UT-BATTELLE

Nuclear Reactor Power for Exploration of Moon, Mars and Beyond

Panel Discussion for Women In Nuclear Region II Conference

The Future of Nuclear Energy – Space Power Applications

Ray F. Holdaway
Space Reactor Technology Program

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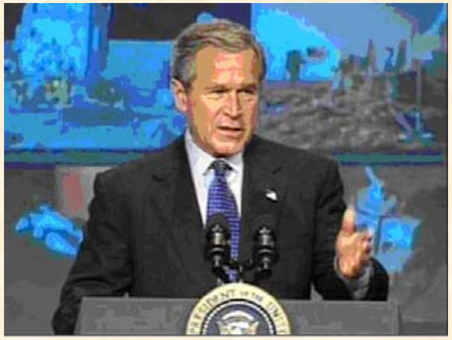
ray@ornl.gov

President Bush launched the Vision for Space Exploration in January 2004 – Moon, Mars and Beyond



Initial milestones for VSE…
- **Build Crew Exploration Vehicle by 2008**
- **Robotic human precursor mission to Mars by 2012**
- **Land astronauts on Moon by 2015 to 2020**

Key comments by President Bush…
- "Inspired by all that has come before and guided by clear objectives, today we set a new course for America's space program."
- "Robotic missions will serve as trailblazers…"
- Regarding the CEV: "…the main purpose of this spacecraft is to carry astronauts beyond our orbit to other worlds."
- "We chose to explore space because doing so improves our lives and lifts our national spirit."

Previous U.S. nuclear space power programs were curtailed for lack of a mission

NB-36H

c.1955

Aircraft Nuclear Propulsion (ANP) Program

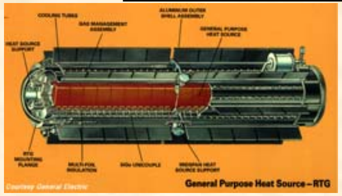
- Developed in 1940s and 1950s
- Extensive development of alloys and systems
- Molten salt fuel reactor – 1 megawatt power
- 47 flights - reactor powered (no propulsion)

SNAP 10A

Space Nuclear Auxiliary Power (SNAP) Program

- Extensive development and test program
- Launched SNAP-10A reactor in 1965 (shutdown but still orbiting)
- Forerunner of current General Purpose Heat Source (GPHS) Radioisotope Thermoelectric Generator (RTG) Program

GPHS RTG



Nuclear Thermal Propulsion

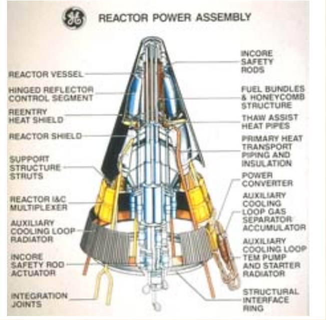
NERVA

- NERVA/Rover program
- 28 engine tests between 1959 & 1972

SP-100

- Development 1980s and early 1990s
- Liquid-metal-cooled thermoelectric 100 kW(e)

SP 100



VSE is enabled by high levels of power provided by nuclear reactors

- **Propulsion**
  - **Chemical rockets unsuitable for Mars manned mission**
  - **Candidates**
    - **Nuclear Electric Propulsion**
    - **Nuclear Thermal Propulsion**

- **Surface power**
  - **Solar cells provide adequate power for small applications on Moon & Mars**
  - **GPHS/RTG power units provide a few hundreds of watts**
  - **Large-scale habitat environmental conditioning or resource utilization requires nuclear reactor power**

A Nuclear Electric Propulsion system performs eight principal functions…

Concept for an NEP spacecraft

1. Generate heat in the reactor core
2. Move heat from reactor core to the heat-to-electricity conversion unit
3. Convert thermal power to electrical power
4. Control the system autonomously
5. Reject waste heat
6. Shield humans &/or sensitive hardware from neutron and gamma radiation
7. Condition and transfer electrical power to the thrusters
8. Thrusters accelerate and eject ions

Nuclear Electric Propulsion (NEP) systems generate very low thrust but can thrust continuously during transit

Several variations of NEP are under consideration

Major element	Technology options	Considerations
Reactor	• Nuclear fuel - e.g., uranium nitrides or oxides • Fuel clad – stainless steel, superalloys, refractory alloys • Reactivity controls – reflectors, absorbers	• Operating temperature • Operating life • Operating power levels and profiles • Conversion efficiency • Radiator size • Control strategies • Human-rated? • Mass – Mass – Mass
Primary heat transfer	• Liquid metals – e.g., Li, K, Na, NaK • Gas – He, Xe, mixtures • Molten salts • Heat pipes	
Power conversion	• Active systems – e.g., Brayton, Rankine or Stirling • Passive systems – e.g., thermoelectric	

A Nuclear Thermal Propulsion system performs three principal functions…

Large NERVA engine

1. **Generate heat in the reactor core**
2. **Transfer heat to flowing stream of hydrogen gas**
3. **Eject the heated hydrogen through a nozzle**

NTP engines can be designed for low thrust (<5,000 lb) to very high thrust (>>100,000 lb)

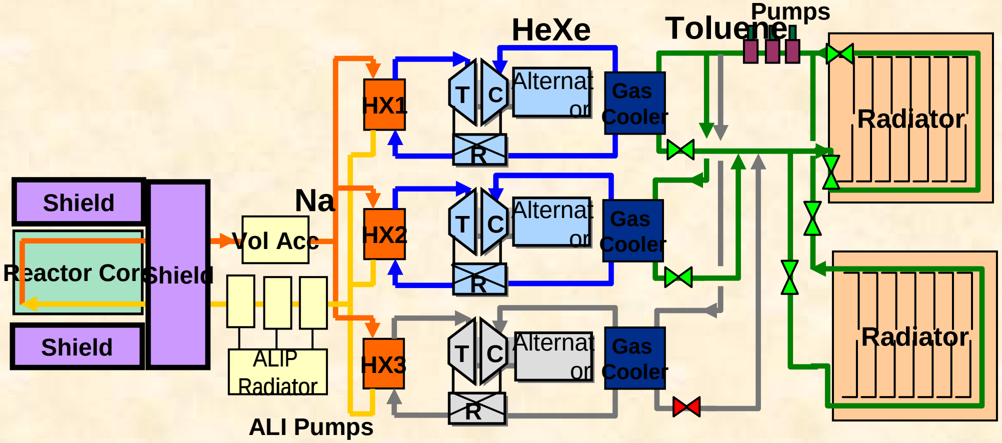
Nuclear Thermal Propulsion (NTP) systems can generate very large thrust but only has to operate intermittently. NTP trip time to Mars is a few <u>months</u> as compared to a few <u>years</u> by NEP.

Several variations of NTP are under consideration

Major element	Technology options	Considerations
Reactor	• Nuclear fuel – e.g., uranium carbide in carbon composite or cermet • Gas pathway geometries • Fuel coatings • Structural materials	• Operating temperature • Operating life • Operating power levels and profiles • Number of firing cycles • Control strategies • Human-rated? • Mass – Mass – Mass
Primary heat transfer	• Hydrogen	
Power conversion	• NA – unless Bimodal*	

*Bimodal NTP systems would produce power for propulsion and electrical power for spacecraft loads

A surface power system performs seven principal functions…



Concept for surface power unit

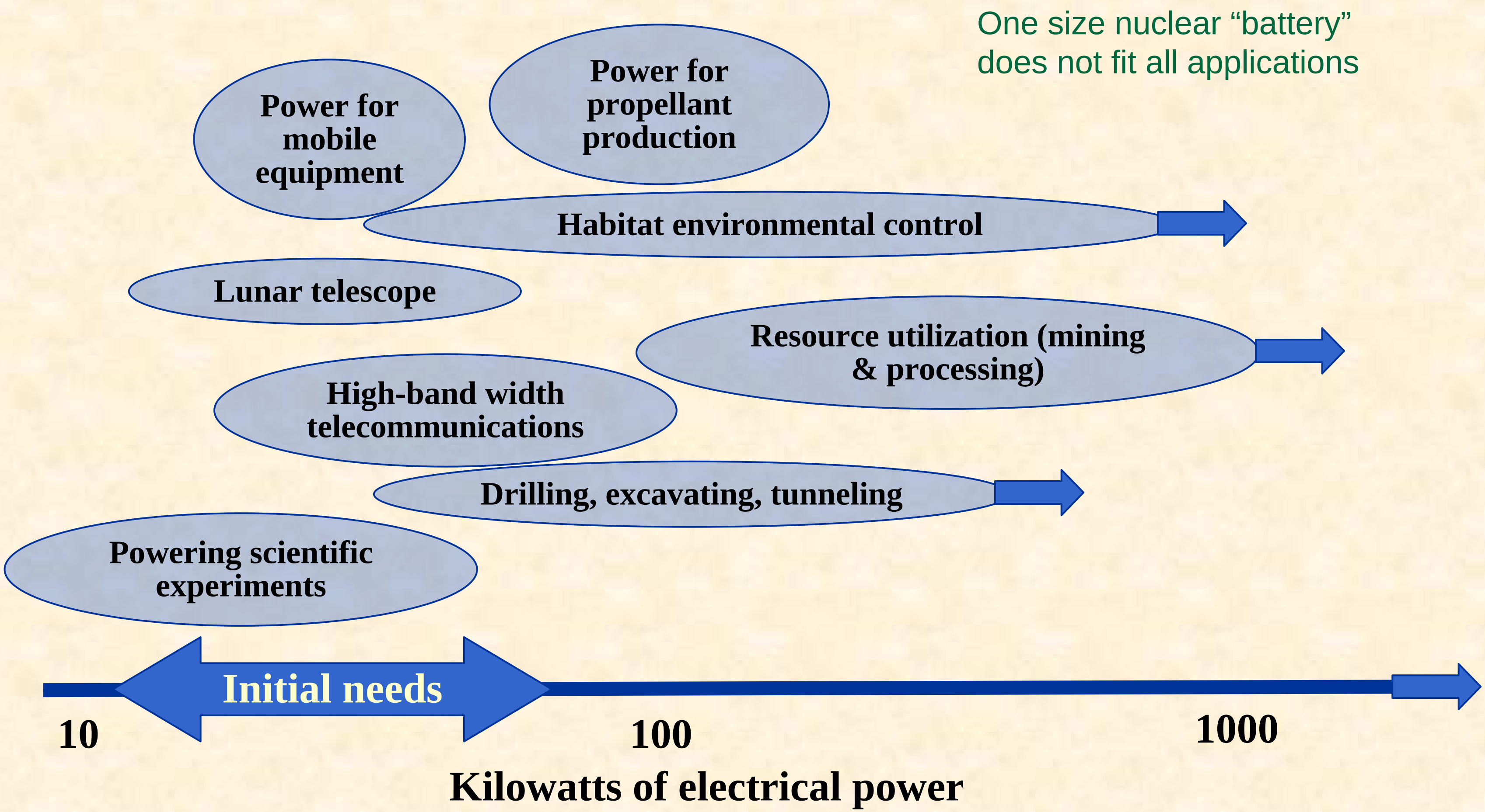
1. Generate heat in the reactor core
2. Move heat from reactor core to the heat-to-electricity conversion unit
3. Convert thermal power into electrical power
4. Control the system autonomously
5. Reject waste heat
6. Condition and transfer electrical power electrical loads
7. Shield humans &/or sensitive hardware from neutron and gamma radiation

Surface power units must provide power for various load conditions and duty cycles – depending on the application

Several nuclear reactor-based surface power concepts are under consideration

Major element	Technology options	Considerations
Reactor	• Nuclear fuel - e.g., uranium nitrides or oxides • Fuel clad – stainless steel, superalloys, refractory alloys • Reactivity controls – reflectors, absorbers	• Operating temperature • Operating life • Operating power levels and profiles • Conversion efficiency • Radiator size • Control strategies • Human-rated? • Radiation shielding strategies • Oxidizing environment on Mars vs vacuum on Moon • Adaptability of in-space reactor for SP applications • Mass – Mass – Mass
Primary heat transfer	• Liquid metals – e.g., Li, K, Na, NaK • Gas – He, Xe, mixtures • Molten salts • Heat pipes	
Power conversion	• Active systems – e.g., Brayton, Rankine or Stirling • Passive systems – e.g., thermoelectric	

Nuclear reactor-based surface power systems for Moon and Mars can be tailored to the need

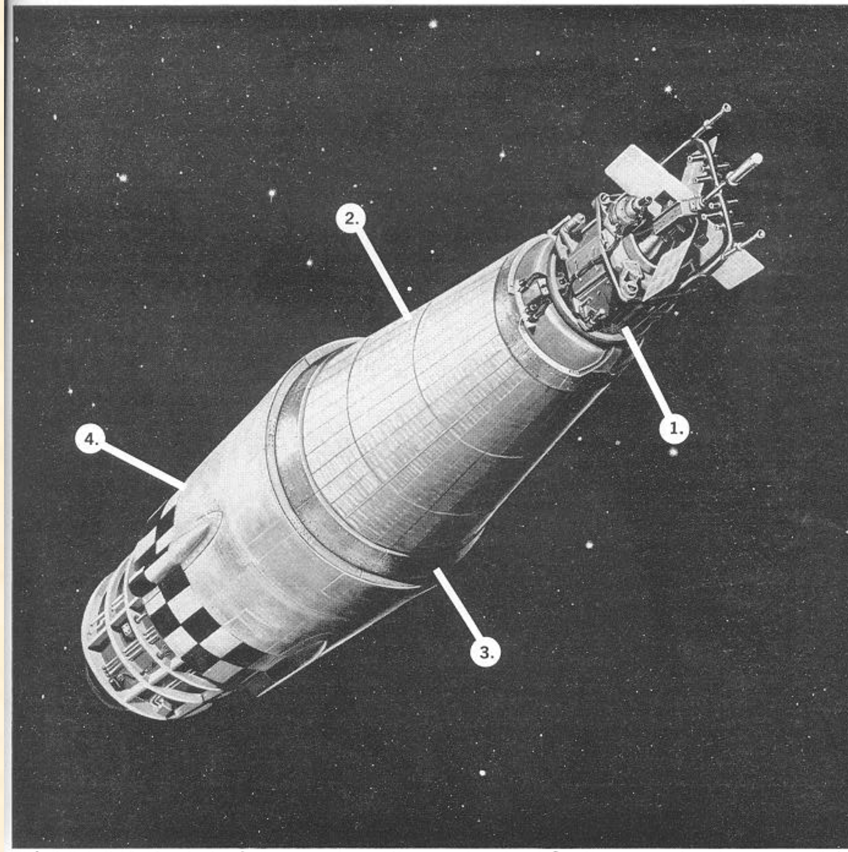


Current VSE focus: Roadmapping – determining what capabilities are needed and affordable and identifying candidate missions

	Moon--→	Mars--→	Beyond
Robotic missions	Human precursor by 2012	Where, how and when?	Where, how and when?
Brief human visits	By 2020?	Where, how and when?	Where, how and when?
Long-term human habitation	Where, how and when?	Where, how and when?	Where, how and when?

The goal of the ongoing roadmapping exercise is to provide the basis for a national consensus on the path forward for achieving the Vision for Space Exploration…

2005 is the 40th anniversary of the launch of SNAP 10A



1. Nuclear reactor to produce heat 2. Thermoelectric units to convert heat into electricity 3. Instrumentation compartment 4. Agena vehicle

This is SNAP 10A

the world's first nuclear reactor in space and the newest addition to America's space power from North American Aviation

SNAP 10A is more than 700 miles out in space... circling the earth every 112 minutes in a 4,000-year orbit. During its 43 days of uninterrupted, flawless operation, it produced over 500,000 watt-hours of electricity. SNAP reactor systems can provide power for observation and weather satellites, orbiting laboratories, electrical propulsion in space, and for communicating directly from space to ordinary antennas on the ground. The SNAP 10A system was designed and built by North American Aviation/Atomics International Division for the Atomic Energy Commission. NAA/Rocketdyne built the Atlas rocket engines that launched it. North American Aviation is a leader in electronics, aviation, life sciences, space flight, atomic energy, rocketry, and basic research.

North American Aviation

Atomics International, Autonetics, Columbus, Los Angeles, Rocketdyne, Science Center, Space & Information Systems

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