Nuclear Power Systems: Enabling Space Exploration

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Space Nuclear Systems & Technology Division

July 12, 2011

Our Plan for Today

- Introductions
- Background
  - Space Exploration – Why? What do we need to make it happen?
  - Radioisotope Power Systems (RPS) or “Space Batteries”
    - RPS Training Module – Hands-On!
  - Fission Power Systems
- What INL Does
  - Space Batteries: Assembly, Testing, Transport and Integration of RPS to Spacecraft
    - Pluto New Horizons Mission
    - Mars Science Laboratory Mission
  - Fission system design and component development
- Questions

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Who Am I?

- Shannon Bragg-Sitton
  - Senior Nuclear Engineer in the Space Nuclear Systems and Technologies Division
  - Basically, I'm a Nuclear Rocket Scientist
  - MS & PhD (Nuclear Engineering), University of Michigan
  - MS (Medical Physics), Univ of Texas Biomedical Sciences
  - BS (Nuclear Engineering), Texas A&
  - Previously worked at…
    - Texas A&M University (Assistant Pr
    - NASA Marshall Space Flight Center
    - Los Alamos National Laboratory (d
  - So, what do I do in my free time??
    - Wife
    - Mom of 3
    - Traveller

Space Travel: What's So Compelling?

- Spirit of exploration
- Allows us to contribute to our understanding of our world – the laws of physics
- Provides new areas for "expansion"
- Various military, commercial and research endeavors

All of these motivations lead to a wide variety of mission purpose, destination, lifetime, physical footprint, mass, power needs, etc.

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“Features” of Space Systems…

- Unique
- Lightweight
- Reliable
- Robust
- Power efficient
- Rooted in the heritage of past successes

Space systems are therefore driven to…

- Meet broad requirements
- Small quantity procurements
- Use relevant technologies that rapidly change
- Expensive
  - High launch costs (large fraction of the payload costs)
  - High retrieval / repair costs

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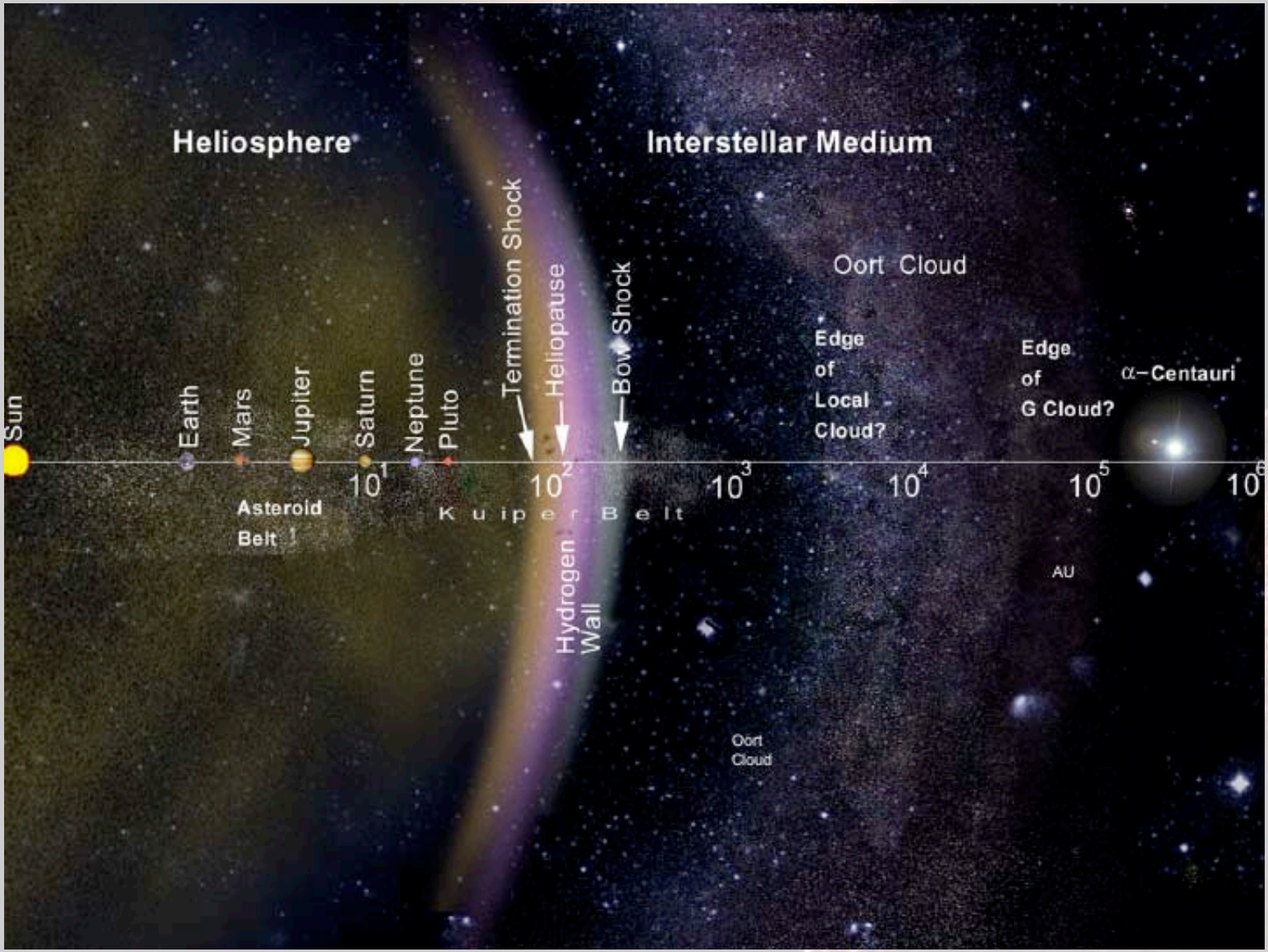
Planetary Science is the Discovery and Exploration of Our Neighborhood in Space

The Ultimate Goals Lead To the Edge of the Solar System and Beyond



Graphic from the Interstellar Probe Science and Technology Definition Team NASA/JPL

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Space Travel, Space Exploration and Space Science Require **Power**

Electrical Energy Needs in Space

Mission / Requirements

- Where is it going?
- How much power is needed to get there, and what will be required at the destination?
- Is it a manned or a robotic mission?
- What kind of science activities are planned?

- Near Earth missions
- Unmanned missions to solar system
- Manned missions to solar system
- Unmanned missions out of the solar system

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Electrical Energy Needs in Space: Solutions

- Chemical
- Solar
- Nuclear
  - Radioisotope
  - Fission
  - Other “advanced” systems
    (low Technical Readiness Level - TRL)
    - Fusion
    - Anti-matter

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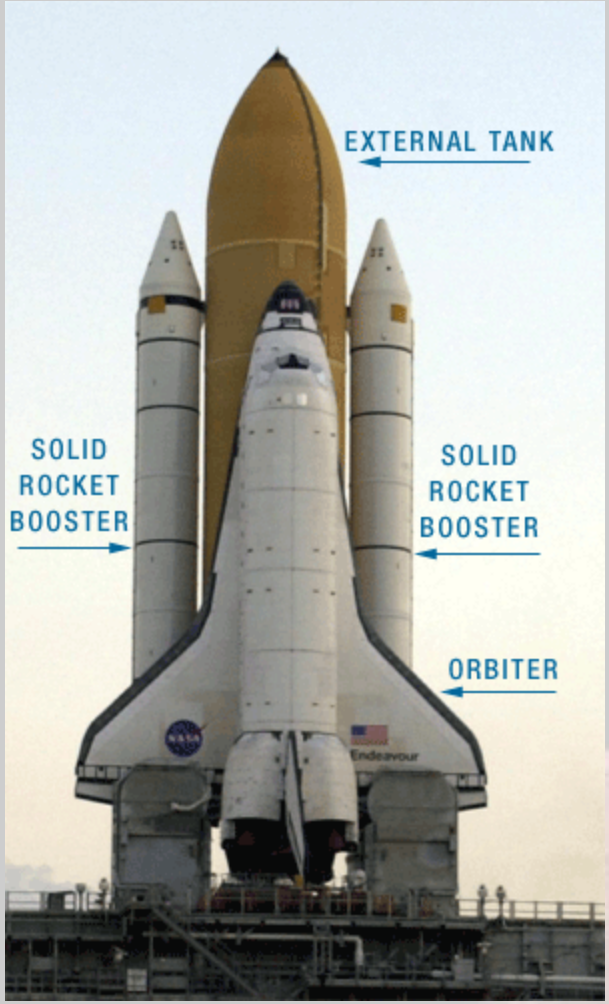
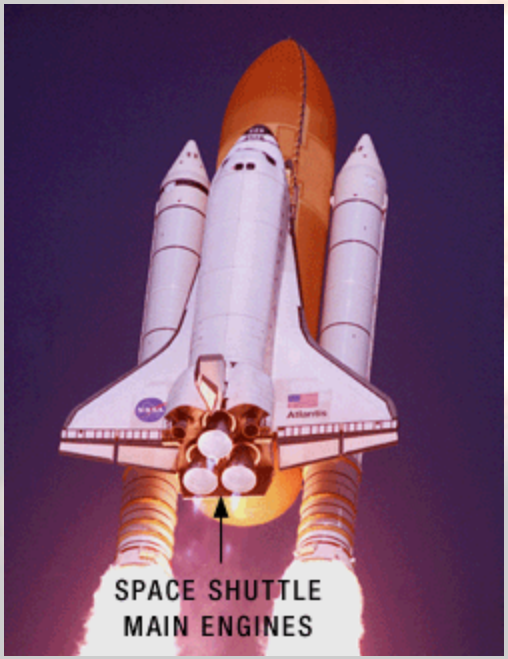
Space Shuttle





Electrical Power:

Fuel Cells

Average of 14 kW consumption

7 kW left over for payloads

Space Shuttle Main Engines:

Operate ~8.5 minutes

External tank is expended and jettisoned; tank is dropped into the ocean for recovery and reuse

Solid Rocket Boosters:

Operate for first 2 min of flight

http://www.nasa.gov/returntoflight/system/system_SRB.html

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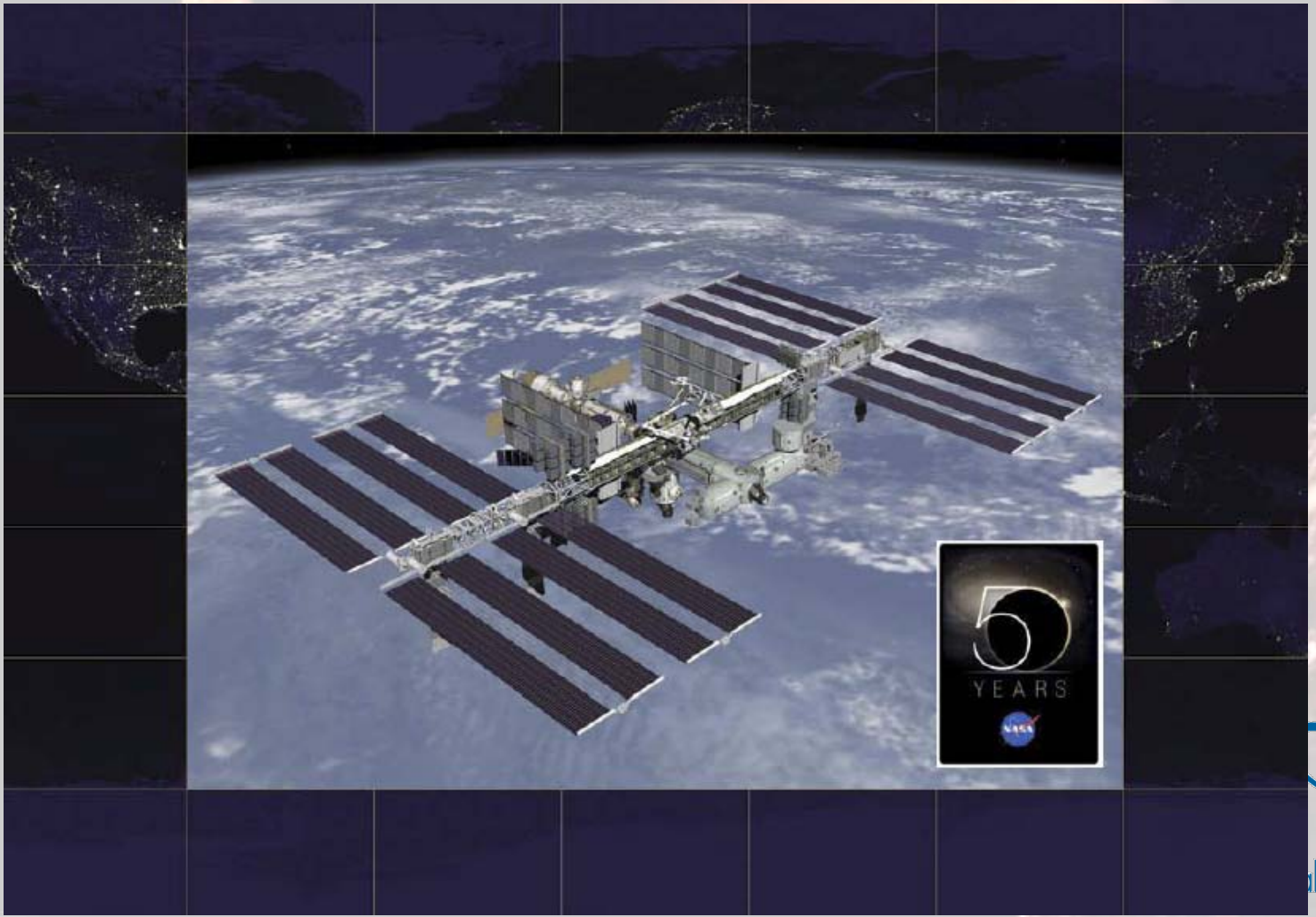
International Space Station

- **Continuous 105 kW_e required**
- Two independent solar power supplies
- 24 NiH batteries (US system) for solar eclipse

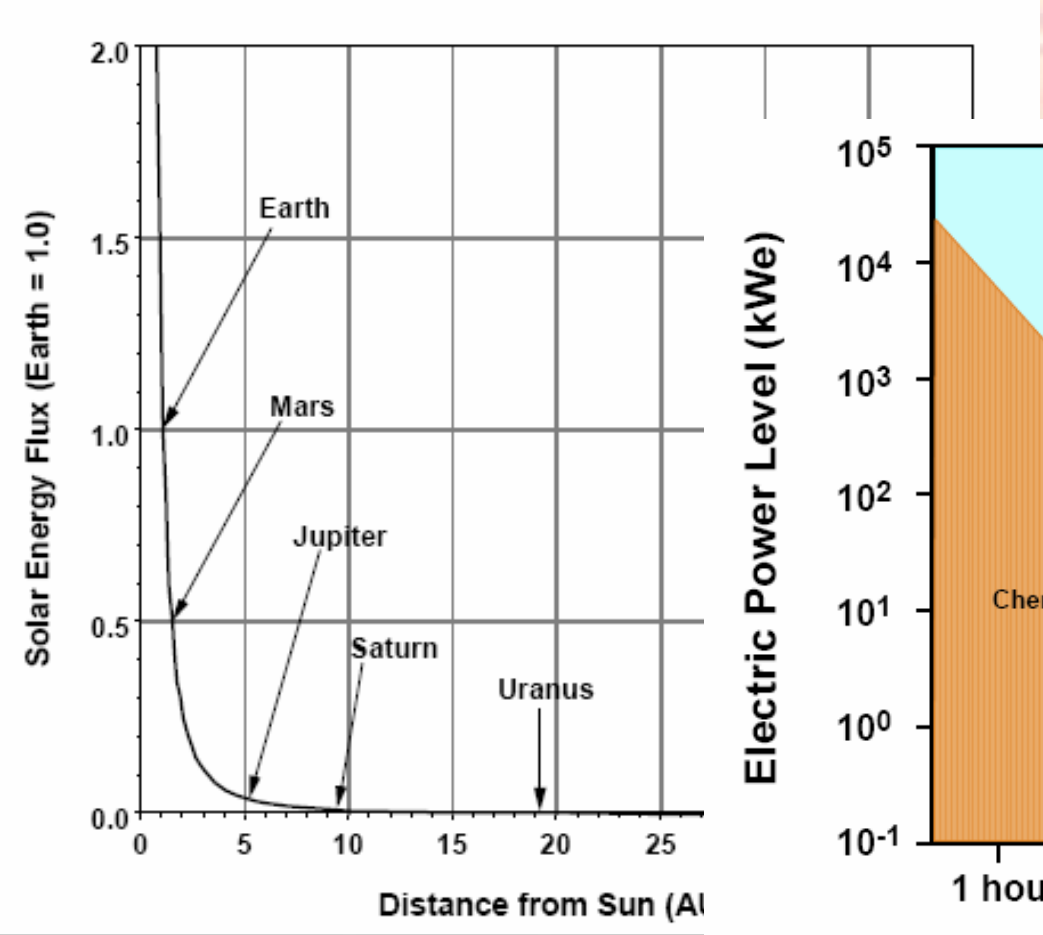


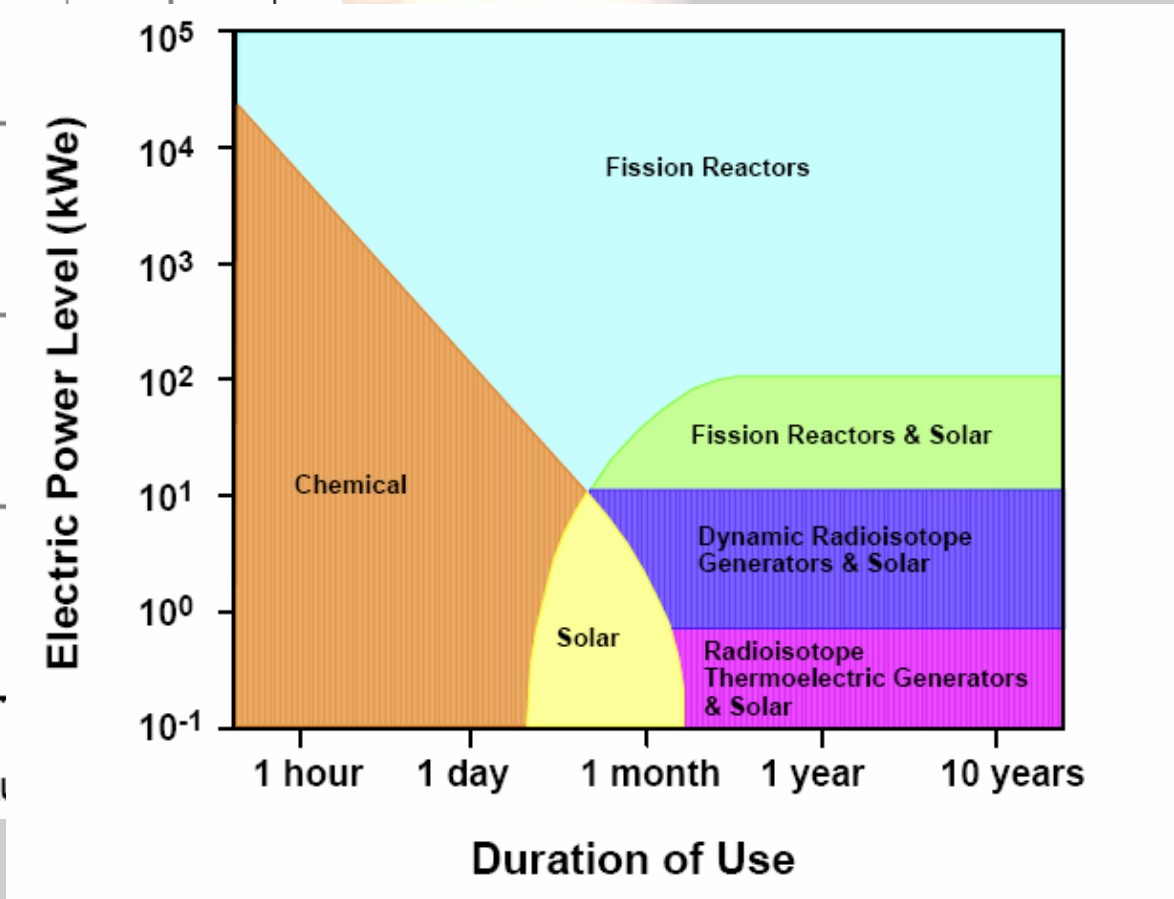
ISS, May 23, 2011, with docked Endeavor, as seen by Soyuz TMA-20

http://www.nasa.gov/mission_pages/station/multimedia/e27depart.html

Regimes of Space Power Applicability

- Nuclear energy sources represent a distinct advantage over conventional energy production for long duration missions or for large power needs → can be applied in electricity production or for propulsion.





LET’S TALK ABOUT RADIOISOTOPES…

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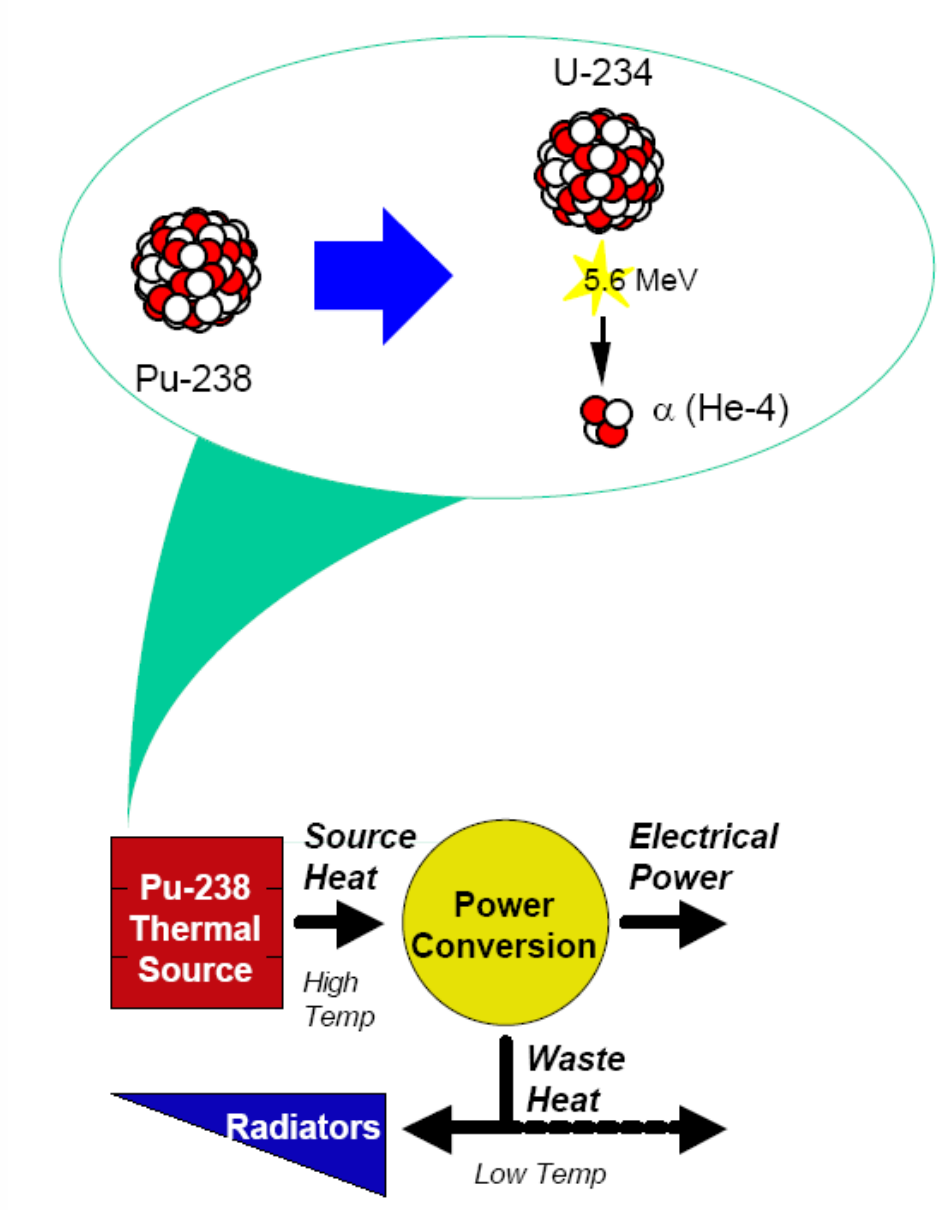
Radioisotope Power Systems (RPS)



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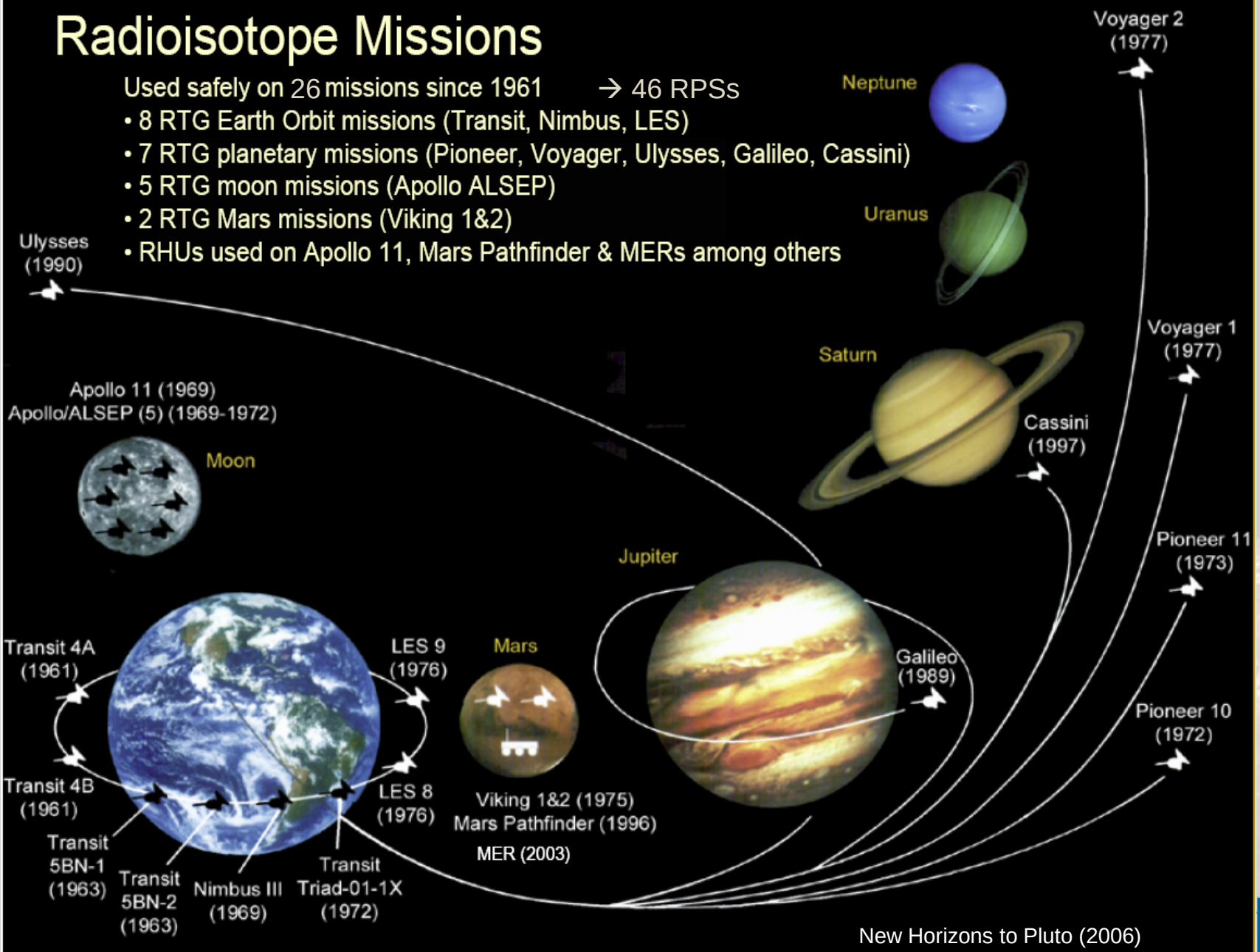
Radioisotope Missions

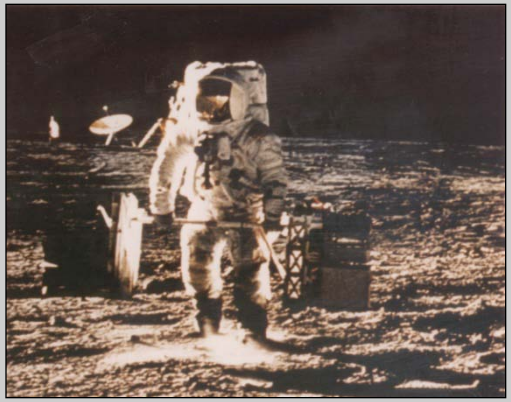
Used safely on 26 missions since 1961 → 46 RPSs

- 8 RTG Earth Orbit missions (Transit, Nimbus, LES)
- 7 RTG planetary missions (Pioneer, Voyager, Ulysses, Galileo, Cassini)
- 5 RTG moon missions (Apollo ALSEP)
- 2 RTG Mars missions (Viking 1&2)
- RHUs used on Apollo 11, Mars Pathfinder & MERs among others

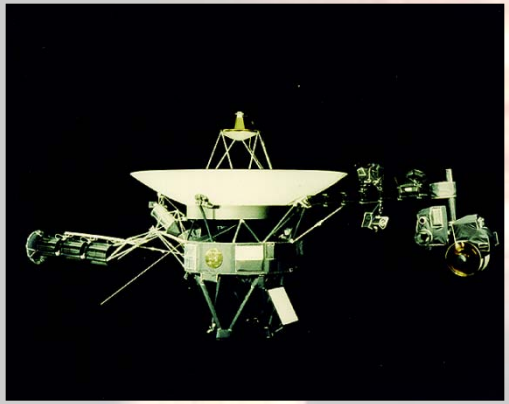


RTG: Radioisotope Thermoelectric Generator
RHU: Radioisotope Heat Unit

Exploring Our Solar System Using Radioisotope Power Systems (RPS)

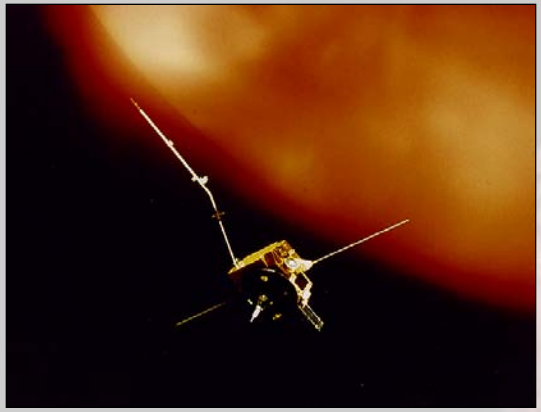


Apollo (1969-1972)



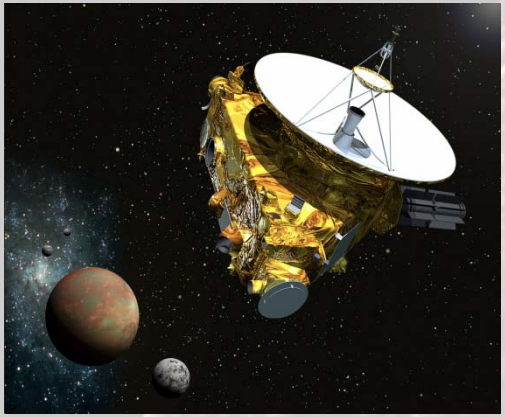
Voyager (1977)

Galileo (1989)



Ulysses (1990)

Cassini (1997)



Pluto New Horizons (2006)

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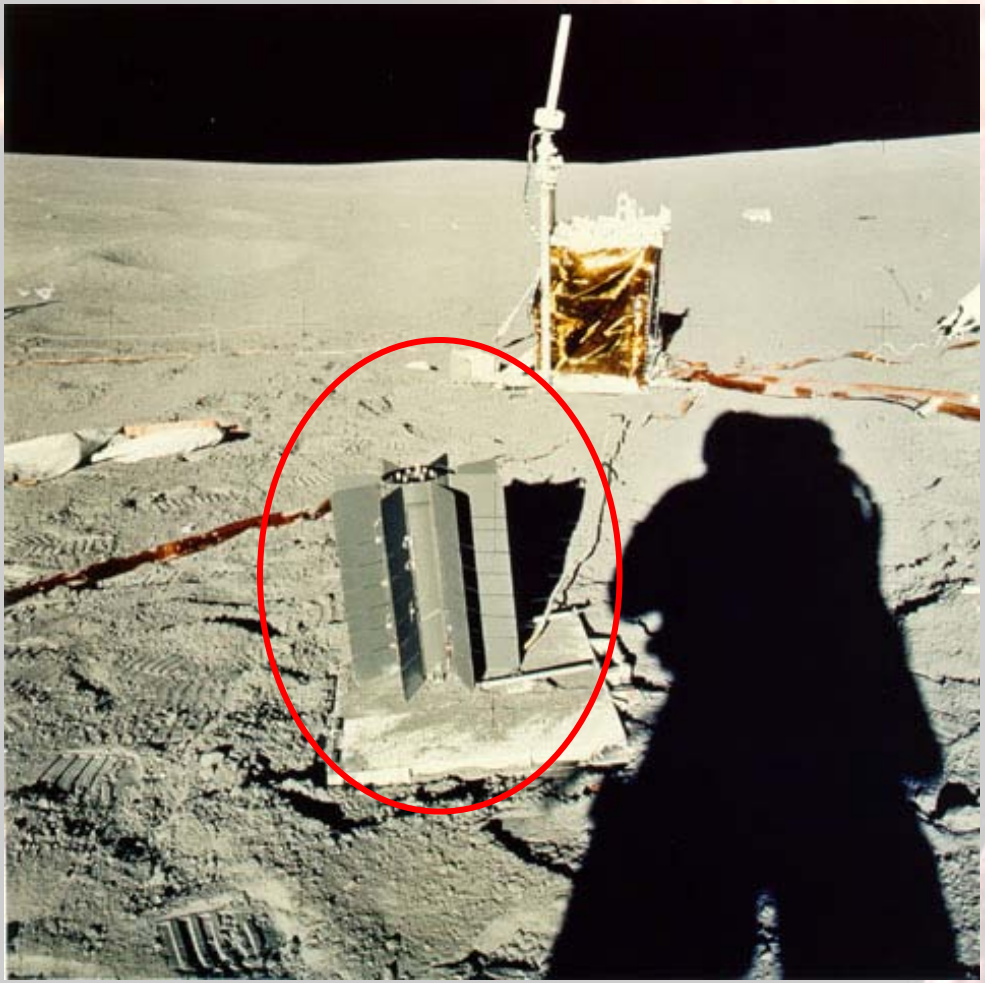
RPS on the Moon



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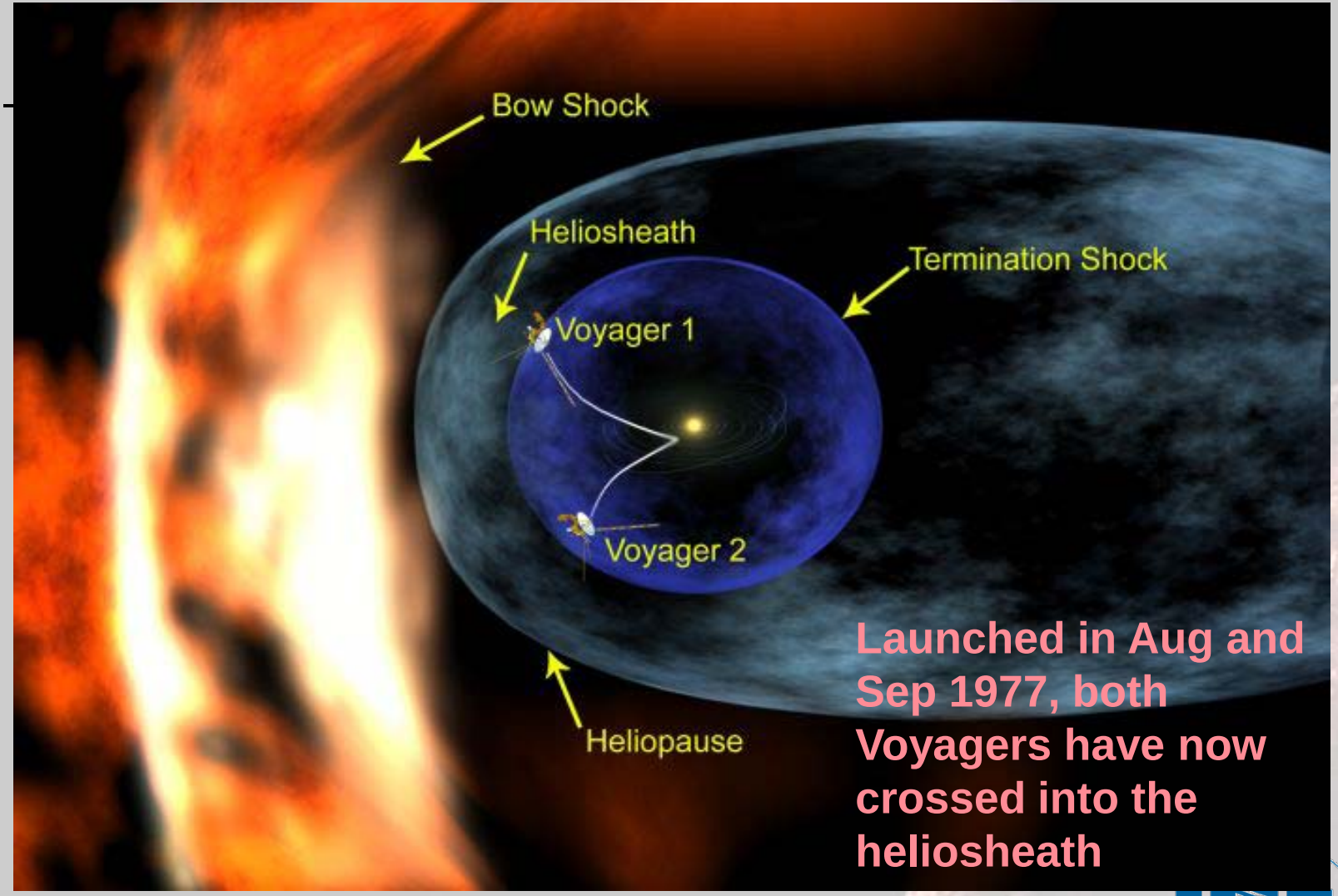
Interstellar Space: Our "Local" Backyard

The Voyagers data still coming back on their way to the stars…



Launched in Aug and Sep 1977, both Voyagers have now crossed into the heliosheath

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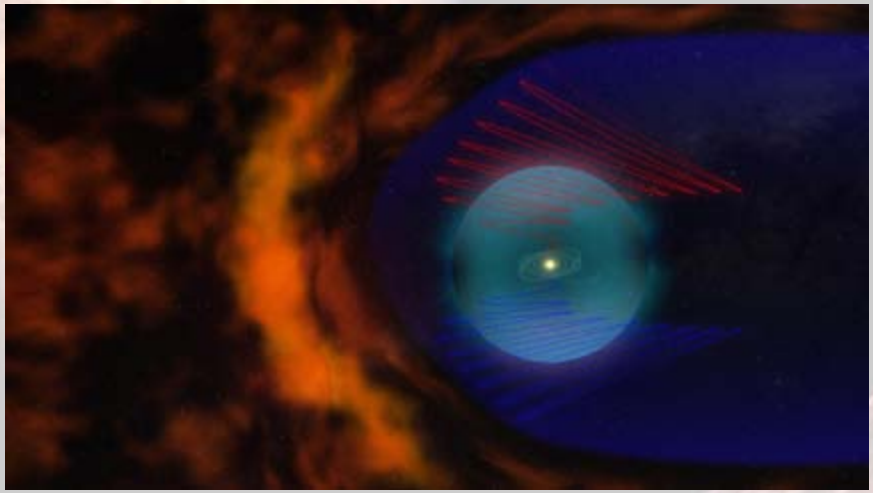
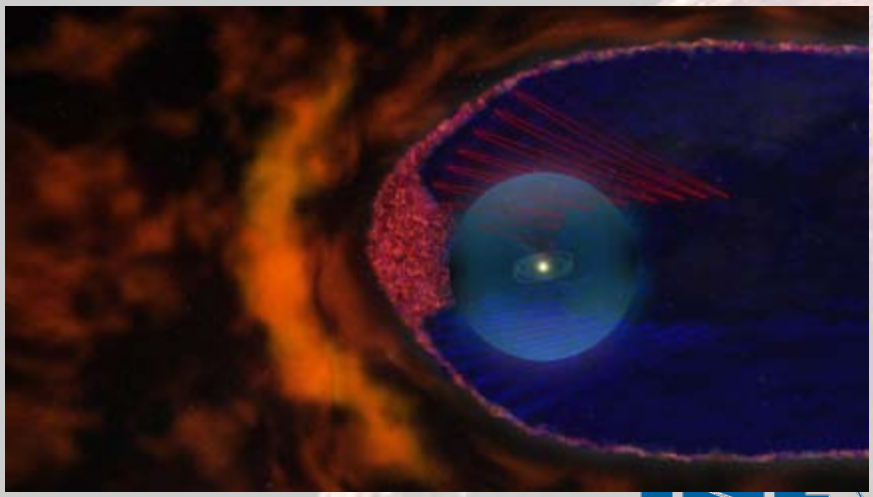
Voyager data may change our understanding of the solar system boundary!

- In the "standard" view of the heliosphere, the boundary between the sun's influence and interstellar space was relatively smooth. (Credit: NASA)



- Based on Voyager data, the boundary between the sun's influence and interstellar space may be marked by a region of magnetic turbulence defined by huge "bubbles" of disconnected magnetic energy. (Credit: NASA)



Voyager spacecraft shed new light on solar system boundary, by William Harwood, 06/09/2011

http://www.cbsnews.com/network/news/space/home/spacenews/files/e5d817129bd24df1b6c3898729eb868f-274.html

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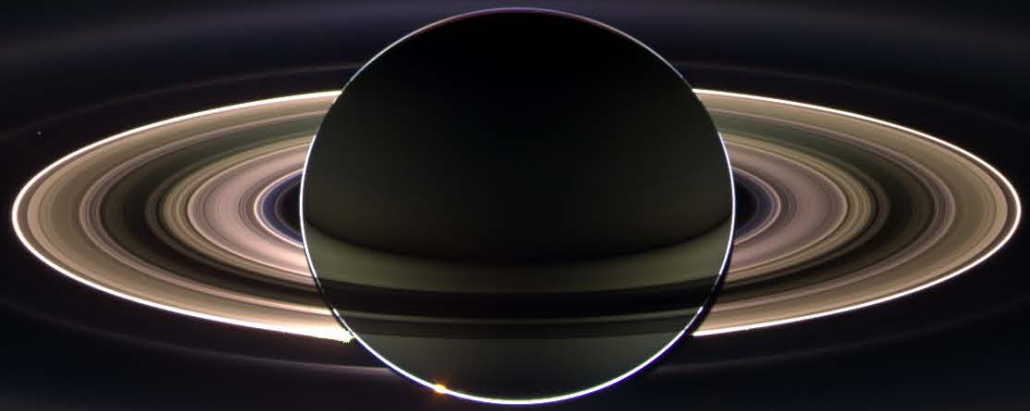
Cassini: Ongoing Mission at Saturn

Titan: A New World to Explore

Cassini-Huygens
5.6 metric tons at launch



Saturn from Cassini in forward-scattered sunlight

The E-ring is clearly visible

Simplified RPS

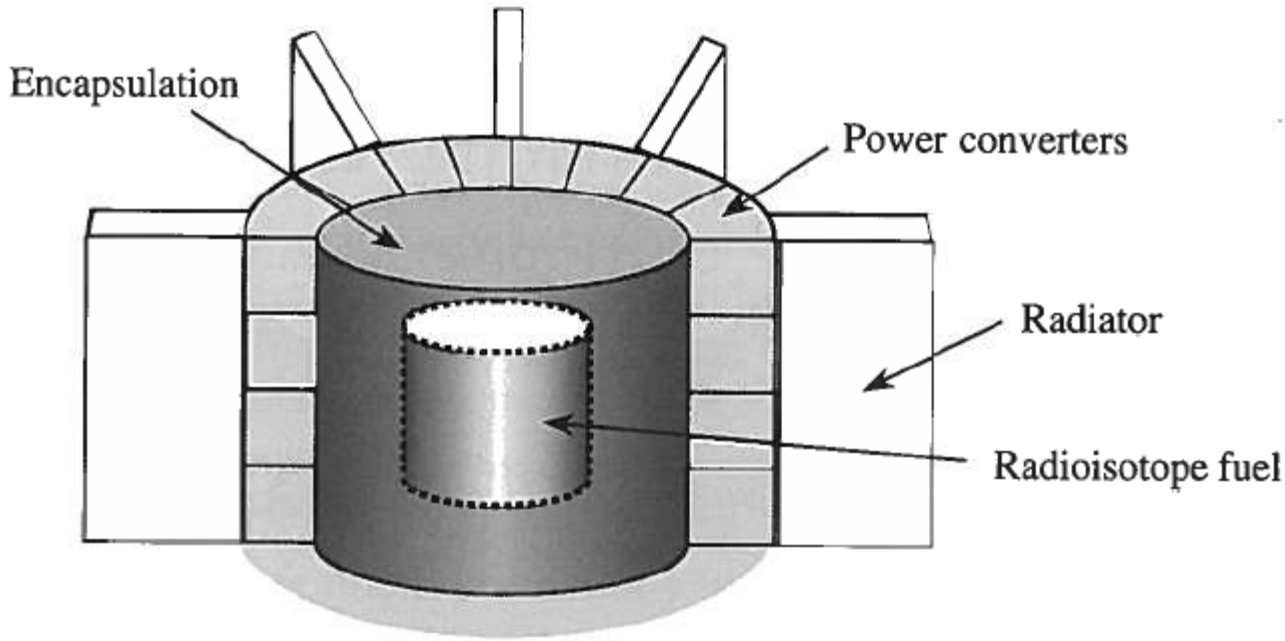


Figure 2.5. Schematic cutaway of a radioisotope power source.

Source: A. Marshall, *Space Nuclear Safety* (2008).

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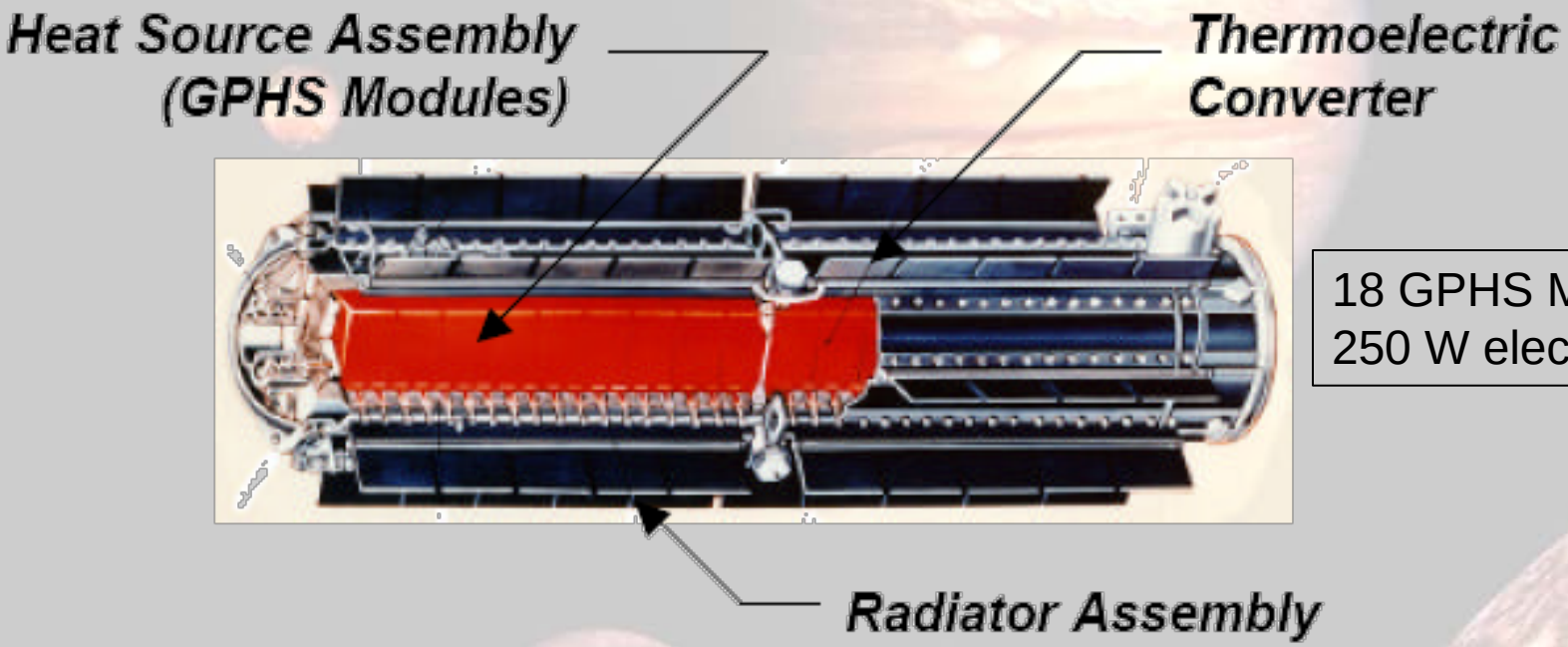
Radioisotope Thermoelectric Generator (RTG)



18 GPHS Modules
250 W electric

GPHS-Radioisotope Thermoelectric Generator (RTG)

- Principle of the “Space Battery”
  - Harness Heat from Radioactive Material & Generate Electricity
  - Unicouples--Silicon Germanium ~570

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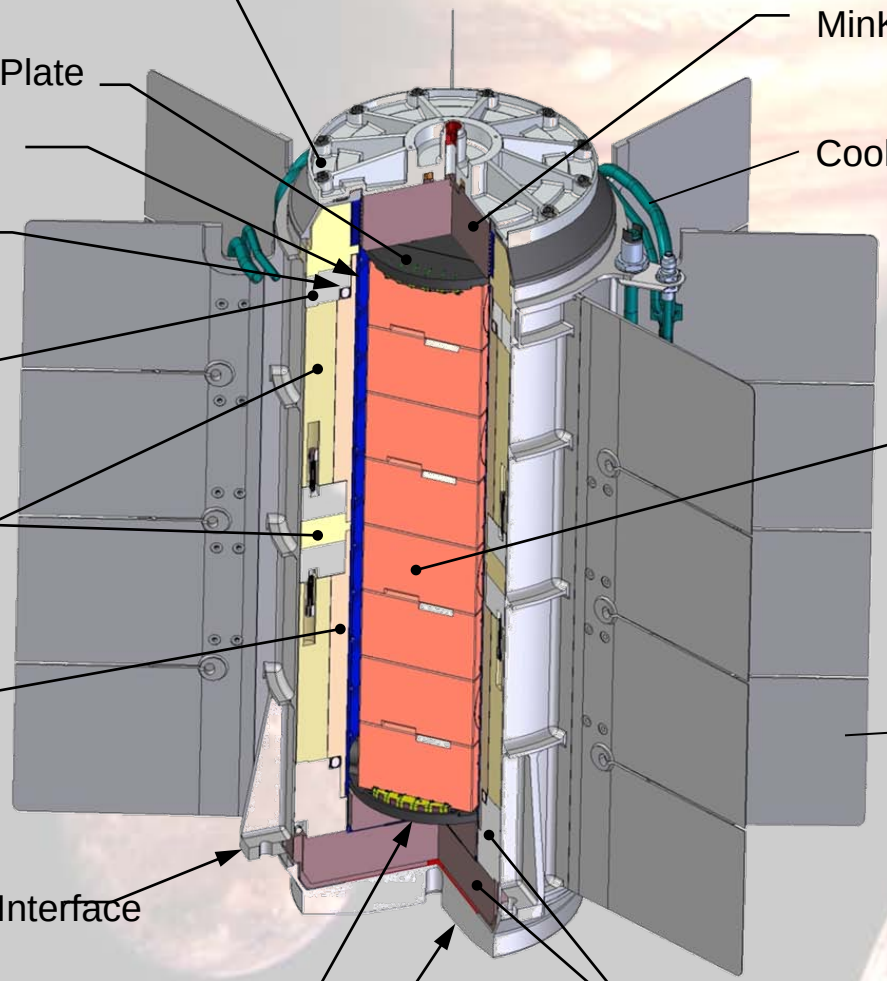
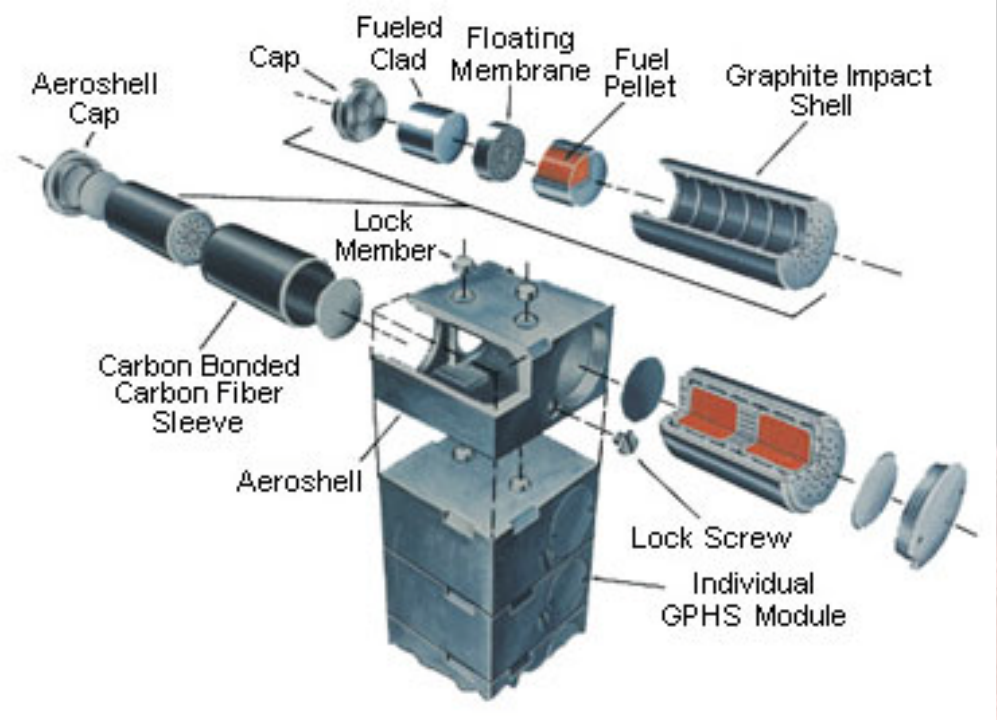
Multi-Mission RTG Overview

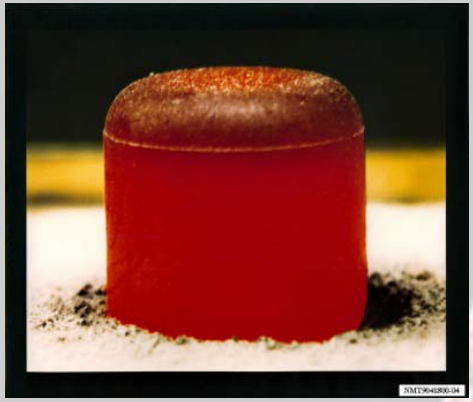


8 GPHS Modules
123 W electric

General Purpose Heat Source (GPHS) Module

- Fuel is assembled into GPHS
- Pu-238 is used for fuel
  - Half life of 87.7 years
  - Requires 1.8 gm to produce 1-thermal watt of power
- Each GPHS module contains ~600 g PuO_2 in 4 fueled clads
- ~250 W thermal per GPHS (~60 W thermal per pellet)
- Pellet Surface Temp: ~2700°F (1500°C)
- Fuel Clad (iridium) Surface Temp: ~1600°F (870°C)
- Module Surface Temp: ~1000°F (540°C)





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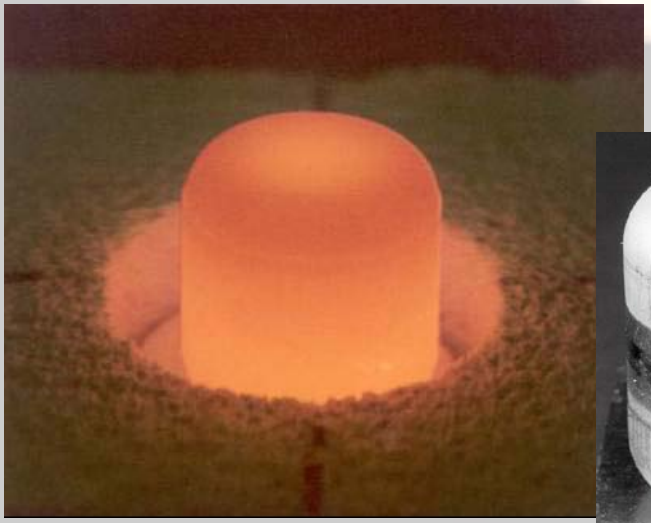
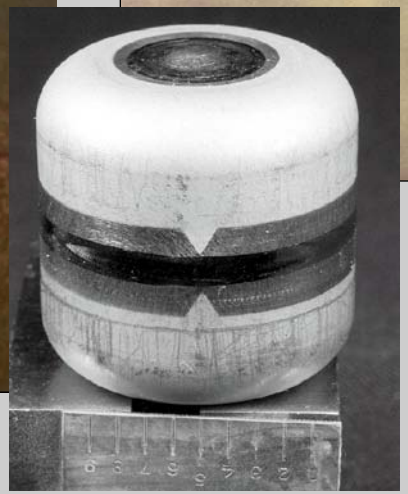
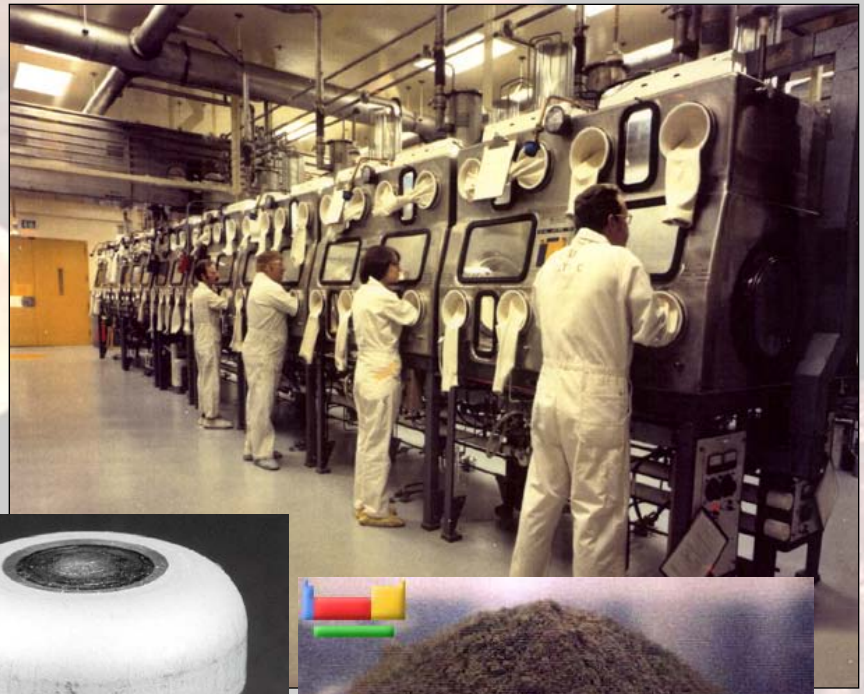
Fueled Clads Made at Los Alamos National Lab in New Mexico

- Purification of Pu-238
- Production of Pu-238 pellets
- Encapsulation of Pu-238 pellets
- Safety testing
- 1500°C/2700°F







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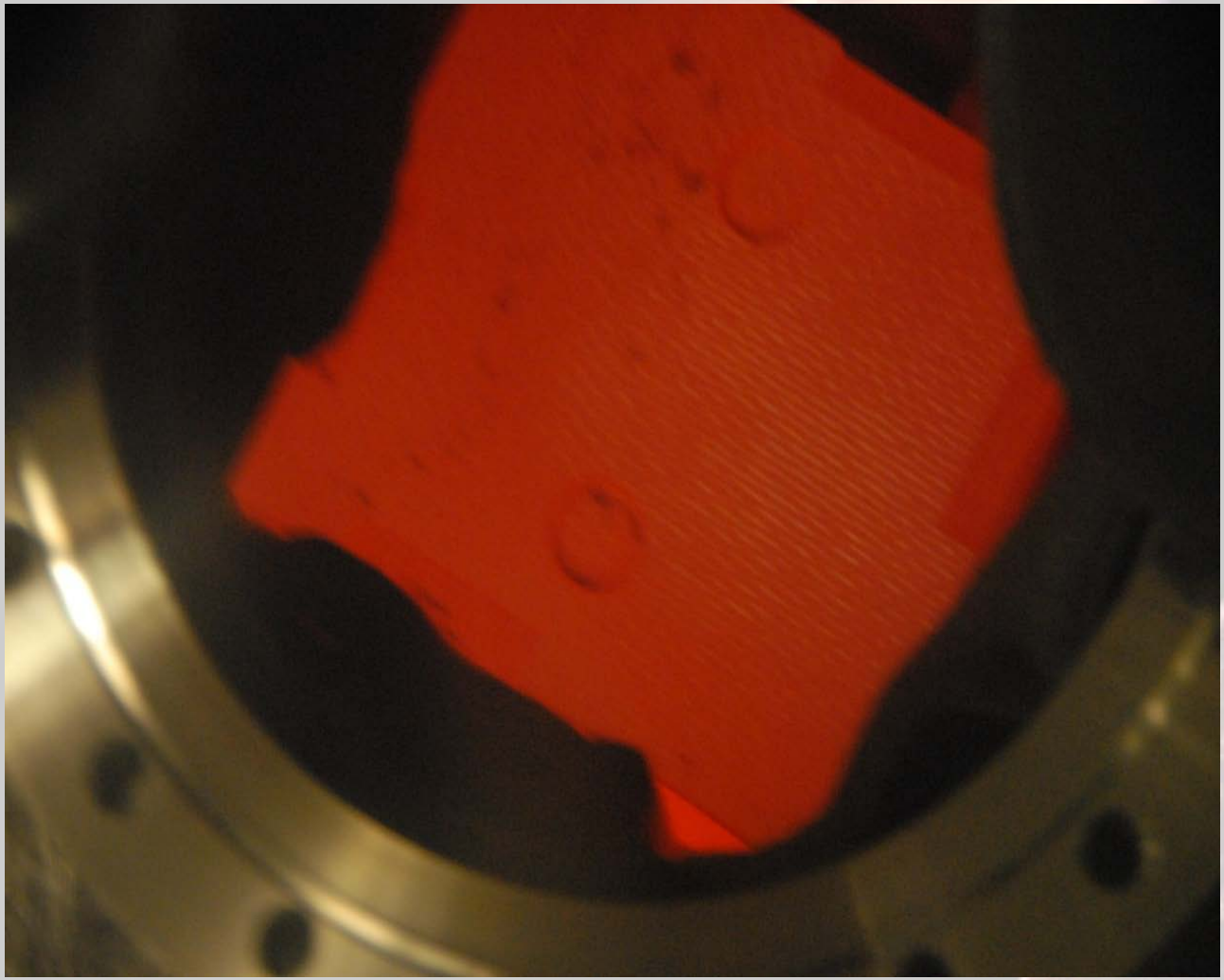
General Purpose Heat Source (GPHS) Module

- Fueled module in special container



Module Surface Temp: ~1000°F (540°C)

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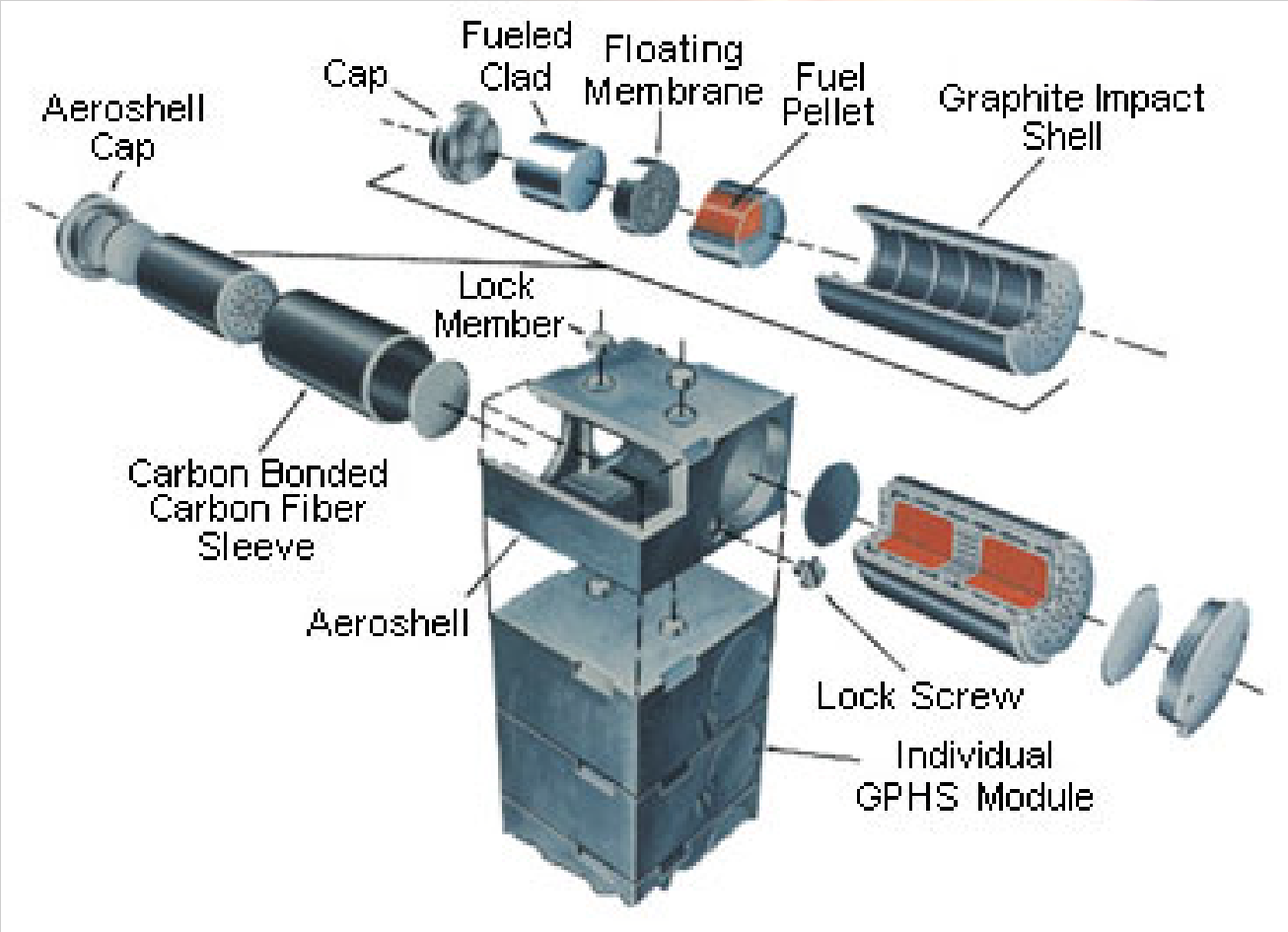
Hands-on with a GPHS (Training) Module



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WHAT IS FISSION POWER?

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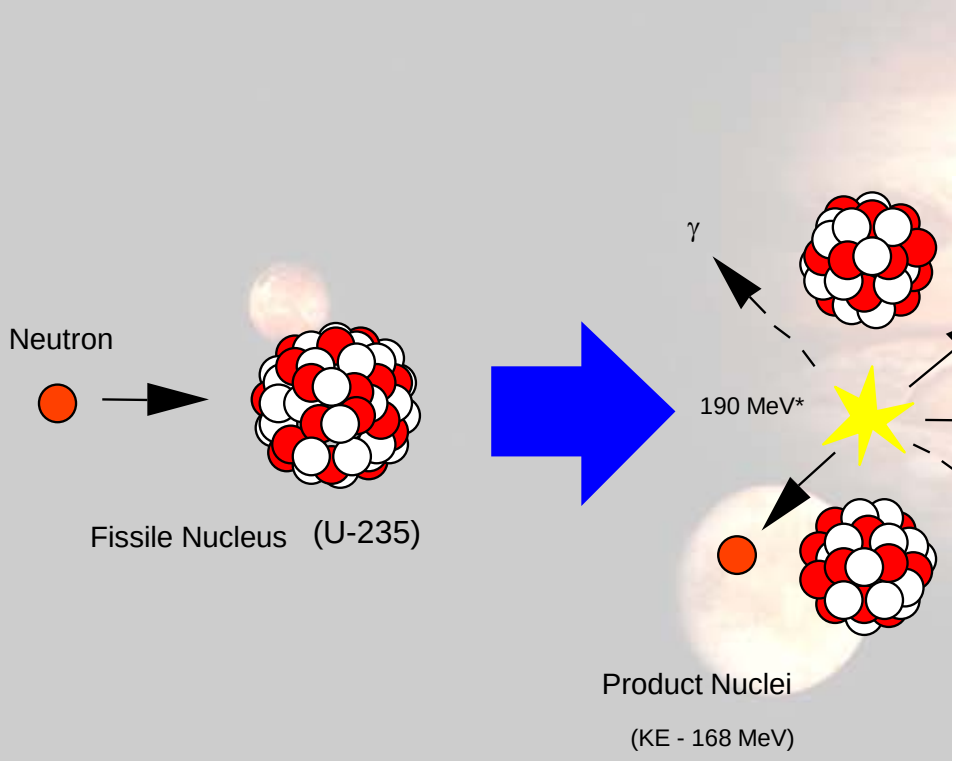
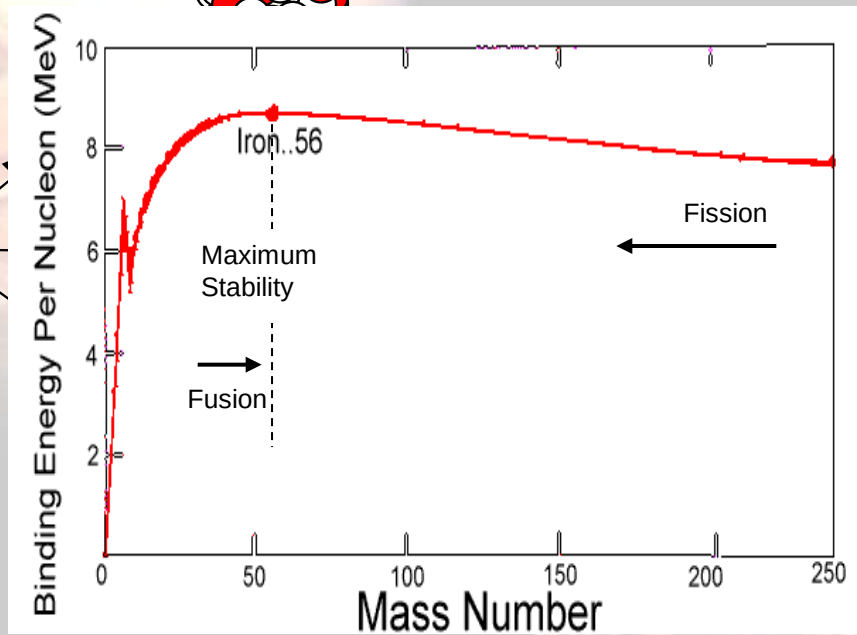
Nuclear Fission Process





- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon. Difference between initial and final masses = prompt energy released (190 MeV).
  - —*Fissile* isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - —Other actinides (U-238) fission at only high neutron energies
- Fission fragment kinetic energy (168 MeV), instantaneous gamma energy (7 MeV), fission neutron kinetic energy (5 MeV), Beta particles from fission products (7 MeV), Gamma rays from fission products (6 MeV), Gamma rays from neutron capture (~7 MeV) → ~200 MeV of useful energy
- For steady power production, 1 of the 2 to 3 neutrons from each reaction must cause a subsequent fission in a *chain reaction* process.

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Nuclear Reactor Basics

Reactor Fuel: Uranium-235

U-235 splits apart when it absorbs a neutron.
The "fission" process releases neutrons and energy – these neutrons go on to produce more fission (a chain reaction), and th

Moderator

Used to slow down neutrons as they bounce off other atoms, making it easier for fuel atoms to capture them – in the U.S., we use water

Enrichment

Ratio of Uranium-235 to Uranium-238
In nature, we find ~7 U-235 atomsper every 1000 U-238 atoms.
We "enrich" the U-235 in US commercial plants to ~3-5%

Poisons

Materials in a nuclear reactor that absorb neutrons.
These materials *do not fission*, and neutrons absorbed by a poison cannot go on to cause fission.

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The Mousetrap Reactor

Enrichment?

Is it moderated?

Is there leakage?

Is it controlled?

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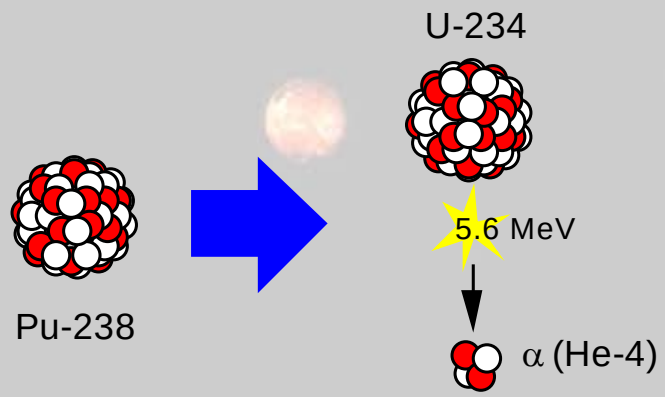
Radioisotope & Fission Power Comparison

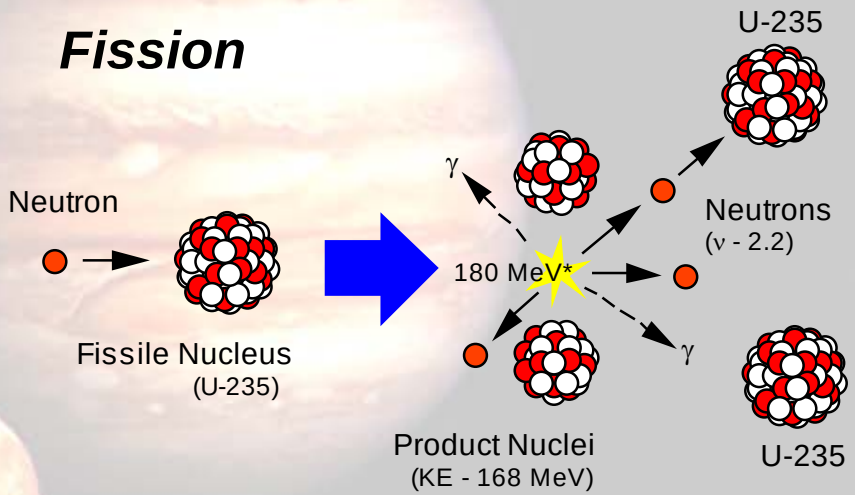
Radioisotope Decay



Heat Energy = 0.024 MeV/nucleon
(0.558 W/g Pu-238)

Natural decay rate
(87.7-year half-life)

Fission



* 180 MeV prompt energy - 27 MeV additional energy released in form delayed beta particles, gamma rays and anti-neutrinos from products

Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate
(variable power levels)

1 kg of ^{235}U contains 500,000 times the energy released by the decay of 1 kg of ^{238}Pu over 10 years!

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Why not chemical?

= 50 x

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

Energy Density: 82 billion joules per gram

- Overcomes limitations of other candidate power sources
- Greatly extends capability, sophistication and reach of future science missions
  → high-performance propulsion & long-duration, power-rich environment
- Improves safety, capability and performance of future human planetary missions
  → rapid transportation, power-rich spacecraft / surface base

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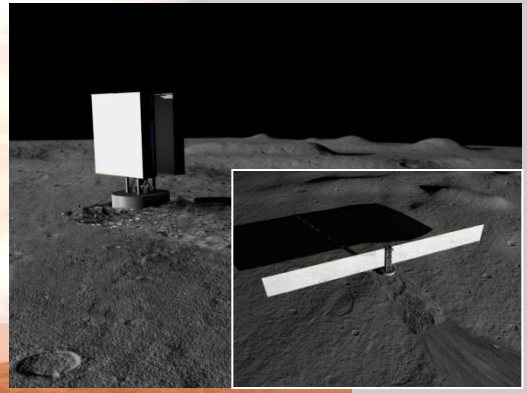
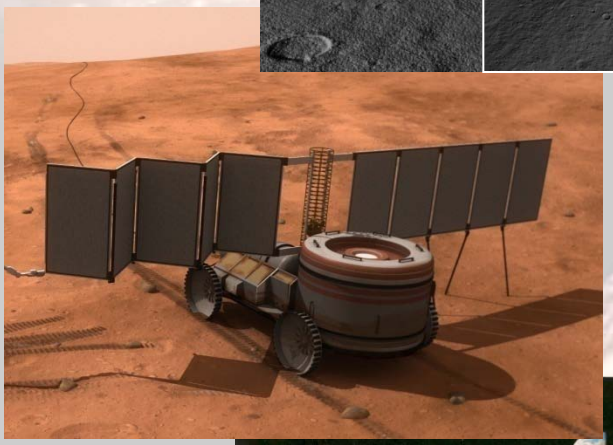
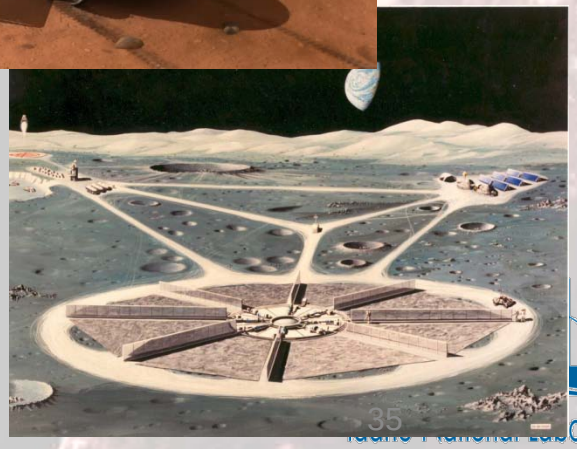
Why Fission Surface Power?

- Continuous day/night power for robust surface operations
- Same technology for moon and Mars
- Suitable for any surface location
- Environmentally robust
- Operationally robust
- Highly flexible configurations
- Safe during all mission phases
- Scalable to higher power levels
- Performance advantages compared to alternatives
- Competitive cost with alternatives
- Synergistic with other technology development activities







SO… WHAT DOES INL HAVE TO DO WITH ALL THIS?

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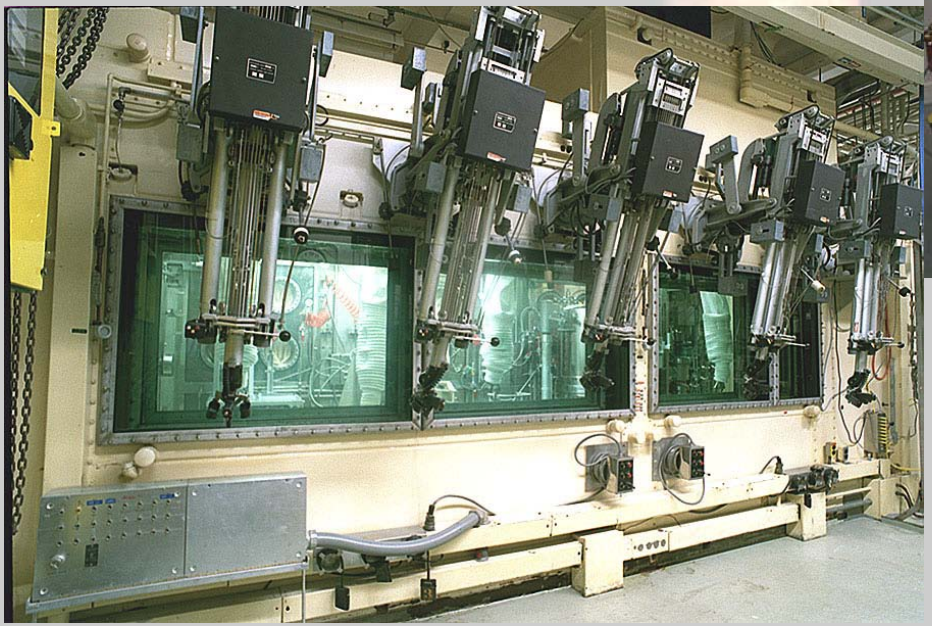
What We Do At INL

- GPHS Assembly
  - GPHS modules in the module assembly glovebox (right)
  - RTGs in the inert atmosphere assembly chamber (bottom)



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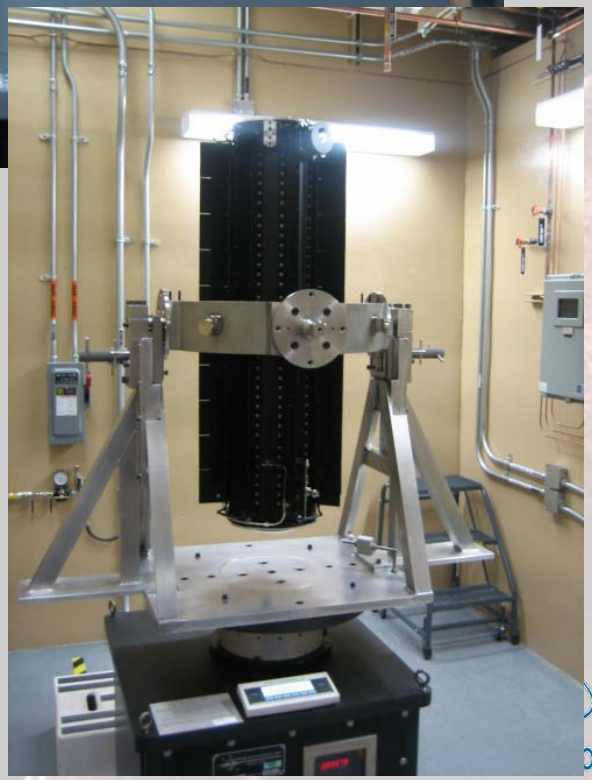
What We Do At INL

- Acceptance Testing
  - Vibration
  - Mass Properties
  - Magnetics
  - Thermal Vacuum



What We Do At INL

- Transport RPS

Note:
Photos show shipment of Pluto New Horizons RPS. The Mars Science Lab RPS shipped to NASA KSC at the end of June.

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What We Do At INL

- Integrate RPS with Spacecraft at Kennedy Space Center in Florida

Preparing New Horizons for Loading into the Rocket

**Spacecraft integration and loading for the Mars Science Lab is imminent!

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Cape Canaveral Air Force Station—Florida

- Spacecraft Integration at Cape Canaveral Air Force Station

Atlas V 551

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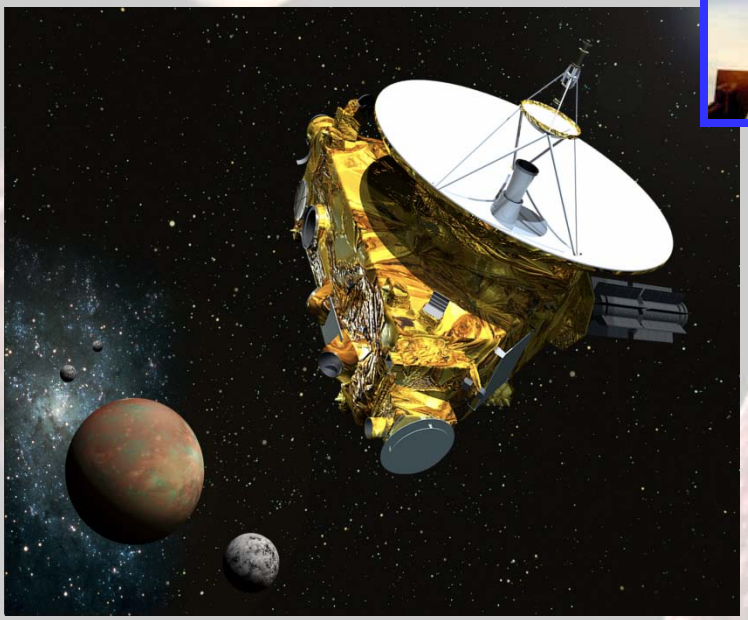
New Horizons Mission to Pluto

- Launched: Jan. 19, 2006
- L+ 9 hrs passed Earth's moon
- L+ 1 yr Jupiter encounter
- L+9 ½ yrs Pluto encounter (July 14, 2015)
- Continues to Kuiper Belt
- A single RTG provides all necessary power



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Launch Day January 19, 2006

Cape Canaveral Air Force Station—Florida

Pluto New Horizons Mission

- Videos:
  - Pluto New Horizons Mission (CNN)
  - News Clip of Launch (Local)

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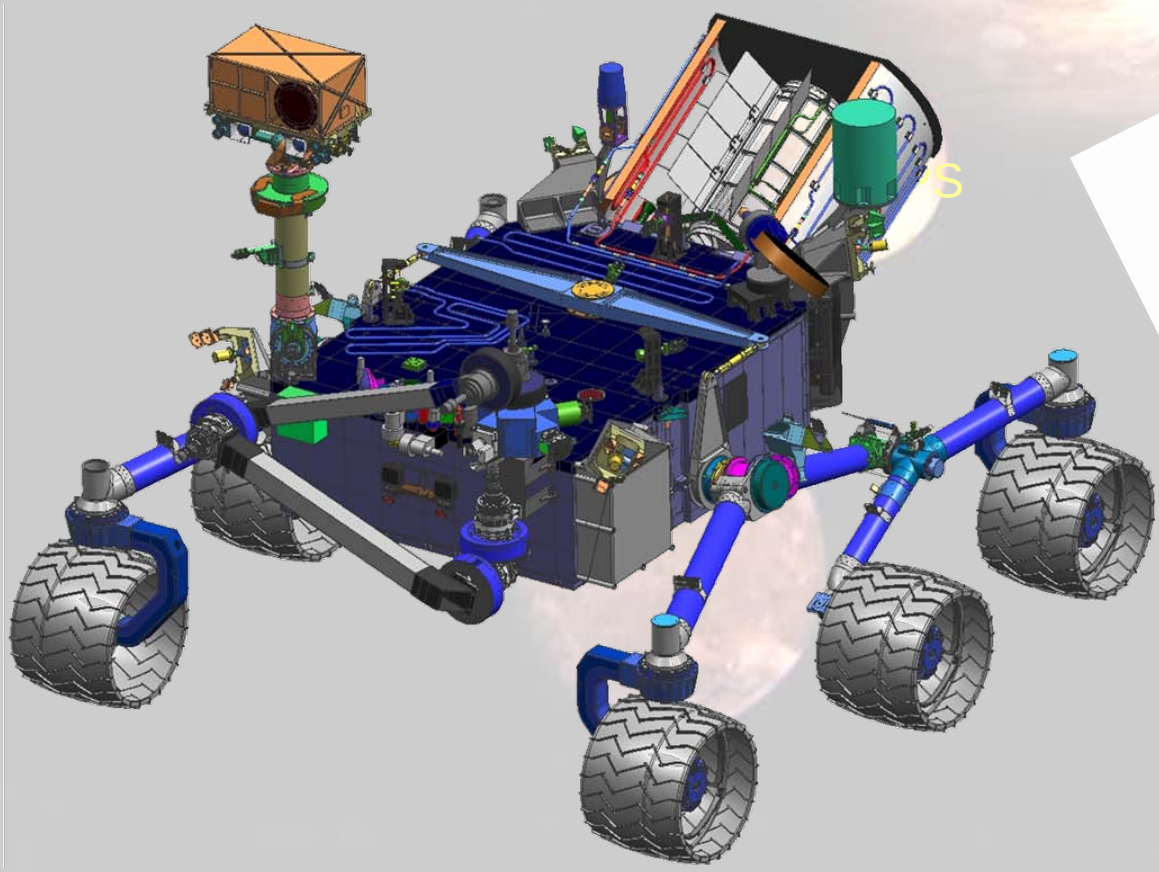
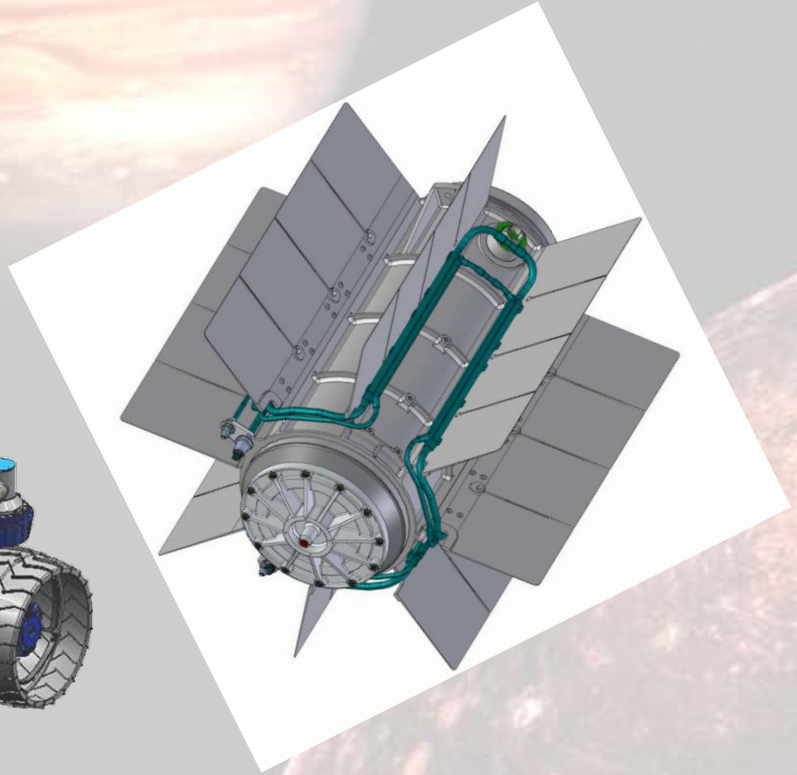
The Next INL Space Battery

- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
- INL will Assemble and Test
- Instruments and Mobile Platform Powered by the MMRTG
- Launch November 2011

http://marsprogram.jpl.nasa.gov/msl/





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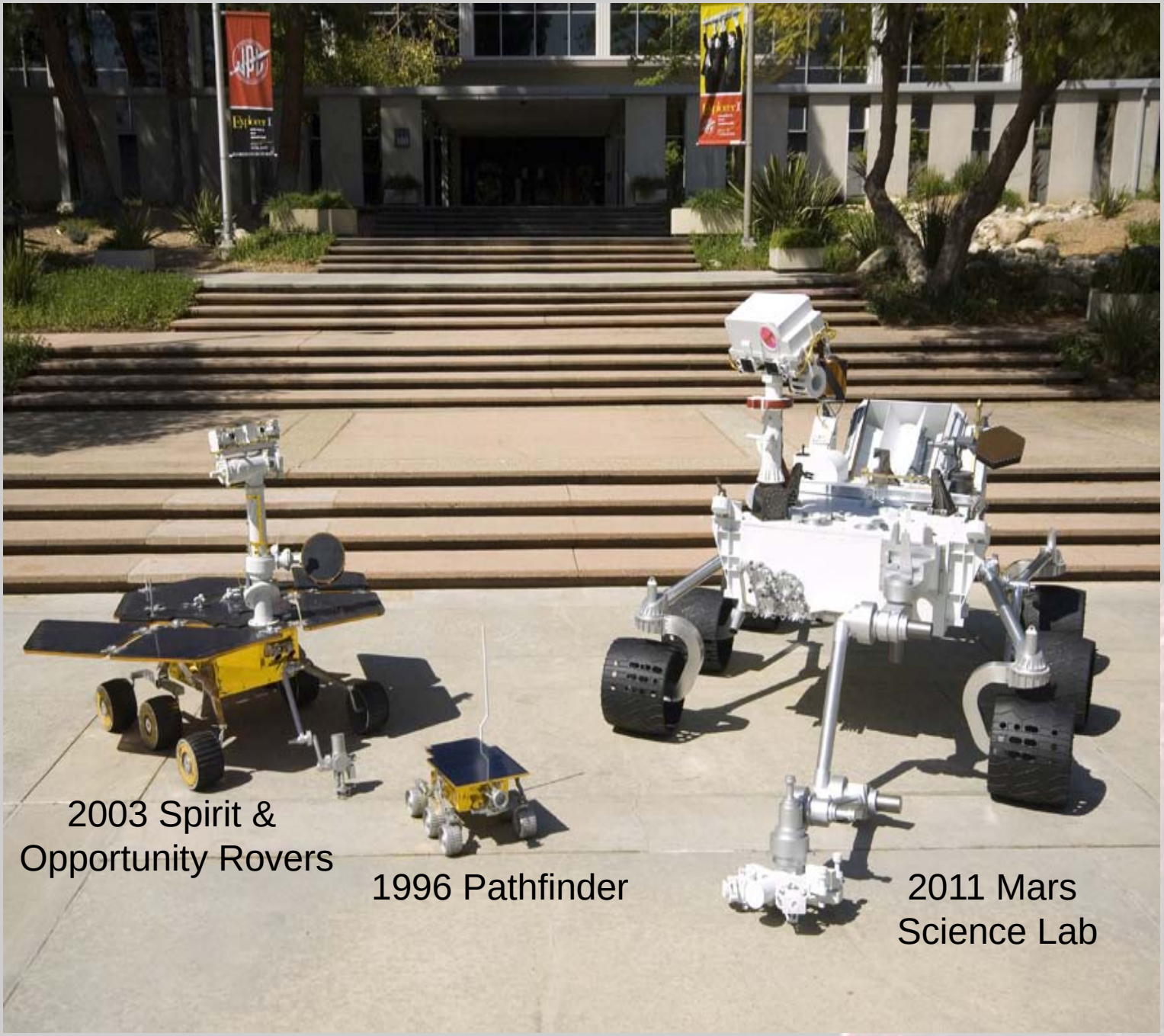
MMRTG at INL

- In storage with cooling fans

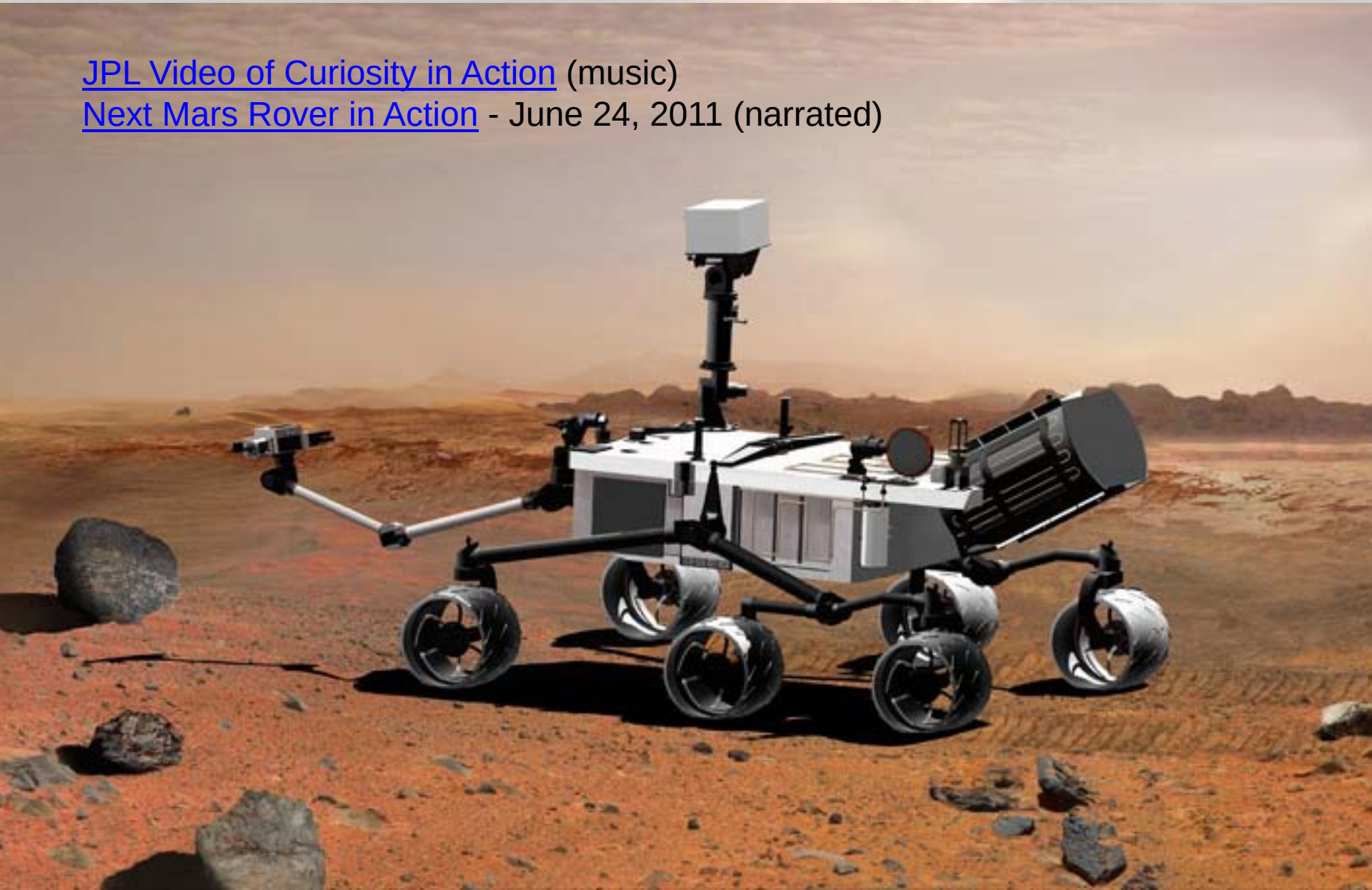
- Magnetics testing


2003 Spirit &
Opportunity Rovers
1996 Pathfinder
2011 Mars
Science Lab

Curiosity – Mars Science Laboratory

Curiosity – Mars Science Laboratory

JPL Video of Curiosity in Action (music)
Next Mars Rover in Action - June 24, 2011 (narrated)



Mars Science Laboratory: Science

Determine whether life ever arose on Mars

Characterize the climate of Mars

Images courtesy of NASA/JPL-Caltech

Characterize the geology of Mars

Prepare for Human Exploration

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FISSION SURFACE POWER WORK AT INL

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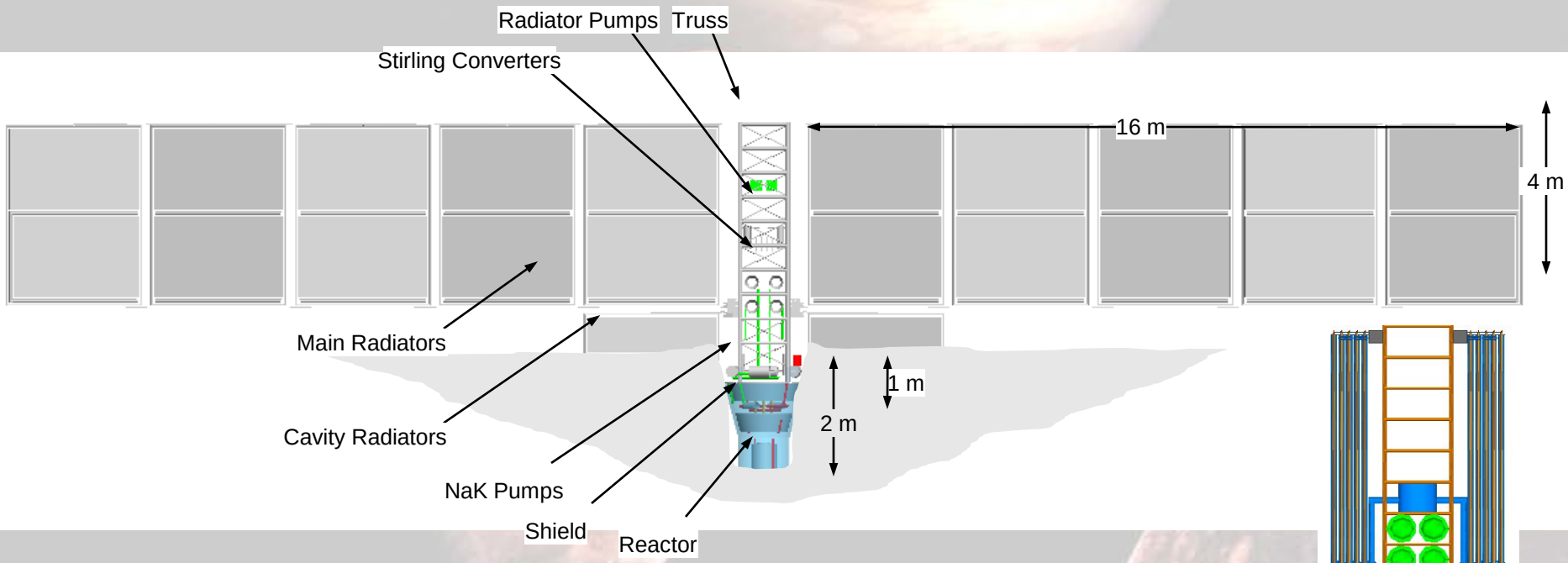
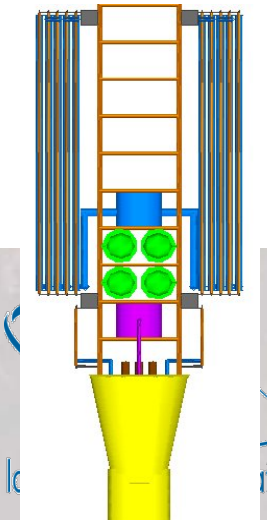
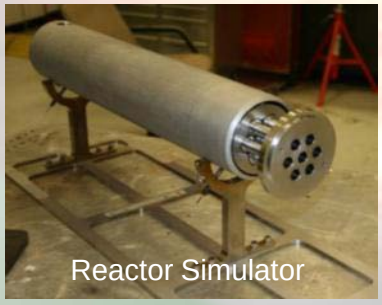
Fission Surface Power Reference Concept

- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO_2 fuel and stainless steel construction

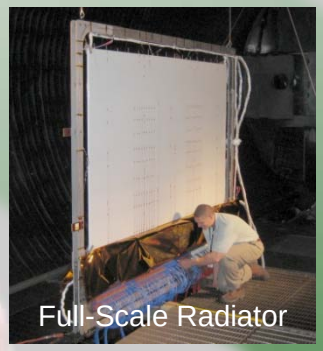




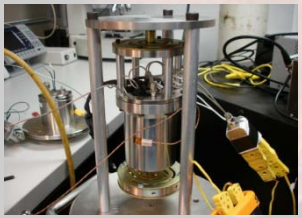
Sampling of Hardware Progression Toward System Level Demonstration



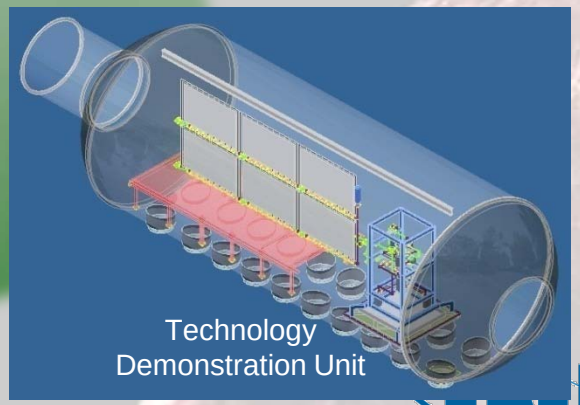
DOE laboratories and NASA work together to design and build complex systems.



Heat Pipe Life Test



Irradiation Testing



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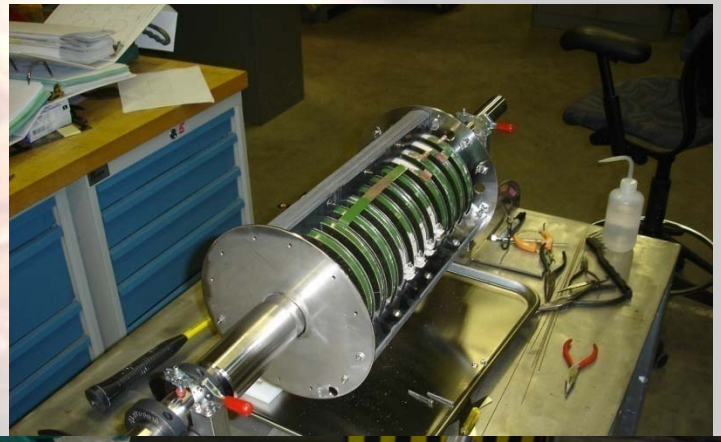
Pump Assembly at INL



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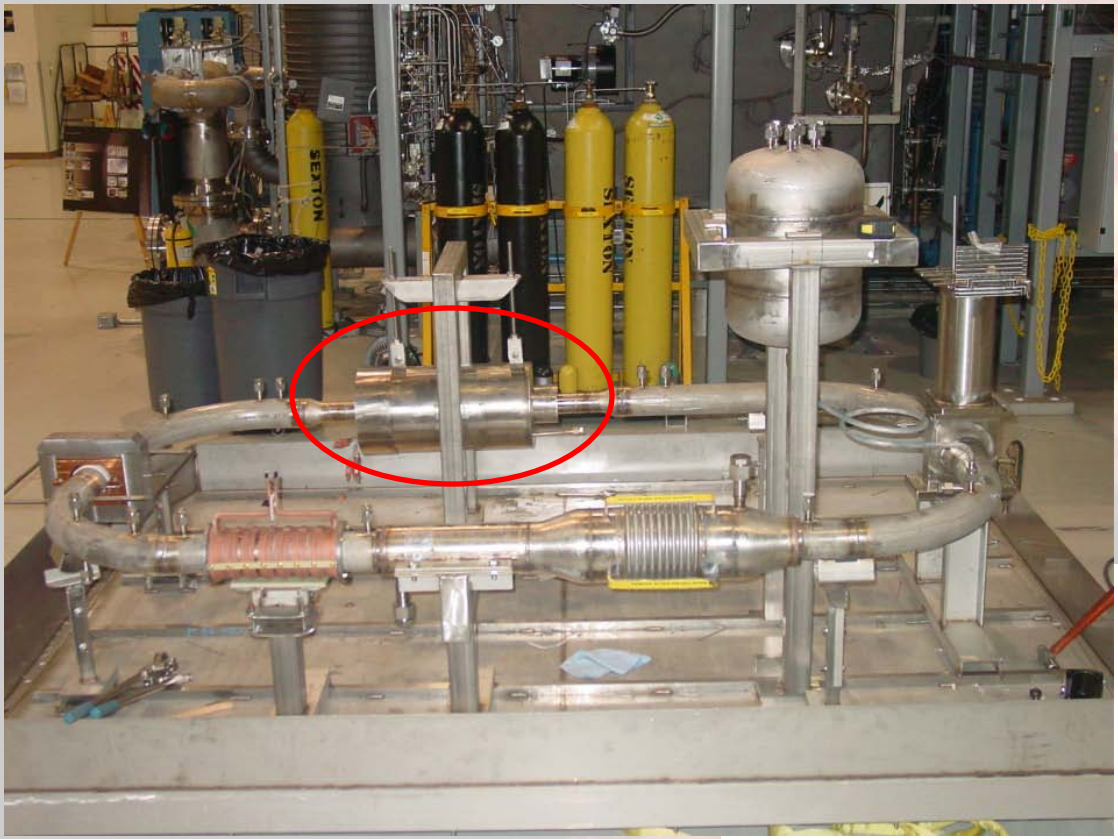
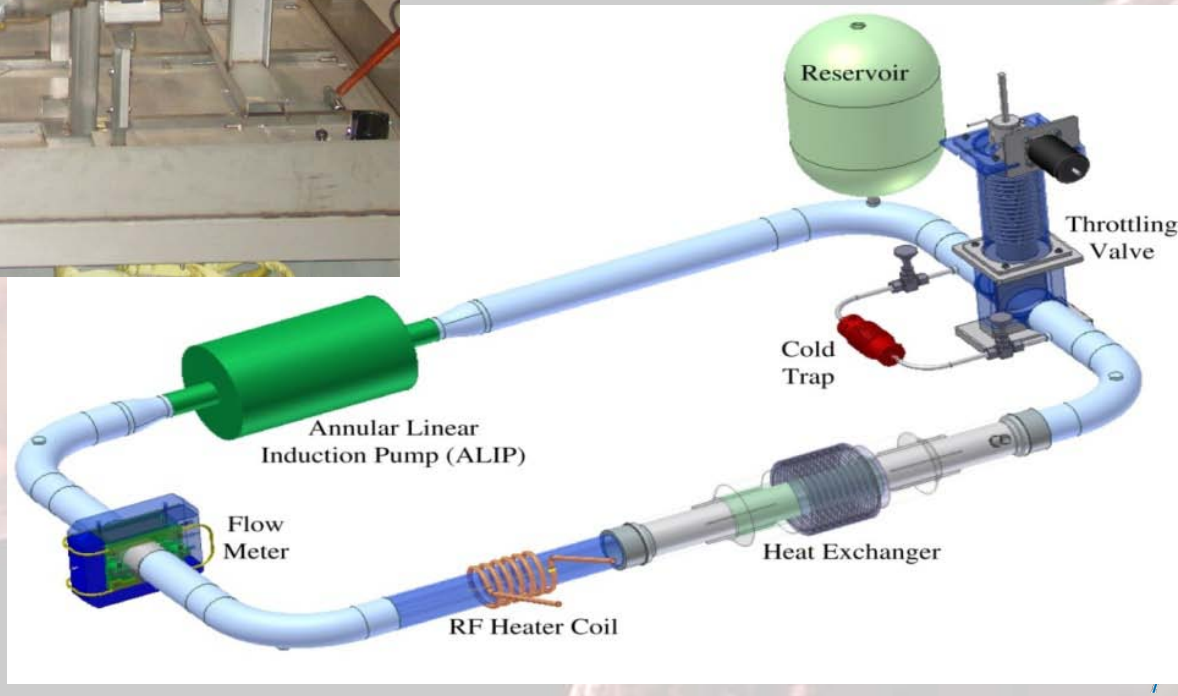
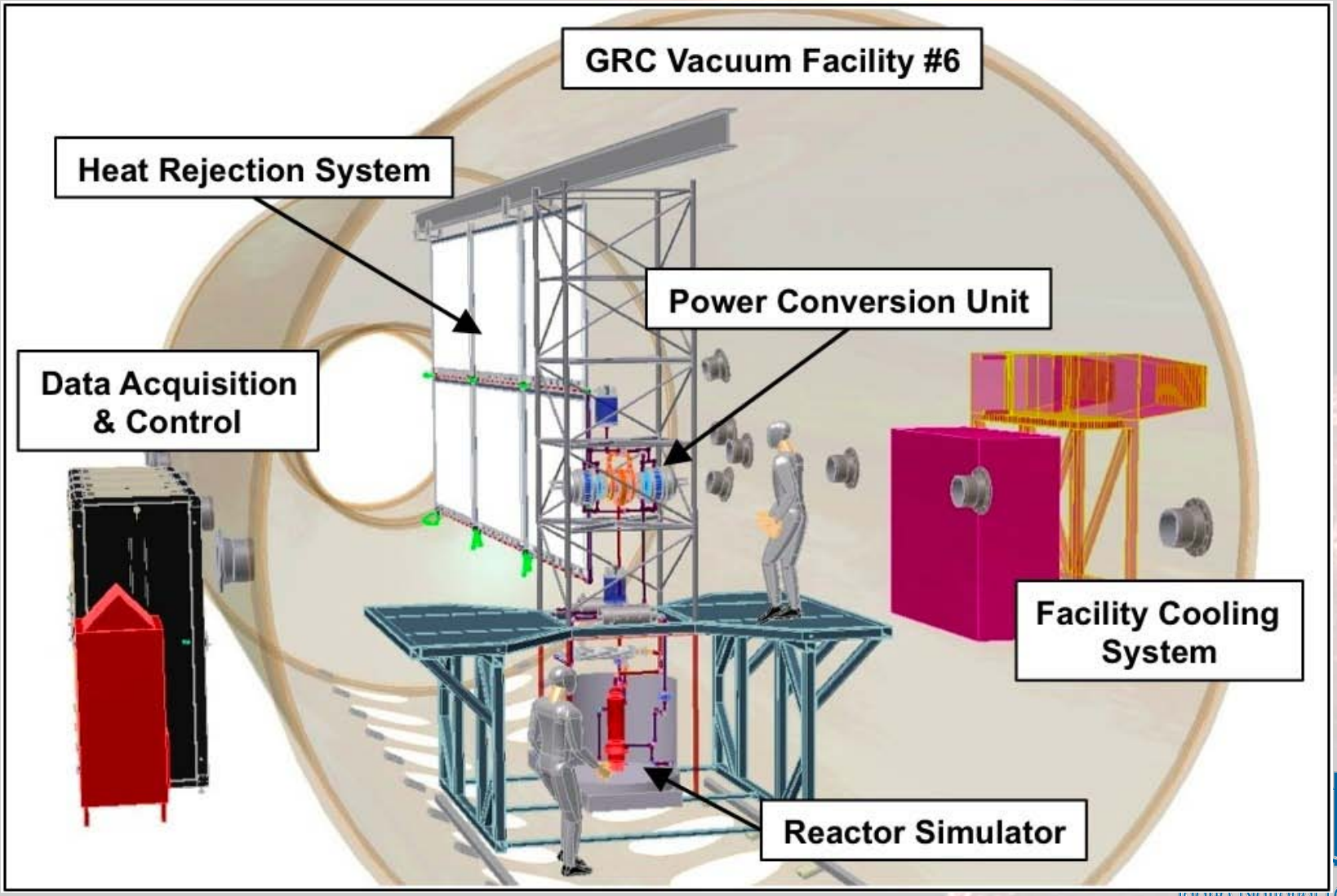
Testing of ALIP at NASA MSFC





Notional Layout for Technology Demonstration Unit at NASA GRC



Questions?

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How Much Power Does a Typical Home Use ?

- Coffee maker = 900–1200 W
- Clothes washer = 350–500 W
- Clothes dryer = 1800–5000 W
- Dishwasher = 1200–2400 W
- Ceiling Fans = 65–175 W
- Hair dryer = 1200–1875 W
- Microwave oven = 750–1100 W
- Personal computer
  - CPU - awake / asleep = 120 / 30 W or less
  - Monitor - awake / asleep = 150 / 30 W or less
  - Laptop = 50 W
- Radio *(stereo)* = 70–400 W
- Refrigerator = 725 W
- Flatscreen TV = 120 W
- VCR/DVD = 17–21 / 20–25 W
- Vacuum cleaner = 1000–1440 W
- Water heater *(40 gallon)* = 4500–5500 W

- If all these were running at max capacity at one time, this would draw on the order of **20 kW** of power.

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What do we need power for?

- Near Earth
  - Broadcast satellites
  - Commercial air traffic radar
  - Space Shuttle
  - International Space Station
  - Military: monitoring, control, tracking
  - Strategic defense
- Lunar or Martian base operations (manned or unmanned)
- Unmanned vehicle propulsion to outer planets
- Propulsion and spacecraft power for manned missions

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Solar Power Limitations

- Mission destination relative to the sun
- Harsh space environment may not allow sustained use of solar cells (radiation, micrometeroids)
- Limitations on landing sites – may have insufficient illumination near lunar or planetary poles
- Night environments of significant duration – may be beyond practical battery capacity
- Subsurface applications or application on a dust- or cloud-enshrouded world may render solar power impractical / impossible

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