Nuclear power for space applications

Dr Mark Ho
Outline

1. Nuclear Thermal Propulsion

2. RTGs
   Radioisotope Thermoelectric Generators – for electricity.

3. Space Fission Systems (> 1 kW)
Choices

100 MW NTP @ $10^5$ kW$_{th}$

100 kW$_e$

Solar

Chemical

ISS 120 kW$_e$

Rosetta

1500 – 400 W$_e$

Philae (lander)

32 W$_e$
to comet 67P/Churyumov–Gerasimenko

Not much Solar in deep space

Solar flux drops as inverse square of distance from Sun (4% of Earth at Jupiter) forcing spacecraft solar arrays to become too large for distant missions.

- Outer solar system missions where solar energy or other internal power sources will not meet mission requirements
- Surface operations in sun starved or shadowed areas
- Near the sun where current solar panel technology cannot perform due to high temperatures

1. Nuclear Thermal Propulsion
Why Nuclear Thermal Propulsion?

\[ \Delta V = v_e \ln \frac{m_0}{m_f} \]

\[ \frac{m_0}{m_f} = e^{\frac{\Delta V}{v_e}} \]

Tsiolkovsky’s equation

The maximum change in velocity is the propellant exhaust velocity multiplied by the natural log of the initial mass and final mass ratio

\[ I_{sp} = \frac{v_e}{g_0} \]

Specific Impulse (sec.)

The time it takes for one kilogram of propellant to produce one newton of thrust.

1. High exhaust velocity is good
2. Optimally the initial and final vehicle mass should be as small as possible.

Higher specific impulse, means higher efficiency.
# Engine selection depends on the mission

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Chemical Rocket</th>
<th>Chem. R.</th>
<th>NTR</th>
<th>Ion drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine name</td>
<td>Raptor 1st stage</td>
<td>J-2 (SLS)</td>
<td>Pheobus 2A</td>
<td>NEXT</td>
</tr>
<tr>
<td>Propellant</td>
<td>CH₄ / LOX</td>
<td>LH₂ / LOX</td>
<td>LH₂</td>
<td>Xenon</td>
</tr>
<tr>
<td>Thrust to Weight Ratio</td>
<td>&gt;180</td>
<td>55</td>
<td>3.2</td>
<td>v. low</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>330 – 380 s</td>
<td>448 s</td>
<td>925 s</td>
<td>4400 s @6.9kW</td>
</tr>
<tr>
<td>Max. Thrust</td>
<td>1,993 kN</td>
<td>1,310 kN</td>
<td>930 kN (tested)</td>
<td>0.236 N</td>
</tr>
</tbody>
</table>

![Raptor](image1.png)  ![J-2](image2.png)  ![Pheobus 2A](image3.png)  ![NEXT](image4.png)
Options other than Hohmann Transfer

• **Opposition-Class Mission Characteristics**  
  (Used in “90-Day” / SEI Mars Studies)  
  - Short Mars stay times (typically 30 - 60 days)  
  - Relatively short round-trip times (400 - 650 days)  
  - Missions always have one short transit leg (either outbound or inbound) and one long transit leg  
  - Long transit legs typically include a Venus swing-by and a closer approach to the Sun (~0.7 AU or less)  
  - This class trajectory has higher ΔV requirements  

  **NOTE:** Short orbital stay missions will likely be chosen for initial human missions to Mars and its moons, Phobos and Deimos.

• **Fast-Conjunction Class Mission Characteristics**  
  (Used in DRM 4.0 and DRA 5.0 Studies)  
  - Long Mars stay times (500 days or more)  
  - Long round trip times (~900 days)  
  - Short “in-space” transit times (~150 to 210 days each way)  
  - Closest approach to the Sun is 1 AU  
  - This class trajectory has more modest ΔV requirements than opposition missions

Source: Glenn Research Centre, NASA  
Taken from M. Houts and S. Mitchell’s presentation  
https://ntrs.nasa.gov/search.jsp?R=20160002256
Performance factors

- Mass ejection backwards ($p = mv$)
- Energy to accelerate propellant to ejection velocity. ($E = \frac{1}{2} mv^2$)
- System mass = Energy source + Propulsion device + Propellant
Hydrogen for Max. Exhaust Vel. ($v_e$)

Root Mean Square of Speed of Particles

$$v_{rms} = \sqrt{\frac{3RT}{M}}$$

- $R = \text{Gas Constant}$
- $T = \text{Temperature (Kelvin)}$
- $M = \text{Molar Mass}$

@ 295 K (Room Temperature)
- $\text{O}_2$: $v = 480$ m/s
- $\text{N}_2$: $v = 512$ m/s
- $\text{CO}_2$: $v = 409$ m/s
- $\text{He}$: $v = 1356$ m/s
- $\text{H}_2$: $v = 1918$ m/s

@ 3000 K (Reactor Temperature)
- $\text{O}_2$: $v = 1529$ m/s
- $\text{N}_2$: $v = 1634$ m/s
- $\text{CO}_2$: $v = 1304$ m/s
- $\text{He}$: $v = 4324$ m/s
- $\text{H}_2$: $v = 6092$ m/s

Exhaust velocity improves with the square root of the mass ratio of two gases.

Heat Transfer: $\text{H}_2$ is ~6 times more conductive & about half as viscous than air. Hydrogen is a neutron moderator.
Neutron cross sections

Incident neutron data / ENDF/B-VII.1 // MT=18 : (z,fission) total fission / Cross section

Fuels
Pu 241
Pu 239
U 235
U 233

Pu 240
U 238

Thermal neutrons

Fast neutrons
Rover / NERVA

KIWI A
1958–60
100 MEGAWATTS
5000 lb THRUST
(22 kN)

KIWI B
1961–64
1000 MEGAWATTS
50,000 lb THRUST
(222 kN)

PHOEBUS 1/NRX
1965–66
1000 and 1500 MEGAWATTS
50,000 lb THRUST
(222 kN)

PHOEBUS 2
1967
5000 MEGAWATTS
250,000 lb THRUST
(1,110 kN design)
(930 kN tested)

Source: U. of Wisconsin
Project Rover / NERVA (1959 - 1972)

NERVA NRX
“Kiwi”

NERVA EX
“Phoebus 1B”

Thrust = 333 kN, $I_{sp} = 850$ s

Various OKBs (1950s - 1989)

RD-410

RD-410: Thrust = 69 kN, $I_{sp} = 900$ s

Source: edX, The Conquest of Space – NTPs, Universidad Carlos III de Madrid
Reactor Features

- 93.15% high enriched uranium
- hydrogen cooled
- graphite moderated
- Epi-thermal neutron spectrum,
- Orifice sizing for flow distribution
- Neutron absorbing drums
- Varied fuel loading for flux flattening

Source: Westinghouse Astronuclear lab.
1st Gen NTP Fuel Element

https://ntrs.nasa.gov/search.jsp?R=20170003378
1 Sv = 100 REM

30 REM = 0.3 Sv

300 milliSievert

US Annual Dose:
3.5 milliSievert

RADIATION MAP

Assumes
Disk Shield and
Single 53 min Burn

Neutron Flux (n/cm²-sec > 0.3 mev)
During 1575-mw Operation

Gamma Dose Rate (rem/hr)
During 1575-mw Operation

Source: U. of Wisconsin
Ionising Radiation

Both Mir and ISS orbits at an altitude of 300 – 400 km

Sergei Avdeyev – 747 days in space
Peggy Whitson – 534 days in space

Source: NASA/JPL-Caltech/SwRI
NTPs, then and now

Then (Rover/NERVA: 1959 - 72)

- Engines tested
  - 50,000 to 250,000 pound force (lbf)
  - 222 kN – 1110 kN of thrust

- H₂ exit temperature
  - 2,350 – 2,550 K (Graphite)

- Iₚ capability
  - 825 – 850 sec (hot bleed cycle)

- Thrust to weight
  - ~3

- “Open Air” testing at Nevada Test Site

Now

- Focus on small NTRs
  - 5,000 – 15,000 lbf
  - 22 kN – 67 kN

- High Temp. fuel under development
  - 2,700 (Composite)
  - 2,990 K (Cermet - W matrix with UO2)
  - ~3,100 (Ternary Carbides)

- Iₚ capability
  - 915 – 1005 sec (expander cycle)

- Thrust to weight improvement:
  - reportedly up to 6 for small NTRs

- Contained Test Facility at INL

- $100 million for NTP research (2019)

Source: NASA/CP—2004-212963/VOL1
Design Ref Arch. 5.0

Source: BWXT
2. Radioisotope Thermoelectric Generators

New Horizons Mission to Pluto & Kuiper Belt

Stats

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>Power (t₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>478 kg</td>
<td>245 Wₑ</td>
</tr>
<tr>
<td>RTG</td>
<td>57 kg</td>
<td>~4000 Wₑ</td>
</tr>
<tr>
<td>PuO₂</td>
<td>11 kg</td>
<td>~4000 Wₑ</td>
</tr>
</tbody>
</table>

Launched: 2006 @ Pluto 2015
Thermo-electric Generator

Basic thermoelectric generator operation

1. Nuclear fuel (e.g., plutonium-238) decays spontaneously producing heat
2. Thermocouples convert heat directly into electricity
3. Electricity is tapped from terminals connected to thermocouples
4. Power output: SiGe + Phosphorus doping

SiGe + Boron doping

RTG missions

*Apollo 11’s lunar experiments package included a heater containing plutonium-238. The Mars rovers Sojourner, Spirit and Opportunity were primarily solar-powered but they also carried heaters with a small amount of nuclear material.

SOURCES: NASA, JET PROPULSION LABORATORY, U.S. DEPARTMENT OF ENERGY

KARL TATE / © SPACE.com
Systems for Nuclear Auxiliary Power (SNAP)

SNAP-9A
plutonium-238
$\lambda = 88$ years
$^{238}\text{Pu} \rightarrow ^{234}\text{U} + ^4\text{He}$
$25$ $W_e$

SNAP-3
polonium-210
$\lambda = 5$ months
$2.5$ $W_e$

AEC Chairman Glenn T. Seaborg, left, compares a SNAP-9A “atomic battery” (bottom center) with a full-scale model of a SNAP-3B atomic battery held by Major Robert T. Carpenter, AEC-SNAP project engineer. (Photo: 434-N-AEC-63-7042. General Records of the Department of Energy, RG 434, National Archives Still Picture Branch, College Park, Maryland)
Pu-238

- Half-life of 87.7 years
- Decays by 5.593 MeV alpha emission
- 1 gram of $^{238}$Pu generates 0.568 W of heat
- Produced by irradiating $^{237}$Np in a High Flux reactor

$^{237}$Np + $^1n \rightarrow ^{238}$Np ($\lambda = 2.12$ d) $\rightarrow ^{238}$Pu + $e^-$

$^{238}$PuO$_2$ pellet

- Ø 2.76 cm, Length 2.76 cm
- Power: 62.5 W$_{th}$
- Weight: 150g
- MP > 2450° C
- Created by sintering $^{238}$PuO$_2$ granules
- Iridium alloy clad (0.55 mm)

Source: Rankin et al. Production of Pu-238 Oxide for Space Exploration, WSRC-MS-2000-00061

Pellet production

Metrology
General Purpose Heat Source (GPHS)
Multi-mission RTG

- 8 GPHS stack
- 4.8 kg of Pu-238
- 2 kW thermal power
- 125 Wₑ initial
- 100 Wₑ after 14 years
- MMGTR = 45 kg
- Currently NASA has enough Pu-238 for 2 more MMTGRs

HFIR (ORNL) restarting Pu-238 production

- 400 grams p.a.
- 1.5 kg p.a. by 2025

Max. Pellet Temp. ~1300°C

Cold Side ~200°C

Source: NASA
Radioisotope Heater Units

- Heat Output - 1 watt
- Weight - 1.4 ounces
- Size - 1 inch x 1.3 inches

RHU = Radioisotope Heater Unit
RTG = Radioisotope Thermoelectric Generator

Graphic: Dr Alan Walter, (Dir. Ret.) Pacific Northwest National Laboratory
3. Space Fission Systems

Kilopower Reactor Lunar Deployment Concept

Thanks to NASA for all following material
Kilopower Reactor 1-3 kW$_e$

1000 W: 400 kg

Titanium/Water Heat Pipe Radiator

Stirling Power Conversion System

Haynes 230/Sodium Heat Pipes (Reactor Coolant)

Lithium Hydride/Tungsten Shielding

Beryllium Oxide Neutron Reflector

Uranium Molybdenum Cast Metal Fuel

$B_4C$ Neutron Absorber Control Rod

Source: NASA
Surface Reactor 3-10 kW\textsubscript{e}

10,000 W: 1500 kg

Source: NASA
KRUSTY: Kilopower Reactor Using Stirling Technology

- Vacuum Chamber for Simulated Space Environment
- Facility Shielding
- COMET Machine used to start and stop reactor by lifting reflectors around core

Flight Concept
Flight Prototypic Power System
KRUSTY Experimental Setup

Source: NASA
Flight vs KRUSTY

Flight Unit

KRUSTY Experiment

Source: NASA
Reactor Testing
Passive, Negative Reactivity Control

The warm criticals proved the simple, stable, passive behavior of the KRUSTY reactor.

In the case below, the reactivity was set so the fuel wants to maintain a temperature of 400°C.

Temperature and Power Data From KRUSTY "60-cent" Run

Note: the period of oscillation is rather long in this example (75 minutes) because the passive power draw is very low (only 100 Watts) – just as lower gravity would make a pendulum take longer to swing back and forth.

Source: NASA
## KRUSTY performance

<table>
<thead>
<tr>
<th>Event Scenario</th>
<th>Performance Metric</th>
<th>KRUSTY Experiment</th>
<th>Performance Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Startup</td>
<td>3 hours to 800 deg. C</td>
<td>1.5 hours to 800 deg. C</td>
<td>Exceeds</td>
</tr>
<tr>
<td>Steady State Performance</td>
<td>4 kWt at 800 deg. C</td>
<td>&gt; 4 kWt at 800 deg. C</td>
<td>Exceeds</td>
</tr>
<tr>
<td>Total Loss of Coolant</td>
<td>&lt; 50 deg. C transient</td>
<td>&lt; 15 deg. C transient</td>
<td>Exceeds</td>
</tr>
<tr>
<td>Maximum Coolant</td>
<td>&lt; 50 deg. C transient</td>
<td>&lt; 10 deg. C transient</td>
<td>Exceeds</td>
</tr>
<tr>
<td>Converter Efficiency</td>
<td>&gt; 25 %</td>
<td>&gt; 35 %</td>
<td>Exceeds</td>
</tr>
<tr>
<td>Converter Operation</td>
<td>Start, Stop, Hold, Restart</td>
<td>Start, Stop, Hold, Restart</td>
<td>Meets</td>
</tr>
<tr>
<td>System Electric Power Turn Down Ratio</td>
<td>&gt; 2:1 (half power)</td>
<td>&gt; 16:1</td>
<td>Exceeds</td>
</tr>
</tbody>
</table>

Source: NASA
Questions?

www.nuclearaustralia.org.au

@AustNuclear
What is Ionising Radiation?

<table>
<thead>
<tr>
<th>Type</th>
<th>Relative Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (helium nucleus)</td>
<td>20</td>
</tr>
<tr>
<td>Beta (electrons)</td>
<td>1</td>
</tr>
<tr>
<td>X-ray &amp; gamma (EM waves)</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>5-20</td>
</tr>
</tbody>
</table>

Combined measure: Sievert (Sv)
Ionising Radiation Everyday

0.05 µSv  Year’s dose at nuke-plant

0.09 µSv  Year’s dose at coal-plant

0.1 µSv  Eating a banana

0.4 µSv  Background dose / hour

40 µSv  7.5 hour flight

100 µSv  2 weeks inside Fukushima Town-hall

3,500 µSv  Australian annual background dose

7,000 µSv  CT chest scan

20,000 µSv  Australian radiation worker limit (1 year)

50,000 µSv  US radiation worker limit (1 year)

100,000 µSv  Maximum 1 year dose without risk of developing cancer

4 million µSv  Fatal dose