



Nuclear Thermal Propulsion

Lessons Learned from the Past

NETS 2022

**Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion Project**

Harold P Gerrish Jr | May 9, 2022

Funded NTP Development Timeline



USSR Solid-Solution Carbide Fuels (1955 – 1990)



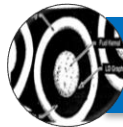
Solid Solution Carbides
Solid Solution Carbonitrides
Carbonitride Cermets

1950 1960 1970 1980 1990 2000 2010 2020 2030 2040



Graphite Matrix
Composite
Solid Solution Carbides

Rover/NERVA
(1955 – 1972)



Coated Particle

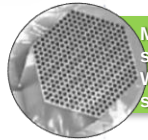
Air Force SNTP
(1987 – 1993)



Cermet,
Composite,
Emerging Fuels

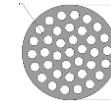
AES NTP, GCD NTP
(2012 – 2019)

Human Mars Mission?



Mo-UO₂ hot-rolled &
sintered
W-UO₂, W-UN
sintered

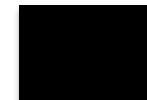
Cermet Development
ANL, NASA LeRC, GE 710
(1962 – 1968)



Cermet,
Cer-Cer.
Composite,

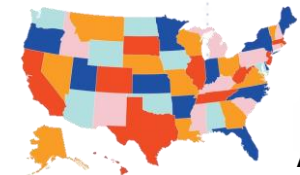
TDM SNP NTP
(2020 – 2027)

Ends with Ground or Flight Demo

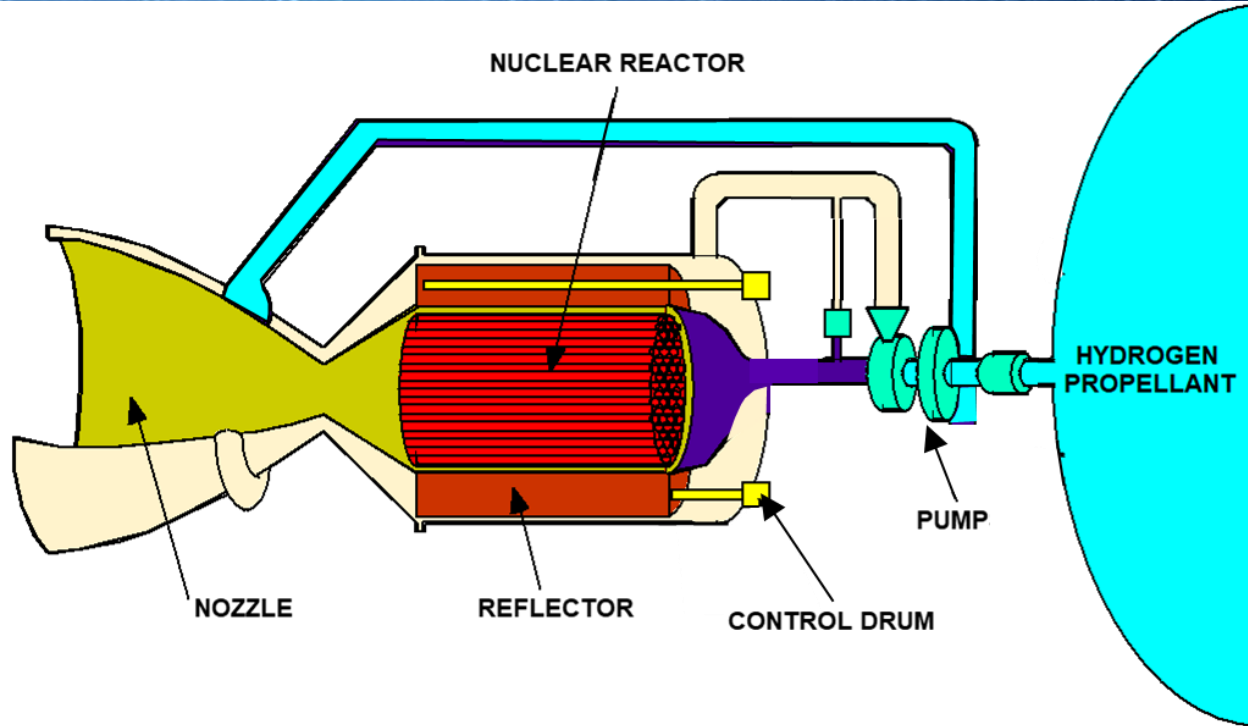


Ends with Flight Demo

DARPA DRACO NTP
(2021 – 2026)



How NTP Works



- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: $100,000 \text{ N} \approx 450 \text{ MW}_{\text{th}}$ at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of H_2/O_2 engine runs hotter than NTP)

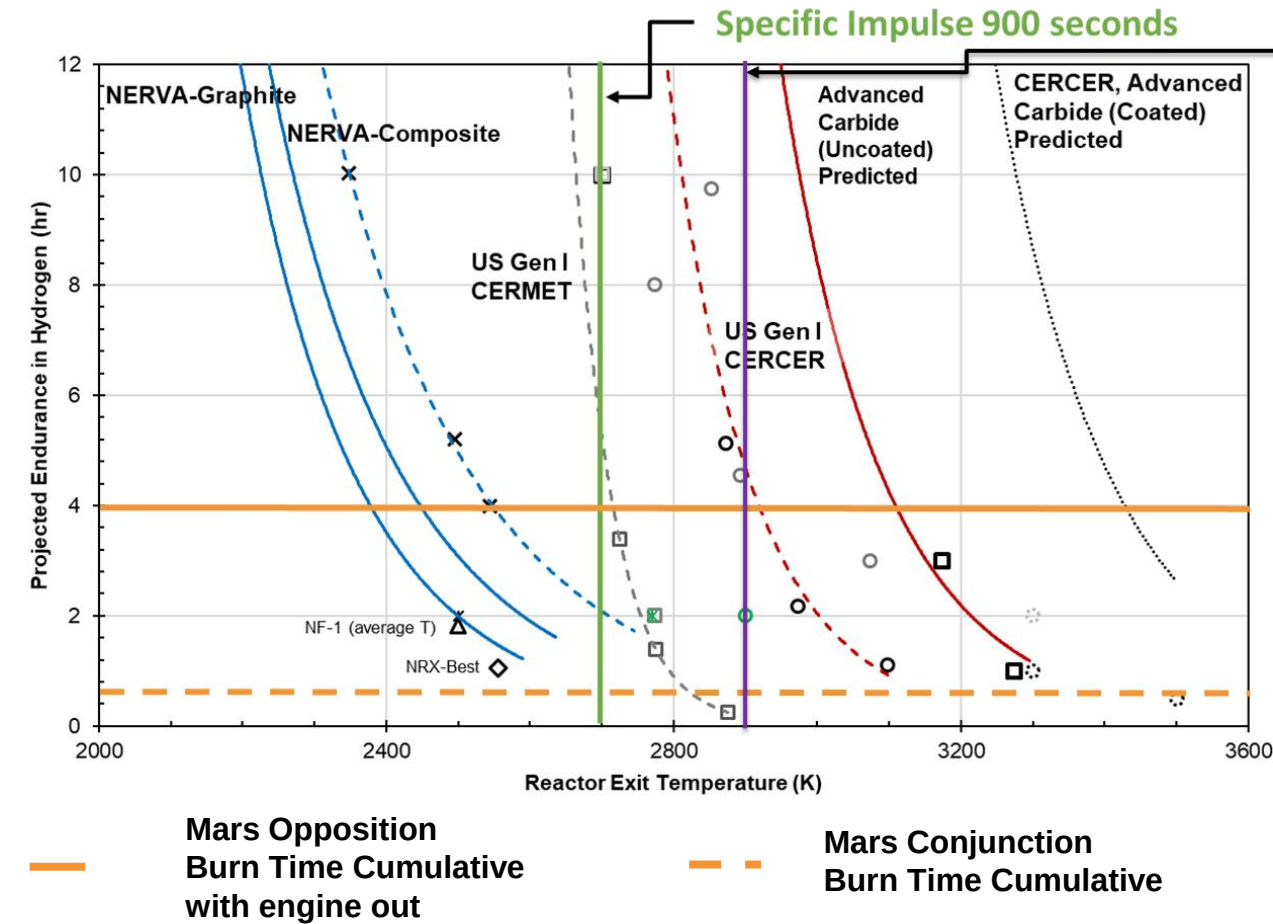


Rover Phoebus 2A

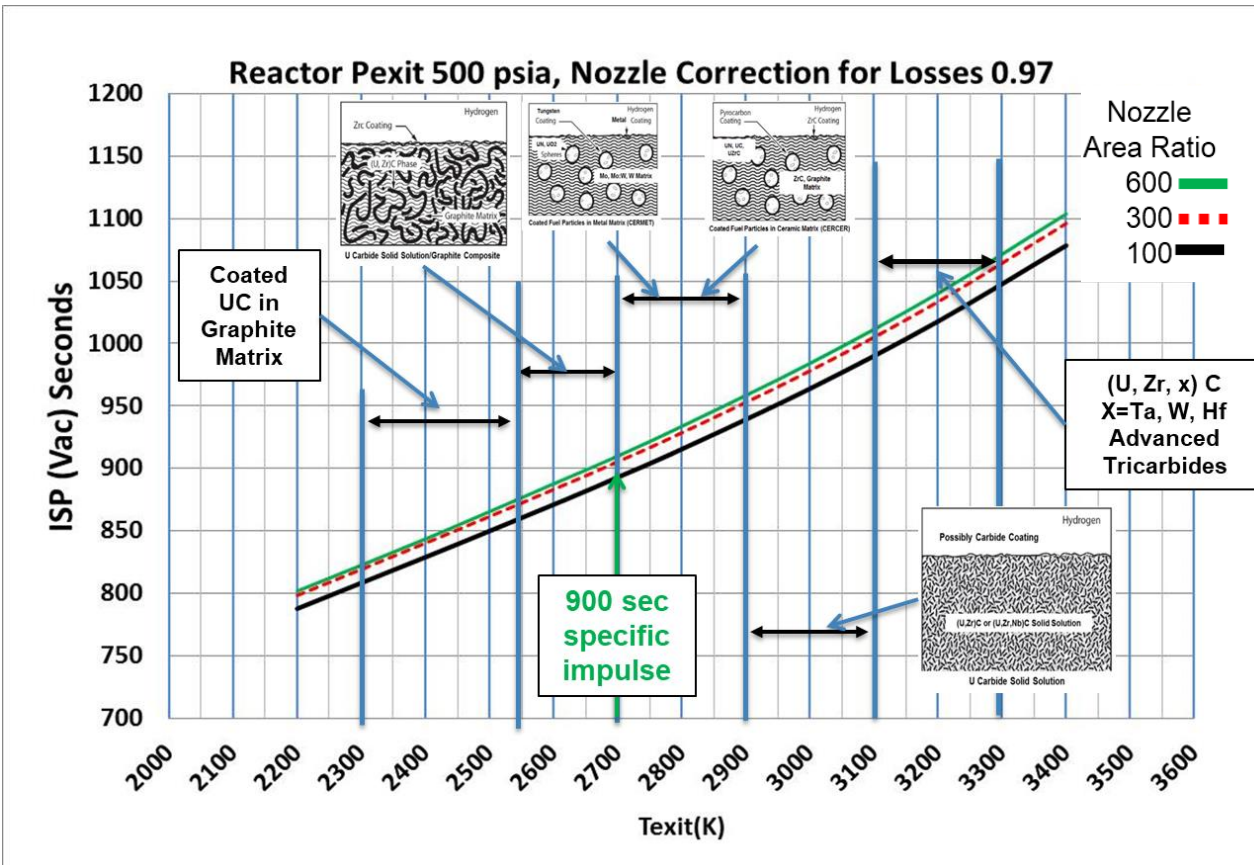


Isp and Fuel Endurance Depends on Temperature

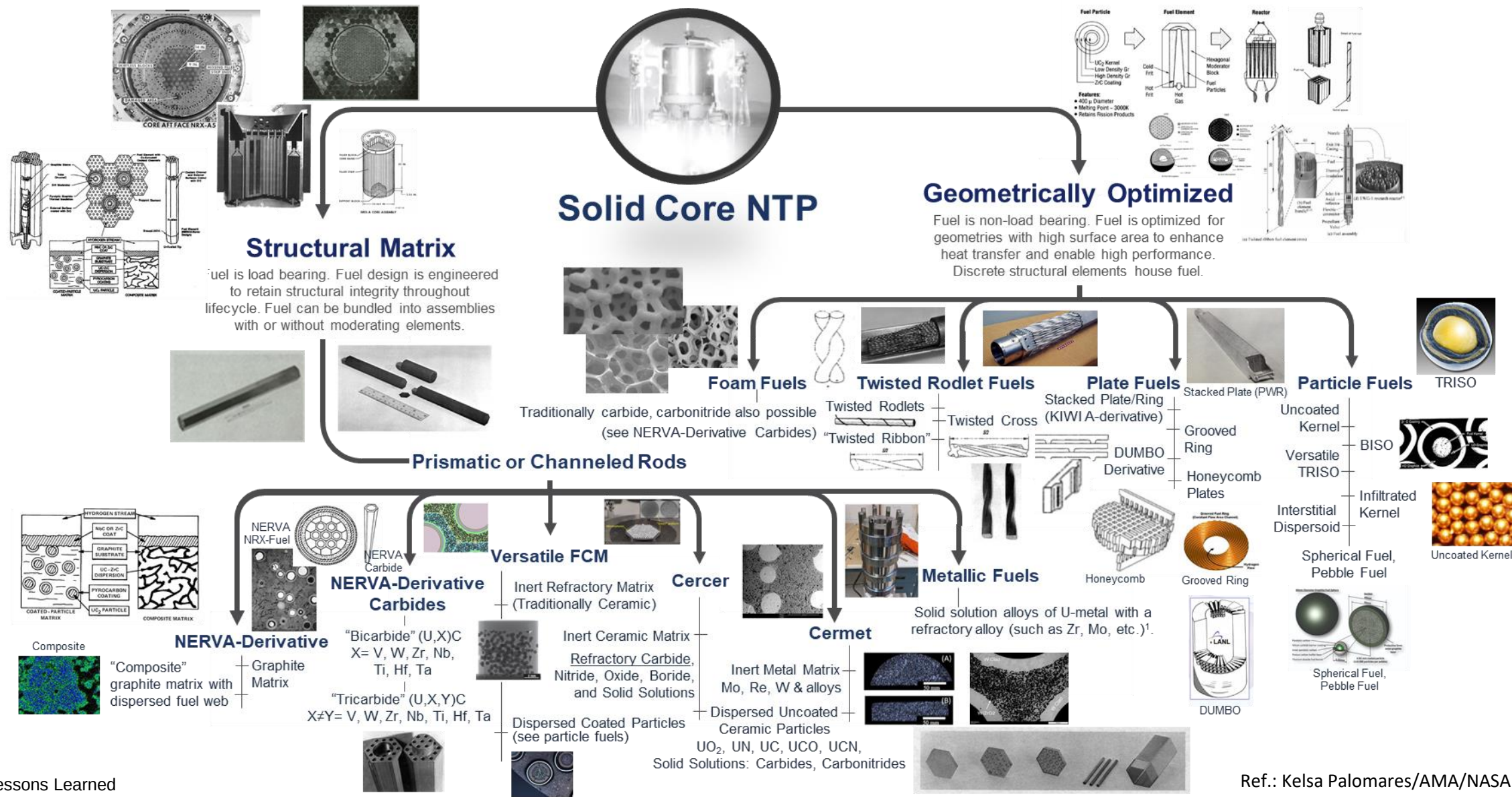
Ref.: Kelsa Palomares/AMA/NASA SNP



2900K Peak



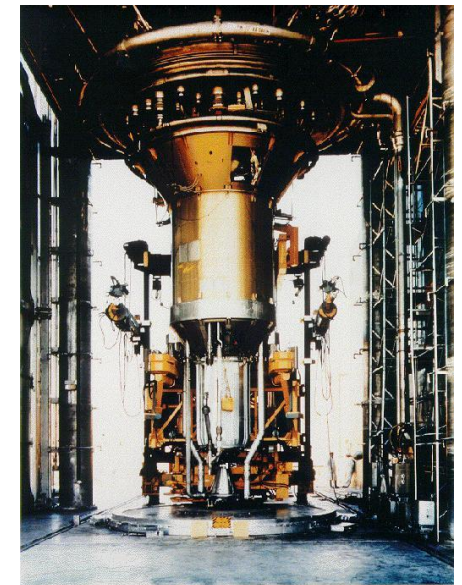
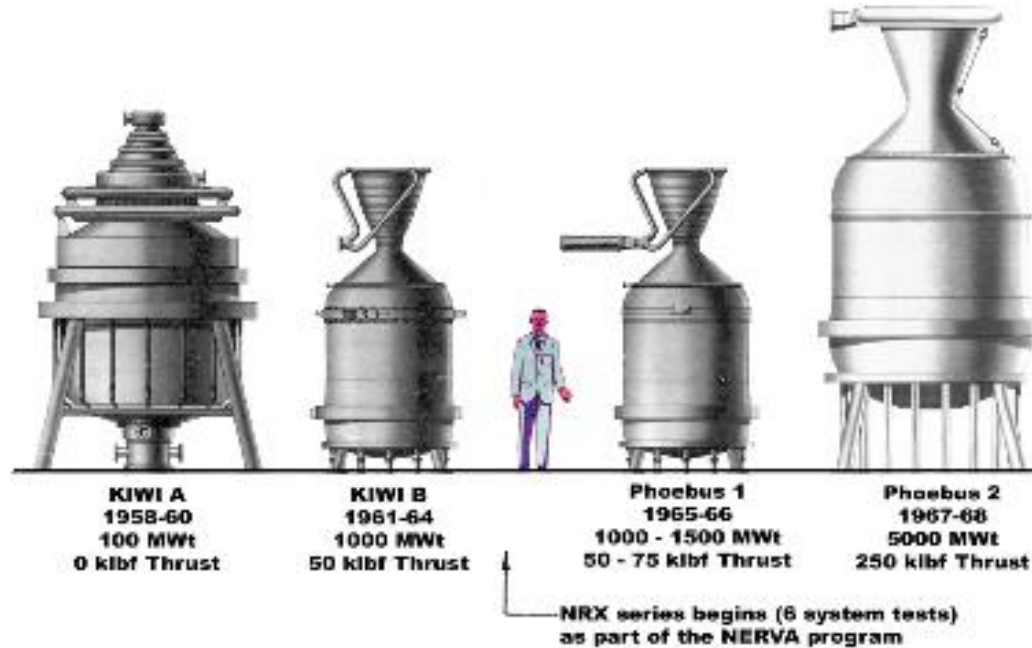
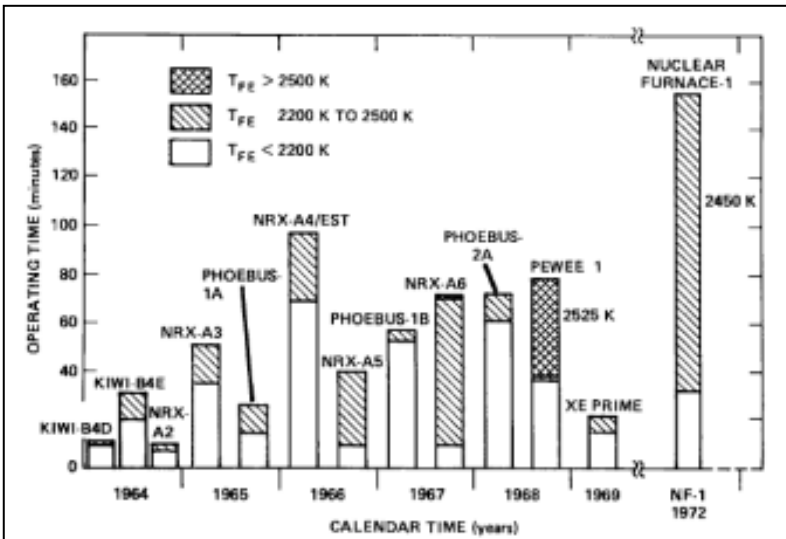
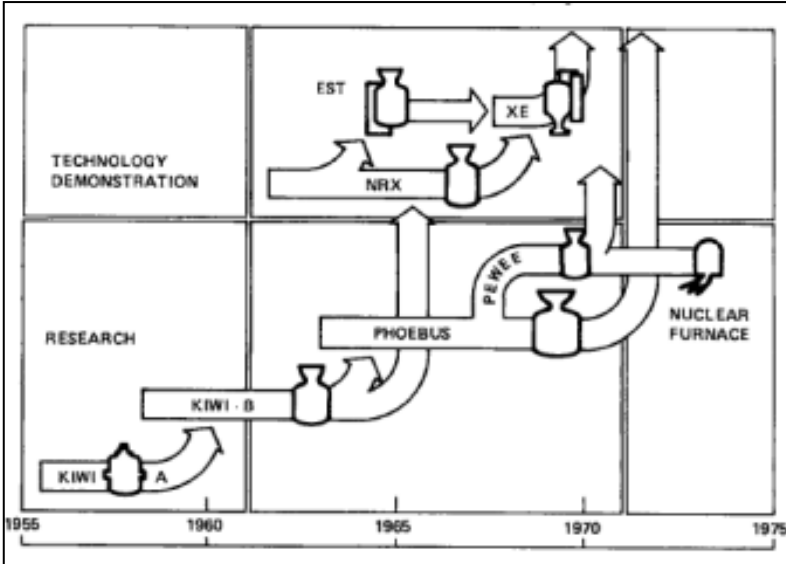
Solid Core NTP Fuel Types



Rover/NERVA (1956-1973)



[1]



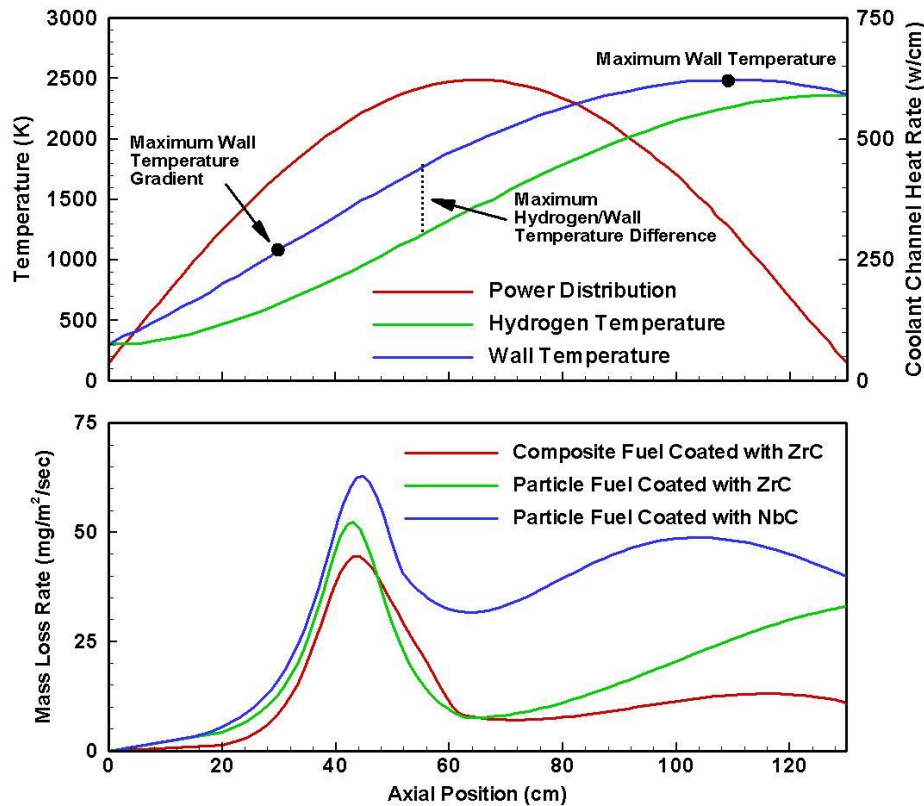
- 20 NTP different reactors designed built and tested during Rover/NERVA
- Two of the reactors used flight like turbopumps powered by the reactor
- \$9.5B invested in 2022 dollars

Rover/NERVA Fuel Development

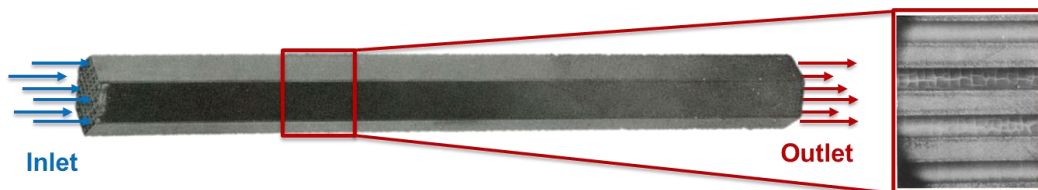


Fuel element Axial Profile

[1,2,3]



- Fuel element performance improved throughout the project. Best possible is
 - ~Isp 860 sec for 2 hours and 20 start-ups
 - ~Isp 875 sec for 1 hour and 3 start-ups
- Mass loss is greatest where fuel temperatures are only half of the maximum
- NF-1 had 8-50 grams mass loss per fuel element from ~90-minute run
- NASA GRC has been investigating new protective coatings



Mid-band corrosion unresolved for NERVA type fuel

Kiwi B4A Cold Flow

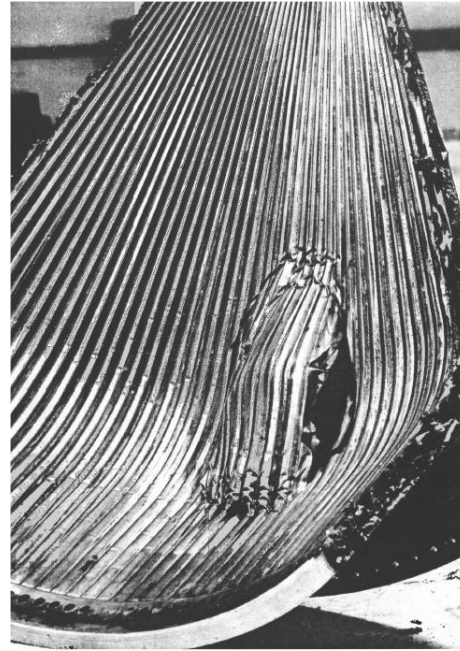
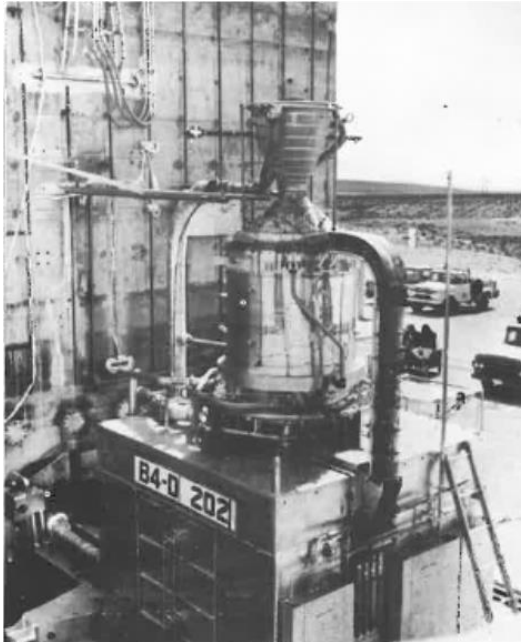


- Kiwi B4A shutdown after reaching 500MW due to frequent flashes. 90% of reactor parts broken [4]
- Harold Finger halted further hot fire testing until vibration problem resolved. Dr Norris Bradbury (LANL Director) said stopping hot fire testing would kill the program. [5]
- Cold Flow test run with nitrogen and non-fissioning reactor and well instrumented. Vibration caused by interstitial flow. Problem resolved with better bundling of the core and seals. Final cold flow tests showed no vibration[5]
- Dr. Norris Bradbury wrote Harold Finger and said **“insistence on a repeat KIWI B-4A cold flow test resulted in a damned interesting experiment! Perhaps we have all learned something!”**[5]

flow induced vibration problem. Non-nuclear cold flow system tests are valuable

Kiwi B4D Micro-explosions

[6,7,8,9]



- Kiwi B4D was shut down after 64 seconds full power 1000MW due to nozzle failure and extensive fire
- Possible cause was liquid air formed close to the liquid hydrogen inlet on the nozzle, flowing down and became trapped. Ozone was formed from liquid oxygen and built up with time.
- The decomposition of ozone can be explosive: ozone in liquid or solid state and the gaseous mixtures of concentrated ozone in oxygen (over 9.2% vol/vol) can explode further to an impact or if they are exposed to heat, a spark, sudden temperature or pressure changes or in the presence of impurities.[9]
- Kiwi B4E nozzle was modified with an inerted shroud to prevent liquid air from entering the interstices between nozzle tubes

Radiation may also affect other nearby liquids

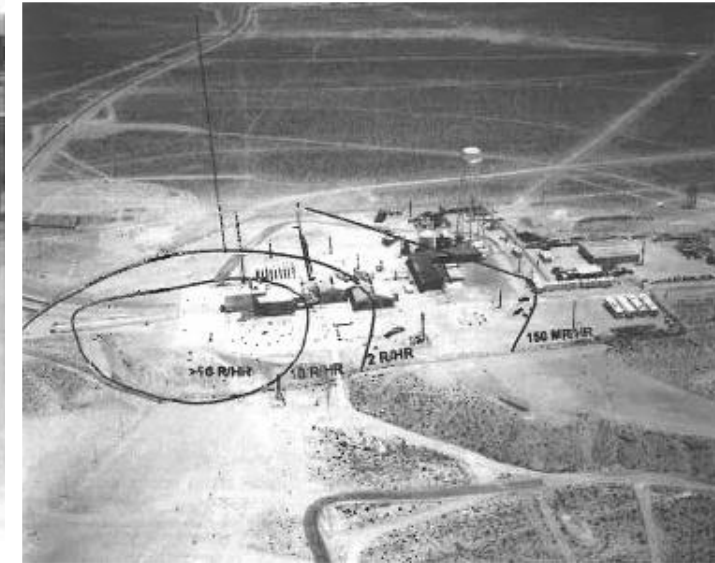
Phoebus 1A Failure and Cleanup



Showering hot fuel element pieces



200 hp vacuum cleaner used for small fuel pieces. Reach extender used to get large fuel pieces

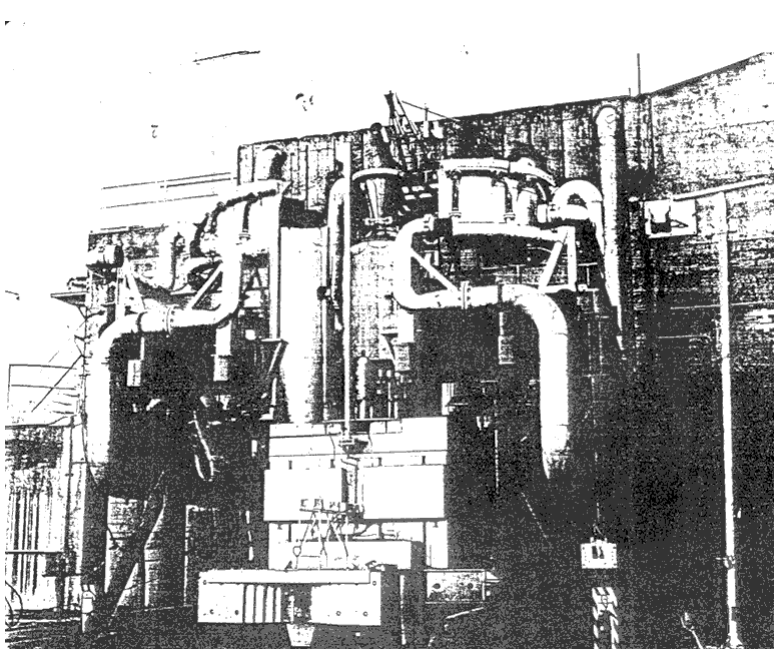


Dose rates in various zones

- Phoebus 1A was a 1100 MWt engine, which after 10.5 minutes failed from false gauge readings caused by radiation and ran out of LH_2 . Automatic scram from turbopump overspeed. 20% of core ejected.
- After waiting six weeks, the decontamination crew cleaned up the test site in two months and prepared for the next test. Average dose to crew .66 rem.[10]
- Emergency shutdown LH_2 now used.
- 5 other engines followed Phoebus 1A and were tested at test cell C

Not like Chernobyl! Better emergency shutdown in all future tests

NRX-A6



- Engine run continuously for 62 minutes and 2220K at test cell C
- LN_2 pulse cooling was completed after 75.3 hours[6]
- Reduction of 75-80% fuel element time rate of corrosion compared to NRX/EST and NRX-A5[6]

Long burn durations are feasible depending on fuel temperature and endurance

Feasibility of Engine Clustering



[10]



- Two reactors. One was KIWI B4, the other was PARKA zero power reactor
- One reactor stationary, while the other moved to distances of 16', 9', and 6'
- Data showed neutron coupling had marginal effects, which were negligible
- Good to double check current reactor concepts

Pewee 1 had ^{135}Xe Buildup



[6,11]



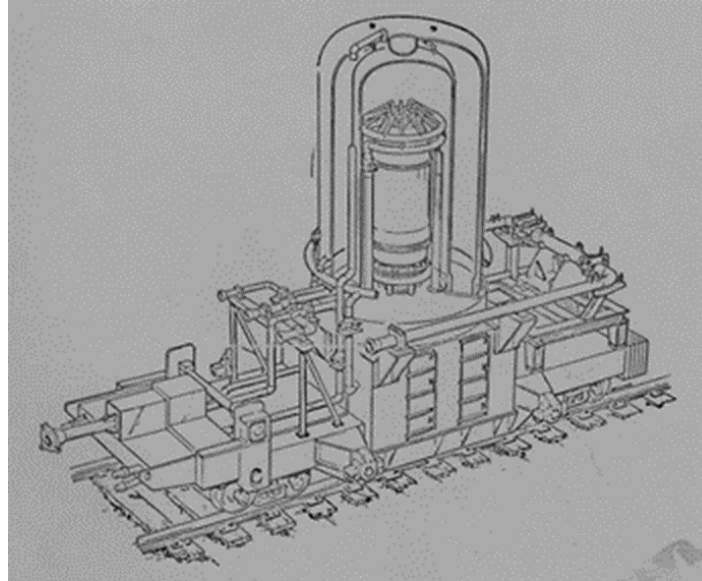
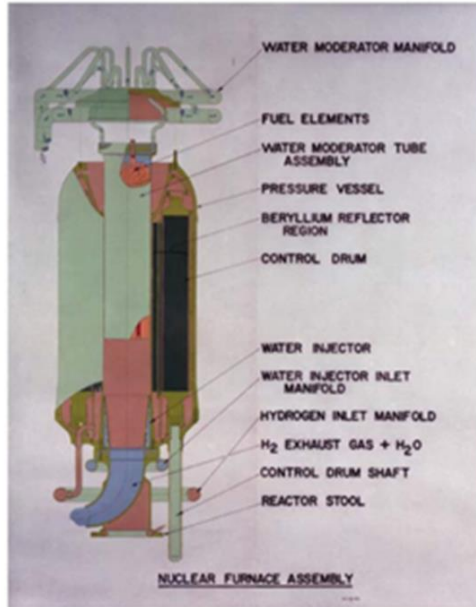
- Pewee set records in power density and temperature. Operated at 503 MW for 40 minutes at 2550K with a peak to 2750K
- ~25k lbf of thrust
- Tested both NbC and ZrC coated fuel elements. ZrC outperformed NbC in reducing corrosion.
- The day following the final run, the concentration of ^{135}Xe (fission product with short half-life) was so high that the reactor could not be made critical with control drums rotated to 180° based on delayed critical measurements. Virtually all Xe had decayed when the final measurement was taken one week after EP-III.

Engine design and operation to account for ^{135}Xe

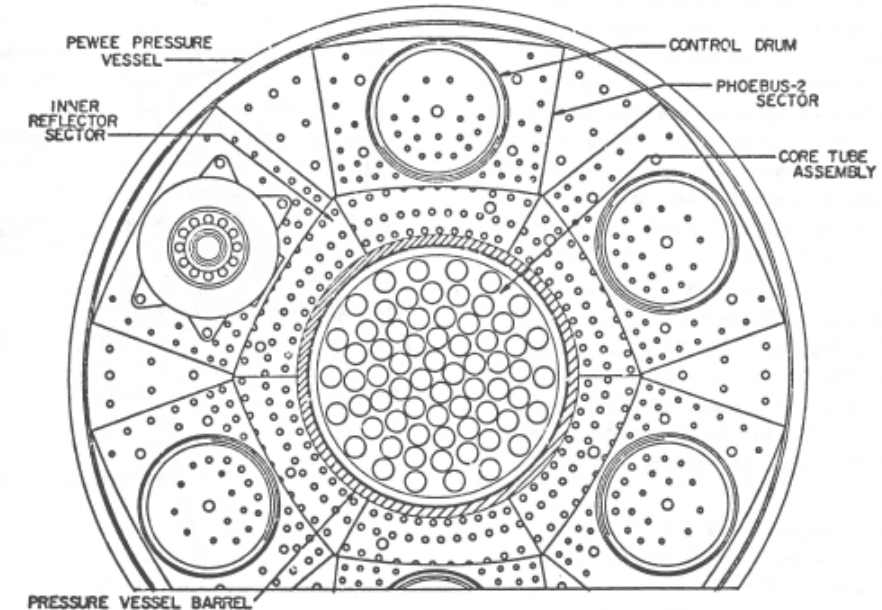
Nuclear Furnace NF-1



[2]



NF-1 on railroad car



NF-1 Transverse View

- 44 MW in size and ran on GH_2 . 49 core elements.
- NF-1 test started in Summer 1972 and was last reactor test done before program canceled
- Six runs were made. Final two runs completed without incident
- Exit gas temperature above 2222K for 121 minutes and above 2444K for 109 minutes total
- Only Rover/NERVA reactor test with successful filtered exhaust before burning hydrogen in flare stack.
- Composite fuel achieved better corrosion performance, while carbide fuel had cracked extensively near center of reactor

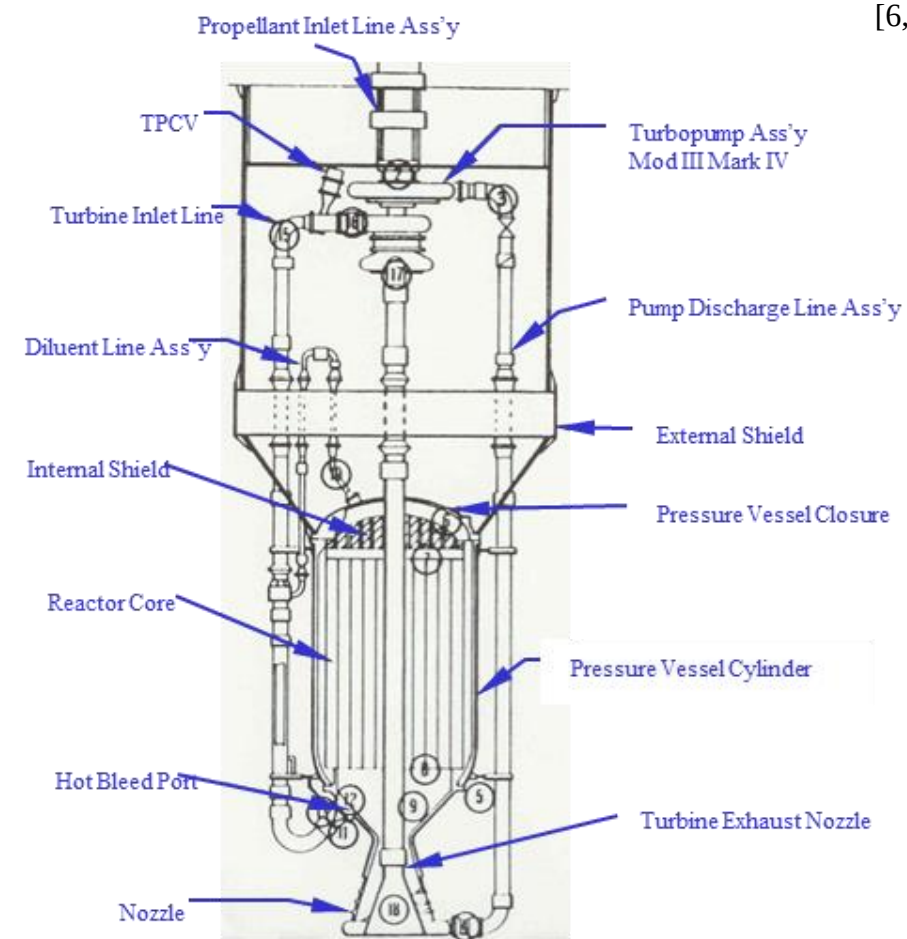
NF-1 tested 49 fuel elements in close operating conditions as a full-scale reactor needing ~1000 fuel elements. Sub-scale demo of full-scale exhaust scrubber system

XE' Experimental Engine



- 55430 lbs thrust, 1140 MW power using NRX-A5 type fuel
- Hot-bleed-cycle in flight like configuration
- 28 start-ups in 1969 using high altitude Engine Test Stand (ETS-1)
- 11 minutes at full power
- Optimum startup, shutdown and cooldown sequence demonstrated
- Turbopump stopped working and was replaced using special shielding
- Remote disassembly showed deformed lines, detached instrumentation, cracks

Successful TRL 6 Demonstration



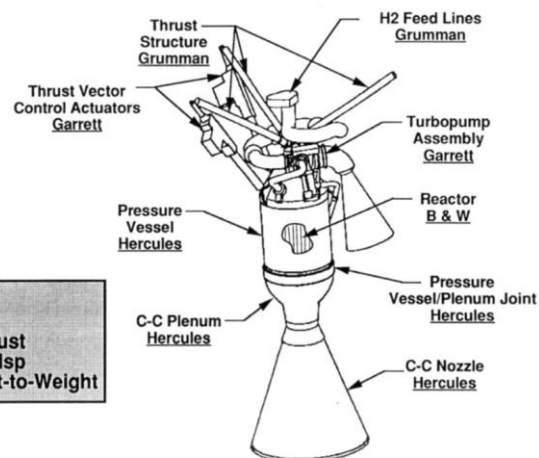
[6,12]

Air Force Space Nuclear Thermal Propulsion (SNTTP)



[13, 14]

SNTTP PBR Engine Description

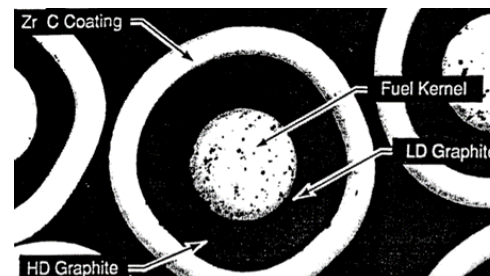
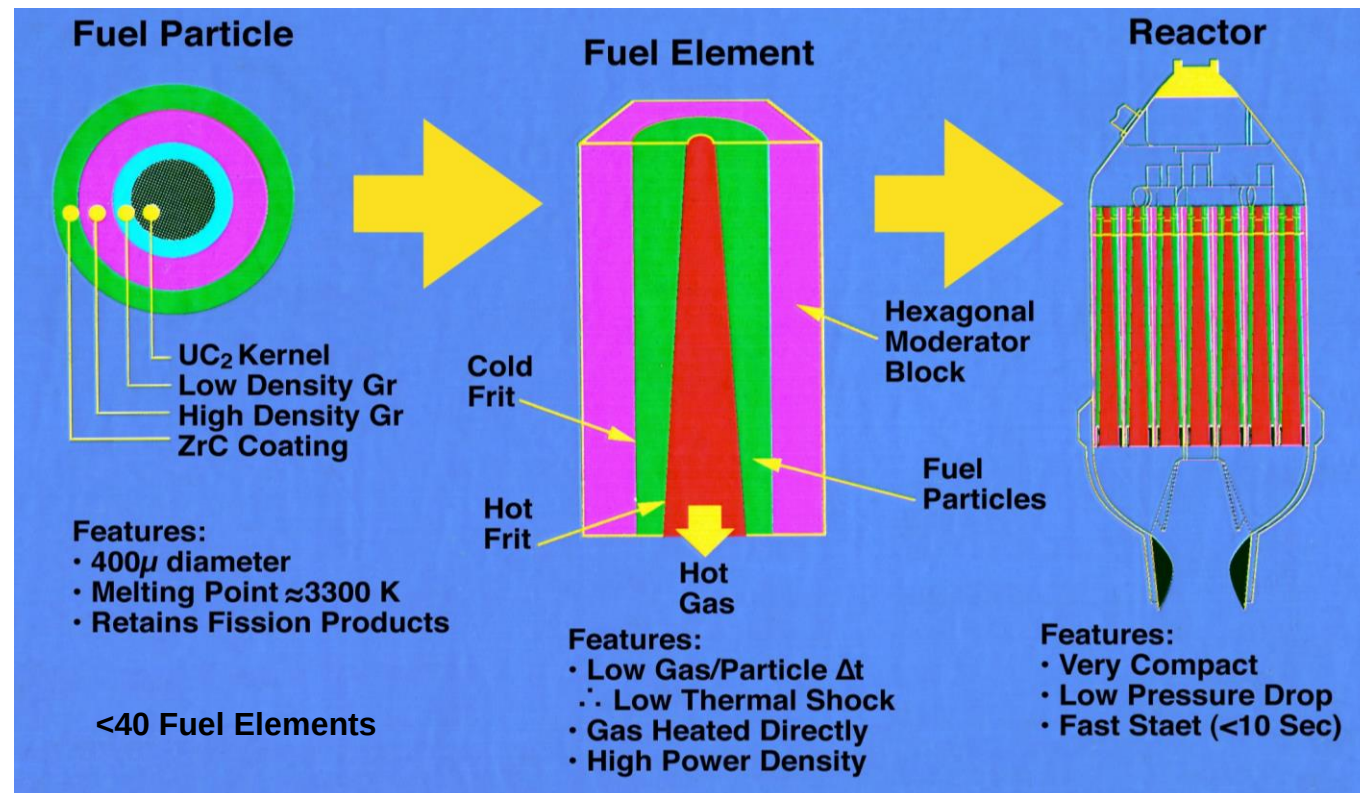


• Design Goals:

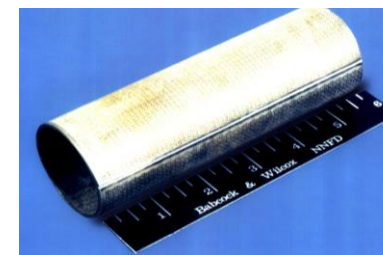
- 20 - 80 klbf Thrust
- 900 - 1000 Sec Isp
- 25 - 35:1 Thrust-to-Weight

Typical Engine Height = 10 Ft (40 klbf Class)

Engine Thrust	20 - 80 Klbf	
Engine Power	500 - 2000 MW	
Specific Impulse at Full Thrust	930 sec.	
Engine Chamber Temperature		3000 K
Turbine Inlet Temperature		2750 K
Engine Chamber Pressure		1000 psia
Engine Thrust-to-Weight Ratio	25 - 35:1	
Nozzle Expansion Ratio		100:1
Maximum Throttling Ratio		5:1
Number of starts		3
Start Transient: 0 -100%		10 sec.
Engine Firing Time:		
Full Power		600 sec.
Full Power + 20% Power		500+700 sec.
Maximum Coast Between Burns		5.5 hrs.
Minimum Coast Between Burns		600 sec.
Chamber Temp. during Coast		1100 - 1500 K



Fuel Particle



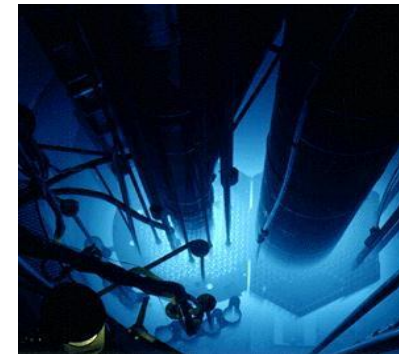
Cold Frit



Hot Frit

SNTP Lessons Learned

- Melting point of UC2-x is between 2700-2800K. Operating limit of baseline particle was 2500K. Advanced fuel development with mixed carbides having potential melt temperatures >3200K, but project was cancelled before final conclusions. [13, 14, 15]
- CTE mismatch resulted in axial failure of hot frit. Double check CTE modeling.
- Major differences between nuclear and non-nuclear tests in both costs and results.
- SNTP completed Environmental Impact Statement (EIS) in 18 months for \$2-3M.
 - NTS selected. EIS final report info is being utilized with current ground test studies.
 - Public meeting discussions is also valuable.
- Lessons learned from the SNTP Nuclear Element Test (NET) rig being used to develop a modification to the MIT reactor to test fuel elements in a 3GV pathway .
 - Funded as a phase II STTR with Little Prairie Services and MIT.



History: USSR Carbide Fuel Development

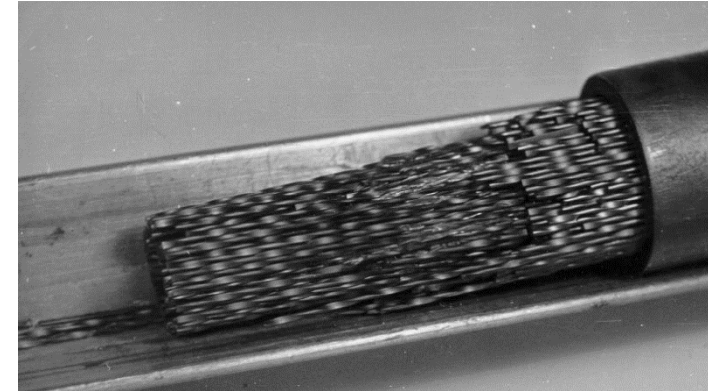


The NTP fuel form development efforts of the former Soviet Union was comparable to United States efforts if not exceeded that of the United States.

[16]

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
- Carbide
 - (U,Zr)C
 - (U,Zr,Nb)C
 - (U,Zr,Ta)C
- Carbonitride
 - (U,Zr)C,N

Type of FE	General form	Cross-section and peculiar dimensions, mm	Arrangement through heat section area Fuel composition
Rod		 $b > 1,0$ $D > 1,6$ $S = 30$	 (Zr,U)C (Zr,Nb,U)C (Zr,U)C+C (Zr,U)N
		 $b > 0,4$ $D > 1,8$ $S = 60$	 (Nb,U)C (Zr,Nb,U)C (Zr,U)C+C (Zr,U)N
		 $D > 1,0$	 (Zr,U)C (Zr,Nb,U)C (Zr,U)C+C (Zr,U)N
Prismatic block		 $d > 1,0$	 (Zr,U)C (Zr,Nb,U)C (Zr,U)C+C (Zr,U)N
Plate		 $b > 1,0$	 (Zr,U)C (Zr,Nb,U)C (Zr,U)C+C (Zr,U)N
Spherical		 $D = 1-10 \text{ mm}$ coating barrier layer fuel	 (Zr,U)C (Zr,U)N (Zr,U)N

Reported tri-carbide fuel performance of operation at 3100 K hydrogen for up to an hour.

NASA Space Nuclear Propulsion (SNP) Project



Overall Nuclear Thermal Propulsion Strategy:

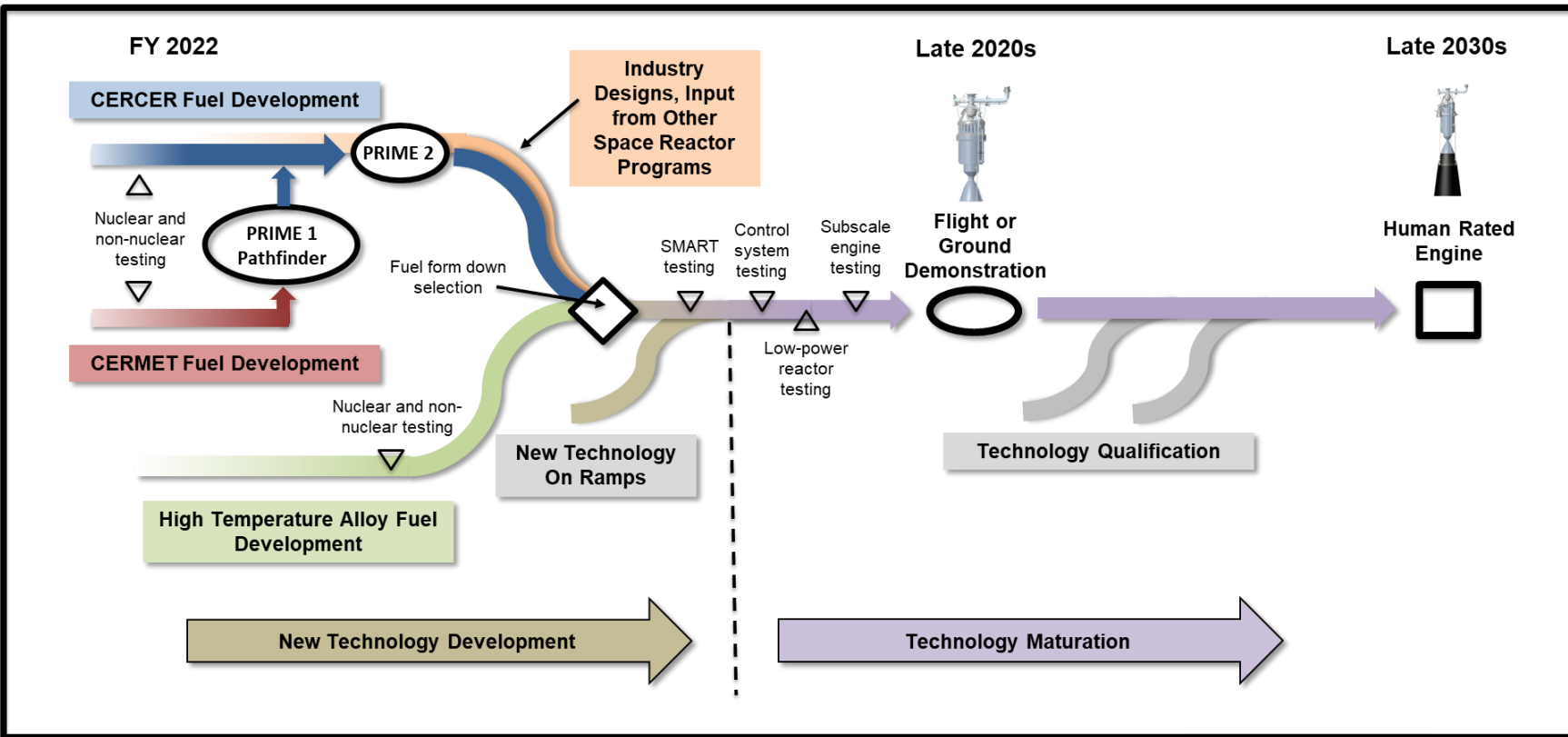
Develop a subscale nuclear engine that demonstrates a viable NTP propulsion system and is scalable to the Mars mission engine needs. Evolve to Mars engine system as a part of a Mars NP propulsive stage.

1. Develop a HALEU solid solution fuel form that can provide reactor exit temperatures ≥ 2700 K (corresponds to ≥ 900 s I_{sp}).
2. Design a reactor with an eye toward capability to be scaled to a size to support Mars mission engine needs. (Scaling is to be an engineering solution rather than further tech development.)
3. Design and develop a subscale engine (Key attribute goals: 10K-15K lbf thrust, 900s I_{sp})
4. Determine Demonstration option (either ground test or demonstration flight).
5. Identify testing and launch regulatory requirements and mitigate issues.
6. Work with CFM project to develop passive and active CFM systems to support NTP mission needs.

Goal is to demonstrate Engine (ground test or flight demonstration) Circa FY2027.



SNP Fuel and Moderator Development Plan



Three industry teams awarded Phase I Prototype Reactor Development:

- BWXT
- General Atomics
- USNC-Tech

Designs with fuel kernels have been evolving over the last 10 years (UO₂, UN, UC)

SNP Lessons Learned



- SNP under the STMD is to mature critical NTP technologies to TRL 6 or TRL 7, not flight certification to TRL 8.
 - Minimum demonstrations to advance the TRL
 - Keep in mind what is needed by future customer.
- Baseline a high assay low enriched uranium (HALEU) reactor design
 - HALEU system analyses closes with selection of materials with low neutron absorption. (e.g., avoid materials like Rhenium).
 - New infrastructure being investigated to produce larger quantities of HALEU for multiple customers
- The larger the total thrust the shorter the mission burn time. Shorter burn times allow higher Isp based on the fuel endurance unless mission reusability is to be considered
- Keep in mind a fuel element design and fabrication process that is simple and not complex or time consuming.
 - In 1964, Rover/NERVA tested 3 different reactors with ~4700 fuel elements not all the same and made at 3 different locations.
- Currently, it is not possible to construct new world class ground test facilities for NTP like Rover/NERVA had. Rely more on computer analysis and slight modifications to existing facilities.
- Subscale Maturation of Advanced Reactor Technologies (SMART) reactor study utilizing lessons learned from Rover/NERVA Nuclear Furnace and SNTP PIPET
- There are advanced NTP concepts being investigated, beyond traditional solid core, with low TRL but low AD^2 , with much higher Isp than 900 seconds



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15. Communications with Roger Lenard
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