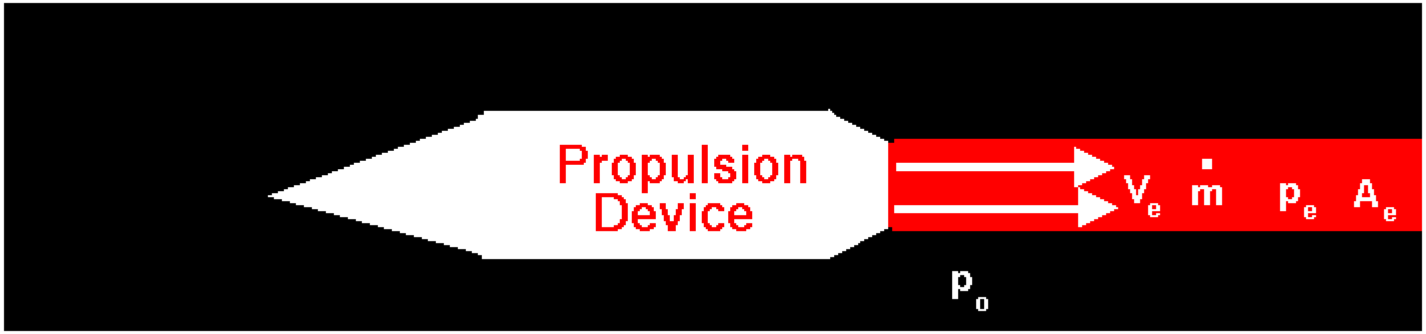
National Aeronautics and
Space Administration

Nuclear Thermal Propulsion:
An Overview of NASA Development Efforts

Ryan Wilkerson| Presented at Missouri S&T | 1031.19

Nuclear Thermal Propulsion Background

How do we assess engine performance?



Thrust

Rocket Thrust Equation

$$F = \dot{m}\, V_e + (p_e - p_o)A_e$$

Equivalent Velocity

$$V_{eq} = V_e + \frac{(p_e - p_o)A_e}{\dot{m}}$$

$$F = \dot{m}\, V_{eq}$$

Thrust is an indicator of how hard an engine can push

Specific Impulse

Total Impulse

$$I = F\Delta t = mV_e$$

Specific Impulse

$$I_{sp} = \frac{I}{mg_o} = \frac{V_{eq}}{g_o} = \frac{F}{\dot{m}g_o}$$

Specific impulse indicates how efficiently an engine uses propellant

Current engine architectures

	Chemical Engines					Advanced Propulsion	
	SRB-SS	SRB-SLS	F-1	J-2	RS-25	Ion NEP	NTP
Sea Level Thrust (klbf)	2800	3600	1800	109.3	418	-	-
Vacuum Thrust (klbf)	-	-	2020.7	232.3	512.3	2E-5 - 2E-2	25-250
Sea Level ISP (s)	242	269	269.7	200	366	-	-
Vacuum ISP (s)	-	-	303.1	421	452.3	2000-8000	800-1000
Propellant	PBAN-APCP	PBAN-APCP	LO2/RP-1	LO2/LH2	LO2/LH2	Xe	LH2

Saturn V

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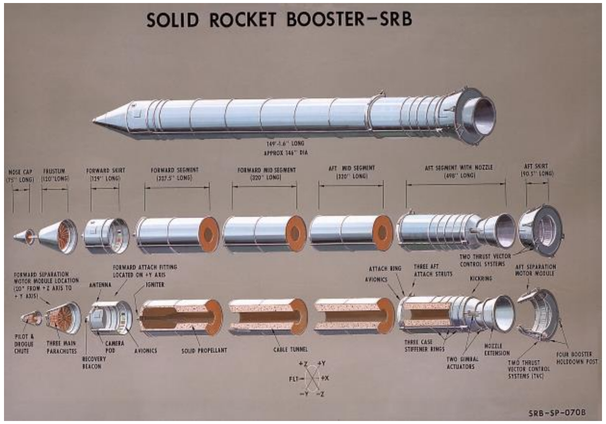

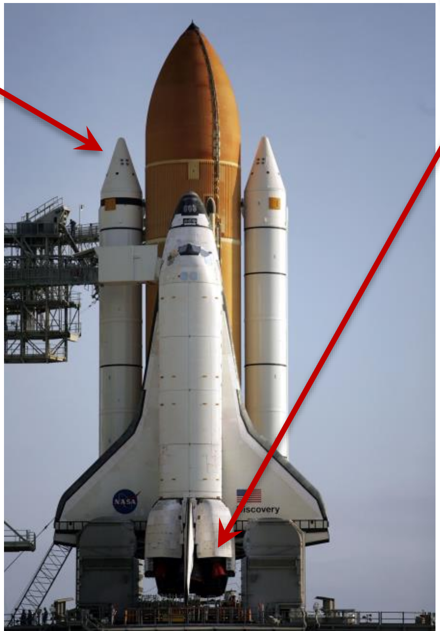

Space Shuttle

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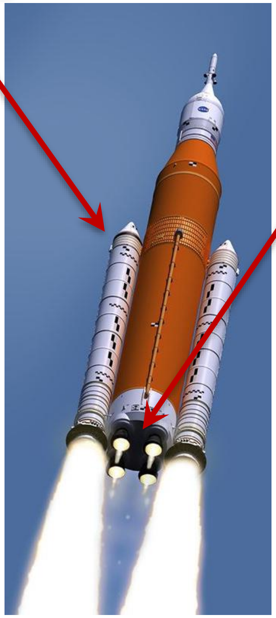

Space Launch System

Current engine architectures

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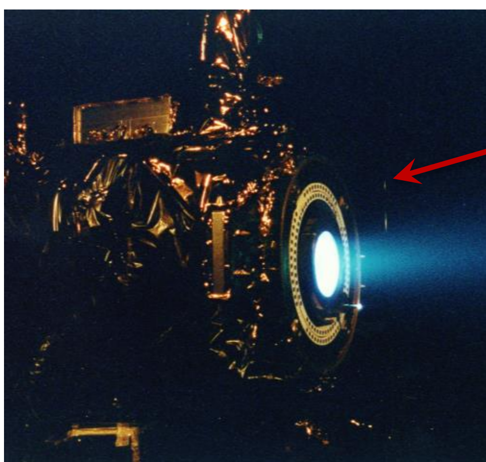
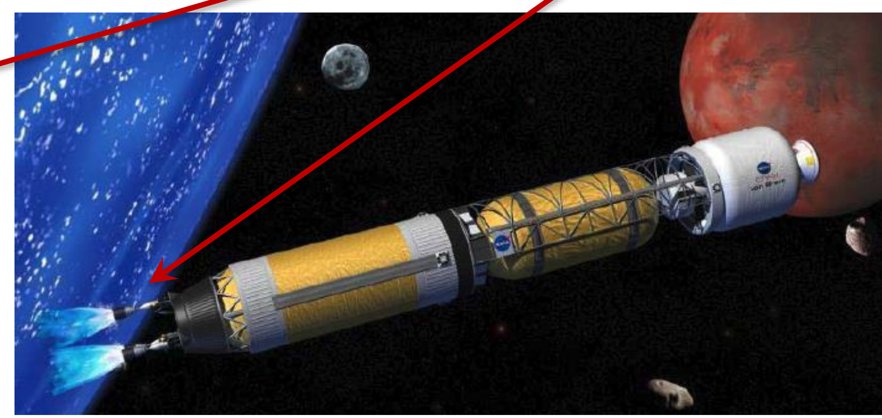


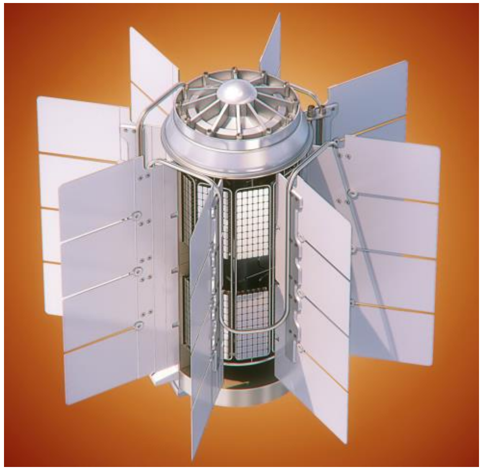
Ion Engine



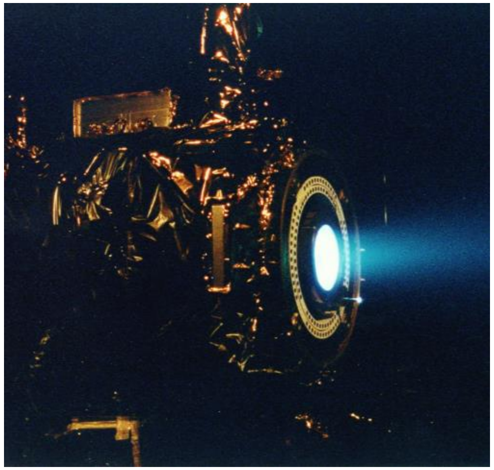
Mars Transit Vehicle

There are many uses for nuclear power in space

Radioisotope Thermal Electric Generators

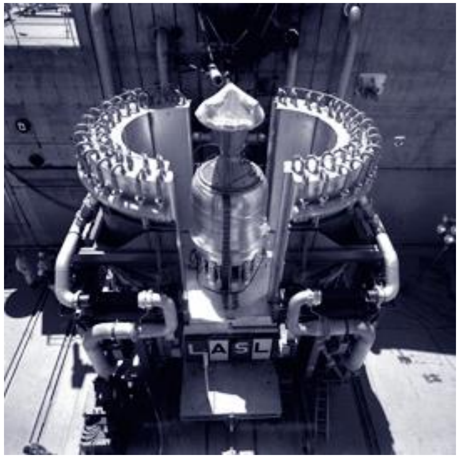


Nuclear Electric Propulsion

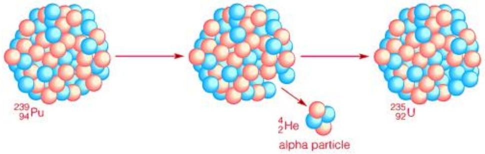


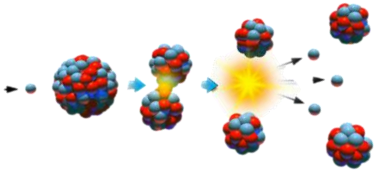
Electricity Generation to Power Thruster

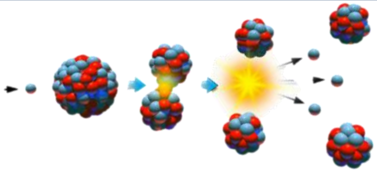
Nuclear Thermal Propulsion



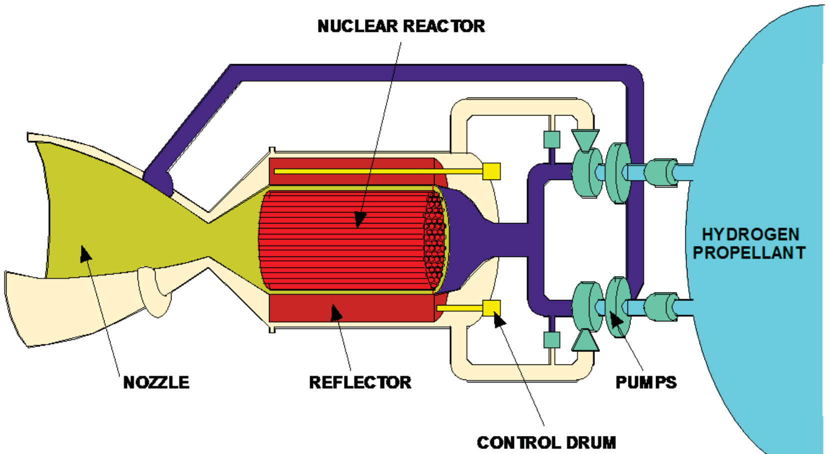
Direct Heating of Propellant to Provide Thrust

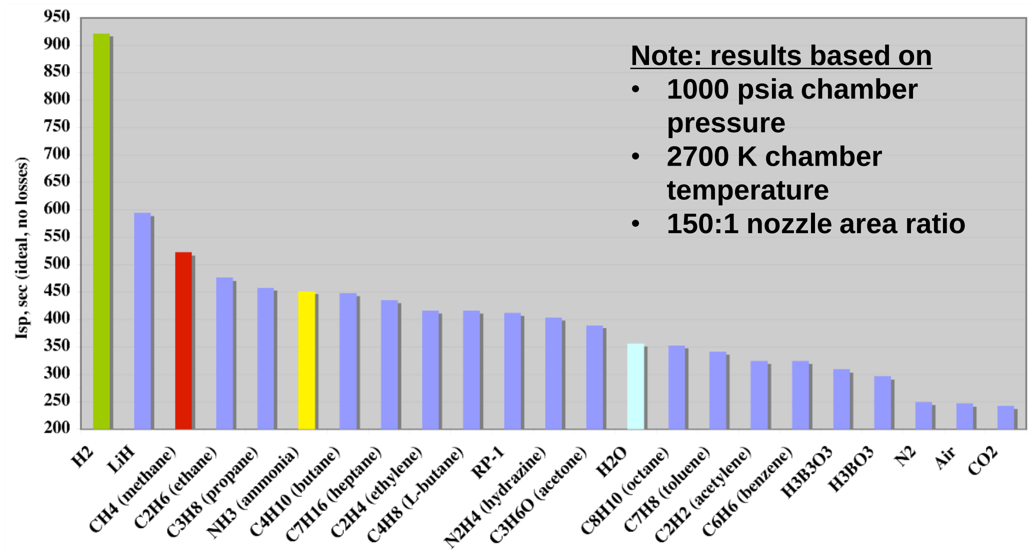






Nuclear thermal rocket engine





Specific Impulse (revisited)

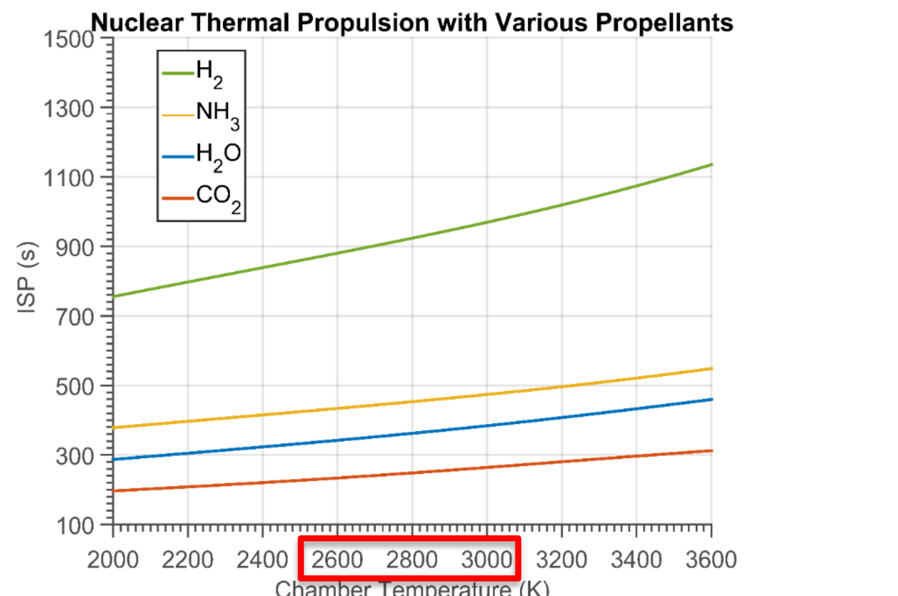
$$I_{sp} = \frac{F}{\dot{m} g_o} = \frac{1}{g_o}\sqrt{\left[\frac{2\gamma}{\gamma - 1}\frac{RT}{M}\right]\left[1 - \frac{p_e}{p_c}\right]^{\frac{\gamma-1}{\gamma}}}$$

$$I_{sp} \propto \sqrt{\frac{T}{M}}$$

-NTP engines produce thrust by heating propellant using a nuclear core

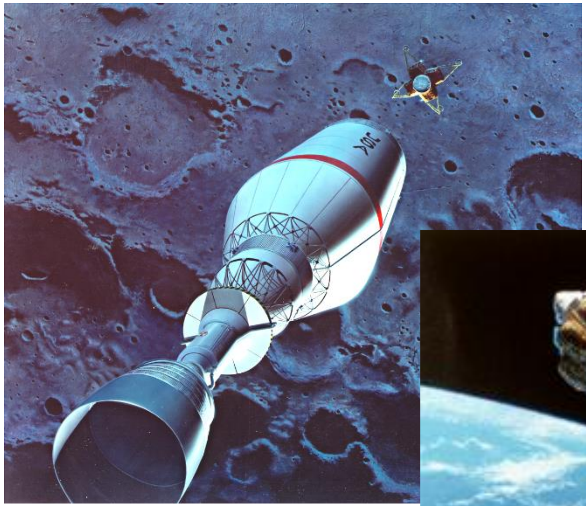
-propellant temperature directly correlates to I_{sp}

-core power and temperature determine exhaust temperature and therefore I_{sp}



NTP mission proposals, from the moon to Mars

Design Transition from Single Large NTR to Clustered Smaller Engines Supplying Modest Electrical Power

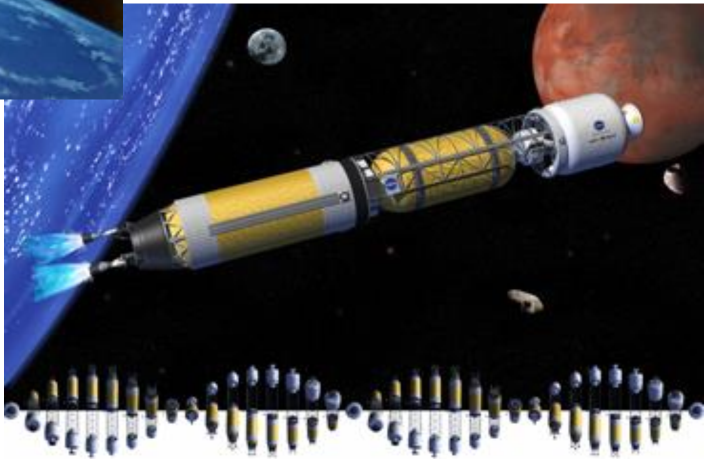


Reusable Lunar Transfer Vehicle using Single 75 klb_f Engine -- SEI (1990-91)

Expendable TLI Stage for First Lunar Outpost Mission using Clustered 25 klb_f Engines -- “Fast Track Study” (1992)

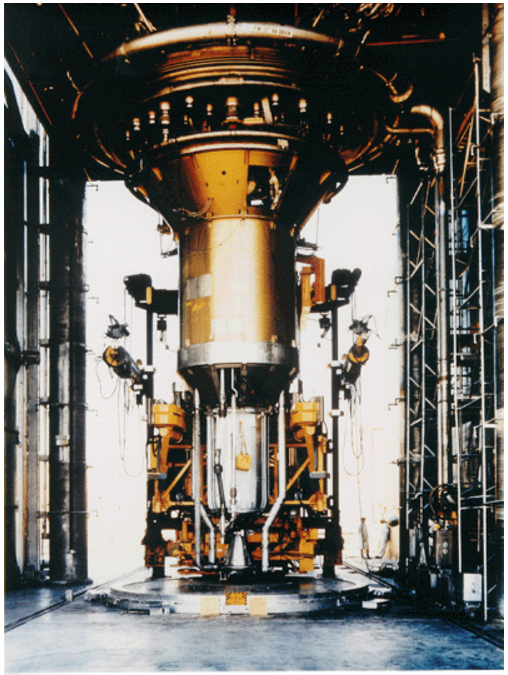
Zero-Gravity Crewed MTV uses 3 - 25 klbf NTR Engines & PVA Auxiliary Power – Mars (2009)

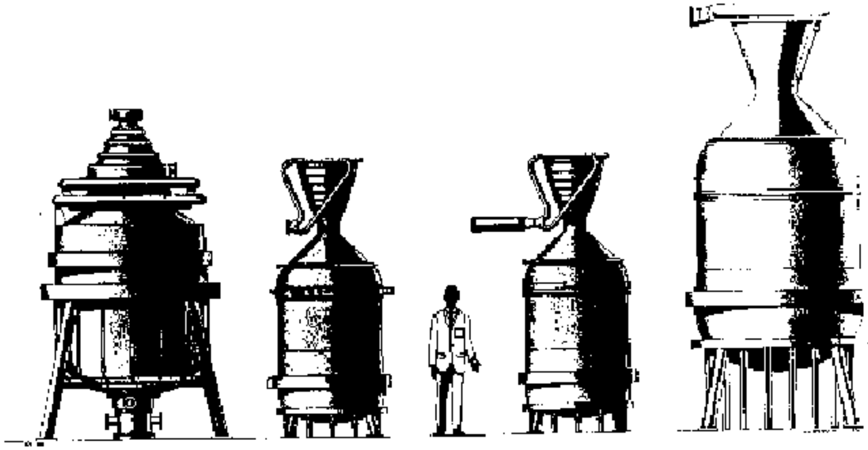
“Bimodal” NTR Earth Return Vehicle using Clustered 15 klb_f / 25 kW_e Engines -- Mars DRM 1.0 (1993)

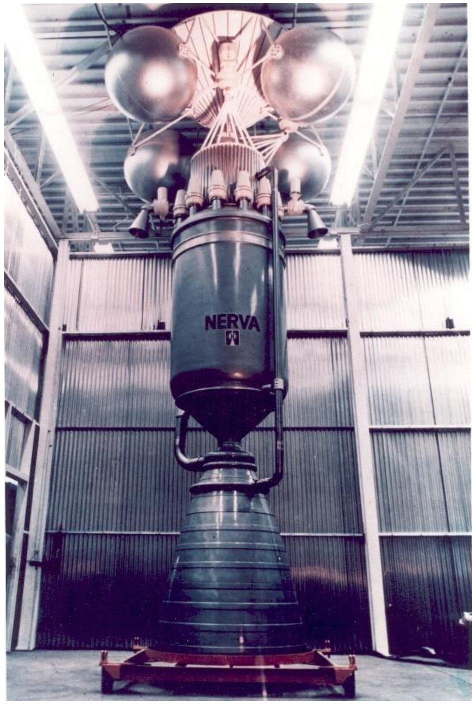


Artificial Gravity BNTR Crewed Transfer Vehicle also using Clustered 15 klb_f / 25 kW_e Engines -- Mars DRM 4.0 (1999)

Historic Nuclear Thermal Propulsion Efforts







Rover/NERVA* era (1955-1972)

- **20 Rocket/reactors designed, built & tested at cost of ~1.4 B$**

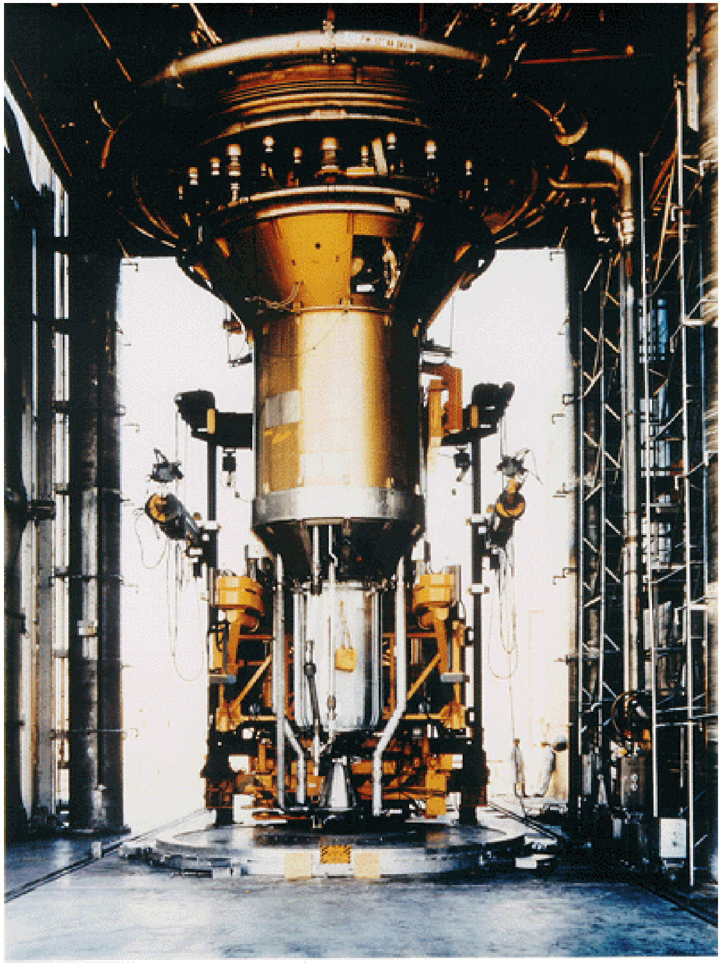
- **Engine sizes tested**
  - **25**, 50, 75 and 250 klb_f

- **H_2 exit temperatures achieved**
  - 2,350-**2,550 K (Pewee)**

- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)

- **Burn duration**
  - **~ 62 min (NRX-A6 - single burn)**
  - **> 3.5 hrs (NRX-XE: 28 burns / accumulated burn time)**
- **Engine thrust-to-weight**
  - ~3 for 75 klb_f NERVA

- **"Open Air" testing at Nevada Test Site**



The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

** NERVA: Nuclear Engine for Rocket Vehicle Applications*

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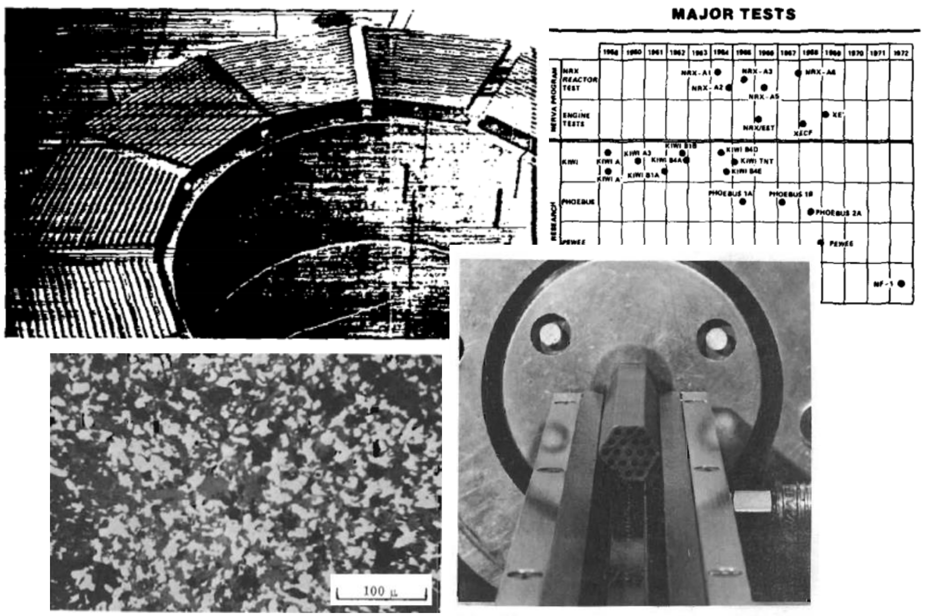
NRX-A6 (1972): Hydrogen exit temperature = 2556 K
1 hr.

** NERVA: Nuclear Engine for Rocket Vehicle Applications*

Rover/NERVA Development Overview



Highest level of development status for any fuel with significant remaining challenges

Geometry – Extruded Hexagonal

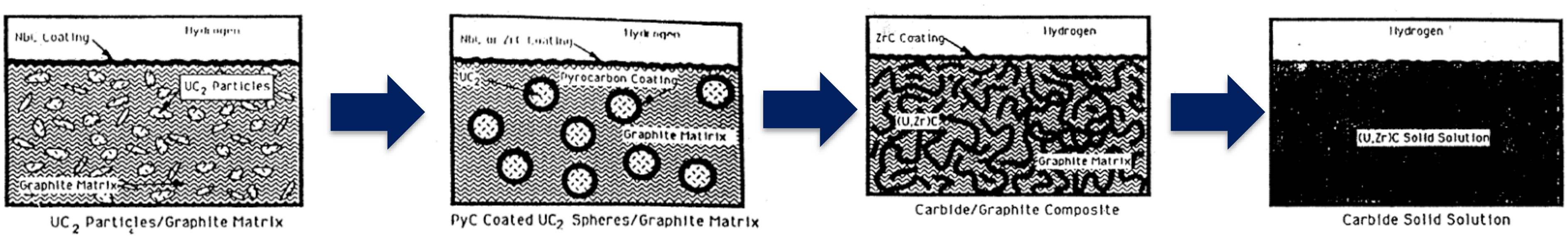
- Length: 51 in.
- Flat-to-Flat: 0.75 in.
- 19 Coolant Channels
- Fabrication: Extrusion and Sinter

Fuel Compound

- UO_2
- UC_2

Emerging Fuels

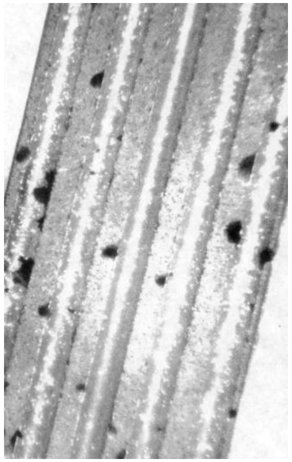
- (U,Zr)C fuel web
- (U,Zr)C solid solution

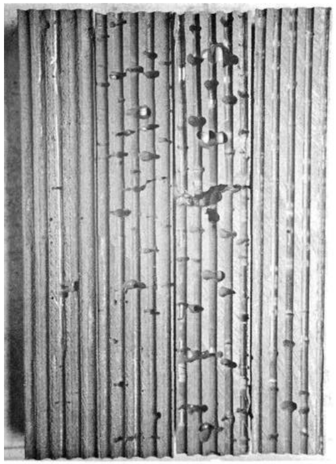


NbC coatings → ZrC coatings → ZrC + Mo coatings

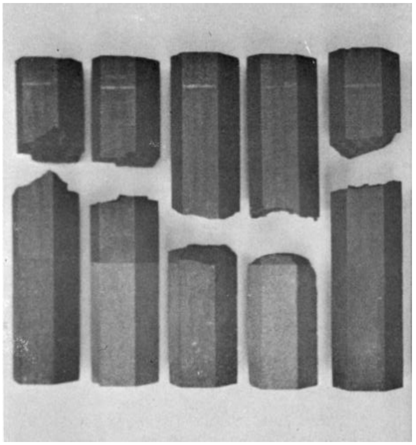
Two major failure mechanisms were discovered through engine testing

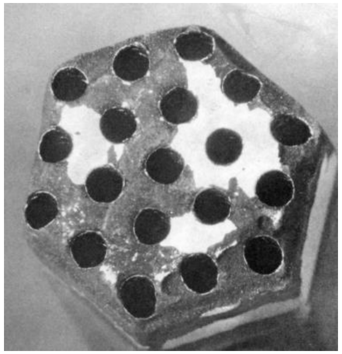
Corrosion

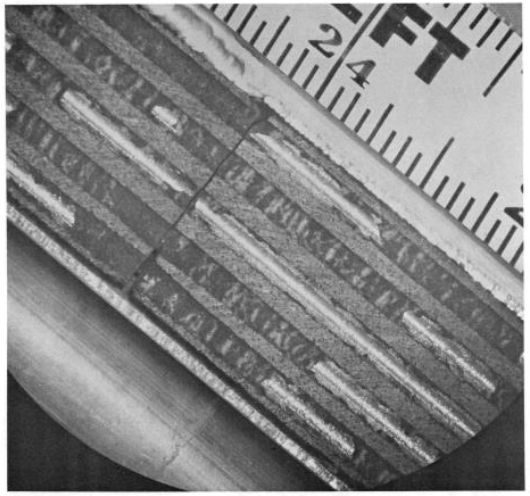




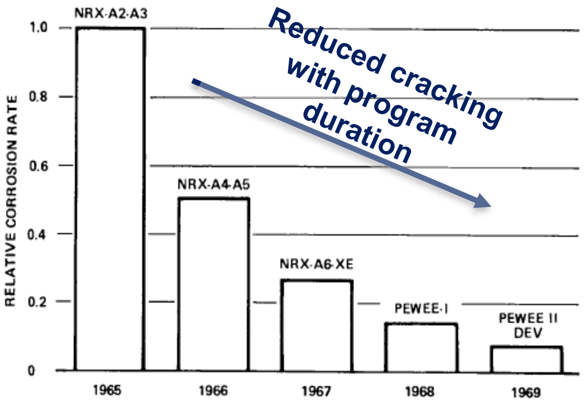
Mechanical Failure

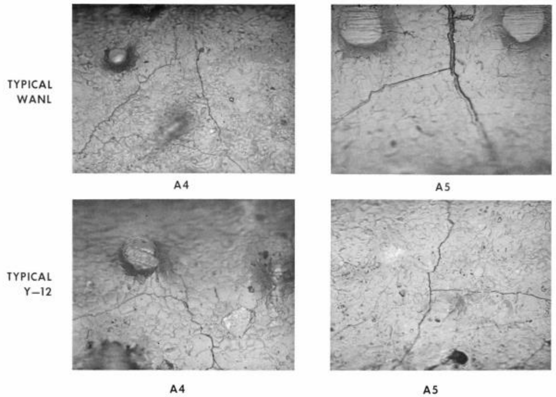






Graphite Matrix: Post Exposure

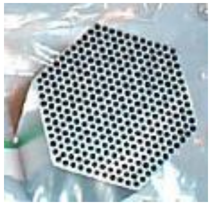




COMPARISON OF A4 &A5 CRACK PATTERNS @ STATION 20
200X

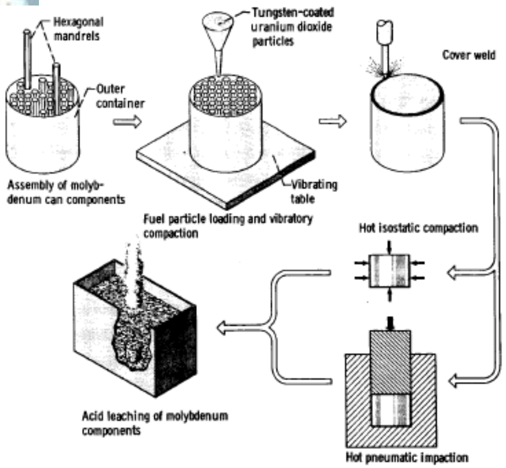
	NbC	ZrC	Graphite	Composite (U,Zr)C-C
CTE (µm/m·K)	7.0 - 7.2	7.6 - 7.7	3.0	6.0 - 6.7

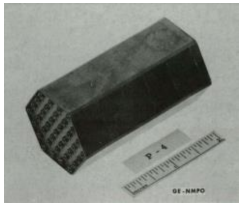
Historic U.S. Cermet Fuel Development (1957-1968)



ANL Nuclear Thermal Propulsion

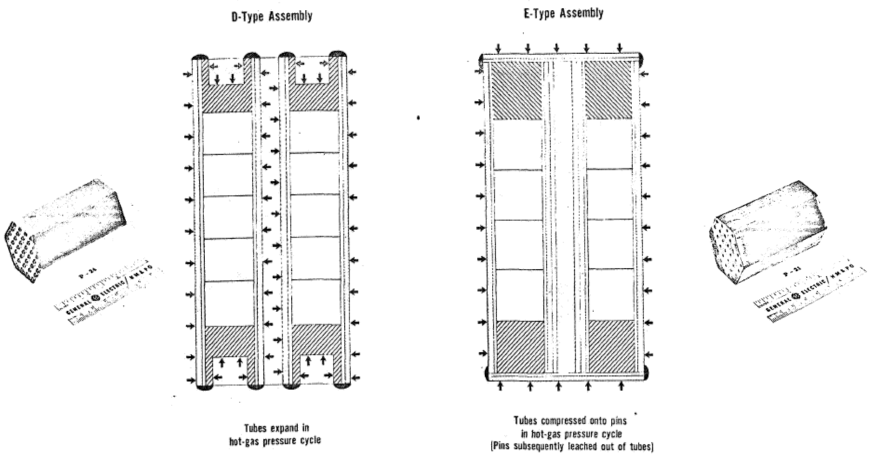
Ceramic Metallic (cermet) Fuels
W-UO_2 (net-shape HIP, prismatic)
(1962 – 1966)

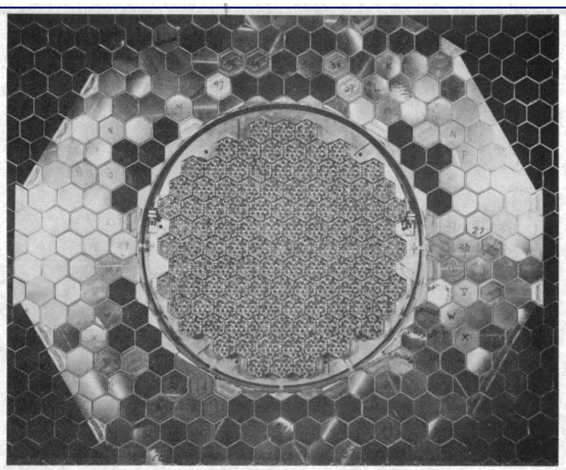


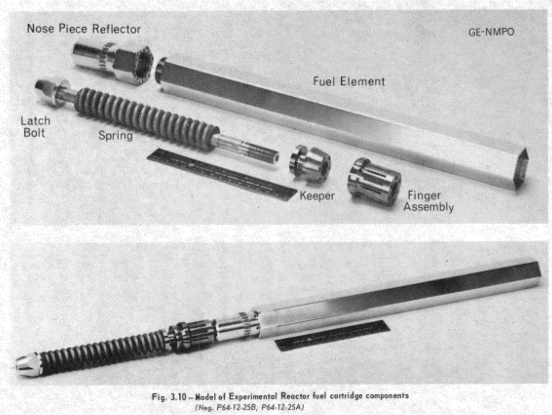


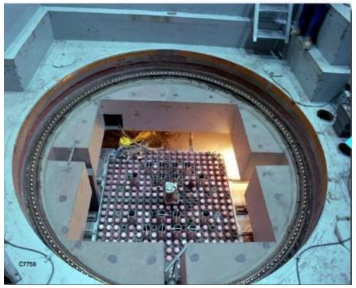
GE-710 Gas Reactor

Ceramic Metallic (cermet) Fuels
W and Mo (net-shape wafer, prismatic)
(1962 – 1968)





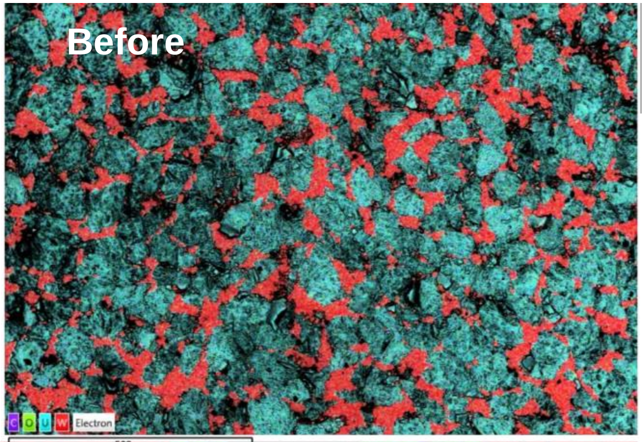


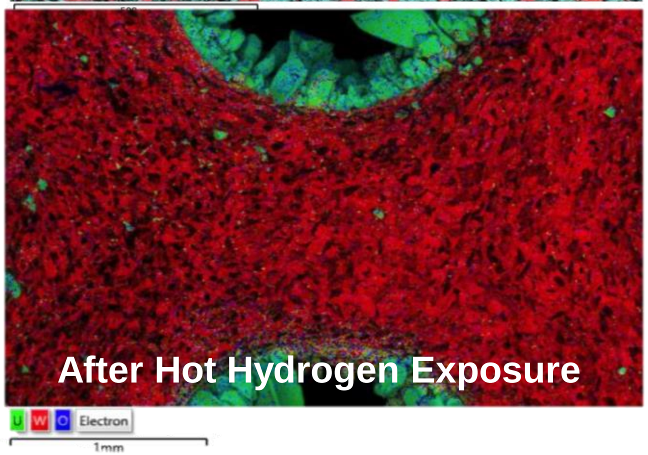


Cermets fail from the inside out due to high temperature instability of ceramic fuel particles

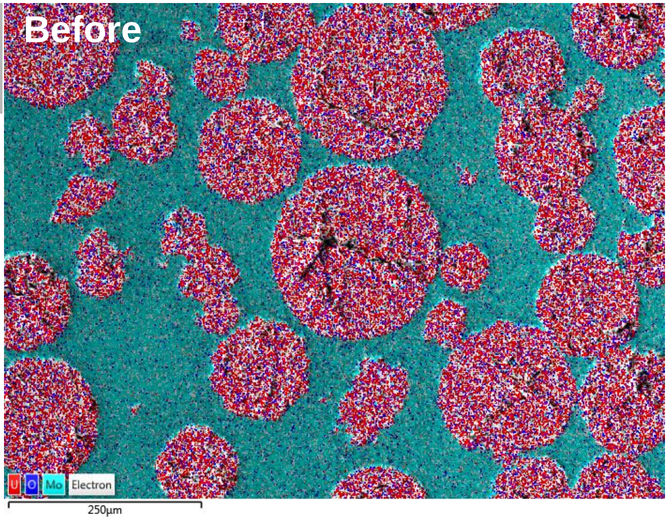
60 vol% UO_2

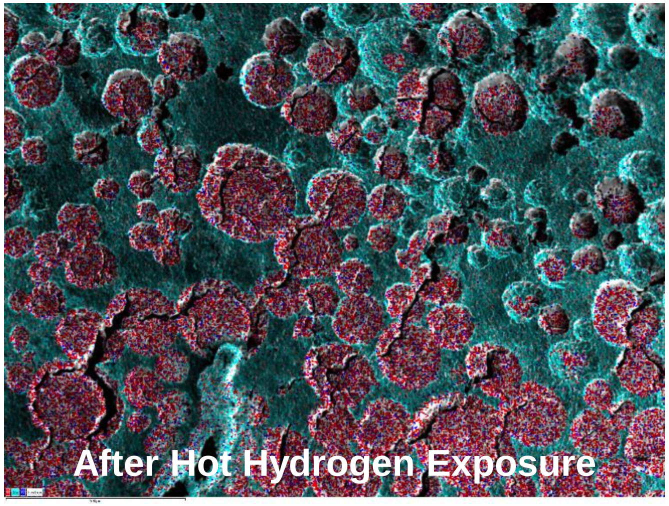
W-dUO_2 cermets





MoW-dUO_2 cermets





Pre-Test

Post-Test

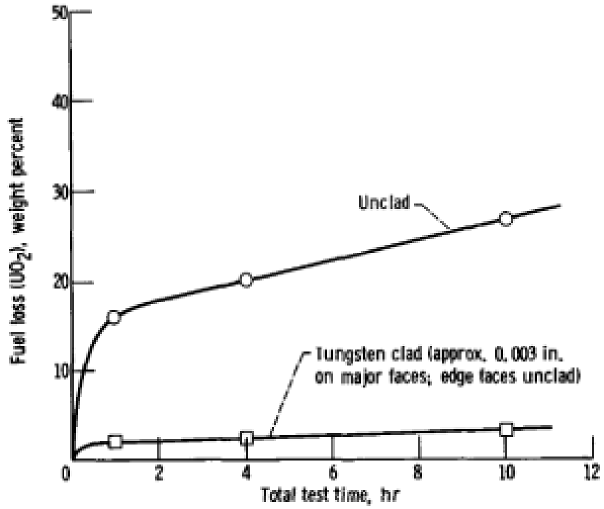
-Oxide and nitride ceramic fuels susceptible to H_2 corrosion

-necessitates the need for fuel cladding

Successfully developed cermets prevented free oxygen loss and thermal stresses

Mass Loss Mitigation Parameters

- W-alloy Claddings
- Gd_2O_3 and ThO_2 stabilizers
- High fuel density to reduce free U, O migration
- Eliminate interparticle connectivity
- Spherical particles to allow for favorable interfaces at grain boundaries
- $UO_2 \rightarrow$ UN fuel particles



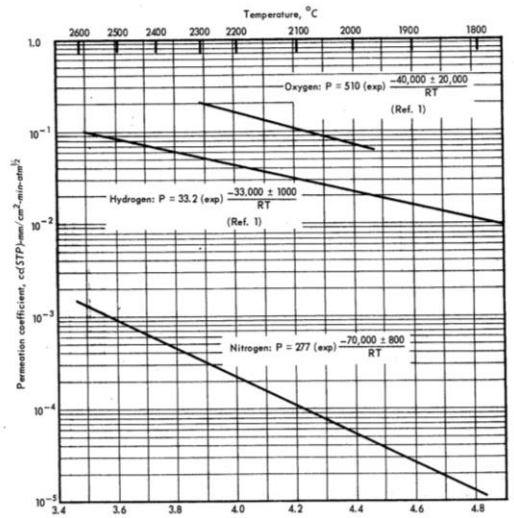
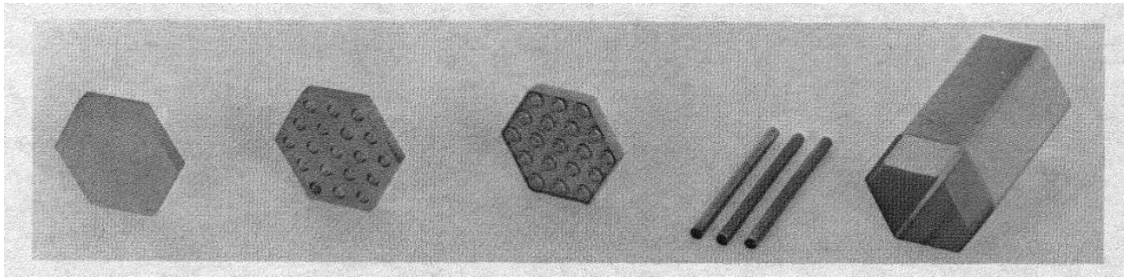
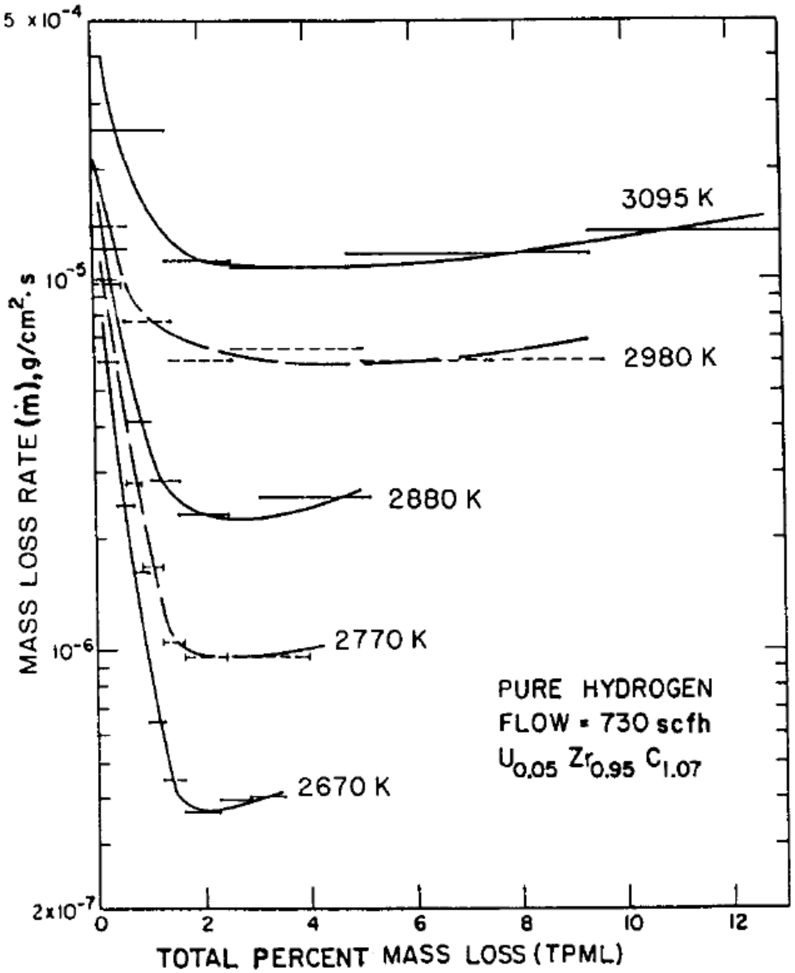


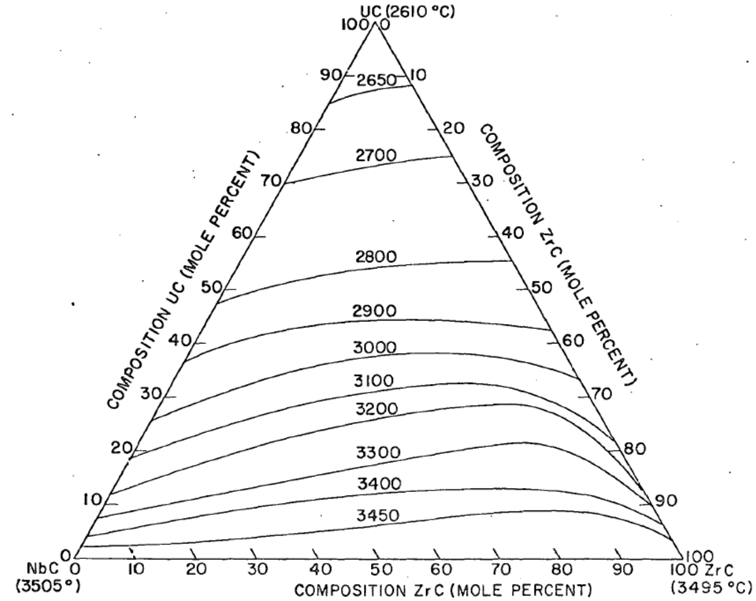
Fig. 5 – Comparison of permeation coefficients for nitrogen, hydrogen, and oxygen through arc-cast tungsten

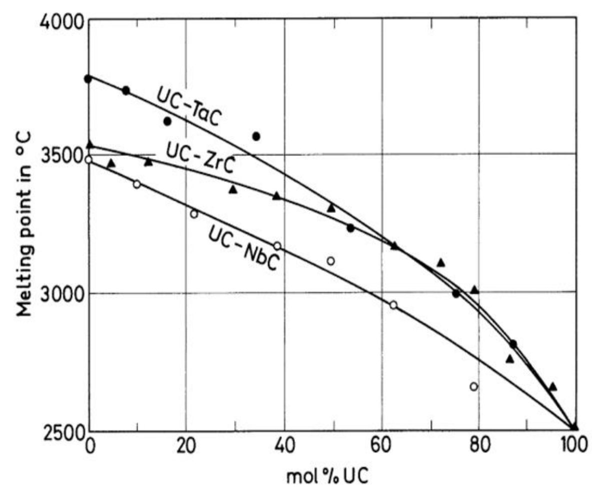


Solid-solution carbides have high melting temperature and exhibit high temperature stability



ZrC rich solid solutions show excellent resistance to hydrogen corrosion



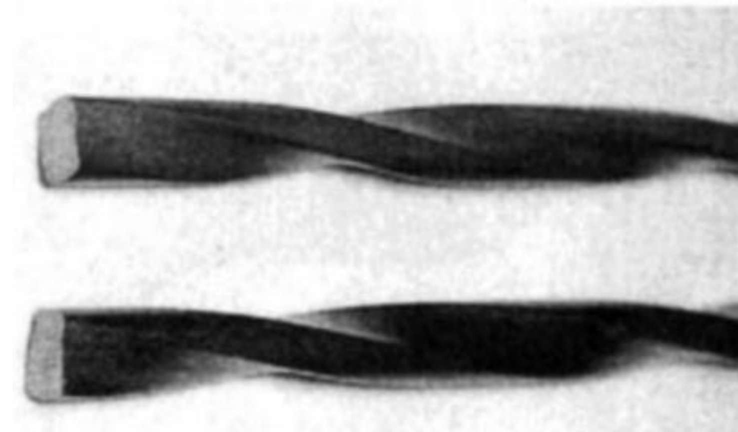


History: USSR RD-0410 Carbide Fuel Development

The NTP fuel form development efforts of the former Soviet Union was comparable to United States efforts if not exceeded that of the United States.

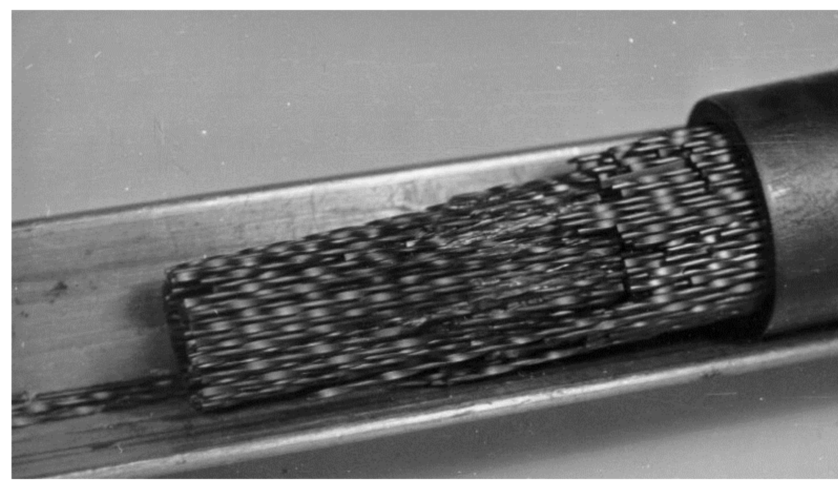
Geometry – ‘Twisted Ribbon’

- Length: ~100 mm
- Diameter: 2 mm
- Attempt to maximize heat transfer while maintaining fuel integrity



Fuel Compounds

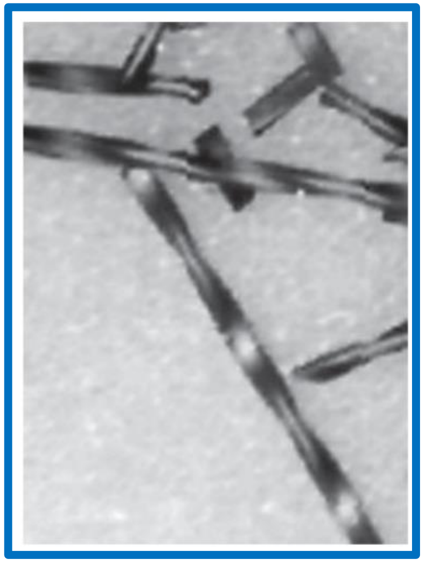
- Fuel composition was focused on maximizing the operating temperature of the fuel
- <u>Carbide</u>
  - (U,Zr)C
  - (U,Zr,Nb)C
  - (U,Zr,Ta)C
- <u>Carbonitride</u>
  - (U,Zr)C,N



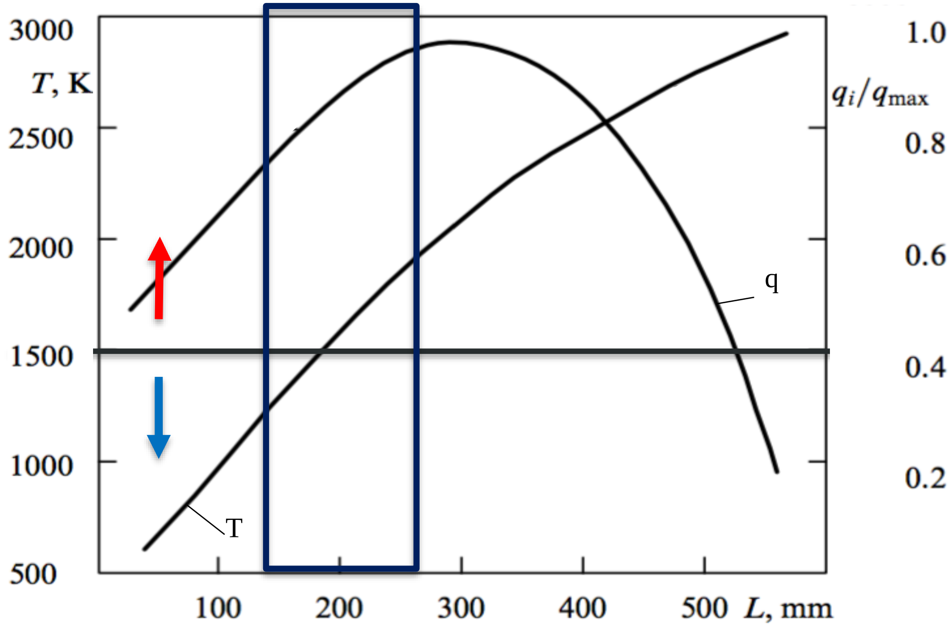
Reported ternary-carbide fuel performance of operation at 3100 K for up to 1 hr.

Carbide fuels also experience the most failure in the mid-band region where power densities are high and ductility low

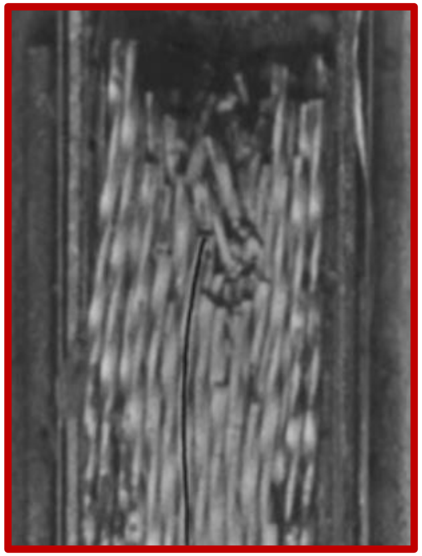
Brittle Failure

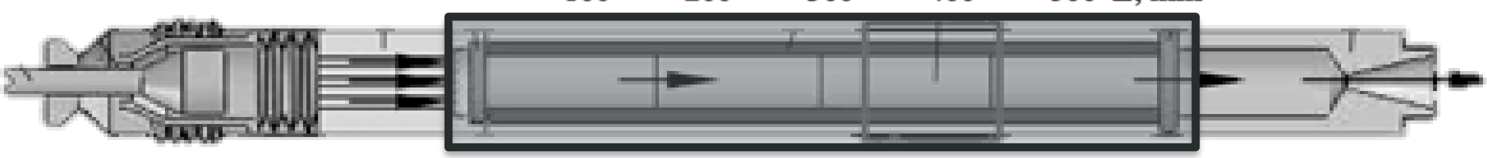


Highest Rate of Failure



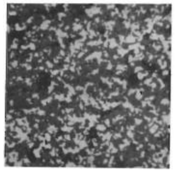
Ductile Failure





Fueled Region

History: US Carbide Fuel Development

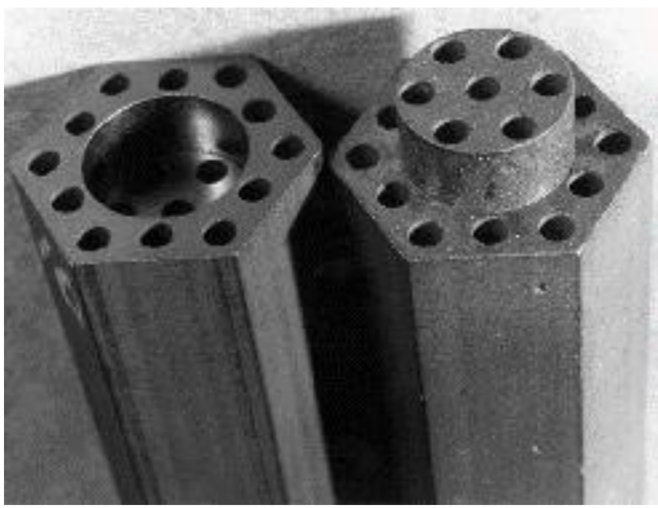


NERVA/Rover

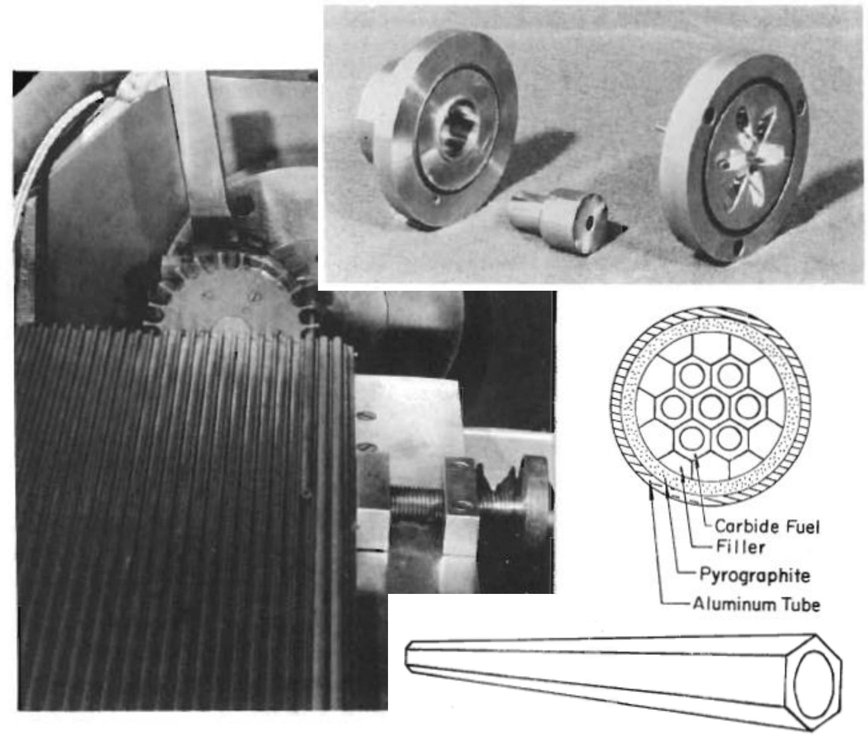
Carbide Fuels

(1955 – 1972)

Hot Hydrogen Static Testing	Hot Hydrogen Thermal Cycling	Prototypic Irradiation Testing	Prototypic Engine Testing
✓	✓	✓	

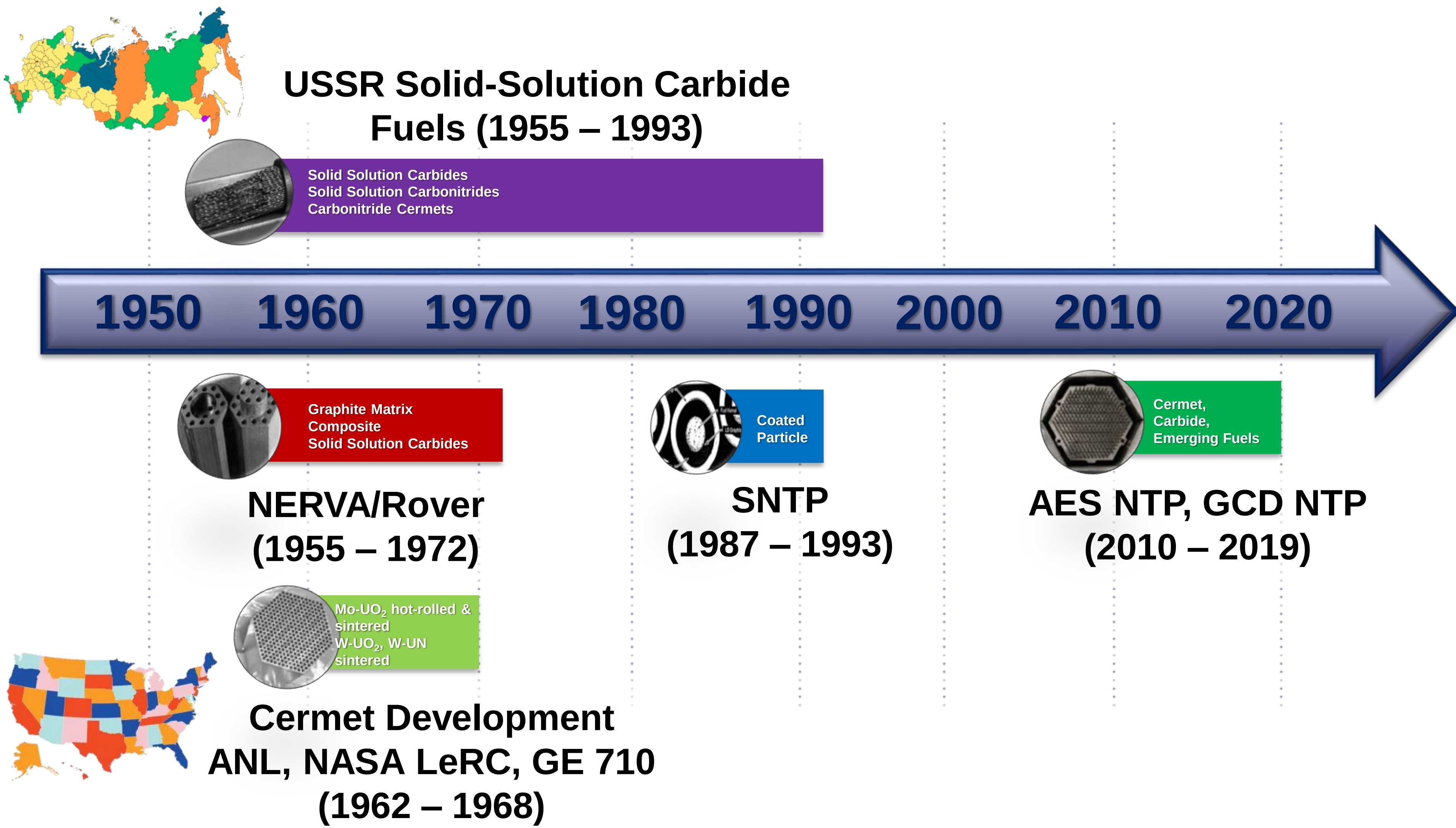


Fuel element architecture that the Rover/NERVA program used for all their fuel compositions



Carbide (U,Zr)C fuels were tested in NF-1 and survived exposure to over 2700 K for 109 minutes under flowing hydrogen and irradiation.

Overview of NTP Fuel Timeline



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Thank you!