[redacted]

SUMMARY

Analysis of High Burnup Fuel Behavior During LOCA, PCM and Operational Transients

by

August W. Cronenberg/Mailstop T2E26
Senior Fellow, Advisory Committee on Reactor Safeguards
US Nuclear Regulatory Commission
Washington, DC 20555
Phone: (301) 415-6809
Fax: (301) 415-5589

Submitted to

International Topical Meeting on
Light Water Reactor Fuel Performance
Portland, OR (March 2-6, 1997)

Results from high-burnup fuel demonstration programs reveal satisfactory operational performance of several thousand rods to 60,000 MWD/t-U and beyond. However, the lack of a clear understanding of high-burnup fuel behavior for design basis accidents (DBA), as well as recent observations of control rod insertion problems in several assemblies irradiated to 42,000-45,000 MWD/t-U, pose potential impediments to regulatory approval of continued utility requests for fuel extensions to ever-higher burnups.

Current research by the Nuclear Regulatory Commission (NRC) largely centers on resolution of safety and failure threshold concerns for high-burnup fuel under Reactivity Insertion Accident (RIA) conditions. Efforts include updating the FRAPCON, MATPRO, and FRAP-T6 codes to account for extended burnup effects, as well as cooperation in international experiments to establish failure limits and mechanisms for high-burnup fuel under RIA conditions [1]. It is anticipated that this research will lead to a set of re-affirmed or modified DBA-RIA fuel licensing criteria [present failure criteria, based on data to 30,000 MWD/t-U, require rod integrity to energy deposition levels of $\approx$280 cal/g-UO_2 (PWR) and 180 cal/g-UO_2 (BWR)]. Recent test data suggest that these criteria may be violated at elevated burnups, which appears tied to loss of cladding ductility for long-term irradiations.

However RIAs are essentially low-probability events, so that regulatory attention is now being directed to the higher risk accidents, namely loss-of-coolant accidents (LOCAs) and power-cooling miss-match (PCM) transients. Concerns here relate to the synergistic effects of fuel expansion/swelling, fission gas buildup, and cladding oxidation/embrittlement on high-burnup fuel failure, which is the subject of this paper.

Physical processes impacting high-burnup fuel failure behavior under LOCA and PCM conditions were examined using the FRAPCON3 (steady-state fuel performance) and FRAP-T6 (transient fuel performance) codes. The recently revised FRAPCON3 code [3] was employed, since it incorporates high-burnup effects, including degradation of fuel thermal conductivity due to gas bubble precipitation within the fuel matrix, fuel irradiation induced swelling/densification, as well as cladding oxide buildup, hydriding, and elevated cladding hoop strains. FRAPCON3 predicted end-of-life conditions at 40,000-80,000 MWD/t-U were used as input to the FRAP-T6 code for simulation of transient fuel behavior. Preliminary predictions indicate the following general trends.

For large-break LOCAs, rapid cladding overheating occurs during the initial core voiding/blowdown phase, accompanied by partial loss of the cladding surface oxide due to blowdown/spallation forces. By the end of the blowdown phase, loss of moderator coolant results in core power reduction to decay levels, initiating a brief period (several seconds) of cladding temperature decline, as the fuel pellet gives up its stored energy. However degraded rod heat transfer conditions then cause a return to cladding overheating, which is exacerbated by exothermic cladding-steam reaction during the initial stages of ECC reflooding and attendant re-buildup of cladding oxide. Cladding overheating itself and changes in oxide thickness however are second order effects, in comparison to changes in differential pressure across the cladding during the blowdown process. Enhanced fission gas release due to fuel overheating, combined with the rapid drop in core pressure, result in a ballooning induced cladding failure mechanism. Although the timing of events is different for small-break LOCAs and power-cooling mismatch (PCM) conditions, predictions indicate similar ballooning type failures for all by the mildest PCM transients.

Fuel rod distortion potential was also estimated for elevated burnups. The situation examined is one where fuel cladding is idealized as a long cylindrical tube, with internal loading due to fission gas pressure buildup. Making use of Euler's analysis [4], estimates are given for the critical buckling pressure (P_{crit}) and rod deformations (δ). Three PWR fuel vendor designs were examined, the Westinghouse 17x17 assembly, the Babcock & Wilcox (B&W) 15x15, and the Combustion Engineering (CE) 16x16 designs. Calculations reveal that at burnup level of ≈40,000 MWD/t-U, rod pressures due to fission gas buildup exceed ΔP_{crit} for Westinghouse fuel. For both B&W and CE fuel designs, higher burnups (45,000-55,000 MWD/t-U) are indicated for buckling. Associated rod deflection estimates indicate that at about 37,500 MWD/t-U, rod bowing for Westinghouse fuel just equals the separation distance between the control-rod guide-tube and their nearest neighbor fuel rods (0.068 inches). At higher burnups, fuel rod deformation forces would then translate to distortion forces on the control rod guide tube, which may account for control jamming problems noted for several Westinghouse assemblies at burnups of 42,000-45,000 MWD/t-U. A comparison of the fuel design parameters, indicate that Westinghouse fuel is most amenable to deformation and buckling instability due to their relatively thin cladding thickness and radius, which translates to relatively small bending moment of inertia as compared to B&W and CE fuel designs. Although such estimates are approximate, they nevertheless indicate burnup-related fuel distortion trends that may contribute to the control rod sticking problems noted for Westinghouse fuel assemblies irradiated to ≈42,000-45,000 MWD/t-U [5], which have not been observed for CE and B&W fuel designs at similar burnups.

References

1. R. Meyer, "High-Burnup Fuel Behavior", Proc. 22ed Water Reactor Safety Meeting, NUREG/CP-0140, (1994).

2. G. A. Berna et al, "FRAPCON-3: A Computer Code for the Calculation of Steady-State Thermal-Mechanical Behavior of Oxide Fuel Rods", ____________________, (1996)

3 L. Siefken et al, "FRAP-T6: A Computer code for the Transient Analysis of Oxide Fuel Rods", NUREG/CR-2148, (1981).

4. J. Fauple and F. Fisher, Engineering Design, Wiley & Sons, New York, Chapter 9, (1981).

5. E. Hiruo, "NRC Warns Westinghouse Plants High Burnup May Be Tied To Control Rod Problems", Inside NRC, (March 18, 1996).