U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Advanced Reactor Research Plan for Fuels Analysis

Dr. Jennifer Uhle
Director, Division of Systems Analysis
Office of Nuclear Regulatory Research
USNRC

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

HTGR Fuels Analysis

Objectives:

- Develop, validate and utilize HTGR fuel behavior and fuel fission product transport analysis models, methods and insights to support safety and licensing reviews.
- Use the HTGR fuel behavior and fuel fission product transport methods and data for developing an accident source term for normal operation and accident conditions for use in the NRC accident analysis evaluation model.
- Develop NRC inspection capability to independently assure the production fuel supply quality.
- Develop NRC staff technical knowledge and capability to effectively review the fuel performance aspects of an HTGR licensing application.

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Key Fuel Safety and Licensing Issues

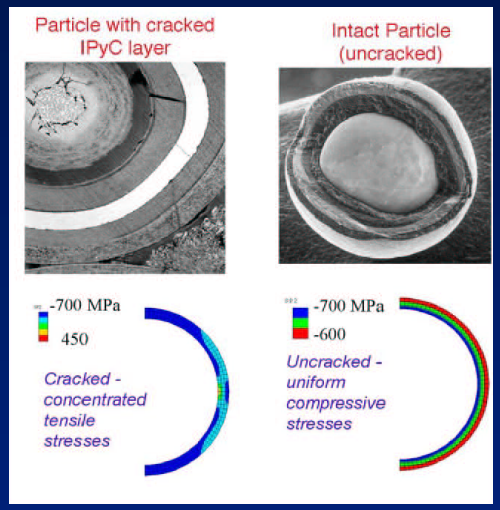
- Predicting fuel *particle failure rates* during:

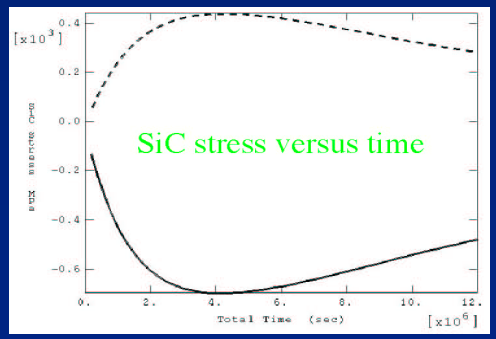
  Normal operation, core heat-up, air ingress, water ingress, large reactivity insertion events
- Predicting fuel *fission product release* during:

  Normal operation, core heat-up, air ingress, water ingress, large reactivity insertion events
- Establishing the *margins* to significantly increased particle failure rates and fuel fission product release during normal operation and accidents
- Determining the magnitude of metallic radionuclides in mobile *graphite dust*
- Confirming the adequacy of fuel qualification irradiation and accident condition *testing methods*
- Providing regulatory assurance of the *quality of the fuel* fabricated over fuel supply lifetime

NRC Fuel Particle Performance Analysis Model Development and Use

- Obtain multi-dimensional behavior, finite element PARFUME code, models, data and manuals from DOE/INL
- Evaluate PARFUME via code-to-code and code-to-data benchmarks
- Conduct sensitivity studies to evaluate variations in important phenomena, qualification test program adequacy, etc
- Use PARFUME to develop NRC staff knowledge of CFP performance and behavior to prepare for licensing reviews
- Update PARFUME with NGNP-specific CFP materials data, irradiation test data, accident condition test data when available
- Use PARFUME sensitivity studies to inform selection of CFP failure rate vs. fuel temperature and B.U. to be used in NRC accident analysis evaluation model





U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

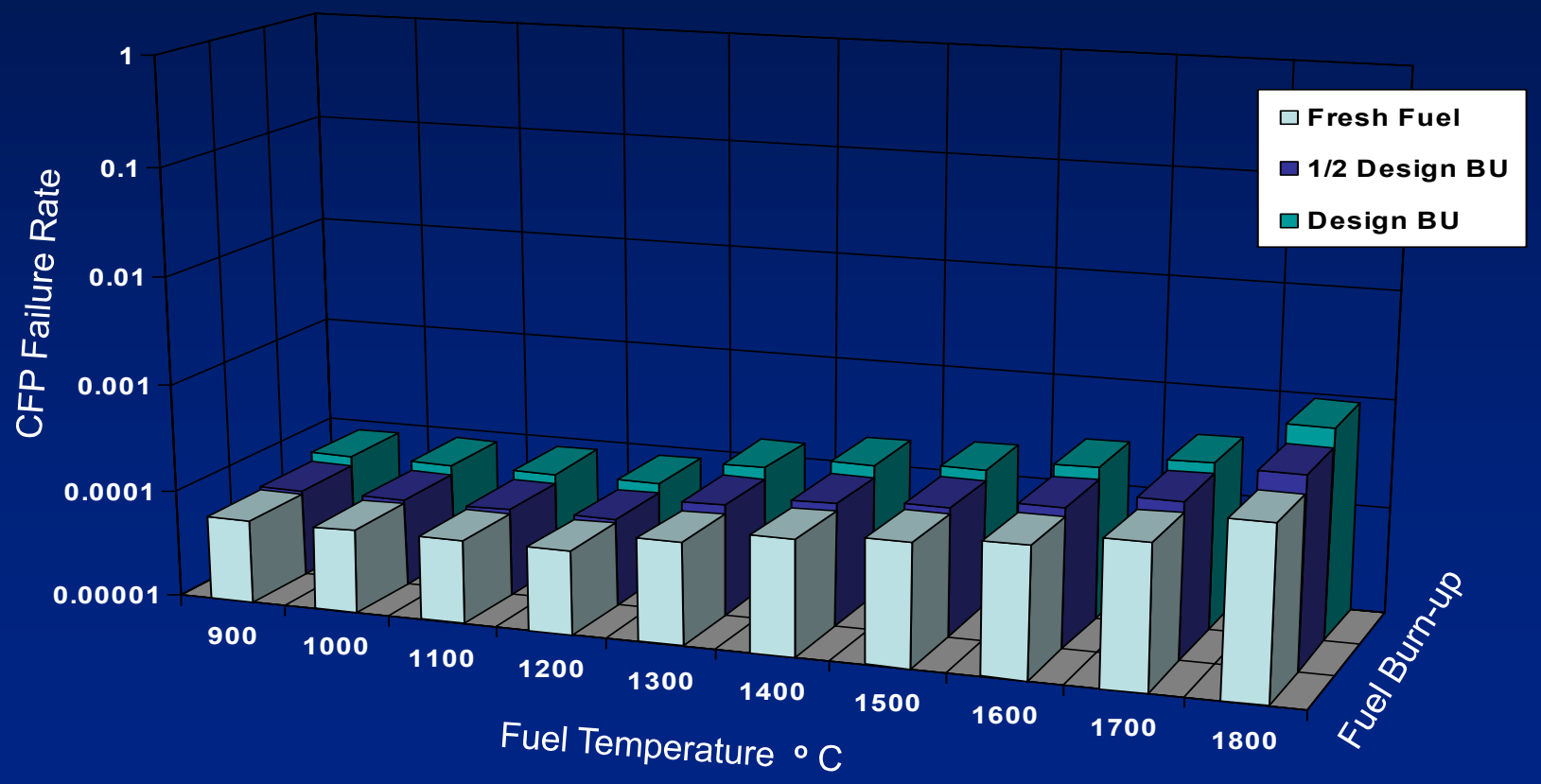
NRC Core-Wide Particle Failure Rate Model Development

NRC Accident Analysis Evaluation Model (EM)

- Establish CFP failure fraction based on NGNP CFP failure fraction design requirements and NGNP fuel qualification program CFP failure fraction data.
- Establish CFP failure fraction versus fuel temperature and burn-up based on the above NGNP failure fraction requirements and data
- Use PARFUME to inform the development of conservative and best estimate CFP failure fraction versus temperature and burn-up
- Commission decisions on mechanistic source term calculation and use will determine where conservative or best estimate CFP failure fraction versus temperature and burn-up will be used in EM for normal operation, transients, DBAs and BDBAs
- Utilize the selected CFP failure fraction function in the NRC accident evaluation model to predict number of CFP failures in the core vs. R, Z and time for normal operation, transients, DBAs and BDBAs
- Compare the NRC CFP failure fraction function to the NGNP COL applicant's CFP failure fraction function
- Near Term: Utilize a CFP failure fraction versus fuel temperature and burn-up based on German reference fuel qualification (irradiation and heat-up) test results

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Particle Failure Fraction vs. Fuel Temperature and Burn-up* (Response Surface)



* Prototypical - for illustration only

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

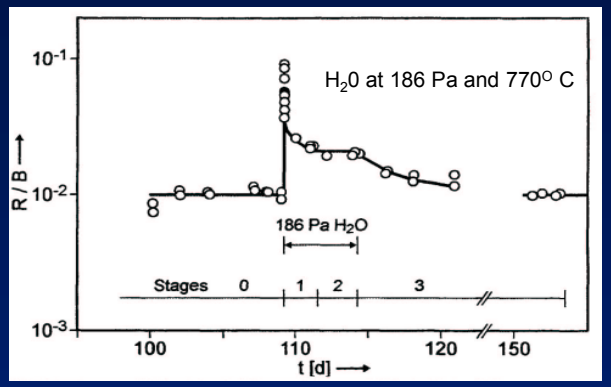
NRC Fuel Fission Product Transport Model Development

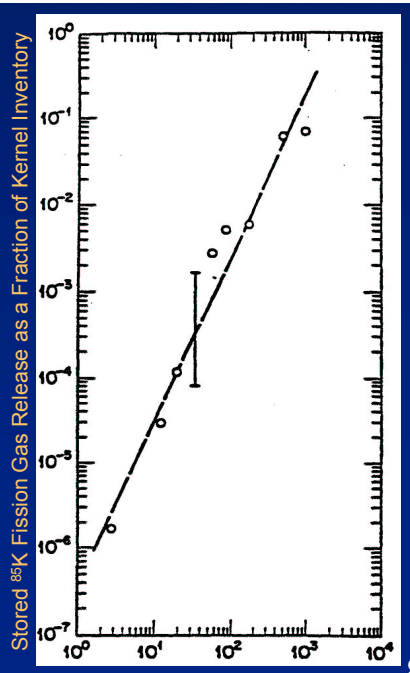
- Evaluate using TMAP4 for calculating fuel FP diffusion and release versus fuel temperature, burn-up and time for: contamination; failed particles; particles with failed SiC layers and; intact particles *or*,
- Develop alternative simplified fuel FP diffusion and release models for calculating fuel FP diffusion and release versus fuel temperature, burn-up and time for: contamination; failed particles; particles with failed SiC layers and; intact particles
- Utilize the selected particle failure fraction response surface together with the selected fuel FP diffusion and release models in the NRC accident analysis EM to calculate the core-wide fuel FP transport and release vs. R, Z and time for normal operation, transients, DBAs and BDBAs
- Near-term: utilize available (IAEA TECDOC) fuel FP diffusion and release rate data
- Long-term: utilize the fuel diffusion and release rate data developed by the NGNP fuel development and qualification program

Fuel Fission Product Release: Effects of Water Ingress

- Oxidants reaching exposed kernels can rapidly/significantly increase fuel particle fission product release
- Release fraction from exposed kernels depends on H_2O partial pressure and fuel temperature
- If NGNP design has steam generators, SG tube failure could significantly increase exposed kernel releases
- NGNP designs with no high pressure, high volume water sources, could limit/preclude increased kernel releases
- Limited fission product release data/models for irradiated compacts with UCO kernels and pebbles with UO_2 kernels
- Additional experimental data for NGNP fuel will be needed to reduce model uncertainties for H_2O ingress FP release
- DOE AGR fuel technology development program may test irradiated fuel with intact and failed particles for H_2O ingress
- NRC has access to DOE test data for developing NRC fuel fission product release models
- Near-term: Use available data/models (e.g., IAEA TECDOC) with uncertainty for NGNP fuel design

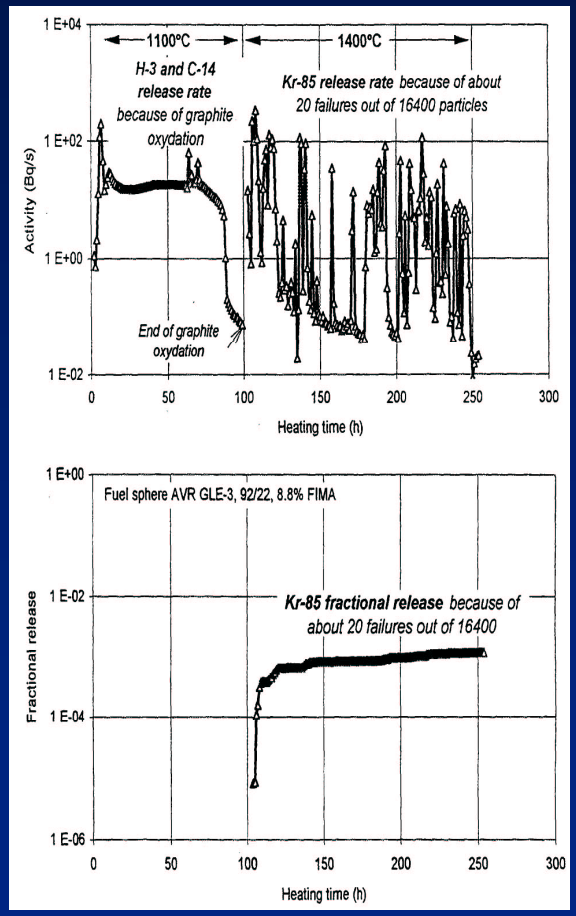
Stored ^{85}K Fission Gas Release as a Fraction of Kernel Inventory





Fuel Fission Product Release: Modeling Air Ingress

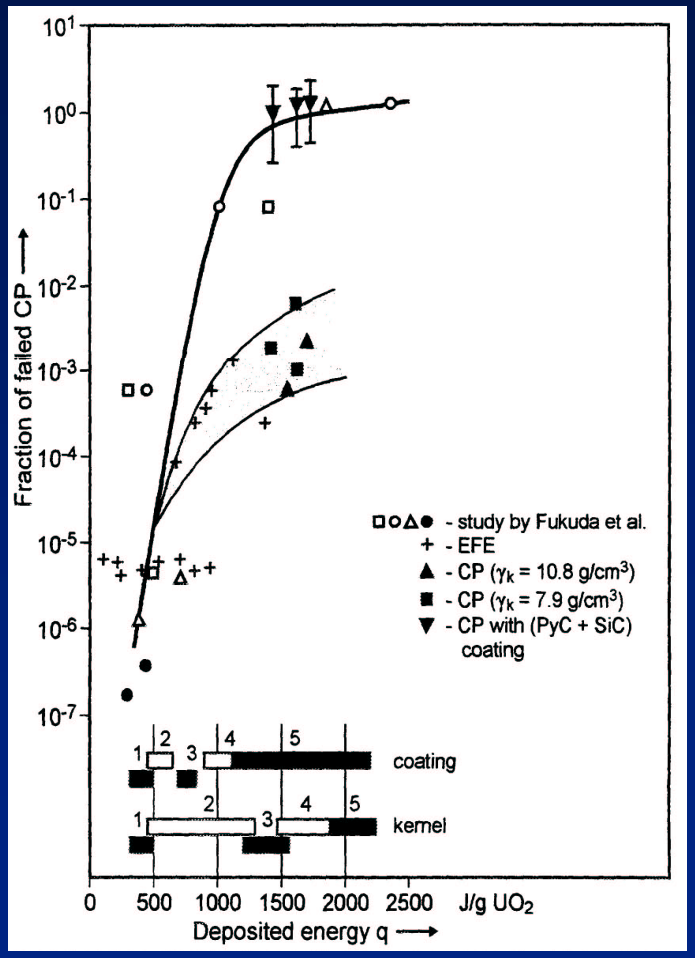
- Fuel matrix/OPyC oxidation can release FP by means other than diffusion
- Oxidation can fail particles by OPyC degradation and/or SiC oxidation (SiC + O_2 -> SiO or SiO_2?)
- Particle failure fraction depends on extent of air supply, particle temperature and can be much greater than heat-up without air ingress
- Low chemical reactivity of PMR nuclear-grade fuel blocks (vs. PBR fuel element matrix material) provides some protection of PMR fuel compacts and particles
- Air ingress provides a HPB opening and motive force for FP transport from HPB
- Existing irradiated fuel oxidation effects data/models are not typical of NGNP fuel design (e.g., burn-up, fluence)
- DOE AGR fuel technology development program may include air ingress testing of irradiated fuel
- NRC has access to DOE test data for developing NRC fuel fission product release models
- Near-term: Use available data/models (e.g., IAEA TECDOC) with uncertainty for NGNP fuel design



Oxidation of two similar fuel spheres in air.
Top: 9% FIMA; Bottom: 8.8% FIMA (IAEA TECDOC-978)

Fuel Fission Product Release: Modeling Reactivity Accidents

- Large/rapid power pulse can release kernel FP and melt kernel, potentially over-pressurizing/failing CFPs
- CFP failure rate depends on energy deposition, deposition rate and fuel kernel transient temp rise
- Severity of reactivity accidents depends on core excess reactivity and control rod (CR) insertion limits
- Concurrent HPB failure (CR ejection) would provide a motive force for fuel FP transport outside the HPB
- Limited reactivity insertion test data/models exist for irradiated fuel and is not typical of NGNP fuel design
- Reactor type (PBR or PMR) and limiting RIA event selection will determine whether NGNP fuel-specific reactivity accident testing is needed
- Near-term: Use available data/models (e.g., IAEA TECDOC) with uncertainty for NGNP fuel design



Particle failure rate vs. pulse energy deposition (IAEA TECDOC-978)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

NRC Fuel Manufacture Quality Assurance Oversight Strategy

Develop an NRC inspection protocol for HTGR production fuel fabrication facilities addressing:

- Conformance with fuel product and process specifications to consistently meet fuel quality and performance requirements
- Fabrication process equipment and process parameters for fuel quality and performance
- Fuel characterization methods to ensure fuel product specifications are being met
- Needed calibration testing equipment and calibration inspection procedures for critical product and process parameters
- Maintenance procedures for fuel fabrication process equipment
- Sampling and Q/C statistical analysis methods
- Process equipment maintenance procedures, calibration and testing
- Procedures, training and qualification of fuel fabrication facility staff
- Automation of process controls and fuel characterizations methods