Fuel & Fuel Cycle – Space Applications

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Why Nuclear in Space?

Two purposes:

Generation of **electrical power**

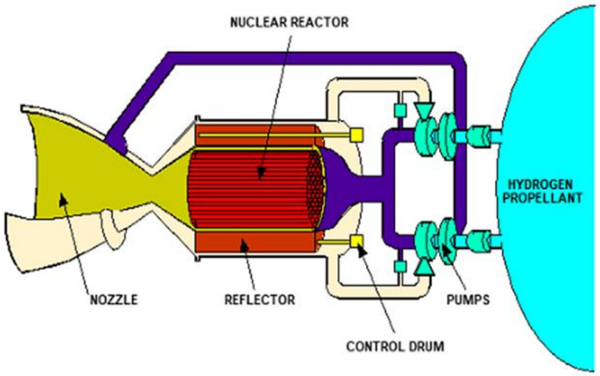
- Radioisotope Thermal Generators (RTG)
- Nuclear reactors in space (KRUSTY)

Generation of **thrust**

- Nuclear Thermal Propulsion (NTP)
- Nuclear Electric Propulsion (NEP)

Why nuclear over other energy sources?

- Continuous and reliable source of energy
- High energy density
- High longevity
- Reduced transfer times



A Typical NTP System

Why Nuclear in Space? Generation of Thrust

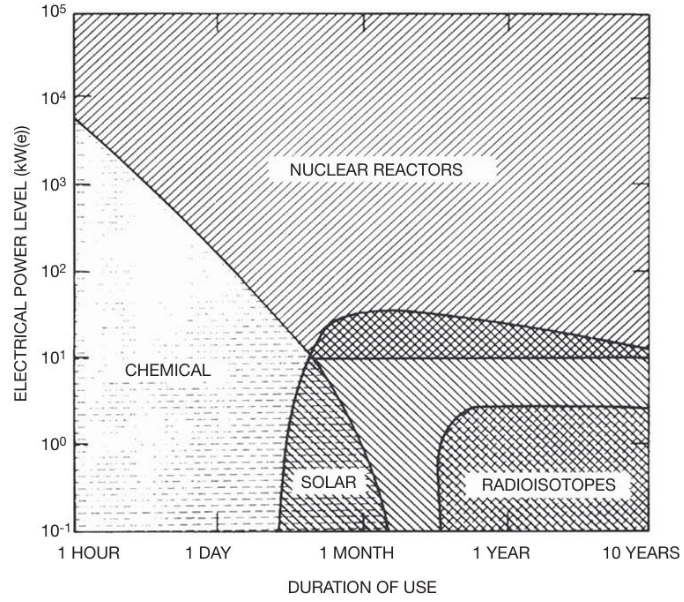
Two main aspect are needed in space propulsion

HIGH **THRUST:** to reach maximum velocity as soon as possible

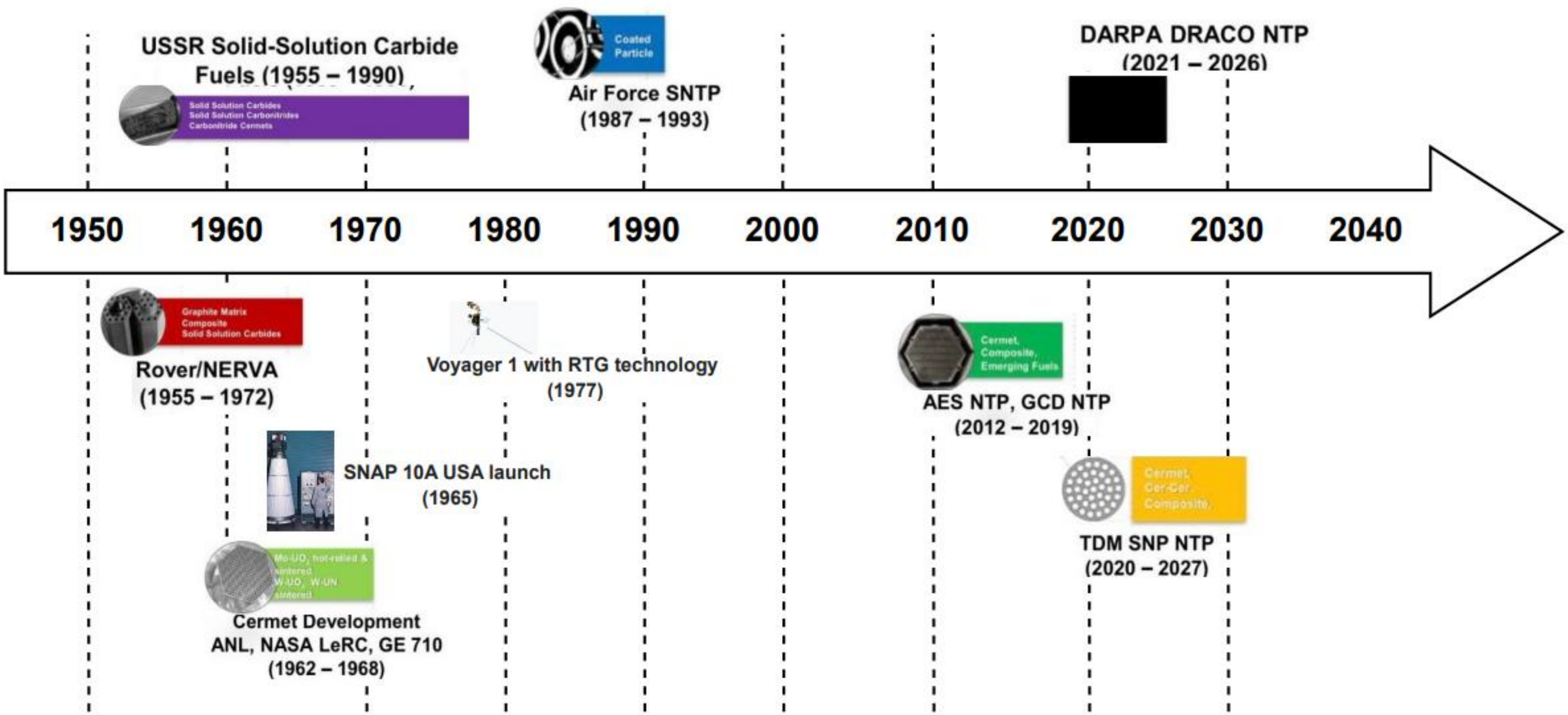
HIGH **SPECIFIC IMPULSE** (Isp): to save propellant

While it is impossible to maximise both, **nuclear power is the only energy source capable of achieving high thrust while mantaining a sufficiently high Isp**

Energy source	Energy density	Isp [s]
Chemical	10^7 J/kg	200-450
Nuclear fission	10^13 J/kg	1000-6000
Nuclear fusion	10^14 J/kg	???
Antimatter	10^17 J/kg	???

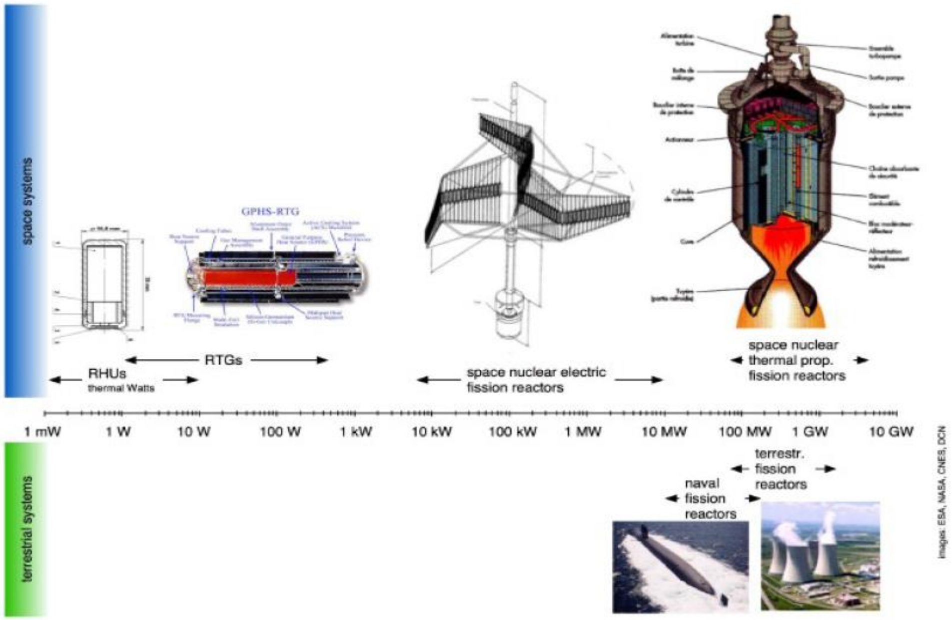


History of Nuclear in Space



Nuclear Power Sources: Space vs Terrestrial

	SPACE	TERRESTRIAL
Fuel	RTG: PuO_2 NERVA: $ZrC+UC_2$	UO_2
Coolant	LH_2	H_2O
Reactor Core Size	Diameter: 0,4-3 m Height: 1-3 m	Diameter: 5-6 m Height: 10-12 m
Mass	NERVA: 5-10 tons RTG: 57 kg	Up to 50 000 tons
Cost (including R&D)	1-3 billion $	6-10 billion $
Power Output (Thermal)	From mWts up to 500 MWt	1 000 to 3 000 MWt



Nuclear Power Sources: Space vs Terrestrial

Further differences regard:

- Nature of applications
- Operating environment
- Nature and autonomy of operation of systems
- Frequency and duration of use
- Safety Measures
- Complexity and design reliability
- Maintenance
- Use of passive/active systems
- End of Life

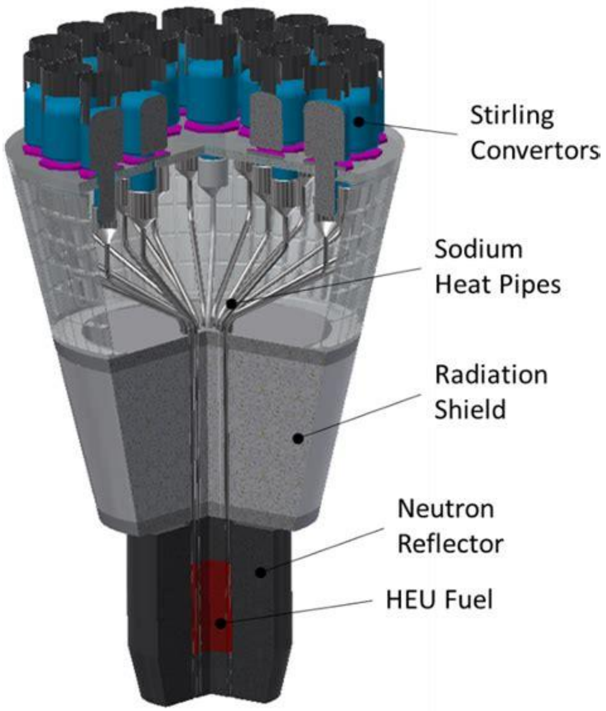
Generation of Electricity in Space - KRUSTY

Kilopower project: it was an experiment by NASA to develop a reactor for electrical generation on the lunar surface. The project was concluded successfully with the development of the **KRUSTY (Kilopower Reactor Using Stirling Technology).**

- Fuel: Uranium-235
- Control: single rod of boron carbide
- Coolant: liquid sodium
- Conversion: Stirling engines

Prototype KRUSTY:

- 4.3 kW thermal output
- 1 kW electrical output
- 28 kg of U-235 fuel



Generation of Electricity in Space - RTG

RTGs (Radioisotope Thermoelectric Generators) are devices that convert the heat released by the decay of radioactive isotopes into electrical power. Let's focus on:

- Fuel: The isotopes typically used in the space applications are the following:

Isotope	Fuel form	Decay	Power Density [W/g]	$\tau_{1/2}$ [yr]
Polonium-210	$GdPo$	α	82	0.38
Plutonium-238	PuO_2	α	0.41	86.4
Curium-242	Cm_2O_3	α	98	0.4
Strontium-90	SrO	β	0.24	28.0

Tab: Typical isotopes used in space applications

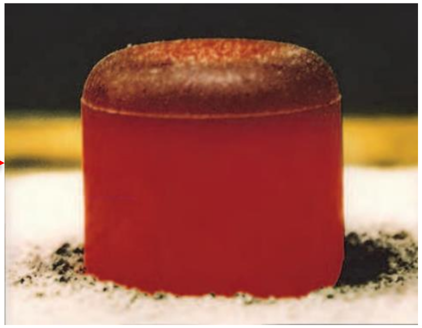


Fig: PuO_2 fuel pellet

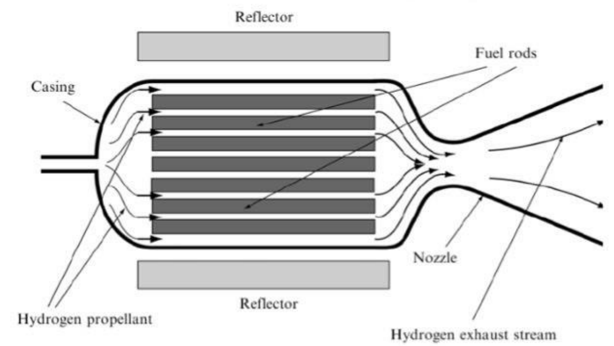
- Conversion processes:
  - **Seebeck effect** efficiency 6 %
  - **Stirling cycles** efficiency up to 30 %

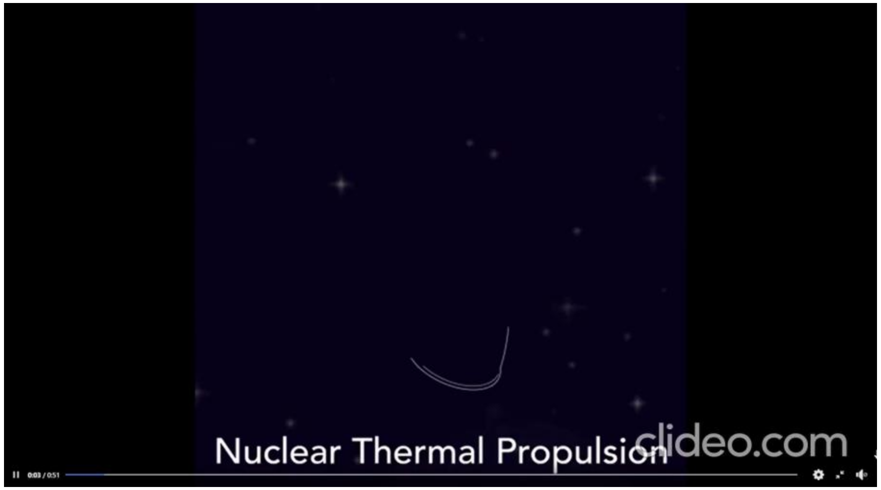
Generation of Thrust in Space - NTP/NERVA

REACTOR

HEAT TO PROPELLANT

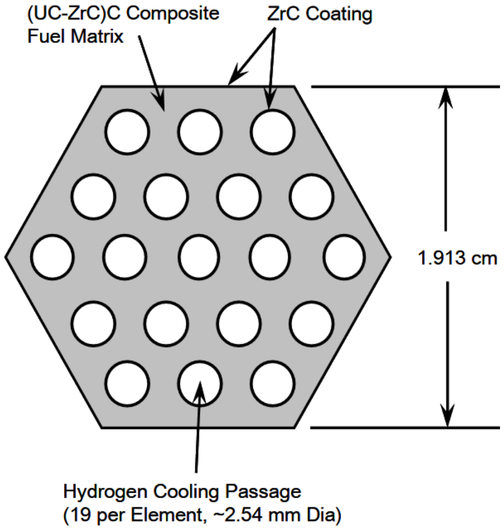
EXPANSION





Differences between NTP and PWR - Fuel

NTP fuel pellet



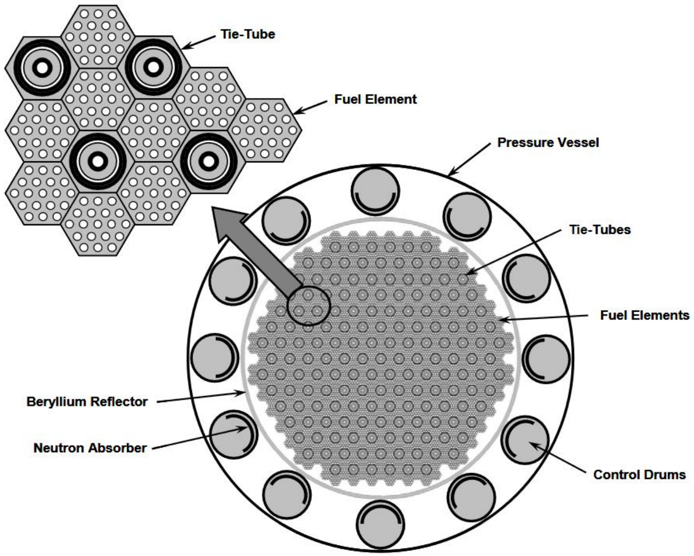
- Uranium carbide (**UC**) and zirconium carbide (**ZrC**) fuel
- **Hexagonal** cross section
- **Internal coolant passage** through holes

PWR fuel pellet

- Uranium dioxide (**UO_2**) fuel
- **Circular** cross section
- **External coolant passage**

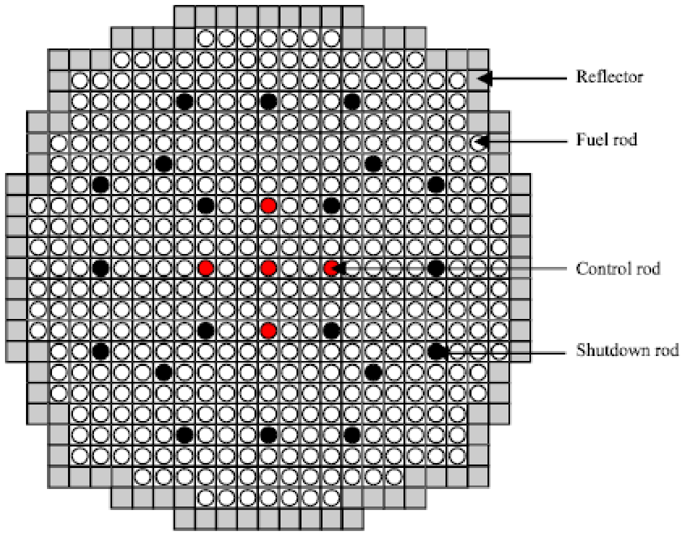
Differences between NTP and PWR – Core

NTP reactor core



- **Rotating control drums**
- **No fuel assembly**
- **Tie-tubes** structural support elements and moderators
- **Liquid hydrogen** (typically) coolant

PWR reactor core



- **Control rods inserted vertically**
- Fuel organized in **fuel assembly**
- **High pressure water** coolant also used as moderator

Generation of Thrust in Space - NEP

REACTOR

HEAT TO ELECTRIC POWER GENERATION

ELECTRIC PROPULSION

OTHER USES

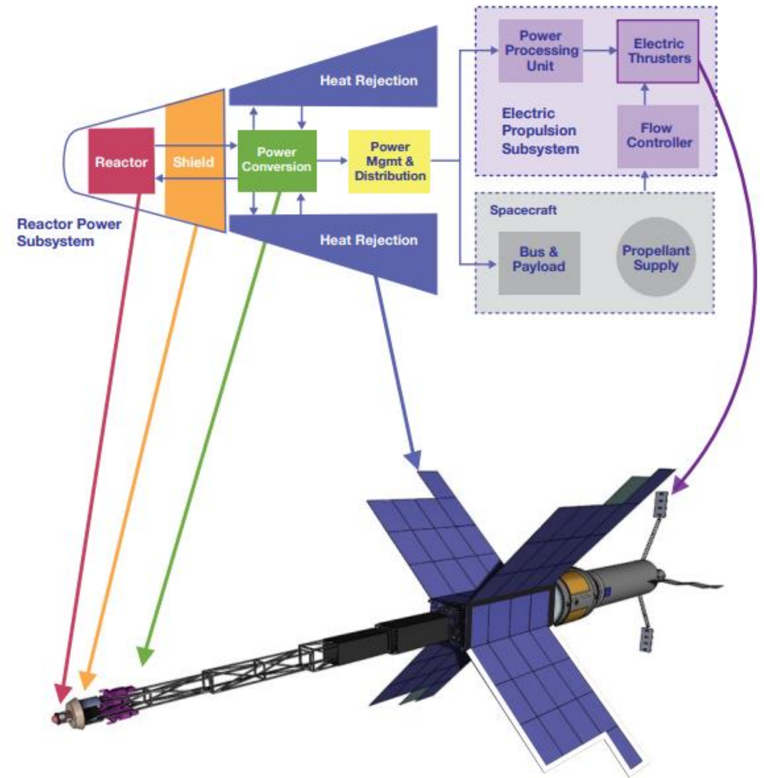


FIGURE 3.1 Nuclear electric propulsion subsystems and conceptual design. SOURCE: Briefing to the committee by Lee Mason, NASA, June 8, 2020.

Requirements

UNOOSA
United Nations Office for Outer Space Affairs

47/68. Principles Relevant to the Use of Nuclear Power Sources In Outer Space

Principle 3. Guidelines and criteria for safe use

1. General goals for radiation protection and nuclear safety
2. Nuclear reactors ("*Nuclear reactors shall use only highly enriched uranium 235 as fuel*")
3. Radioisotope generators

IAEA

1972 Convention on International Liability for Damage Caused by Space Objects

Challenges: Safety

Safety is relevant in all phases of the mission, in particular:

- **On ground**, to **protect ground crews** from radiation exposure
- **During launch**, to **avoid dispersion of radioactive materials** in the atmosphere
- **In orbit**, to **protect** on-board instrumentation and **astronauts**
- **During reentry**: to **avoid dispersion of radioactive materials** in the atmosphere

A few examples of launch failures

Challenges: Testing and Fuel Corrosion

Nuclear Thermal Rocket Element Environment Simulator (NTREES) at Marshall Space Flight Center, Huntsville, AL

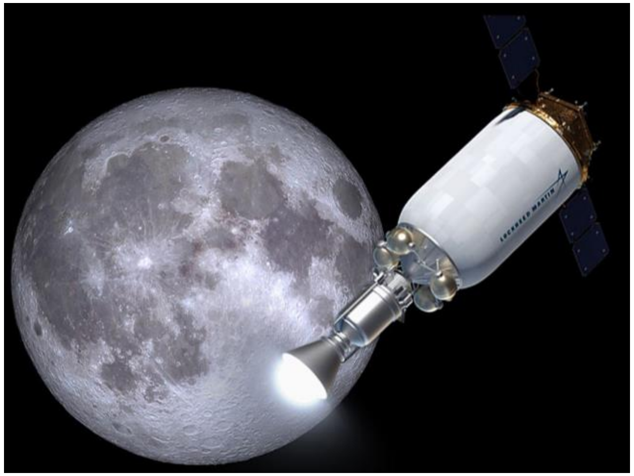
Pre-Test

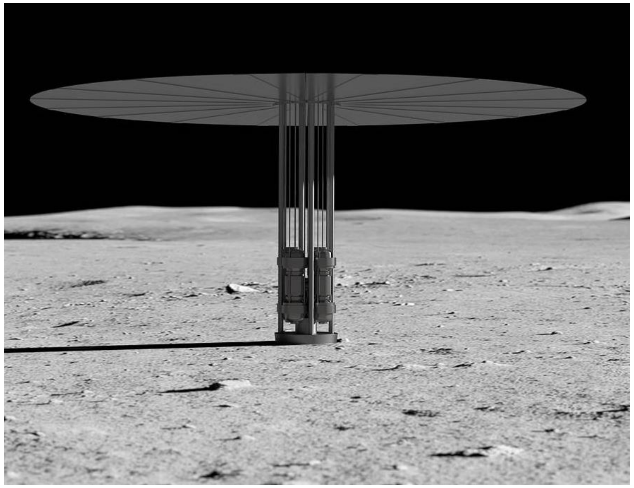
Post-Test

Samples of fuel elements subjected to LH_2 flow

Conclusions and Future Prospects

PROJECT	FUTURE PROSPECTS
NTP	• Faster transit to Mars • Low-enriched uranium fuels • Advanced reactor designs
KRUSTY	• Lunar and Martian surface power • 1 kW fission power system development
RTG	• Improve thermal conversion efficiency • Long-lasting energy supply • Next-Generation RTG mission concepts
NEP	• Long-term missions • Efficient energy distribution systems
NTP - NEP	• Combined propulsion systems • Optimized mission profiles • White House Space Policy Directive 6
DRACO	• NTP demonstration in cislunar space • Advanced spacecraft integration





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