THE 4TH INTERNATIONAL TOPICAL MEETING ON
NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

XA04N0557

DESIGN AND ANALYSIS CHALLENGES FOR ADVANCED NUCLEAR FUEL

H. Klepfer, D. Abdollahian, A. Dias, C. Durston,
L. Eisenhart, R. Engel, P. Gilmore, P. Rank,
N. Kjaer-Pedersen, and J. Sorensen
S. Levy Incorporated
3425 S. Bascom Avenue
Campbell, CA 95008 USA
FAX: 1-408-371-6804

R. Yang and L. Agee
Electric Power Research Institute
P.O. Box 10412
3412 Hillview Avenue
Palo Alto, CA 94303 USA
FAX: 1-415-855-1026

ABSTRACT

Significant changes have been incorporated in the light water reactor (LWR) fuel designs now being offered, and advanced fuel designs are currently being developed for the existing and the next generation of reactor designs. These advanced fuel design configurations are intended to offer utilities major economic gains, including: (1) improved fuel characteristics through optimized hydrogen to uranium ratio within the core; (2) increased capacity factor by allowing longer operating cycles, which is implemented by increasing the fuel enrichment and the amount and distribution of burnable poison, gadolinia, boron, or erbium within the fuel assembly to achieve higher discharge burnup; and (3) increased plant power output, if it can be accommodated by the balance of plant, by increasing the power density of the fuel assembly. The authors report here work being done to identify emerging technical issues in support of utility industry evaluations of advanced fuel designs.

INTRODUCTION

Advanced fuel designs for existing reactors have been implemented for both pressurized water reactors (PWRs) and boiling water reactors (BWRs). However, the widest variety of advanced fuel designs are currently associated with BWRs. This situation exists because BWR fuel assemblies are designed such that each has its own discrete envelope with a flow barrier (channel) that eliminates the potential for cross flow. This design concept gives the fuel designer a substantial amount of flexibility in the fuel assembly design within the assembly envelope. BWR fuel suppliers have taken advantage of the design flexibility in an attempt to optimize fuel cycle economics and increase plant capacity factors through increased operating cycle lengths, while satisfying other design and safety requirements. PWR fuel suppliers, designing within the constraints of open channels, have significantly changed the nuclear design of fuel assemblies for existing reactors in order to increase the operating cycle length and to permit low neutron leakage core loadings.

Examples of fuel design changes that have been implemented in the development of advanced fuel assemblies include: (1) a larger number of smaller diameter fuel rods; (2) introduction of additional non-voided water; (3) more efficient BWR spacer PWR grid designs, including all Zircaloy PWR spacer grids; (4) debris resistant lower end castings; (5) higher uranium enrichments; and (6) the use of mixed oxide fuel (MOX). The core nuclear and thermal-hydraulic operating characteristics of the advanced fuel designs, particularly those designs with MOX and those with an increased number of fuel rods, can be significantly different from those of currently operating fuel. As a result, additional detailed plant performance evaluations may be required to demonstrate the operational acceptability of advanced fuel designs. Potential concerns have been identified related to advanced fuel designs. This paper presents the results of some of the work performed by the authors to assess the significance of these concerns.

CAPABILITY OF CURRENT NUCLEAR METHODS TO ACCURATELY EVALUATE THE ADVANCED FUEL ASSEMBLY GEOMETRIES

With the advent of the new generation of nuclear fuel designs, a new variety of reactivity characteristics are yet to be fully understood. A higher water- to-fuel ratio will lower the void reactivity coefficient (less negative) in BWRs. The presence of Zircaloy rods in PWR fuel will change the moderator density reactivity coefficient. Higher burnable poison loadings of resonance absorbers (gadolinium or erbium) can cause inaccurately calculated pin power distributions in conventional lattice codes for both PWRs and BWRs. Novel boron poison geometry loadings in advanced PWR designs can also be a source of modeling error. Higher uranium fuel loadings and mixed oxide (MOX) fuels need to be benchmarked to applicable data.

The existing integral transport lattice theory computer codes that have been the mainstay in the industry have a series of mathematical and physical approximations to the actual reality of the lattice and the physical data. In order to be able to assess the accuracy of these calculations, Monte Carlo capabilities have evolved as the reliable benchmark. Modern Monte Carlo methods use continuous energy with ENDF/B-V & VI Doppler broadened evaluations for all cross sections. The spatial complexity of the lattice is handled exactly through geometric particle tracking.

Modern BWR fuel geometries have been evaluated for various lattice conditions, employing the MCNP-4 Monte Carlo code with isotopic data bases evaluated at 300°K, 600°K, and 900°K. The BWR results at various void fractions have been compared with analytical approximate results to provide benchmark solutions for both the assembly reactivity and each individual pin power. Highly accurate solutions have been generated using 8,000,000 histories per lattice configuration. Now it is possible to have an accurate tool to assess such BWR phenomena as the reactivity and pin power changes due to the voiding of a water rod. It is also possible to understand the errors in the deterministic methodologies such as the spatial homogenization or the multigroup approximation to the continuous energy distributions for both types of LWR fuel. Various reactivity coefficients can also be precisely evaluated by running two Monte Carlo cases and then comparing with the inferred results from the approximate procedures.

THERMAL HYDRAULIC COMPATIBILITY OF DIFFERENT FUEL DESIGNS OVER THE ALLOWABLE RANGE OF POWER AND FLOW CONDITIONS

Transition from a resident fuel to an advanced fuel design, in an existing reactor will require operating with a mixed core configuration. This is a potential problem for both BWR and PWR. All of the advanced BWR fuel designs have thermal–hydraulic characteristics that are different from those of the resident fuel. The new fuel assemblies have, in general, the design flexibility to have about the same pressure drop as the resident fuel at rated assembly flow and power. Rated conditions are typically the focus of thermal–hydraulic compatibility evaluations. This compatibility is accomplished by the spacer design, the number of spacers, the upper and lower tie plate designs, and, in some cases, by the use of part length fuel rods. Thermal–hydraulic compatibility is also affected by water rod/water cross design and by the design of the leakage flow paths from the fuel assemblies to the common bypass region. Water rod/water cross flow must be sufficient to preclude boiling at high power and high flow operating conditions. Leakage flow to the common bypass region must be adequate to preclude gross boiling in the core bypass.

Because of fundamental design differences, the distribution of the fuel assembly pressure drop for the advanced BWR fuel designs will be different from that of the resident fuel. That is, the ratio of two-phase to single-phase pressure drop can be significantly different given the same total pressure drop and the same assembly power. Therefore, in a mixed core configuration, there can be significant differences in the fuel assembly flow versus core pressure drop at off-rated conditions. If the flow in the new fuel assemblies is greater than the flow in the resident fuel assemblies, then the thermal margin of the resident fuel will be degraded (and vice versa). Because of the potentially significant thermal–hydraulic differences at off-rated conditions with new fuel designs, particular emphasis needs to be given to these conditions.

The effects of differences in thermal–hydraulic characteristics may be amplified during a transient. Most licensing basis transient events are analyzed as starting from rated flow and rated power because it has been determined that this initial condition will produce the greatest challenge to fuel design limits for these events. This conclusion needs to be reconfirmed for a variety of transition core configurations. Furthermore, it has been demonstrated that some events are more limiting at off-rated conditions, e.g., increase in recirculation flow. The bounding values for the thermal limits as a function of core flow are established by these events and need to be reconfirmed for mixed core configurations.

The features of the advanced BWR fuel designs that have the most significant impact on thermal–hydraulic compatibility are those that affect the fuel assembly pressure drop characteristics. These features are: spacer design; upper tie plate design; fuel assembly wetted perimeter; lower tie plate design; and the part length fuel rods that are incorporated in some fuel designs. Desirable thermal–hydraulic compatibility attributes of reload fuel designs are a reduced two-phase component of the overall core pressure drop and the flexibility to adjust the lower tie plate pressure drop so as to match the hydraulic characteristics of the resident fuel.

To address these challenges, a methodology has been developed to evaluate the steady-state thermal-hydraulic performance and flow distribution characteristics of mixed configuration BWR cores containing a advanced fuel designs and older fuel designs.

IMPACT OF ADVANCED FUEL DESIGNS ON BWR CORE AND CHANNEL STABILITY

There is a special concern about the ability to predict stability margins and to define stability exclusion regions for mixed core configurations (transition from one fuel thermal-hydraulic design to another) in BWR plants. Since stability is a concern only at low flow and low power conditions, it is expected to be significantly affected by differences in the thermal–hydraulic characteristics of the old and new fuel designs. There is also a concern that a mixed core configuration may be more vulnerable to regional or local instability than is a core with a uniform fuel design.

The parameters that have a significant impact on BWR stability and that are directly affected by the advanced BWR fuel designs are: axial power distribution; void coefficient; fuel thermal time constant; and core flow resistances.

Some of the advanced BWR fuel designs contain part length fuel rods and these designs tend to result in a more bottom peaked axial power distribution. A more bottom peaked axial power distribution tends to have a destabilizing effect for both core and channel stability.

Void coefficient is affected by the fuel assembly water to fuel ratio. Water to fuel ratio is influenced by the introduction of additional non-voided water in the fuel assemblies. All of the advanced BWR fuel designs have a higher water to fuel ratio than older BWR fuel designs. This produces a less negative void coefficient which has a stabilizing effect for core stability and no direct effect on channel stability.

The fuel thermal time constant is directly proportional to fuel rod diameter (i.e., inversely proportional to the number of rods in the fuel assembly) and is inversely proportional to the rod initial fill gas pressure and directly proportional to pellet/cladding gap size. Advanced BWR fuel designs that have a larger number of smaller diameter fuel rods have a lower fuel thermal time constant than older BWR fuel designs. This tends to have a destabilizing effect for core stability.

As indicated in the previous section, the core flow resistance is significantly affected by the advanced BWR fuel designs. The spacer design, the upper tie plate design, the lower tie plate design, and the fuel assembly wetted perimeter all impact the core flow resistance. From a stability perspective, this leads to an additional consideration that for a given total core pressure drop, a reduction of the ratio of the two-phase pressure drop to the single-phase pressure drop has a stabilizing effect for both core and channel stability. Advanced fuel designs with reduced spacer or upper tie plate pressure drop or increased lower tie plate pressure drop have the potential to increase stability margins as long as these pressure drop changes offset the increased friction of designs with a larger number of smaller diameter fuel rods.

For these reasons, a methodology capable of evaluating the core and channel stability margins for BWR cores, including mixed core configurations involving any advanced fuel designs (Reference 1) is being developed.

ACCELERATED CLADDING CORROSION AND HYDRIDING IN BOTH PWRS AND BWRS

All advanced fuel designs for LWRs employ zirconium alloy cladding. However, disquieting instances of accelerated corrosion in both BWRs and PWRs have been observed. These observations have prompted concerns about whether advanced fuel design objectives will be limited by accelerated corrosion of zirconium alloys.

During the 1980s, by far the most prevalent threat to BWR fuel integrity was localized corrosion failures; sometimes called crud-induced localized corrosion, or CILC, failures. These failures occurred, however, in only some BWRs; those having high power density cores, condensate filter demineralizers, and copper-nickel alloy condenser tubes. Local hydriding was not a significant contributing factor to these failures. Research (Reference 2) also led to predictive correlations between certain parameters of early life (less than 2900 MWd/T exposure) coolant chemistry history and localized corrosion failure fuel batch failure fractions. Notably, early-life coolant conductivity transient severity and off-nominal feedwater copper in-leakage were found to predict long term cladding oxidation rates. In addition, some cladding material batches were far more sensitive to localized corrosion failures than others. Susceptible plants replaced copper-nickel condenser tubing with titanium or stainless steel tubing and/or increased discipline in coolant impurity in-leakage control. Cladding alloy composition control and process heat treatment improvements were made by cladding and fuel vendors. Recent fuel performance in BWRs has improved with no further cladding corrosion failures reported. However, EPRI continues to assist utilities as they monitor BWR fuel cladding corrosion as fuel burnups are extended.

PWR cladding uniform corrosion and hydriding rates have been observed to accelerate at burnups above exposures as low as 30,000 MWd/MT in some PWR plants. More disquieting was the fact that the observed corrosion and hydriding accelerations were not predicted by available corrosion predictor models. Recently available PWR cladding corrosion predictors were reviewed and refined (Reference 3). For high power density, high coolant exit temperature plants, it is clear that improvements in cladding corrosion resistance will be required to achieve advanced PWR fuel burnup objectives. On the other hand, cladding alloy composition control (especially at lower tin content levels) and process heat treatment controls have been shown to improve corrosion resistance by an amount that may be sufficient to meet advanced fuel objectives in lower power density PWRs with lower exit temperatures.. In addition, PWR fuel vendors have introduced modified zirconium alloys as cladding. In support of utilities, EPRI monitoring of the success of these potential improvements continues as advanced fuel burnup objectives are approached.

CAPABILITY TO PREDICT POTENTIAL SEVERE RELEASES FROM FUEL RODS FOLLOWING AN INITIAL CLADDING FAILURE

Fuel rod failures in LWRs have been decreasing in frequency but continue to occur. Primary failure can be caused by pellet cladding mechanical interaction, fretting, or other mechanisms. Despite current trends, continued occurrence of primary failures can not be precluded, and if a failure deteriorates into a severely degraded failure, the consequences are immediately raised coolant activity levels and carryover to the next cycle due to released fuel particles.

A severely degraded failure is characterized by high offgas release per failed rod plus a large amount of tramp uranium activity in the coolant. The damage mechanism is secondary hydriding attack, followed by fast-propagating axial cladding cracks followed by removal of fuel material by the coolant water, due to oxidation and erosion at fuel grain boundaries. Severe degradation can sometimes be prevented, provided the primary failure is detected in time, i.e., within a few weeks. How to prevent severe degradation after detection is discussed in Reference 4. The detection and location of the primary failure may be accomplished by coolant activity analysis and flux tilting. Coolant activities are best evaluated by use of "trending plots". A primary fuel failure is associated with a step increase in coolant activity. The most sensitive detection is obtained if the background activity level ("tramp") is subtracted by a numerical analysis, for instance by the CHIRON code (Reference 5). The total EPRI program on fuel degradation is described in Reference 6.

Variations in activity level may also result from other causes (like routine control rod movements). Therefore, supporting evidence is needed for failure confirmation. CHIRON offers "number of failed rods" estimates, which can be compared with the measured activity levels. Other indicators of fuel failure are ratios of short- and long-lived isotopes, e.g., Xe- 138/Xe-133; I-134/I-131, and Xe-138/I-131, which tend to drop at the time of failure, because of the suddenly increased release of the longer-lived isotope.

Protection against enhanced secondary hydriding may be achieved by power suppression (opening up the fuel-cladding gap), since this tends to allow free mixing of steam and hydrogen, preventing "steam starvation", the condition essential for secondary hydriding. Finally, the Np-239 activity is useful in monitoring the opening of a larger defect. A Np-239 activity increase normally signals that a secondary failure is developing. However, for some primary failures Np-239 levels have been seen to rise for a limited time, then to decline again due to coolant cleanup action and isotopic decay.

In summary, activity step increases indicate potential failures. Simultaneous CHIRON failure indications and decreases in the xenon-, iodine-, and "mixed" isotopic ratios further reinforce the indication of failure. Finally, Np-239 activities warn that fuel is released from the failed rod(s), indicating a large primary or (most likely) a secondary defect.

INTERACTION BETWEEN FUEL DESIGN AND REACTOR DESIGN AS ADVANCED DESIGNS ARE INTRODUCED IN THE EXISTING AND THE NEXT GENERATION OF REACTORS

Subtle changes in subsystems of existing LWRs are being made aimed at performance optimization, including plant materials corrosion performance optimization. Advanced reactor system designs include an even larger number of changes. Past experience suggests the potential for system interaction surprises in reliable fuel rod performance as these changes are introduced. For example, the introduction of filter demineralizers as replacements for deep bed demineralizers contributed to the CILC corrosion fuel failures in BWRs and higher LiOH additions to PWR coolant may have contributed to accelerated uniform corrosion at high burnup.

The combination of system evolutions to higher power density combined with fuel advances clearly exacerbated to BWR stability problem. Newer fuel designs appear to have corrected this fuel - system interaction problem. LWR plant modifications combined with inadequate lower tie plate designs are now believed to have contributed to the recently increasing frequency of debris-fuel cladding fretting corrosion failures. Newer fuel designs attempt to improve the lower tie plate design in this regard.

In the future, the authors are especially concerned that advanced fuel designs not increase the susceptibility to flow-induced vibration caused spacer grid to cladding fretting failures. Recent PWR fuel failures of this type have been observed.

Subtle changes in fuel assembly design features such as spacer grids, mixing vanes, unvoided water tubes, and burnable poison disposition in fuel rods are being made to optimize coupled nuclear/thermal-hydraulic performance. It is not intended that these changes diminish fuel rod mechanical integrity. However, field experience at extended burnup targets for advanced fuel designs has not yet been demonstrated with high statistical confidence.

Therefore, continued monitoring of LWR fuel performance is essential to assure that there is no degradation in the high level of fuel reliability demonstrated by current fuel designs.

CONCLUSIONS ON THE SIGNIFICANCE OF CONCERNS RELATED TO ADVANCED FUEL DESIGNS

Methods Capability

New fuel designs incorporated as reloads in old reactors and advanced fuel designs loaded in new reactors must be carefully evaluated. New study results are available for benchmarking such efforts.

Steady-State Thermal-Hydraulics

Care must be taken to extend normal analyses to special analyses of off-rated and transient conditions. Utility sponsored studies of specific advanced core designs have established methods for these needed special analyses.

BWR Stability

BWR nuclear/thermal-hydraulic instabilities have been observed and have been addressed by regulators. Advanced BWR fuel designs have the potential to drastically affect stability. Methods are being developed to assist in evaluating new BWR designs in this regard. Early results indicate that some advanced fuel designs can improve BWR stability.

Cladding Corrosion and Hydriding

PWR corrosion and hydriding is a major concern. EPRI is supporting the utility industry in monitoring vendor efforts to improve this situation.

Severe Releases from Failed Fuel Rods

Advanced fuel rod designs must not inadvertently lead to increased susceptibility for severe rod degradation following a primary defect. EPRI is cooperating in an international effort to develop the technology necessary for the utility industry to evaluate advanced fuel designs in this regard.

Fuel Design and System Interactions

To minimize surprises due to system-fuel interactions, fuel performance monitoring and technology development activities are continuing.

REFERENCES

1. A.F. DIAS, L.D. EISENHART, and J.M. SORENSEN, "Benchmarking ARROTTA/VIPRE-02 Against BWR Cores," *Proceedings: Seventh International RETRAN Conference*, EPRI TR-100361, February 1992.

2. H. KLEPFER, "Investigation of In-Leakage and Fuel Corrosion in Certain BWRs," EPRI NP-6779-M, March 1990.

3. P.M. GILMORE, H. KLEPFER, J.M. SORENSEN, and BO CHENG, "PWR Cladding Corrosion Predictions," to be published in 1994.

4. H.H. KLEPFER, N. KJAER-PEDERSEN, P. RANK, and O. OZER: "Severe Degradation of BWR Fuel Failures: Coolant Activity Analysis," EPRI TR-102 799, July 1993

5. W. MICHAELS, B. PAULSON, K. WATKINS, and N. KJAER-PEDERSEN, "CHIRON - A Fuel Failure Prediction Code," Version 2.1, EPRI TR-102297, July 1993

6. R. YANG, O. OZER, S. YAGNIK, B. CHENG, H. KLEPFER, N. KJAER-PEDERSEN, and P. RANK, "EPRI Failed Fuel Degradation R&D Program," in publication 1994.