Thermionic Programs of the Early 1990s – TFEVP and Topaz International Program

presented by

Mike Houts
Michael.houts@nasa.gov
Basics of Nuclear Systems

Pu-238 $\rightarrow$ U-234

$\alpha$ (He-4) $\rightarrow$ Neutron

$\gamma$ Neutrons

U-235 $\rightarrow$ Fissile Nucleus (U-235)

Product Nuclei (KE 168 MeV)

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

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
Fission Introduction

• Creating a fission chain reaction is conceptually simple
  – Requires right materials in right geometry
• Good engineering needed to create safe, affordable, useful 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
Typical Space Fission System 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
Safe, Compact, Near-Term Fission Power Systems Could Help Enable Higher Power Fission Propulsion Systems

**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
- Site Survey Landers
- Remote Science Packages
- Comm Relay Stations
Fission Can Provide the Energy for Either Nuclear Thermal or Nuclear Electric Propulsion Systems

- NEP Power System Performance Projections from 2001 STAIF Conference
- Fission Surface Power and Prometheus Concepts Superimposed

Near=Liq Metal Rx, Brayton, 1300K, 6 kg/m², 200 Vac (Available ~10 yrs)
Mid=Liq Metal Rx, Brayton, 1500K, 3 kg/m², 1000 Vac (Available ~ 15-20 yrs)
Far=Liq Metal Rx, Brayton, 2000K, 1.5 kg/m², 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, 1.6x10^15 nvt, 1.2x10^8 rad @ 2 m
Crew=Human rated shielding, 5 rem/yr @ 100 m, 7.5° half angle

Chart courtesy Lee Mason, NASA GRC
NASA is Currently Funding an “Advanced Exploration Systems” Project Investigating Nuclear Thermal Propulsion (NTP)

- Nuclear thermal propulsion (NTP) is a fundamentally new capability
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- Initial systems will have specific impulses roughly twice that of the best chemical systems
  - Reduced propellant (launch) requirements, reduced trip time
  - Beneficial to near-term/far-term missions currently under consideration
- Advanced nuclear propulsion systems could have extremely high performance and unique capabilities
- A first generation NTP system could serve as the “DC-3” of space nuclear power and propulsion
Potential Advantages

Extremely high temperatures (~1800 K) confined to fuel and clad. Remainder of system can use traditional materials.

Good efficiency and high heat rejection temperature (~900 K) results in small radiator.

Potential Concerns

All thermionic converter materials must have adequate radiation resistance.

Changes in thermionic converter design directly affect reactor design.
Russian 5 kWe TOPAZ Thermionic Space Reactor
Goal:
Demonstrate the technological readiness of a Thermionic Fuel Element (TFE) suitable for use as the basic element in a thermionic reactor having an electric power output in the 0.5–to 5-MWe range and a full-power life of 7 years.

4 x 10^{22} \text{n/cm}^2 \ (E > 0.1 \text{ MeV})

5.3\% \text{ burnup}

Insulator seals, sheath insulators, fueled emitters, cesium reservoirs, interconnective TFE components
Thermionic Fuel Element Verification Program (TFEVP)

FIGURE 1. Schematic of a Typical TFE, Showing Fuel, Emitter, Ceramic-to-Metal (Insulator) Seal, and Other Components.
Accomplishments:

Preliminary design of a 2 MWe system. 9.3% efficiency, 24,000 kg. Emitter OD 12.7 mm, length 50.8 mm, 7 A/cm² current density, 1800 K emitter, 1000 K collector.

Converter performance models correlated to test data

Alumina taper seals (5 x 10²¹ n/cm², E >0.1 MeV)

Alumina-based trilayer seals (5 x 10²² n/cm², E>0.1 MeV)

Alumina insulators (5 x 10²¹ n/cm², E >0.1 MeV)
Thermionic Fuel Element Verification Program (TFEVP)

Accomplishments:
Cesium reservoirs \((1.5 \times 10^{22} \text{n/cm}^2)\)

Fueled emitters (2% burnup)

Single TFE tests (1H1, 1H2, 1H3) and multicell TFE tests (3H1, 3H5)
TOPAZ International Program

90 tons of equipment from Russia, including 2 unfueled TOPAZ 2 reactors

TOPAZ II test facility (Baikal Rig)

9 ft diameter x 20 ft high vacuum chamber, all associated equipment

TFE test rig

TISA test stand

Cesium test rig
Personnel preparing TOPAZ II for testing
TOPAZ II ready for installation of vacuum chamber
Close up of TOPAZ II reactor

Installation of heater
TOPAZ II with resistance heaters installed
Out-of-Core Thermionic Reactor

FIGURE 2.1. Reference OTR Showing Inner Core Radius (R_i), Outer Core Radius (R_o), Core Length (L), and the Location of the Central Plug, Fuel Rings, Fuel Trays, Thermionic Converters, Inner Radial Reflector, Outer Radial Reflector, Radiator, Axial Reflector, and Shadow Shield.
Out-of-Core Thermionic Converter

Figure 2.2. Thermionic Power Conversion System Showing the Tungsten Heat Collector, Thermionic Emitter, Emitter Sleeve/Electrical Lead, Thermionic Collector, and Sodium Heat Pipe (from GA Technologies, 1987).
Observations

Space nuclear power and propulsion systems can be enhancing or enabling for ambitious space missions.

Thermionic technology has potential advantages for certain applications.

Thermionic reactors have flown in space.

Previous programs have conducted research and development related to both in-core and out-of-core thermionic systems.