Nuclear Energy for Space Exploration

Presented

June 5-6, 2010

Dr. Michael G. Houts
Marshall Space Flight Center

NASA Speakers Bureau
Basics of Space Nuclear Systems

Radioisotope Decay (Pu-238)

Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)
Natural decay rate (87.7-year half-life)

- Long history of use on Apollo and space science missions
  - 44 RTGs and hundreds of RHUs launched by U.S. during past 4 decades
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production

Fission (U-235)

Heat Energy = 0.851 MeV/nucleon
Controllable reaction rate (variable power levels)

- Used terrestrially for over 65 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a “chain reaction” process
- Heat converted to electricity, or used directly to heat a propellant
Creating a fission chain reaction is conceptually simple
- Requires right materials in right geometry

Good engineering needed to create safe, useful, long-life fission systems

- 1938 Fission Discovered
- 1939 Einstein letter to Roosevelt
- 1942 Manhattan project initiated
- 1942 First sustained fission chain reaction (CP-1)
- 1943 X-10 Reactor (ORNL), 3500 kWt
- 1944 B-Reactor (Hanford), 250,000 kWt
- 1944-now Thousands of reactors at various power levels
Fission Reactor Operation

- System power controlled by neutron balance
- Average 2.5 neutrons produced per fission
  - Including delayed
- Constant power if 1.0 of those neutrons goes on to cause another fission
- Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0
- System controlled by passively and actively controlling fraction of neutrons that escape or are captured
- Natural feedback enables straightforward control, constant temperature operation
- 200 kWt system burns 1 kg uranium every 13 yrs
### Reactor Operation (Notional)

**Power Level $\propto$ Fission Rate $\propto$ Neutron Flux**

<table>
<thead>
<tr>
<th>Power Level</th>
<th>Power Production</th>
<th>Reactor Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (k &gt; 1)</td>
<td>3 (k &gt; 1)</td>
<td>Startup (k &gt; 1)</td>
</tr>
<tr>
<td>2 (k = 1)</td>
<td>4 (k = 1)</td>
<td>Steady Power Production</td>
</tr>
<tr>
<td>5 (k &lt; 1)</td>
<td>5 (k &lt; 1)</td>
<td>Shutdown (k &lt; 1)</td>
</tr>
</tbody>
</table>

**Time (not to scale)**

1. Control drums rotate to provide positive reactivity (supercritical). Power increases, reactor heats up.
2. As reactor temperature increases, natural feedback reduces reactivity to zero. System maintains temperature.
3. Control drums rotate to provide additional reactivity, until desired operating temperature is achieved.
4. Reactor follows load, maintaining desired temperature. Control drums rotate ~monthly to compensate for fuel that is consumed.
5. Control drums rotate to shut system down.

---

**Thermal Power**

\[ P(t) \propto N(t) \]

**Reactivity**

\[ \rho \equiv \frac{k - 1}{k} \]

\[ k \equiv \text{Multiplication Factor} \]

\[ \frac{dN}{dt} = \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t/l_n)}{N(t)} \]

- \( < 1 \) (subcritical, \( dN/dt < 0 \))
- \( = 1 \) (critical, \( dN/dt = 0 \))
- \( > 1 \) (supercritical, \( dN/dt > 0 \))
Natural uranium consists of

- U-234 0.0055%
- U-235 0.720%
- U-238 99.274%

Most reactor designs use uranium fuel enriched in U-235

Prior to operation at power, uranium fuel is essentially non-radioactive and non-heat producing

Following long-term operation, fission product decay power is 6.2% at $t=0$ (plus fission power from delayed neutrons)

- 1.3% at 1 hour
- 0.1% at 2 months

Space reactor radiation exposure risk is primarily from inadvertent system start while personnel are near reactor

- Prevent inadvertent start via procedures, hardware, and design techniques developed over the past 6 decades
Radiation Shielding

- Reactor needs to be shielded during operation and for a period of time following operation at significant power.

- Hydrogen bearing compounds (e.g. LiH, H₂O) are most mass effective neutron shields.
  - Neutron shielding only needed while operating.

- High density, high atomic number materials (e.g. tungsten, uranium) best for gamma shielding, although areal density (mass/area) is primary requirement.

- NTP missions typically propose using propellant, consumables, and other “available” materials for shielding.

- Reactor can be shielded to any level desired.
  - Dose rate drops rapidly following shutdown.
Fission is Highly Versatile with Many Applications

- **Small research reactors**
  - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< $50M)

- **Advanced, high-power research reactors and associated facilities**
  - Examples include the US Fast Flux Test Facility (400,000 kWt, ~$3.0B FY08)

- **Commercial Light Water Reactors**
  - 1,371,000 kWe (3,800,000 kWt)
    - Recent TVA cost estimate ~$2.2B

- **Space reactors**
  - SNAP-10A 42 kWt / 0.6 kWe
  - Soviet reactors typically 100 kWt / 3 kWe (some systems >150 kWt)
  - Cost is design-dependent
Fission is Highly Versatile with Many Applications (continued)

♦ Naval Reactors
  - Hundreds of submarines and surface ships worldwide

♦ Production of medical and other isotopes

♦ Fission Surface Power
  - Safe, abundant, cost effective power on the moon or Mars

♦ Nuclear Thermal Propulsion
  - Potential for fast, efficient transportation throughout inner solar system

♦ Nuclear Electric Propulsion
  - Potential for efficient transportation throughout solar system

♦ Highly advanced fission systems for solar system exploration
Recent interest in Fission Surface Power (FSP) to support moon / Mars exploration

- Continuous Day/Night Power for Robust Surface Operations
- Same Technology for Moon and Mars
- Suitable for any Surface Location
  - Lunar Equatorial or Polar Sites
  - Permanently Shaded Craters
  - Mars Equatorial or High Latitudes
- Environmentally Robust
  - Lunar Day/Night Thermal Transients
  - Mars Dust Storms
- Operationally Robust
  - Multiple-Failure Tolerant
  - Long Life without Maintenance
- Highly Flexible Configurations
  - Excavation Shield Permits Near-Habitat Siting
  - Option for Above-Grade System or Mobile System (with shield mass penalty)
  - Option for Remote Siting (with high voltage transmission)
  - Option for Process Heat Source (for ISRU or habitat)
Safe During All Mission Phases
- Launched Cold, No Radiation Until Startup
- Safe during Operation with Excavation or Landed Shield
- Safe after Shutdown with Negligible Residual Radiation

Scalable to Higher Power Levels (kWs to MWs)

Performance Advantages Compared to PV/RFC
- Significant Mass & Volume Savings for Moon
- Significant Mass & Deployed Area Savings for Mars

Competitive Cost with PV/RFC
- Detailed, 12-month “Affordable” Fission Surface Power System Cost Study Performed by NASA & DOE
- LAT2 FSP and PV/RFC Options had Similar Overall Cost
- Modest Unit Cost Enables Multiple Units and/or Multiple Sites

Technology Primed for Development
- Terrestrial Reactor Design Basis
- No Material Breakthroughs Required
- Lineage to RPS Systems (e.g. Stirling) and ISS (e.g. Radiators, Electrical Power Distribution)
“Affordable” Design Philosophy

♦ Conservative
- Low Temperature
- Known Materials and Fluids
- Generous Margins
- Large Safety Factors
- Terrestrial Design Basis

♦ Simple
- Modest Power & Life Requirements
- Simple Controls
  - Negative Temperature Reactivity Feedback: assures safe response to reactor temperature excursions
  - Parasitic Load Control: maintains constant power draw regardless of electrical loads and allows thermal system to remain near steady-state
- Slow Thermal Response
- Conventional Design Practices
- Established Manufacturing Methods
- Modular and Testable Configurations

♦ Robust
- High Redundancy
- Fault Tolerance... including ability to recover from severe conditions such as:
  - Loss of Reactor Cooling
  - Stuck Reflector Drums
  - Power Conversion Unit Failure
  - Radiator Pump Failure
  - Loss of Radiator Coolant
  - Loss of Electrical Load
- High TRL Components
- Hardware-Rich Test Program
- Multiple Design Cycles

Minimize Cost by Reducing Risk -- Accept Mass Penalties if Needed
### Key Design Features

#### Reactor Core:
- Well-known UO₂ fuel and SS-316 cladding at moderate temperature (<900K)
- Low power (<200 kWt), low fuel burn-up (~1%)
- Fluence levels well below material thresholds
- NaK coolant: low freeze temp (262K), extensive space & terrestrial technology base
- Simple and safe, negative temperature feedback control

#### Reactor Module:
- Fault-tolerant, radial Be reflector control drums
- Low-risk B4C and SS shielding with regolith augmentation
  - <2 Mrad and 1x10¹⁴ n/cm² at power conversion; <5 rem/yr at outpost (100 m)
  - SS-316 primary & intermediate coolant loops with redundant EM pumps
  - Cavity cooling with surface-mounted radiators

#### Stirling Power Conversion:
- High efficiency (>25%) at low hot-end temperature (830K)
- Pumped-water cooling (400K)
- Smallest radiator size among PC options
- 4 dual opposed engines, 8 linear alternators
- 400 Vac power distribution
- Demonstrated technology at 25 kW size in 1980’s
- Potential to leverage current RPS program
♦ 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 UO₂ Fuel and Stainless Steel Construction
2 kWe NaK Stirling Demonstration Test

Test Validated Reactor-Stirling Heat Transfer Approach for FSP (Stirling provided by NASA–GRC)

- 2.4 kWe at Thot=550ºC, Tcold=50ºC
- 32% Thermal Efficiency
- <5ºC Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK

Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core

Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory
EFF-TF ALIP Test Circuit

Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory
NaK Pump Testing

ALIP Drawing

ALIP unpacked at MSFC EFF-TF by INL and MSFC team members
Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

ALIP Test Circuit (ATC)

Enhanced heating assembly ready for application of insulation

ATC ready for chamber prior to NaK fill

Enhanced heating assembly

NaK fill

ATC Testing
Feasibility Test Loop:

Investigate potential issues and optimizations related to pumped alkali metal systems
Fission Surface Power – Primary Test Circuit (FSP-PTC)
7 – Pin Reactor (Rx) Core Simulator Testing

7-pin Rx Core Sim Rendering

MSFC Designed Advanced Simulators

7-Pin Rx Core Sim

37 – Pin TDU Rx Core Sim

Revised FSP-PTC layout for 7 – Pin Rx Core Sim

7 Pin Rx Core Sim installed in FSP-PTC
FSPS Accomplishments

Recent Activities Focused Towards TDU Reactor Simulator

MILESTONES
Fabricate & Test: 2010-2011
Ship to GRC 2012
Space Nuclear Power and Propulsion

FSP Technology Project: Risk Reduction

- 20 kWt NaK Reactor Simulator
- 2 kWt NaK Stirling System
- 2 kWt Direct Drive Gas Brayton
- 5 kWt Stirling Demonstrator
- NaK Annular Linear Induction Pump
- 10 kWt Stirling Alternator Test Rig
- 25 kWt Dual Brayton System
- Ti-H2O Heat Pipe Life Test
- 1 kWt Radiator Demo Unit
Typical system: hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust

~850 second Isp demonstrated in ground tests at high thrust/weight

Potential for > 900 s Isp with advanced fuel forms and cycles

Potential Applications

- Rapid robotic exploration missions throughout solar system
- Piloted missions to Mars and other potential destinations
- Potential to significantly reduce propellant needs and/or trip time
NTP Concerns

- Cost/schedule – new engine system, nuclear testing, launch processing, potential opposition, INSRP process, etc.
- Potential operational constraints.

NTP Benefits

- Significant new capability. Reduce mission mass and/or time.
- Flexible choice of propellant, effectively unlimited energy.
- Significant cost savings /sustainable exploration program.
Nuclear Thermal Propulsion (NTP) Has The Potential to be Mission Enabling

Comparison of IMLEO vs. Trip Time for All-up Opposition and Conjunction Mars Missions*

Short Stay-Time Missions: NTP captures most opportunities, and chemical systems capture only one opportunity

*Source: NASA's Office of Aeronautics, Exploration and Technology, presented to Stafford Synthesis Team in 1991
Proposed Types of Nuclear Thermal Propulsion

- **SOLID CORE NUCLEAR ROCKET**
- **LIQUID CORE NUCLEAR ROCKET**
- Open-Cycle Gas Core Nuclear Rocket
- Closed-Cycle Gas Core Nuclear Rocket
## NTP History

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>Phoebus 2</td>
<td>5,000 MW, 250,000 lbf</td>
</tr>
<tr>
<td></td>
<td>N.E.R.V.A. (NERVA)</td>
<td>1960s program for developing nuclear space propulsion engines</td>
</tr>
<tr>
<td></td>
<td>K.I.W.I.</td>
<td>Dead end study for a small, low-power reactor</td>
</tr>
<tr>
<td></td>
<td>Pewee</td>
<td>Low-power experimental reactor</td>
</tr>
<tr>
<td></td>
<td>N.F. Furnace</td>
<td>Nuclear furnace for testing nuclear fuels</td>
</tr>
</tbody>
</table>

### Research & Technology Development

- **1950s**
  - Fundamental feasibility
  - Engine burn time
  - Start-up & shut-down cycles
  - Thermal transients
  - Ground testing

- **1960s**
  - Characterized performance for human lunar and Mars applications
  - CERMET fuel fabrication and fundamental feasibility

- **1970s**
  - Carbide fuel development
  - Particle-bed reactor

- **1980s**
  - Human system concept design & development
  - Tradespace definition for human Mars missions
  - Human missions to outer planets, asteroids, and early Mars vicinity
  - Systems studies for human Mars mission applications
  - NTP facility and design studies

### System Studies

- Reusable Mars Transfer Vehicle using Single 75 klbf Engine

### Project Formulation

- Flight test system formulation

### US Contracts

- XE-Prime 1969
  - 1,140 MW
  - 55,400 lbf
NTP could enhance the ability to reach new destinations

NTP could enable a steady, progressive, regular and affordable exploration program

As envisioned, NTP reduces required launch mass, reduces trip time, and increases mission opportunity. Over time, NTP could reduce exploration costs
Rover/NERVA Engine Comparison

Progression of Rover Reactors

KIWI A
1958-1960
100 MW
0 lbf Thrust

KIWI B
1961-1964
1,000 MW
50,000 lbf Thrust

Phoebus 1
1965-1966
1,000 & 1,500 MW
50,000 lbf Thrust

Phoebus 2
1967
5,000 MW
250,000 lbf Thrust

XE-Prime
1969
1,140 MW
55,400 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

Culmination of NERVA Program
Phoebus-2A

- Tested 1968
- 5 GW Reactor Core (tested at 4.2 GW)
- 805 seconds Isp space Equiv.
- 250,000 lbf Thrust
XE’ Engine
- Tested 1969
- 1.1 GW Reactor Core
- 820 seconds Isp space Equiv.
- 55,000 lbf Thrust
Over a thousand Kuiper Belt objects identified since 1992
- Composed primarily of methane, ammonia, water
Small icy moons, asteroids, and comets also identified
Use nuclear thermal “steam” rockets to change orbits of icy bodies?
- In theory, any vapor can be used for NTP propellant
  - No chemical reactions required
  - Improved NTP materials will improve performance
  - Gravity assists to reduce required ΔV
Use icy bodies for propellant depots?
- Volatiles used directly as propellant in NTP-based transportation system
Use icy bodies for terraforming?
Three-Burn Quick Mars Trip
Quickest Mission w/o Becoming Hyperbolic

1000 A.U. Ellipse is Near to a Solar System Escape Trajectory
Time to Mars approx. 2.3 months

1. $\Delta V_1$ (from LEO) = 5.01 km/s
2. $\Delta V_2$ (from S$_1$ to S$_2$) = 5.75 km/s
3. $\Delta V_3$ (from S$_2$ to Mars) = 20.3 km/s

Payload: 100 mt
IMLEO: 1763.6 mt

Earth’s Path
Mars’ Path
Post $\Delta V_1$ Ellipse
Post $\Delta V_2$ Ellipse
Mars “Fast” Trajectory

Larry Kos
MSFC/TD31
08/04/99
Planetary Trip Times
Quickest Missions w/o Becoming Hyperbolic

Spacecraft
Trip Time, one-way
(30 days = 1 unit)

Distance (A.U.)

Hyperbolic Trip Time (e = 1.0011)
Elliptical Trip Time (e = 0.998)
Fusion Reactions

Sun

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + \text{antielectron} + \text{neutrino} \]

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + \text{antielectron} + \text{neutrino} \]

\[ \text{electron} + \text{antielectron} \rightarrow \text{photon} + \text{photon} \]

\[ \text{electron} + \text{antielectron} \rightarrow \text{photon} + \text{photon} \]

\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \text{photon} \]

\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \text{photon} \]

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^1\text{H} + ^1\text{H} \]

Net Result:

\[ 4\ ^1\text{H} + 2\text{e} \rightarrow ^4\text{He} + 2\text{neutrinos} + 6\text{gamma (26 MeV)} \]

Potential Small, Controlled Systems

D + T \rightarrow n^0 (14.07 \text{ MeV}) + ^4\text{He} (3.52 \text{ MeV})

D + D \rightarrow n^0 (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV}) (50\%)

D + D \rightarrow p (3.02 \text{ MeV}) + ^3\text{He} (1.01 \text{ MeV}) (50\%)

D + ^3\text{He} \rightarrow p (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV})

^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p (12.9 \text{ MeV})

p + ^{11}\text{B} \rightarrow 3 ^4\text{He} (8.7 \text{ MeV})
Beyond Fission: Potential Futuristic Nuclear Energy Sources

Fusion: The performance potential of lightweight, high gain fusion propulsion systems operating with aneutronic fuels (e.g. p-^{11}B) theoretically exceeds that of fission by an order of magnitude.

Fundamental Issues to Resolve:
1. **Aneutronic Fuels.** The performance potential of fusion propulsion systems operating with deuterium or tritium bearing fuels (e.g. D-T, D-D, or D-^{3}He) is severely limited because of waste heat production from neutron kinetic energy, and the additional waste energy released when a neutron of any energy is captured. The use of aneutronic fuels (e.g. p-^{11}B) will be required for high performance.

2. **High Gain.** Recent studies (Chakrabarti et al., 2001) have shown that high engineering gain (Q>50) is needed to minimize the mass of the fusion reaction driver and enable high performance.

3. **Compact Systems.** Significant funds and five decades have been spent on research related to controlled fusion. While the two leading approaches for achieving engineering breakeven are extremely massive, knowledge and experience from the ongoing terrestrial fusion effort may be useful in devising compact systems suitable for space propulsion applications.
Antimatter: Energy stored as antimatter has a specific energy of $1.8 \times 10^{17}$ J/kg, over 500 times that of fission or fusion.

**Fundamental Issues to Resolve:**

1. **Production.** Antiproton production rates must increase by several orders of magnitude, and the cost per antiproton must decrease correspondingly.

2. **Storage.** Effective methods for long-term antiproton storage and transportation must be developed.

3. **Thrust Production.** Effective methods for converting energy stored as antimatter into high specific impulse thrust must be devised.
Summary

♦ Nuclear power and propulsion systems can enable exciting space exploration missions. These include bases on the moon and Mars; and the exploration, development, and utilization of the solar system.

♦ In the near-term, fission surface power systems could provide abundant, constant, cost-effective power anywhere on the surface of the Moon or Mars, independent of available sunlight. Affordable access to Mars, the asteroid belt, or other destinations could be provided by nuclear thermal rockets.

♦ In the further term, high performance fission power supplies could enable both extremely high power levels on planetary surfaces and fission electric propulsion vehicles for rapid, efficient cargo and crew transfer. Advanced fission propulsion systems could eventually allow routine access to the entire solar system. Fission systems could also enable the utilization of resources within the solar system. Fusion and antimatter systems may also be viable in the future.