Overview of Space Nuclear Propulsion and Power (SNPP)

Greg Meholic
Launch and Propulsion Concepts,
Civil Systems Technology

December 2024

Approved for public release. OTR 2024-01042

Outline

- All information is UNCLASSIFIED and public release
- Does not contain contractor proprietary information

Sections

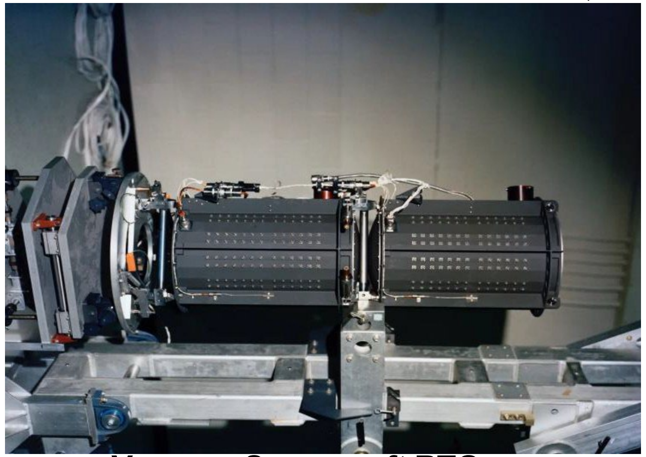
- What Is Space Nuclear Propulsion and Power (SNPP)?
- Nuclear Fission Basics
- Nuclear Thermal Propulsion (NTP) and Space Nuclear Propulsion (SNP) Definitions
- Advantages and Challenges (NTP and SNP)
  – NTP Characteristics
  – SNP Critical Technology Elements (CTEs)
- What Is Different Now?
- Government Support of SNPP
- History and Current Projects (NTP and SNP)
- General SNPP Challenges and Considerations
- Closing Statements

Acknowledgments: Randy Bell, Jeff Laube, and Torrey Radcliffe

What Is SNPP?

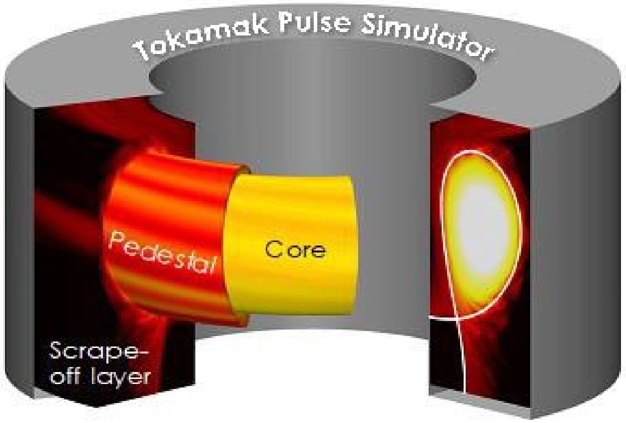
SNPP is a category of space propulsion and power where the thermal effects or energetic particles from nuclear reactions are used to do work.

- **Radioisotope**—utilizes particle emissions from element isotopes (typically plutonium-238) to create electricity or heat
  - "Decay-based" power, radioisotope power systems, and radioisotope thermoelectric generators (RTGs)
  - Typically, only a few hundred watts of electric power (We); always "on"
  - Space application heritage (more than 40 launched; Galileo, Cassini, Voyager, New Horizons, etc.)
- **Nuclear Fusion**—releases energy from merging light atomic nuclei to form heavier nuclei under extreme conditions
  - Creates other energetic nuclei fragments that combine in the same way
  - Sustained fusion yet to be achieved; active research and development efforts
- **Nuclear Fission**—releases energy from splitting of heavy atomic nuclei to form lighter nuclei by the absorption of additional neutrons
  - Neutrons that are released continue the process
  - Decades of terrestrial use; small-scale test reactors flown



Voyager Spacecraft RTG

(Source: National Aeronautics and Space Administration [NASA]. "Voyager Radioisotope Thermoelectric Generator." https://science.nasa.gov/image-detail/voyager-rtg/, accessed on 23 August 2024.)



Artist Concept of Research Fusion Reactor

(Source: Oak Ridge National Laboratory. "Three Projects to Accelerate Fusion Energy Development Awarded to ORNL." https://www.ornl.gov/news/three-projects-accelerate-fusion-energy-development-awarded-ornl, accessed on 23 August 2024.)

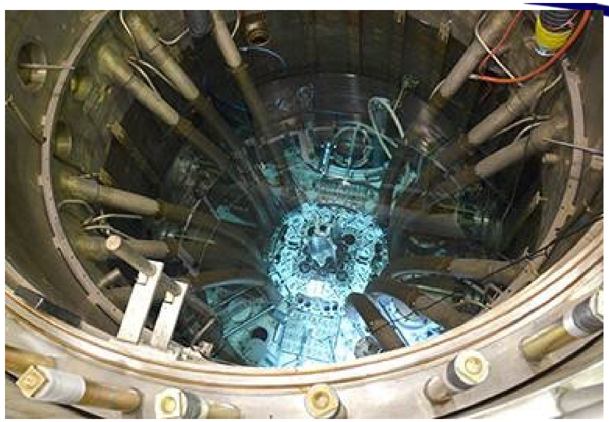
Terrestrial Nuclear Fission Reactor

(Source: Shutterstock)

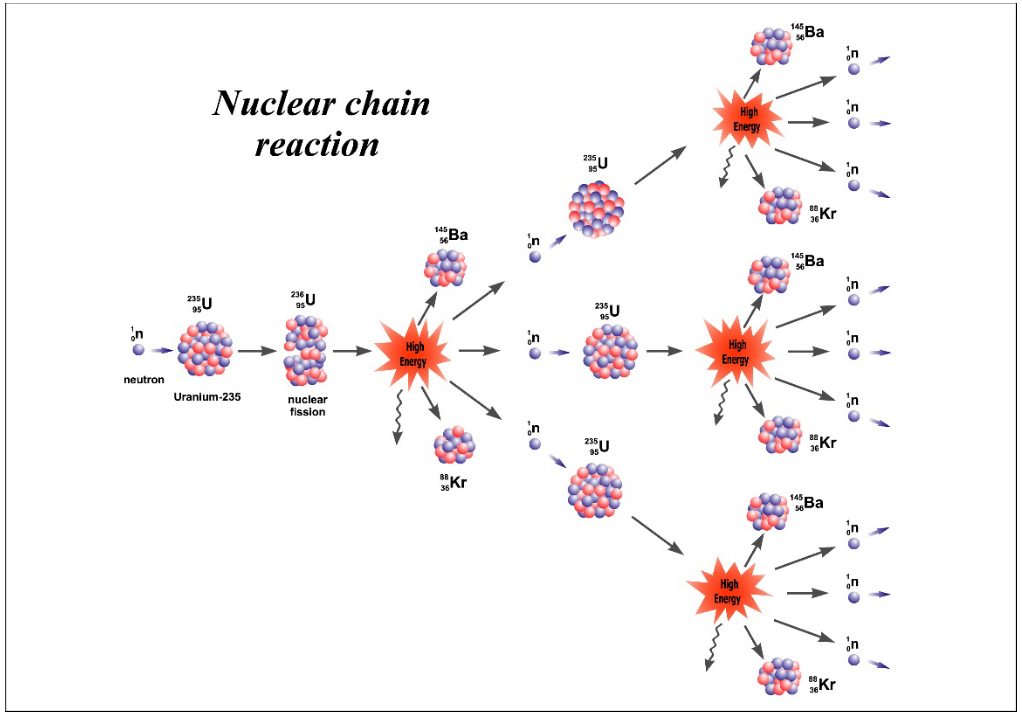
Generalized Fission Process

Physics Inside the Nuclear Fission Reactor

1. Uranium-235 (most common fission fuel) **absorbs a neutron** and becomes uranium-236
2. Uranium-236 immediately overcomes binding energy and **splits** (fissions) into various fission fragment combinations
   - 2−3 more neutrons are produced, as well as gamma rays
   - Energy density (heat release per volume) is **10^5−10^7 times** that of Hydrogen gas oxygen combustion—**significant heat flux**
   - Reactor materials can approach or exceed 3,500 K (~6,000 °F)
3. Released neutrons cause **additional fissions** (some are lost)
4. Process **"goes critical"** and becomes **self-sustaining** if reaction density is high enough
   - Activity is controlled using neutron-absorbing, reflecting, and moderating materials (e.g., boron, beryllium, etc.)
     – Modulates power and thermal output
     – "Control rods" or "control drums"
   - Want enough neutrons to be released to maintain stable chain reaction
   - Do not want **supercritical**, where fission proceeds at increasing rate, runaway reaction (nuclear weapons)
   - **Process remains "off" and inert** until directed to begin
     – Different than decay-based systems like RTGs that are always "hot"



(Source: Idaho National Laboratories. "Advanced Test Reactor Overhaul Complete; System Testing Underway to Resume Normal Operations." https://inl.gov/nuclear-energy/advanced-test-reactor-overhaul-complete-system-testing-underway-to-resume-normal-operations/, accessed on 23 August 2024.)

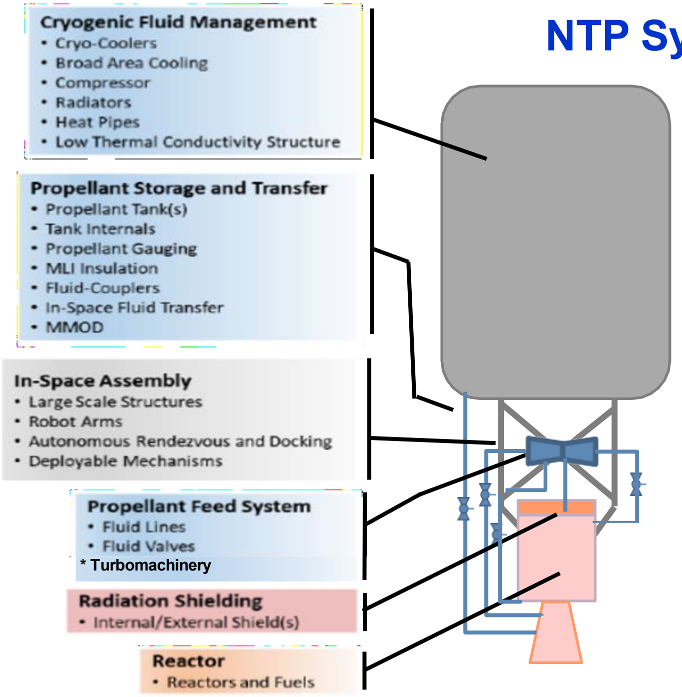


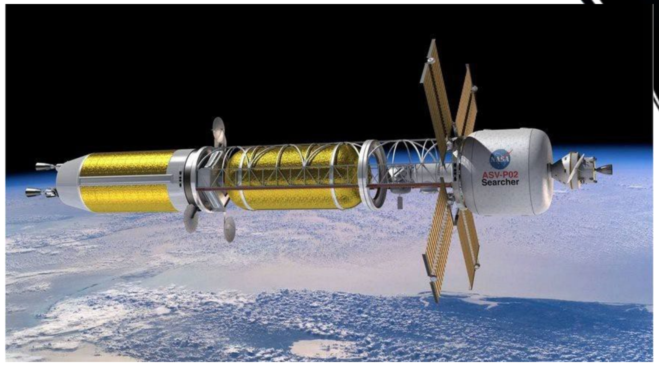
(Source: Shutterstock)

NTP and SNP

- **NTP:** Heat from fission is used to thermally energize a propellant, which is then expelled through a rocket nozzle
  - Looks and operates like a traditional rocket engine (pumps, valves, feedlines, nozzle, etc.)
  - Has few subsystems
  - Has "short" operation periods; high thrust
  - Has "very high" reactor temperatures (~3,000 K at outlet)
- **SNP:** Heat from fission is coupled to a power-generation system to produce electricity
  - Several **CTEs** (red boxes), options, and integration aspects; becomes a powerplant in space (“system of systems”)
    - ○ **Nuclear electric propulsion (NEP)** utilizes the electricity produced from a nuclear source to power electric propulsion (EP) thrusters
  - Many subsystems
  - "Long" operation periods, low thrust (if coupled to EP)
  - "High" reactor temperatures (~1,200 K at outlet)

NTP Systems

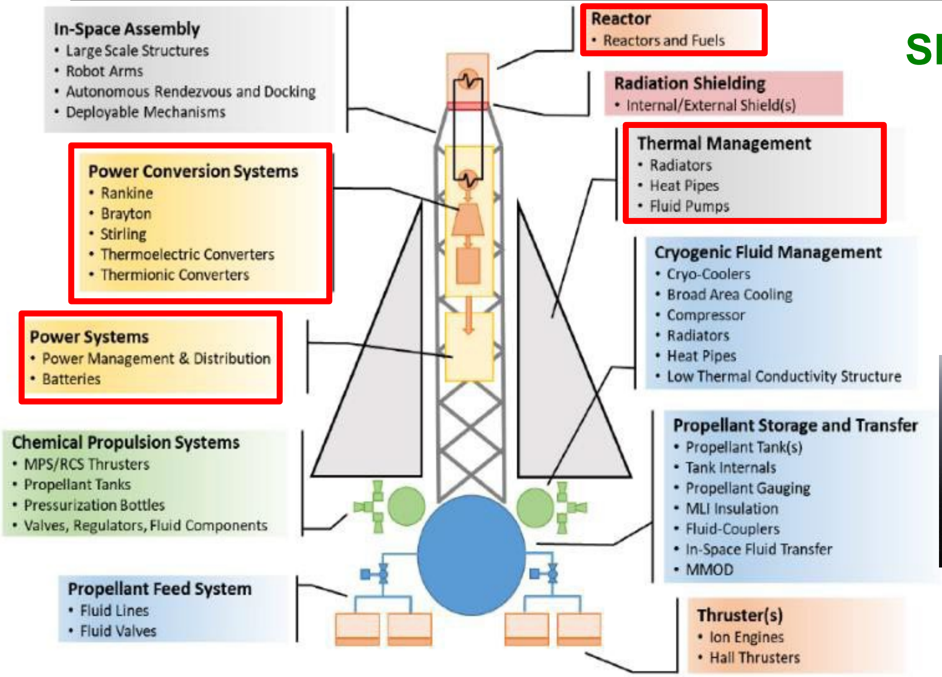




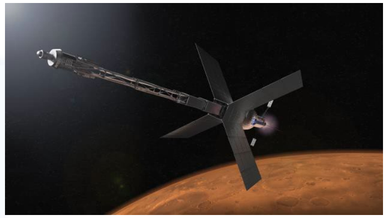
Artist Concept of NTP Spacecraft

(Source: NASA. "NASA Announces Nuclear Thermal Propulsion Reactor Concept Awards." https://www.nasa.gov/news-release/nasa-announces-nuclear-thermal-propulsion-reactor-concept-awards/, 21 October 2024.)

SNP Systems



Artist Concept of NEP Spacecraft

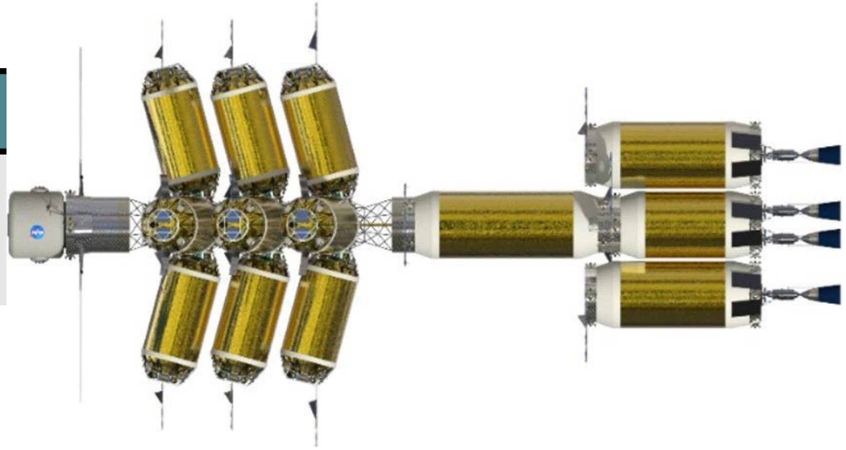


(Source: NASA. "Nuclear Propulsion Could Help Get Humans to Mars Faster." https://www.nasa.gov/solar-system/nuclear-propulsion-could-help-get-humans-to-mars-faster/, 21 October 2024.)

NTP Advantages and Challenges

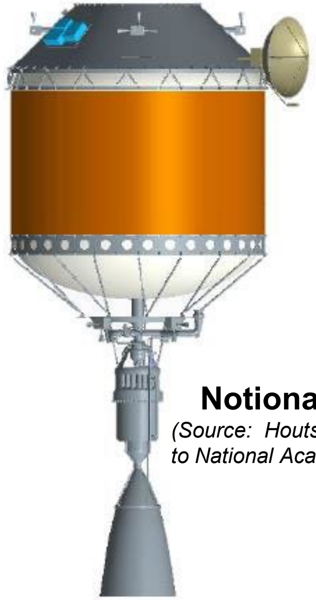
Compared to Traditional, Chemical Propulsion

Advantages
Is nearly 2–3x more thermodynamically efficient (higher specific impulse [Isp], 900 s vs. 470 s)
May enhance delivery and/or performance capabilities for large-payload missions (deep space/planetary)
Uses a single propellent (usually liquid hydrogen [LH2])
Has same sizes and thrust classes as upper-stage engines
Has integration similar to traditional rocket engines
Can use multiple inert propellant types
Heritage programs (Nuclear Engine for Rocket Vehicle Applications [NERVA], Space Nuclear Thermal Propulsion [SNTP])



Conceptual NTP Spacecraft for Crewed Mars Mission

(Source: Polzin, K. "NASA's Space Nuclear Propulsion Project." Presented at AIAA ASCEND, Las Vegas, NV, 2022.)



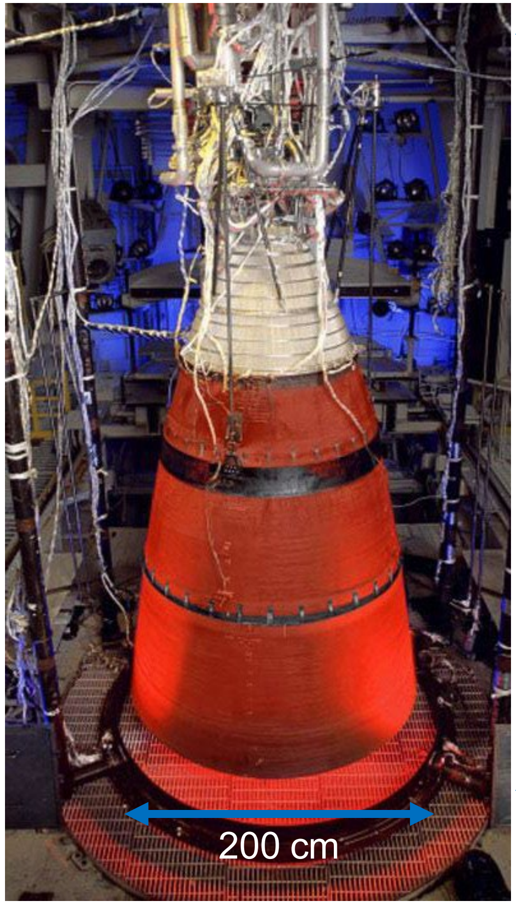
Notional NTP Demonstration Vehicle

(Source: Houts, M. "Nuclear Thermal Propulsion." Presented to National Academy of Science Panel, 8 June 2020.)

Challenges
Needs significant alterations to spacecraft subsystems and components (~3x volume of LH2 for same energy [Δv])
Needs very high-temperature materials for reactor (hotter than LH2/liquid-oxygen [LOX] flame temperature)
Is radioactive during and after use; requires shielding (added mass)
Has low thrust to weight (~10 vs. 120+)
Cannot [currently] be ground tested
Must follow regulatory considerations (launch/reentry of nuclear material)
Has extended start and shutdown transients (30–60 s vs. 3–7 s)

NTP Characteristics

Many similarities between existing upper-stage engines and NTP concepts.

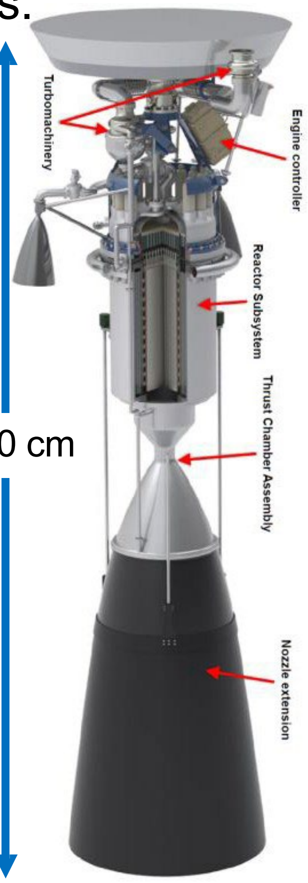


500 cm

(Source: Houts, M. “Nuclear Thermal Propulsion.” Presented to National Academy of Science Panel, 8 June 2020.)

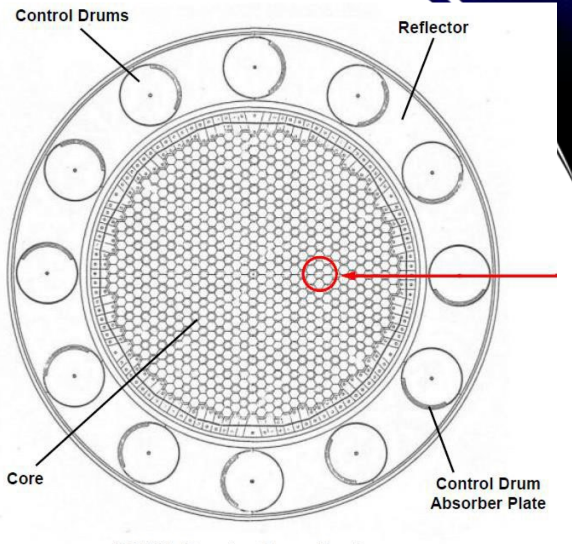
RL10B-2 (Delta IV Upper Stage)		**Notional NTP Engine (Mars Transport)**
LH2/LOX	Propellant	LH2
Expander	Cycle	Expander
24,750 lbf	Thrust	25,000 lbf
750 lb	Weight	**~11,000 lb**
52 lb/s	Flow Rate	**~28 lb/s**
633 psi	Chamber Pressure	~1,000 psi
285	Nozzle Area Ratio	~300
465 s	Isp	**~900 s**
<3 s	Time to Full Thrust	**30–60 s**

~750 cm

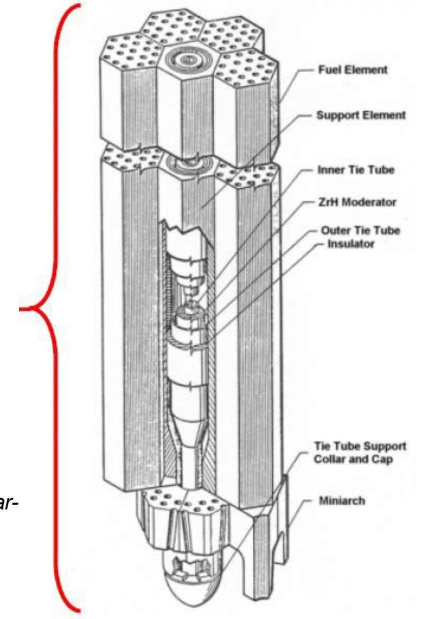


220 cm

(Source: NASA. "Nuclear Thermal Propulsion Systems." https://www1.grc.nasa.gov/research- and-engineering/nuclear-thermal- propulsion-systems/, 23 August 2024.)



NERVA Reactor Cross Section



Fuel Segment Cluster

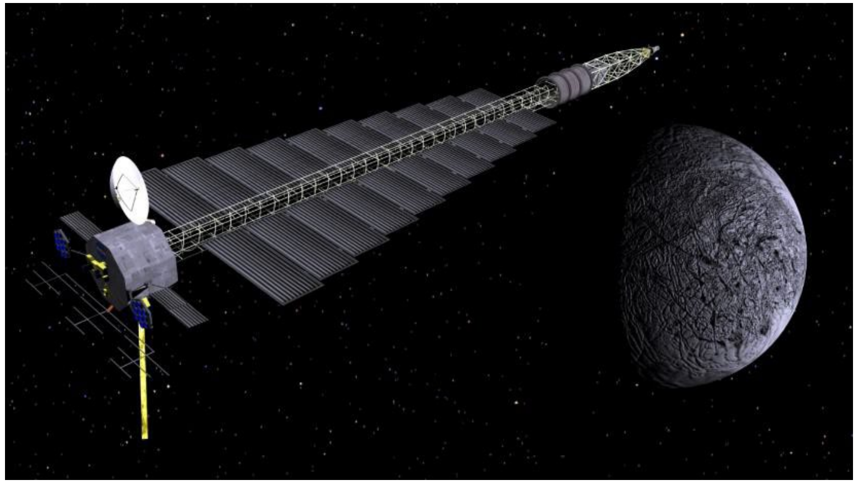
(Source: Houts, M. “Space Reactor Design Overview.” NASA, 2 April, 2021.)

NTP offers the same thrust and <u>~2x the efficiency</u> (half the flowrate) but can be <u>~20x heavier</u>.

SNP Advantages and Challenges

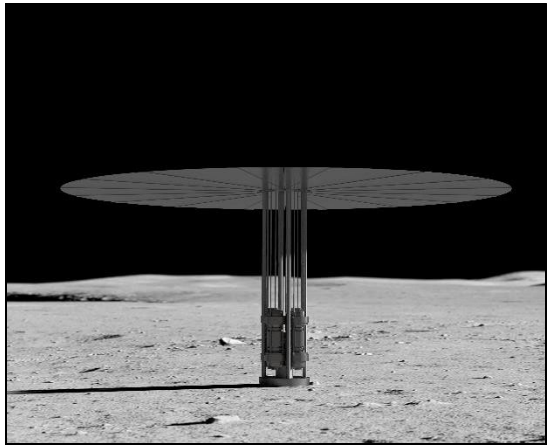
Compared to RTG, Solar or Battery-Power Systems

Advantages
Scalable to a broad power range (100s kWe or MWe)
Continuous power, regardless of solar alignment/exposure
Many options for technology, power cycle, and integration
Possibility to enhance payload and/or mission capabilities (as supplement to other power sources)
Manageable reactor temperatures
Heritage programs (System for Nuclear Auxiliary Power [SNAP]-10A, Jupiter Icy Moons Orbiter [JIMO]/Prometheus, Russian Thermionic Experiment With Conversion in Active Zone [TOPAZ])



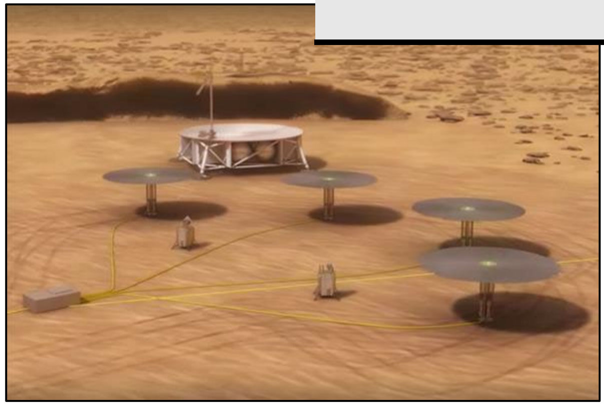
JIMO With Prometheus Reactor

(Source: NASA. "JIMO Illustration." Wikimedia Commons, 17 August 2024.)



Conceptual Fission Surface Power (FSP) System

(Source: NASA. "Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power." https://www.nasa.gov/news-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power/, 25 July 2024.)



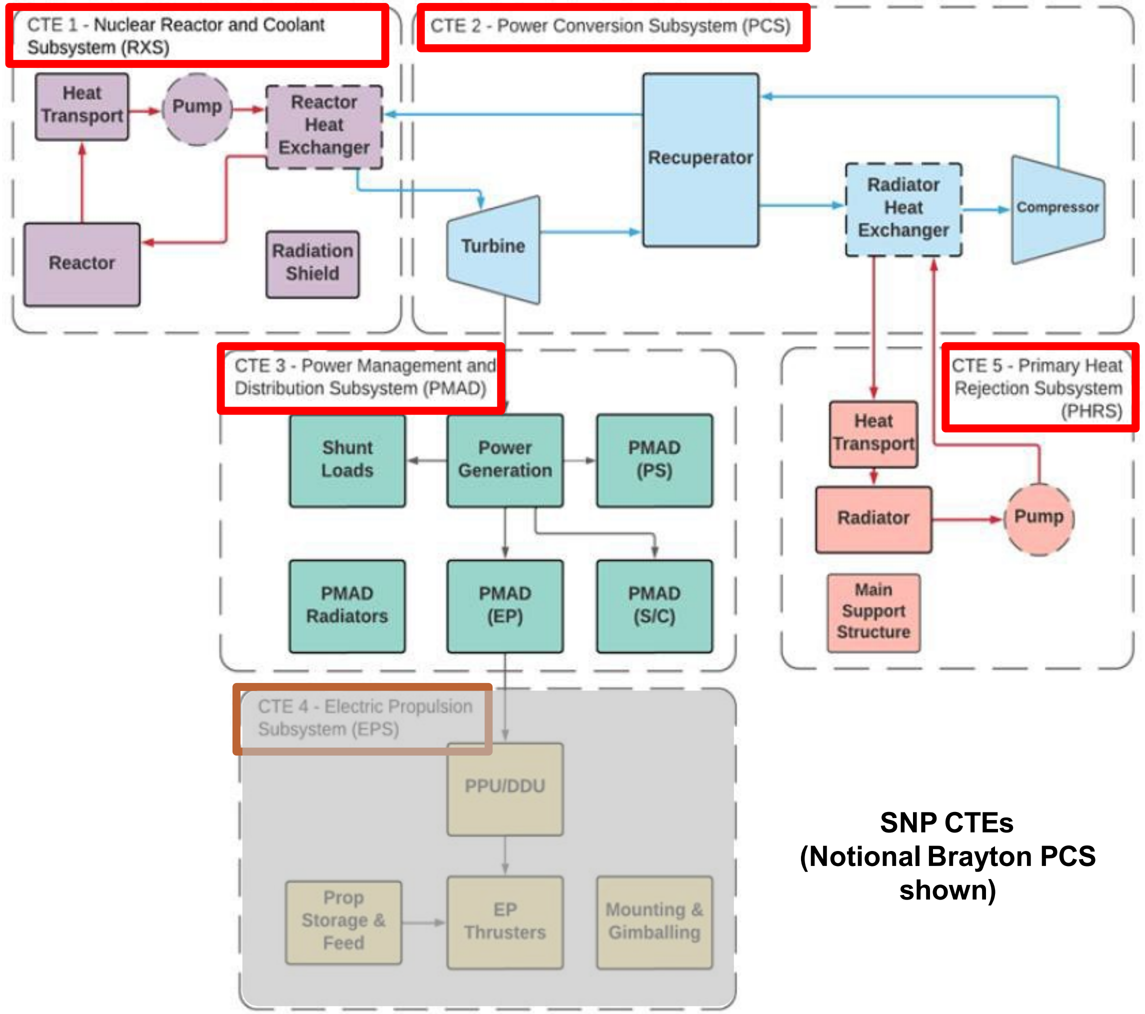
Conceptual Lunar Surface Power (LSP) System

(Source: NASA. "Fission Surface Power." https://www.nasa.gov/space-technology-mission-directorate/tdm/fission-surface-power/, 25 July 2024.)

Challenges
Integration and operation of multiple complex systems for power production
Significant alterations to spacecraft subsystems and components (traditional power systems may still be required)
Possible employment of multiple working fluids
Radioactive during and after use; requires shielding (added mass)
Regulatory considerations (launch/reentry of nuclear material)

SNP (CTEs)

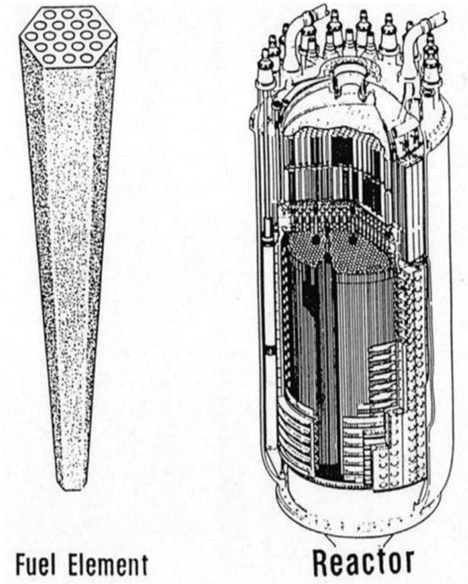
- **CTEs** must be integrated to form the complete SNP system
  - **CTE-1: Reactor**
    - Uranium fuel type, enrichment level, "fast" vs. "thermal" design
  - **CTE-2: Power Conversion Subsystem (PCS)**
    - Brayton, Stirling, Rankine, Thermionic, Thermoelectric
  - **CTE-3: Power Management and Distribution**
    - Switching systems, transformers, etc., will be driven by the needs of the end application(s)
  - CTE-4: EP (gray)—only if propulsion is considered
  - **CTE-5: Primary Heat Rejection (thermal management)**
    - Pumped fluid loop or heat pipe radiators, liquid metal or nonliquid metal working fluids
- Each CTE has options that must be traded to determine the best fit for mission needs
  - No "one-size-fits-all" solution/combination for the integrated system
  - Each option/combination must be traded against others **and** against conventional power systems
  - Individual challenges and technology maturation considerations
- Maturing each CTE could be considered a standalone technology development effort
  - Long timelines, lengthy qualification, and substantial investments
- Regardless of the end application(s), **every SNP system will have the same CTEs** that enable power generation



SNP CTEs (Notional Brayton PCS shown)

What Is Different Now?

- U.S. Department of Defense (DoD) and civil and commercial space enterprises recognize the need for alternatives to traditional propulsion and power options that may enable novel missions or enhance mission-unique capabilities
  – Renewed interest in Mars, cislunar spacecraft operations, surviving the lunar night
- SNPP has become a viable consideration based on decades of advancements in:
  – Uranium fuel form development, enrichment, and processing
  – Reactor design and manufacturing (materials, additive manufacturing)
  – Nuclear industrial base growth (new companies, capabilities, facilities)
  – Interests in space applications across government and commercial communities



(Source: Sedwick, R., B. Cassenti, B. Donahue, and C. R. Joyner. "Nuclear Thermal Propulsion For Space Transfer Overview." In-Space Chemical Propulsion Technical Interchange Meeting, NASA Marshall Space Flight Center, Huntsville, AL, 4–6 April 2017.)

Prior Space Reactors

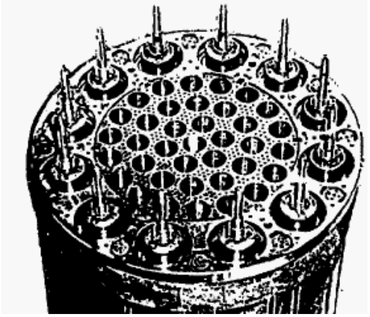
- Highly enriched uranium
- Uranium nitride chips embedded in graphite
- Tie-rod prismatic reactor
- Material and structural issues from temperature mismatches
- Little modeling available

60+ years

Modern Space Reactors

- **High-assay low-enriched uranium (HALEU)—easier to obtain and nonweaponizable but less efficient**
- Advanced fuel forms—tristructural isotropic (know as TRISO), accident tolerant, production history (terrestrial and Naval)
- Multiple core configurations—moderator block, tie rod, particle/pebble bed
- High-temperature materials and manufacturing techniques—additive manufacturing, welding, ceramic composites
- Validated physics modeling and design tools—reduces cost/risk, improves design

Russian Moderator Block Reactor



(Source: Houts, M. "Nuclear Thermal Propulsion." Presented to the National Academy of Science Panel, 8 June 2020.)

Advanced fuels and reactors, novel missions, relaxed regulatory processes, and potential benefits have enabled fission-based SNPP to become tradable options.

Government Support of SNPP

- The potential benefits of SNPP have led to the creation of government directives and documents (since 2019) that specifically address in-space nuclear systems for propulsion or power

Document Title	ID Number	Publication Date	Subject	Originator	Document Type
Energy for Space		Jan 06, 2021	Exploration, Infrastructure, Nuclear	Department of Energy	Report
Promoting Small Modular Reactors for National Defense and Space Exploration	EO 13972	Jan 05, 2021	Nuclear	President, Nat'l Space Council	Policy Directive
National Strategy for Space Nuclear Power and Propulsion	SPD-6	Dec 16, 2020	Nuclear, Exploration	President, Nat'l Space Council	Policy Directive
Launch of Spacecraft Containing Space Nuclear Systems	NSPM-20	Aug 20, 2019	Nuclear	President, Nat'l Space Council	Memo

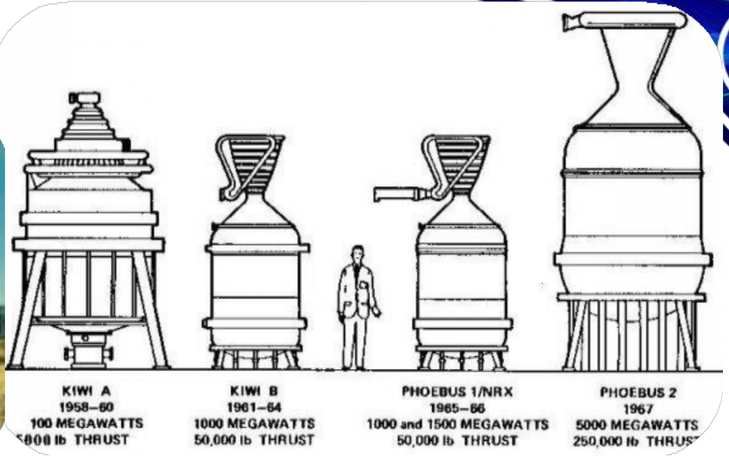
Note: SPD-6 provides a good summary of national strategy needs.

- Government agencies have adapted strategies for including and addressing SNPP in their operations
  - Multiple agencies with regulatory authority over various aspects of the launch/reentry of fission-based nuclear material that has yet to be practiced (Federal Aviation Administration [FAA], U.S. Environmental Protection Agency, Department of Commerce, etc.)
  - Establishment of several interagency safety review boards (NASA, DoD, etc.)
  - Orbital debris of SNPP systems also considered

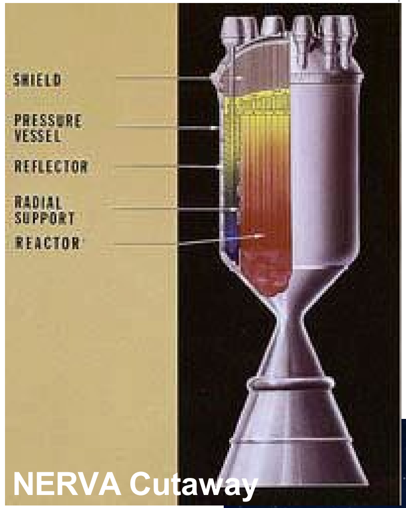
Processes for safety assurance and cross-agency coordination (launch approval, processing, operations) need to be considered early in project development and mission planning.

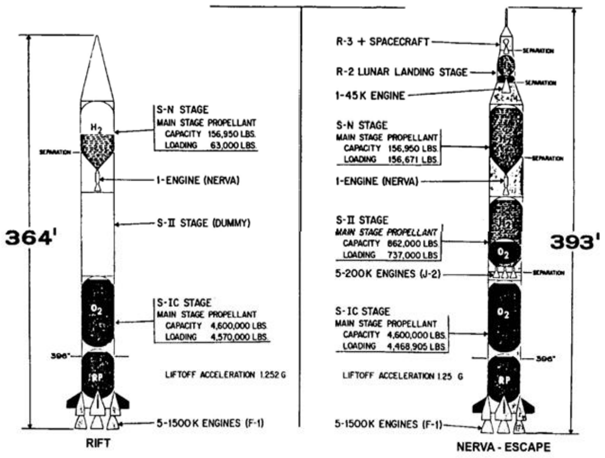
NTP History and Current Projects

- Nuclear Energy for the Propulsion of Aircraft and Aircraft Nuclear Propulsion (1946–1961)
  - Nuclear reactors driving turbojets
  - Successful full-scale ground tests
  - Reactor shielding tested aboard NB-36H aircraft (1956)
- Project Pluto/Tory (1957–1964)
  - Air-breathing nuclear ramjet for supersonic intercontinental ballistic missile
  - Successful full power ground tests (~500 MW)
- NERVA (1960–1972)
  - Most prolific NTP project
  - Phoebus 2A: 4 GW, 210-klbf thrust, highest power reactor ever tested
  - Successful full-power ground tests, various thrust classes
- Reactor In-Flight Test (1962–1964)
  - Intended as test bed for NERVA engine
  - Potential growth to Saturn class
- SNTP (1987–1994)
  - High-performing, lighter NTP engine with pebble-bed reactor (Timberwind)
- **NASA SNP (2016–2023)**
  - High-temperature materials and fuel development for Mars mission systems
  - Three near-Preliminary Design Review NTP reactor designs (from industry)
- **Defense Advanced Research Projects Agency (DARPA) Demonstration Rocket for Agile Cislunar Operations (DRACO) (2019–present)**
  - DARPA-led, NASA as partner (2023)
  - Launch in 2027, may be first NTP to fly in space



(Source: NASA. "The Nuclear Cryogenic Propulsion Stage." "https://ntrs.nasa.gov/api/citations/20140012916/downloads/20140012916.pdf, August 2014.)

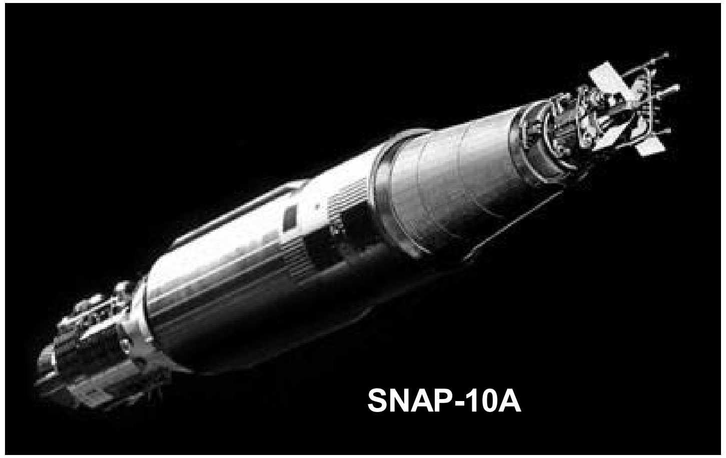




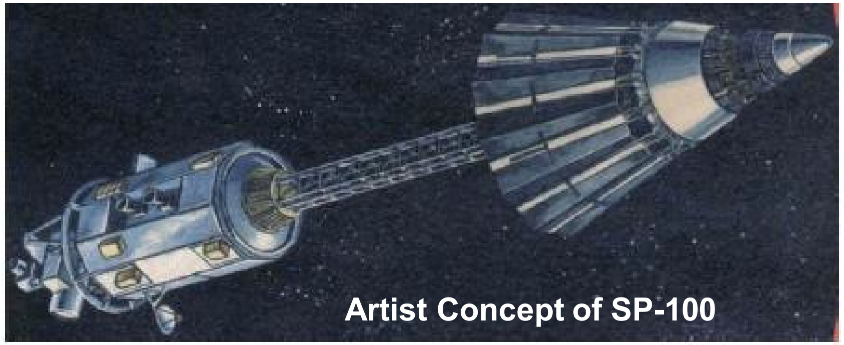
(Source: Wikimedia Foundation, Inc. "Demonstration Rocket for Agile Cislunar Operations." Wikipedia, https://en.wikipedia.org/wiki/Demonstration_Rocket_for_Agile_Cislunar_Operations, 16 July 2024.)

SNP History and Current Projects

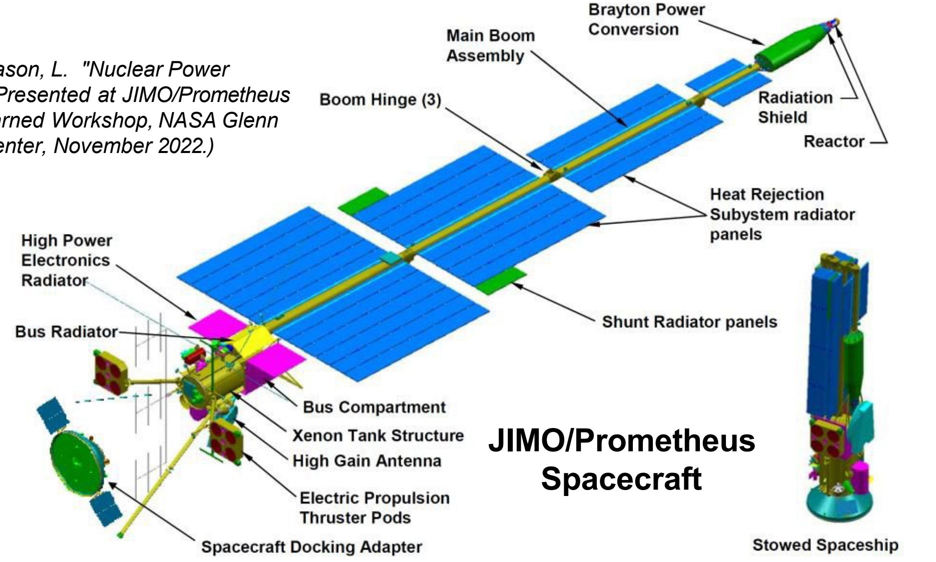
- SNAP (early 1960s)
  – SNAP-10A has been the only U.S. flight reactor
  – 0.5 kWe at 1.4% efficiency
- Soviet Space Reactors: Radar Ocean Reconnaissance Satellite (known as RORSAT), TOPAZ (1967–88)
  – ~1-kWe demonstration systems
  – Over 30 reactors launched; some have reentered
- SP-100 (1983–1992)
  – 100 kWe, 2.5 MW, 1,350 K reactor outlet temperature
  – Growth to 500-800 kWe for LSP
  – Silicon-germanium thermoelectric conversion with growth to Brayton and Stirling
- NASA JIMO/Prometheus (2000–2005)
  – 200 kWe, 800 kW, 1,150 K reactor outlet temperature, multiple helium-xenon Brayton power conversion systems
  – Significant research and development by industry and government
- NASA Constellation (2007–2012)
  – 40 kWe at 875 K temperature, Stirling conversion
- Kilopower Reactor Using Stirling Technology (KRUSTY) (2015–2018)
  – ~0.8 kWe from two (of eight possible) Stirling systems
  – Ground demonstration only; built from today's technology; not intended for space
- **NASA FSP (2005–present)**
  – Exploring growth of KRUSTY to ~40 kWe for planetary surface power
- **Air Force Research Laboratory Joint Emergent Technology Supplying On-Orbit Nuclear Power (JETSON) program for Spacecraft NEP (2022–present)**
  – JETSON Low: 1–5-kWe RTG-based systems
  – JETSON High: ~40-kWe fission-based systems



(Source: Mason, L. "Current Prospects for Space Nuclear Power & Propulsion." Presentation to NASA Space Technology Mission Directorate, February 2020.)



(Source: Mason, L. "Nuclear Power Overview." Presented at JIMO/Prometheus Lessons Learned Workshop, NASA Glenn Research Center, November 2022.)



General SNPP Challenges and Considerations

- HALEU Processing
  - Significant investment needed to develop facilities for enrichment of low-enriched uranium to HALEU to meet prospective needs
- Development of Very High-Temperature Materials and Assembly Processes
  - Required for NTP where internal reactor temperatures can exceed 3,500 K (~6,000 °F)
  - Will also benefit SNP systems that have much longer operational lifetimes
- Reactor Ground Testing Not (Currently) Possible
  - No facilities exist in the United States that can support reactor ground testing (larger than KRUSTY)
  - NTP testing requires that engine exhaust be scrubbed of radiologics before being released
    - Could result in substantially large, prohibitively expensive facilities that take years to build and qualify
  - SNP systems require reactor testing with partially and/or fully integrated CTEs
- Complex System Engineering and Integration (SNP)
  - CTEs must autonomously interact to ensure stability and control across the power-demand range
  - Must be packaged and qualified for space applications
  - Multiple, lengthy, expensive test/qualification programs
- Commercial Launch Operator Must Obtain License to Launch Nuclear Material
  - SNPP asset must undergo several multi-agency reviews to assess safety assurance
  - FAA license application process can take 12–24 months
  - License might also cover debris and/or disposal, depending on mission
- Modifications to Launch Vehicle, Pad, and Ground Systems to Support SNPP
  - May require requalification, thus driving schedule and cost
  - May result in substantial investments for unique, infrequent, one-off missions

The investments and time needed must be considered when trading SNPP against traditional alternatives and mission needs.

Closing Statements

- In addition to past programs, decades of studies have been and continue to be performed by industry, academia, and government on fission-based SNPP
  - Missions and applications, technology development/concepts, performance comparisons, policy, maturation plans, technology readiness level assessment, etc.
- Since SNAP-10A, the United States has not flown another fission-based SNPP system
  - Regulatory issues, obviated need, cost/time to develop flight-ready prototypes
  - Foreign interests in SNPP may influence the United States
  - DRACO may be the world's first NTP engine
- None of the prior SNPP projects mentioned were canceled due to safety reasons, technology failures, or heightened risk of radioactive hazards
  - Terminated mainly due to lack of need, cost, change in national priority, or "something better came along"
- Mars exploration and lunar night survivability (NASA), as well as space mobility and logistics near earth (DoD), have renewed the interest in nuclear alternatives
- Recent advances in policy and in proposed use of HALEU fission fuel have enabled SNPP to generate broad interests and positive support within DoD, civil, and commercial space sectors
  - Government recognition of SNPP need and issuance of supporting directives
- Standards are being drafted to address SNPP operational considerations
  - Part of the American Society for Testing and Materials Commercial Spaceflight Committee (F47)
  - Multi-agency participation
- Adopting SNPP systems will require careful consideration of their cost, development time, benefits, and challenges when performing mission-level comparisons to current systems

Technology advancements, novel missions, and potential benefits have enabled fission-based SNPP systems to become viable options tradable with traditional systems.

Thank you!