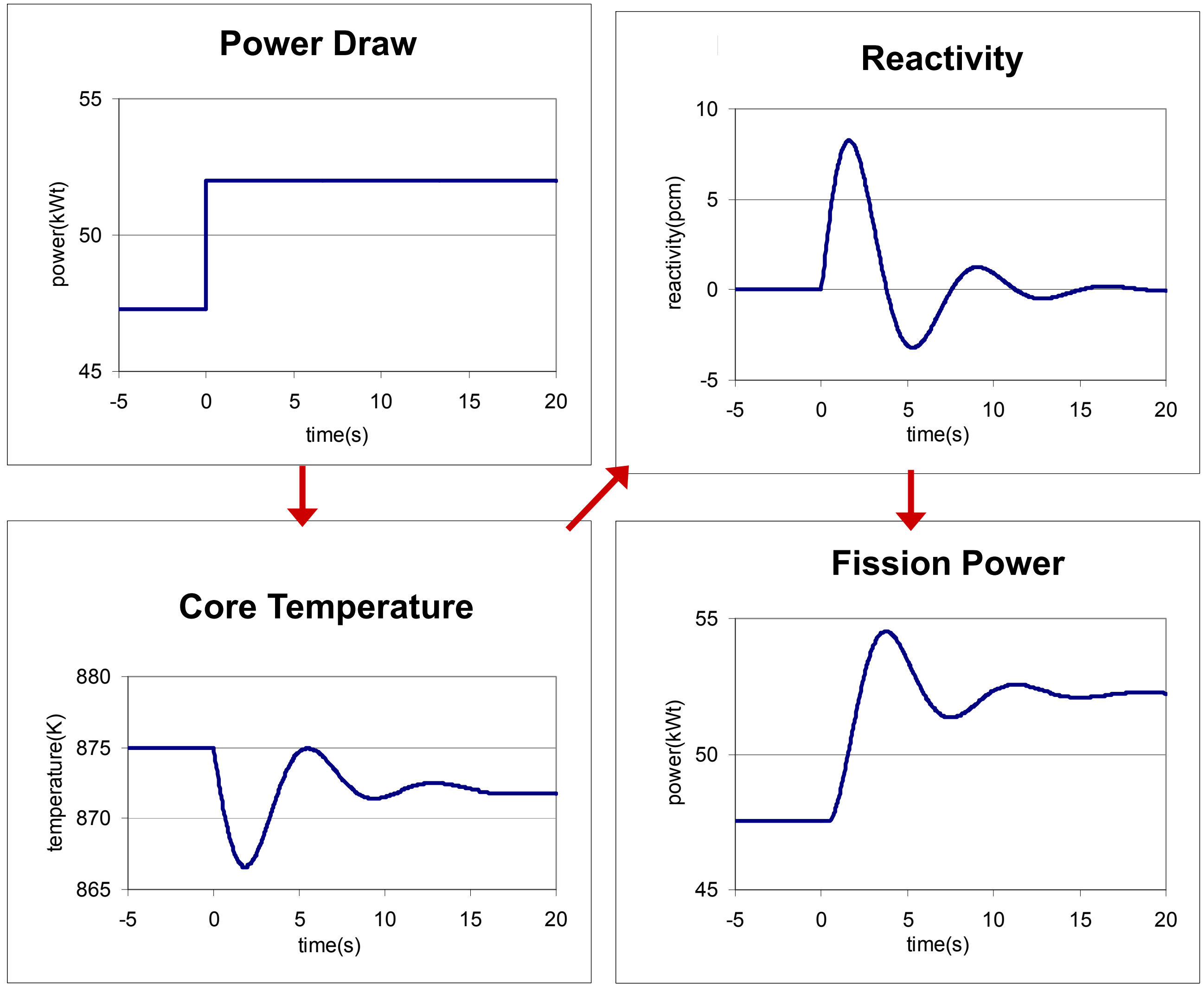
Reactor Dynamics

- Reactivity is a measure of reactor neutron multiplication, or the slope of neutron population.
  - If the reactor is critical (i.e. keff=1) then reactivity is zero
  - If the reactor is supercritical (i.e. keff>1) then reactivity is >0
  - If the reactor is subcritical (i.e. keff<1) then reactivity is <0
- Reactivity is primarily dictated by material density, geometry and nuclear interaction probabilities (cross sections)
  - Temperature affects density, geometry and cross sections – thus changes in temperature are what drive changes in reactivity.
- Several reactor components can contribute to reactivity feedback.
  - In most reactors, dynamics are very complex
    - Due to temperature changes and movements of fuel, fuel clad, pin lattice, assemblies, control elements, vessel, axial reflectors, core coolant, radial reflector, Doppler broadening, self-shielding, isotope buildup and depletion, changes in neutron spectrum, coolant void fraction, etc.
  - We designed our concept to make reactivity feedback simple and predictable.
    - Fast spectrum (minimizes changes in cross section), solid block fuel (minimizes unwanted movements of fuel/core) and simple (very few components that could impact reactivity).

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.

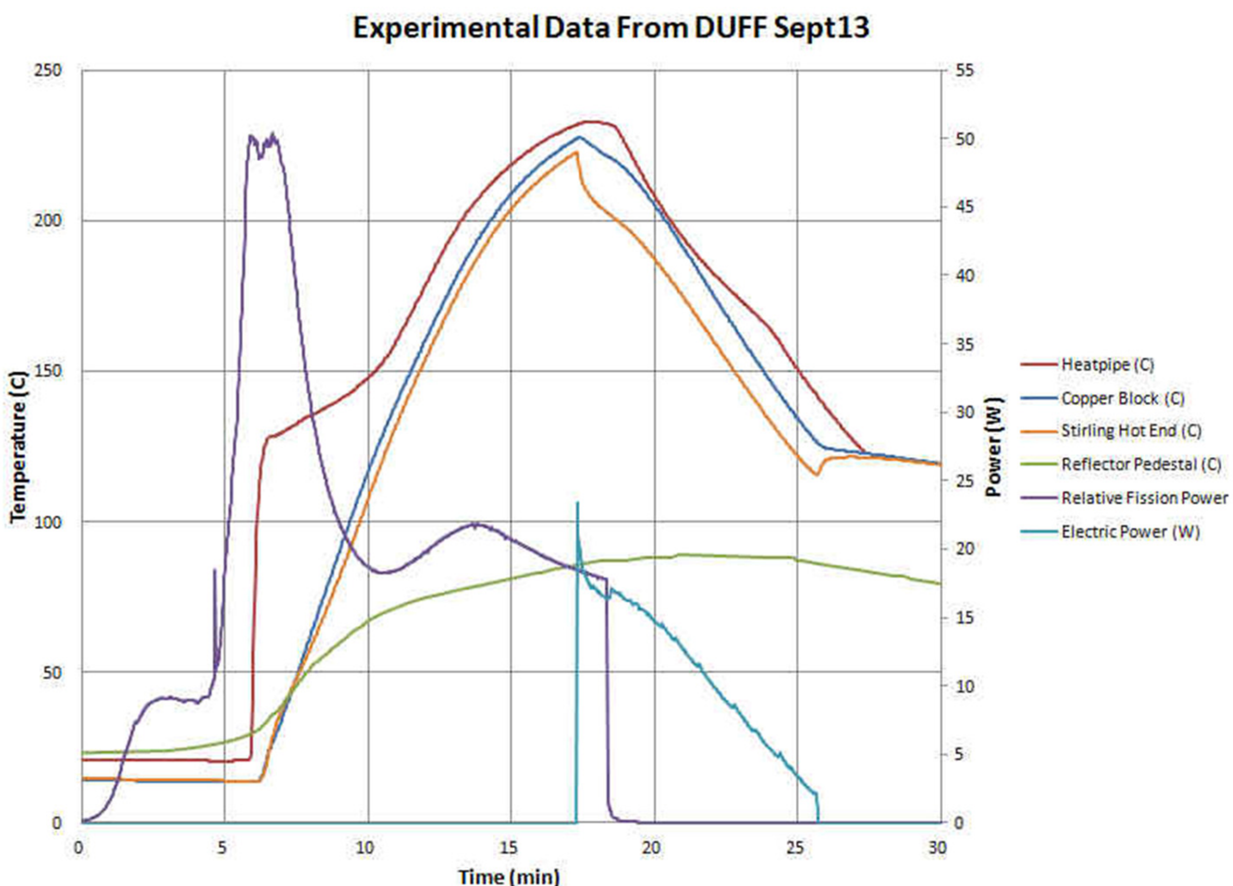
DUFF Timeline

- Tuesday, Sept. 11th – Experiment setup
- Wednesday, Sept. 12th – Approach to critical
- Thursday, Sept. 13th – First run
- Monday, Sept. 17th – Modifications
- Tuesday, Sept. 18th – Second run

- Project duration limited because facility was needed for other priorities
  - More tests of DUFF possible in future if desired

Thursday, Sept. 13th 10:50 am PDT – First Run of DUFF

- **T=0 min:** Reactor operator starts to take power up to moderate level (~2 kW), a small amount of heating occurs.
- **T=5 min:** Operator inserts reactivity (~30 cents) and power quickly rises to about ~10 kWt. Natural temperature feedback lowers reactivity, and operator continually inserts reactivity via control rods to maintain power for ~1 minute.
- **T=5 min:** Internet connection to computer that records DUFF temperatures fails, no temperature data other than Flattop pedestal temperature, which reads much lower than the fuel (appears to read pedestal reflector material)
- **T=6 min:** Flying blind. Model calculates the core is heating up at rate of ~2 C/sec.
- **T=6+ min:** Despite the hot core, the cold end remains below room temperature (due to chiller). System waits for the water in the heat pipe to establish its internal 2-phase passive circulation loop.
- **T=7 min:** The heat pipe "turns on" and heat flows to the Stirlings. The HP power quickly goes to about 400 W.
- **T=7+ min**: Heat pipe power causes a quick rise the in HP temp just past evaporator, and then begins to heat copper block and Stirling.
- **T=8 min:** Pedestal temperature remains cool ~50 C. Model calculates peak fuel temp of ~330 C (which would have peaked closer to 380 C if HP had not started cooling reactor).



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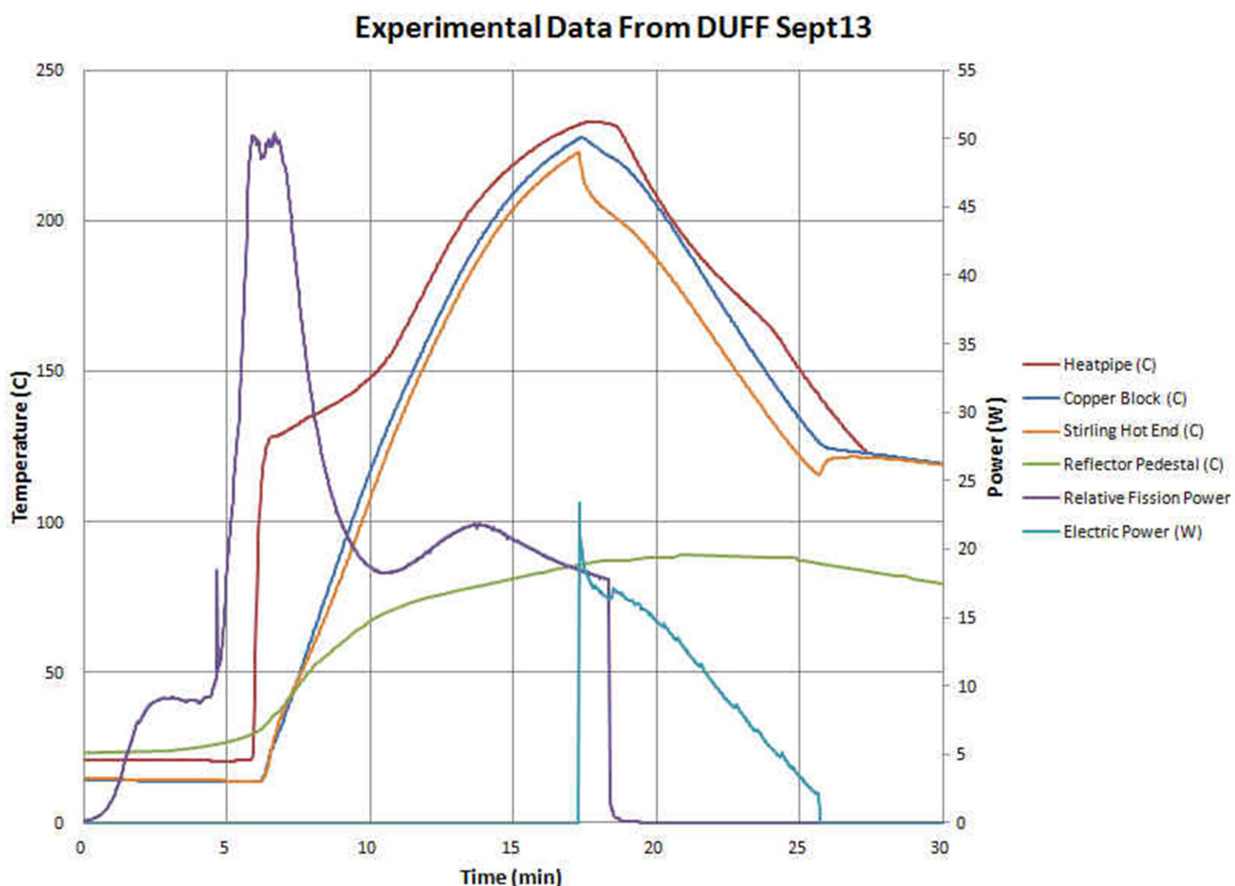
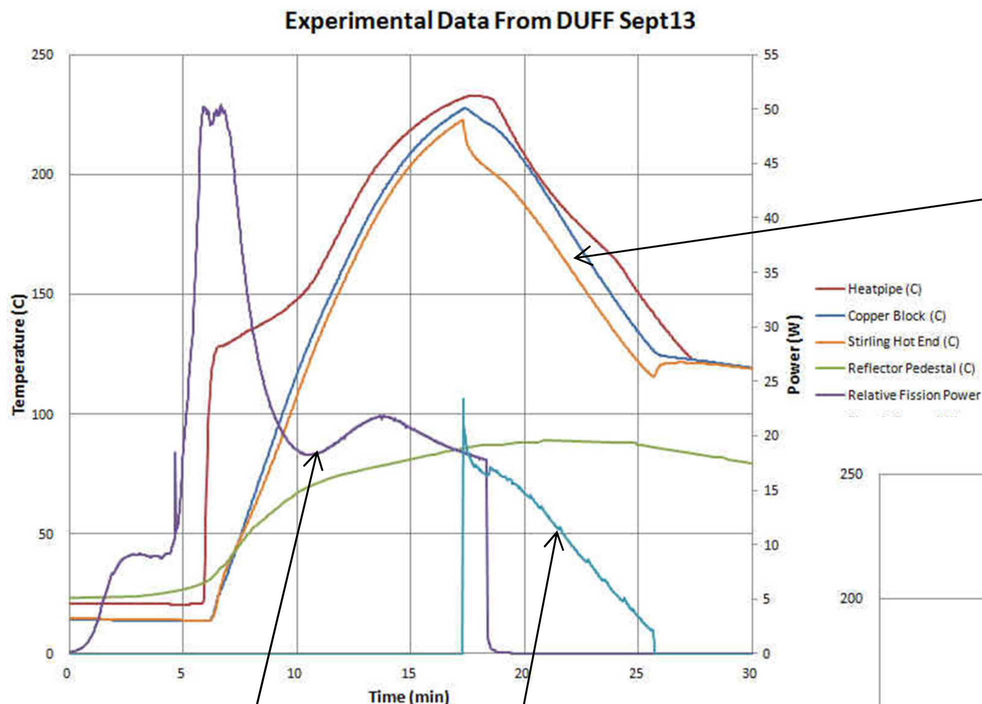
First Run of DUFF (cont'd)

- **T=7 to 17 min:** As the heat pipe draws power from the reactor, it heats up the Stirling by about 200 C over ~10 minutes, while also keeping the core cooler (thus adding more reactivity and causing additional reactor power).
- **T=17min:** Stirling engine technician starts the engine when the hot end is 225 C, providing 24 Watts of electricity.
- **T=17+ min:** The Stirling hot end cools quickly (thus sharp drop in electrical output). Temperature gradients start to set up to allow ~steady-state power flow from core over the next minute. Stirling power starts to level off at ~18 W.
- **T=18 min:** Flattop scrammed (fission power to ~zero).
- **T=18+ min:** Stirling draws power from stored energy and decay heat for ~8 minutes, cooling all components by ~100 C. Stirling continues to produce electricity, but at diminishing efficiency and power as temperature drops.
- **T=26 min:** Stirling engine stalls when temperature hits ~120 C. Entire DUFF apparatus cools slowly from there.
- **T=4 hours:** A huge sigh of relief in the control room when we find that the data from the DUFF computer exists! Only the communication was lost.



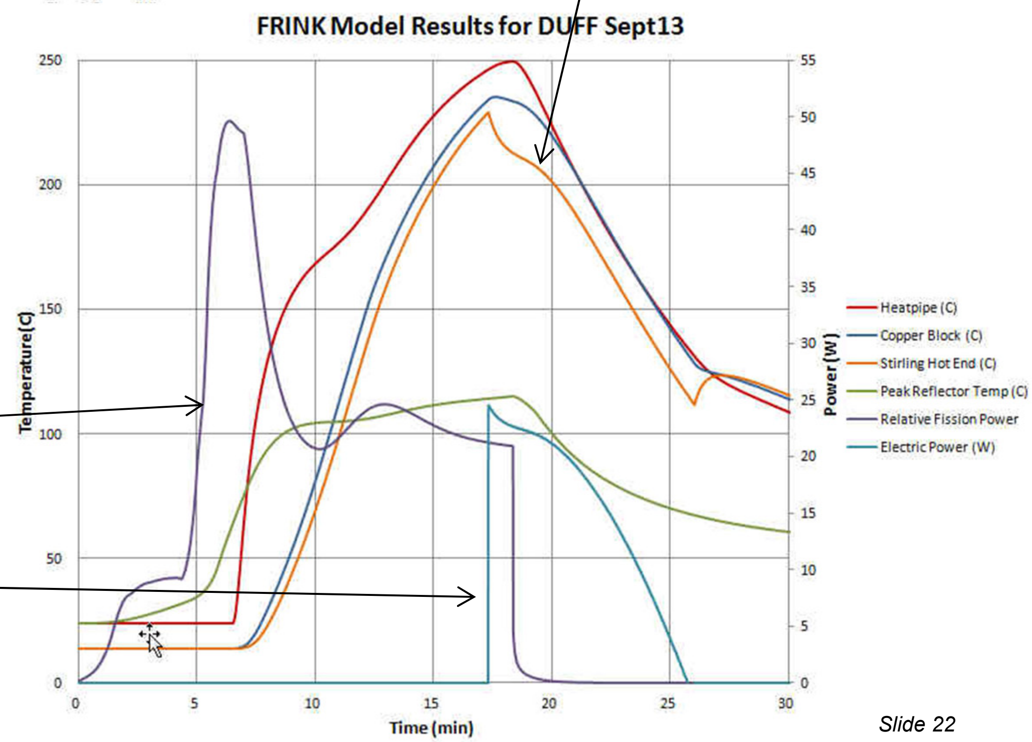
Sept 13th Test Results Compared with System Model



Power Conversion System Temperatures

Reactor Thermal Power

Electric Power

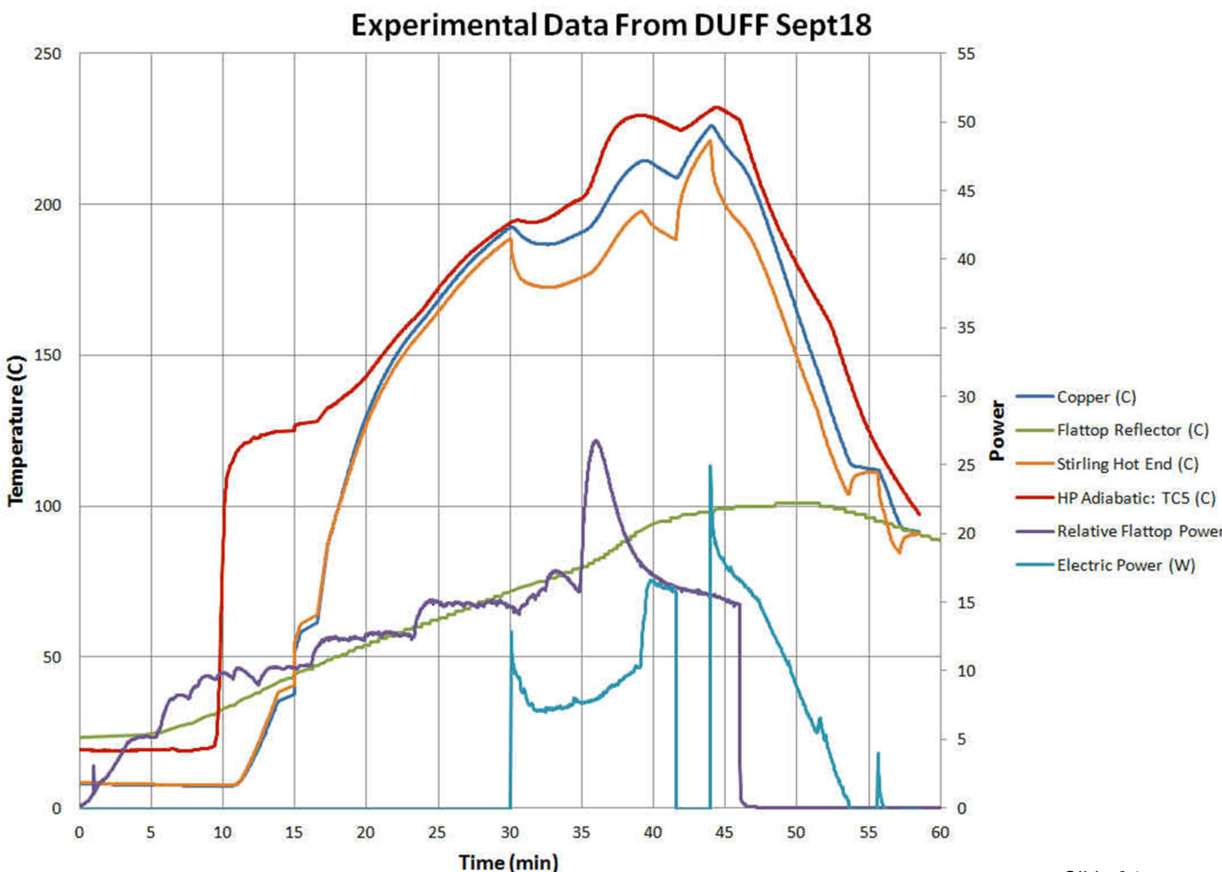


Results

- Tuesday, Sept. 18th – Second Run
  - Follow same checkout procedures as listed for first run
  - Several in attendance test, including NASA-HQ Radioisotope Power System program executive.
  - Goals of second test
    - Slower transients, lower power, longer run of Flattop
    - Start and restart Stirlings to look for neutronic impact of heat removal on Flattop
    - Reproduce results of first test (i.e. see if power the same at the same temperature – 24 Watts at 225 C)
  - Note: test goals had to be balanced with programmatic goals for upcoming projects in the facility – room activation was to be minimized, which limited how long we could run the reactor.
    - Due to the slow thermal lag of the system (i.e. for temperature changes in core to fully impact Stirlings and vice versa), each change would ideally be held for about 10 minutes. Instead they were held for 2 or 3 minutes, so the feedback effects of were small (but still clearly present).

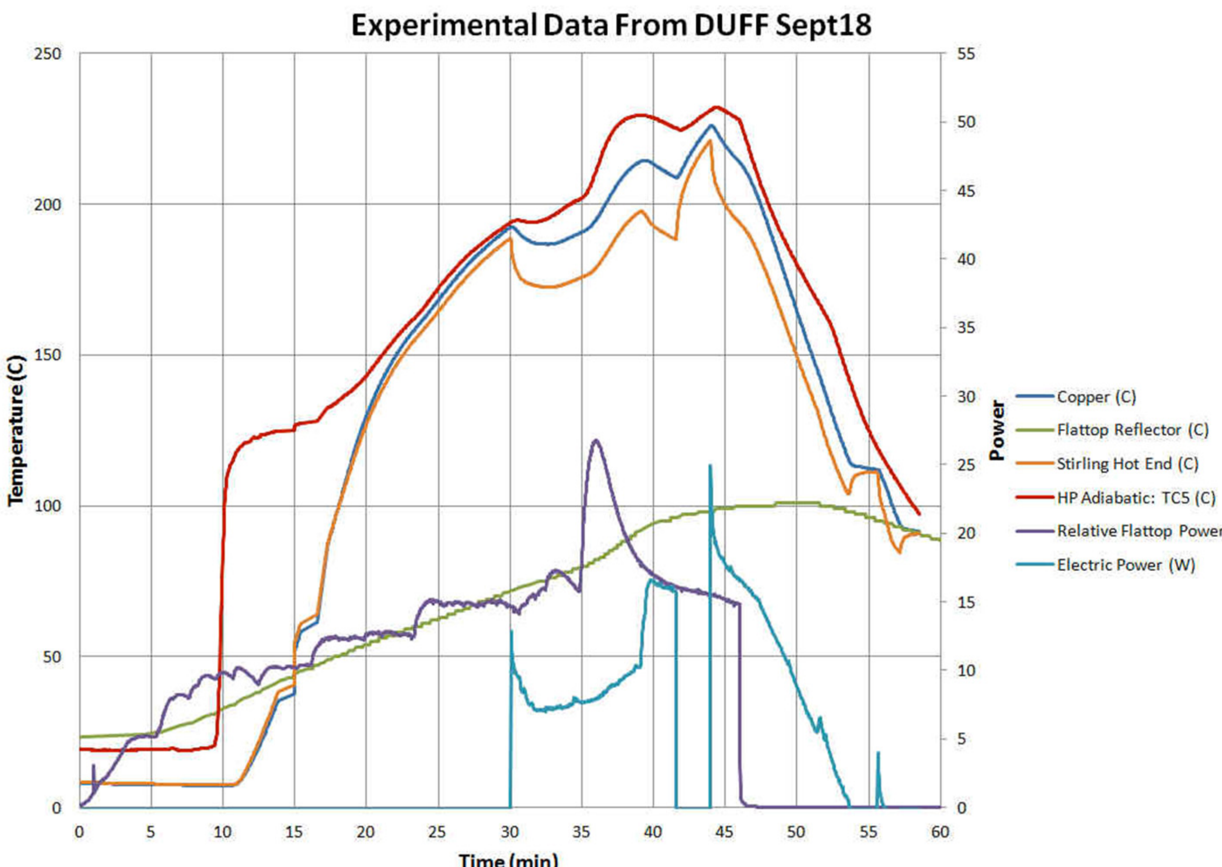
Tuesday, Sept. 18th 11:30 am PDT – Second Run of DUFF

- **T=0 min:** Reactor operator inserts reactivity and slowly increases power.
- **T=2 min:** Model shows fuel temperature begin to rise, average rate of ~15C/min (.25C/sec) over next ~7 minutes.
- **T=4 min:** First sign of sensible heat any DUFF thermocouples: pedestal/reflector thermocouple.
- **T=8 min:** Reactor operator levels off power at ~2 kWt, holds power with small reactivity insertions over next 8 minutes.
- **T=9 min:** Heat pipe kicks and starts cooling core and heating Stirling. Model shows peak fuel temp currently ~140 C.
- **T=16 min:** Operator begins series of insertions to increase fission power from 2 to 3.5 kWt over next ~20 min.
- **T=22 min:** The temperature of heat pipe and the Stirlings converge; i.e. heat flux from the heat pipe has fully soaked the thermal inertia of the copper block and Stirling – all components at ~160 C.
- **T=22+ min:** Over the next 8 minutes, the core temperature continues to increase due to fission power – the HP and Stirling track the core temperature increase in tandem, at rate of ~5 C/min
- **T=30 min:** Stirling engine technician starts the engine at a reduced engine stroke (a lower power setting) at a hot head temperature of 180 C, the electric power output is 13 Watts.

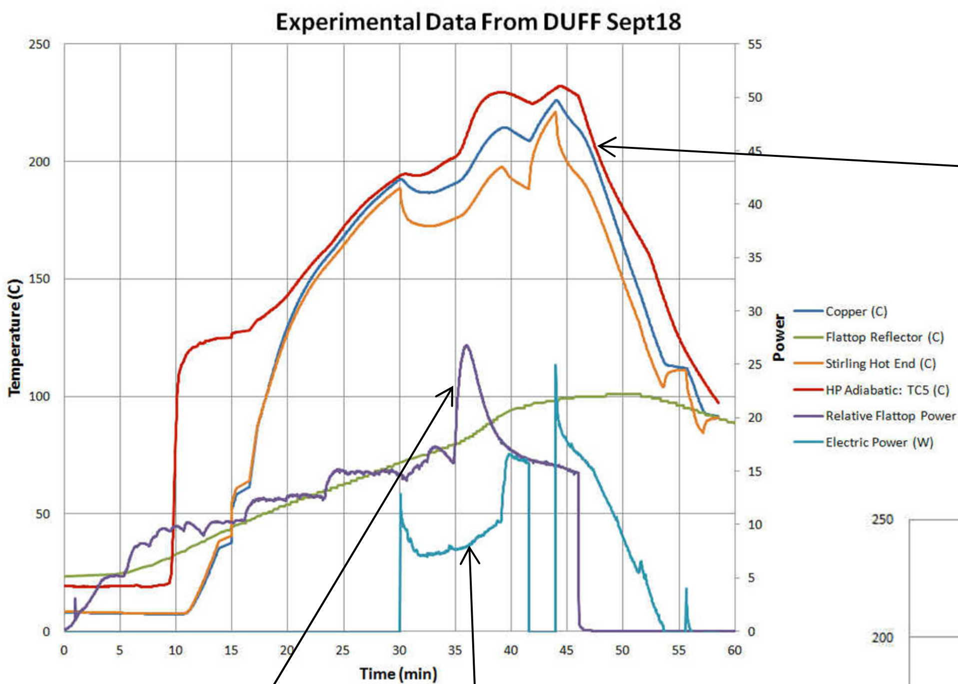


Tuesday, Sept. 18th 11:30 am PDT – Second Run of DUFF

- **T=31 min:** The power draw from the engine quickly cools the hot head of the Stirling and the power level drops to a ~steady state value of ~7 Watts.
- **T=32 min:** Over the next 8 minutes electric power tracks increases in power and temperature, from 7 W to 11 W.
- **T=35 min:** Reactor operator inserts a large final reactivity insertion, bringing peak fission power to ~5.5 kWt.
- **T=36+ min:** Reactor power quickly drops due to negative temperature feedback, from 5.5 kWt to ~3 kWt in 5 minutes.
- **T=39 min:** Stirling technician increases stroke of the engine causing electric output to increase from 11 W to 17 W.
- **T=42 min:** Stirling technician stops engine. Engine hot end temperature increases from 185 C to 225 C.
- **T=44 min:** Stirling technician restarts engine. Reconfirms electric power of 24 Watts at same 225 C as Sept 13 run.
- **T=46 min:** Flattop scrammed (fission power to ~zero).
- **T=46+ min:** Stirling draws power from stored energy and decay heat for ~5 minutes.
- **T=54 min:** Stirling engine stalls when temperature hits ~115 C. Entire DUFF apparatus cools slowly from there.
- **T=56 min:** Stirling gets warm enough for last gasp.



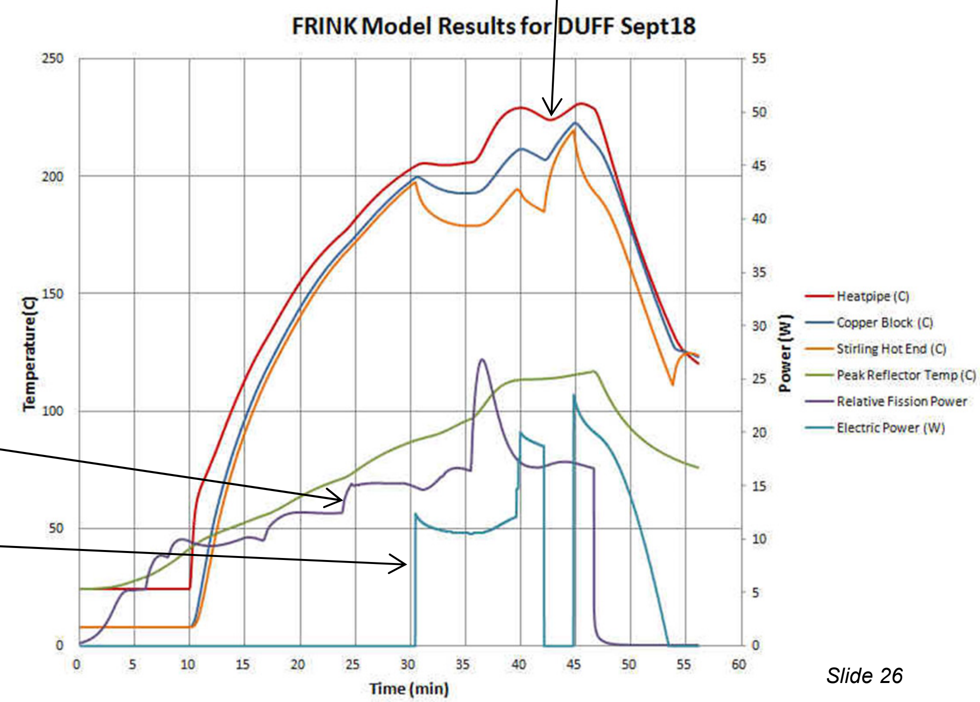
Sept 18th Test Results Compared with System Model



Power Conversion System Temperatures

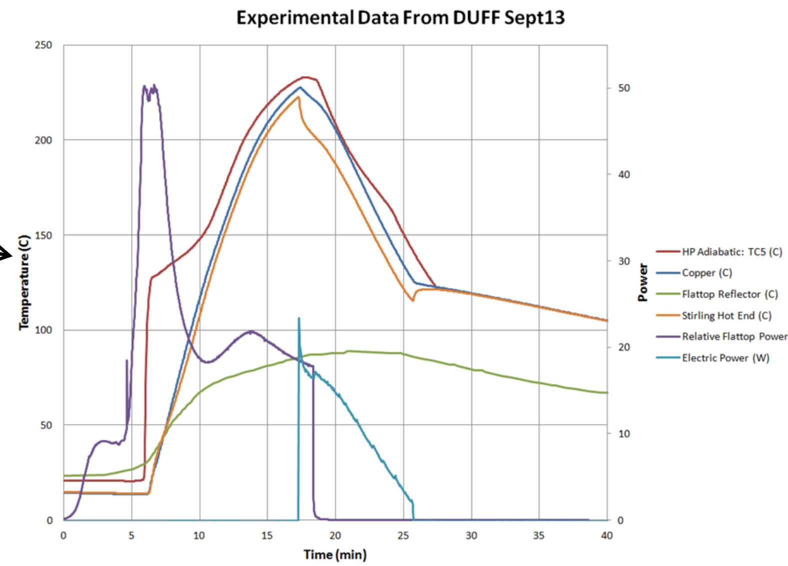
Relative Reactor Thermal Power

Electric Power

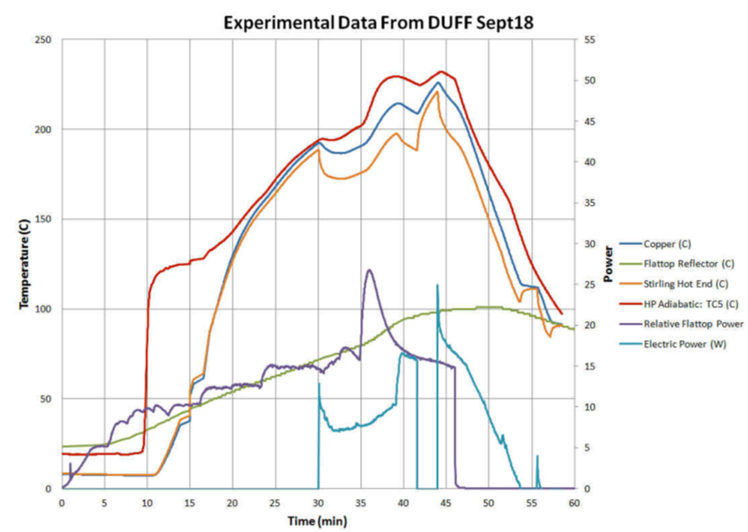


Summary of DUFF Results

- **1st DUFF Test: Sept 13th, 2012**
  - Goal: Produce electricity and light the LED panel.
  - Result: Produced peak power of 24 Watts. Reactor scrammed shortly thereafter, and power decreased as reactor cooled down.



- **2nd DUFF Test: Sept 18th, 2012**
  - Goal: Create data pertaining to transient response, and if possible, demonstrate reproducibility of power/temps in Test 1.
  - Result: Successfully increased convertor power and then cycled it off and on. Recreated 24 W at same temperatures. Twenty minutes of Stirling operation.



Value of Experiment

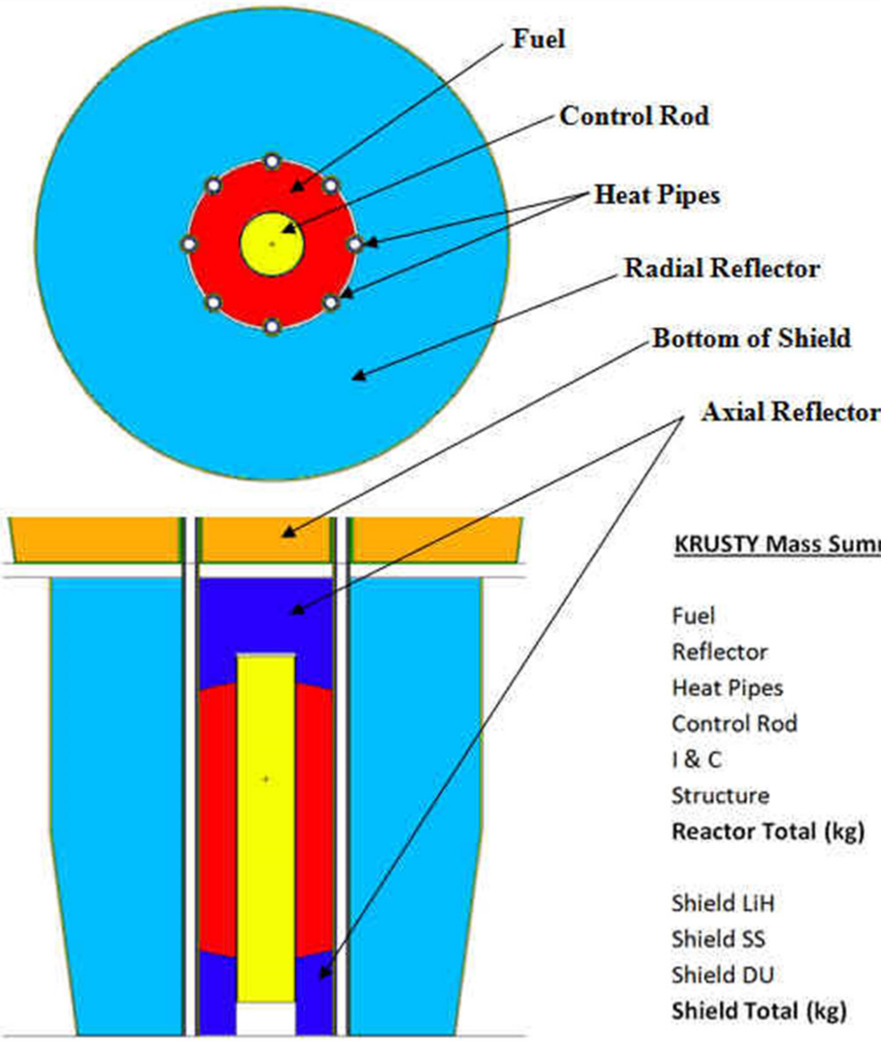
- The nuclear demonstration accomplishes many firsts:
  - First reactor power system operated at NCERC
  - First LANL reactor ever to produce electricity
  - First nuclear space power demonstration to operate in almost half a century
    - First for DOE since it was formed
  - First heat pipe power reactor of any size
  - First reactor power system using Stirling conversion
- Demonstration of basic reactor physics for simple space power system
- Benchmarking of MCNP and system modeling tool (FRINK.)
- Provided basis for follow-on project to develop a simple low power space reactor

Long-Term Programmatic Value

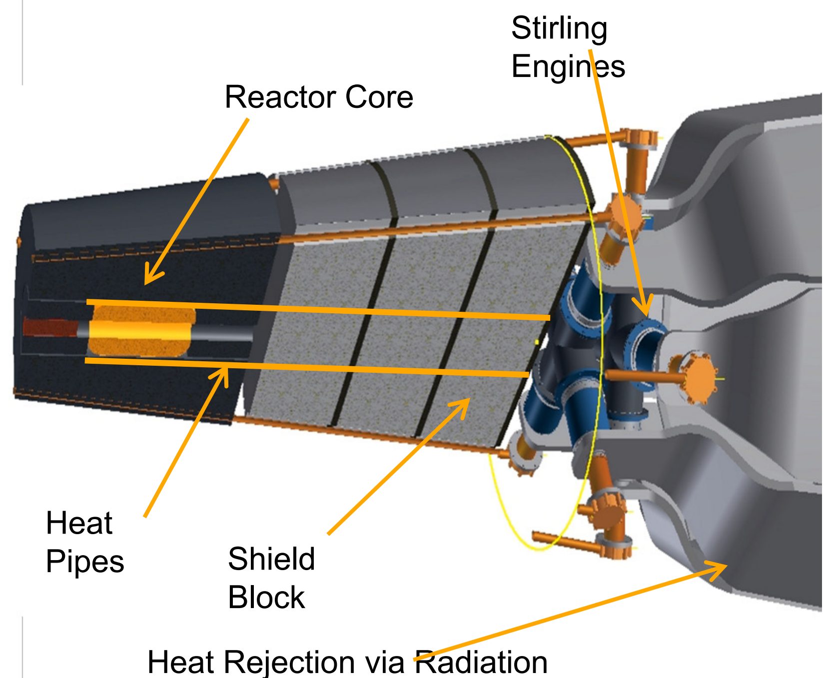
- Demonstration and/or launch of *any* reactor system provides a basis for expanding to larger, more ambitious systems
  - Four light bulbs at EBR-I (first electricity-producing power plant) led to current commercial nuclear industry
  - The truly enabling value of space reactors lies at much higher powers
- Development of capability for nuclear prototype testing for future reactor concepts in Nevada
  - Taking baby steps is seen as a path to developing capability
    - Small reactor concepts to larger concepts
      - Develops expertise
      - Builds confidence
      - Regulatory limits pushed incrementally
  - Must exercise care, however, to avoid establishing ground demonstration as a prerequisite for all larger-scale missions
    - Conventional ground nuclear tests for large systems would require specialized, expensive facilities

Latest Design…

Kilowatt Reactor Using Stirling TechnologY (KRUSTY)



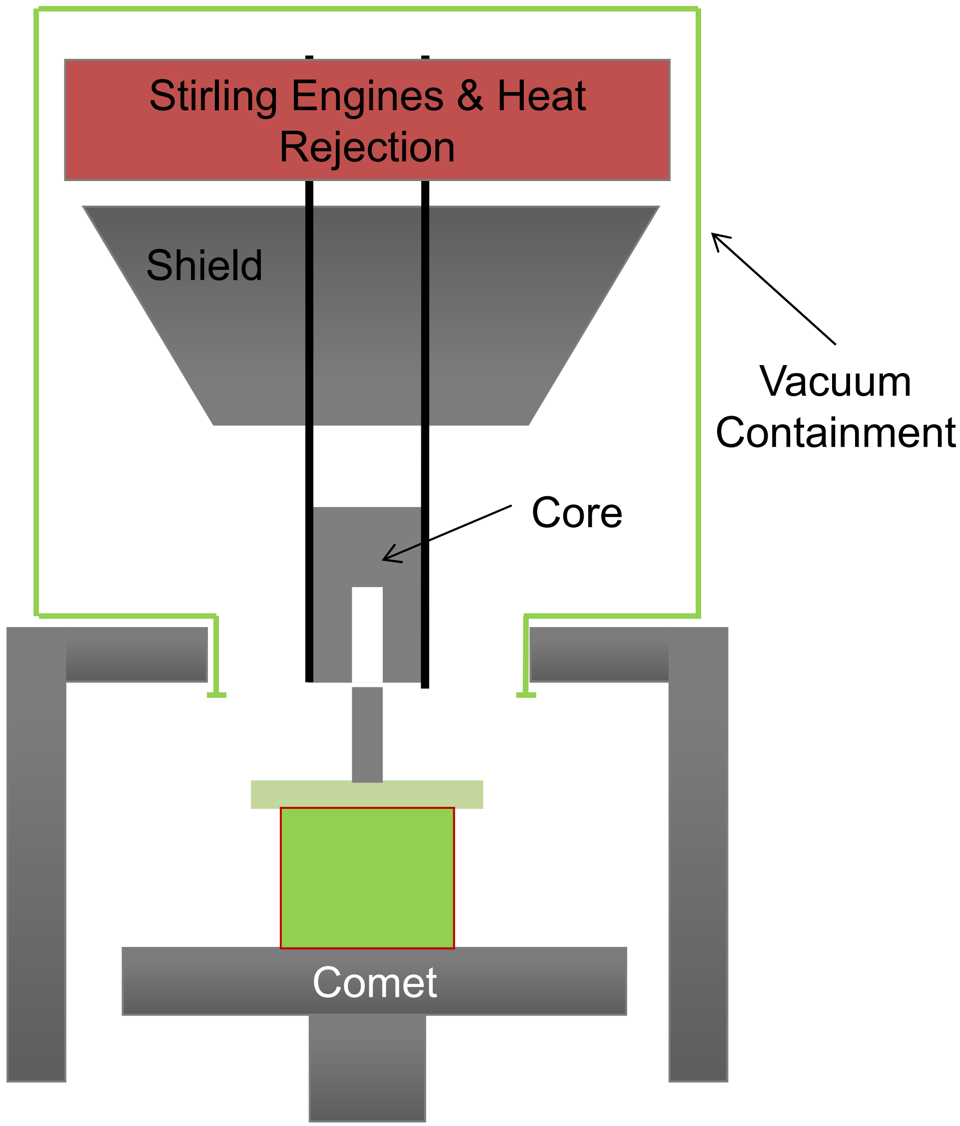
FY14 NASA Project = KiloPower



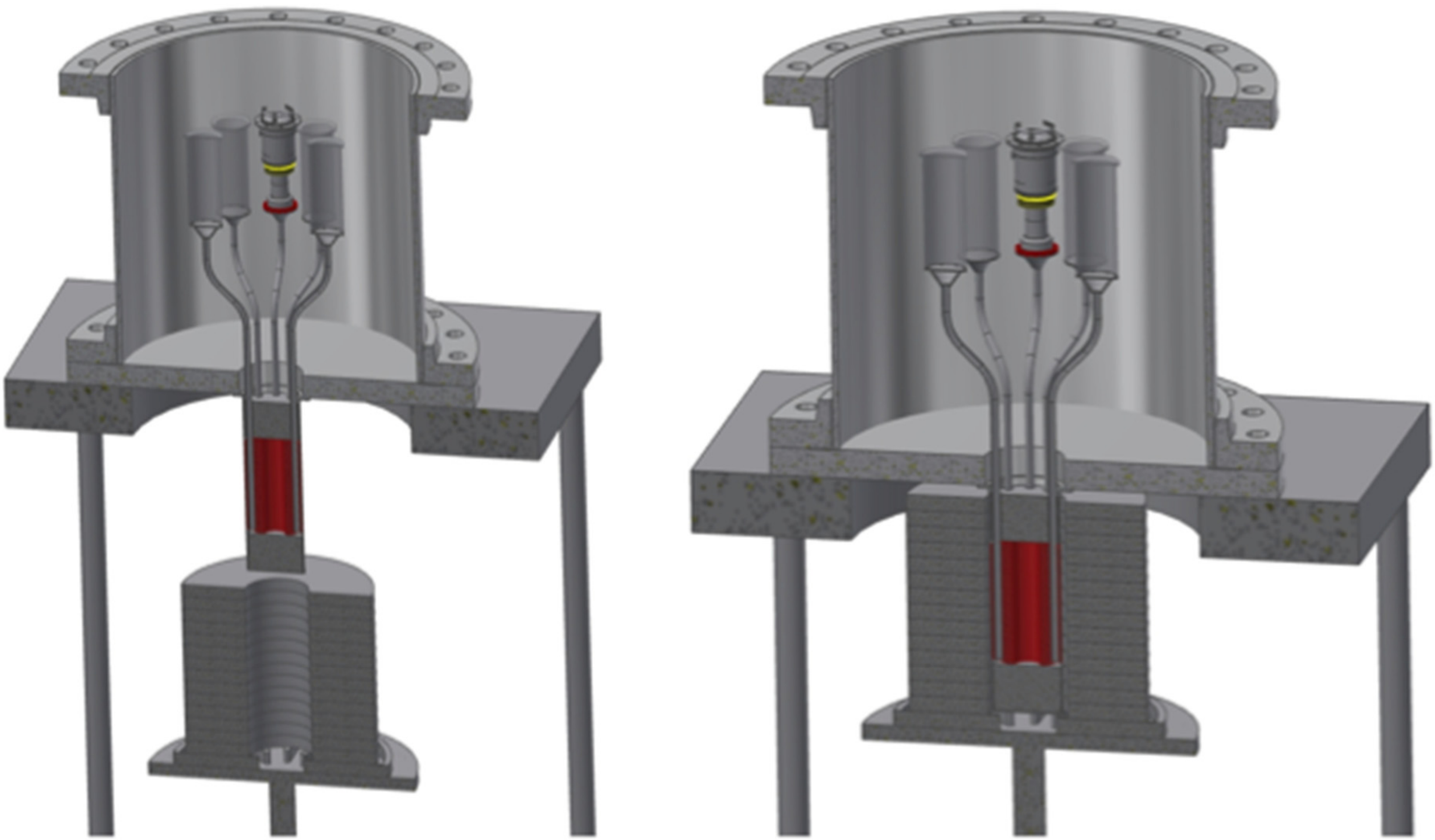
KRUSTY Mass Summary (kg)

Fuel	26.7
Reflector	70.5
Heat Pipes	4.1
Control Rod	0.8
I & C	10.0
Structure	10.0
Reactor Total (kg)	**122.1**
Shield LiH	40.4
Shield SS	13.0
Shield DU	45.3
Shield Total (kg)	**98.7**

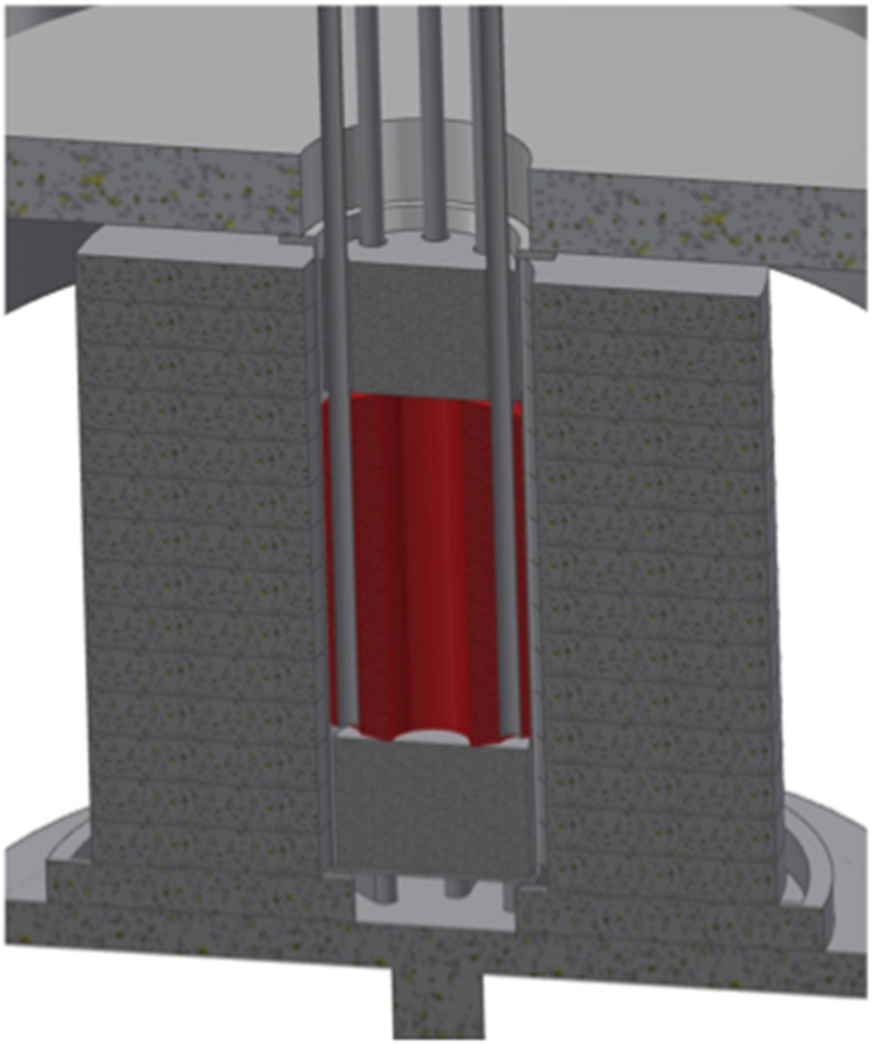
What Next – DUFF II aka Krusty



KRUSTY Update



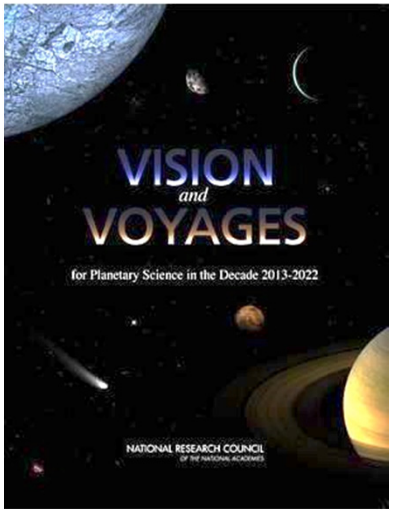
KRUSTY cont'd



- Axial Reflectors in vacuum core can
- Core to have MLI all around
- Core O.D. can have air flow with bottom wagon wheel spacer
- Convertor mounting to center core and can (not shown)
- Assembly:
    1. Convertors, heat pipes, and structure mounted in vacuum vessel on Comet
    2. Slide upper axial reflector over heat pipes
    3. Slide Core up heat pipes, clamp, and attach MLI
    4. Core can with lower axial reflector slides up and bolts to vacuum vessel

Small Fission Power

- Small Fission Systems are recognized as an important capability to fulfilling NASA's Strategic Goals
  - NRC Planetary Science Decadal Survey evaluated small fission power feasibility in 2010
  - NRC Review of NASA Technology Roadmaps identified fission power generation as 1 of 16 high priority technologies
  - NASA Technology Executive Council (NTEC) endorsed recommendation to specify small fission as focus area for near-term technology investment

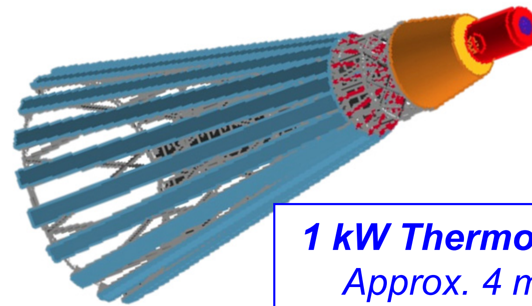


- Kilopower technology development project aims to advance technology readiness of small fission systems from TRL 3 to 5
  - Build on successful DUFF Proof-of-Concept test performed at Nevada Test Site in 2012
  - Objective is to design and build a breadboard power system with a prototype Uranium-235 reactor core coupled to two ASRG-derived Stirling convertors for a nuclear-heated technology validation test
  - 3 year, $10M project with anticipated cost sharing between SMD and STMD

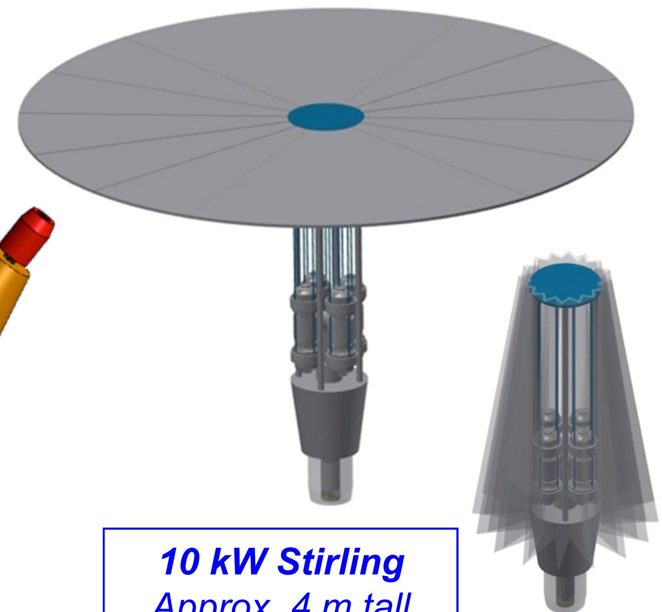
- Availability of Kilopower technology addresses gap in agency power technology portfolio to support future SMD, STMD, and HEOMD missions
  - Near-term technology funding provides technology push for next Decadal Survey and Human precursor mission consideration

Kilopower Concepts Family

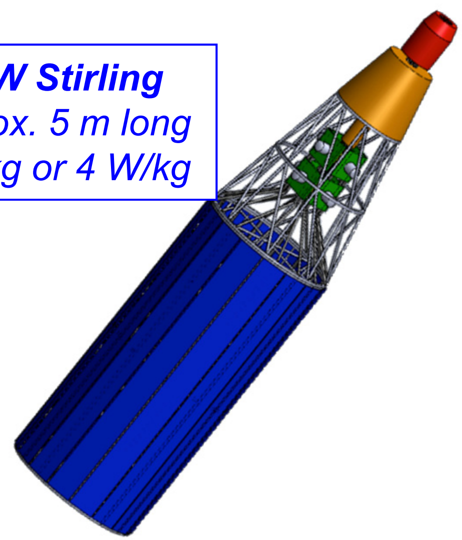
- Common Design Features include:
  - 0.5 to 10 kWe; >10 year design life
  - Utilize available UMo reactor fuel from DOE
  - Minimize thermal power to simplify reactor design and control
  - Incorporate passive Na heat pipes for reactor heat transport
  - Leverage power conversion technologies from RPS Program (TE, Stirling)
  - Design system so that it can be tested in existing DOE nuclear facilities



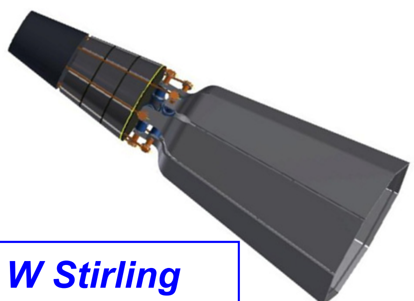
1 kW Thermoelectric
Approx. 4 m long
600 kg or 1.7 W/kg



10 kW Stirling
Approx. 4 m tall
2000 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

Why Now?

- **Science missions are seeking greater power and functionality**
  - Several Decadal Survey mission studies identified kilowatt-class Nuclear Electric Propulsion (NEP) as enabling; benefits include launch flexibility, expanded science orbits, and multiple mission targets
  - More power = more capable instruments, increased instrument duty cycles, onboard scientific analysis, higher data-rate communications, smaller antennas

- **A long-life, uninterruptible, and environment-tolerant power source is needed for exploration precursors**
  - Collecting site engineering data needed to design crew systems
  - Conducting in-situ resource utilization experiments
  - Establishing communication networks for Earth-based tele-operations
  - Powering remote science packages that relay geologic and climatologic data
  - Recharging battery-powered rovers that perform site reconnaissance

- **Radioisotope Pu-238 fuel supply is very limited**
  - NRC Decadal Survey Report: "The committee is alarmed at the status of Pu-238 availability for planetary exploration. Without a restart of Pu-238 production, it will be impossible for the United States, or any other country, to conduct certain important types of planetary missions after this decade."
  - U.S. Pu-238 stockpiles are low and production restart has just begun
  - Even with new production, high-power mission fuel demand may exceed supply

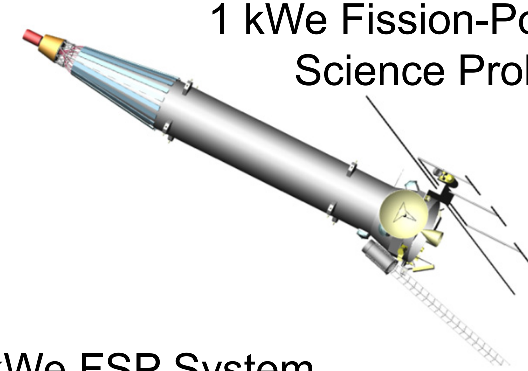
Projected NASA Applications for Fission Power Systems

1. **Planetary/Space Science**
   - <1 to 10 kWe
   - 10 to 20 yr life
   - Unmanned, Autonomous
   - Low Mass; Competitive with RTGs
   - Non-Obtrusive; Shouldn't interfere with Science Objectives

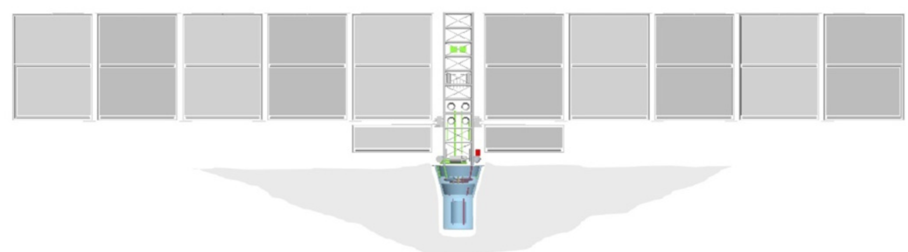
2. **Fission Surface Power (FSP)**
   - 10 to 100 kWe
   - 5 to 10 yr Life
   - Human-rated
   - Robust and Reliable; Mass is Secondary
   - Adaptable to Multiple Missions and Environments

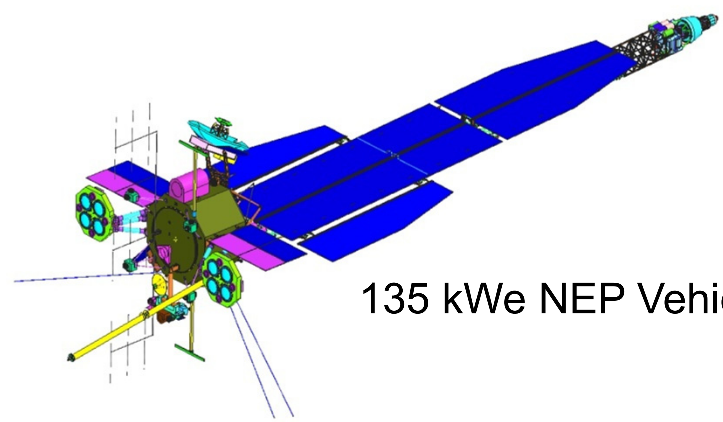
3. **Nuclear Electric Propulsion (NEP)**
   - 100 kWe to Several MWe's
   - 5 to 15 yr Life
   - Cargo or Piloted Missions to Mars
   - Low Specific Mass (kg/kW); Must provide benefits over SEP
   - Flexible Operations: Thrust, Coast, Science, Standby

1 kWe Fission-Powered Science Probe



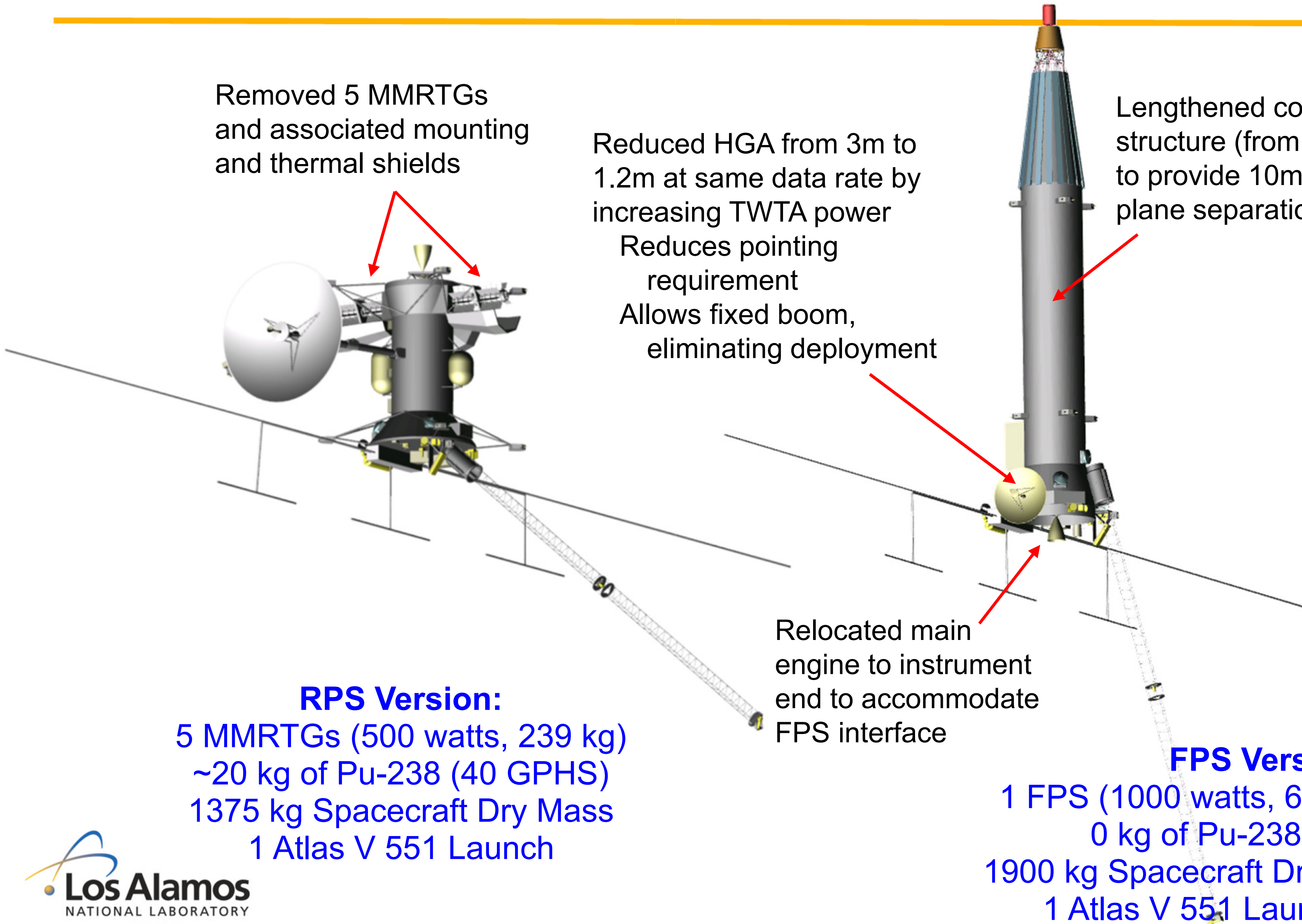
40 kWe FSP System





135 kWe NEP Vehicle

Jupiter Europa Orbiter

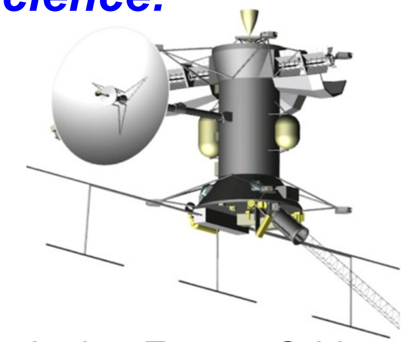


RPS Version:
5 MMRTGs (500 watts, 239 kg)
~20 kg of Pu-238 (40 GPHS)
1375 kg Spacecraft Dry Mass
1 Atlas V 551 Launch

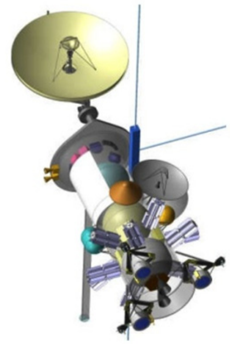
FPS Version:
1 FPS (1000 watts, 604 kg)
0 kg of Pu-238
1900 kg Spacecraft Dry Mass
1 Atlas V 551 Launch

Mission Pull: Space exploration and dominance

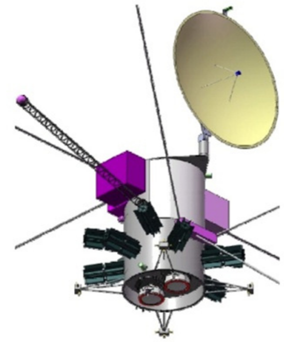
Science:



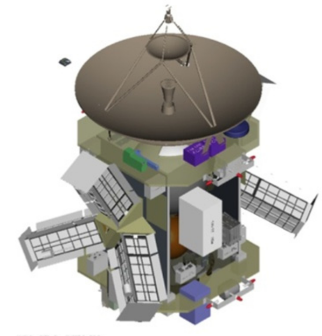
Jupiter Europa Orbiter
~600 We (5 to 6 RPS)



Neptune Systems Explorer
~3 kWe (9 Large RPS)



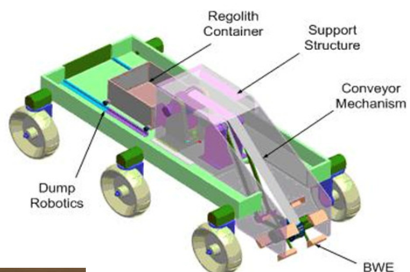
Kuiper Belt Object Orbiter
~4 kWe (9 Large RPS)

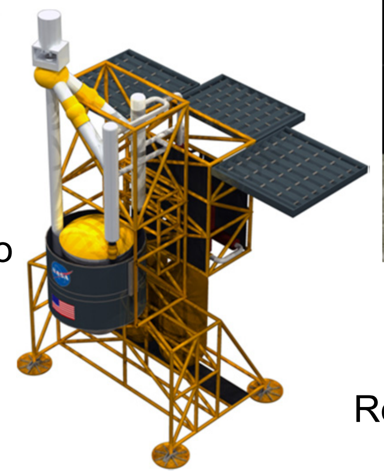


Trojan Tour ~800 We (6 RPS)

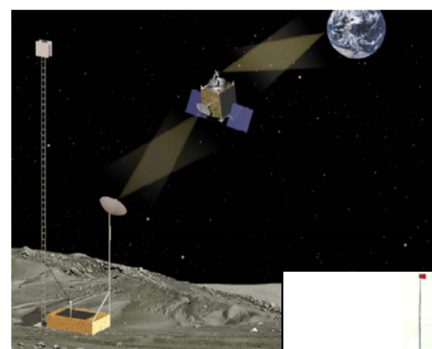
Exploration:

Teleoperated Rovers

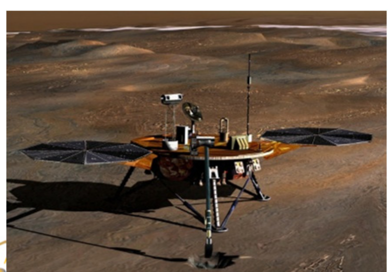




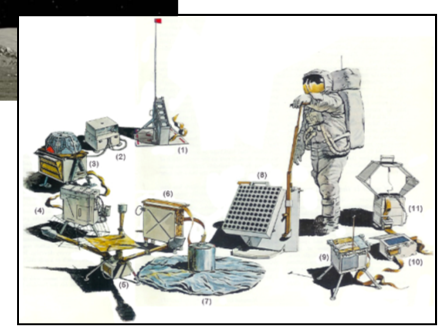
ISRU Demo Plants



Comm Relay Stations



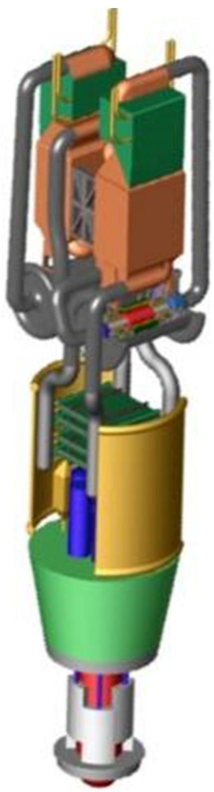
Site Survey Landers



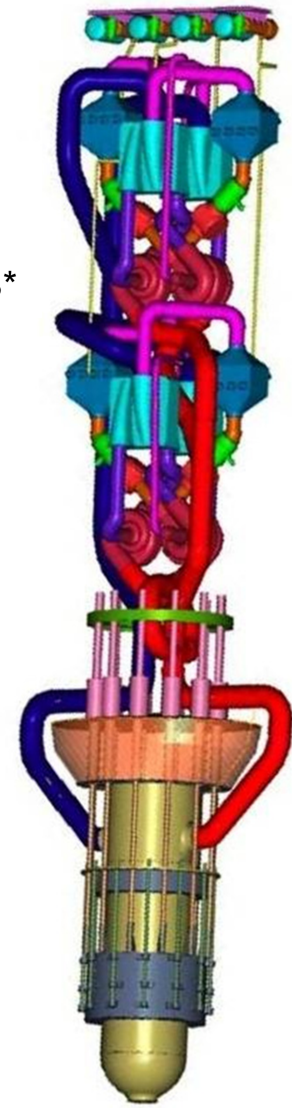
Remote Science Packages

Design Simplicity… An ideal 1st Step in Space Reactor Technology

Initial JIMO Concept
UN/Li-cooled/Brayton
135 kWe, 10 yrs & $2-3B*



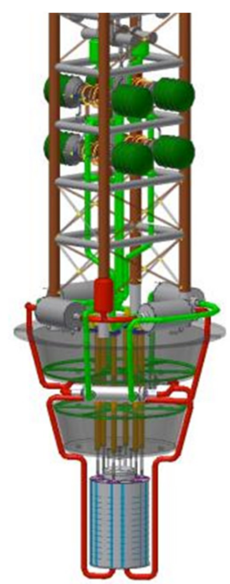
5 m



9 m

Final JIMO Concept
UO2/Gas-cooled/Brayton
200 kWe, 10 yrs & $3-5B*

Fission Surface Power
UO2/NaK-cooled/Stirling
40 kWe, 8 yrs & $0.8-1B*



4 m

Kilopower
U-Metal/Na HP/
Stirling
1 kWe, 8 yrs &
$300-500M*

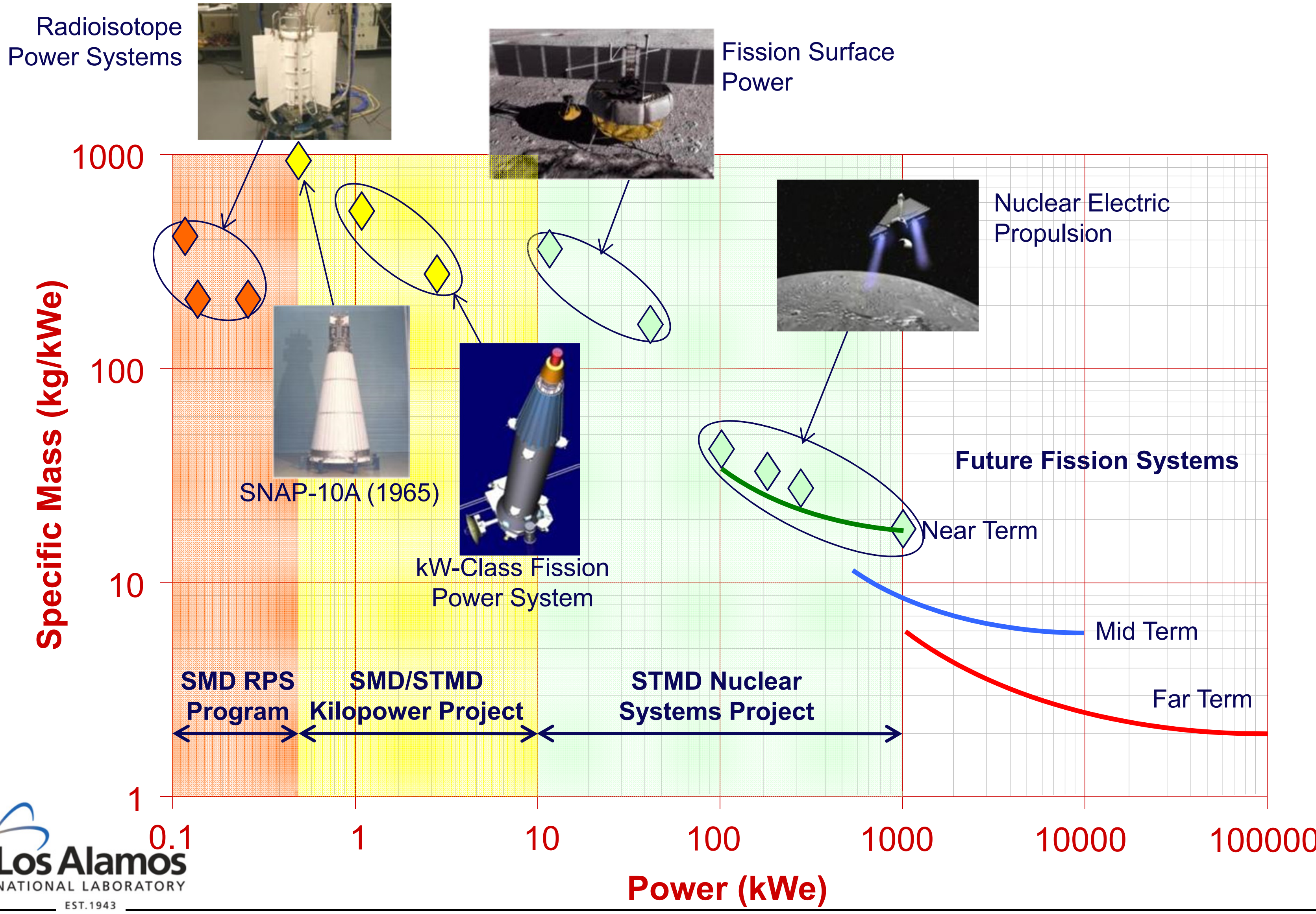
1 m

ASRG
Pu-238/GPHS/
Stirling
140 We, 8 yrs &
$250M*

1 m

* Costs reported are ROM estimates for power system DDT&E

Kilopower Fills Gap in Nuclear Portfolio



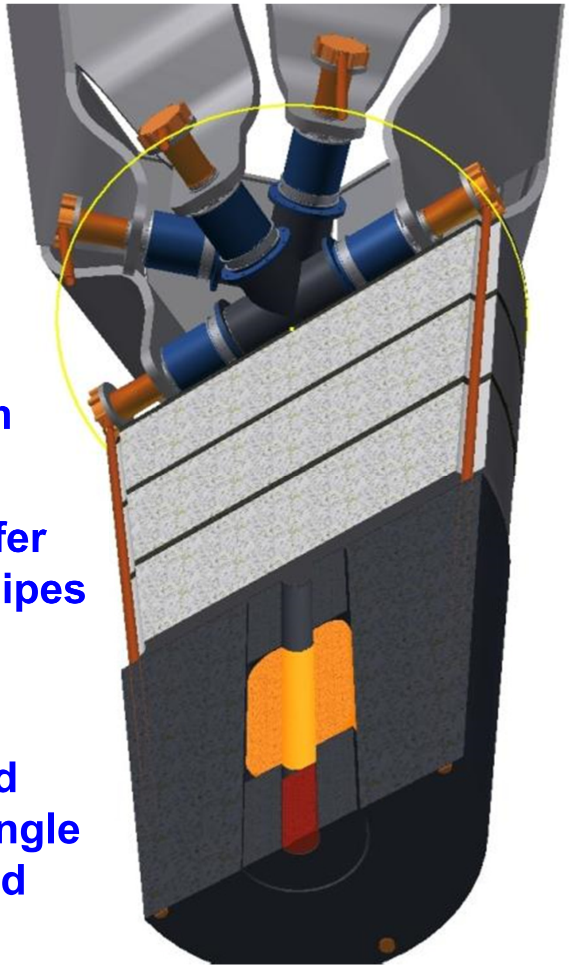
Even Smaller and Simpler…

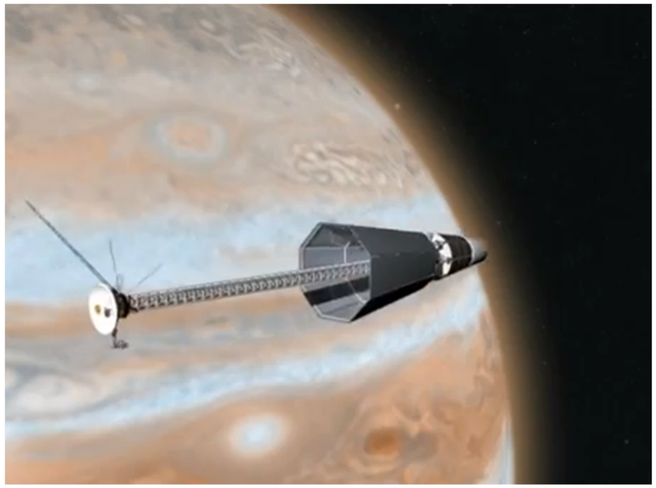
Radial Core Heat Spreaders and Ti-H2O Heat Pipe Radiators

Advanced Stirling Convertors from ASRG Flight System

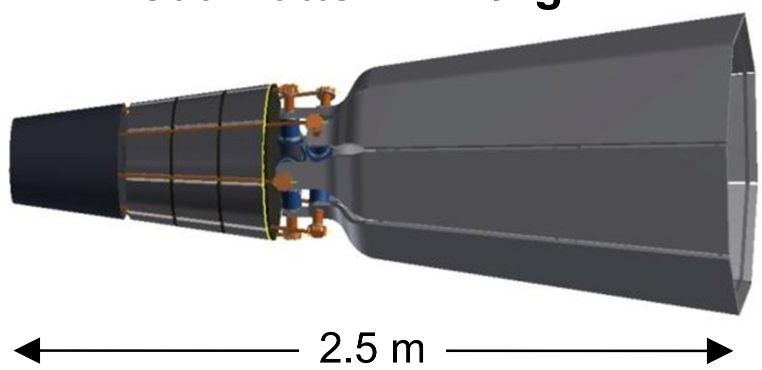
Reactor Heat Transfer via Ex-core Na Heat Pipes in Be Reflector

Highly-Enriched U-235 Core and Single B4C Control Rod



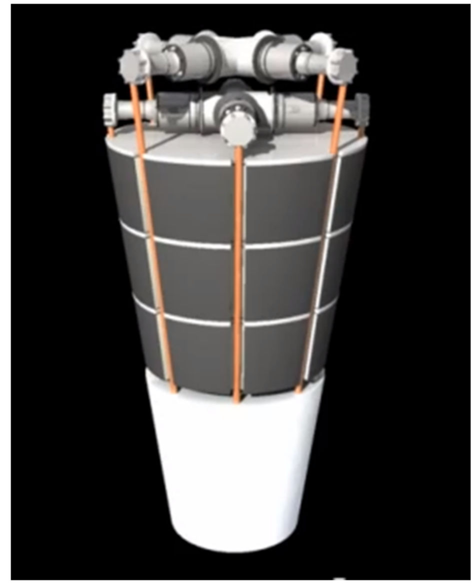


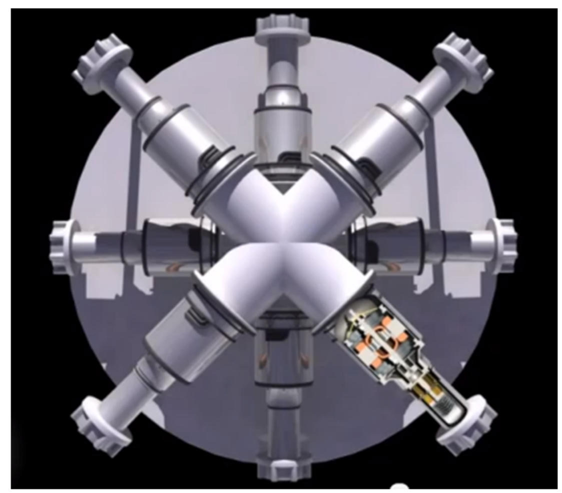
800 watts – 2 W/kg



Kilopower Mission Benefits

- **10X power increase over current RPS**
  - Enables kilowatt-class deep space nuclear missions
  - Technology is extensible from kilowatts to megawatts
- **Simplified launch and mission operations**
  - Launched cold with essentially no radioactive hazards
  - Single control action required for reactor startup after orbit insertion
  - Inherent thermal load following (reactivity feedback) provides fault tolerance; little or no power degradation over mission life
- **High projected reliability and fault tolerance**
  - Well-characterized fuel operated within established limits
  - Highly-redundant heat transport and power conversion
  - Low reactor power to reduce stresses and assure tolerance to potential transients
  - Low fuel burnup to minimize radiation effects on reactor materials and spacecraft equipment
- **Single, optimized power source rather than large number of low power units**
  - Less complex spacecraft integration and operations
  - Easier accommodation of science instruments (body mounting, field of view, etc)
- **Reduced dependence on limited Pu-238 fuel supply**
  - Up to 28 kg of Pu-238 required per kWe of spacecraft power
  - Allows continued Pu-238 use for smaller missions





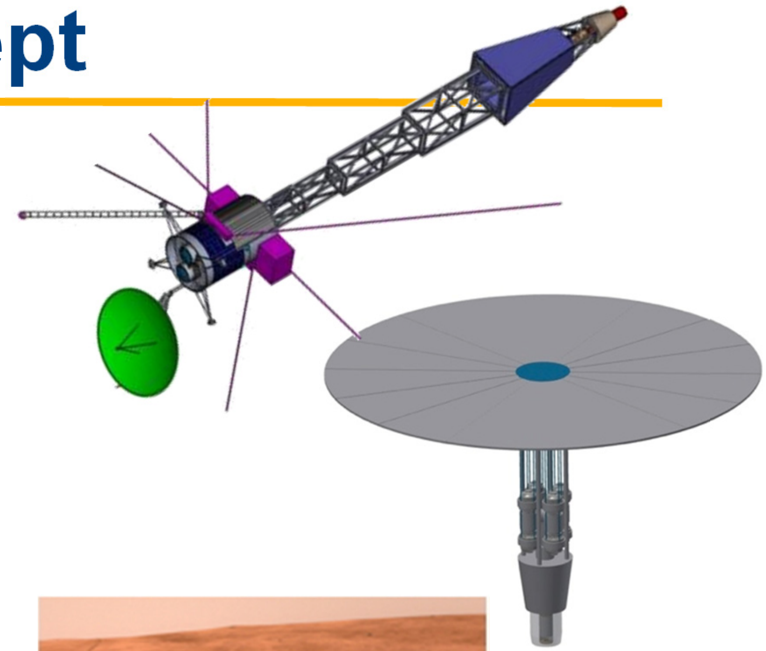
Extensive Project Leveraging

- Existing NNSA nuclear test facilities operated within current safety basis
- Available high-enrichment U235 fuel and other nuclear materials from Y-12
- Existing, benchmarked LANL reactor design codes
- Phase II SBIR with Advanced Cooling Technologies for Kilopower-specific Na heat pipes
- Existing Advanced Stirling Convertors and design expertise from ASRG Project
- Stirling cold-end H2O heat pipes from RPS Technology Advancement Project
- GRC heat pipe microgravity test flights from NASA Flight Opportunities Program
- Extensive MSFC experience-base in reactor thermal simulators and custom electric resistance heaters

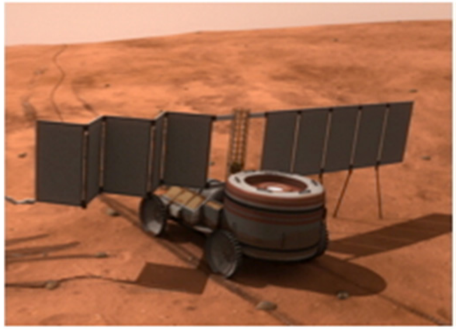
Device Assembly Facility (DAF)
Nevada Test Site

Advanced Stirling Convertor (ASC)
From ASRG Project

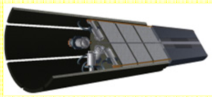
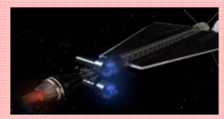
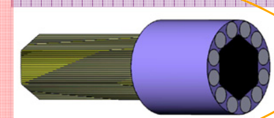
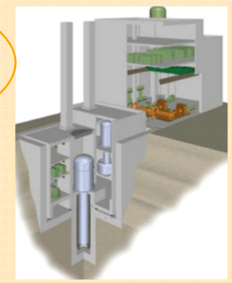
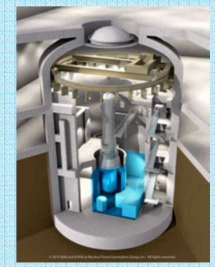
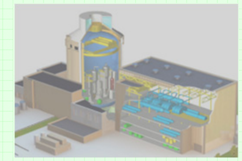
Summary of Space Concept



- The Kilopower system ***addresses a major agency-level concern*** regarding Pu-238 fuel availability
- The concept represents ***a revolutionary near-term approach*** to reducing the size and mass of space reactors while maintaining simplicity and robustness
  - Solid cast U-235 fuel form, passive heat pipe cooling, existing Stirling convertors from RPS Program
- The system design is ***readily applicable from <1 up to 10 kWe*** for robotic probes and human precursors
  - Modular design provides workhorse power unit for wide range of mission applications
  - Joint STMD/STP ***flight demonstration could be accomplished in less than 10 yrs***
- The technology is ***extensible from 10s of kilowatts to megawatts*** for human outposts, NEP cargo vehicles, and NEP piloted vehicles
  - Kilopower development will establish required design and manufacturing infrastructure, test capabilities, and launch safety protocols for all future fission power systems



Nuclear Reactors come in all sizes….

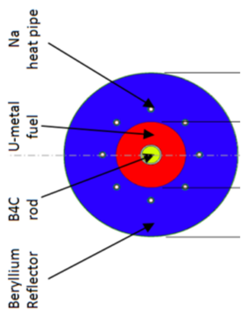
					
500 W to 10 KW Reactor Non-LWR Deep space Power	10 KW to 1MW KW Reactor Non-LWR Space propulsion Planetary surface Power Military apps (Unmanned Sub)	1 MW to 10 MW Portable Reactor Non-LWR FOB bases Remote Locations Disaster Relief	10 MW to 50 MW Small Modular Reactor Non-LWR 4S Gen 4 Power to Grid CONUS bases Process heat	50 MW to 300 MW Small Modular Reactor LWRs NuScale mPower WEC SMR Non LWRs PRISM Power to Grid CONUS bases Burn actinides	GigaWatt Commercial Nuclear Power LWR Focus AP1000 ABWR EPR Power to Grid

10^0 10^1 10^2 10^3 10^4 10^5 10^6

Power Level in Kilo-Watts Electric

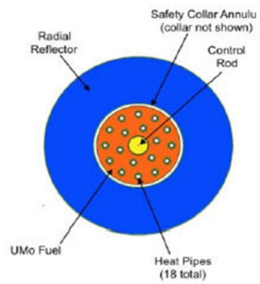
Reactor serves as basis for follow on concepts

Characteristics of LEU Fueled Heat Pipe Reactors of Increasing Size



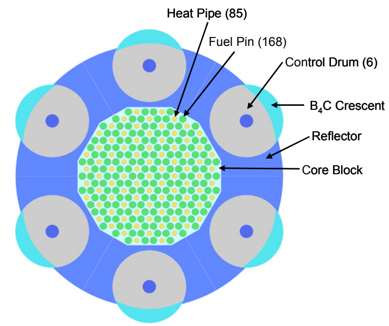
- **4 kWt**
- **1 kWe**

- Metal fuel
- 280 Kg fuel
- 660 Kg Rx Mass
- 40 cm Rx Dia
- 50 cm Rx Length
- 8 Heat Pipes



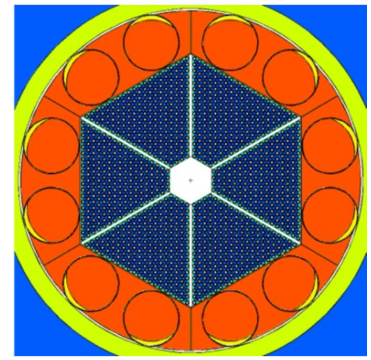
- **40 kWt**
- **10 kWe**

- Metal fuel
- 350 Kg fuel
- 800 Kg Rx Mass
- 50 cm Rx Dia
- 70 Rx Length
- 20 Heat Pipes



- **500 kWt**
- **200 kWe**

- Oxide fuel
- 600 Kg fuel
- 3000 Kg Rx Mass
- 65 cm Rx Dia
- 100 cm Rx Length
- 200 Heat Pipes



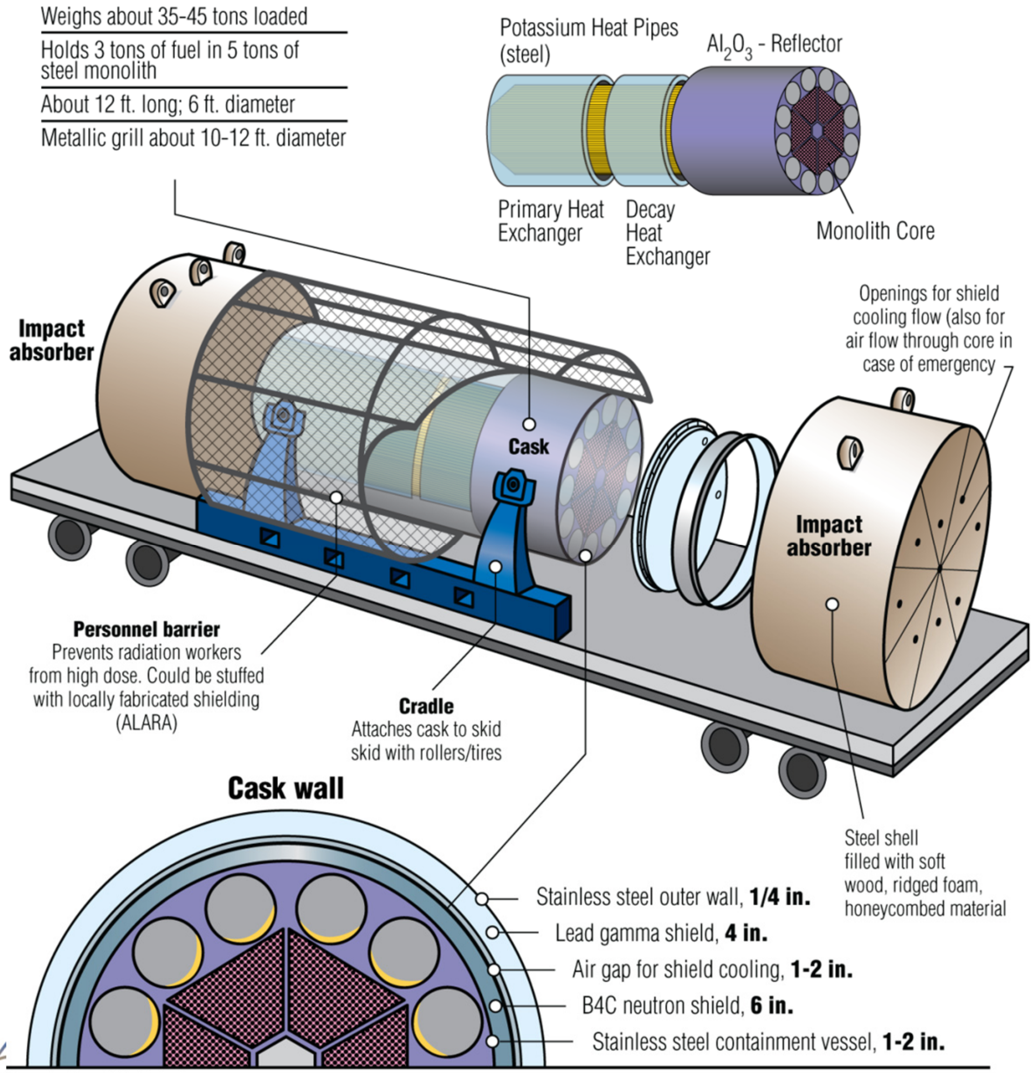
- **5 MWt**
- **2 MWe**

- Oxide fuel
- 5100 Kg fuel
- 22000 Kg Rx Mass
- 150 cm Rx Dia
- 200 cm Rx Length
- 2112 Heat Pipes

Increasing Reactor Power

MegaPower Reactor Systems

Nominal 2 MWe (5 MWth) Design



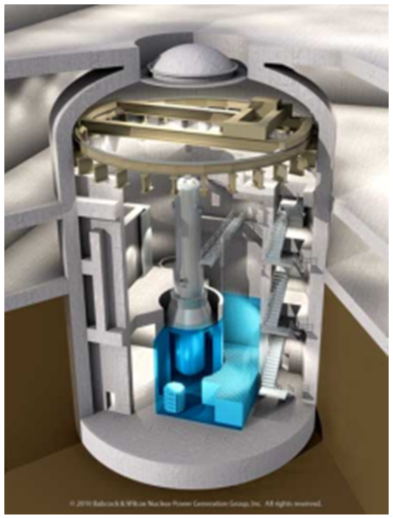
Source: Los Alamos National Laboratory

Design becomes smaller and lighter at lower power levels

Key Performance Parameters
KPP1: Seamless multi-modal transport of the fresh and used reactor system
KPP2: No significant consequences from the design basis threats
KPP3: Transportable by C-17 aircraft (Type C container)
KPP4: Installed and operating within 72 hrs.
KPP5: Shutdown, cool down, disconnect and “bug-out” in less than 7 days (‘should not be long-pole in the tent’)
KPP6: Capable of immediate shutdown and passive cooling
KPP7: No significant increase in risk to the military personnel or to the environment
KPP8: Greater than 2-year refueling
KPP9: Minimal proliferation risk
KPP10: Design scalable to 10 MWe

Much Smaller Than Commercial SMR

Current Small Modular Reactor



(Facility covering 10's of acres)

- 200 MW electric (City)
- Large industrial stationary facility
- High pressure light water cooled
- Large concrete containments
- LEU fuel (4.5% enriched)

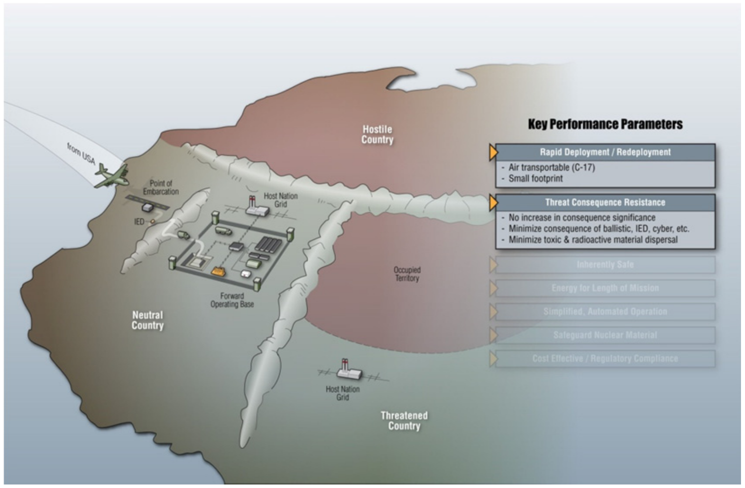
Proposed Small Special Purpose Reactor

(Transportable by truck or air)

- 2 MW electric (DoD Base)
- Transportable by truck or air
- Heat pipe cooled (no water)
- No moving parts or high pressure
- LEU fuel (16-19% enriched)

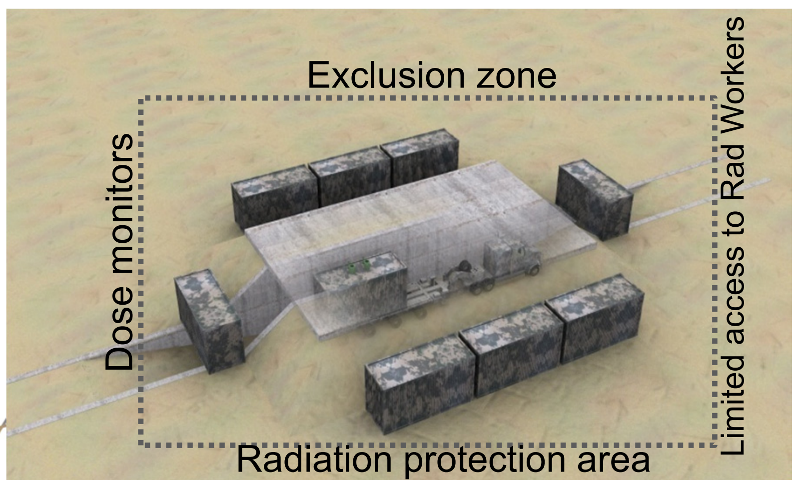
Concept of Operations: Transport to Theater & FOB

Fly reactor to theater

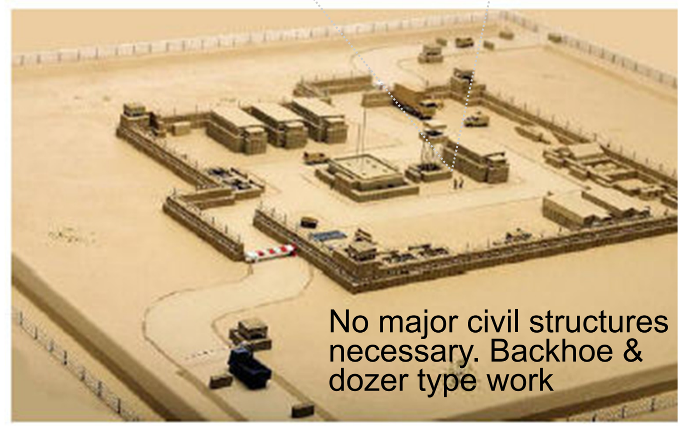


Transport by truck to the base

Protect by earth, barriers, & water jackets



Integrate into the base



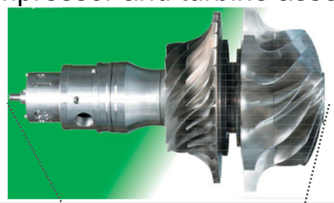
“Plug-and-Play”into Electric Distribution Network

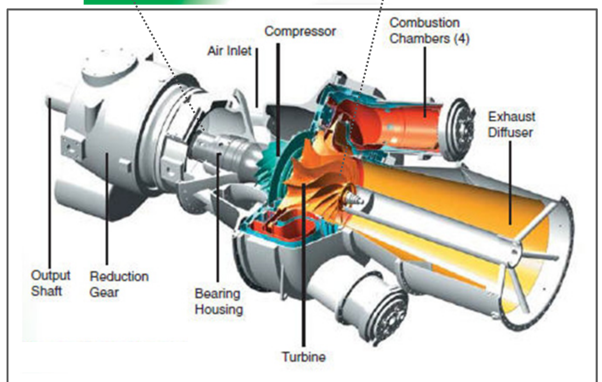
On-site operator connects the turbine to the reactor heated-air outlet and on-the-fly^ realigns gas-turbine to reactor-mode!

Enduring bases are powered by diesel generators with gas-turbine technologies.

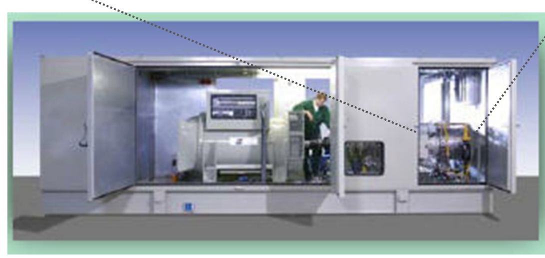
^ OTF operation detail: Gas turbines can be designed *a priori* to switch operational mode from internal combustion to heated air Brayton cycle. This will enable on-the-fly switchover.

compressor and turbine assembly





Enlarged view of the gas-turbine



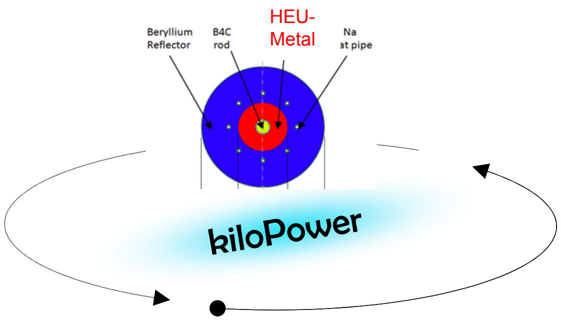
No major changes would be necessary to the generator, regulator and the PLC.

No changes to the base switch-gear or distribution network.

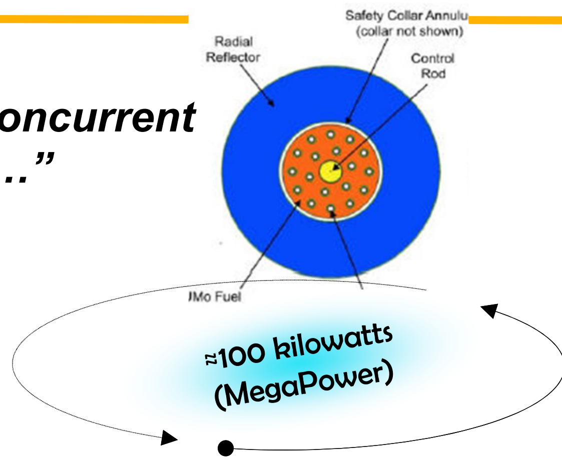
ConOps

Leverage Non-DoD Investments

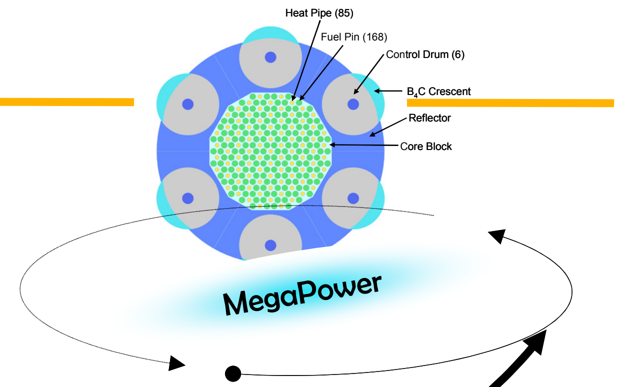
"...incremental upgrades concurrent with emerging technology..."



Spiral 0, 2012-15



Spiral 1, 2015-18



Spiral 2, 2018-20

<u>Spiral 0</u>
- Space reactor
- Proof-of-Principle (uranium metal at low temperature) – Completed Sept, 2012
- Proof-of-Concept (U metal alloy @ Temperature)
- Prototype Construction, Technology Demonstration

<u>Spiral 1</u>
- Space or DoD Reactor
- Systems Engineering Study
- Principles of self-regulation for larger power systems
- Build and test nuclear and non-nuclear engineering demonstration unit

<u>Spiral 2</u>
- Scale design for a FOB
- Systems Engineering Study
- Team with technology providers for power conversion system
- Build and test nuclear and non-nuclear engineering demonstration unit