Nuclear Energy for Advanced Propulsion

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presented by

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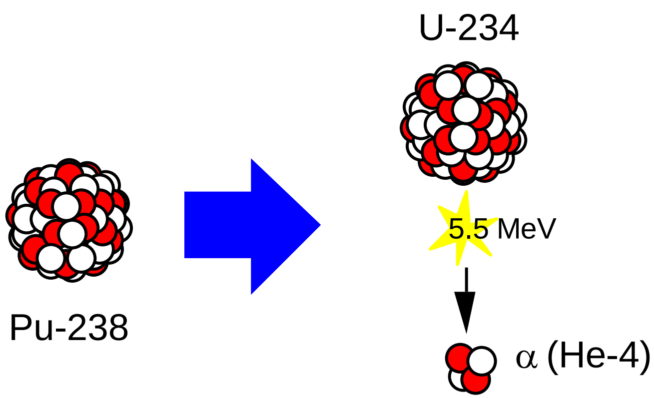
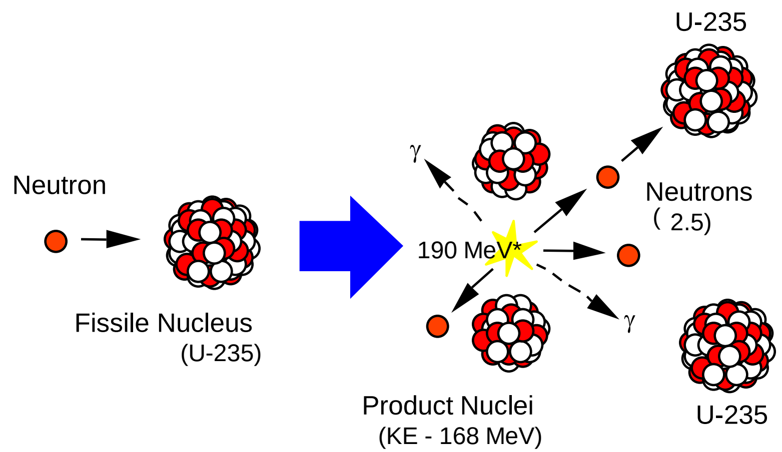
Basics of Nuclear Systems





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 4 decades
- Heat produced from natural alpha (a) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production

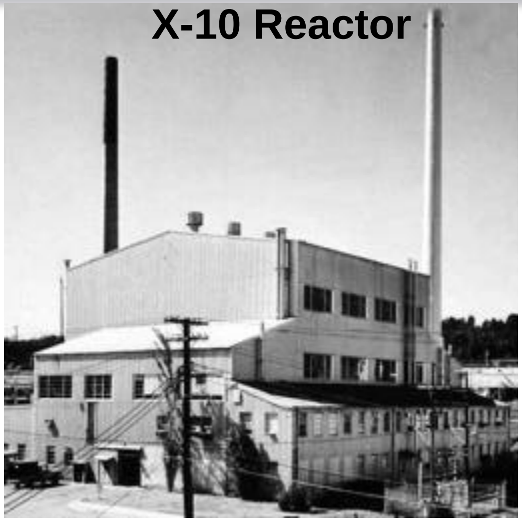
Heat Energy = 0.851 MeV/nucleon

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

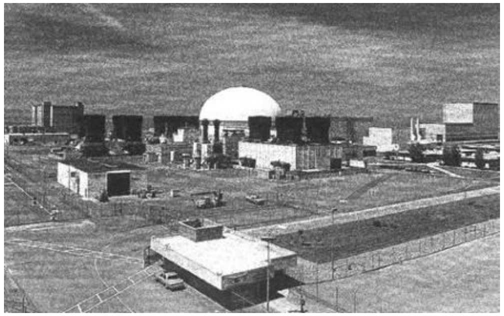
- **Creating a fission chain reaction is conceptually simple**
  - **Requires right materials in right geometry**
- **Good engineering needed to create safe, affordable, useful fission systems**



- ***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***

Fission is Highly Versatile with Many Applications

- Small research reactors
  - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< $50M)



- Advanced, high-power research reactors and associated facilities
  - Examples include the US Fast Flux Test, EBR-II, ATR, HFIR
- Commercial Light Water Reactors 1,371,000 kWe (3,800,000 kWt)

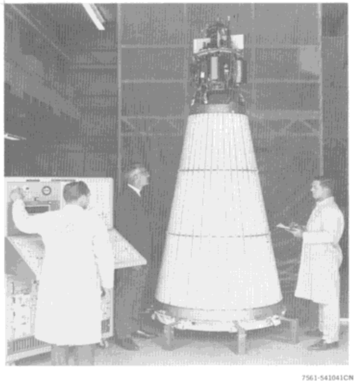


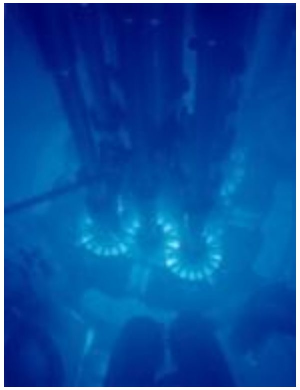
Figure II-92. SNAP 10A Flight System

- Space reactors
  - SNAP-10A 42 kWt / 0.6 kWe
  - Soviet reactors typically 100 kWt / 3 kWe (some systems >150 kWt)
  - Cost is design-dependent

Fission is Highly Versatile with Many Applications (continued)

- Naval Reactors
  - Hundreds of submarines and surface ships worldwide

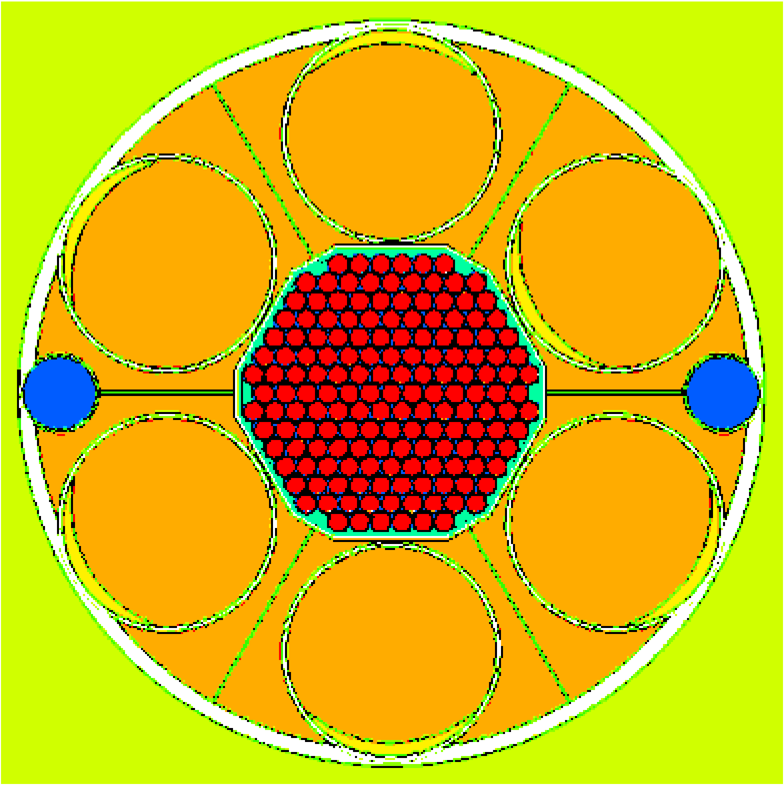
- Production of medical and other isotopes



- 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

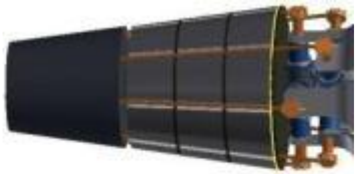
Typical Space Fission System Operation



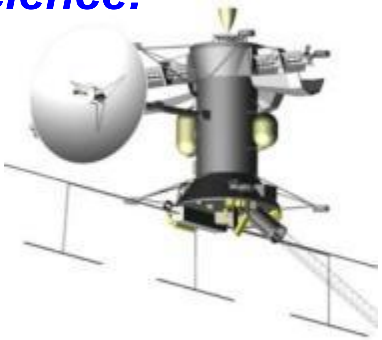
0.5 m

- 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

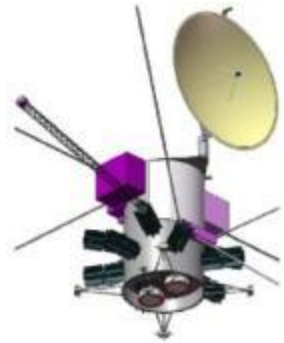


Science:

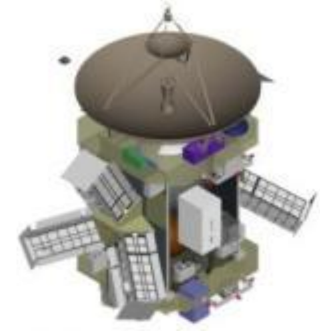


Jupiter Europa Orbiter
~600 We (5 to 6 RPS)

Neptune Systems Explorer
~3 kWe (9 Large RPS)



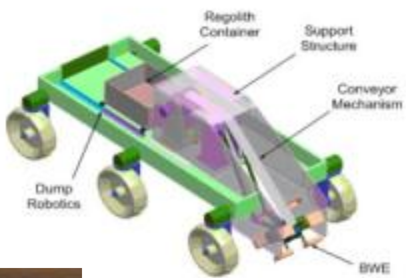
Kuiper Belt Object Orbiter
~4 kWe (9 Large RPS)

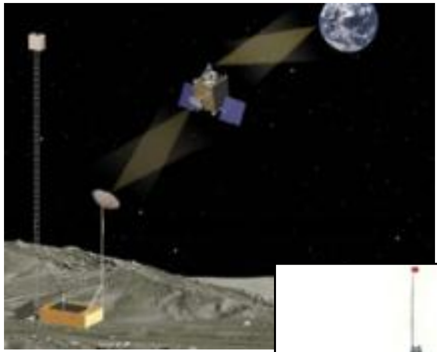


Trojan Tour
~800 We (6 RPS)

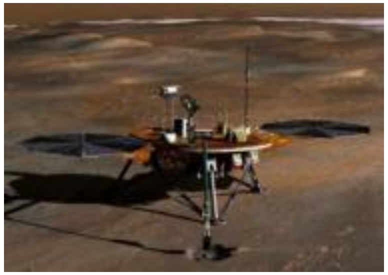
Exploration:

Teleoperated
Rovers





Comm Relay
Stations

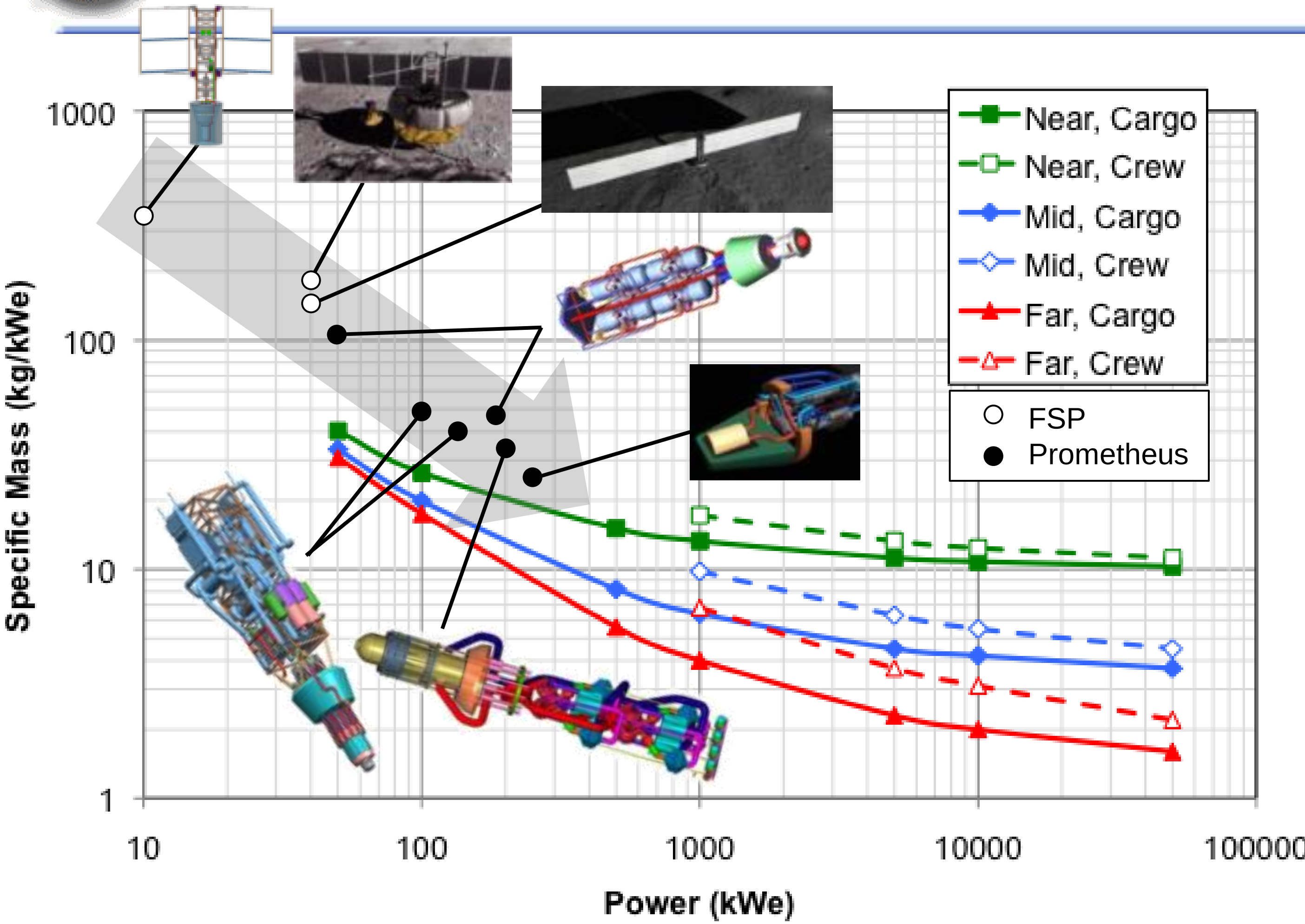


Site Survey
Landers

ISRU Demo
Plants

Remote Science
Packages

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

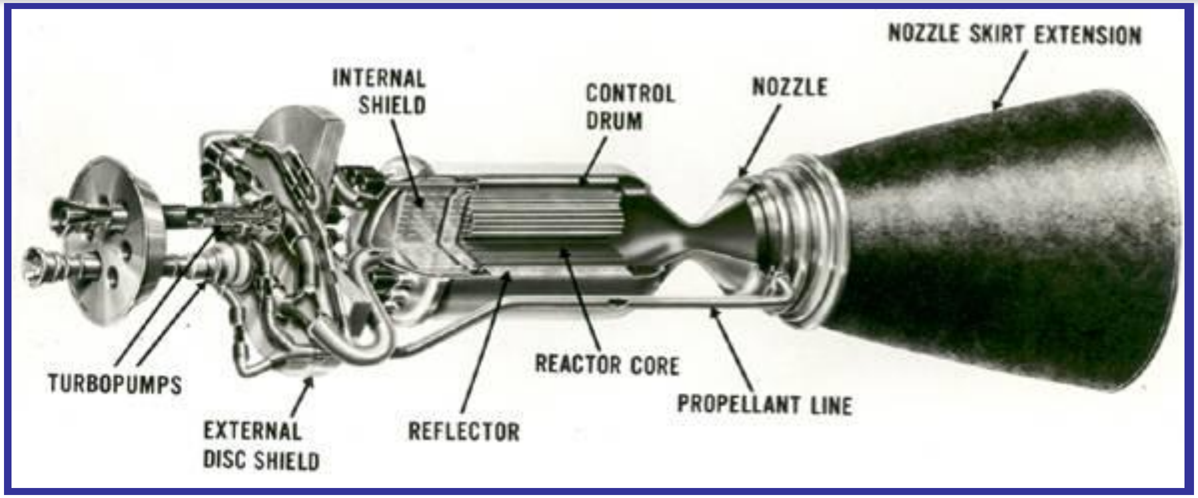


Near=Liq Metal Rx, Brayton, 1300K, 6 kg/m2, 200 Vac (Available ~10 yrs)
Mid=Liq Metal Rx, Brayton, 1500K, 3 kg/m2, 1000 Vac (Available ~ 15-20 yrs)
Far=Liq Metal Rx, Brayton, 2000K, 1.5 kg/m2, 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, 1.6x10^15 nvt, 1.2x10^8 rad @ 2 m
Crew=Human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

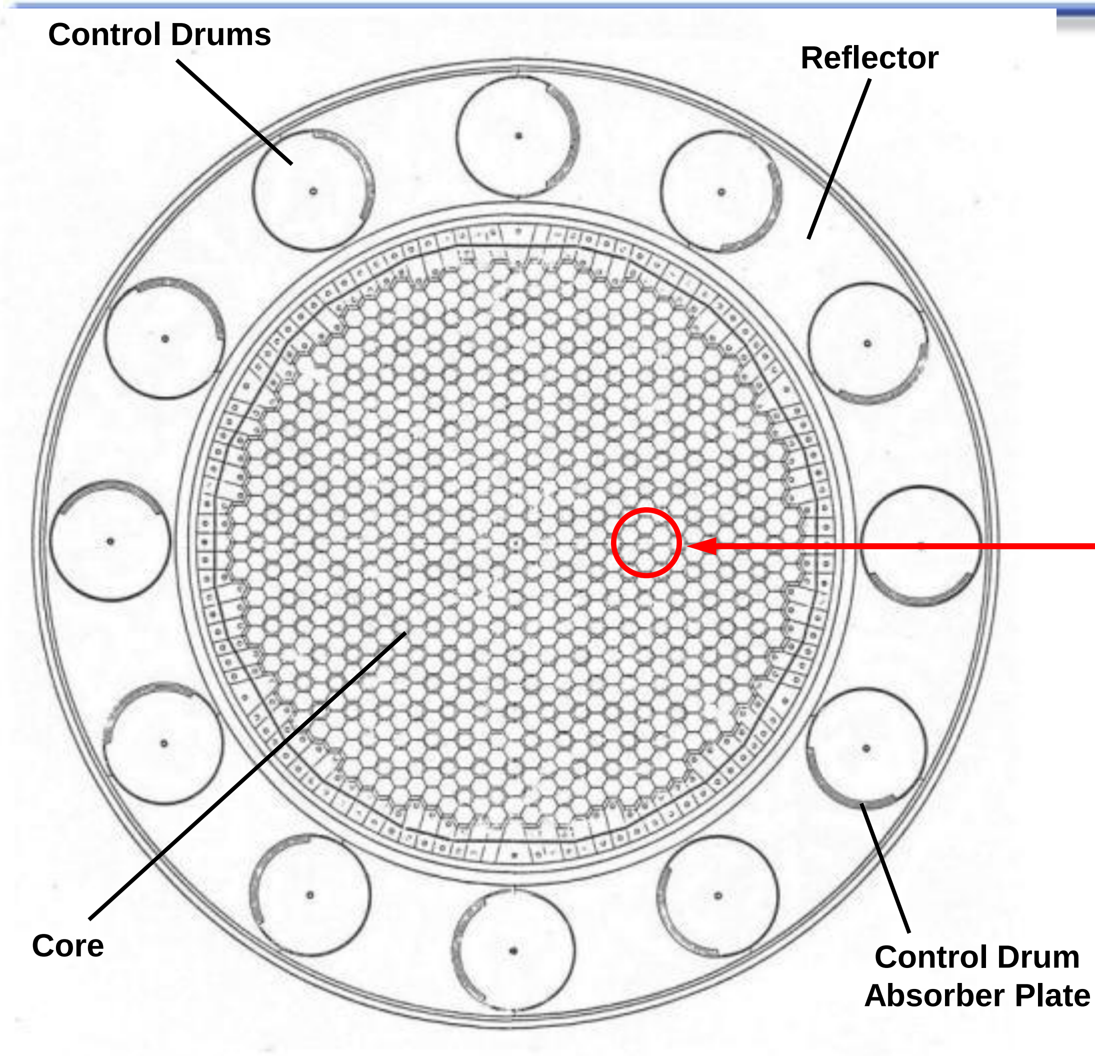
Chart courtesy Lee Mason, NASA GRC

NASA is Currently Funding an "Advanced Exploration Systems" Project Investigating a Nuclear Cryogenic Propulsion Stage (NCPS)

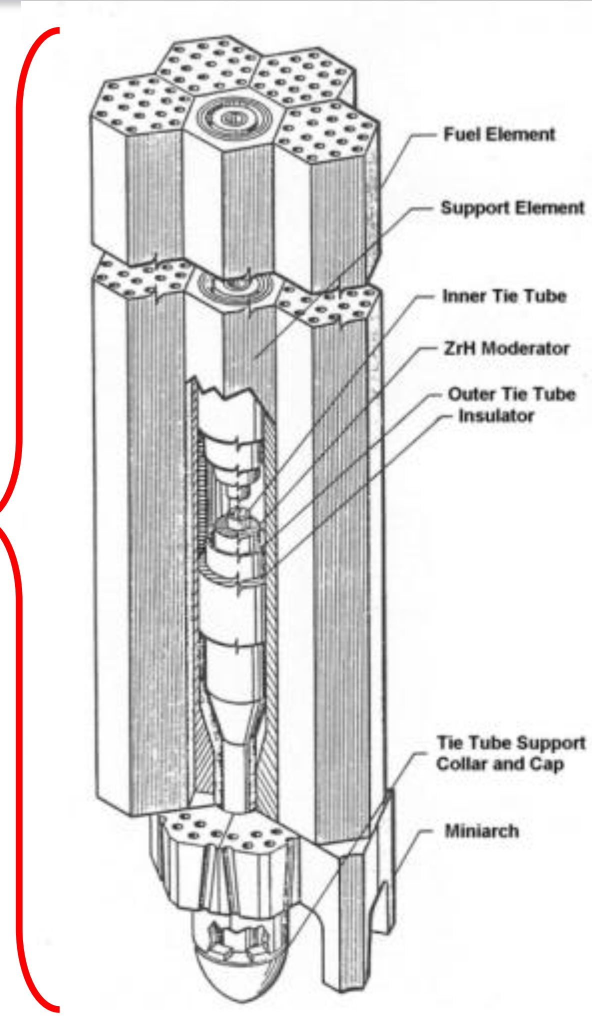


- Nuclear thermal propulsion (NTP) is a fundamentally new capability
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- Initial systems will have specific impulses roughly twice that of the best chemical systems
  - Reduced propellant (launch) requirements, 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
- The NCPS could serve as the "DC-3" of space nuclear power and propulsion

NCPS Builds on Previous NTP Engine Designs / Tests

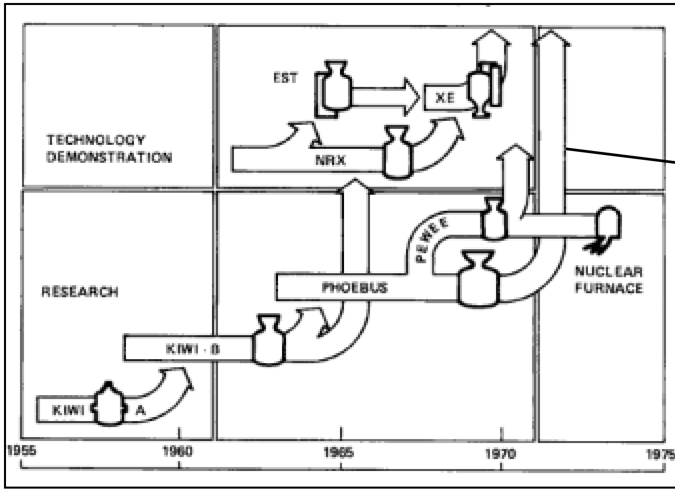


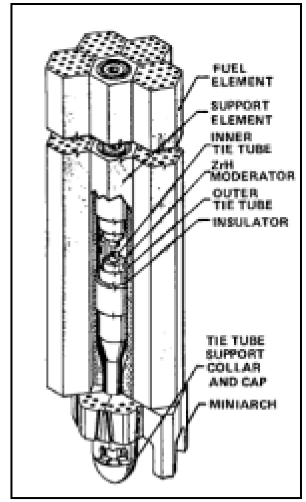
NERVA Reactor Cross Section

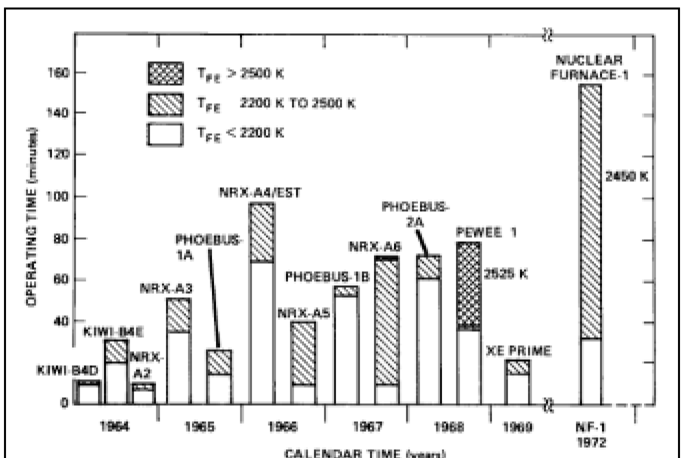


Fuel Segment Cluster

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







PHOEBUS NUCLEAR ROCKET ENGINE

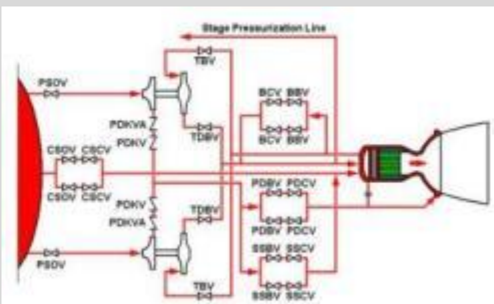
The most powerful nuclear rocket engine ever tested (Phoebus 2a) is shown during a high-power test. The reactor operated for about 32 minutes, 12 minutes at power levels of more than 4.0 million kilowatts.

NCPS Project Work Breakdown Structure

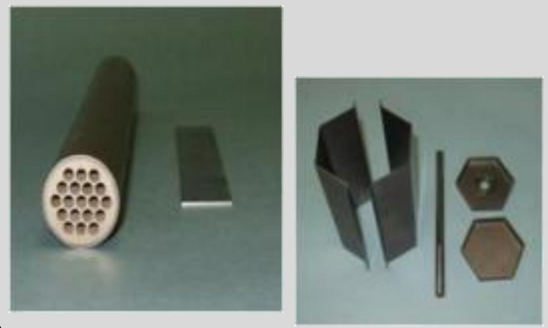
1.0 NCPS Project Management

Project Manager:	Mike Houts (MSFC)
DOE Lead:	Ryan Bechtel
GRC Lead:	Stan Borowski
JSC Lead:	Jeff George

2.0 Pre-conceptual Design of the NCPS & Architecture Integration
Task Lead: Tony Kim



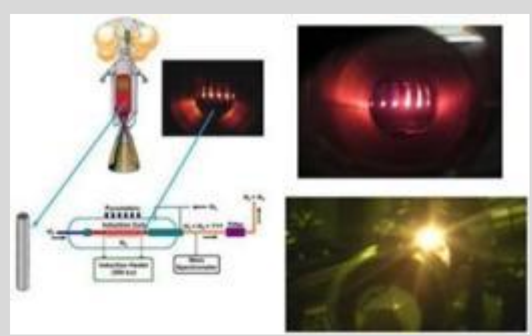
4.0 NCPS Fuel Design / Fabrication
PI: Robert Hickman, MSFC
Task Lead: Jeramie Broadway



6.0 Affordable NCPS Development and Qualification Strategy
Task Lead: Harold Gerrish

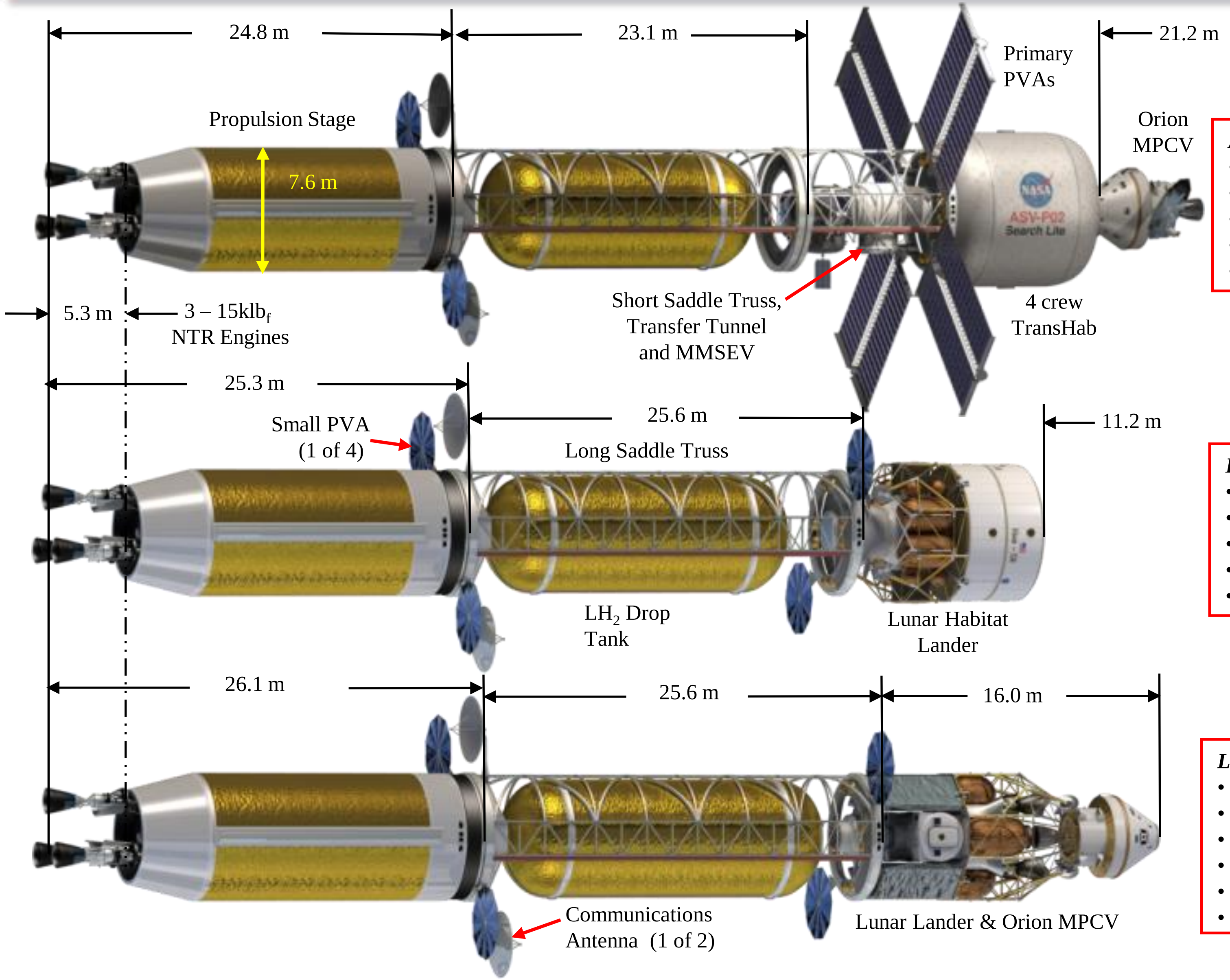
3.0 High Power (≥ 1 MW) Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
Task Lead: Bill Emrich

5.0 NCPS Fuels Testing in NTREES & CFEET
Co-Lead: Bill Emrich
Co-Lead: Jeramie Broadway



7.0 Second Generation NCPS Concepts
Task Lead: Rob Adams

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

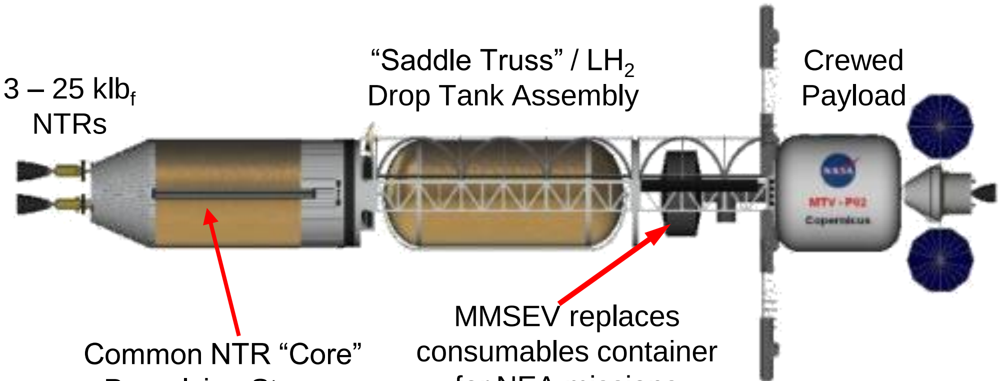


ASV 2000 SG344:
- 4 crew
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH_2 tanks
- IMLEO ~178.7 t
- Max Lift ~67 t

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

Growth Paths Identified using Modular Components to Increase Vehicle LH_2 Capacity & Mission Applications



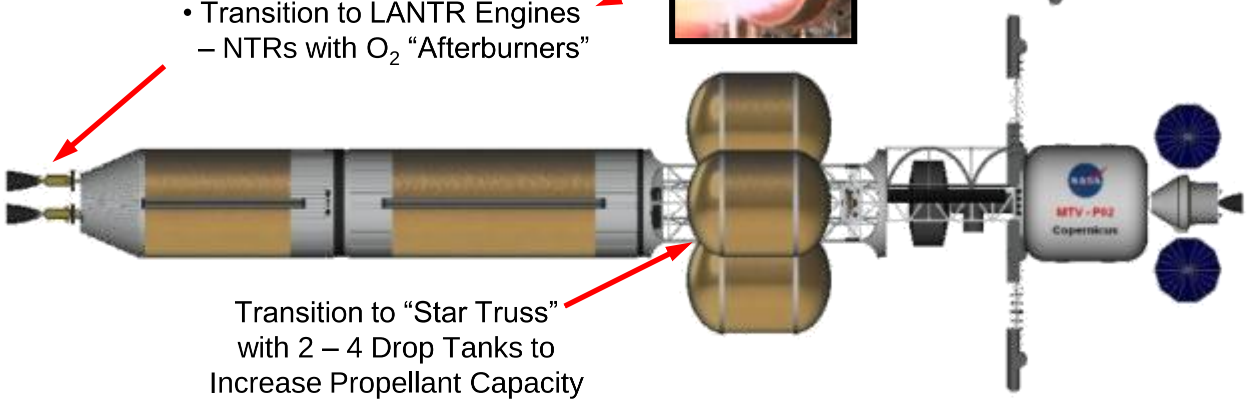
Configuration 1 Applications:

- Fast Conjunction Mars Landing Missions – Expendable
- "1-yr" Round Trip to Large NEAs 1991 JW (2027) and Apophis (2028) – Reusable
- Propulsion Stage & Saddle Truss / Drop Tank Assembly can also be used as:
  - Earth Return Vehicle (ERV) / propellant tanker in "Split Mars Mission" Mode – Expendable
  - Cargo Transfer Vehicle supporting a Lunar Base – Reusable

Configuration 2 Applications:

- Fast Conjunction Mars Landing Missions – Reusable
- 2033 Mars Orbital Mission 545 Day Round Trip Time with 60 Days at Mars – Expendable
- Cargo & Crew Delivery to Lunar Base – Reusable

Options for Increasing Thrust:
- Add 4th Engine, or
- Transition to LANTR Engines – NTRs with O_2 "Afterburners"



Configuration 3 Applications:

- Fast Conjunction Mars Landing Missions – Reusable or Expendable
- 2033 Mars Orbital Mission 545 Day Round Trip Time with 60 Days at Mars – Reusable
- Some LEO Assembly Required
  – Attachment of Drop Tanks
- Additional HLV Launches

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

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*		

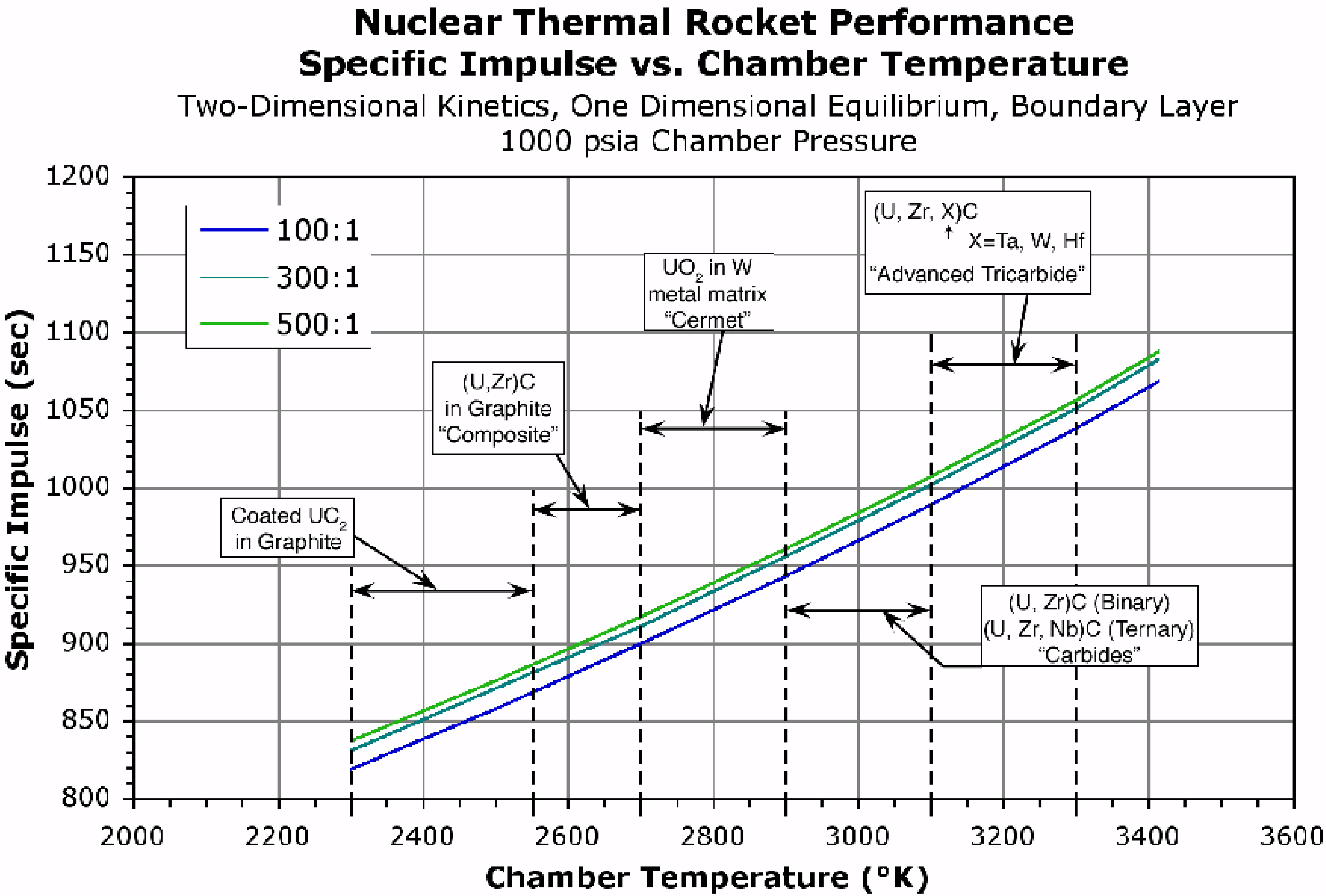
NTP Transfer Vehicle Description:

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

High Temperature Fuels Are Key to NTP Performance

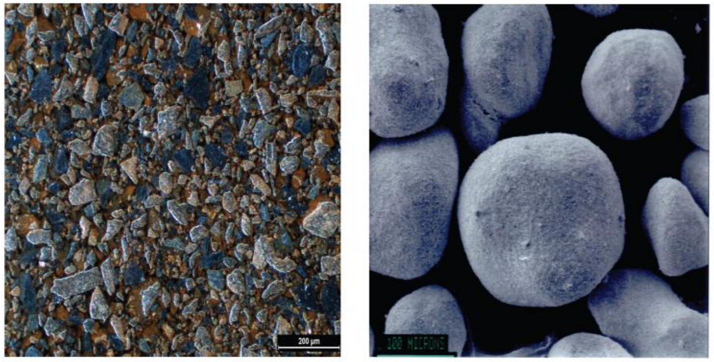


Fuel Material Development

- Develop/evaluate multiple fuel forms and processes in order to baseline a fuel form for NTP
  - CERMET: Hot Isostatic Pressing (HIP), Pulsed Electric Current Sintering (PECS)
  - Graphite composites
- Materials and process characterization
  - Develop and characterize starting materials
    - W coated fuel particles are required for CERMETS
    - Particle size, shape, chemistry, microstructure
  - Develop and characterize consolidated samples
    - Microstructure, density, chemistry, phases
  - Optimize material/process/property relationships
    - Fuel particle size/shape vs. properties
    - Cladding composition and thickness
- Hot hydrogen testing
  - Early development to validate test approach
  - Screen materials and processes (cyclic fuel mass loss)
    - Particle size, chemistry, microstructure, and design features (claddings)

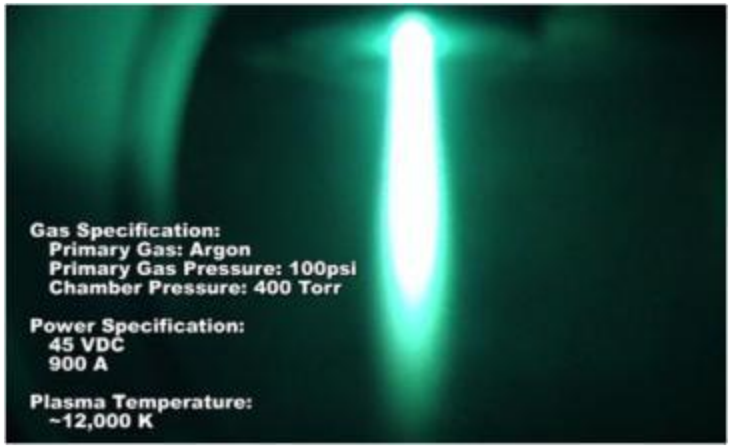
Uranium Dioxide (UO_2) Particle Development

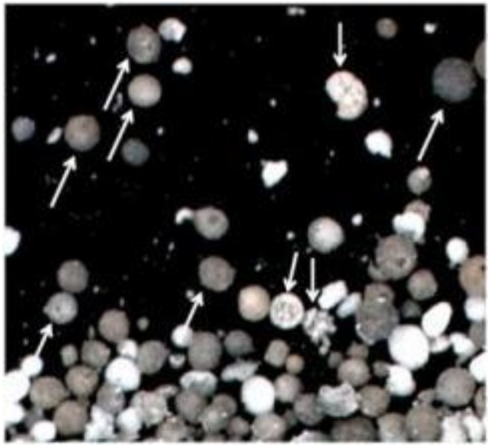
- UO_2 Particle Procurement
  - Procured 2kg of dUO_2
  - Particle size ranges:
    - <100um
    - 100um – 150um
    - >150um
- Plasma Spheroidization System (PSS)
  - System design and assembly
  - Start-up July 2012



a.) b.)

Y-12 Feedstock, (a) Depleted UO_2 and (b) Natural UO_2





Initial Results

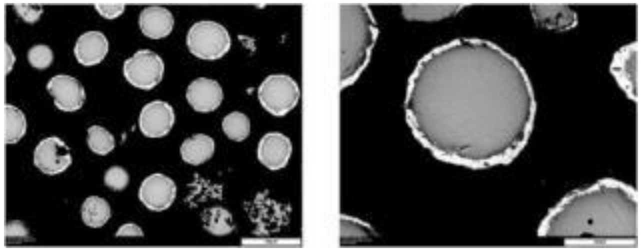
Completed MSFC PSS assembly

Chemical Vapor Deposition (CVD) Coated Particle Development

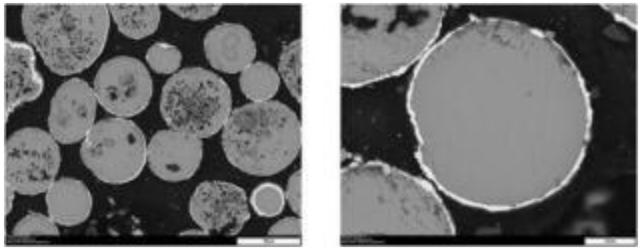
- MSFC Tungsten Hexachloride (WCl_6) Process Development
  - Redesigned and upgraded CVD system complete
  - Demonstrated W coating on Al_2O_3 substrate
  - Ongoing fluidization trails
  - Reactor design optimization for fluidization

- Tungsten Hexafluoride (WF6) Process Development
  - Process being developed by Ultramet
  - Currently coating ZrO_2 particles
  - Have demonstrated 20 vol% W coating

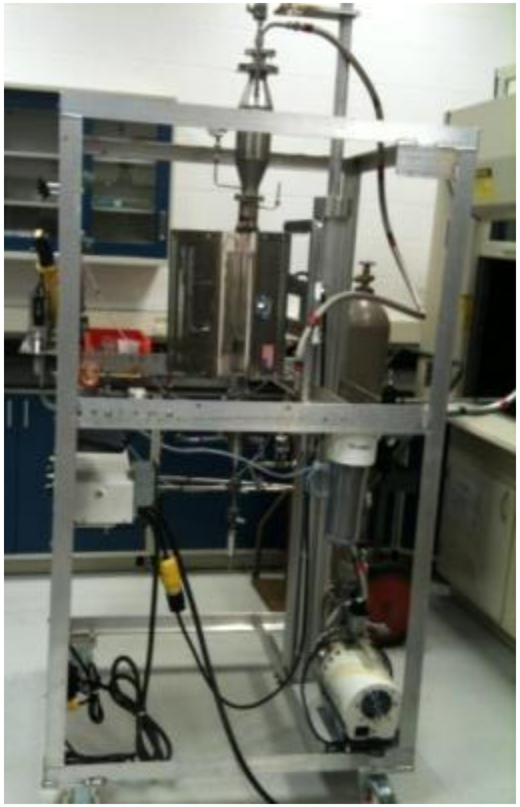
- 40 vol% W coated spherical particles required for HIP and PECS consolidation process development



W coated ZrO2, average particle OD 31.0 μm, average coating thickness 1.76 μm.



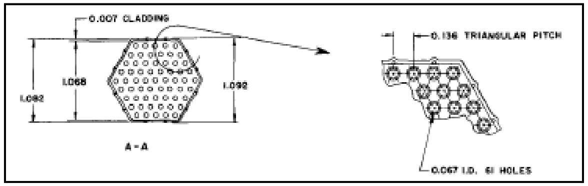
CVD Run 5: 30 minutes. W coated ZrO2.



Redesigned CVD System

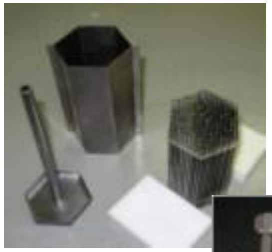
CERMET Consolidation Process Development (CEO_2)

- ANL 200MW element chosen for NCPS reference design



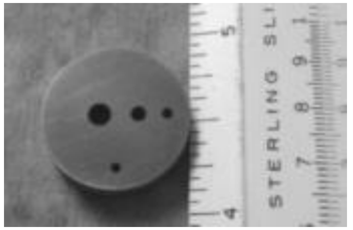
ANL 200MW Reference Design

- Hot Isostatic Pressing (HIP) process development
  - In-house HIP furnace upgrades underway
  - Identified glove box limitations for full size cans
  - Established process schedule tolerance
  - Updated can designs based on lessons learned
  - Initiated manufacture of HIP cans



HIP Parameters Study Cans

- Pulsed Electric Current Sintering (PECS) Development
  - Completed pure W microstructural morphology study
  - Fabricated 7 specimens of W-40vol%CeO_2 with varying ratios of particle sizes, W vs. CeO_2 (uncoated)
    - CeO_2 encapsulated W particles when W > CeO_2 (microstructure image shown)
    - Studies ongoing for CeO_2 > W particle size
  - EDM machining investigated as a method to drill coolant channels into W-CeO_2 specimens

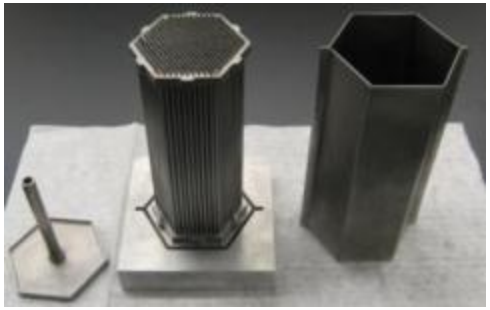


EDM Trials on W-CeO_2 Specimen


Hexagonal W-CeO_2 Specimen (PECS)

Recent Fuels Fabrication Activities

H2 Powder Furnace In Assembly



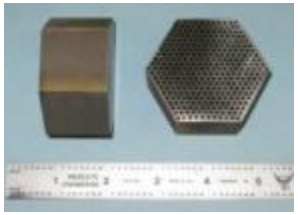
Molybdenum mandrel assembly for 331 Hexagonal demonstration

W powder in H2 furnace

Piece parts of integrally cladded HIP sample (top). Cladded HIP sample post HIP

Top end cap welding of 331 Hex demo

331 Hexagonal demonstration post HIP



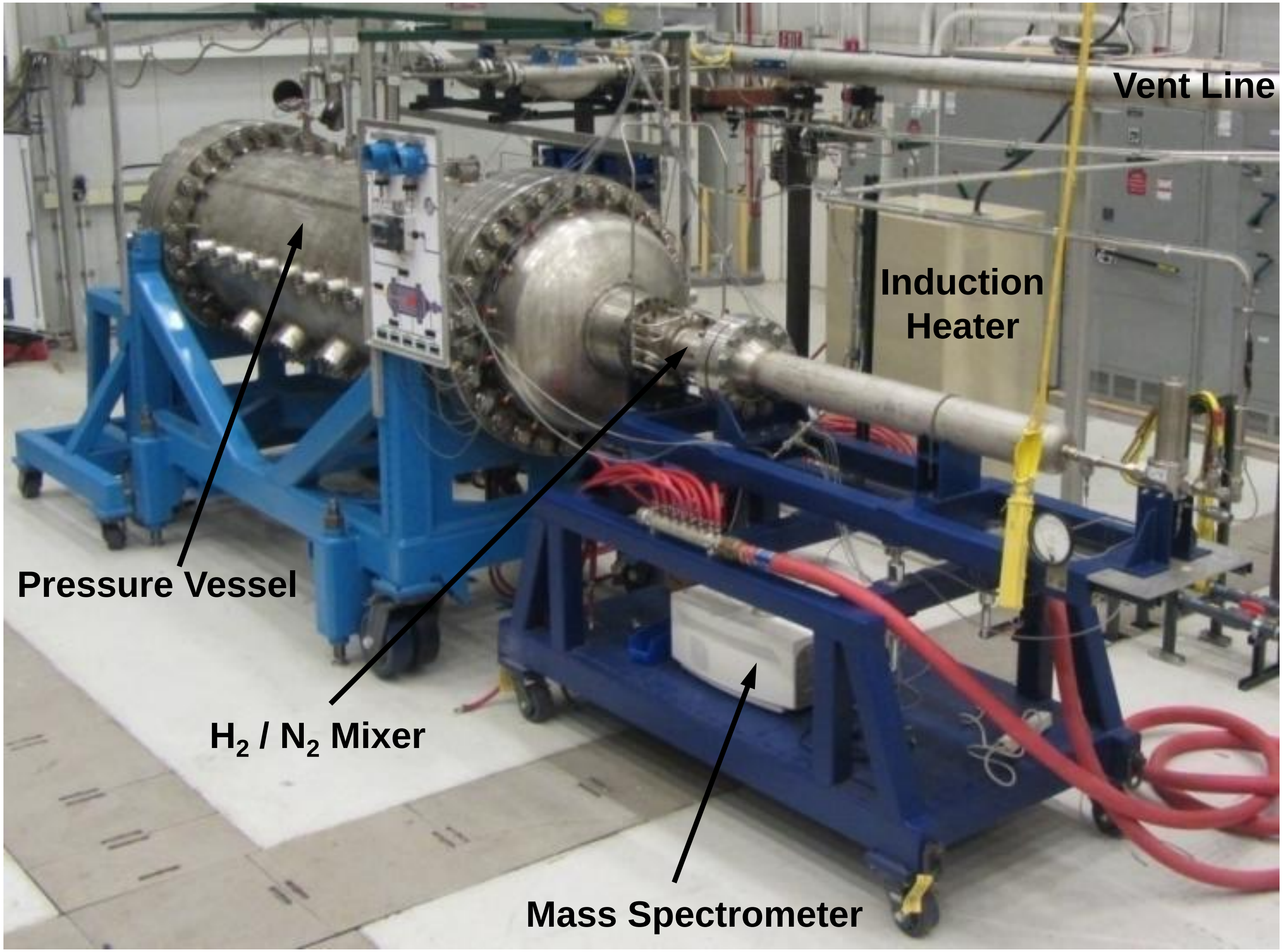
Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

A key technology element in Nuclear Thermal Propulsion is the development of fuel materials and components which can withstand extremely high temperatures while being exposed to flowing hydrogen

NTREES provides a cost effective method for rapidly screening of candidate fuel components with regard to their viability for use in NTR systems

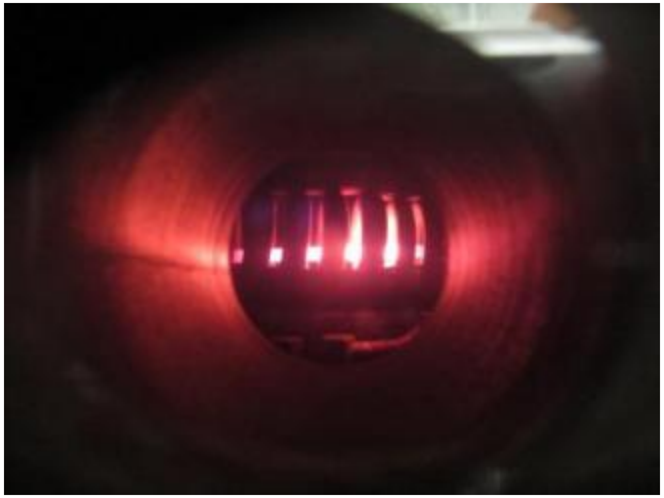
- The NTREES is designed to mimic the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation
- The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated control hardware and instrumentation coupled with inductive heaters to simulate the heat provided by the fission process
- The NTREES has been designed to safely allow hydrogen gas to be injected into internal flow passages of an inductively heated test article mounted in the chamber

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)



NTREES Undergoing Power Upgrade

- NTREES induction power supply is being upgraded to 1.2 MW
- Water cooling system is being upgraded to remove 100% of the heat generated during testing
- Nitrogen system is being upgraded to increase the nitrogen flow rate to at least 4.5 lb/sec
- New piping is being installed to handle the increased flow rates
- The H_2 / N_2 mixer is being upgraded to handle the increased heat loads
- Platform is under construction to allow the new induction heater to be located underneath the NTREES pressure vessel

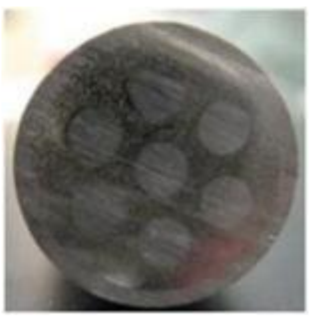


NTREES Testing

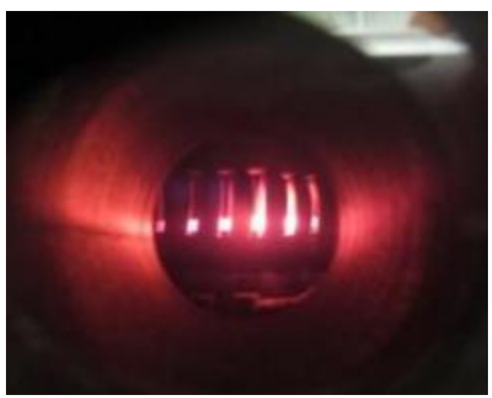
Hot Hydrogen Tests of W-HfN CERMET fuel element sample

- Sample completed over two full DRA5 mission profiles
  - 39.4 min full power, cool down
  - 17.8 min full power, cool down
  - 15 min full power, cool down
  - 23.5 min full power, cool down
- Maximum temperature achieved- 2073K

Etched and machined sample pre-test



Sample cross section prior to etch

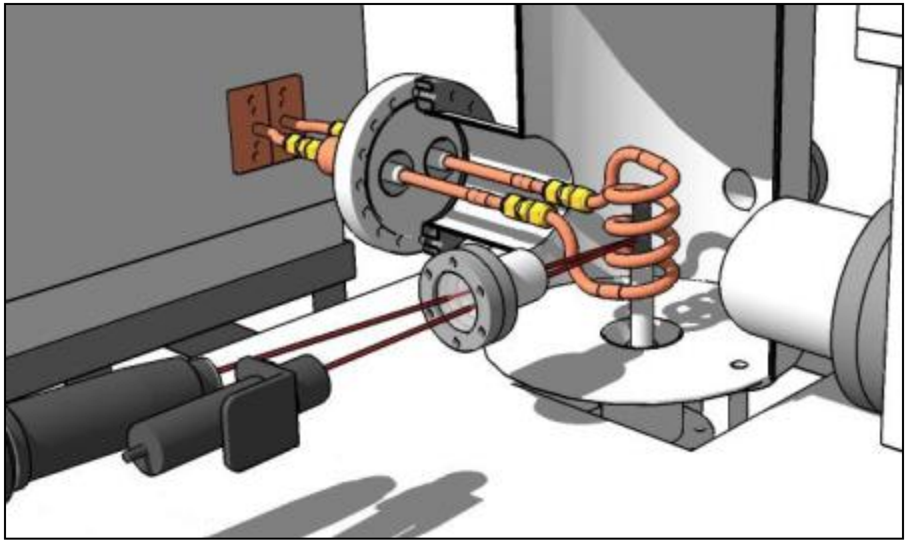


Sample Testing

NTREES Test Video
2 min of 30 min test run

CERMET Fuel Element Environmental Test (CFEET) System

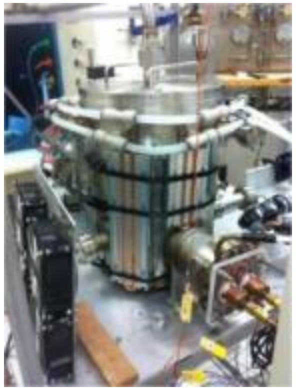
- Coupon level thermal cycle testing
- 0.5” -6” long, 0.5” dia. samples can be thermally cycled at high temperatures quickly
- Flowing hydrogen environment
- System is complete and operational



Cross section of CFEET chamber showing heating coils and sample

W/Re sample loaded into heating coil as viewed through the pyrometer viewport

Compact Fuel Element Environmental Tester (CFEET)



Chamber Water Jacketed

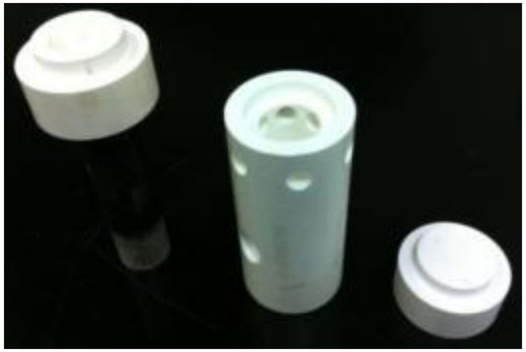
Molybdenum Thermal Shield

2 Ton Chiller

H_2 Feed and Burn-stack

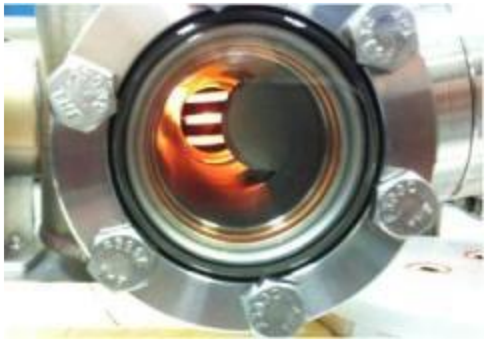
Optimized Coil

Flow Controller Calibration



Next Generation BN Pedestal

G-10 & Lexan Flanges



Sight Baffle

CFEET First Hot H_2 Test

- Heated Tungsten sample to 2523K while exposed to flowing H_2 at 16.5 SLPM
- All systems operated nominally

W Sample (0.5” OD x 1.5” L)

Pyrometer Port with sample at 2523 K

H2 Burn Stack

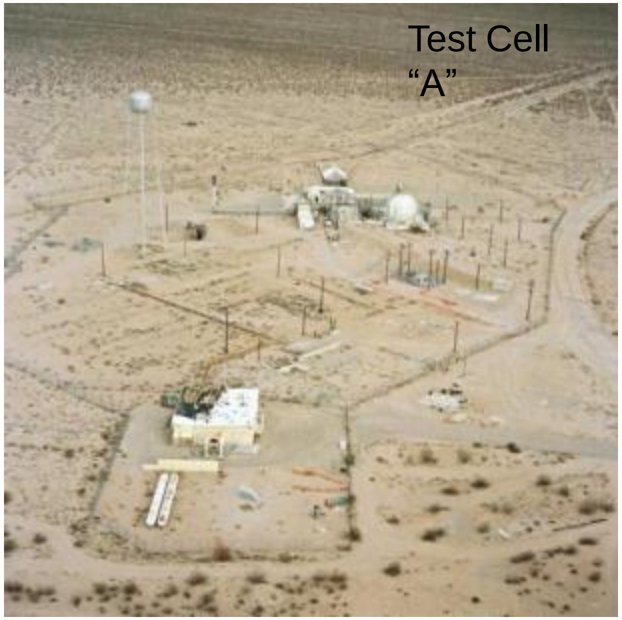
Temperature Profile

Affordable NCPS Development and Qualification Strategy

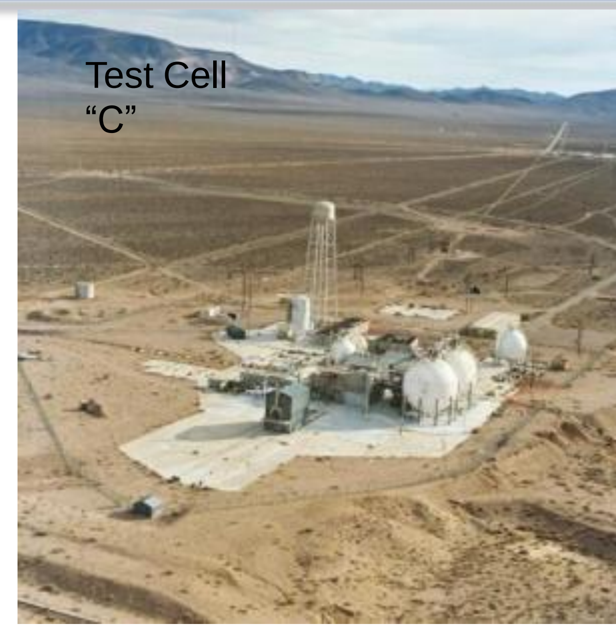
- Objective
  - Ensure ease of integration / applicability (SLS, other)
  - Devise an affordable NCPS development and qualification strategy
  - The integrated program development and test strategy will include fuel qualification and selection
    - Will use separate effects tests (hot H_2 and irradiation), innovative ground testing, state-of-the-art modeling, and the development of NCPS engines with an emphasis on affordability

- Key Deliverables
  - Yearly Reports
  - Estimated Cost and Schedule
  - Final Report: NCPS Development and Qualification Strategy

Nuclear Rocket Development Station (NRDS) Assets During Rover/NERVA Program



Test Cell "A"



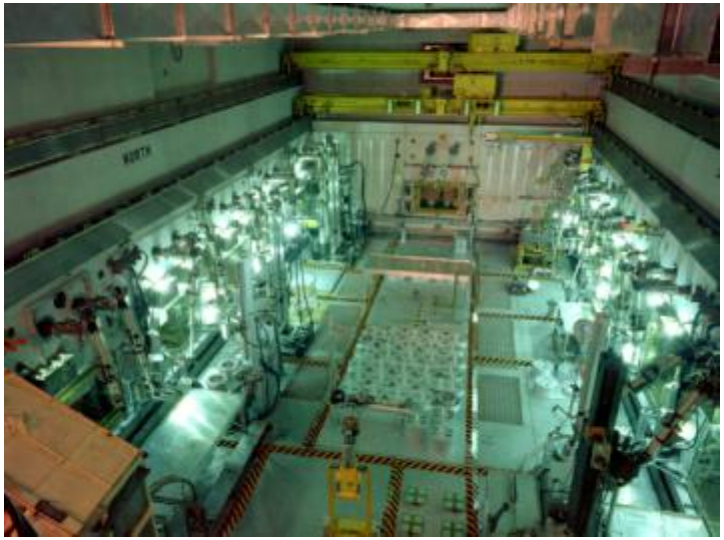
Test Cell "C"

E-MAD used to assemble nuclear rocket engines for testing and to disassemble and inspect engines after testing

NERVA Engine Test Stand (ETS)

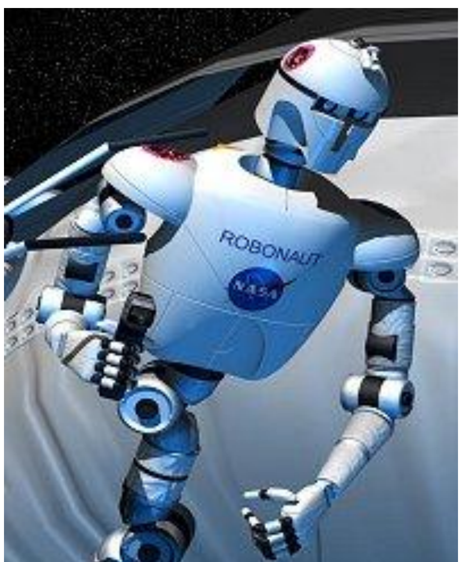
Nevada Test Site Bore Hole

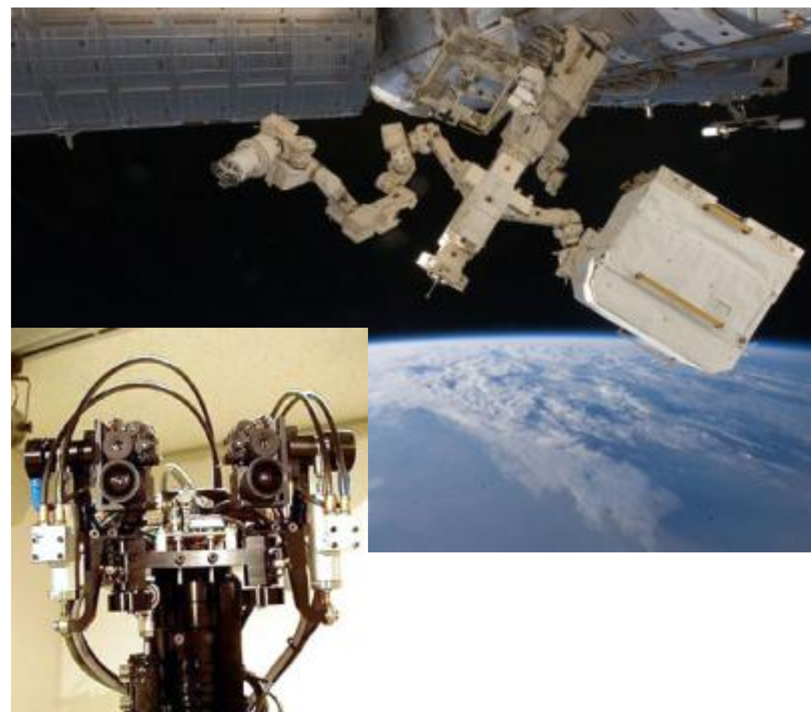
Existing Facilities at Idaho National Laboratory (INL)



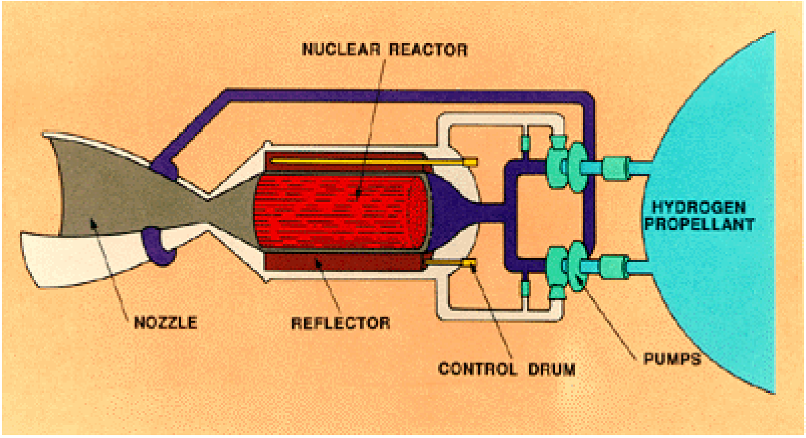
Demonstration Flight

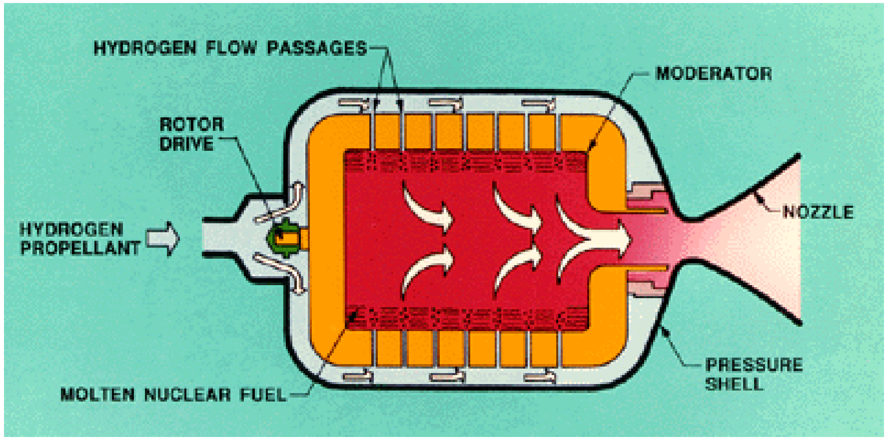
- Assess the viability and desirability of an NCPS demo flight
- Assess potential data gathering and analysis techniques for both the operating and post-operational phases
- Assess impact of limits on information that could be obtained from a demo flight



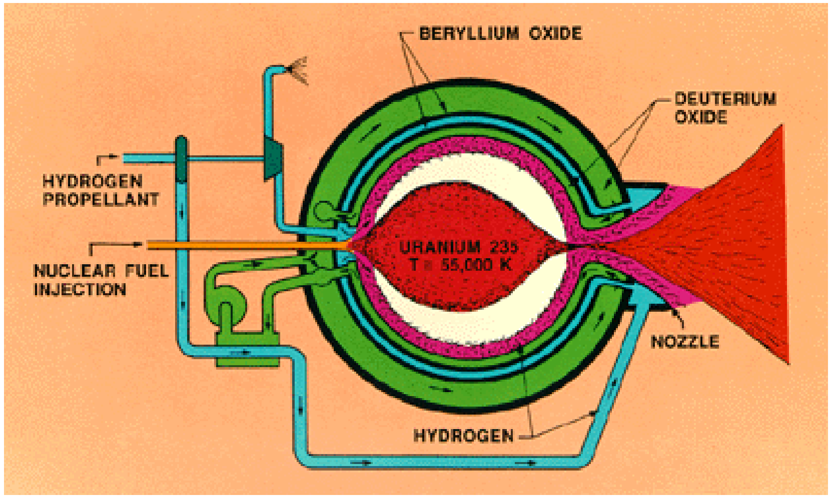


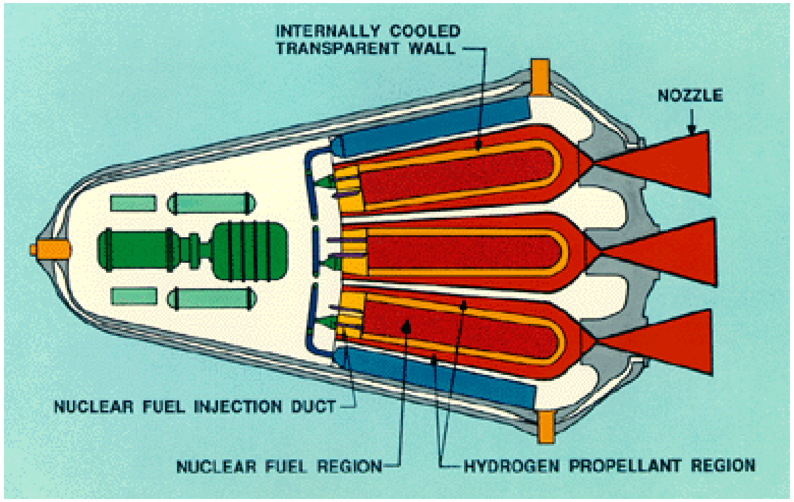
Proposed Types of Nuclear Thermal Propulsion





SOLID CORE NUCLEAR ROCKET





Beyond Fission: Potential Futuristic Nuclear Energy Sources

Fusion: The performance potential of lightweight, high gain fusion propulsion systems operating with aneutronic fuels (e.g. p-^{11}B) theoretically exceeds that of fission by an order of magnitude.

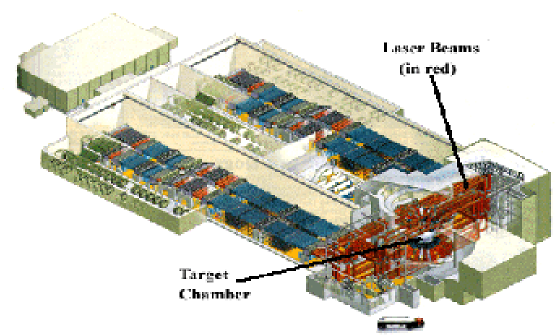
Fundamental Issues to Resolve:

1. Aneutronic Fuels. The performance potential of fusion propulsion systems operating with deuterium or tritium bearing fuels (e.g. D-T, D-D, or D-^{3}He) is severely limited because of waste heat production from neutron kinetic energy, and the additional waste energy released when a neutron of any energy is captured. The use of aneutronic fuels (e.g. p-^{11}B) will be required for high performance.

2. High Gain. Previous studies (Chakrabarti et al., 2001) have shown that high engineering gain (Q>50) is needed to minimize the mass of the fusion reaction driver and enable high performance.

3. Compact Systems. Significant funds and five decades have been spent on research related to controlled fusion. While the two leading approaches for achieving engineering breakeven are extremely massive, knowledge and experience from the ongoing terrestrial fusion effort may be useful in devising compact systems suitable for space propulsion applications.

Photo Courtesy of EFDA-JET



National Ignition Facility

Beyond Fission: Potential Futuristic Nuclear Energy Sources

Antimatter: Energy stored as antimatter has a specific energy of 1.8×10^{17} J/kg, over 500 times that of fission or fusion.

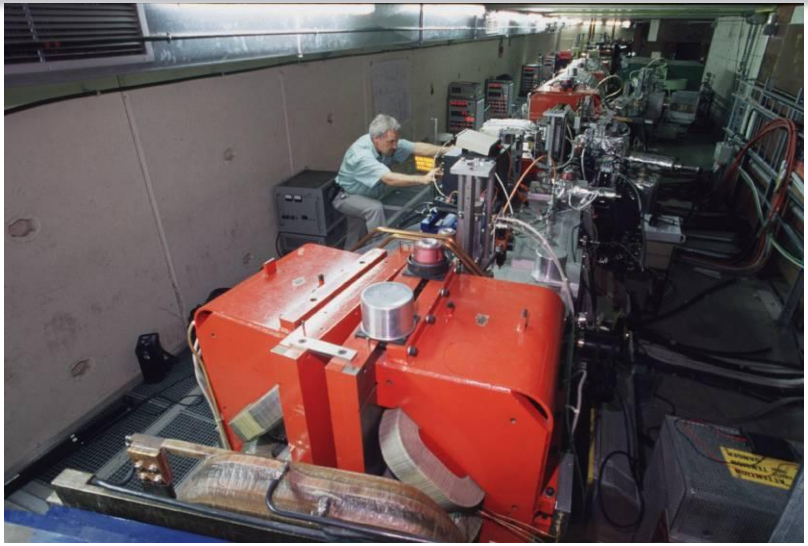


Photo Courtesy of Cern

Fundamental Issues to Resolve:

1. Production. Antiproton production rates must increase by several orders of magnitude, and the cost per antiproton must decrease correspondingly.

2. Storage. Effective methods for long-term antiproton storage and transportation must be developed.

3. Thrust Production. Effective methods for converting energy stored as antimatter into high specific impulse thrust must be devised.

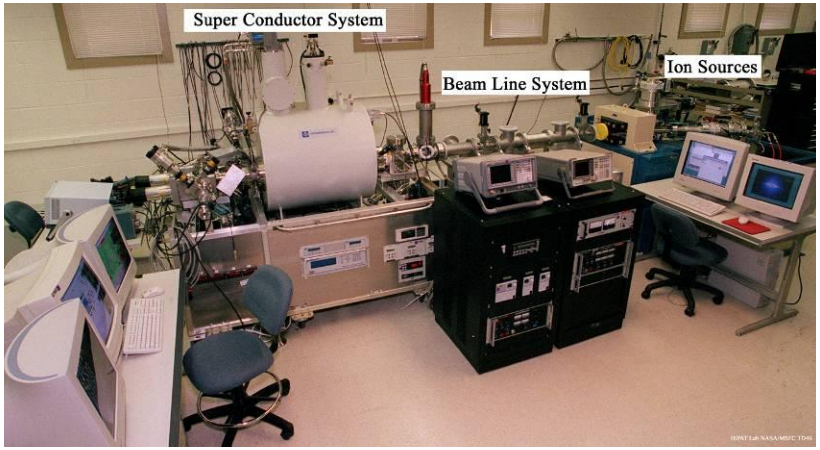


Photo: Marshall Space Flight Center

Summary

- Nuclear power and propulsion systems can enable exciting space exploration missions. These include bases on the moon and Mars; and the exploration, development, and utilization of the solar system.

- In the near-term, fission surface power systems could provide abundant, constant, cost-effective power anywhere on the surface of the Moon or Mars, independent of available sunlight. Affordable access to Mars, the asteroid belt, or other destinations could be provided by nuclear thermal rockets.

- In the further term, high performance fission power supplies could enable both extremely high power levels on planetary surfaces and fission electric propulsion vehicles for rapid, efficient cargo and crew transfer. Advanced fission propulsion systems could eventually allow routine access to the entire solar system. Fission systems could also enable the utilization of resources within the solar system. Fusion and antimatter systems may also be viable in the future.