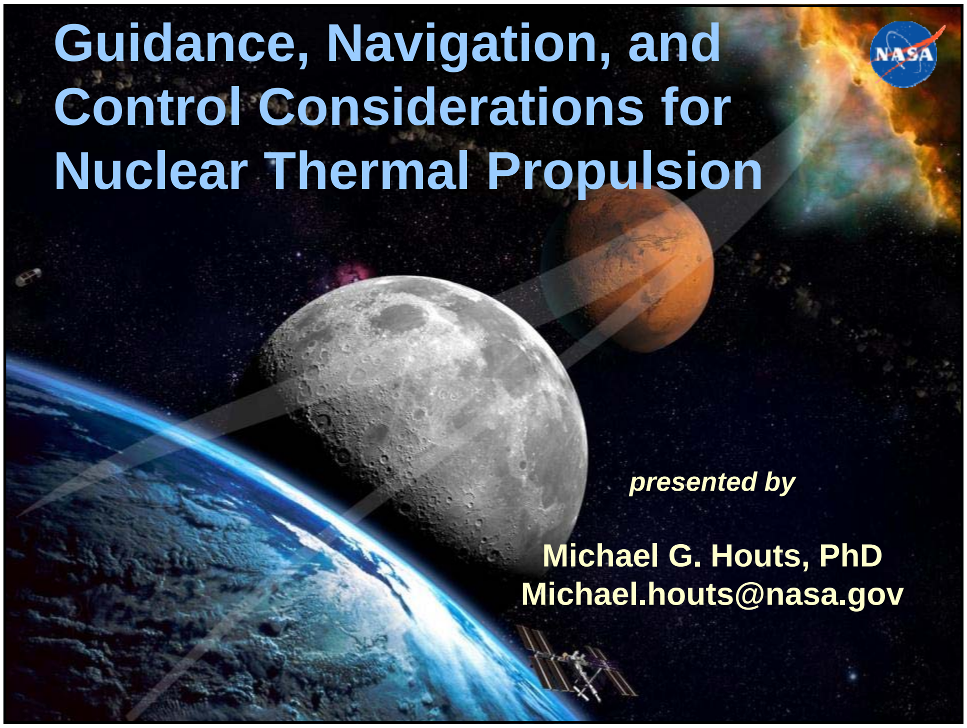

Guidance, Navigation, and Control Considerations for Nuclear Thermal Propulsion

presented by

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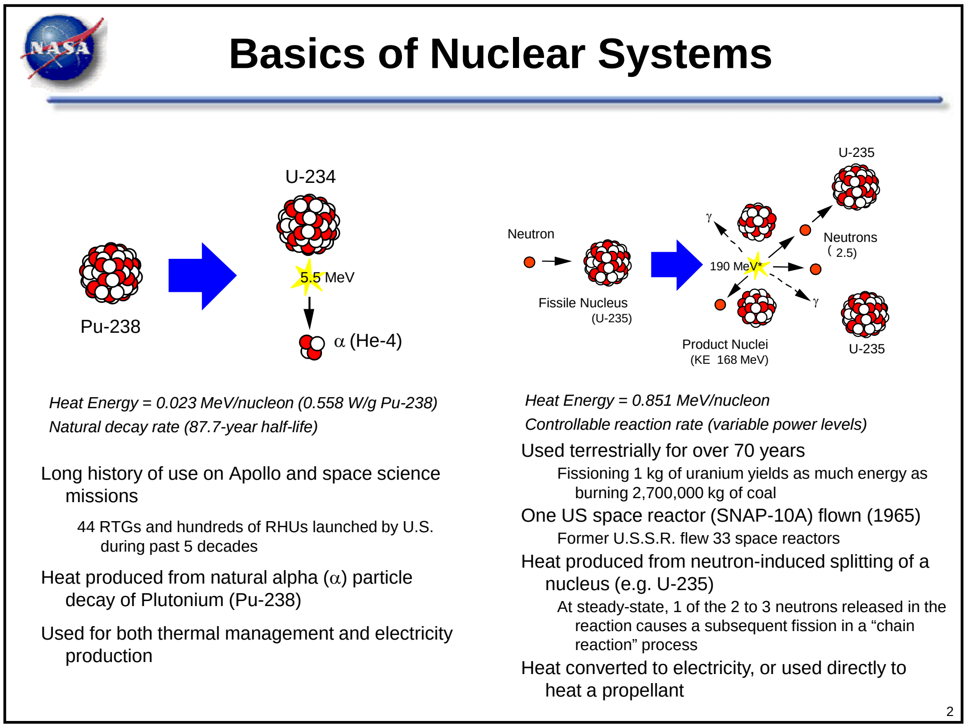


Basics of Nuclear Systems

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 5 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)

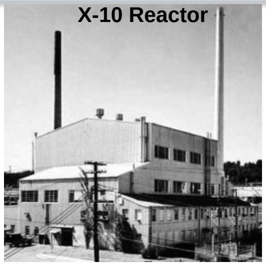
- Used terrestrially for over 70 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - At steady-state, 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***

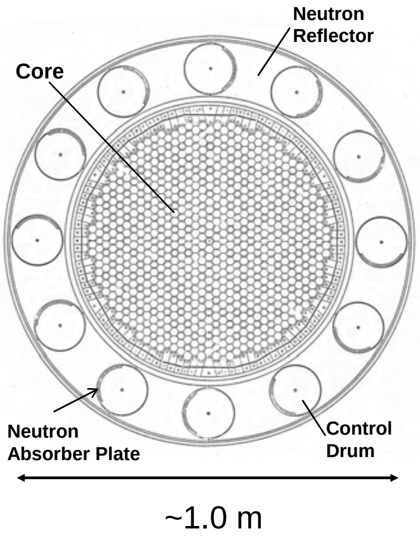
X-10 Reactor



Fission is Highly Versatile with Many Applications (continued)

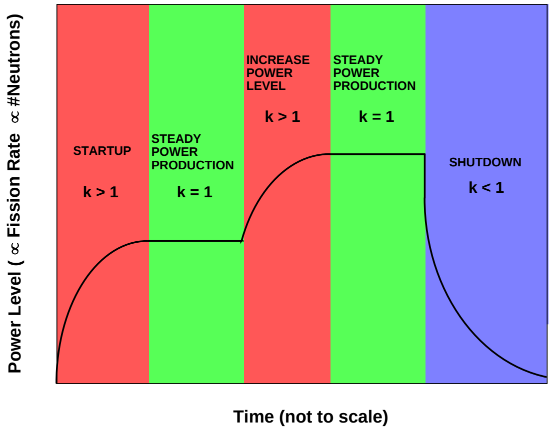
- Commercial Power Reactors
  - 430 commercial nuclear power stations operable in 31 countries, 70 more under construction
- Naval Reactors
  - 150 submarines and surface ships worldwide
- Production of medical and other isotopes
- Fission Surface Power
  - Safe, abundant, cost effective power on the 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

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
- 45 grams per 1000 MW-hr

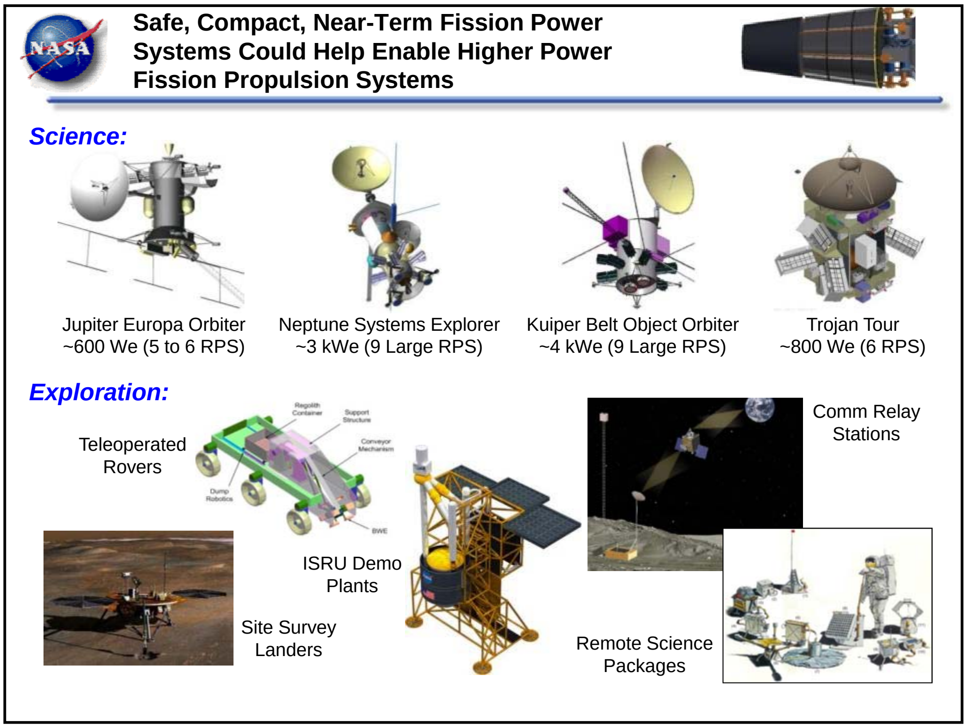
Control of Reactor Conditions



$$k \equiv \text{Multiplication Factor}$$

$$= \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t+l_n)}{N(t)}$$

$$\begin{array}{ll} <1 & (\text{subcritical},\ dN/dt < 0) \\ =1 & (\text{critical},\ dN/dt = 0) \\ >1 & (\text{supercritical},\ dN/dt > 0) \end{array}$$



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:

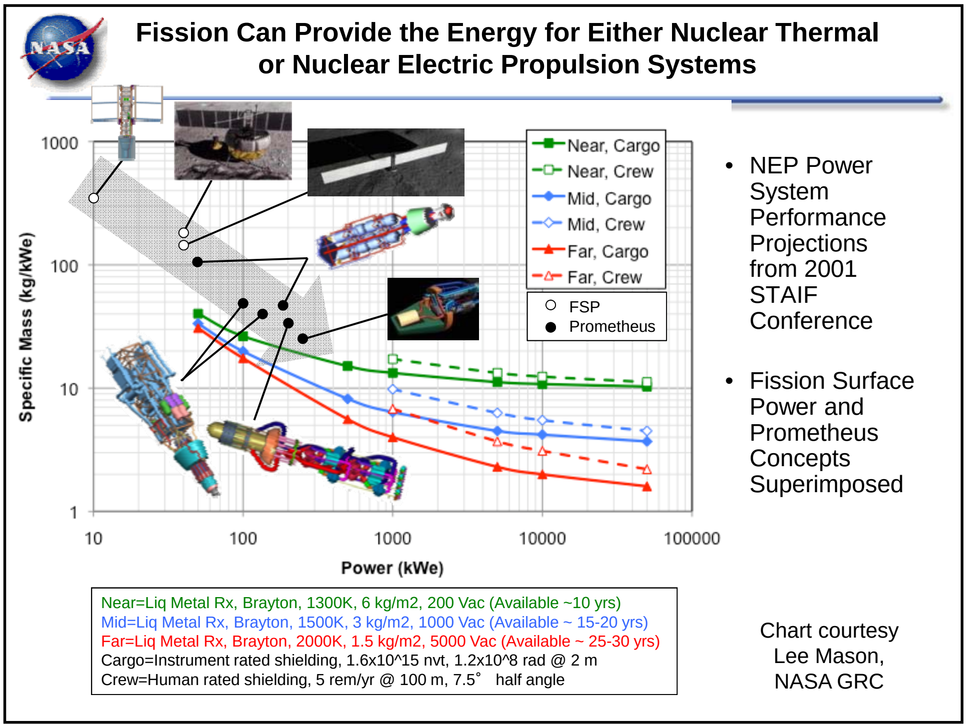
Teleoperated
Rovers

ISRU Demo
Plants

Site Survey
Landers

Comm Relay
Stations

Remote Science
Packages



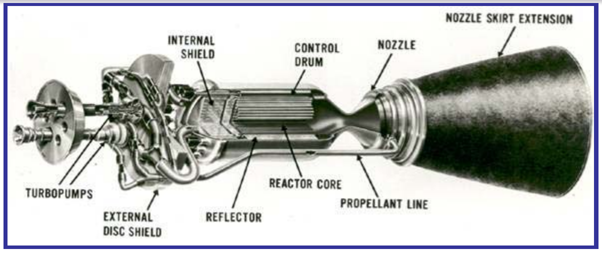
Fission Can Provide the Energy for Either Nuclear Thermal or Nuclear Electric Propulsion Systems

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

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

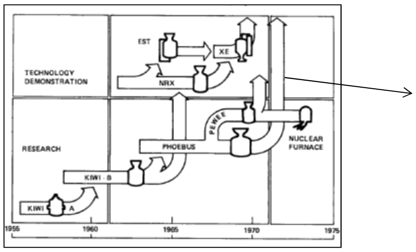
Chart courtesy
Lee Mason,
NASA GRC

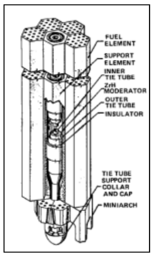
NASA is Currently Funding an “Advanced Exploration Systems” Project Investigating Nuclear Thermal Propulsion (NTP)

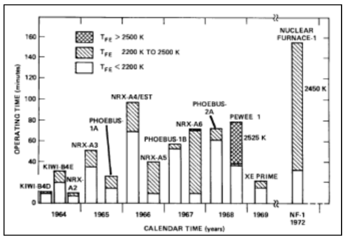


- Nuclear thermal propulsion (NTP) is a fundamentally new capability
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- Initial systems will have specific impulses roughly twice that of the best chemical systems
  - Reduced propellant (launch) requirements, 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

Leverage the highly successful Rover/NERVA program (1955-1973) and more recent programs







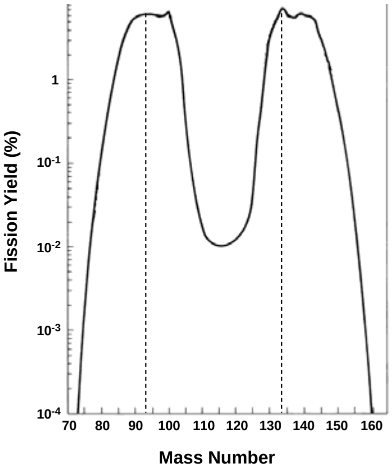
PHOEBUS NUCLEAR ROCKET ENGINE

The most powerful nuclear rocket engine ever tested (Phoebus 2a) is shown during a high-power test. The reactor operated for about 32 minutes, 12 minutes at power levels of more than 4.0 million kilowatts.

Fission Products

- Fission events yield bimodal distribution of product elements.
- These products are generally neutron-rich isotopes and emit beta and gamma particles in radioactive decay chains.
- Most products rapidly decay to stable forms – a few, however, decay at slow rates or decay to daughter products which have long decay times.
- Example fission products of concern:
  - —Strontium-90 (28.8-year half-life)
  - —Cesium-137 (30.1-year half-life)
- Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives.
- Decay power 6.2% at t=0 (plus fission from delayed neutrons), 1.3% at 1 hour, 0.1% at 2 months (following 5 years operation).

Product Yields for Thermal Neutron (0.025 eV) Fission of U-235

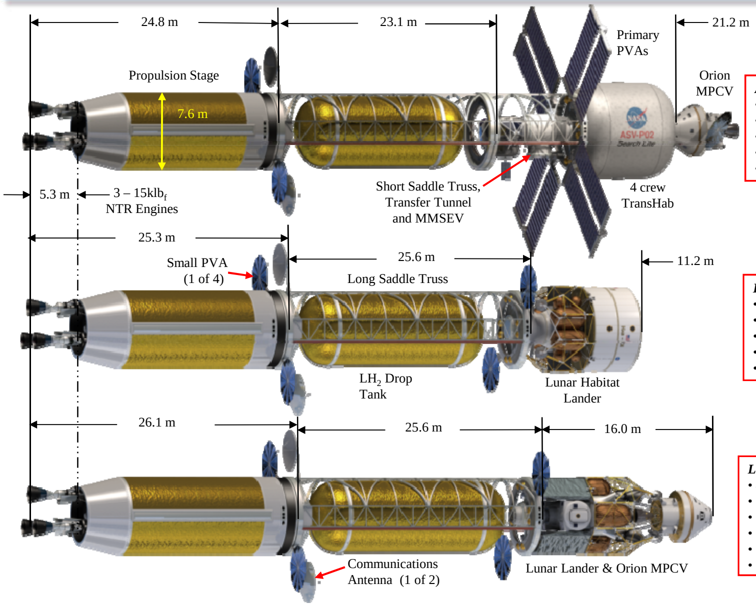


Guidance Navigation and Control: Unique Considerations

- Relatively slow engine start (up to 1 minute from zero thrust to full thrust).
- Potential for significant feedback during engine start.
  - Introduction of hydrogen into reactor
  - Temperature change in fuel
  - Temperature change in neutron reflector
  - Control drum rotation
- Deviations between predicted thrust and actual thrust during startup.
- Heat from fission products precludes instantaneous shutdown. Desire to minimize mission performance penalty associated with cool down.
- Second generation (or beyond) NTP systems may incorporate electric propulsion at some level, using energy from the reactor to power electric thrusters. This “bimodal” operation may also have unique guidance, navigation, and control characteristics.

NTP Transfer Vehicles for Reusable NEA, Lunar Cargo and Crewed Lunar Landing Missions using ~70 t-class SLS

(Courtesy Stan Borowski, NASA GRC)



ASV 2000 SG344:
- 4 crew
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH$_2$ tanks
- IMLEO ~178.7 t
- Max Lift ~67 t

Lunar Cargo:
- 57 t Habitat Lander
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH$_2$ tanks
- IMLEO ~198 t
- Max Lift ~69.3 t

Lunar Landing:
- 4 crew
- 34.5 t Lunar Lander
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH$_2$ tanks
- IMLEO ~197.5 t
- Max Lift ~72.8 t

Notional NCPS Mission -- 2033 600 day Mars Piloted Stack
Core Stage, In-line Tank, & Star Truss w/ (2) LH_2 Drop Tanks

(Courtesy Stan Borowski, NASA GRC)

Design Constraints / Parameters:

• # Engines / Type:	3 / NERVA-derived
• Engine Thrust:	25.1 klbf (Pewee-class)
• Propellant:	LH2
• Specific Impulse, Isp:	900 sec
• Cooldown LH2:	3%
• Tank Material:	Aluminum-Lithium
• Tank Ullage:	3%
• Tank Trap Residuals:	2%
• Truss Material:	Graphite Epoxy Composite
• RCS Propellants:	NTO / MMH
• # RCS Thruster Isp:	335 sec (AMBR Isp)
• Passive TPS:	1" SOFI + 60 layer MLI
• Active CFM:	ZBO Brayton Cryo-cooler
• I/F Structure:	Stage / Truss Docking Adaptor w/ Fluid Transfer

Mission Constraints / Parameters:

- 6 Crew
- Outbound time: 183 days (nom.)
- Stay time: 60 days (nom.)
- Return time: 357 days (nom.)
- 1% Performance Margin on all burns
- TMI Gravity Losses: 265 m/s total, f(T/W_0)
- Pre-mission RCS ΔVs: 181 m/s (4 burns/stage)
- RCS MidCrs. Cor. ΔVs: 65 m/s (in & outbnd)
- Jettison Both Drop Tanks After TMI-1
- Jettison Tunnel, Can & Waste Prior to TEI

		Inline	(2) drop	payload	core
	Power Level (kW)	5.25		44.75	7.07
	Tank Diameter (m)	8.90	8.90		8.90
	Tank Length (m)	19.30	13.58		17.10
	Truss length (m)		19	12	
	Liquid LH2	72.18	96.29		62.90
Total	Foodstores			8.01	
6	Crew			0.79	
	Dry weight	17.67	19.30		36.41
	TransHab+Crew Science			34.649	
	Samples			0.25	
	CEV			10.10	
Total	Launch Element Mass (mt)	100.50	121.48	67.93	101.94
	RCS Total Propellant	18.66			
	Total Launched Mass	391.84	mt		

NTP Transfer Vehicle Description:

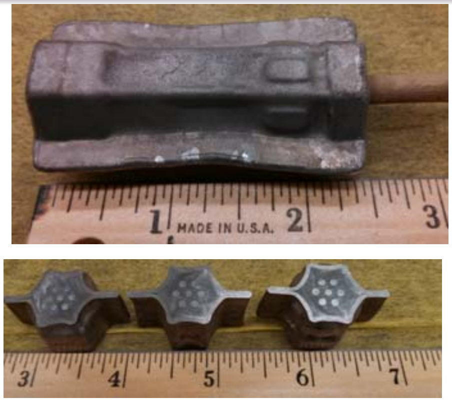
NTP system consists of 3 elements: 1) core propulsion stage, 2) in-line tank, and 3) integrated star truss and dual drop tank assembly that connects the propulsion stack to the crewed payload element for Mars 2033 mission. Each 100t element is delivered on an SLS LV (178.35.01, 10m O.D.x 25.2 m cyl. §) to LEO -50 x 220 nmi, then onboard RCS provides circ burn to 407 km orbit. The core stage uses three NERVA-derived 25.1 klbf engines. It also includes RCS, avionics, power, long-duration CFM hardware (e.g., COLDEST design, ZBO cryo-coolers) and AR&D capability. The star truss uses Gr/Ep composite material & the LH2 drop tanks use a passive TPS. Interface structure includes fluid transfer, electrical, and communications lines.

	ΔV (m/s)	Burn Time (min)
1st perigee TMI + g-loss	2380	39.4
2nd perigee TMI	1445	17.8
MOC	1470	15
TEI	3080	23.5
	8375	95.7

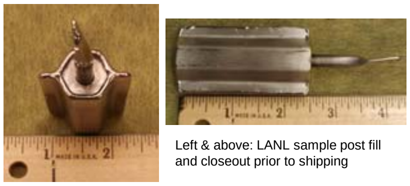
Notional Example of Human Mars Mission

W/UO_2 CERMET Fuel Element Fabrication: 7 Channel Element with Depleted Uranium

Above left/right: 7 channel W-UO_2 FE during HIP process



Above/Below: 7 channel WUO_2 fuel element post HIP and cross sections



Left & above: LANL sample post fill and closeout prior to shipping

Short, 7 Channel W/UO_2 Element Fabricated and Tested in Compact Fuel Element Environmental Tester (CFEET)

CFEET (50 kW, fuel element segment testing)

Left: View looking down into the CFEET chamber during shakeout run 1. BN insulator and bright orange sample inside

Above/left: Pure W sample post shakeout run 2. Sample reached melting point (3695K) and was held in place by the BN insulator.

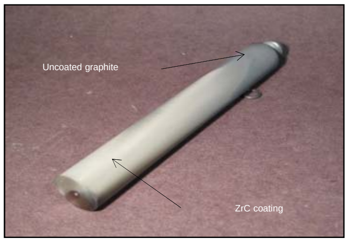
Initial Testing of Short W/UO_2 Element Segment

Coated Graphite Composite Development (ORNL)

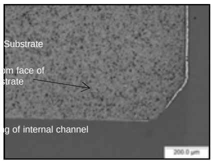
Above: Members of Oak Ridge National Laboratory fuels team with the graphite extruder; Left: Graphite extruder with vent lines installed for DU capability

Above and Left: Extrusion samples using carbon-matrix/Ha blend .75” across flats, .125” coolant channels

Right: Layoff base / Graphite insert



Above: Test Piece highlighting ZrC Coating
Right: Coating primarily on external surface



Nuclear Thermal Rocket Element Environmental Simulator (NTREES)


NTREES Phase 1 50kW (2011)


NTREES Phase 2 – 1MW Upgrade (2015)

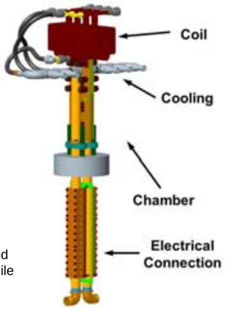

Cooling Water System provides 2 separate systems that cool induction coil and power feedthrough, induction heater and H_2N_2 mixer respectively

General Description:

- Water cooled ASME coded test vessel rated for 1100 psi
- GN_2 (facility) and GH_2 (trailer) gas supply systems
- Vent system (combined GN_2/GH_2 flow)
- 1.2 MW RF power supply with new inductive coil
- Water cooling system (test chamber, exhaust mixer and RF system)
- Control & Data Acquisition implemented via LabVIEW program
- Extensive H_2 leak detection system and O_2 monitoring system
- Data acquisition system consists of a pyrometer suite for axial temperature measurements and a mass spectrometer
- “Fail Safe” design

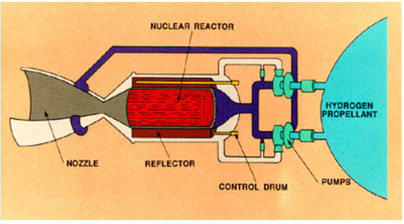

New Coil is Heavily Insulated and Rugged


Old Coil was Uninsulated and Somewhat Fragile

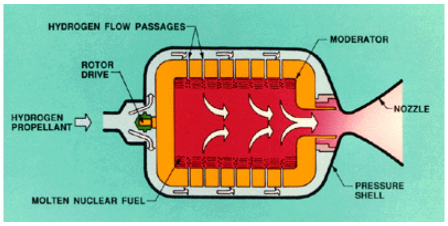


Coil and Feedthrough Assembly

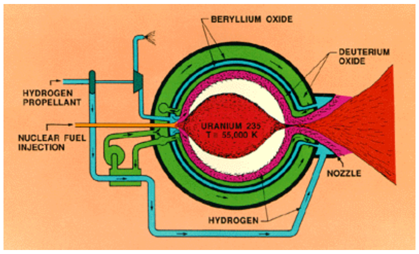
Proposed Types of Nuclear Thermal Propulsion



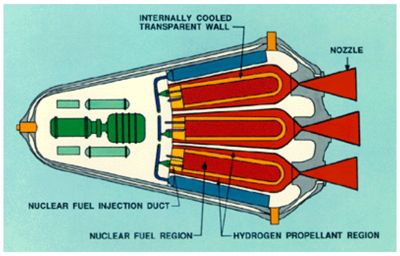
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket

Observations

- Space fission power and propulsion systems are game changing technologies for space exploration.
- First generation NTP systems could provide significant benefits to sustained human Mars exploration and other missions.
- Advanced space fission power and propulsion systems could enable extremely ambitious space exploration and development.
- Some aspects of guidance, navigation, and control will be unique for NTP systems. However, there do not appear to be insurmountable issues or concerns.