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TRISO Fuel

Considerations for Unconventional Fuel Designs

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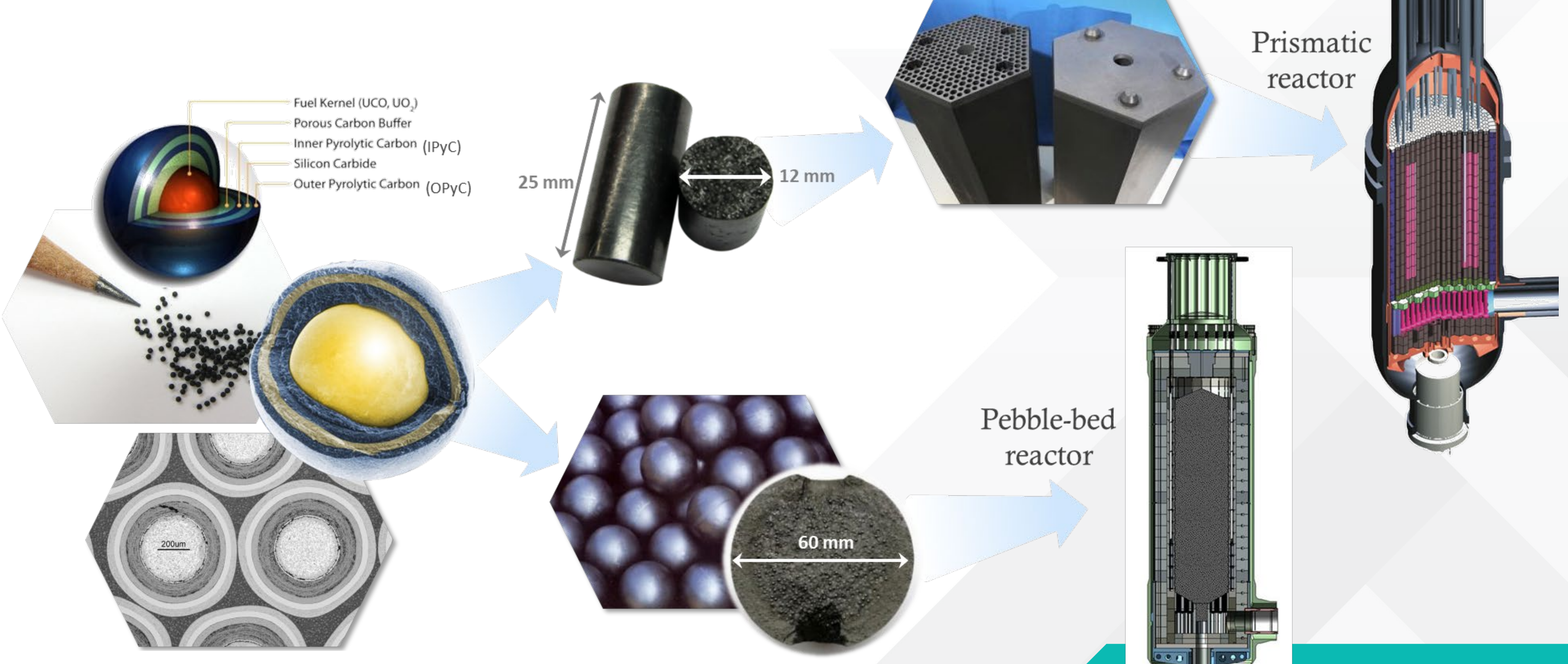
Tristructual Isotropic (TRISO) Coated Particle Fuel



Micro-scale confinement of radioactive fission products within the fuel particle

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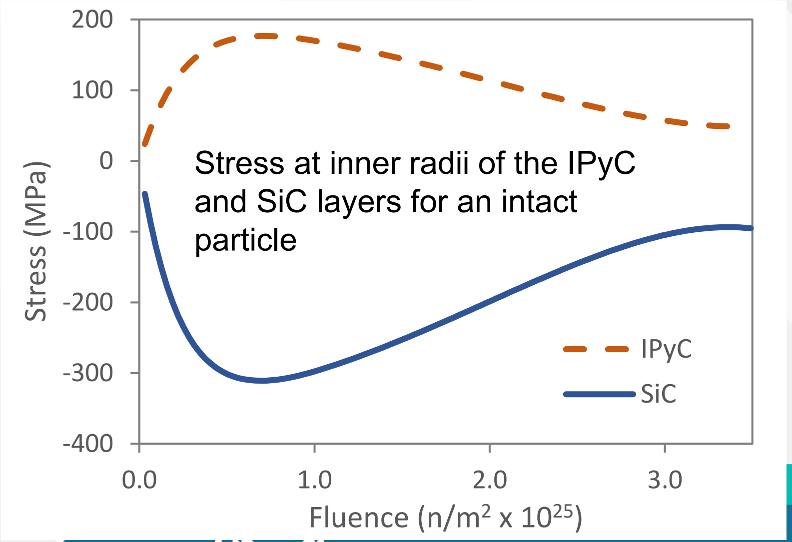
TRISO Fuel Quality and Performance

- Main goal: Retain fission products in fuel
  - Limit coating layer failure
  - Minimize radionuclide transport through intact coatings
- Coatings are engineered to contain fission gas pressure and limit SiC fracture
- PyC and SiC layers allow negligible transport of nearly all fission products
- High fuel quality equates to very low initial particle defect fractions ($10^{-5} – 10^{-4}$)
- Fuel matrix and core graphite also significantly attenuate radionuclide transport

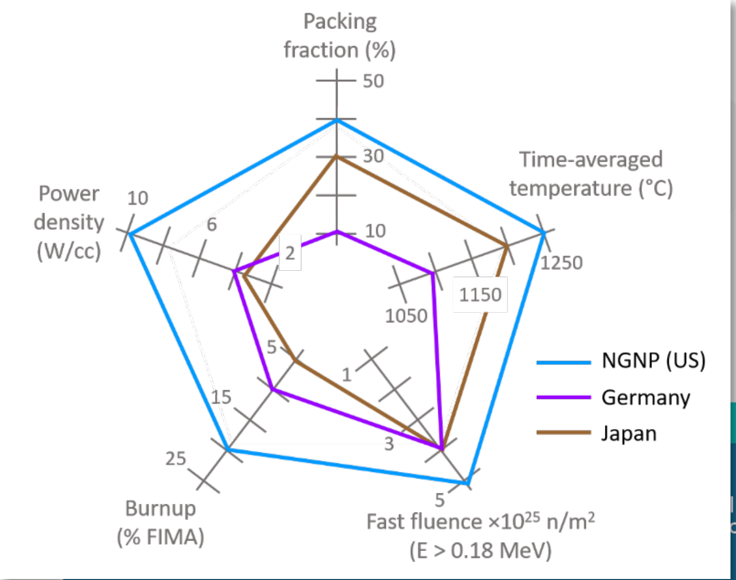
1. Gas pressure is transmitted through IPyC
2. IPyC shrinks, pulling away from the SiC
3. OPyC shrinks, pushing on the SiC



TRISO Fuel Performance

- Particle failure mechanisms
  - Thermomechanical
    - Pressure vessel failure
    - Failure of IPyC layer from stresses during irradiation
  - Thermochemical
    - Corrosion of SiC layer by fission products (e.g., Pd) or CO(g)
- Failure rates can be increased in abnormal particles
  - Asphericity/faceting
  - Metallic or carbon inclusions in coating layers
  - Missing coating layers
  - Etc.

- Failure frequency reduced by:
  - Improved particle design and quality
    - Changing kernel composition to minimize CO(g) generation (e.g., UCO)
    - Improving properties and property distributions
    - Lowering defect fractions
  - Limiting operating conditions within acceptable envelope
    - Key parameters determining fuel performance are **time** (impacts neutron fluence, burnup) and **temperature**

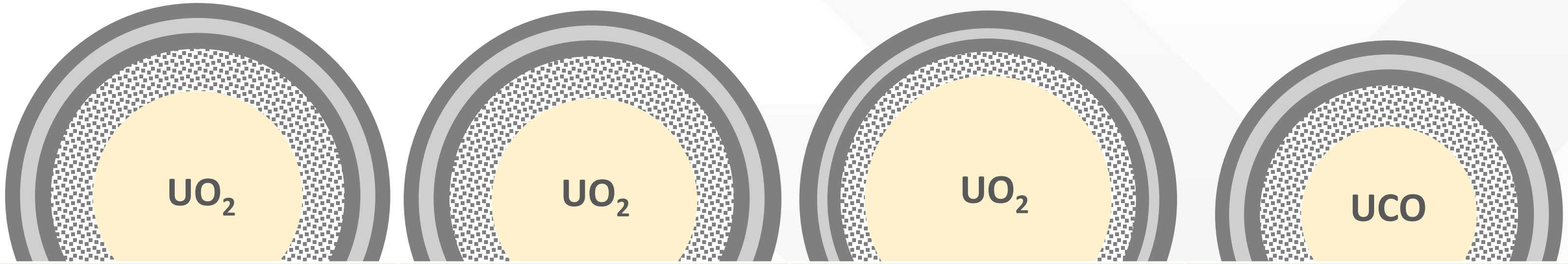


Fuel Operating Conditions

Parameter	Fuel Performance Impacts
Temperature distribution	• Fission product release behavior • Fission product corrosion • Coating thermomechanical behavior (e.g., thermal creep)[1]
Burnup	• Fission product generation (impacts gas pressure in particle) • CO(g) generation • Kernel swelling
Fast fluence	• Coating thermomechanical behavior (e.g., PyC irradiation strain, creep; buffer densification)
Duration	• Time-at-temperature (TAT) phenomena (e.g., fission product corrosion)
Atmosphere/coolant	• Heat transport and fuel thermal gradients
Accident conditions (e.g., temperature, duration, oxidants)	• TAT phenomena • Fuel/core oxidation and degradation • Increased fission product transport
RIA events[2]	• Heat deposition rates, thermal shock, particle temperature gradient

[1] Note that low fuel temperature has driven IPyC failure early in irradiation in performance models, although AGR-5/6/7 experimental data have contradicted these predictions
[2] Reactivity insertion is relatively slow compared to other reactor concepts

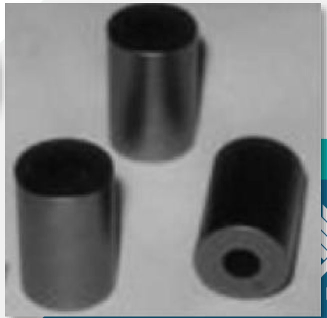
Common Fuel Particle and Sphere/Compact Properties



Property	German proof-test	HTR-PM[a]	HTTR[a]	US AGR-5/6/7
Kernel type	UO_2	UO_2	UO_2	UCO
Kernel diameter (µm)	508	500	600	426
Enrichment (wt% ^{235}U)	10.6	9	3 – 10	15.5
Target peak burnup (% FIMA)	10-12	10-12	3.6	18
Buffer thickness (µm)	102	95	60	100
IPyC thickness (µm)	39	40	30	39.2
SiC thickness (µm)	36	35	25	36.2
OPyC thickness (µm)	38	40	45	35
Particles per sphere/compact	14,600	12,000	13,000	3,400
Sphere/compact dimensions	60 mm diameter	60 mm diameter	39 mm x 29 mm OD x 10 mm ID	25 mm x 12.3 mm OD

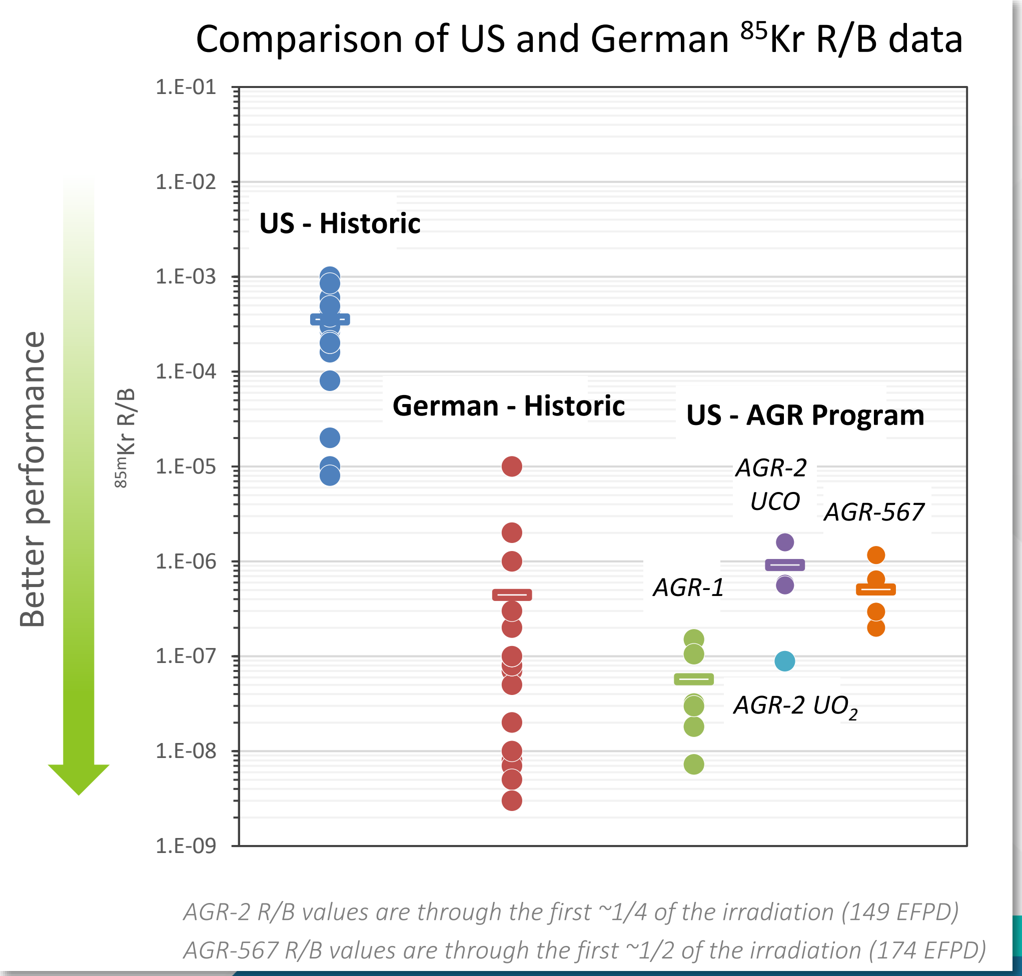
[a] Properties are nominal values from specifications, not measured values

Matrix: Graphite flake + pyrolyzed binder phase



U.S. DOE Advanced Gas Reactor Fuel Development and Qualification Program

- In progress ~22 years
- **Four** irradiation experiments completed in Advanced Test Reactor (three tests to demonstrate fuel performance)
- **~1,000,000** UCO TRISO particles irradiated
- Burnup to **~20%** FIMA
- Time-average temperature to **1432 °C**
- Demonstrated low in-pile particle failure fractions (< 1/50,000 particles)



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Unconventional Coated Particle Fuel Designs

New reactor designs (e.g., microreactors, molten salt-cooled reactors) and proposed applications of TRISO fuel (e.g., nuclear thermal propulsion) are prompting experimentation with unconventional coated particle fuel designs

Selected characteristics of coated particle fuel designs and service conditions

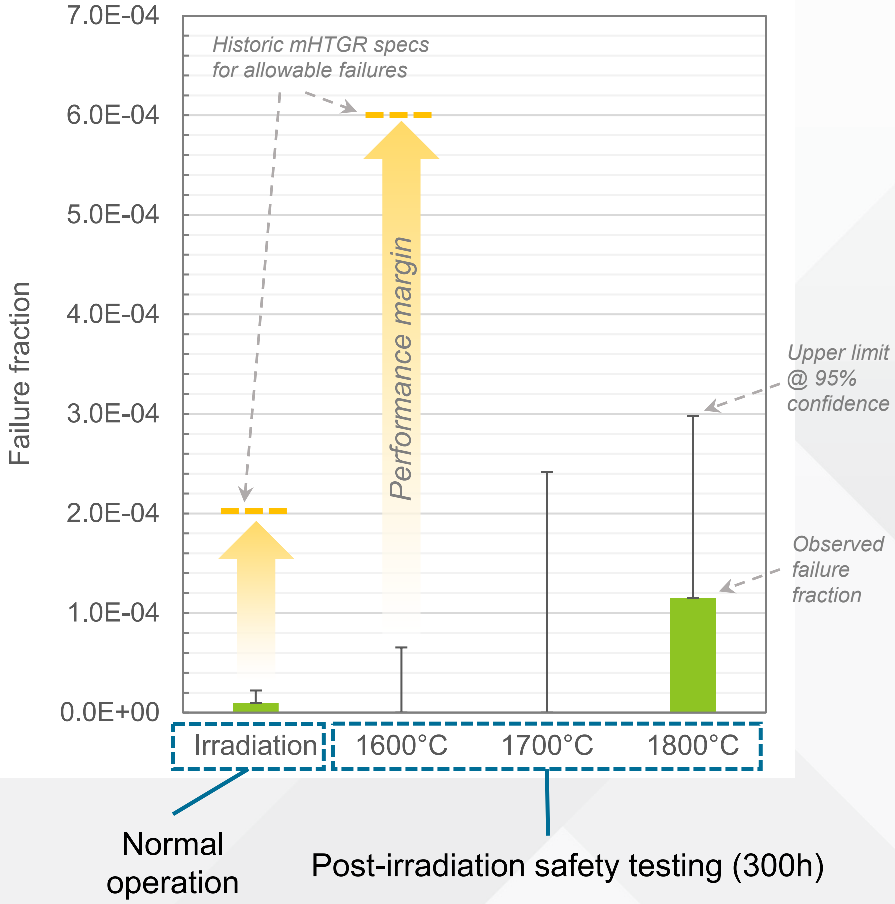
Kernel	Kernel diameter	Coating architecture	Matrix material	Fuel form	Coolant
UCO UO_2 U(C,N)	350 µm – 800 µm	Conventional TRISO “Modified” TRISO	Graphite and pyrolyzed resin SiC Other	Standard cylindrical compacts Standard 60 mm pebbles Modified compacts (different size and packing fraction) Modified pebbles (different diameter; variable density) Custom geometry via AMM	Helium FLiBe

Many of these fuel forms have limited or no irradiation data

Fuel Performance Demonstrations

- Fuel performance demonstrated in major fuel qualification programs (US-AGR, Germany, China)
- Often based on established performance requirements that drive fabrication specifications and irradiation testing programs
- No "cliff edge" effect within current test envelope where failure fraction rapidly increases (e.g., melting point)
  - Incremental degradation in performance under increasingly severe conditions
- AGR/NGNP Program preliminary reference design[1]:
  - 600 MW_{th} prismatic core
  - 750 °C outlet
  - 1250 °C peak time-average fuel temperature

Experimental TRISO failure fractions for AGR-1 + AGR-2



[1] *Fuel performance requirements basis provided in: D. Hansen, Technical Basis for NGNP Fuel Performance and Quality Requirements, GA-911168 (2009)*

Defining Fuel Performance Requirements

- Fission product attenuation in the core impacts radionuclide source term determination
- Imposed dose requirements and reactor/plant design will dictate fuel **quality** and **performance** requirements
  - Acceptable level of particle defects (as fabricated)
  - Acceptable level of in-pile particle failure
  - Acceptable level of fission product release
- Substantial benefit to designers to start with fuel quality and performance requirements prior to fuel development and testing
  - Meeting higher fuel quality specifications increases costs
  - Demonstrating high level of fuel performance is more demanding

DOME Experiments: Assumptions and Expectations

- Relatively short duration tests (days, weeks, months)
  - Low burnup
  - Low neutron fluence
  - Substantial reduction of time-at-temperature (TAT) effect severity
- Fuel temperatures are design-specific
- Accident scenarios
  - Power transients could differ from mHTGR designs
  - Core heating during accidents: Less severe (peak temperature, duration) than mHTGR designs?
  - Oxidant ingress – Magnitude and duration design dependent
- Relatively low core radionuclide inventory compared to mHTGR

Fuel Form Deviations from AGR Reference Fuel

- Kernel Size and Buffer Thickness
- Kernel Composition
- Coating Layer Geometry and Properties
- Matrix Material
- Fuel Form Geometry

Kernel Size and Buffer Thickness Variations

Performance impacts

- A key parameter is Vol_{kernel}:Vol_{buffer} ratio which impacts internal pressure
- Fuel burnup is also important as it dictates fission product generation
- Larger kernel relative to coating surface area = greater inventory of fission products per unit area

Mitigations

- Low burnup – Low fission product (incl. gas) generation
- Short duration – Minimize TAT effects
- Fuel temperature – Lower fuel temperatures minimize TAT effects
- Fuel performance models (e.g., Bison) can be used to compare gas pressure, SiC stress to conventional fuel (e.g., AGR Program UCO TRISO)

Examples with V_k/V_b > AGR UCO reference particle

- German 500 µm UO_2 TRISO – ≤12% FIMA, ~1100°C
- HTTR 600 µ m UO_2 TRISO – 1% FIMA (no PIE data)

$$\sigma \propto \frac{B * V_k}{V_b} * \frac{r_{SiC}}{t_{SiC}}$$

σ = SiC stress
B = Burnup
V_k = Kernel vol
V_b = Buffer vol
r_{SiC} = SiC radius
t_{SiC} = SiC thickness

EPRI Topical Report
EPRI-AR-1(NP)-A (2020)

Kernel Composition Variations

Brief survey of kernel compositions used in TRISO

- UC_2
  - No CO(g) formation
  - Poor retention of lanthanide FPs (La, Nd, Eu, etc.)
- UO_2
  - Mitigates oxidation issues during fab and handling
  - Good retention of lanthanide FPs as oxides
  - CO(g) formation – leads to CO attack of SiC, kernel migration
- UCO
  - Thermochemically minimizes CO(g) formation
  - Good retention of most lanthanide FPs as oxides
  - Less retention of Eu, Sr than UO_2 (although still room for optimization)
- UN, U(C,N)
  - Minimal data for TRISO application

Performance impacts

- Fission product, fission gas retention
- Kernel swelling rates
- CO(g) generation

Mitigations

- Low burnup minimizes FP generation
- Short duration minimizes TAT effects
- Need data on UN thermochemistry

Precedents for non-oxide fuel

- Carbide fuel – Fort St Vrain
- Nitride fuel – Very limited for TRISO

Coating Layer Geometry and Property Variations

Performance impacts

- Thermomechanical layer performance
- Fission product retention
- Particle fabricability and defect fractions

Mitigations

- Computational models can predict particle performance, but failure predictions are not well validated in existing models (e.g., Bison)
- Fabrication trials can address fabricability concerns
- Short irradiation duration could mitigate impacts, but there is higher uncertainty due to lack of data and validated models

Matrix Material Variations

Performance impacts

- Interaction with particles (impact on failures)
- Matrix cracking or damage
- Retention of fission gases or other FPs (affects importance of particle failures)

Mitigations

- Short duration, low burnup – Uncertain if this will impact likelihood of cracking/failure

Precedents

- TCR fuel (SiC matrix) test in MITR – Suggests potential issues with matrix cracking damaging particles (Petrie et al., JNM 580 [2023] 154410)
- TCR fuel (SiC matrix) test in TREAT – Matrix cracking and coating failure at high doses (Woolstenhulme et al., JNM 575 [2023] 154204)
- Various graphite-based matrix formulations used in past programs (e.g., GA-led MHTGR program); matrix interaction with particles sometimes implicated in particle performance

Fuel Form Geometry

Performance impacts

- Mainly impacts fabricability and as-fabricated fuel quality
- Could impact fuel operating conditions (e.g., temperature distributions)

Conclusion

- Establish fuel performance requirements to drive product and performance specifications
- Irradiation conditions can significantly impact severity of fuel failure probability and fission product transport (temperature, duration, etc.)
- Models can be used to support fuel performance expectations, within the limits of the model capabilities
  - Prediction of fundamental conditions (gas pressure)
  - Failure predictions involve complex behavior and are not validated
- Particle failure rates may not be significant driver for dose calculations for DOME demonstrations
  - Initial fuel quality may be main driver

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