Unmet Challenges for SCDAP/RELAP5-3D

Analysis of Severe Accidents for Light Water Nuclear Reactors with Heavily Fouled Cores

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2003 RELAP5 International Users Seminar, West Yellowstone, Montana, August 27-29

Fouling impacts fuel pin heat transfer and fuel pin axial growth

At the 2002 RELAP5 Users Seminar, Knudson listed Fuel pin failure timing analyses among the Wide Range of Analyses Completed. However, none of the five volumes of SCDAP/RELAP5-3D instructions explicitly address the impact of fouling at the start of the events on the timing of fuel pin failure or the propagation of fuel pin failures. The Volume 4 has extensive tables of properties of fuel pin components, but there is no reference to properties of fouling.

Volume 4 does not address the change in length of fuel pins due to the thermal impact of fouling.

Thermal impact of fouling

The heat transfer characteristics of the fouling in today's LWRs have not been reported. However, operational experience reveals that with fouling and corrosion the fuel pin heat transfer characteristics are vastly degraded in contrast to clean pins.
At the River Bend BWR, the severe fouling led to corrosion thicknesses sufficient to penetrate the cladding of many fuel pins.
At more than 20 units fouling has trapped boron and this led to offsets in the power distribution. In one case, control rod binding was traced to guide tubes that deformed when fouled fuel pins lengthened beyond end space limits and bent. At Paks Units 1-3, reduced flow restricted the power level. Several units now employ ultrasonic means to remove fouling.

Fouling is ubiquitous

River Bend
Paks-2

Experimental Boiling Water Reactor (EBWR)
Argonne Low Power Reactor (SL-1)

More than 20 LWR's have had power distribution shifts caused by boron trapped in fouling.

Two units have deployed ultrasonic fuel cleaning to remove fouling: South Texas Project and Callaway.

River Bend Station Unit 1

A SCDAP/RELAP5-3D analysis of fuel pin failure timing for severe accidents at the River Bend Station would be revealing. Multiple fuel pin failures were attributed to "…an unusually heavy deposition of crud on the fuel bundles." It was, "Determined that an insulating layer of crud caused accelerated fuel rod corrosion." There is no quantitative disclosure of the effective thermal conductivity of the insulating layer of crud. It is disclosed that "Measured zircaloy oxide thickness on high power unfailed HGE bundles was up to 6 mils at the 50" level where the perforations occurred." However, there has been no public disclosure of the measured zircaloy oxide thickness on the **failed** HGE bundles.

Paks Units 1-3

A SCDAP/RELAP5-3D analysis of fuel pin failure timing for the Paks Units 1-3 would be revealing. In a May 2003 report to the Chairman, Hungarian AEC, the extensive fouling of the Paks units is candidly discussed. There is no description of the thermal resistance of the fouling or the amount of zircalloy corrosion. However, the fouling (magentite)) has been extensive. Quoting, "...magnetite deposits in the fuel assembles increased and the cooling water flow-rate decreased. Consequently the power of Units 1-3 had to be decreased." Chemical cleaning of fuel elements in batches of seven elements became routine. In 2002, Framatome ANP expanded the cleaning process to 30 element batches.

Paks Units 1-3 (Continued)

On 10 April 2003, while the assemblies were being cleaned for Unit 2, severe damage occurred to an entire batch. The state of the fuel prior to the accident has not been disclosed. But as this data including the extent of fouling become available, it is likely that analysis will yield further insights on the impact of fouling on severe accidents. The cleaning process for the 30 element batch was designed by Framatom ANP. V. Asmolov, the Director of the Kurchatov Institute observed, "... it was a hand-made accident caused by those who, mildly speaking, clumsily thrust where they shouldn't. This is a precious experience." Clearly, this accident is a challenge for the analysts who deploy SCDAP/RELAP5-3D and related tools.

Axial Offset Anomaly (AOA)

More than 20 LWR's have had power distribution shifts caused by boron-loaded fouling. EPRI reports, "The root cause of AOA is corrosion product deposition in the upper spans of fuel assemblies as a result of sub-cooled nucleate boiling." EPRI does not report the thermal conductivity of the deposits or the extent of zirconium oxidation. Deposits were scraped from several fuel assemblies following a cycle that experienced AOA. The thickness of the samples was in the range of 125 microns, however, that likely does not include zirconium oxides that are integral with the base cladding. Again, it is clear that the deposits constitute a significant thermal resistance that should be incorporated in SCDAP/RELAP5-3D.

AOA (continued)

NRC Information Notice 97-85 clarifies AOA:
Axial offset (AO) is a measure of the difference between power in the upper and lower portions of the core. This difference must remain within limits established in the technical specifications to ensure that both SDM and clad local peaking factors are not exceeded. Exceeding these limits could result in the reactor fuel exceeding 10 CFR 50.46 limits on fuel clad temperature (1204C). If the reactor approaches these limits, compensatory measures, including a power reduction, must be taken to maintain the reactor within its operational limits.
However, the Notice does not include any discussion of the very substantial temperature increase of the limiting fuel pins

AOA (continued)

that results from the same fouling that leads to the AOA. This temperature increase likely exceeds 250C, however the consequent increase beyond the 1204C limit of 10.46 is far greater than 250C because the fuel rods bend, distort and burst during the accident. There is a simultaneous set of physical and chemical occurrences. The fouling layers and the zirconium oxide layers become cracked, broken, shocked and loosened while zirconium-water reactions proceed at accelerating rates as additional zirconium is exposed to the water steam conditions at increasing temperatures. The AOA data reveal starting conditions that must be considered in related SCDAP/RELAP5-3D analyses of 10.46 accidents.

South Texas Project and Callaway

Quotes from EPRI press release: *Ultrasonic Fuel Cleaning*
While AOA has not been a problem for the ***South Texas Project****, the utility purchased ultrasonic fuel cleaners for each of its two units as a proactive measure for corrosion product control after replacing steam generators and uprating both units. All reload fuel for the Unit 2 reactor was cleaned in October 2002. Reload fuel for Unit 1 will be cleaned in April 2003.*
According to Ameren's Gail Gary, the core at the ***Callaway*** *plant remained free of AOA throughout the fuel cycle for the first time in the eight most recent cycles after one fuel cycle in which all reload fuel was ultrasonically cleaned.*

Experimental Boiling Water Reactor

The Experimental Boiling Water Reactor (EBWR) was designed and operated by Argonne National Laboratory during the late 1950s and early 1960s. An unfortunate selection of aluminum alloy for core filler pieces led to deposits of hydrated alumina on the zirconium clad fuel elements. Thickness of the fouling was 0.013 cm, the thermal conductivity was 0.008 W/cm-C; thus the heat transfer coefficient was 0.6 W/(cm2)(C). The peak heat flux in today’s large light water reactors is in the range of 150 W/cm2 and the temperature gradient for EBWR-type fouling would be 250 C. However, the heat transfer coefficient for the combined fouling and zircaloy oxide of today's units is likely substantially less than the EBWR case.

Argonne Low Power Reactor (SL-1)

The SL-1 was destroyed in a Reactivity Insertion Accident (RIA) on January 3, 1961. Fouling of the aluminum clad fuel plates likely intensified the severity of the accident. However, fouling was not considered by the analysts who investigated this RIA. Here is a quote from GE Report, Additional Analysis of the SL-1 Excursion, Report IDO-19313, 1962: *"The thickness of the cladding has an important effect on the magnitude of the excursion. Because of the extremely short period, this 0.89 mm cladding became an effective thermal insulator and impeded the flow of heat to the reactor water where it could initiate shutdown of the reactor."*

Now, inasmuch as the thermal conductivity of aluminum is

SL-1 (continued)

about 200 times greater than the corrosion on the fuel plate, a corrosion layer only 0.00445 millimeters thick would have the same temperature gradient as 0.89 mm of aluminum cladding. Alternatively, the measured corrosion product thickness of 0.09 mm has 20 times the temperature gradient of the aluminum cladding. Ignoring the corrosion thus yields a grossly incomplete analysis in determining turnaround characteristics.

FLECHT Run 9573 (ref. WCAP-7665)

Document, “Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Cooled Nuclear Reactors-Opinion of the Commission,” Docket No. RM50-1, December 28, 1973, the Commission concluded, “It is apparent , however, that more experiments with zircaloy cladding are needed to overcome the impression left from run 9573.”

The extensive failure of the FLECHT assembly at 18 seconds after reflood was not anticipated. (Limited runaway.) This may be fertile territory for SCDAP/RELAP5-3D. Tasks would include analysis of Run 9573 as well as design and analysis of further tests.

Severe Fuel Damage - Scoping Test

On Feb. 22, 1983, MacDonald of INEL at ACRS, discussed a destructive test in PBF of a 32 rod array of PWR 17x17 fuel, 36 inches long. *"We observed rapid oxidation of the lower portion of the bundle. It wasn't expected. It cannot be calculated with existing models. It is a falme-front phenomena which is not addressed in the existing models. It will probably be addressed in the coming months or years. ... Think of a sparkler. That kind of phenomenon. One of the problems with the existing models, all the axial loadings are extremely course. They just do not deal with the spread of a zircaloy fire."*

This was a case of substantial and unexpected runaway.

Fouling and Runaway

Denying Leyse's Petitions PRM-50-73 & 73A the NRC wrote:
"Under conditions where heavy crud deposition occurs, fuel damage could eventually lead to cladding cracks or ballooning effects. The crud layer may then break off and fuel pellets will be cooled directly by the water, thus lowering the cladding temperature. Although the elevated cladding temperature could theoretically trigger a metal-water reaction in a very limited area of the fuel cladding, the crud also shields the cladding from the water and causes significant resistance to the metal-water reaction. Therefore, the NRC has concluded that the petitioner's concern about autocatalytic zirconium-water reactions is not valid."

Summary and Challenges

Fouling is ubiquitous

Fouling is a substantial thermal resistance

Fouling has a greater impact than burnup

Current fouling must be classified: thermal characteristics, composition, porosity, etc.

Fouling must be incorporated in SCDAP/RELAP