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Assessment of Coated Particle Fuels for Space Nuclear Power and Propulsion Systems

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Agenda

1. Introduction and Background

2. Assessment Process and Results

- Fission Surface Power
- Nuclear Electric Propulsion
- Nuclear Thermal Propulsion

3. Summary and Conclusions

New fuel development activities are ongoing in advanced terrestrial reactor development programs

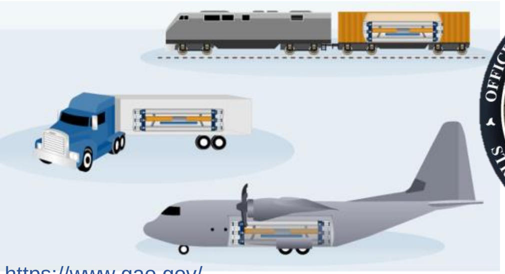
There has been significant government investment in advanced reactor development

- Department of Defense: Project Pele, mobile reactor development, DARPA DRACO
- Department of Energy: Advanced Reactor Demonstration Program, Advanced Gas Reactor Qualification Program

High Assay Low Enriched Uranium (HALEU) is being investigated as a pathway toward enabling new test reactor facilities and advanced reactor concepts

- New reactors are proposed to operate under more demanding operating conditions (higher temperatures, higher burnup, different neutron spectrums, novel working fluids) than our current LWR fleet and benefit from increased enrichment.

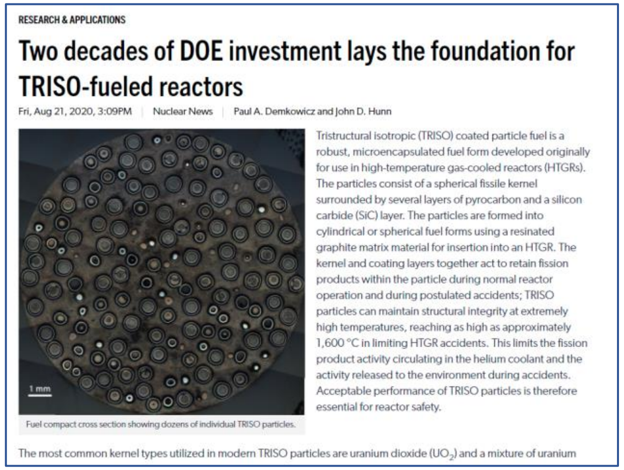
Coated particle fuel production capabilities are being heavily invested in by DoD, DoE, and NASA



https://www.gao.gov/

https://www.cto.mil/

https://www.energy.gov/ne/advanced-reactor-demonstration-program



RESEARCH & APPLICATIONS

Two decades of DOE investment lays the foundation for TRISO-fueled reactors

Fri, Aug 21, 2020, 3:09PM | Nuclear News | Paul A. Demkowicz and John D. Hunn

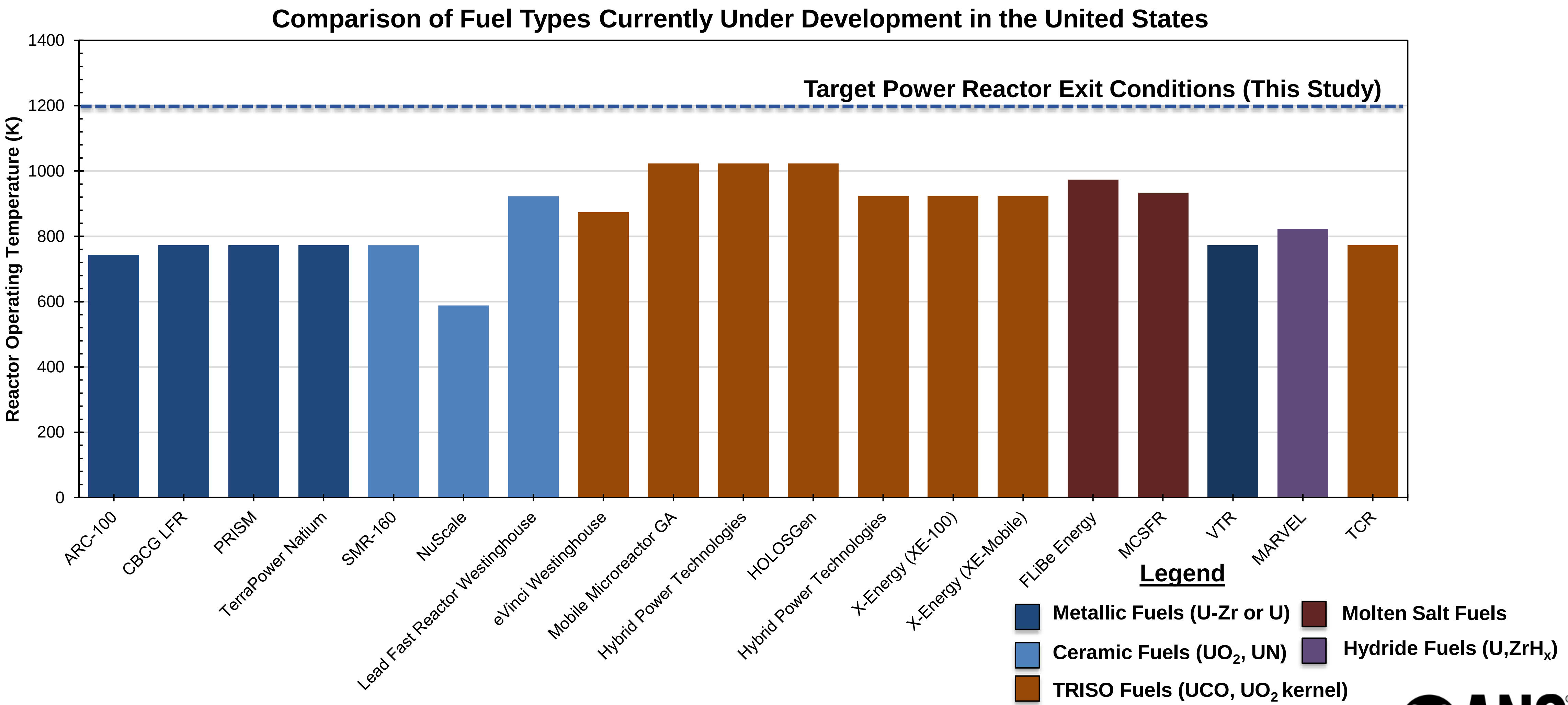
Fuel compact cross section showing dozens of individual TRISO particles.

Tristructural isotropic (TRISO) coated particle fuel is a robust, microencapsulated fuel form developed originally for use in high-temperature gas-cooled reactors (HTGRs). The particles consist of a spherical fissile kernel surrounded by several layers of pyrocarbon and a silicon carbide (SiC) layer. The particles are formed into cylindrical or spherical fuel forms using a resinated graphite matrix material for insertion into an HTGR. The kernel and coating layers together act to retain fission products within the particle during normal reactor operation and during postulated accidents; TRISO particles can maintain structural integrity at extremely high temperatures, reaching as high as approximately 1,600 °C in limiting HTGR accidents. This limits the fission product activity circulating in the helium coolant and the activity released to the environment during accidents. Acceptable performance of TRISO particles is therefore essential for reactor safety.

The most common kernel types utilized in modern TRISO particles are uranium dioxide (UO_2) and a mixture of uranium

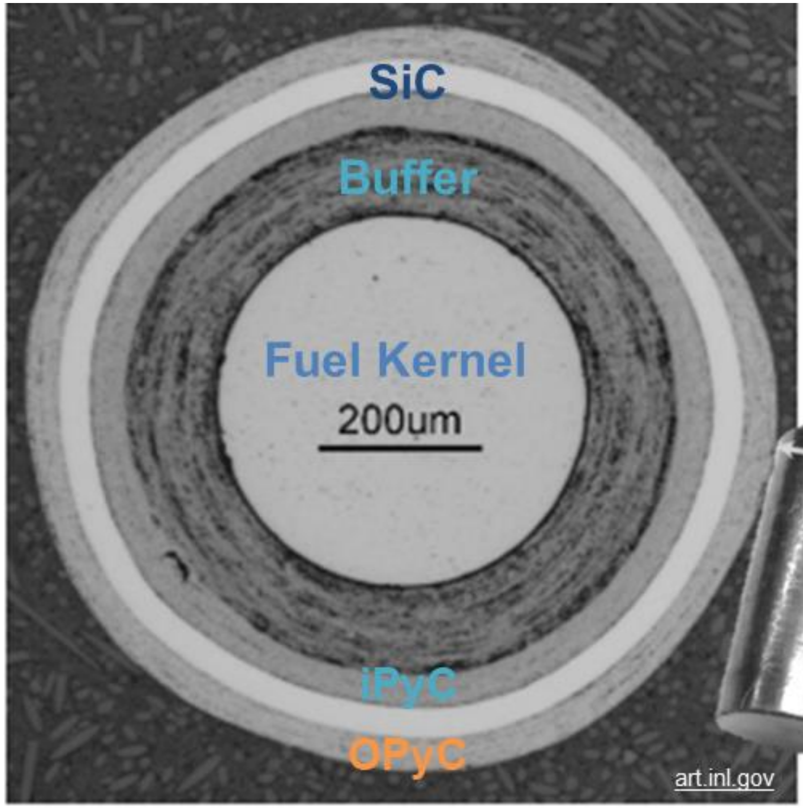
https://www.ans.org/

There are a variety of different fuel types under development which exhibit synergies with the required attributes for space reactors



Qualification testing for AGR has been completed after 23 years and $367M total investment

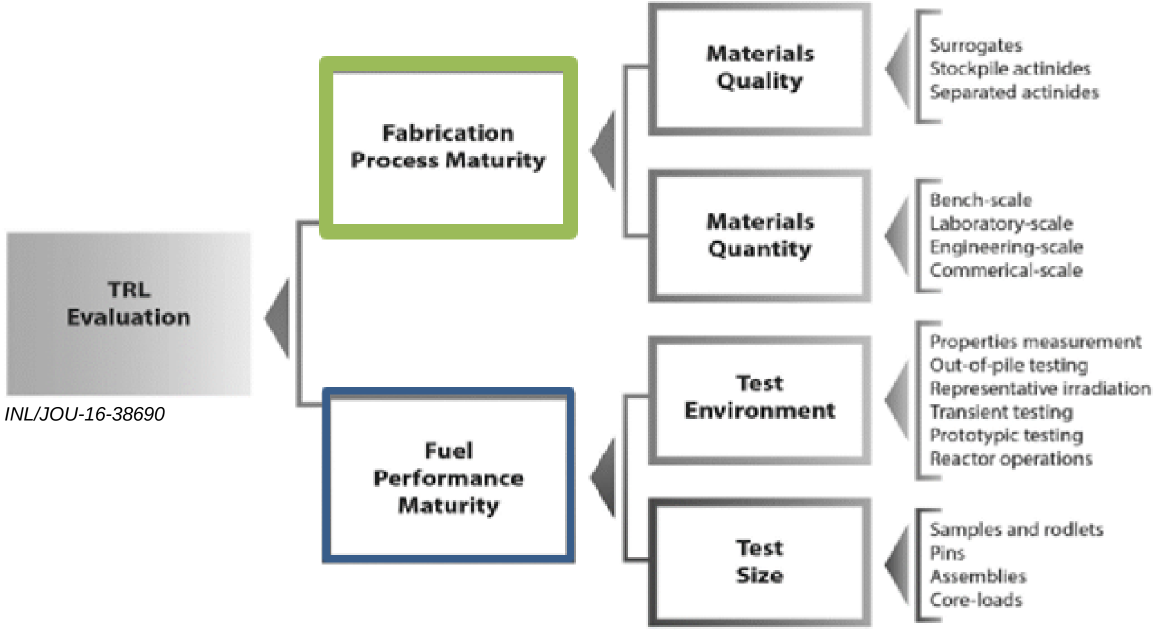
- The advanced gas reactor (AGR) program has been the primary fuel qualification program for modern U.S. TRISO fuels.
  - AGR: Qualification of a specific TRISO Fuel Particle Architecture for specific applications (temperature: 1250 °C, burnup: 20% FIMA).
  - Post irradiation examination of AGR-5/6/7 is ongoing (projected to end FY23).
- Demonstrating desired *reliability* (measured by fission product release fraction) is a key goal for the development of this fuel form in order to demonstrate that the fuel design serves as a fission product containment mechanism.
- Fuel qualification is anticipated to be a major element of the space reactor development program



Typical AGR TRISO Fuel Particle

"Technical Program Plan for INL Advanced Reactor Technologies Advanced Gas Reactor Fuel Development and Qualification Program" (INL/MIS-10-20662)

Guiding Considerations for Fuel Qualification Needs



INL/JOU-16-38690

Objectives of Fuel Qualification (NUREG-2246):

1. Demonstrate process to reliably *fabricate* a fuel product in accordance with a specification

2. Demonstrate *fuel performance* and ability to meet reliability needs or licensing safety-requirements through *analysis* and *testing*

Motivation

For NASA applications, it is desirable for fuel technologies to be sufficiently mature with an established fabrication infrastructure to reduce cost and schedule for fuel development

- Fuel qualification is expected to be a major element of each space reactor development program, which encompasses all fuel fabrication, testing, and analysis activities to mature a space reactor fuel form capable of meeting performance and mission requirements.
- There is no existing qualified fuel form for any of the space reactors currently of interest to NASA and existing infrastructure dedicated to space reactor fuel development is limited.
- Purpose of this study was to assess the readiness of terrestrial nuclear fuels for space applications, including identification of key technology development needs and related risk (technical, cost, schedule).

Assessment Process and Results

Assessment Scope and Process

Representative fuel forms based upon industry coated particle fuel technologies were assessed

- **Assessment Categories:**
  - **Performance:** projected operating range and existing database
  - **Technical Risk:** technology development gaps
  - **Programmatic:** cost and schedule
- **Comparative Assessment:** Historic fuel forms were compared to industry coated particle fuels
- **Systems Evaluated:**
  - Fission Surface Power (FSP)
  - Nuclear Electric Propulsion (NEP)
  - Nuclear Thermal Propulsion (NTP)

Application	Reactor Power	Reactor Outlet Temperature	Reactor Coolant	Lifetime	Mass / Volume
FSP	50 kWt	1200 K	Na Heat Pipes	10 yrs	minimize
NEP	10 MWt	1200 K	Li or HeXe	5 yrs	minimize
NTP	500 MWt	2700 K	LH_2	10 hrs	minimize

Application	Historic Fuel Derivative (Reference)	Coated Particle Fuel Derivative
FSP	**UO_2 Pellet** (2010 FSP Project)	**AGR TRISO in Graphite** UCO kernel with PyC-SiC coatings
NEP	**UN Pellet** (SP-100)	**Modified TRISO in Graphite** UN kernel with PyC-SiC coatings
NTP	**UC_2-Graphite Matrix** (NERVA / Rover)	**Cercer with Modified Coated Particle** ZrC or C matrix with dispersed UN kernels with PyC-ZrC coatings

Fuel Performance Parameter Matrix

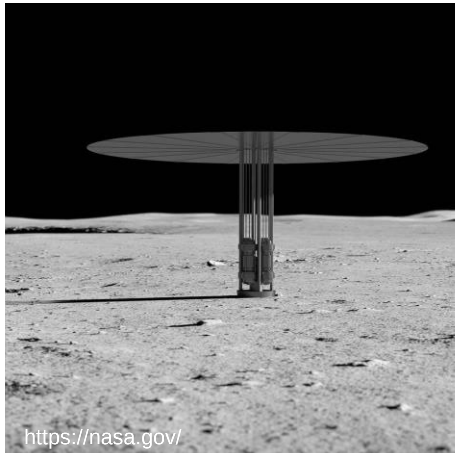
Comparing fuel performance parameter goals for reference missions to pre-existing databases exposes knowledge gaps that will require further development

Application	Power Density	Peak Fuel Operating Temperature	Heat Transfer	Lifetime (Fluence)
FSP	>100 W/cm^3 (~0.1 MW/L)	1400+ K	Na Heat Pipes (Mo)	10 yrs (5 x 10^{25} n/m^2)
NEP	>100 W/cm^3 (~0.1 MW/L)	1400+ K	Li or HeXe	5 yrs (2.5 x10^{25} n/m^2)
NTP	>5,000 W/cm^3 (5 MW/L)	2850+ K	LH_2	10 hrs (3.6 x10^{23} n/m^2)

Fission Surface Power Assessment - Overview

- FSP systems require a kilowatt class, low mass reactor (including shield) capable of operation up to 10 years

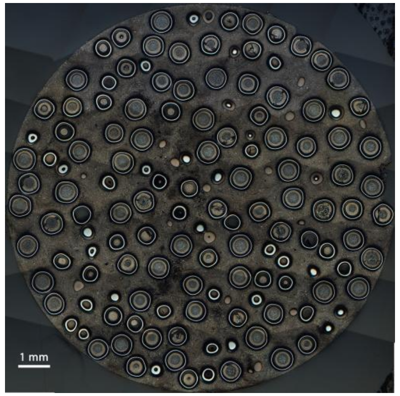
Application	Reactor Power	Reactor Outlet Temperature	Reactor Coolant	Lifetime	Mass / Volume
FSP	50 kWt	1200 K	Na Heat Pipes	10 yrs	minimize



- **Desirable fuel attributes**
  - High readiness
  - High uranium density
  - High operating temperature capability
  - Irradiation tolerance (low fission gas release and swelling)

https://world-nuclear-news.org/Articles/TVEL-to-supply-fuel-pellets-for-Tarapur

UO_2 Pellet



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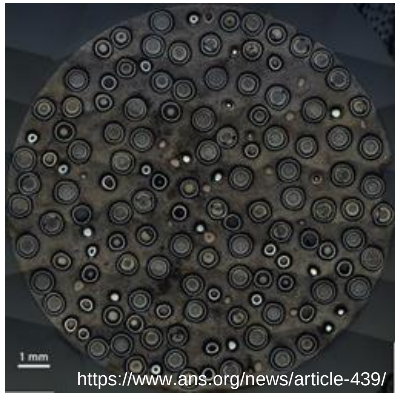
AGR TRISO

Fission Surface Power Fuel Assessment

UO_2 Pellet



AGR TRISO

	UO_2 Pellet	AGR TRISO in Graphite UCO kernel with PyC-SiC coatings
Performance	Fast and thermal reactors possible with HALEU. Moderated-UO_2 reactors would yield the lowest mass.	Epithermal and thermal reactors possible with HALEU. Moderated TRISO reactors would yield the lowest mass.
Existing Performance Database	Fully established separate effects testing data (irradiation, high temperature studies), combined effects and reactor demonstration testing needed.	AGR irradiation database exists for relevant temperature range and burnups (gaps exist for representative power densities), combined effects and reactor demonstration testing needed.
Technology Gap Assessment	4 Technology Gaps Identified	6 Technology Gaps Identified
Cost	**Low** Limited investment may be needed for facilities modification on the order of $25M or less throughout the length of the program.	**Low** Limited investment may be needed for facilities modification on the order of $25M or less throughout the length of the program.
Schedule	**Low** There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029.	**Moderate** There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.

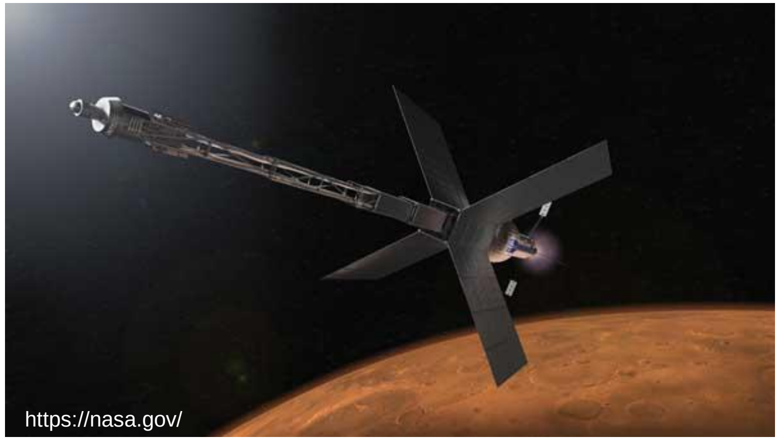
Fission Surface Power Assessment - Key Findings and Takeaways

- **Due to higher uranium loadings, reactors will be smaller (lower volume and mass) with UO_2 or UN pellet fuels compared to TRISO fueled reactors.**
  - Shielding (volume and mass) will scale proportionally with reactor volume
  - Technology development would be focused on cladding, moderator, and heat pipe development to meet reference system parameters
  - If peak operating temperature requirement is reduced (< 900 K): UO_2 cores could be developed faster (infrastructure, performance database, and fabrication methods exist).
  - If the temperature cannot be reduced, the TRISO reactor design may be a better option
- **Key Reactor Technology Development Challenge: Moderator**
  - Moderator dimensional and compositional instability negatively impacts reactivity worth, power profile, and structural integrity of the core
  - High temperature moderators will require technology development to establish net shape fabrication processes or extend the existing performance database
- **Ten-year lifetime requires a combined system ground test to obtain a complete performance database.**
  - For demonstration missions: demonstrate integrated fuel, moderator, heat pipe integrity under reactor operations
  - For qualification: reliability, instrumentation, system interfaces need to be demonstrated

Nuclear Electric Propulsion Assessment - Overview

- NEP systems require a megawatt class, low mass reactor capable of operation up to 5 years

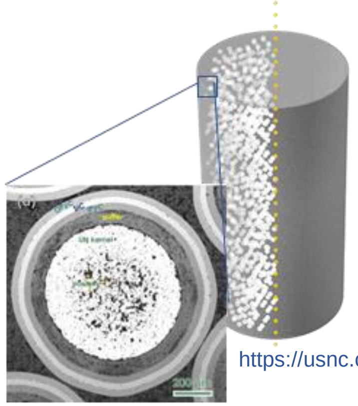
Application	Reactor Power	Reactor Outlet Temperature	Reactor Coolant	Lifetime	Mass / Volume
NEP	10 MWt	1200 K	Li or HeXe	5 yrs	minimize



- **Desirable fuel attributes**
  - High uranium density
  - High thermal conductivity
  - High operating temperature capability
  - Irradiation tolerance (low fission gas release and swelling)
  - Chemical compatibility with cladding and working fluid

L. Mason "Nuclear Electric Propulsion" Presentation to the National Academy of Science Engineering and Medicine, 2020.

UN Pellet



https://usnc.com/

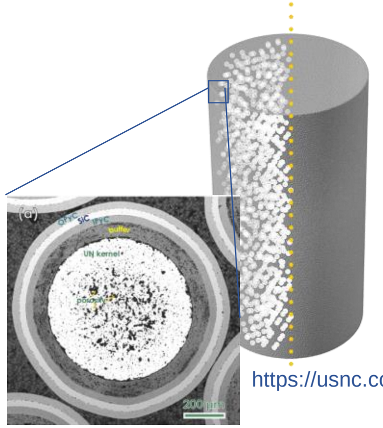
https://doi.org/10.1016/j.jnucmat.2020.152034

modified TRISO

Nuclear Electric Propulsion Fuel Assessment

L. Mason "Nuclear Electric Propulsion" Presentation to the National Academy of Science Engineering and Medicine, 2020.

UN Pellet



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https://doi.org/10.1016/j.jnucmat.2020.152034

modified TRISO

	UN Pellet	**Modified TRISO in Graphite** UN kernel with PyC-SiC coatings
Performance	Fast and thermal reactors possible with HALEU. Moderated-UN reactors would yield the lowest mass.	Epithermal and thermal reactors possible with HALEU. Moderated TRISO reactors would yield the lowest mass.
Existing Performance Database	Fully established separate effects testing data (irradiation, high temperature studies), combined effects and reactor demonstration testing needed.	Limited test data exists (particle irradiation experiments), combined effects and reactor demonstration testing needed.
Technology Gap Assessment	7 Technology Gaps Identified	8 Technology Gaps Identified
Cost	**Moderate** Some new facility infrastructure investment may be needed but is not anticipated to exceed $100M throughout the length of the program.	**Moderate** Some new facility infrastructure investment may be needed but is not anticipated to exceed $100M throughout the length of the program.
Schedule	**Moderate** There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.	**Moderate** There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.

Nuclear Electric Propulsion Assessment - Key Findings and Takeaways

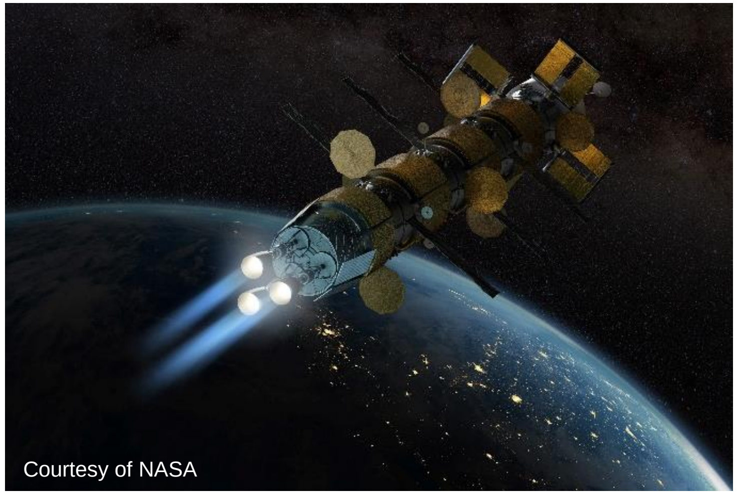
- **For NEP systems, we believe alpha to be the primary driver and thus minimizing reactor mass / volume is of high interest.**
  - UN pellets best fuels candidate to meet this need. Development of refractory cladding would be required
  - Moderator development (high temperature) will likely drive schedule
  - Modified TRISO fuels offer good high temperature, high burnup characteristics. However, there no heritage from historic fuel form development and has a limited terrestrial fuel performance database (not qualified under AGR)
    - Technology development would be required to establish fuel fabrication processes and performance database
- **Key reactor technology development challenges**
  - Moderator
  - Structural Materials (cladding)
  - System Ground Test
- **Extensibility: UN is more extensible than both UO_2 and TRISO fuel forms assessed for FSP.**
  - UN was assessed to allow for the most compact reactor design and is capable of high operating temperatures.
  - A common fuel form between FSP and NEP would enable a common fuel production line to be leveraged for both applications.
  - A common fuel form would reduce the design and testing needed to mature and qualify flight hardware which could reduce overall cost and schedule for the development of both systems.

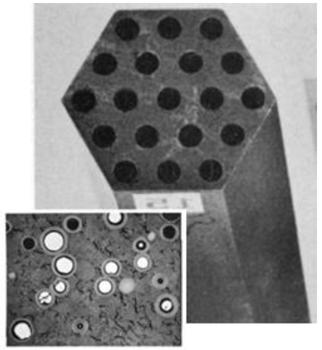
Nuclear Thermal Propulsion Assessment - Overview

- NTP systems require a very high temperature, hydrogen compatible reactor capable of operation for multiple short burns

Application	Reactor Power	Reactor Outlet Temperature	Reactor Coolant	Lifetime	Mass / Volume
NTP	500 MWt	2700 K	LH_2	10 hrs	minimize

- **Desirable fuel attributes**
  - High melting temperature / high temperature stability
  - Hydrogen compatibility
  - High uranium density
  - Thermal shock / cycling resistance
  - Slow degradation mechanisms


Courtesy of NASA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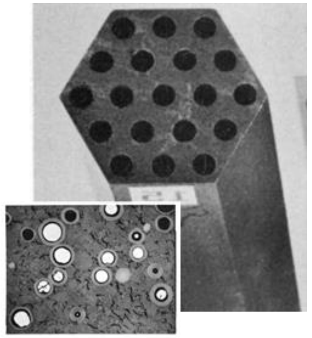
NERVA (Graphite) Derivative (UC_2 BISO)


https://orcid.org/0000-0001-7017-2666

Cercer (ZrC) with modified TRISO

Nuclear Thermal Propulsion Fuel Assessment



https://doi.org/10.2172/4154952

NERVA (UC_2) Derivative

https://orcid.org/0000-0001-7017-2666

Cercer (ZrC) with modified TRISO

	Rover / NERVA Graphite Matrix (Graphite matrix with dispersed UC_2 kernels with PyC-coating)	**Cercer with Modified Coated Particle** (ZrC matrix with dispersed UN kernels with PyC-ZrC coating)
Performance	Operation above 2700 K requires molten kernel operation, lifetime extension to 10 hours possible with protective channel coating technology development.	Operating temperatures up to 3100 K proposed (theoretical melting point of UN). Unknown failure modes, lifetime limiting phenomena not known.
Existing Performance Database	Fully established separate effects testing data up to 2500 K (irradiation, high temperature studies), high temperature combined effects and reactor demonstration testing needed.	Limited test data exists (some fuel and surrogate testing), combined effects and reactor demonstration testing needed.
Technology Gap Assessment	9 Technology Gaps Identified	11 Technology Gaps Identified
Cost	**High** Significant investment in facility infrastructure investment may be needed and is likely to exceed $100M throughout the length of the program.	**High** Significant investment in facility infrastructure investment may be needed and is likely to exceed $100M throughout the length of the program.
Schedule	**Moderate** There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.	**Moderate** There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.

Nuclear Thermal Propulsion Assessment - Key Findings and Takeaways

- **I_{sp} is the primary KPP driving the need for technology development. Modern NTP programs will require higher performance fuels than historic programs.**
  - Current desired performance parameters (2700 K exit temperature, 10 hour lifetime, 5+ MW/L power density) will require fuel forms to exceed historic operating conditions
  - Longer lifetime, higher temperature fuel performance is needed. A significant development effort is still necessary regardless of fuel form selection

- **UC_2 Derivative Fuels**
  - Advantage: ability to leverage historic design and performance databases
  - Disadvantage: fuel melting point must be exceeded to meet KPPs (beyond demonstrated failure limits)
  - Technology development is required for this fuel form to demonstrate performance capability

- **Cercer (ZrC matrix) with Modified Coated Particle Fuels**
  - Advantage: fuel form design leverages high melting temperature and hydrogen compatible materials to provide a path to higher temperatures and longer lifetimes
  - Disadvantage: no historic comparison or direct commercial development analog, fuel failure modes are unknown
  - Technology development is required for this fuel form to demonstrate performance capability

Summary and Conclusions

Summary

	FSP		NEP		NTP	
	UO_2 Pellet	AGR TRISO in Graphite	UN Pellet	Modified TRISO in Graphite	Rover / NERVA Graphite Matrix	Cercer with Modified Coated Particle
Performance	Fast and thermal reactors possible with HALEU	Moderated TRISO reactors may yield competitive mass	Fast and thermal reactors possible with HALEU	Epithermal and thermal reactors possible with HALEU	Operation above 2700 K requires molten kernel operation	Operating temperatures up to 3100 K proposed (UN theoretical T_M)
Existing Performance Database	Fully established separate effects testing data	AGR irradiation database exists for relevant temperature range and burnups	Fully established separate effects testing data	Limited test data exists (particle irradiation experiments)	Fully established separate effects testing data up to 2500 K	Limited test data exists (some fuel and surrogate testing)
Technology Gap Assessment	**4**	**6**	**7**	**8**	**9**	**11**
Cost	**Low**	**Low**	**Moderate**	**Moderate**	**High**	**High**
Schedule	**Low**	**Moderate**	**Moderate**	**Moderate**	**Moderate**	**Moderate**

Conclusions

- Space reactors can leverage terrestrial fuel technologies. Ongoing advanced reactor development activities are maturing fuel forms capable of higher operating temperatures and burnups in the range desired for space reactor applications.
- Meeting high performance KPPs will require deviation from established fuel types which will introduce new technical risks and require technology development.
- New testing infrastructure is needed to prove out reactor operations / reliability
  - Reliability requirements will drive overall testing program
  - Power reactors require facilities dedicated for long lifetime testing
  - NTP reactors require unique facilities capable of handling the H_2 propellant and unique reactor (engine) operations

Back Up Slides

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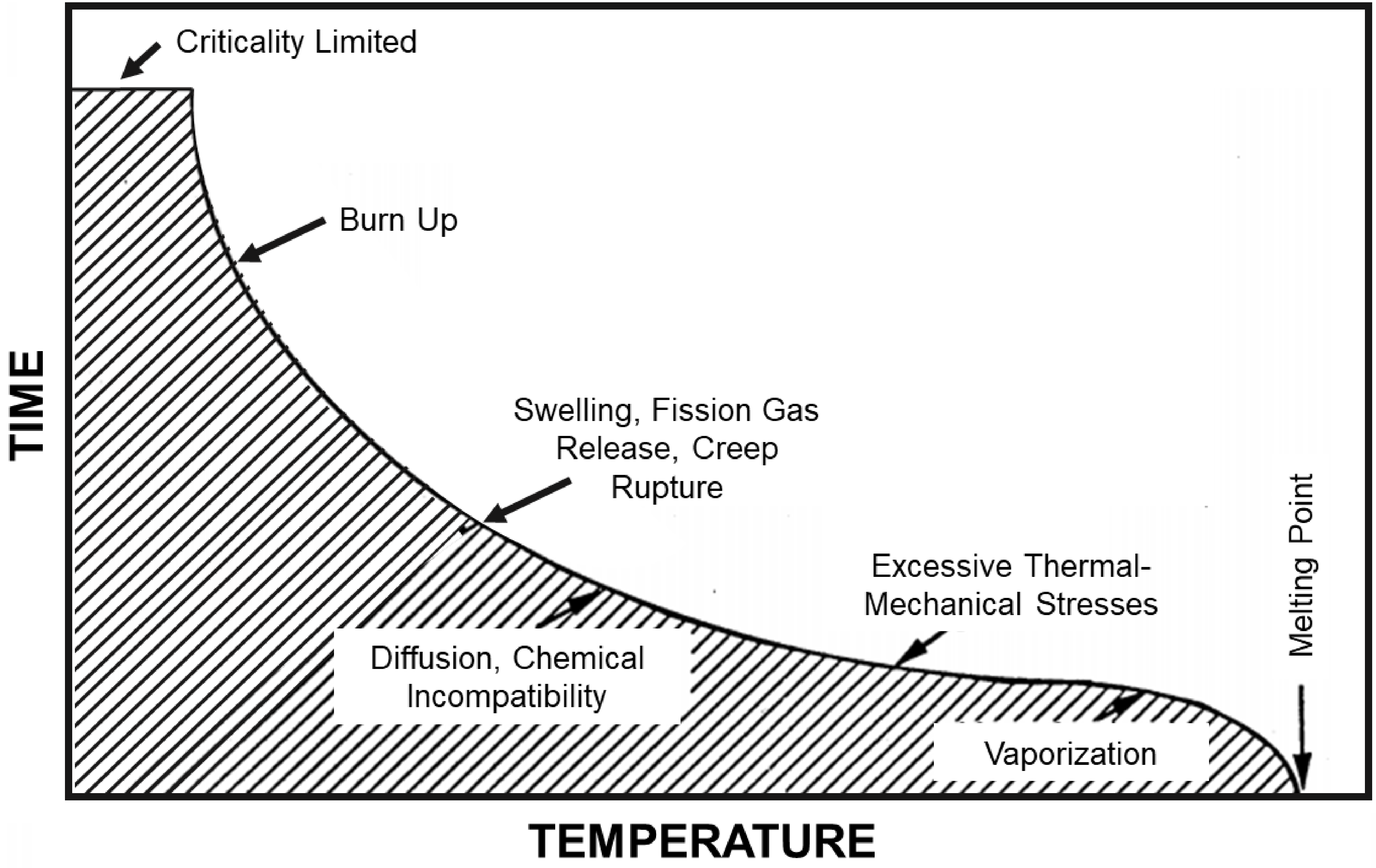
High Temperature and Irradiation Considerations for Space Reactors

In-reactor materials for space reactors can fail through a variety of mechanisms which are time and temperature dependent

Adapted from: Bhattacharyya "An Assessment of Fuels for Nuclear Thermal Propulsion" 2001 (ANL/TD/TM01-22).



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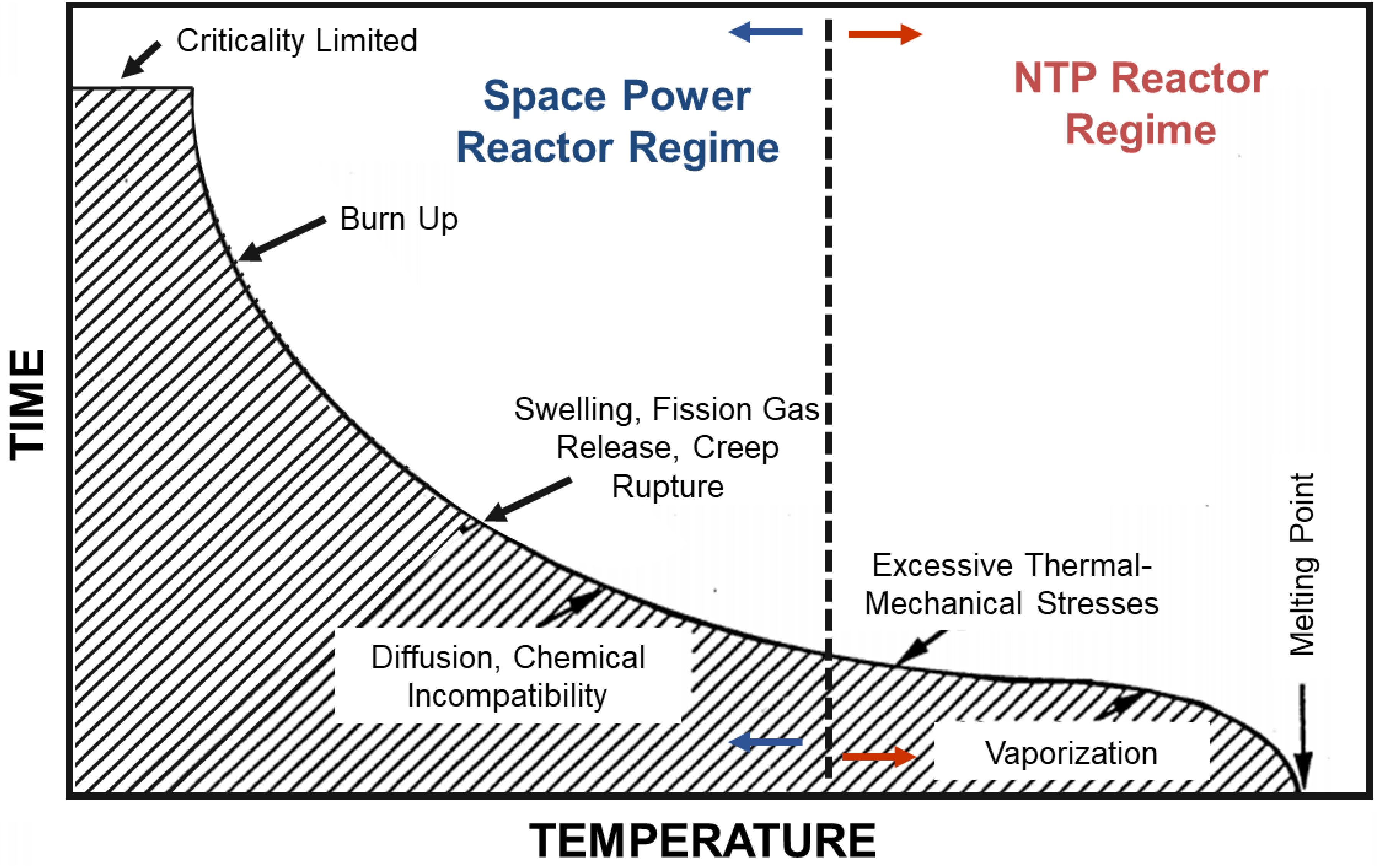
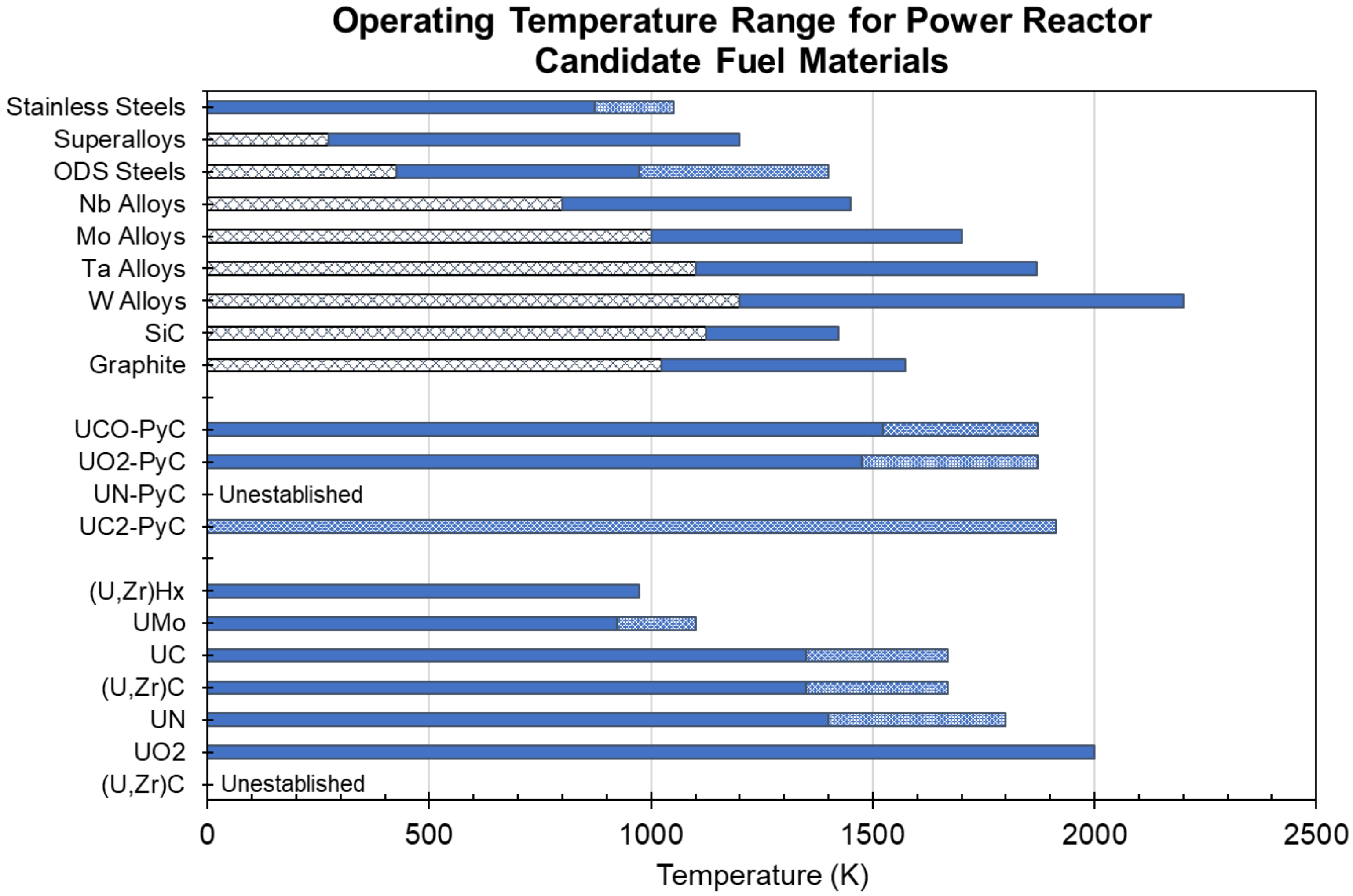


Power Reactor Material Operating Breakpoints and Lifetime Considerations

Creep rupture and corrosion resistance controls maximum structural material operating temperature, low temperature use of components must be limited to above the irradiation embrittlement regime*

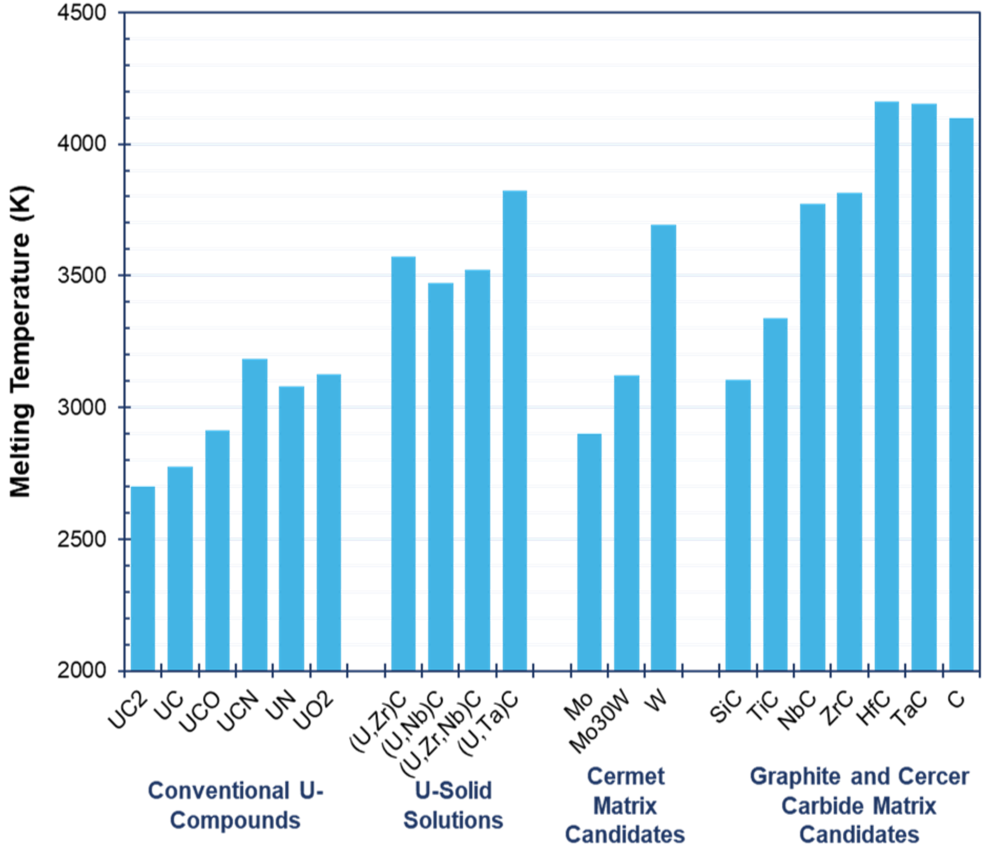


*fuel materials / elements are limited by allowable fuel swelling, fission gas release, and chemical / thermal interactions with surrounding structural materials

NTP Material Operating Breakpoints and Lifetime Considerations

Melting point limits maximum NTP fuel operating temperature (solid core NTP), high temperature stability / hot hydrogen corrosion resistance impacts fuel lifetime at temperature (fuel endurance)

Melting temperature of NTP fuel material candidates



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Predicted endurance of NTP fuels based on historical test data