Nuclear Fuel Performance

NE-533

Spring 2023

Notes on MOOSE final project

- Final report
- Has a discussion of all three parts in a more “complete” form
- Includes presentation and analysis of results
- Max of 10 pages
- All final input/output files should be uploaded to moodle submission

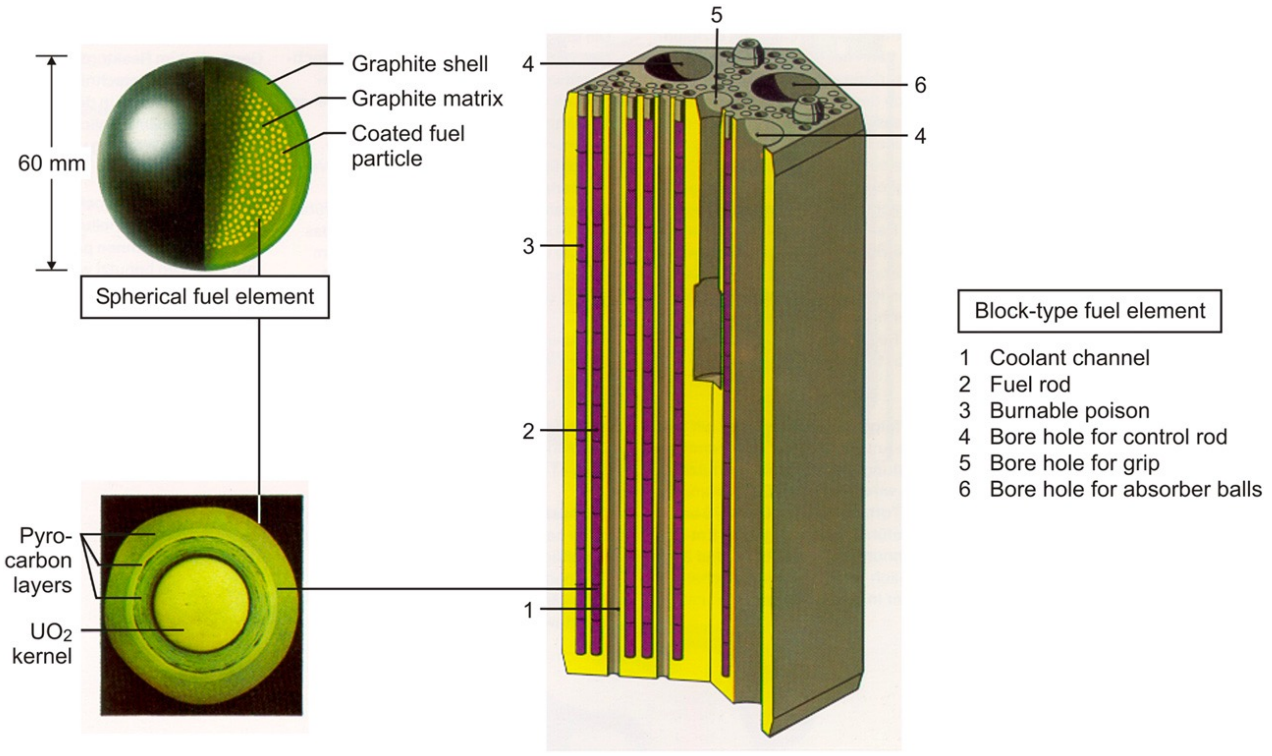
Last time

- MOX Transients:
  - Three main types of transient of interest in MOX SFRs: slow power transient (CRWA), blockage of a subassembly, unprotected loss of flow accident
  - Fuel melting is one of the most critical concerns
- Metallic fuel: U-Zr alloys
  - Metal fuel can go to high burnup, good accident performance, inherent safety, easy to make
  - Complex phase and composition environment, rapid, substantial swelling, followed by fission gas release, FCCI limits lifetime

TRISO FUEL PERFORMANCE

High Temperature Gas Reactor TRISO Fuel

- The HTGR fuel concept is based on TRISO fuel particles embedded in a graphite matrix
- The core of a modular design (~500 MWth) contains approximately 1 billion TRISO particles
- Coated particles have changed throughout the years, but have converged on the current TRISO particle concept



TRISO Layers Purpose

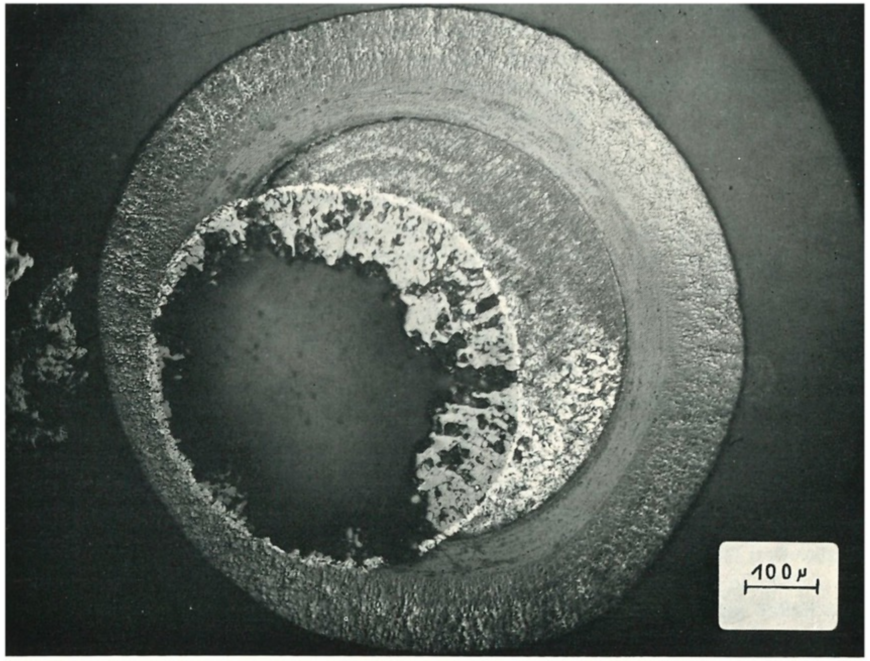
- Fuel kernel: fissile material, generates heat; typically UO_2 or mixture of UO_2 and UC (uranium oxycarbide : UCO); UC or UN are also fuel kernel materials
- Buffer: Porous graphite with ~50% theoretical density; serves as a gas plenum to accommodate fission gases; removes stresses from fuel swelling; sacrificial layer for fission product damage
- IPyC: pyrolytic carbon; load bearing layer against kernel internal pressure; protects fuel kernel during fabrication; retains most fission products
- SiC: silicon carbide; main fission product barrier; load bearing layer
- OPyC: pyrolytic carbon; protects the SiC during handling and compaction; further diffusion barrier for fission products; load bearing layer

Phenomena in TRISO

- Pressure build-up:
  - Fission liberates oxygen which can bind to the carbon buffer and form CO
  - Suppression of excess CO formation is especially critical for high burnup
  - In the US, UCO fuel is used to allow for the conversion of UC_2 into UO_2 in the fuel kernel, controlling excess oxygen and limiting the CO production
- Irradiation growth
  - Fuel kernel will swell as a function of time, while the buffer layer will shrink
  - PyC layers will initially shrink under irradiation, but will eventually reach a turnaround point where swelling will occur
  - Radial swelling of PyC layers puts the SiC into compression
  - Irradiation creep will eventually work to relieve stresses in the PyC layers

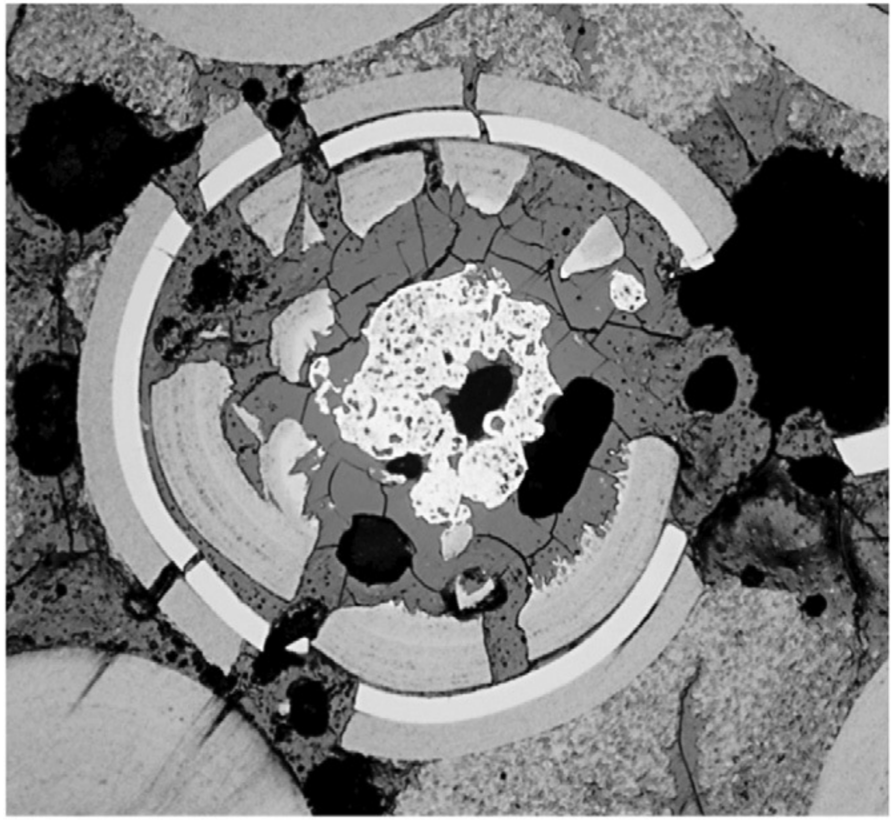
Phenomena in TRISO

- Kernel migration
  - the movement of the kernel toward the TRISO coating, also known as the amoeba effect, may lead to a failure of the particle coating if the kernel reaches the iPyC layer
  - The phenomenon is associated with carbon transport in the particle in the presence of a temperature gradient
  - More likely to occur in oxide fuels due to the presence of free O, forming CO gas



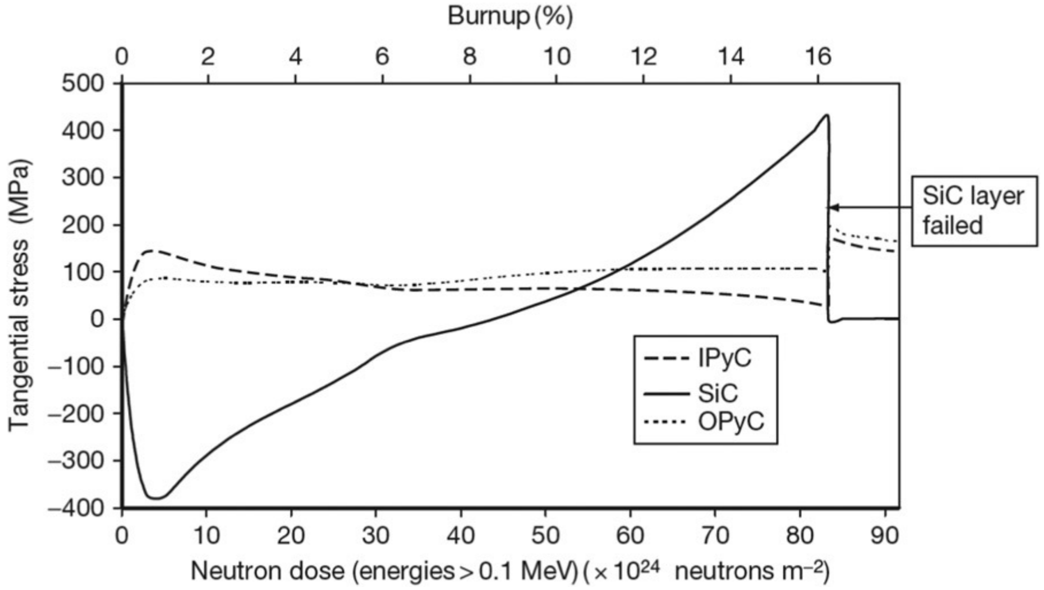
Phenomena in TRISO

- Pressure vessel failure
  - The inner pressure buildup from both fission gases and the CO increases with burnup and results in tensile stresses on the coating layers of the particle
  - If these stresses exceed the tensile strength of the coating, it will burst into pieces
  - Assuming that fabrication specifications are met, particle failure should not occur



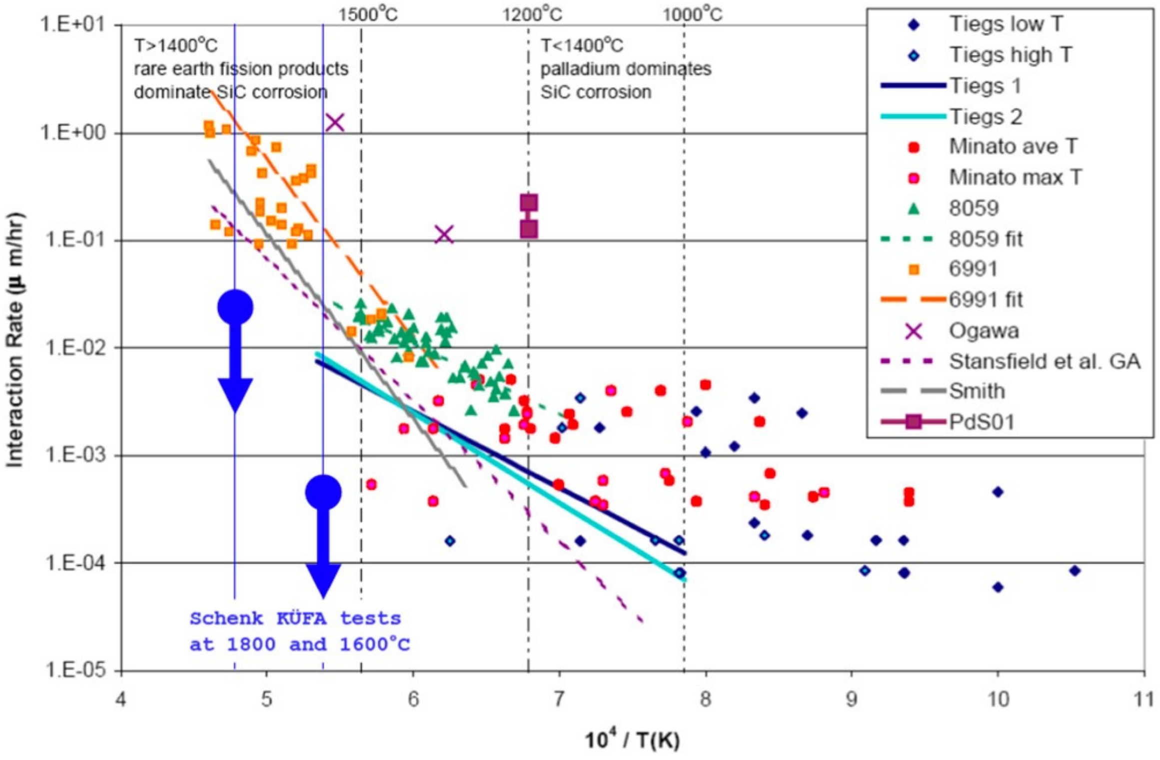
TRISO Pressure Vessel

- The SiC represents the pressure vessel wall which will fail as soon as the stress induced in the SiC layer by the internal gas pressure exceeds the tensile strength of the SiC
- Initially stresses in the SiC layer are compressive because of the attempted shrinkage of the two PyC layers, but as the gas pressure increases, they become tensile until failure occurs
- While stresses in the OPyC vary little during the course of the irradiation, they decrease in the IPyC layer because of an increasing compressive component from increasing gas pressure



Phenomena in TRISO

- Fission product attack
  - experiments show that noble metals can be transported to the SiC, where they can chemically interact
  - Pd-Si compounds can form and lead to degradation of the SiC layer
  - Ag has been observed to diffuse through intact SiC layers
  - If the IPyC is cracked, CO formed can interact with SiC to for SiO gas, degrading the SiC layer



SiC thinning rates due to Pd corrosion

Fuel Performance Codes

- Primary FP codes in the US are PARFUME and BISON
  - PARFUME is a mechanistic thermomechanical code that determines the failure probability of a population of fuel particles
  - BISON utilized PARFUME as a basis to develop a fully 3-D mechanistic fuel performance model
- The NRC has modified the FAST code to include FAST-TRISO
  - 1-D thermomechanics, material properties, failure modes
- Failure modes that need to be captured: 1) Cracking of the IPyC layer; 2) Partial debonding of the IPyC from the SiC; 3) Pressure vessel failure of an aspherical particle; 4) Kernel/SiC interaction resulting from the Amoeba effect; 5) Thinning of the SiC layer by palladium attack of the SiC.

Summary

- Quick overview of TRISO fuel performance
- The failure mechanisms and performance limits of reference HTGR fuels as a function of particle design parameters are relatively well established
- Fuel fabrication and quality assurance is key to retention of fission products
- A few fuel performance codes exist, but experimental data is limited for benchmarking
- The Advanced Gas Reactor (AGR) program and experiments (AGR 1-7) are providing data for qualification