Light Water Reactor Fuel Performance: Current Status, Challenges, and Future High Fidelity Modeling

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There is a long-standing tie between modeling and nuclear fuel performance, from predicting core physics to optimizing the fuel reloading pattern to designing safety margins into fuel assemblies. This paper reviews current fuel performance and fuel reliability challenges facing the industry, including a description of the most common fuel failure mechanisms observed in pressurized water reactors. A description of a new Energy Innovation Hub, the Consortium for Advanced Simulation of Light Water Reactors (CASL), funded by the Department of Energy is then provided that introduces an approach to utilize high performance computing to investigate the coupled physics controlling nuclear fuel performance. The article concludes by summarizing the future challenges of modeling nuclear fuel behavior addressed by the CASL program.

INTRODUCTION

For simplicity, this article focuses on pressurized water reactors (PWRs), although many of the concepts are transferable to boiling water reactors (BWRs). A PWR fuel assembly consists of a number of fuel rods, most commonly in a 15×15 or 17×17 array, within a skeleton consisting of control rod guide tubes attached to the upper and lower tie plates. The fuel rods are roughly 1 cm in diameter and 4 m long. Spacing between the rods is maintained by a number of spacer grids along the length of the assembly. The spacers at the top and bottom are commonly made of an Inconel alloy for high strength (to maintain spring force) and to minimize pressure drop of the coolant. The remaining spacer grids are typically a zirconium alloy to reduce parasitic neutron capture. The grids enhance thermal performance of the fuel assembly by mixing the coolant flow, in addition to supporting the fuel rods. Many designs have additional grids to further enhance mixing. The high velocity water coolant enters the bottom of the fuel assembly at temperatures around 290°C and is heated as it progresses towards the top. The bulk coolant temperature as the flow exits the assembly is typically around 320°C. This is below the saturation temperature at the operating pressure of about 15 MPa, and is thus sub-cooled although some degree of sub-cooled nucleate boiling occurs in the upper spans of the assembly.

The fuel rods themselves consist of hundreds of cylindrical UO_2 ceramic fuel pellets encased within a zirconium alloy cladding. UO_2 is the fuel of choice in light water reactors (LWRs) largely due to ease of fabrication and relative stability in water in the event of a cladding breach. In addition to the previously mentioned low neutron absorption cross section, zirconium alloys are selected for the cladding because of good corrosion properties under PWR conditions. Fuel rods are designed to initially have a gap between the pellet and the cladding, but swelling of the fuel pellets, which naturally results from thermal expansion and the production of fission products, in combination with cladding creep-down close that gap. With continued volumetric fission product swelling, the cladding is under a bi-axial tensile stress state for most of the operating life of the fuel rod. See the sidebar for background on LWR fuel performance.

FUEL FAILURE MECHANISMS

Grid-to-Rod Fretting

Grid-to-rod fretting (GTRF) is a failure mechanism driven by fluid structure interactions that produce a relative motion between the fuel rod and the spacer grid/spring. A necessary condition for GTRF is the reduction in contact force between the spacer grid/spring and the fuel rod, which can occur as a result of irradiation and thermally induced deformations. The relative motion accelerates wear of the fuel rod surface, and the spring, at the point of contact. Failure occurs when the cladding wear is through-wall (or sufficiently through-wall to compromise cladding integrity). There are a number of factors that influence a fuel assembly's resistance to GTRF, including the fuel assembly design and the operating

How would you…

…describe the overall significance of this paper?

This paper provides a concise description of the nuclear fuel used in pressurized water nuclear reactors and the most commonly observed fuel failure mechanisms.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

This paper introduces nuclear fuel performance challenges that are the subject of a Department of Energy modeling and simulation HUB for nuclear energy: the Consortium for Advanced Simulation of Light water reactors (CASL).

…describe this work to a layperson?

Nuclear energy supplies nearly 20% of the U.S. electrical demand. Better understanding and predictive simulation capability of nuclear fuel performance can enable increased power output and lifetime from this low-carbon emitting energy supply.

conditions. Since fretting wear is ultimately driven by the relative motion of the fuel assembly components, the key factors include fuel assembly stiffness and structural response to fluid flow. The current designs are tested extensively to make sure the frequencies of the fuel rods, spacer grids, and fuel assemblies are all acceptable and compatible.

In-core conditions can also provide significant challenges to GTRF resistance. For example, features in a number of plants induce significant cross-flow through the assembly. These include various core inlet and outlet configurations, in addition to flow perturbations near the core wall, known as the "baffle." Therefore, the design must be able to operate over a range of combined axial and radial flow. In some cases, GTRF failures have been experienced when core flow was increased in connection with a power uprate. Core design can also provide significant challenges. Low neutron leakage cores place the highest burnup fuel on the core periphery, but the high burnup fuel assemblies have the lowest contact forces (and/or largest gaps) between the spacer grid spring and the fuel rod while the core periphery typically produces the most challenging cross-flow conditions. Mixed cores, where multiple fuel assembly designs (e.g., designs from different vendors or different generation designs from the same vendor) are present in the same core, pose additional challenges including the introduction of additional cross-flow when the pressure drop along the fuel assembly length is different in adjacent assemblies.

Corrosion-Related Failures

The corrosion performance of today's cladding is generally sufficient to avoid corrosion-related failures, with two exceptions. The first is where some combination of design and operation results in a higher than designed temperature on the fuel cladding surface. The higher surface temperature accelerates the corrosion rate and can lead to through-wall corrosion or sufficient corrosion to locally embrittle the cladding by hydrogen pickup. The second mechanism is where corrosion products, typically referred to as "crud",

LWR FUEL PERFORMANCE

The term *fuel performance* in an LWR broadly applies to all aspects of in-reactor behavior. Fuel reliability, or the absence of fuel failures, is one important aspect of performance. A fuel failure is any breach of the cladding that allows coolant to enter the fuel rod and contact the fuel pellets and fission products. Fuel failures are not generally a regulatory issue, since the regulatory limits on the extent of fuel failures typically greatly exceed operational practices, but fuel reliability is nonetheless one of the most important aspects of commercial nuclear power. This is primarily because the fuel cladding is the first barrier to fission product release (the others being the reactor pressure vessel and the primary containment structure), driving an expectation of "operational excellence" relative to maintaining integrity of the fuel. Other factors, including cost and worker dose, further enhance the importance placed on fuel reliability. Costs associated with fuel failures include replacement of the fuel and replacement of lost power generation (fuel failures can cause a plant to shut down in some cases; depending on the specific details, this can cost on the order of one million dollars per day in lost generation and power replacement costs). Fuel failures also impact the radiation dose rates in working areas of the plant, which can challenge plans to keep worker doses low. Other aspects of fuel performance relate to the safety margins to a number of fuel design limits and regulatory limits. Examples include allowable pressure inside the fuel rod (related to fission gas release), corrosion thickness and hydrogen pickup in the cladding, cladding strain, and component growth or distortion. Figure A shows the improving trend of fuel failures over time for U.S. PWRs (although not shown in the figure, U.S. BWRs have also shown significant improvement over this time period). The data in this figure have been summarized from a review of the EPRI fuel reliability database (FRED), which contains detailed information about the U.S. fleet of nuclear reactors since 2000.

Improvements in fuel performance have driven overall improvements in plant operating capacity factors and an increase in average fuel burnup. The predominant fuel failure mechanisms can also shift as knowledge and implementation of improvements in one area out-pace the level of understanding in another area. In the case of PWRs, however, grid-to-rod fretting has almost always been the most common failure mechanism. An overview of fuel failure mechanisms observed in PWRs during the decade of the 2000s is shown in Figure B, as also summarized from the EPRI FRED database.

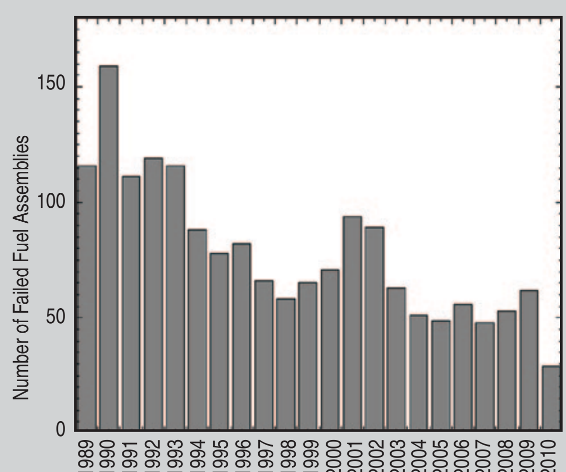

Figure A. Fuel failure trends in U.S. pressurized water reactors, as summarized from a review of the EPRI fuel reliability database (FRED).

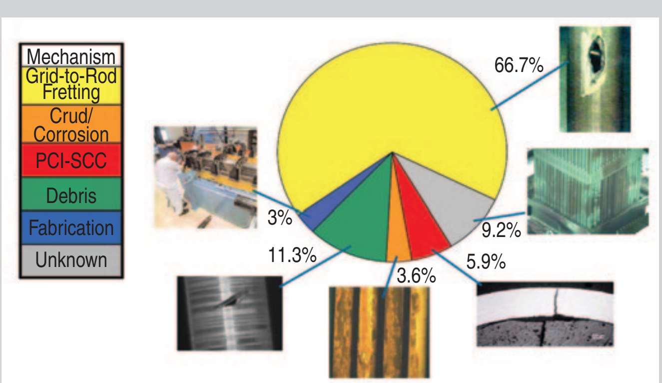

Figure B. Relative contribution of key failure mechanisms to overall fuel reliability (note: percentages are for U.S. PWRs and BWRs over the past decade).

build up on the cladding surface and locally raise the surface temperature or concentrate aggressive species (like lithium) on the surface of the fuel rod that increase local corrosion rates. Interestingly, all of the corrosion-related failures in U.S. PWRs in the last fifteen years have been crud-related.

Corrosion that occurs on the surfaces of the balance-of-plant (e.g., Inconel steam generators and stainless steel piping in PWRs) provides the source of the metallic species in the crud, which are predominately nickel ferrite spinels. These corrosion products are transported to the core where local heat transfer conditions lead to deposition on the fuel rod surface. Crud deposition is not always detrimental (a thin layer of crud can actually improve heat transfer), but significant deposits can challenge fuel reliability. Crud deposition can also lead to operational issues. For example, in a mechanism known as axial offset anomaly (AOA) or crud-induced power shift (CIPS), boron can precipitate in the crud layer at sufficient levels to alter the local power as a result of the very large thermal neutron absorption cross section of boron. Thus, the power is lowered in regions with high boron precipitation, forcing additional power from other regions of the fuel rod. In some cases, this can lead to fuel failure by a corrosion-related mechanism, but the primary impact is on operations since the plant has limits on acceptable levels of axial offset.

Pellet-Cladding Interaction

As already noted, a gap exists between the oxide fuel pellet and the cladding at the beginning of life. During operation, the clad experiences thermal and irradiation creep, and the fuel pellets expand due to thermal expansion and fission product accumulation, such that there is mechanical contact between the pellet and clad, and gap closure. Pellet-cladding interaction (PCI) is a stress-corrosion cracking mechanism from the combination of stress due to pellet-clad contact and an environment at the inner clad surface containing aggressive fission products, primarily iodine. This mechanism has historically been observed in BWRs where the control rod strategies lead to somewhat frequent (and more abrupt) power changes, and corresponding stress changes, throughout the cycle. However, the mechanism can also occur in PWRs when cladding stresses are sufficiently high. In general, PWRs are most vulnerable to PCI during the start-up in second cycle because the pellet-cladding gap is closed and the shuffling of fuel between cycles can lead to an assembly starting up in a higher power location than it was conditioned to in the previous operating cycle. Most of the recent failures in both BWRs and PWRs have been attributed to missing pellet surface (defects in fuel pellets that amplify local stress concentrations in the cladding).

THE CASL PROGRAM

There is a long-standing tie between nuclear fuel performance and modeling, from predicting core physics to optimizing the fuel reloading pattern to designing safety margins into fuel assemblies. For each of the fuel failure mechanisms discussed above, there have also been specific modeling efforts as summarized in the next three articles in this issue. Recently, the United States Department of Energy (DOE) established three Energy Innovation Hubs that, according to DOE, will "help advance highly promising areas of energy science and engineering from the early stage of research to the point where the technology can be handed off to the private sector. In other words, this work will ultimately lead to new clean energy solutions and new jobs for America's families."[1] One of these Hubs is focused on the modeling and simulation of nuclear reactors, and aims to answer the question: "How can we use modeling and simulation technologies to make significant leaps forward in nuclear reactor design and engineering?"[1] by utilizing high performance computing to investigate the coupled physics controlling nuclear fuel performance. The Consortium forAdvanced Simulation of Light Water Reactors (CASL) program is applying existing modeling and simulation capabilities, in addition to developing advanced capabilities where required, to create a usable environment for predictive simulation of light water reactors. Ultimately, this environment will incorporate science-based materials models, state-of-the-art numerical methods, modern computational science and engineering practices, and uncertainty quantification and validation against data from operating PWRs, single effect experiments, and integral tests. It will couple state-of-the-art fuel performance, neutronics, thermal-hydraulics (T-H), and structural models, and will be designed for implementation not only on today's leadership-class computers, but also for advanced architecture platforms now under development by DOE, as well as the engineering workstations of the future.

In order to address key phenomena that currently limit PWR fuel performance, especially when considering higher burnups or power uprates, CASL will focus on a set of technical challenge problems around GTRF, PCI and CRUD with a later emphasis on fuel assembly deformation issues that can also influence reactor operations. To provide solutions to these challenge problems, CASL is organized into five technical focus areas. Of particular relevance to fuel performance is the Materials Performance Optimization (MPO) focus area. The goal of this focus area is to deliver materials physics-based constitutive models and the appropriate materials performance modeling frameworks to the virtual reactor for GTRF, CRUD formation and growth, and PCI. For each of these challenge problems, MPO has identified a 3-D, coupled physics, engineering-scale simulation capability, which is the conduit by which MPO will provide input to the virtual reactor. These engineering-scale codes also serve as the repository for continuum models of fuel behavior that will be generated using lower length scale input.

CONCLUSION

Nuclear fuel performance broadly impacts all aspects of in-reactor behavior and can have profound effects on the power operation as in the case of axial offset anomaly. Over the past two decades, nuclear utilities working with the Electric Power Research Institute have significantly improved fuel reliability and limited fuel failure through improvements in operation and improved knowledge of fuel failure mechanisms. The most common types of fuel failure observed in recent years are grid-to-rod fretting, crud-induced corrosion failures and pellet clad interaction. While trends in fuel reliability have definitely improved, the desire to increase fuel burnup and reactor power levels may reverse that trend.

Better understanding of the coupled thermal hydraulics, neutronics and materials phenomena responsible for nuclear fuel performance, coupled with advancements in predictive simulation, provide the opportunity to both improve fuel utilization and to increase reactor power levels and operating lifetimes while continuing the fuel reliability trends. This is exactly the objective of a new Energy Innovation Hub, the Consortium for Advanced Light Water Reactors (CASL), funded by the Department of Energy. CASL is attempting to build computational tools that will enable improved reliability and utilization of nuclear energy. Success of CASL is predicated on the development of industrially-relevant computational design and analysis tools that ultimately are useful to the entire nuclear energy community to evaluate PWR fuel performance. The following articles in this issue describe the approaches to modeling fuel performance, the complicated challenges associated with understanding fuel clad degradation due to corrosion and hydrogen pickup and the use of lower length scale models to improve fuel property modeling.

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