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Office of Nuclear Reactor Regulation

Licensing High Burnup Fuel

Office of Nuclear Materials and Safeguards

High Burnup Fuel In-Reactor Performance

By: Paul Clifford (NRR/ADES/DSS)

Regulatory Basis

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (SRP), Chapter 4.2, "Fuel System Design," provides guidance for the review of fuel system designs. In accordance with SRP Section 4.2, the objectives of the fuel design review is to provide reasonable assurance that:

1. the fuel system is not damaged as a result of normal operation and anticipated operational occurrences,
2. fuel system damage is never severe enough as to prevent control rod insertion when it is required,
3. the number of fuel rod failures is not underestimated for postulated accidents, and
4. coolability is always maintained.

Regulatory requirements related to fuel system design and in-reactor performance include the following:

- General Design Criterion (GDC) 2, "Design Bases for Protection Against Natural Phenomena," in Appendix A, "General Design Criteria for Nuclear Power Plants," to Part 50, "Domestic Licensing of Production and Utilization Facilities," of Title 10, "Energy," of the Code of Federal Regulations (10 CFR 50) and Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR 50, as they relate to ensuring that the fuel is capable of performing its safety functions during natural phenomena including the safe-shutdown earthquake.
- GDC 10, Reactor Design as it relates to assuring that specified acceptable fuel design limits (SAFDLs) are not exceeded during any condition of normal operation, including the effects of Anticipated Operational Occurrences (AOOs).
- GDC 27, Combined Reactivity Control Systems Capability, as it relates to the reactivity control system being designed with appropriate margin and, in conjunction with the Emergency Core-Cooling System (ECCS), being capable of controlling reactivity and cooling the core under post-accident conditions.
- GDC 28, Reactivity Limits, as it relates to limiting the potential amount and rate of reactivity increase to assure that the effects neither (1) result in damage to the reactor coolant pressure boundary greater than limited local yielding nor (2) sufficiently disturb the core, its support structures, or other reactor pressure vessel internals to impair significantly the capability to cool the core.
- Emergency Core Cooling," and 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors, as they relate to providing an ECCS to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal water reaction is limited to negligible amounts.
- 10 CFR 50.34, as it relates to defining limiting conditions of operation to ensure fuel performance during AOOs and postulated accidents.
- Contents of Applications; Technical Information, as they relate to determining the acceptability of a reactor site based on calculating the exposure of an individual to radiation as a result of fission product releases to the environment following a major accident scenario.

Licensing Challenges

During the fuel design review, in-reactor performance requirements and fuel design limits are established based on all known degradation mechanisms and failure modes under both normal operating conditions and a wide range of accident conditions. Fuel burnup is one of several fuel design limits established to ensure fuel reliability and acceptable performance during postulated accidents.

Many aspects of in-reactor fuel performance are influenced either directly or indirectly by fuel burnup and all must be evaluated in order to identify the controlling parameter used to set the fuel burnup limit. One of the most important aspects of any fuel design review is the calibration and validation of computer models used to predict fuel performance under normal operating conditions and a wide range of accident conditions. These models are based on a variety of data sources, including separate-effects testing to measure material and mechanical properties of unirradiated and irradiated fuel specimens and integral testing performed in hot-cells and instrumented research reactors. With respect to these analytical methods, fuel burnup limits may be established (1) based upon the extent of data used to validate any one specific model (e.g., fuel thermal conductivity) or (2) based upon the extent of data used to validate the integral assessment of the entire model (e.g., fission gas release).

Additional aspects of fuel design and in-reactor performance which might govern the burnup limit (or equivalent fluence or residence time) include:

Fuel Assembly Design:

- Dimensional stability and clearances
- Irradiation-induced growth
- Corrosion and hydrogen uptake
- Fatigue and wear
- Flow-induced vibration (e.g., grid-to-rod fretting)
- Component corrosion and hydrogen uptake - Figure 1
- Seismic and loss-of-coolant accident (LOCA) loads (e.g., grid crush strength)

Fuel Rod Design:

- Rod internal pressure
- AOO and accident performance
- AOO pellet-to-cladding mechanical interaction (PCMI) failure threshold
- Reactivity-initiated accident (RIA) PCMI failure threshold – Figure 2
- RIA coolability criteria
- LOCA time-at-temperature criteria – Figure 3

Fuel Pellet Design:

- Decay-heat load
- Accident source term – Figure 4
- Retention of fission products
- Fragmentation and dispersal during accidents – Figure 5

Figure 1:
Fuel Cladding Hydrogen Uptake

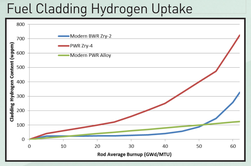


Figure 2:
RIA PCMI Cladding Failure Threshold

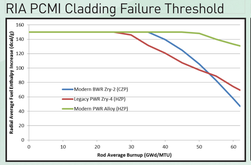


Figure 3:
LOCA Time-at-Temperature Criteria

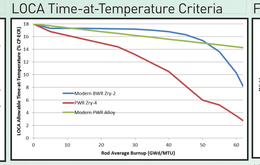
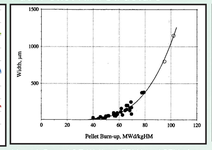
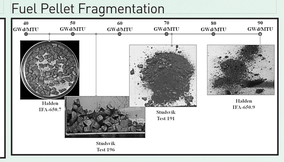


Figure 4:
Fuel Pellet Rim Structure



Manzel, R., and C.T. Walker, "EPMA and SEM of fuel samples from PWR rods with an average burn-up of around 100 MWd/kgHM," Journal of Nuclear Materials 301(2-3):170-182, March 2002.

Figure 5:
Fuel Pellet Fragmentation

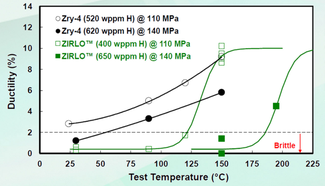


High Burnup Fuel in Spent Fuel Storage and Transportation

By: High Burnup Fuel Task Force
Presented by: Huda Akhavannik, Project Manager

Ductile-to-Brittle Transition Temperatures

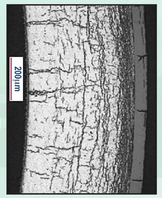
High burnup fuel (HBF) is defined as fuel with assembly average burnups exceeding 45 GWd/MTU. Research performed at Argonne National Laboratory has shown that "pre-storage drying-transfer operations and early stage storage subject cladding to higher temperatures and much higher pressure-induced tensile hoop stresses relative to in-reactor operation and pool storage. Under these conditions, radial hydrides may precipitate during slow cooling and provide an additional embrittlement mechanism as the cladding temperature decreases below the ductile-to-brittle transition temperature (DBTT)."



Billone, M.C., T.A. Burtseva, and R.E. Einziger, "Ductile-to-brittle transition temperature for high-burnup cladding alloys exposed to simulated drying-storage conditions", *Journal of Nuclear Materials*, Volume 433, Issues 1–3, Pages 431-448, February 2013, ISSN 0022-3115, http://dx.doi.org/10.1016/j.jnucmat.2012.10.002.

Licensing Challenges

10 CFR 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste In storage, protection of fuel cladding against gross rupture to meet 72.122(h) requirements and enabling ready retrieval of spent fuel to meet 72.122(l) storage requirements.



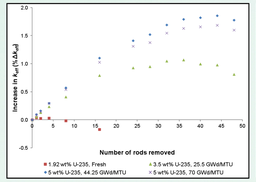
Cross-Section of a Fuel Rod with Significant Radial Hydride Orientation.

Image taken from U.S. Department of Energy High Burnup Dry Storage Cask Research and Development Project (CDP) Draft Plan

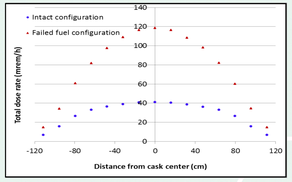
10 CFR 71 In transportation, corresponding considerations must be in place for fuel geometry during loading and unloading, normal conditions of transport, and hypothetical accident conditions per 10 CFR 71.55.

DRAFT Licensing Approach

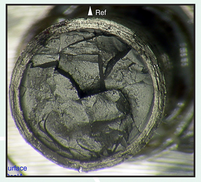
Future research results and materials data can be used to meet the regulatory requirements necessary to obtain certification or licensing of HBF. If results or data are not available or do not pertain to the fuel type, the impact of fuel failure may be assessed with respect to criticality, thermal shielding, and containment regulatory requirements.



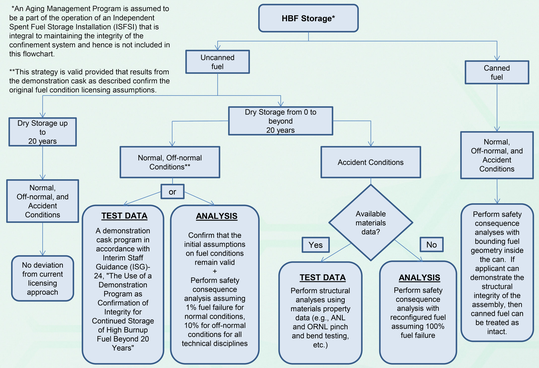
Change in k_{eff} in GBC-32 as a function of number of rods removed *(Oak Ridge National Laboratory Consequence Analysis)*

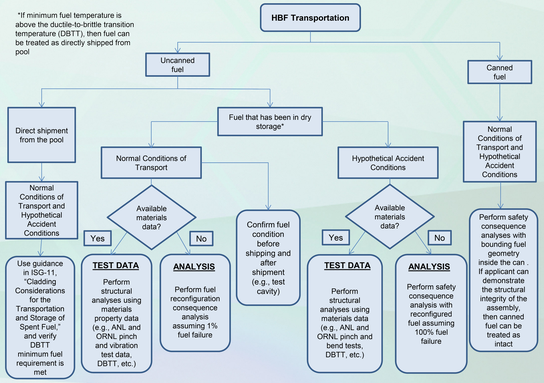


Total dose rate profiles along the PWR transport package external top surface for the intact fuel configuration and the failed fuel configuration with 25% fuel mixture collected into the assembly bottom region, NCT *(Oak Ridge National Laboratory Consequence Analysis)*



"Ref" indicates the circumferential position in maximum compression *(Argonne National Laboratory Bend Tests)*





Research

As part of the further development of the licensing approach, stakeholders throughout the nuclear industry are engaged in ongoing research to better understand HBF performance. Research such as cask demonstrations, cladding failure consequence analyses, vibration testing, and fuel rod bend tests will provide more cladding material properties data. Staff believes that these research activities will validate the position that HBF which has undergone the hydride reorientation will be able to meet the regulatory requirements necessary for licensing.

If research data is not applicable to a certain fuel type, conservative consequence analyses (assuming certain percentages of failed fuel) are used to bound the possibility of the fuel failing. Argonne National Laboratory has performed pinch tests on HBF to develop stress-strain curves.

Oak Ridge National Laboratory is performing vibration tests on HBF to determine the number of cycles before the fuel fails. Additionally, Oak Ridge National Laboratory has performed consequence analyses assuming different percentages of failed fuel.

A DOE-sponsored cask demonstration project will provide data on the normal conditions of storage for HBF.

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