# Overview of High Temperature Material Needs for Space Nuclear Propulsion Reactors

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# Acknowledgements

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Task No. 10.022.000

# Agenda

1. **Introduction**
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   – Overview of Space Nuclear Propulsion Technologies

2. **Nuclear Thermal Propulsion Development Status and Materials Needs**
   – NTP Design Considerations
   – Overview of Materials Needs for NTP

3. **Nuclear Electric Propulsion Development Status and Materials Needs**
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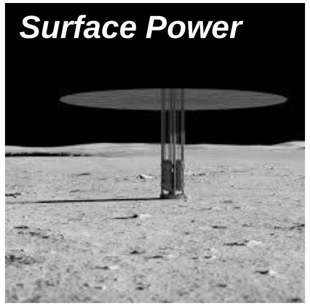
   – Overview of Materials Needs for NEP

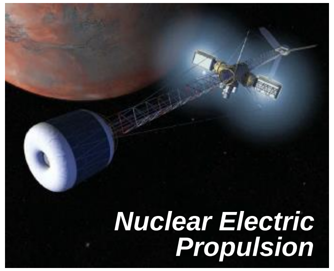
4. **Conclusions**
   – Ongoing SNP Materials Development Activities
   – Summary and Conclusions

# Benefits of Nuclear for Space Applications

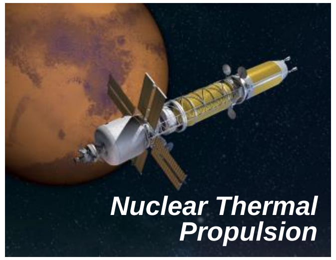
*Space reactors are advantageous for in-space power and propulsion due to their capability for high power density and long operating lifetimes*



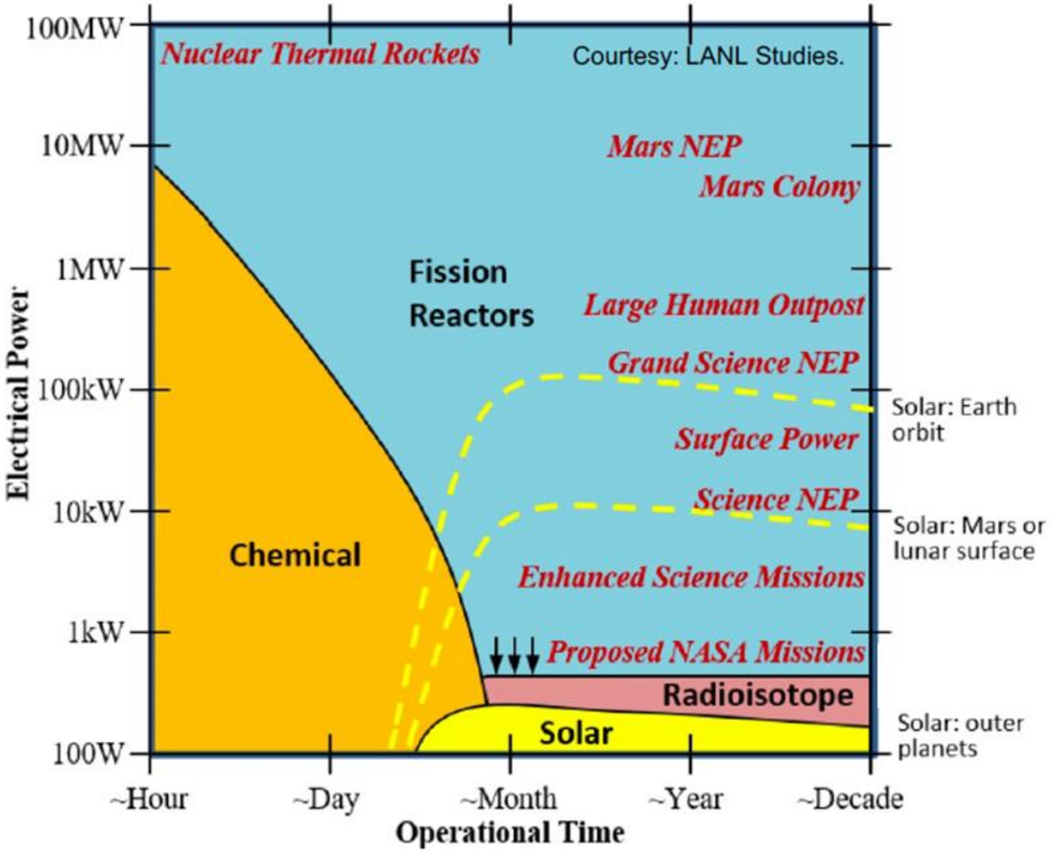

https://nasa.gov/




John Frassanito & Associates in [The Vision for Space Exploration (nasa.gov)]




https://www.rocket.com/innovation/nuclear-thermal-propulsion




**Nuclear energy has the capability to provide high power levels for long periods of time**

- Fission provides the potential for the highest power density per unit mass
- This leads to the potential for enabling more complex missions or adding robustness, capability to baseline missions

**Three fundamental applications of space fission power and propulsion**

- **Surface Power:** fission is a source of power for providing electricity to crew, life, and mission support
- **Nuclear Electric Propulsion (NEP):** fission is a source of power converted to electricity for long duration, high efficiency thrusters to enable fast transit to far away destinations
- **Nuclear Thermal Propulsion (NTP):** fission is a heat source and a reactor acts as a heat exchanger for high efficiency, high thrust applications (long or short durations outside of earth's atmosphere)

**There exists an extensive development history of space reactor technologies, but none have yet been fully demonstrated in space by the U.S.**

- The US has an extensive history and success with radioisotope thermoelectric generators (RTGs)
- The US has successfully demonstrated one reactor in space, but its operation was prematurely terminated due to a non-nuclear system failure

# Overview of Historic U.S. Space Nuclear Propulsion Development Programs

*The United States has a rich history of developing space nuclear thermal and electric propulsion systems, but neither system is at the readiness required for modern space nuclear propulsion missions*

***"It is a most important decision that we make as a nation…"***

- "First, I believe that this nation should commit itself to achieving the goal before this decade is out, of landing a man on the moon and returning him safely to the earth…"
- "Secondly, an additional $23M, together with $7M already available, will accelerate the development of the Rover nuclear rocket. ***This gives promise of some day providing a means for even more exciting and ambitions exploration of space, perhaps beyond the moon, perhaps to the very end of the solar system itself***…"
- "Third, an additional $50M Dollars will make the most of our present leadership, by accelerating the use of space satellites for world-wide communications…"
- "Fourth, an additional $75M of which $53M is for the Weather Bureau will help five us the earliest possible time a satellite system for world-wide weather observation..."

President John F. Kennedy "[Special Message to the Congress on Urgent National Needs];"
Delivered in person before a joint session of Congress May 25, 1961

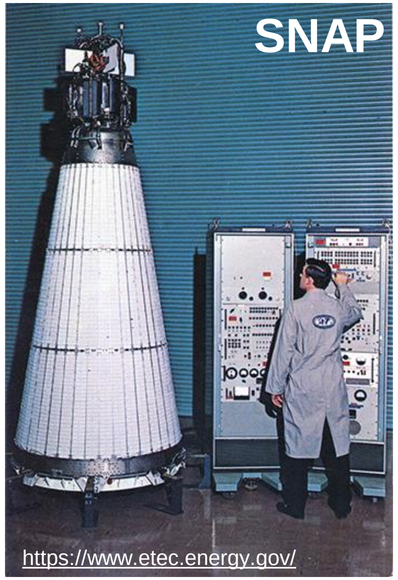
## Historic U.S. Nuclear Space Power Programs

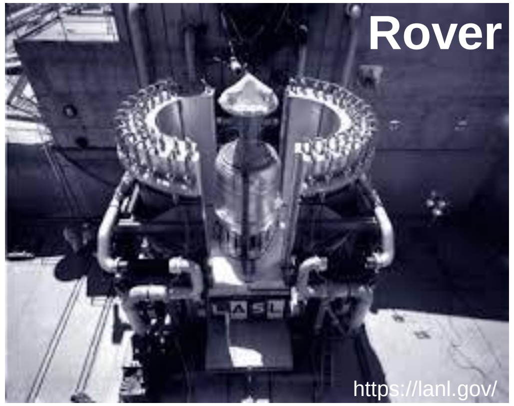
- 1957 – 1973: Systems for Nuclear Auxiliary Power (SNAP)
- 1961 – 1992: Topaz (led by USSR, collaboration with U.S.)
- 1983 – 1993: Space Reactor Prototype (SP)-100 and Multi-Megawatt
- 2003 – 2006: Jupiter Icy Moons Orbiter (JIMO) / Prometheus

## Historic U.S. Nuclear Thermal Propulsion Programs

- 1955 – 1972: Nuclear Engine for Rocket Vehicle Application (NERVA) / Rover
- 1965 – 1968: GE-710 (also NEP application)
- 1957 – 1968: Historic Cermet Development Programs: LANL DUMBO / Argonne National Laboratory / NASA Lewis Research Center
- 1987 – 1991: Timberwind / Space Nuclear Thermal Propulsion


President John F. Kennedy touring the nuclear rocket development station (NRDS). *Courtesy: www.energy.gov*



# Space Nuclear Propulsion Project Overview

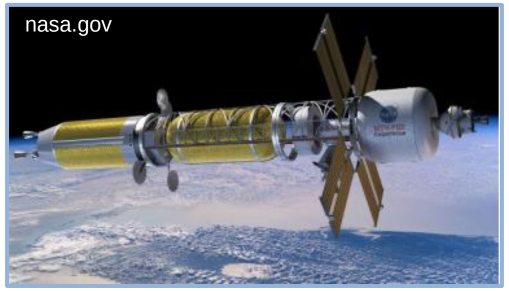
*Nuclear technologies have the potential to enable high performance and reliable in-space propulsion*

**The Space Nuclear Propulsion Project is Developing HALEU Fueled Reactor Technologies for High Performance In-Space Propulsion**

- Crewed Mars Missions in the Late 2030s / Early 2040s
- Nuclear Electric – Chemical Propulsion Hybrid
- Nuclear Thermal Propulsion
- HALEU: high uranium loading density and moderation is more important for HALEU fuel designs than historic HEU designs

**Through the Fuel and Moderator Development Plan, NASA supported by the Department of Energy is developing novel material technologies as a risk reduction activity**

- Fuel research activities: ceramic metallic (cermet), ceramic ceramic (cercer), and solid solution carbide fuels
- High temperature structural and insulator materials
- Hydride-based moderators
- These materials may benefit future industry NTP or NEP designs

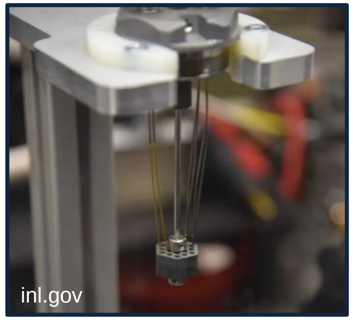



***Nuclear Thermal Propulsion Concept***


***Nuclear Electric Propulsion Concept***


***Testing facilities at NASA, DOE, industry, and university laboratories provide unique environments for understanding material performance***

***NTP fuel specimen prepared for testing in TREAT (INL)***



# Benefits of Fission Power for In-Space Propulsion

*Fission can enable high power levels for long durations which is desirable for surface power and in-space propulsion methods for crewed missions*

**NEP and NTP technologies are capable of much higher efficiencies than traditional chemical propulsion methods.**

- **NTP** – direct heating of a hydrogen propellant enables high thrust and twice the specific impulse of the highest efficiency chemical rockets
- **NEP** – electricity generation powers high efficiency EP thrusters which are capable of nearly an order of magnitude greater specific impulse than NTP but much lower thrust

**These attributes can enable trip times of up to a half that compared to chemical rocket engines.**

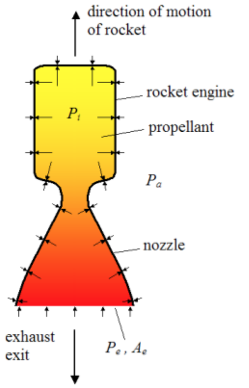
| Type of Propulsion | Specific Impulse (s) | Thrust (klbf) | Propellant | Time of Single Burn (s) |
|---|---|---|---|---|
| Chemical (SSME) | 452 | 471 | $LH_2 + LO_2$ | $10^3$ |
| NTP | 800 - 900 | 25 - 250 | $LH_2$ | $10^3$ |
| Ion NEP | 6,000 – 8,000 | 0.001 - 0.1 | Xe | $10^7$ |

Table originally from: Benensky, K. *Summary of Historical Solid Core Nuclear Thermal Propulsion Fuels.* Pennsylvania State University.2013.

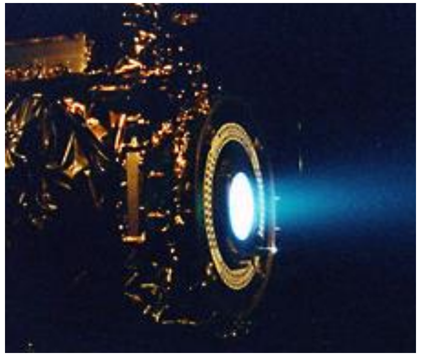
## Rocket Science 101: Specific Impulse and Thrust

**Thrust** is the forward force that accelerates the rocket

$$F_{thrust} = v\frac{dm}{dt} \approx v_e\dot{m}$$



real-world-physics-problems.com


https://www.nasa.gov/centers/glenn/technology/Ion_Propulsion1.html

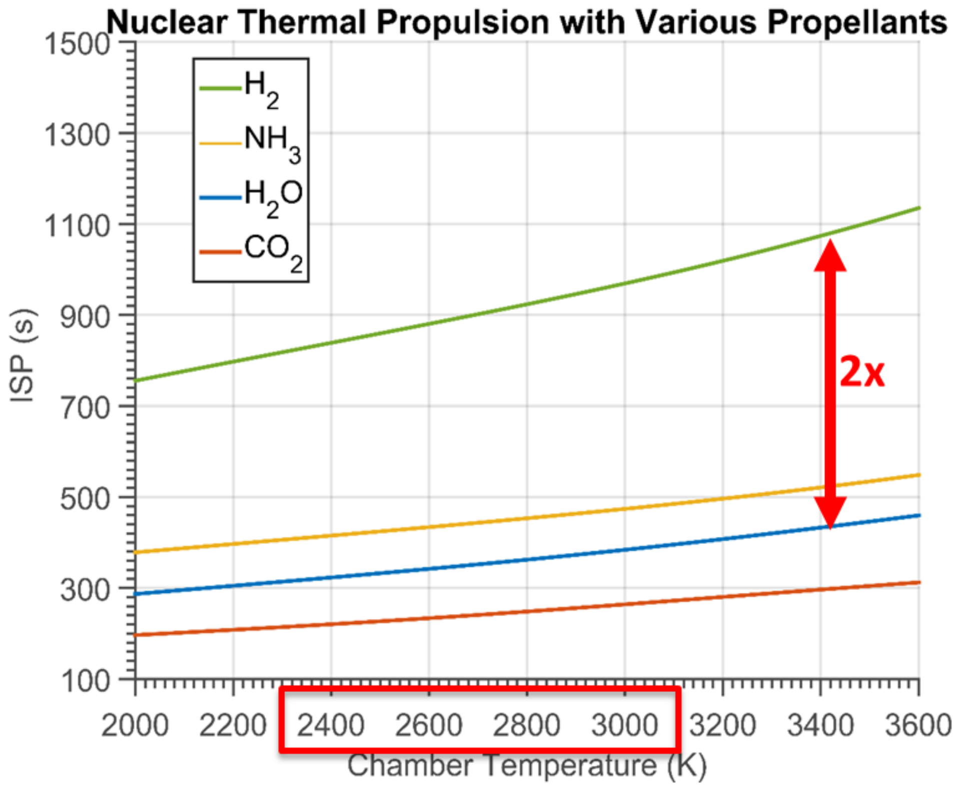
**Specific impulse** is a measure of propulsive efficiency

***Increased $I_{sp}$ reduces the propellant mass that must be carried throughout the mission and allows for thrust to be more proportionally applied to accelerating the spacecraft.***

# How it Works: Nuclear Thermal Propulsion

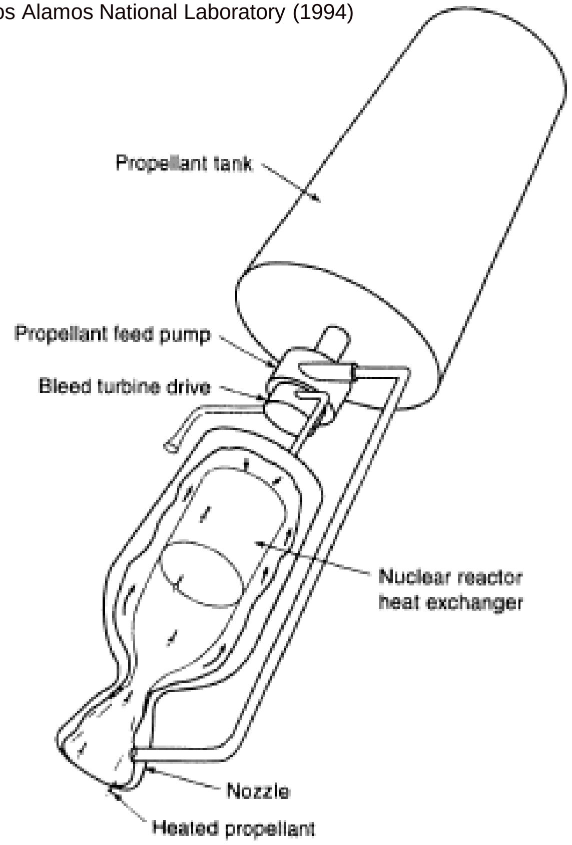
*In a nuclear thermal propulsion engine, the reactor acts as a heat exchanger to directly heat a hydrogen propellant for high efficiency in-space propulsion*

Benensky, K., et. al., in *Nuclear and Emerging Technologies for Space*. 2016 (Presentation)

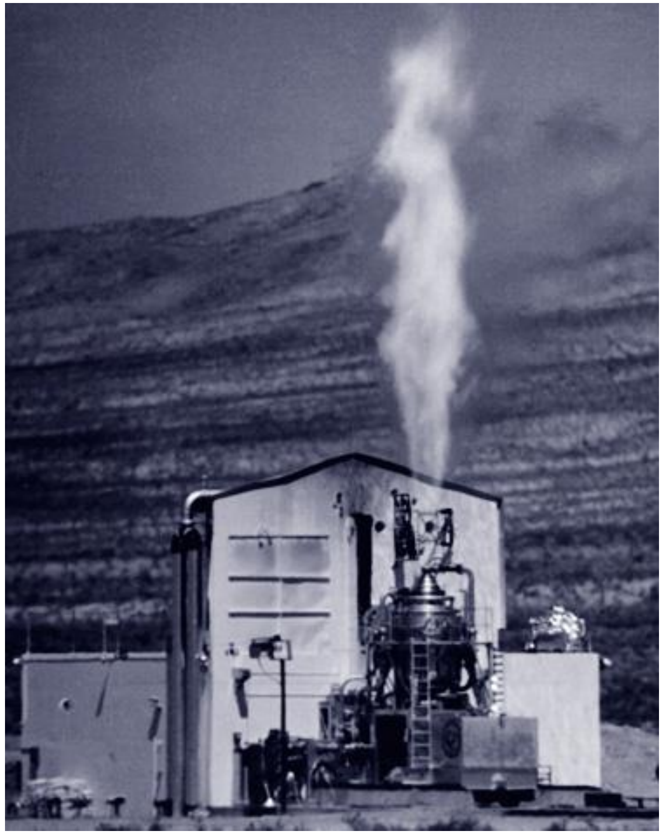



$$I_{sp} = \frac{F_{thrust}}{\dot{m}} = \frac{1}{g_0}\sqrt{\left[\frac{2\gamma}{\gamma-1}\frac{RT}{M}\right]\left[1-\frac{p_e}{p_c}\right]^{\frac{\gamma-1}{\gamma}}} \propto \sqrt{\frac{T}{M}}$$

Watson, C. *Report No. LA-12784-MS.*
Los Alamos National Laboratory (1994)




[NUCLEAR ROCKETS: To Mars and Beyond | National Security Science Magazine | Los Alamos National Laboratory (lanl.gov)]

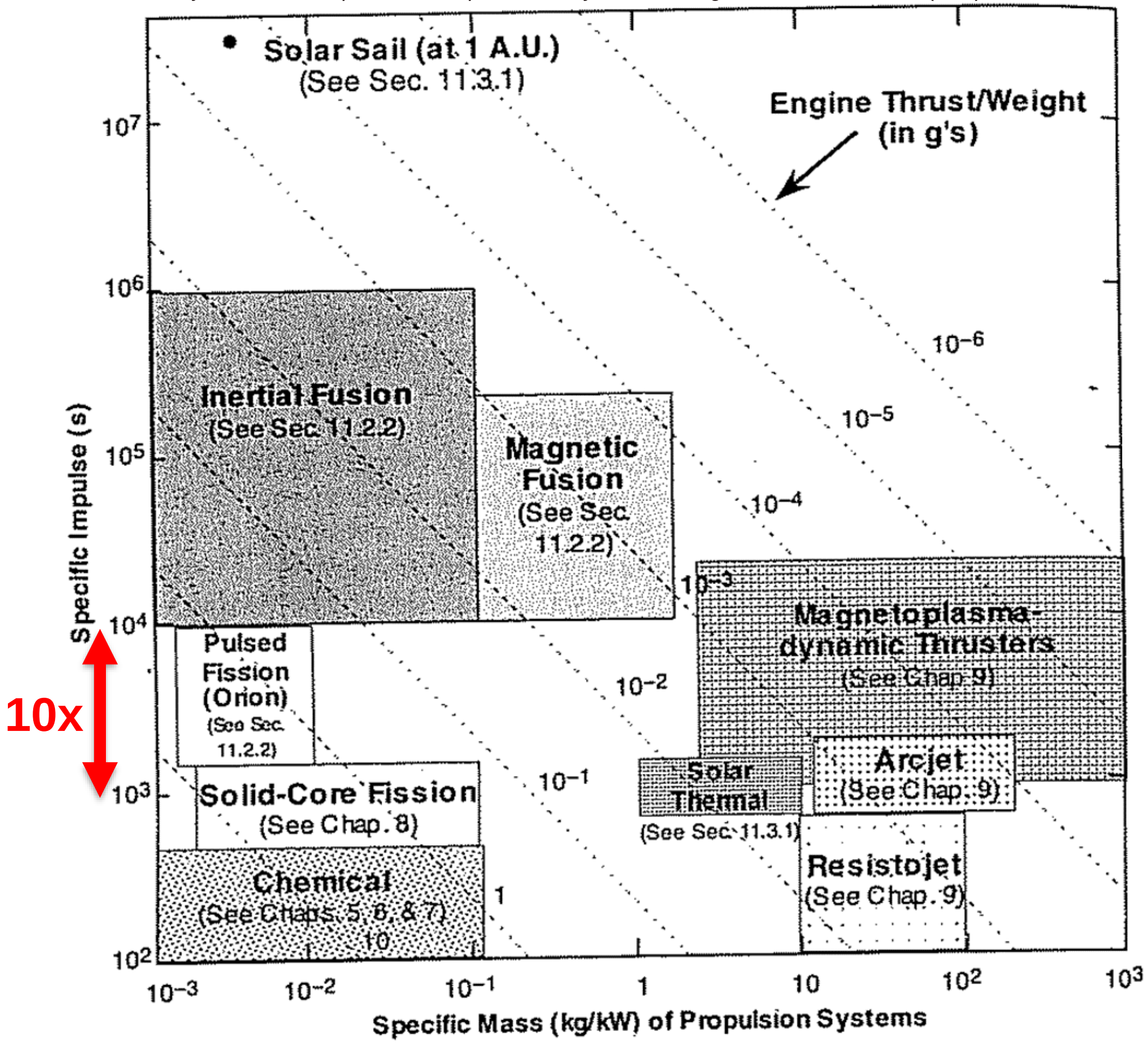


***Total operation time is dependent upon the mission, but is typically on the order of 1 – 4 hours of full power operation for crewed Mars missions.***

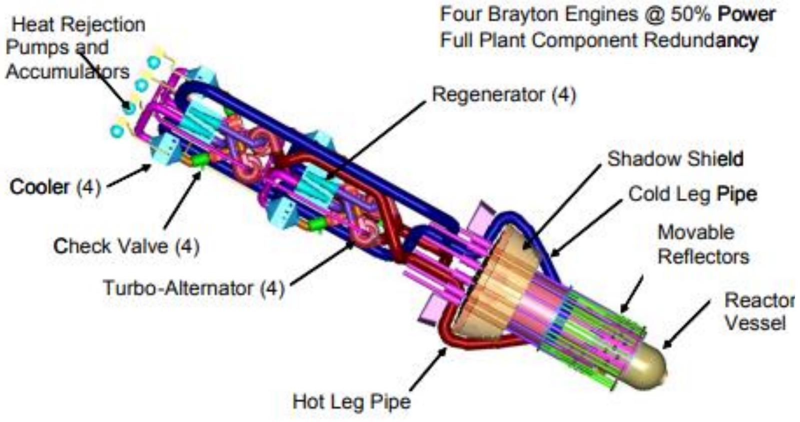
# How it Works: Nuclear Electric Propulsion

*Nuclear electric propulsion reactors heat a working fluid to generate electricity to power high efficiency electric thrusters*

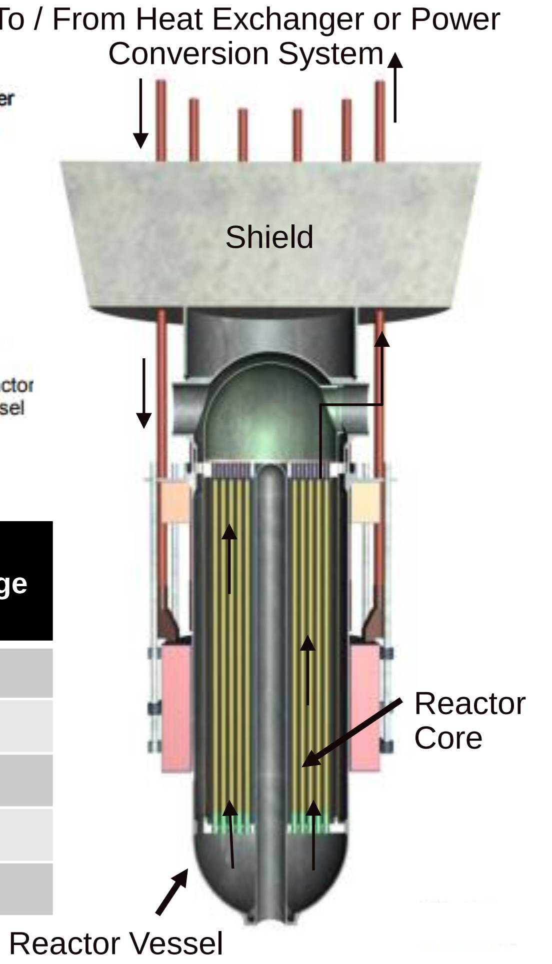
Henry, G. et. al., in *Spacecraft Propulsion Analysis and Design*. McGraw-Hill 1995 (Text)




Ashcroft, J. and Eshelman C. *Report No. LM-05K188* .
*Lockheed Martin Corporation* (2006)

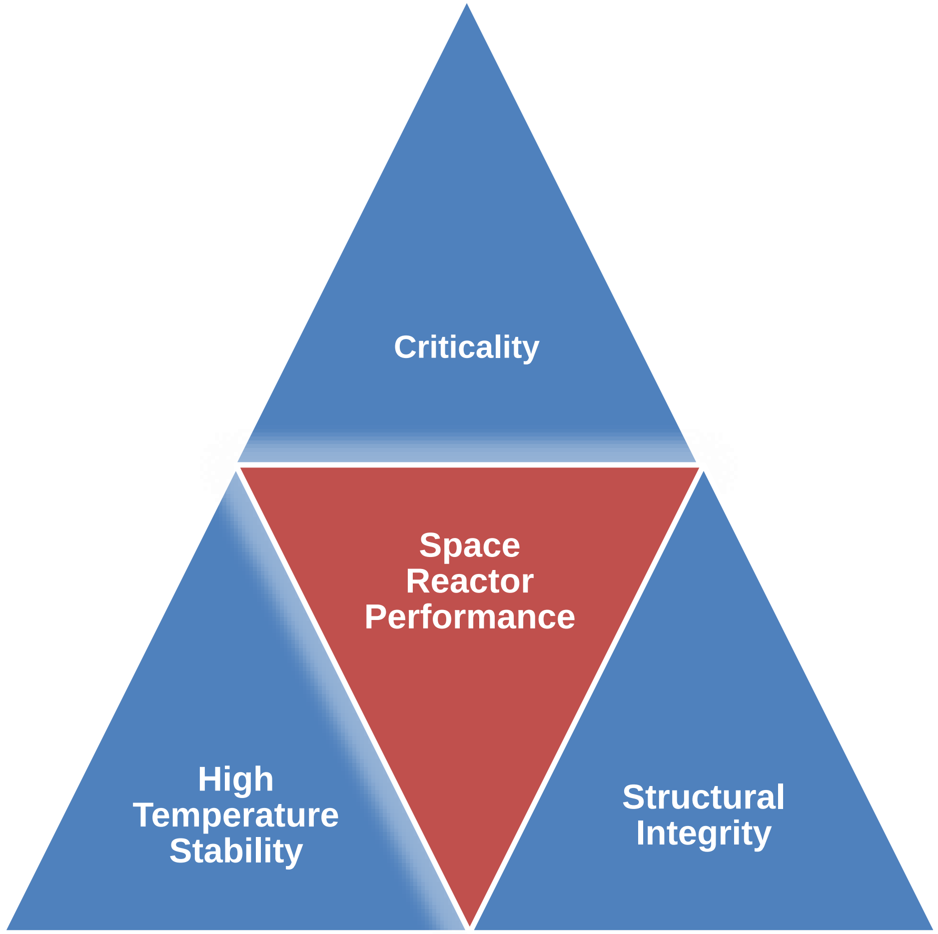


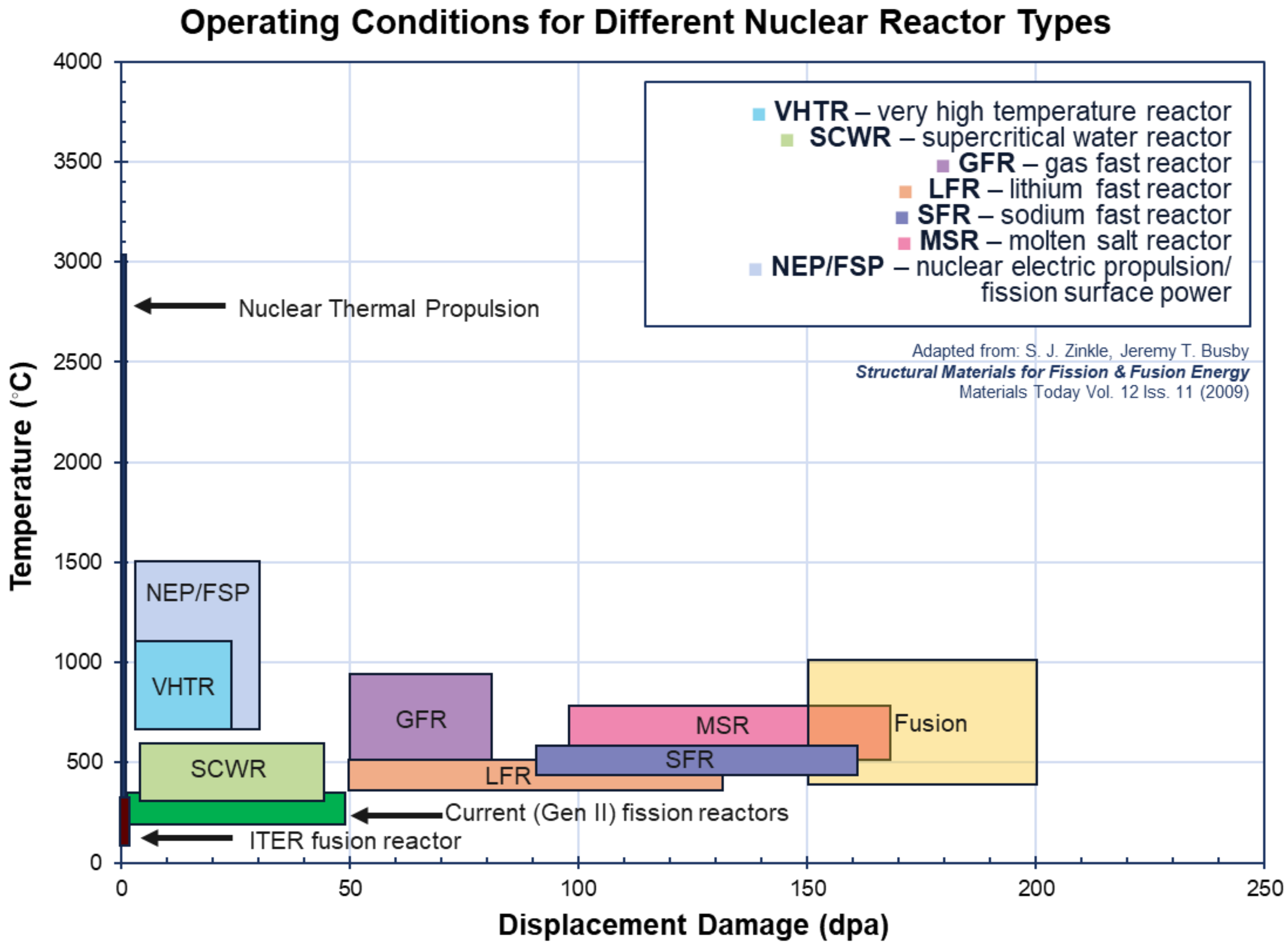

| Power Conversion Technology | Power Level Range | Efficiency Range |
|---|---|---|
| Thermoelectric | 10 – 100 kWe | < 10% |
| Thermionic | 10s – 100s kWe | < 20% |
| Stirling | 1 kWe – 100s kWe | < 30% |
| Rankine | 10s kWe – MWe | 20-30% |
| Brayton | 1 kWe – MWe | 25-35% |




***Due to low thrust, NEP reactors operate nearly continuously throughout the mission (months – years). Efficiency is primarily dependent on overall power conversion cycle selection.***

# High Temperature Materials are Enabling for Space Propulsion Reactors




***In order to maintain performance over lifetime, materials must exhibit acceptable dimensional, structural, and compositional stability.***

# Nuclear Thermal Propulsion

*State of the Art and Materials Challenges*

# Nuclear Thermal Propulsion Reactor Components and Operating Conditions

*The goals of NTP reactor design are to maximize specific impulse and thrust while minimizing reactor mass*

**Maximizing specific impulse requires:**

- Maximizing fuel temperature for heat transfer (2500+ K maximum operating temperature)
- Avoiding hydrogen corrosion (materials will be exposed to high pressure, flowing hydrogen)

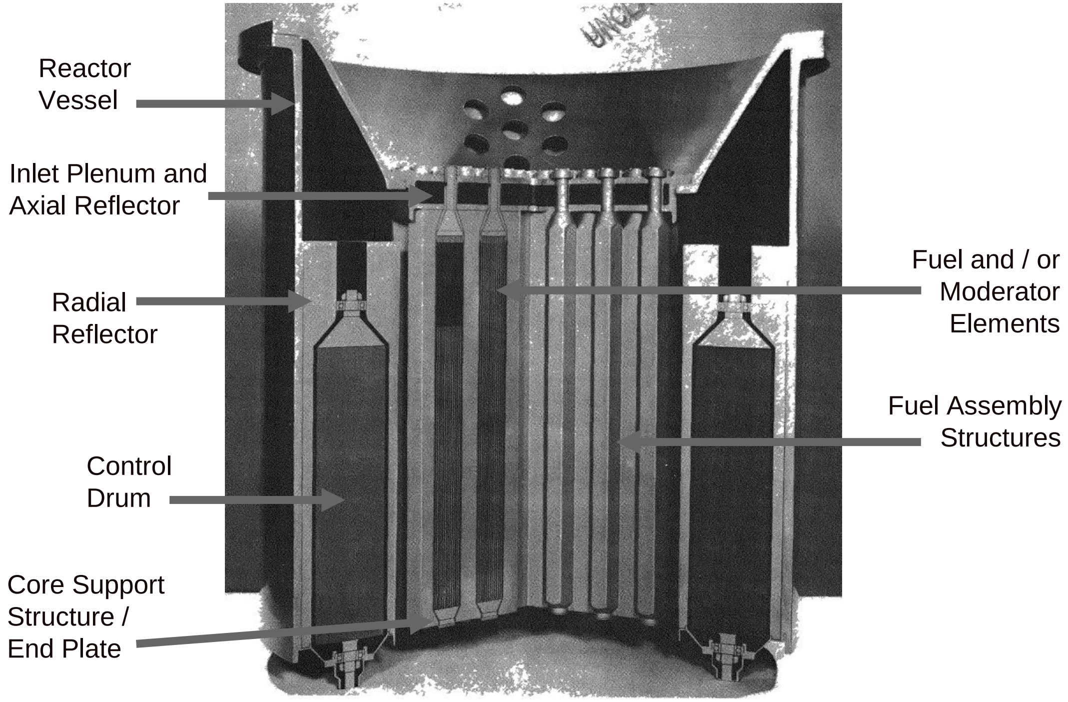
**Thrust is proportional to reactor thermal power. Minimizing reactor mass requires:**

- Maximizing power density (5+ MW/L)
- Selection of materials with desirable nuclear properties (low absorption, tailor design of neutron spectrum)

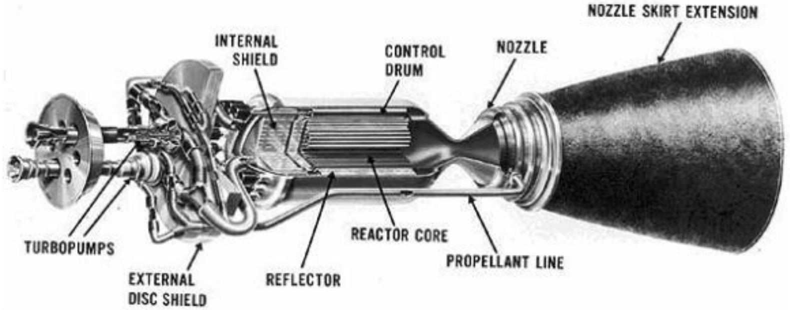
**To enable engine operation, the reactor must be capable of:**

- Multiple burns (thermal cycling, 4 – 6 burns typical for a roundtrip mission) for short total lifetimes (< 10 hours)
- Rapid start up, shut down (intense thermal transients ~100 K/s)

***The fuel is the most important material to ensure performance is met throughout the mission, however moderator and structural materials may be just as important to ensure criticality and structural integrity.***




"710 High Temperature Gas Reactor Program Summary Report" *Report No. GEMP-600 Vol. 1 General Electric Company* (1967)




Fittje, J. E. "Upgrades to the NESS (Nuclear Engine System Simulation) Code" In *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit Proceedings* Cincinnati, OH. American Institute of Aeronautics and Astronautics

# Hydrogen corrosion and retention of structural integrity under extreme conditions is the most outstanding challenge for NTP fuel forms

**Desirable attributes for NTP fuel forms:**

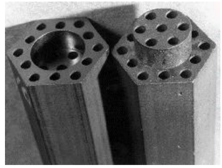
- High melting point
- Hydrogen compatibility / high temperature stability
- High uranium loading and low absorption cross section

**Past fuel forms developed:**

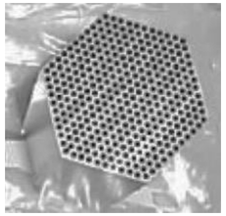
- Ceramic Metallic (Cermet): W alloy matrix with dispersed $UO_2$ or UN particles
- Ceramic Ceramic (Cercer): Graphite matrix (or other refractory carbide) with dispersed coated particles or (U,Zr)C fuel web
- Solid Solution Carbide: UC in solid solution with higher melting temperature transition metal carbides
- Particle Fuels: $UC_2$ or other high temperature fuel with multiple functional coatings

**Knowledge gaps:**

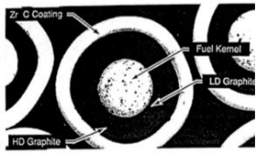
- Fuel performance database under combined effects conditions or very high operating temperature
- Manufacture processes for net shape fuel elements

[1]


NERVA/Rover
Graphite Composite Fuels

[1]


GE-710 Gas Reactor
Ceramic Metallic (cermet) Fuels
W and Mo matrix

[2]



Space Nuclear Thermal Propulsion (SNTP)
Carbide "Particle" Fuels

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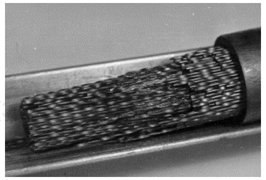
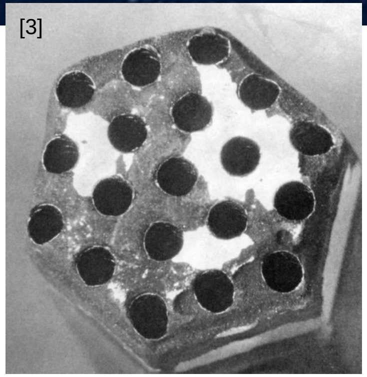


Russian NTP Program
Carbide "Twisted Ribbon" Fuels

[3]


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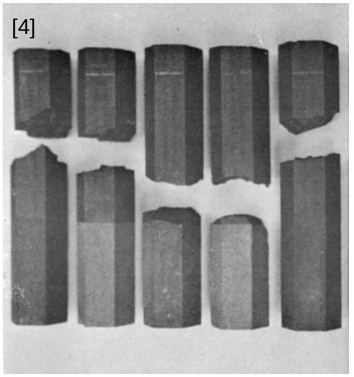
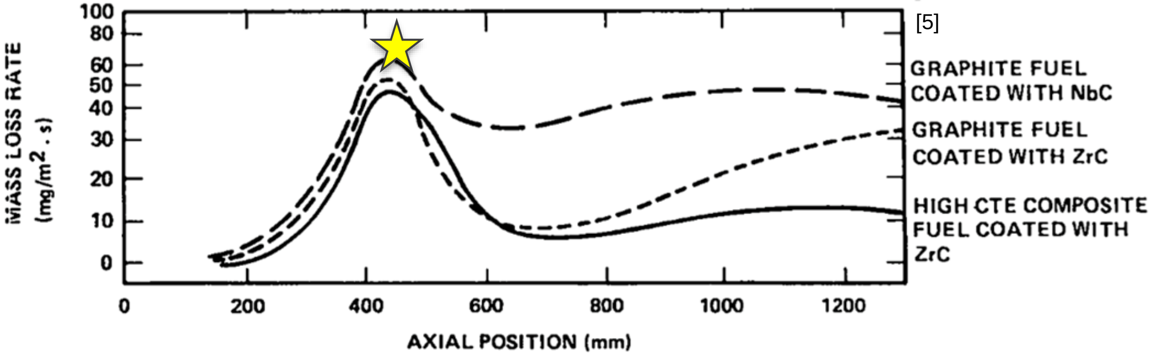


[5]



***Fuel was most susceptible in the 'mid-band' where thermal stresses are high and ductility still low***

[1] Bhattacharyya, S. K. *An assessment of fuels for nuclear thermal propulsion*. Argonne National Laboratory ANL/TD/TM01-22 (2002)
[2] Haslett, R A. *Space nuclear thermal propulsion program. Final report, September 1989-May 1995.* United States: N. p., 1995. Web.
[3] Boltax, A, and Tobin, J M. *WANL contribution to the twentieth high temperature fuel committee meeting*. United States. 1965. Web.
[4] Morris, W P. *Joint WANL/LASL/Y-12 fuel and reactor development review*, WANL, October 11-- 12, 1966. United States.1966.
[5] Lyon, L L. *Performance of (U,Zr)C-graphite (composite) and of (U,Zr)C (carbide) fuel elements in the Nuclear Furnace 1 test reactor.* United States, 1973.

# NTP Moderators Must be Capable of Withstanding a High Pressure Hydrogen Environment under Extreme Thermal Stresses

**Desirable attributes for NTP moderators:**

- Nuclear properties for slowing down neutrons
- Hydrogen compatibility
- Thermal stress resistance – thermal shock during start up, high temperature gradients during operation

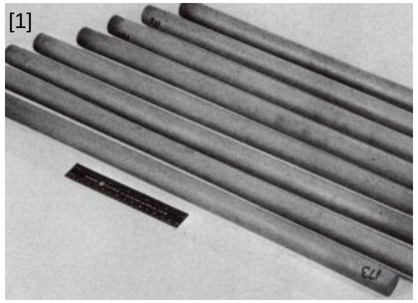
**Past moderator types developed:**

- Zirconium hydride ($ZrH_x$) – sleeves (demonstrated in Pewee-1) or block moderator
- Tory program: Beryllium oxide

**Knowledge gaps:**

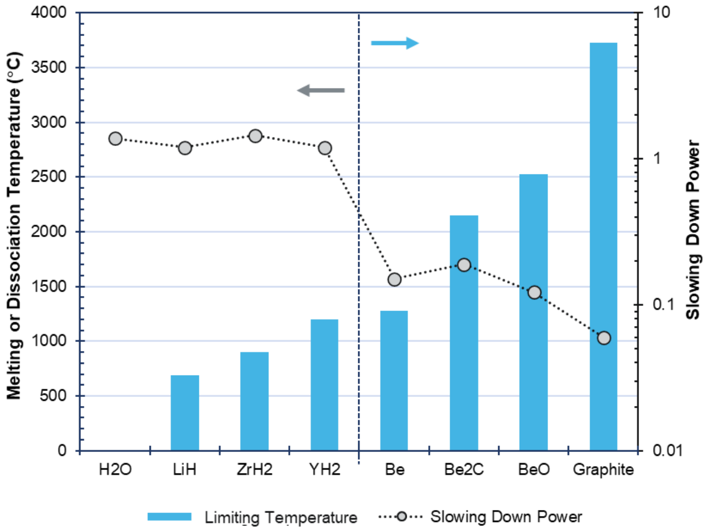
- Moderator stability under high pressure hydrogen and high thermal stresses (compositional evolution)
- Manufacture processes for net shape moderator elements

***Example moderator geometries for NTP***

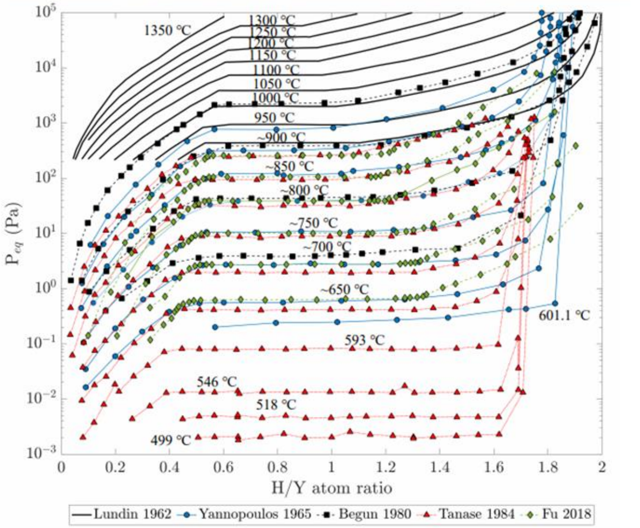




[3] **Common Reactor Moderator Candidate Properties**




[4] The stability of different $YH_x$ stoichiometries at high temperatures



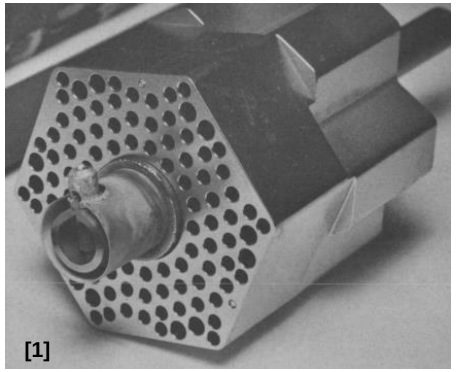
# Other Applications of Ceramics and Composites Beneficial for NTP

## Insulators

- Thermally insulate the fuel from moderator
- Thermally insulate the core from reflector and external reactor structures
- Minimizing thermal conductivity reduces required insulator thickness and overall reactor geometry

## Core Structural Materials

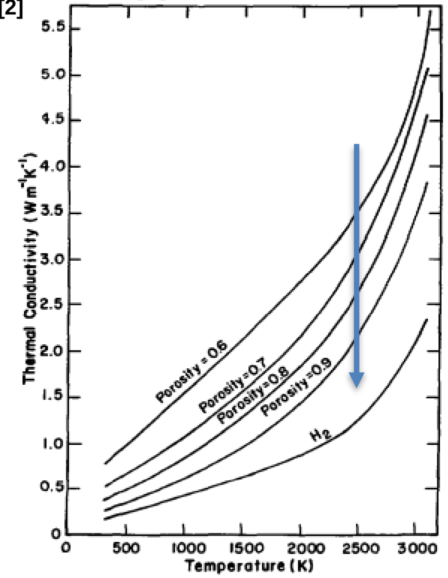
- NTP requires structural components capable of retaining high temperature strength
- Composite materials (such as C-$C_f$) may offer benefits as a fuel assembly structure or channel liners for improved robustness under NTP conditions
- Structural components may be exposed to hydrogen and require protective coatings



[1]

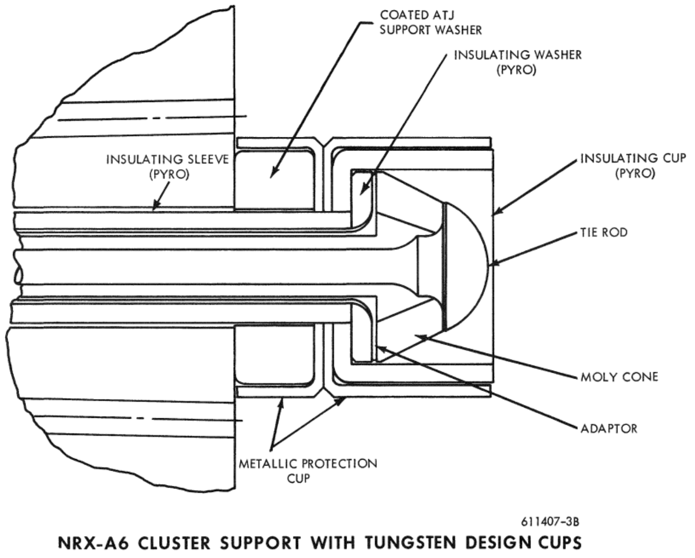
***NERVA Rover Fuel Cluster Support Hardware***

[2]



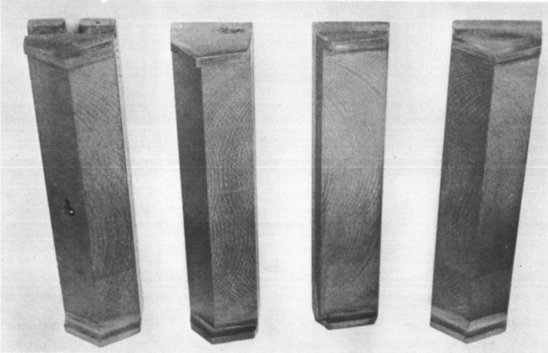

***Porous ZrC may be an effective NTP insulator due to high melting point and hydrogen stability.***

[3]




NRX-A6 CLUSTER SUPPORT WITH TUNGSTEN DESIGN CUPS

[4]



***Radial insulating materials can act as a thermal barrier between the reactor and reflector***


[1] Boltax, A, and Tobin, J M. *Minutes of instrumentation review meeting at Sacramento on March 7--8, 1967*. Rep. No. WANL-TME-1606. Westinghouse Astronuclear Laboratory. 1967.
[2] Morris, .W P. *Joint WANL/LASL/Y-12 fuel and reactor development review*. United States. Rep. No. WANL-TME-1532. Westinghouse Astronuclear Laboratory. 1965.
[3] Wagner, P. *Research, Development, and Production of Substoichiometric Zirconium Carbide for High-Temperature Insulation*. Rep. No. LA-5224 United States. 1973.
[4] Kiefer, K P. *Core insulation assembly thermal test. Final report*. United States. Rep. No. WANL-TME-902. Westinghouse Astronuclear Laboratory. 1964.

# Nuclear Electric Propulsion

*State of the Art and Materials Challenges*

# Nuclear Electric Propulsion Reactor Components and Operating Conditions

*The goals of NEP reactor design are to <u>maximize reactor lifetime</u> to <u>satisfy the power conversion cycle interface</u> while <u>minimizing reactor mass</u>*

**Typical NEP Reactor-Power Conversion Cycle Interface:**

- Reactor exit working fluid temperatures of 1200 – 1800+ K (fuel temperatures of: ~1400 – 2000+ K)
- Power generation is nearly continuous throughout the mission, a high burnup fuel form, dimensionally and compositionally stable moderator (if used), and inert, creep resistant structures are desired.

**Electric power produced will be proportional to reactor thermal power. Other factors include:**

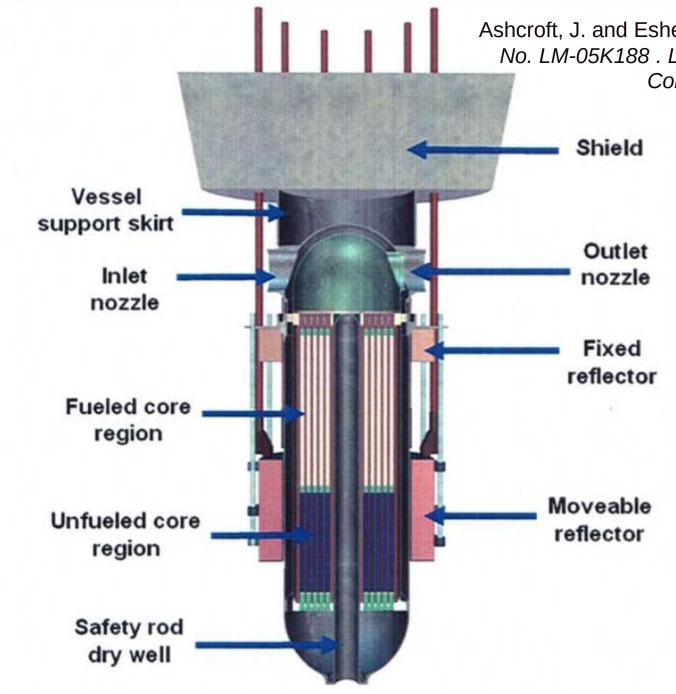
- Power conversion cycle selection and efficiency (efficiency traditionally scales with maximizing the difference between inlet and exit temperature of the PC cycle)
- Selection of working fluid to efficiency extract heat from the reactor. Avoid working fluid incompatibility of reactor core and vessel structures or piping. Typical working fluids are: Li, NaK

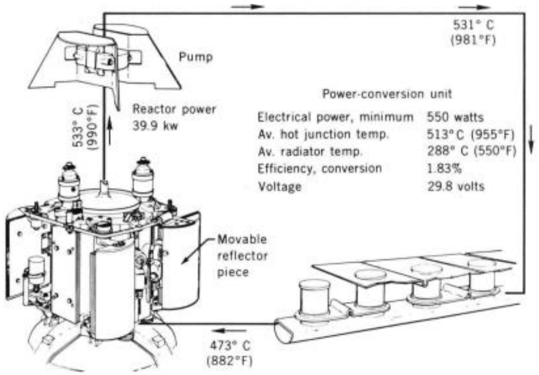
**Minimizing overall system mass, rather than just reactor mass, is the driving factor and minimum reactor size may not be necessary. Some considerations include:**

- Minimizing reactor mass is still important and may lead to higher power densities in NEP reactors compared to traditional terrestrial designs
- Required heat rejection temperature and radiator mass (radiators rid the system of waste heat not converted into electricity)

**The <u>fuel</u> is the most important material to ensure reactor *performance** is met throughout the mission. However, <u>moderator</u> and <u>structural materials</u> are just as important to ensure *criticality* and *structural* integrity over long lifetimes.**

Ashcroft, J. and Eshelman C. *Report No. LM-05K188 . Lockheed Martin Corporation* (2006)




Corliss, W. R. [*SNAP Space Reactors*] US Atomic Energy Commission (1966)

*NEP system performance is also limited by selected EP thruster selection and power conversion system efficiency (materials technologies also limit PCS operating temperature)

# Fuel Forms for NEP Applications

**Desirable attributes for NEP fuel forms:**

- High uranium loading and low absorption cross section
- Long duration dimensional, compositional, and structural stability under high temperature irradiation
- Established performance database and manufacture processes

**Past fuel forms developed:**

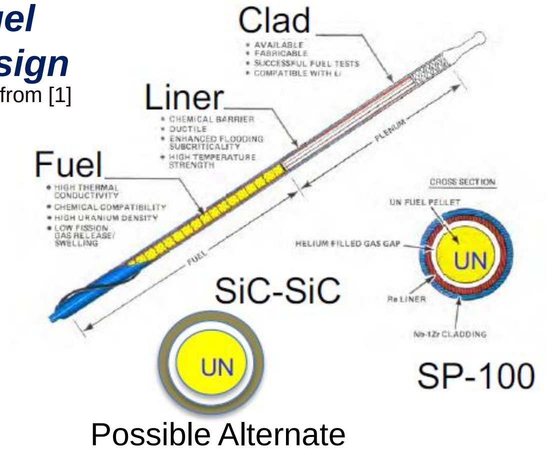
- Monolithic Pellet Fuels: $UO_2$ and UN
- Hydride Fuels: $(U,Zr)H_x$
- Composite and NTP fuel forms have also been proposed (example: GE-710 program explored cermet fuel development for NTP and NEP)

**Knowledge gaps:**

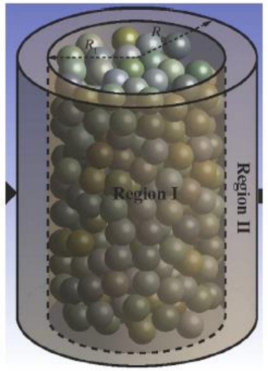
- Extending the fuel performance database to higher temperatures may be required dependent on technology selection
- Chemical compatibility knowledge gaps may exist; consider other components in contact with fuel or working fluid (design dependent)

***SP-100 Fuel Element Design***

Courtesy LANL, modified from [1]




[2]




***Example pellet fuel with dispersed coated particles***

[3]

| Characteristic | $UC_2$ | UN | $UO_2$ | (U,Zr)C |
|---|---|---|---|---|
| U Density ($g/cm^3$) | 10.6 | 13.5 | 9.66 | 2.88 |
| Melting Point (K) | 2710 | 3035 | 3100 | 3350 |
| Thermal Conductivity (W/m·K) | 18 | 25 | 3.5 | 30 |
| Relative Stability | High | Low | Mid | High |
| Relative Swelling | Low | Mid | Low | High |
| Fission Gas Release | Low | Low | High | Mid |
| Fabricability | Difficult | Moderate | Easy | Difficult |

More desirable than average candidate for this parameter

Average for candidates for this parameter

Less desirable than average candidate for this parameter

[1] Buden, D. *Summary of Space Nuclear Reactor Power Systems*. Idaho National Engineering Laboratory Report No. INEL/MISC-93085 (1993)
[2] Courtesy of Los Alamos National Laboratory
[3] Adapted from: Matthews, B. et al. “Fuels for Space Nuclear Power and Propulsion: 1983 – 1993” in A Critical Review of Space Power and Propulsion: 1984 - 1993

# NEP Moderators Must Exhibit Stability for Long Lifetimes at High Temperatures

**Desirable attributes for NEP moderators:**

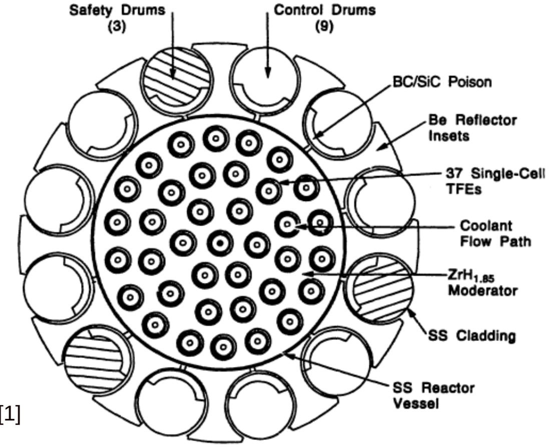
- Nuclear properties for slowing down neutrons
- Long duration, high temperature stability

**Past moderator types developed / takeaways:**

- Zirconium hydride ($ZrH_x$) – block moderator and $(U,Zr)H_x$ SNAP reactor
  - Hydrogen retention limited lifetime, structural failure of moderator block led to loss of criticality
- Be-based ceramics also proposed

**Knowledge gaps:**

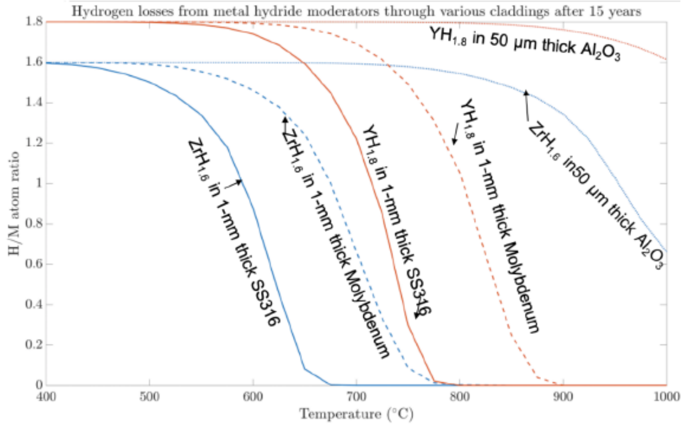
- Improving hydride operating temperature and lifetime (hydrogen retention over long durations)
- Establish material performance database for higher temperature operation (T > 1000 K)
- Manufacture processes for net shape moderator elements

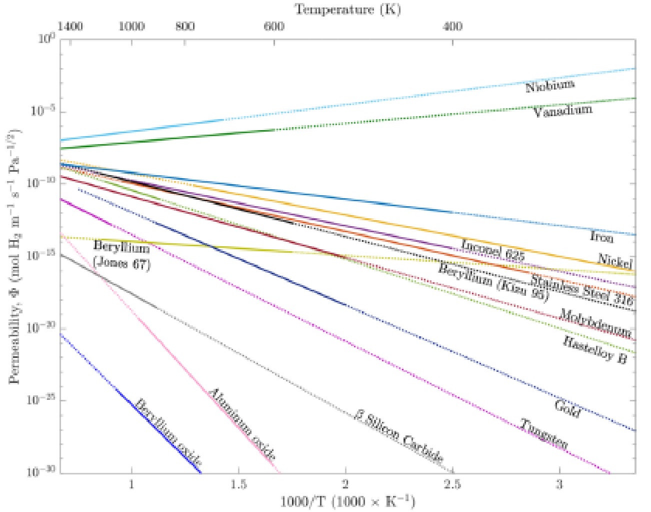



[1]

*Example Topaz-II NEP Moderator Block Reactor Concept*


*Example yttrium hydride coupons fabricated at Los Alamos*




*Metallic hydrides may require hydrogen barrier coatings to enable long duration operation (years)*

[1] *Voss, S. S.* Topaz II System Description Los Alamos National Laboratory Report No. LA-UR-94-4 (1994)

Other images courtesy of Los Alamos

# Other Applications of Ceramics and Composites Beneficial for NEP

[see presentation notes for citations]

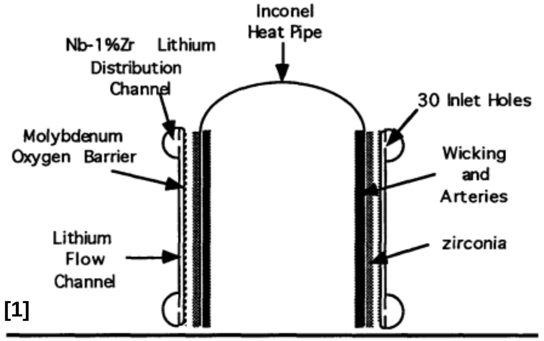
**Insulators**

- Thermally isolate core materials or reactor from interface with other subsystems.
  - May be important for moderated reactor concepts to reduce the operating temperature of moderator.
- Consider nuclear properties in addition to thermal conductivity.
- Dimensional stability and chemical compatibility over lifetime must be acceptable.

**Reflector / Structural Materials**

- Be-based ceramics offer the best nuclear properties as a reflector for NEP applications
- Ceramics (such as graphite or SiC) with established manufacture processes and performance databases are desirable structural materials for forming the reactor core due to their high temperature capability and low neutron absorption cross section
  - Consider interfaces with heat transfer technology elements: working fluid, heat pipe structures, etc.

[1]

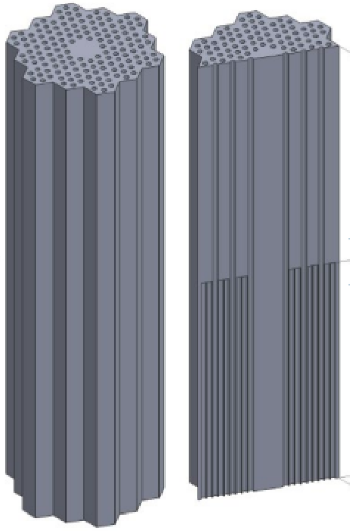



*Heat pipe design with a $ZrO_2$ thermal insulator*

[3]

*BeO reflectors (white) can reduce overall reactor mass*

[2]



*Example core structure geometry for a heat pipe reactor*

[4]

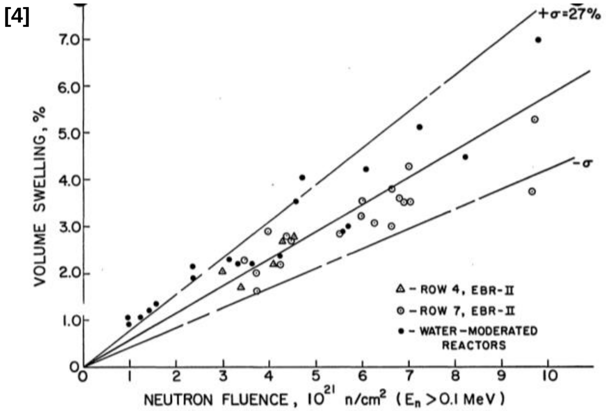



Fig. 10. VOLUME SWELLING OF LUCALOX $Al_2O_3$ vs NEUTRON FLUENCE, $E_n$ > 0.1 MeV

*Long irradiation exposures may induce swelling in core materials*

# Summary and Conclusions

*Reactor Materials Challenges to Enable Space Nuclear Propulsion*

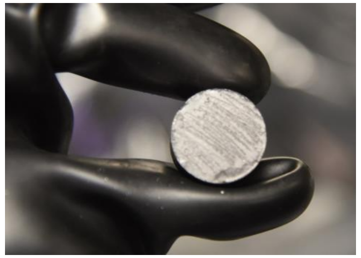
# Ongoing SNP Materials Development Activities

*SNP is actively investing in government led, risk reduction materials development activities*

- **Ongoing Ceramic and Composite Material Development Activities**
  - Cercer fuel forms: ZrC matrix, UN coated particle (primary)
  - Carbide fuel forms: solid solutions of UC (alternative)
  - Metallic hydride moderators
  - Ceramic matrix composites for fuel assembly and channel liner materials

- **Production and Manufacture Research Areas**
  - Fuel particle kernel and coating fabrication techniques
  - Optimization of sintering techniques via spark plasma sintering
  - Net-shape moderator element machining, fabrication, and assembly
  - High temperature material characterization techniques

- **Testing Research Areas**
  - Fundamental Material Studies: High temperature chemical compatibility and thermal stability testing
  - Separate Effects Testing: hot hydrogen testing in CFEET and NTREES, low fluence irradiation testing at MITR, transient irradiation testing at TREAT
  - Prototypic Reactor Irradiation for Multicomponent Examination (PRIME): Combined Hot Hydrogen – Transient of a representative reactor unit cell (fuel, moderator, insulator, structures) in TREAT
  - Advanced Modeling and Simulation: multi-scale materials performance, thermal-hydraulic, structural, and neutronic analysis of reactor and engine systems



23 mm diameter cercer sample fabricated using SPS: angular UN particles and ZrC matrix fabricated to 88% of theoretical density.

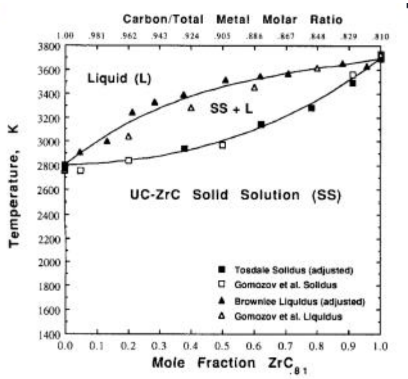


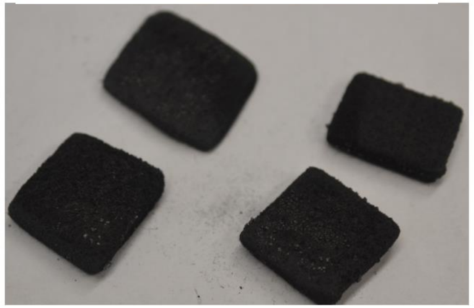

**Fig. 4.** The $UC–ZrC_{0.81}$ pseudobinary phase diagram showing solidus and liquidus temperature data for the $(U_xZr_{1-x})C_y$ solid solution.[16-18]

YH-Discs in Moly Can

YH-Discs undergoing thermal aging

$(U_{0.2}Zr_{0.8})C_{0.9}$

Carbon preform infiltrated with $ZrO_2$ sol gel (pre-formed annular jacket on inverted jar lid).



Porous ZrC from C felt preform.

# Conclusions

**Both NTP and NEP can enable significant performance benefits compared to traditional chemical engines and have the potential to reduce interplanetary trip times by a factor of a half.**

**Due to inherent differences in the function of the reactor, materials challenges for NTP and NEP systems differ.**

- NTP requires materials which can withstand extreme high temperature (> 2500 K), power density, hydrogen environments for short lifetimes (multiple short duration burns, for a total operating time of ~hours)
- NEP requires materials capable of continuous operation at high operating temperatures (> 1200 K) to high burnup (lifetime: ~years, continuous operation)

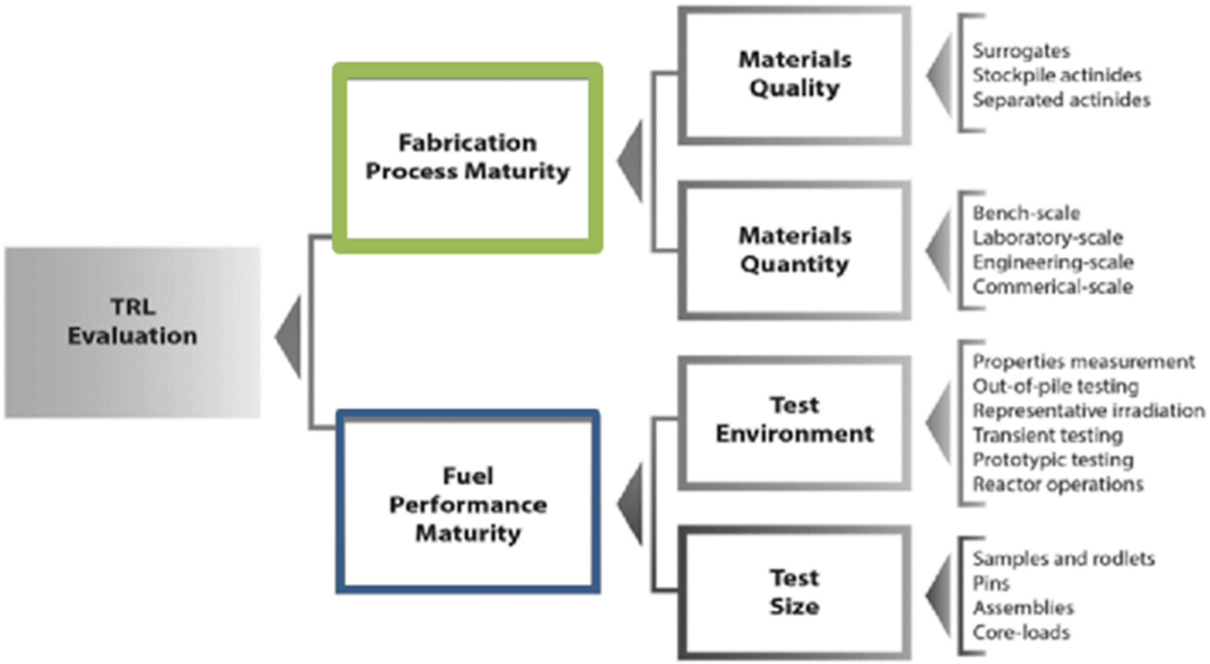
**Modern missions may require advancement in materials technologies, beyond which has been previously demonstrated.**

- Advancements in modern fabrication technologies, modeling and simulation techniques, and ongoing investment in advanced and microreactor technology development activities may benefit future space reactor development activities.
- Ceramic and composite material systems will play an important role in enabling space reactor technologies

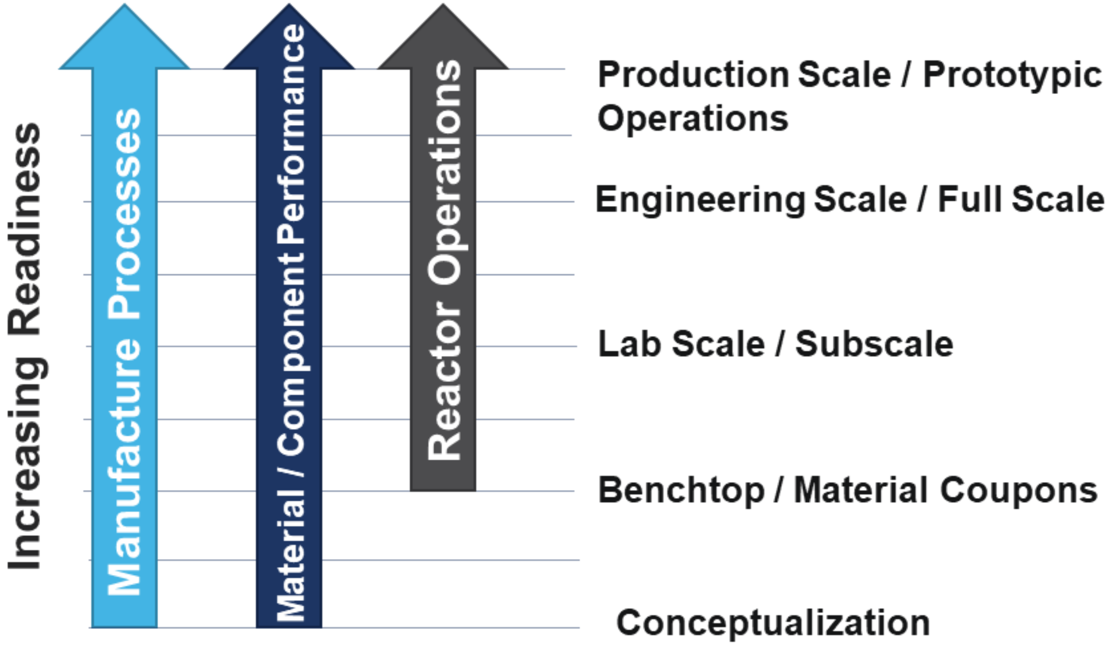
# Back Up Slides

# Readiness and Implementation Considerations for Reactor Systems

***Space reactor designs require components to be developed and demonstrated to prototypic geometries, scales, conditions, and operations***

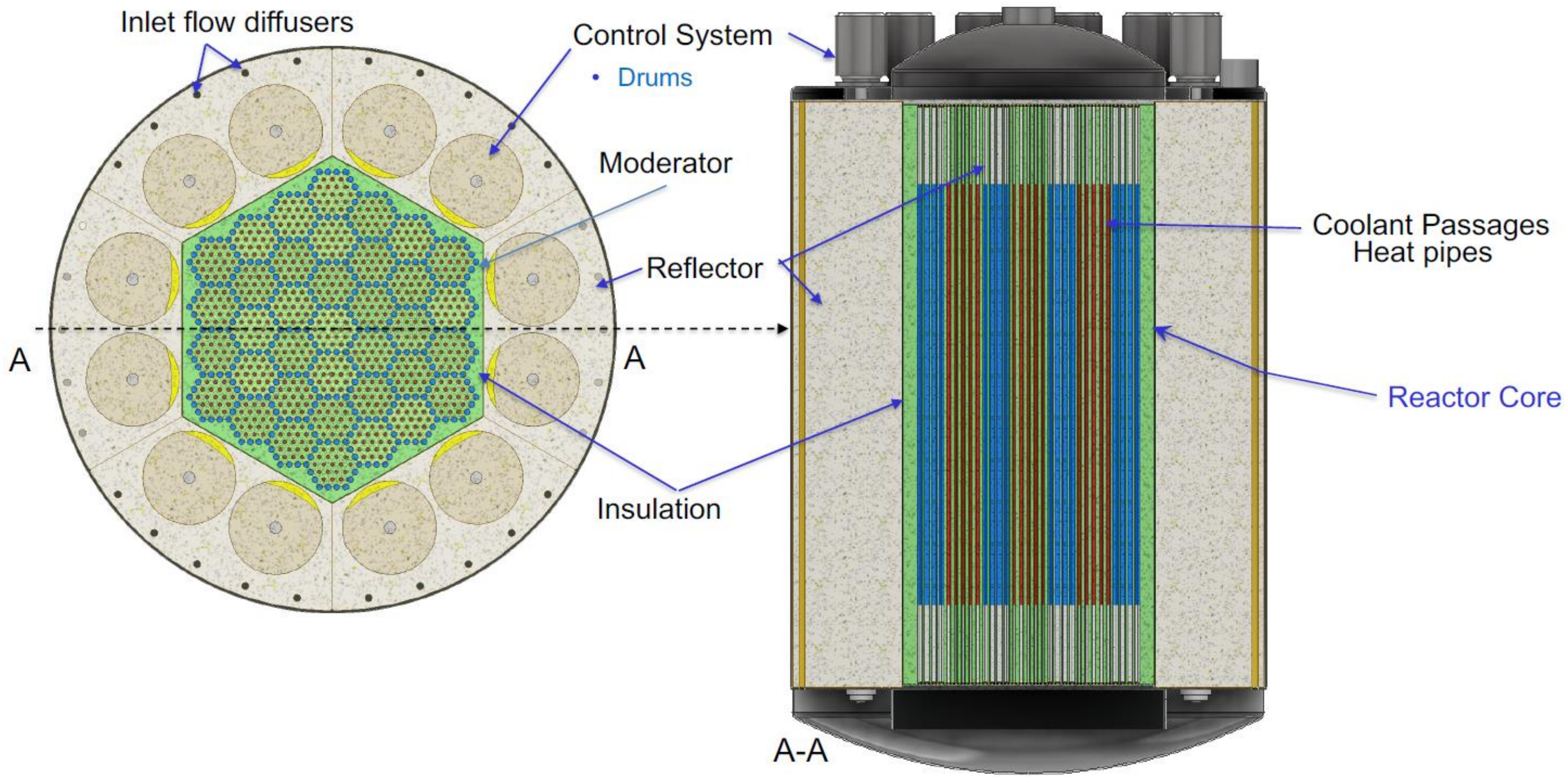



*Carmack, W. et. al. "Technology Readiness Levels for Advanced Nuclear Fuels and Materials Development" (INL/JOU-16-38690)*




*Palomares, K. "Moderator Considerations for Space Nuclear Power and Propulsion" in Proceedings of the Nuclear and Emerging Technologies for Space 2021 Conference*

# NEP Reactor Example Design for NASA SNP



# Summary of Historic U.S. NTP Development Efforts

*There has been significant U.S. effort in the development of NTP technologies*

### Historic U.S. NTP Programs

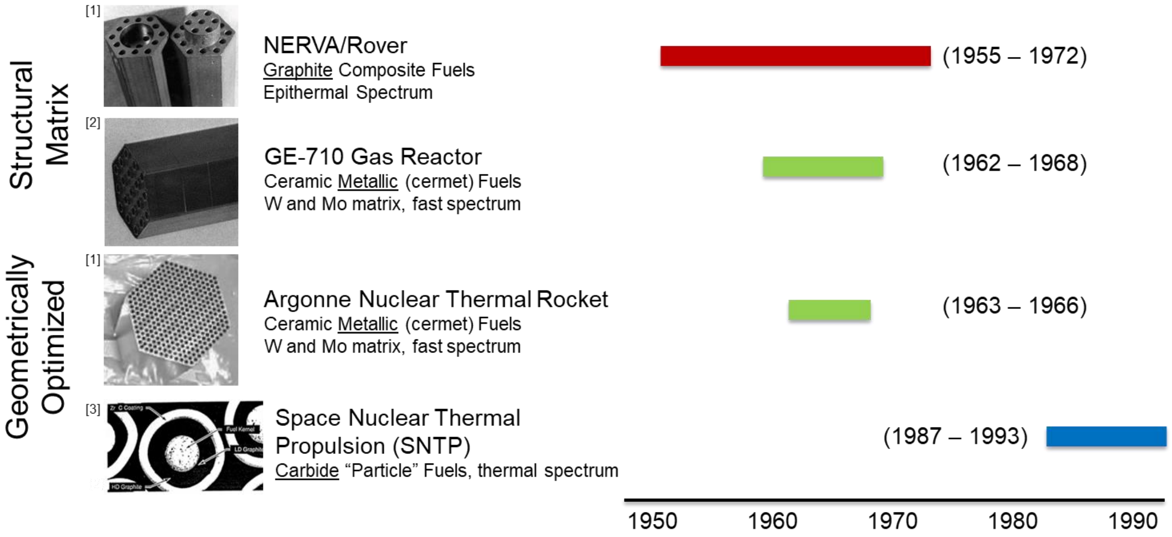
- Nuclear Engine for Rocket Vehicle Application (NERVA)/Rover Program (1955 – 1972)
- General Electric (GE) 710 Gas Reactor Program (1962 – 1968)
- Argonne Nuclear Rocket Program (1963-1966)
- Space Nuclear Thermal Propulsion Program (1987 – 1993)

### Goals of NTP reactor development varied for each program

- Fuel operating temperatures must exceed reactor exit temperature
- Combination of thrust and reactor mass impact power density of the reactor
- Reactor components must typically exhibit acceptable hydrogen compatibility for up to 10 hours
- Demonstrated performance under programs did not yet verify that goals could be achieved – technology gaps exist for each reference design.

### Use of primary use of ceramics and composites for NTP applications

- Fuel – all historic NTP fuel forms were either ceramics or composites
- Moderator – historic moderator designs have also typically been ceramic based (metallic hydrides)
- Insulating materials – NTP designs are extremely high temperature and require insulating materials to allow high temperature reactor materials to interface with lower temperature structural materials
- Structural materials –composite materials capable of high temperature strength, low neutron absorption, and hydrogen compatibility




| | $I_{SP}$ (s) | Reactor Exit Temperature (K) | Thrust (klbf) | Reactor Mass (kg) | Lifetime (hours) |
|---|---|---|---|---|---|
| NERVA / Rover | 825 | 2361 | 75,000 | 14,700* | 10 |
| GE-710 | 850 | 2475 | 30,000 | ~2,100 | 10 |
| ANL NTP | 832 | 2500 | 100,000 | 9,440 | 1 - 10 |
| SNTP | 930 | 3000 | 40,000 | 500 | 0.35 |

***Reactor and engine mass***


[1] Bhattacharyya, S. K. *An assessment of fuels for nuclear thermal propulsion*. Argonne National Laboratory Report No. ANL/TD/TM01-22 (2002)

[2] *710 High Temperature Gas Reactor Program Summary Report*. General Electric Company Report No. GEMP-600 Vol. 1 (1967)

[3] Haslett, R A. *Space nuclear thermal propulsion program. Final report.* Grumman Aerospace Corporation Report No. PL-TR-95-1064 (1995)

# Primary NTP Development Challenges

***Nuclear thermal propulsion can enable high specific and high thrust by using a reactor as a heat exchanger to directly heat rocket fuel (propellant)***

## Fuel

- NTP fuel forms are necessary to enable performance of the reactor
- Requires fuel design capable of ultrahigh operating temperatures (T > 2500 K), high power density, hydrogen compatibility, extreme thermal transient, thermal cycling
- Historically developed fuels: ***graphite matrix, cermet, carbide fuels***

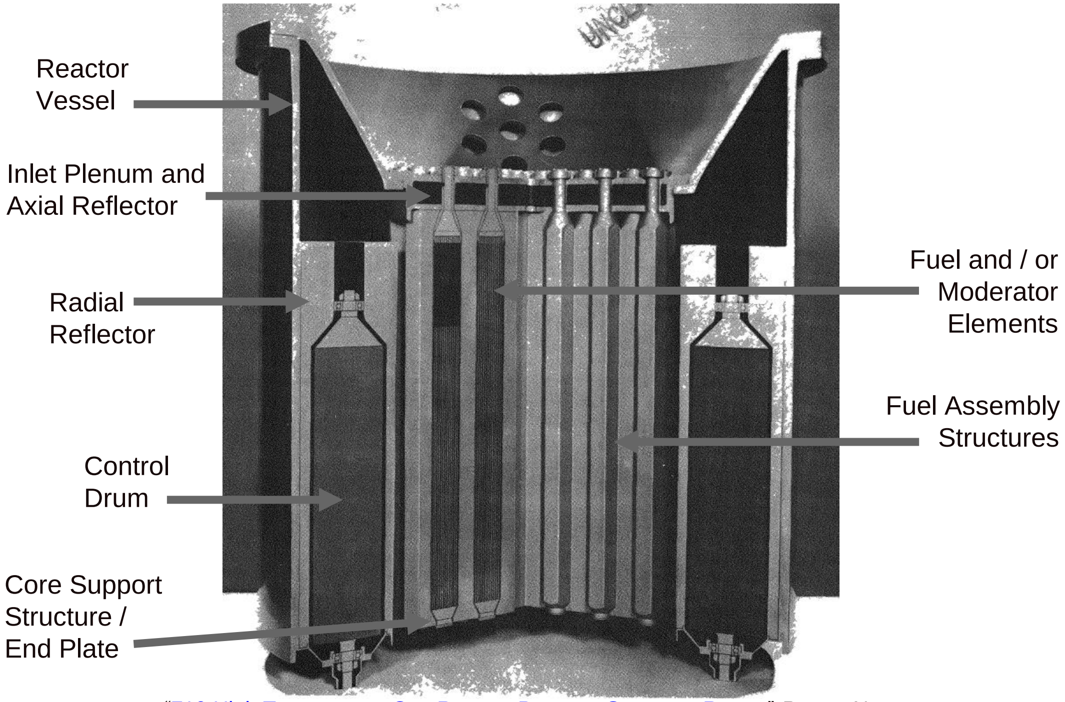
## Moderator

- Primary function is to minimize critical mass of the reactor
- Low operating temperatures, high thermal gradients, thermal cycling with alternating active cooling (high pressure, flowing hydrogen), idle mode of reactor decay heat
- Historically developed moderators: ***$ZrH_x$***, ***other metallic hydrides***, polyethylene

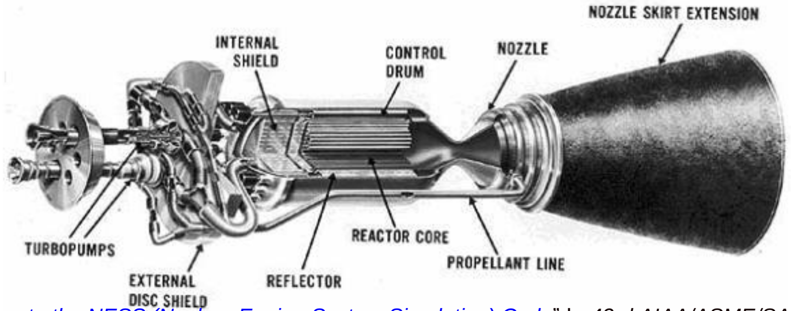
## Structural Materials

- Form and support overall NTP core, in-reactor structures to support or house fuel and moderator
- High thermal stresses, high temperature hydrogen exposure, avoid recrystallization and permanent plastic deformation
- Historic structural materials: Inconel, beryllium and ***beryllium oxide***, W and Mo alloys

## Other material needs: insulators and reflector / control materials, shielding materials (gamma and neutrons)




"710 High Temperature Gas Reactor Program Summary Report" *Report No. GEMP-600 Vol. 1 General Electric Company* (1967)




Fittje, J. E. "Upgrades to the NESS (Nuclear Engine System Simulation) Code" In *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit Proceedings* Cincinnati, OH. American Institute of Aeronautics and Astronautics

# Summary of Historic U.S. Nuclear Electric Propulsion Development Efforts

*There have been four major U.S. NEP development programs, each program differed based upon fuel type, spectrum, and power conversion technology*

## Historic Programs

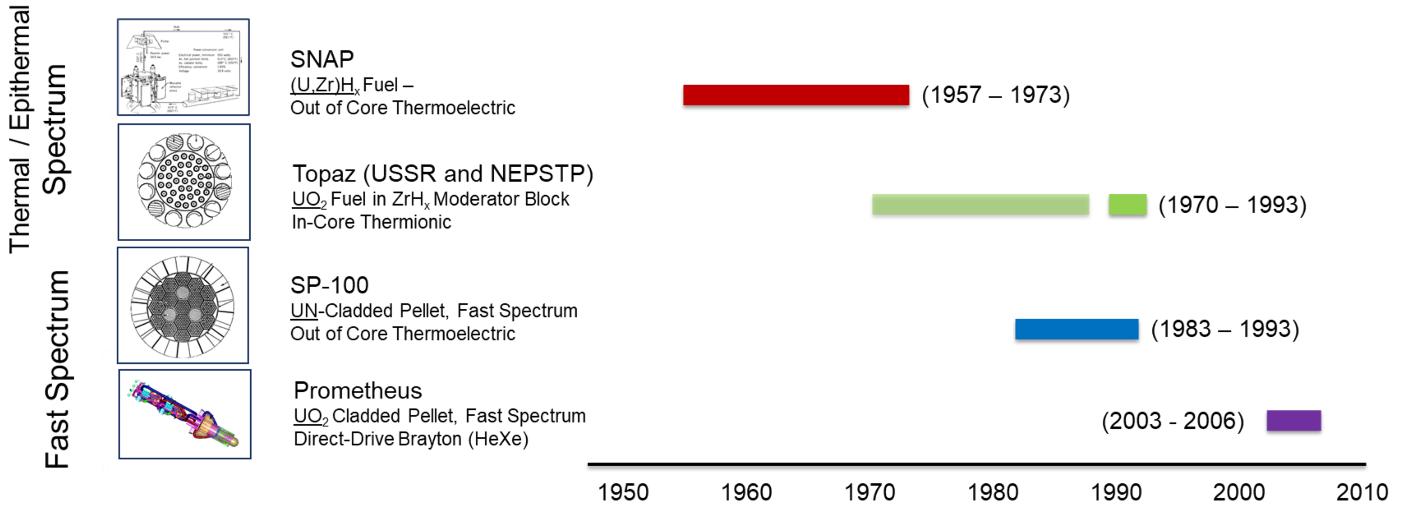
- Space Nuclear Auxiliary Power (SNAP) Program (1957 - 1973)
- TOPAZ Reactor Development Program (USSR: 1970 – 1989, NEPSTP: 1992, 93)
- Space Prototype (SP)-100 Development Program (1983 – 1993)
- Project Prometheus / JIMO Program (2003 – 2006)

## Goals of NEP reactor development varied for each program

- Fuel operating temperatures must exceed power conversion interface temperature.
- Reactor specific mass impacts reactor power density. Lifetime impacts overall reactor burnup
- Demonstrated performance under programs did not yet verify that goals could be achieved – technology gaps exist for each reference design.

## Use of primary use of ceramics and composites for NTP applications

- Fuel – all historic NEP fuel forms were ceramic based
- Moderator – historic moderator designs have also typically been ceramic based (metallic hydrides)
- Reflector materials– NEP designs typically operate out of core materials at higher operating temperatures then NEP. BeO and other ceramic reflectors may be necessary.
- Structural materials – composite materials capable of high temperature strength, low neutron absorption, and good creep strength




| | Power Conversion | Conversion Temperature (K) | Power Level (kWe) | Reactor Specific Mass (kg/kWe) | Lifetime (years) |
|---|---|---|---|---|---|
| SNAP | Thermoelectric | 772 | 0.5 | 908 | 1+ |
| TOPAZ | Thermionic | 843-73 | 5.5 | 192 | 3 |
| SP-100 | Thermoelectric | 1350-75 | 100 | 40 | 7 |
| Prometheus | Brayton | 1050 | 200 | 22.8 | 15 |

# Primary NEP Development Challenges

***Nuclear electric propulsion reactors provide high power levels for long periods of time to continuously power high efficiency thrusters***

**Fuel**

- NEP fuel forms must be capable of long duration operation and high operating temperatures without significant property degradation or dimensional instability
- Requires fuel design capable of high burnups while avoiding thermodynamic instability and undesirable swelling. Pellet fuels should avoid significant fission gas release or fuel-cladding interactions
- Historically developed fuels: ***$(U,Zr)H_x$, $UO_2$, UN***

**Moderator and Reflector**

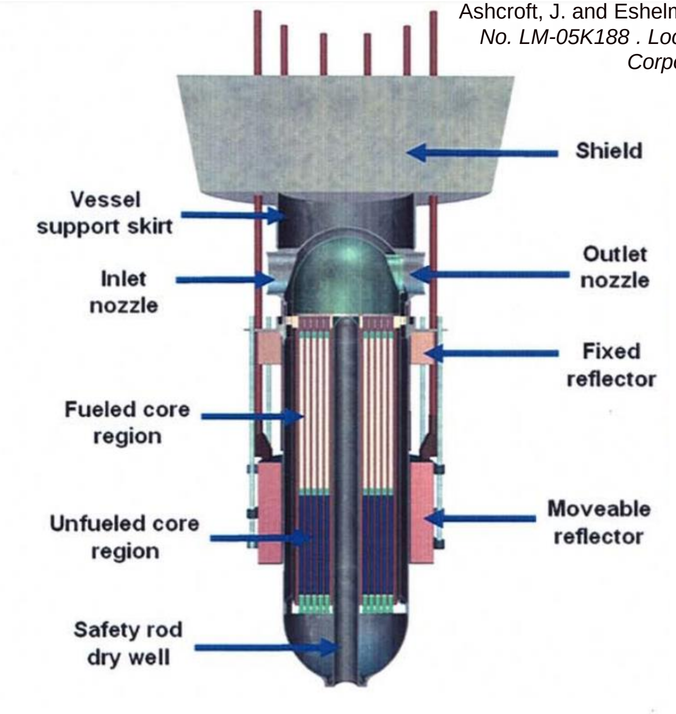
- Minimizes critical mass of the reactor and enables criticality over lifetime; not required for fast reactor systems
- High operating temperatures, long lifetimes, avoid swelling and compositional evolution
- Historically developed moderators: ***$(U,Zr)H_x$, $ZrH_x$ , BeO***

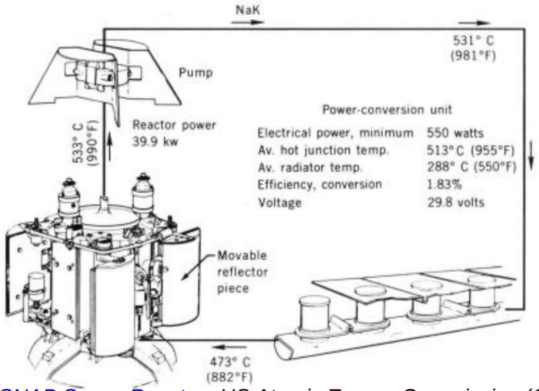
**Structural Materials**

- Form and support overall NEP core, fuel cladding materials, in-core support structures
- High temperature mechanical strength, avoid recrystallization, creep or radiation induced embrittlement / swelling
- Historic structural materials: stainless steels, superalloys, ***graphite***, refractory metals (cladding)

***Other material needs:* high temperature reflector / control materials, power conversion / heat transfer component materials, shielding materials**

Ashcroft, J. and Eshelman C. *Report No. LM-05K188 . Lockheed Martin Corporation* (2006)




Corliss, W. R. SNAP Space Reactors US Atomic Energy Commission (1966)

# Comparison of Fuel Forms Developed for Space Applications

## NTP Desired Attributes

Thermal Stability (Low Mass Loss)
High Melting Point (>3200 K)
High Fuel Density (U> 10 vol%)
Thermal Shock Resistance
Slow Degradation Mechanisms
Chemical Compatibility
Fabricability
High Fission Product Retention

## NEP / FSP Desired Attributes

High burnup
Low Fuel Swelling
Fuel / Clad / Fission Product Compatibility
Fuel Pin Integrity (Creep Resistance)
High Fuel Density (U > 10 vol%)
Benign Off-Nominal Behavior
Mature Fabrication Processes
High Fission Product Retention

| Characteristic | $(U,Zr)H_x$ | UMo* | $UC_2$ | UC | UN | $UO_2$ | (U,Zr)C |
|---|---|---|---|---|---|---|---|
| U Density ($g/cm^3$) | 2.75 | 16.4 | 10.6 | 13.0 | 13.5 | 9.66 | 2.88 |
| Melting Point (K) | 1023* | 1408 | 2710 | 2775 | 3035 | 3100 | 3350 |
| Thermal Conductivity (W/m·K) | 21.3 | 11.3 | 18 | 23 | 25 | 3.5 | 30 |
| Relative Stability | Low | Low | High | High | Low | Mid | High |
| Relative Swelling | Low | Mid - High | Low | Mid | Mid | Low | High |
| Fission Gas Release | - | High | Low | Mid | Low | High | Mid |
| Fabricability | Easy | Easy | Difficult | Easy | Moder-ate | Easy | Difficult |

* limiting dissociation temperature

More desirable than average candidate for this parameter
Average for candidates for this parameter
Less desirable than average candidate for this parameter

Adapted from: Matthews, B. et al. "Fuels for Space Nuclear Power and Propulsion: 1983 – 1993" in *A Critical Review of Space Power and Propulsion: 1984 - 1993*

**Many fuel options exist for space reactors, no one fuel provides all desired attributes**