

Robust PCI Monitoring During PWR Operation at Southern Nuclear

Adel Alapour, Ryan M. Joyce
Southern Nuclear Operating Company
42 Inverness Center Parkway
Birmingham, AL 35242 USA
aalapour@southernco.com

Arthur S. DiGiovine, Shaun Tarves, Nestor Patino
Studsvik Scandpower, Inc.
1087 Beacon St.
Ste 301
Newton, MA USA 02459 USA
arthur.digiovine@studsvik.com

Andrew Worrall, Robbie Gregg, Glyn Rossiter
UK National Nuclear Laboratory
A709, Springfields
Salwick, Preston
Lancashire, UK
andrew.worrall@nnl.co.uk

Abstract – *Emerging industry practice is transitioning from global ramp rate monitoring to local power monitoring for PCI concerns. In consideration of these changes, Southern Nuclear has worked with Studsvik and the UK National Nuclear Laboratory (NNL) to evaluate more robust PCI monitoring capabilities during plant operation. Using Studsvik's automated reactivity management system, CMSOps and NNL's fuel performance code, ENIGMA, an actual operational event from one of Southern's PWR's was evaluated using several PCI methodologies. This study was of particular interest since there was an indication of leaking fuel within 24 hours of the event described herein. The methodologies applied in evaluating this event range from simplistic calculations of changes in nodal linear heat generation rates, to explicit individual pin-by-pin thermo-mechanical fuel performance assessment. The merits and deficiencies of the various methods are presented. The clear choice is the coupled CMS to ENIGMA capability, termed ONUS. In the case evaluated here for Southern Nuclear, the analyses confirmed that the fuel failure mechanism was not due to classical PCI, thereby, allowing the utility to eliminate this mechanism from further investigation.*

I. INTRODUCTION

Emerging focus on improving fuel performance and efforts to diminish fuel failures has led to better fuel mechanical designs and analysis techniques employed in analyzing fuel failure mechanisms. Additionally, recent focus has raised the question whether these modeling approaches can be applied not only during fuel loading core design calculations, but during actual plant operation as well.

This paper details recent developments in techniques for improving analysis of PCI during plant operation.

Several modeling approaches used to evaluate PCI are presented. The methods range from inference of margin to PCI via examining changes in LHGR to detailed thermo-mechanical fuel performance analysis of actual fuel clad stress and clad crack length propagation. Finally, the methods are applied to an actual operating PWR operational transient.

II. PCI ANALYSIS METHODS OVERVIEW

Fuel performance has long been a part of reload core design and analysis. Typically, only bounding analysis of the most limiting fuel pins is included in the core design process.

The difference in the analysis presented here is two-fold. First, an actual transient from operating reactors that resulted in changes to LHGR is analyzed for margin to PCI. Second, since PCI is a pin-based phenomenon, all fuel pins in the core are equally analyzed (e.g., no bounding analysis of only limiting pins was used).

The assessment demonstrates that the various methods for examining PCI can be applied to actual operating events and screening criteria for bounding analysis is not necessary.

II. A. Delta-kW/ft Model

In a delta-kW/ft model, changes in linear heat generation rate (LHGR) between successive calculation points (statepoints) are examined to ensure the values are within acceptable limits. The LHGR values can be node-averaged data, where LHGR's for each pin in an assembly are normalized within an assembly and divided axially into nodes.

The delta-kW/ft model uses the maximum change in LHGR as a potential indicator of a PCI violation. The disadvantage to this approach is that it may ignore a relatively small change in LHGR that could indicate a PCI violation if the LHGR was already near the limit. Additionally, this approach could incorrectly recognize a relatively large change in LHGR as a potential PCI issue, even though the large change occurred in a pin that was operating well below violation limits. This is illustrated in Fig. 1.

To compensate for these shortcomings, conservative values for the limiting delta-kW/ft are typically applied. Although this does lend itself to mitigating PCI concerns during a power maneuver, for example, it can be economically inefficient, requiring a slower return to power than is actually needed to preclude PCI.

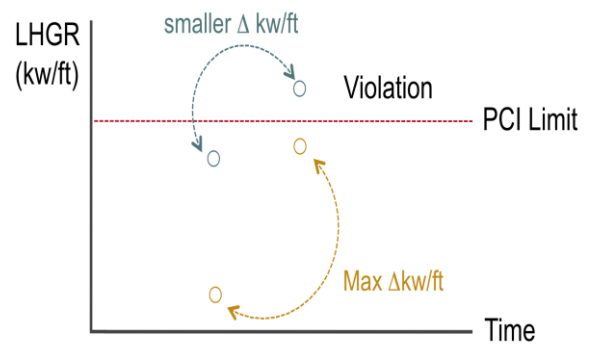


Fig. 1. Limitations to delta kW/ft model

The advantage of the delta-kW/ft model is that data is readily available from the core simulation neutronic models, with relatively fast computational times.

II. B. Threshold LHGR PCI Model

A more sophisticated method of monitoring PCI using LHGR data is to account for the physical phenomenon of pin conditioning, the time-dependent annealing that occurs when a pin LHGR remains at the same power for an extended period. By modeling conditioning, greater changes in LHGR are achievable without violating PCI limits, since the pellet and cladding conditioning are factored into the calculation.

Fig. 2 presents a graphical depiction of how a threshold model works. The lower dashed line represents the conditioning threshold. The upper dashed line is the PCI violation limit, which is a delta above the PCI threshold. If, during plant operation, a pin LHGR value exceeds the threshold, "conditioning" begins for that pin. During conditioning the threshold increases and, since the PCI limit is a fixed delta above the threshold, the PCI violation limit also increases. Provided the LHGR increases at a rate slow enough to remain below the PCI limit, no violation occurs. However, if the LHGR changes more rapidly than the threshold changes, a PCI violation may occur.

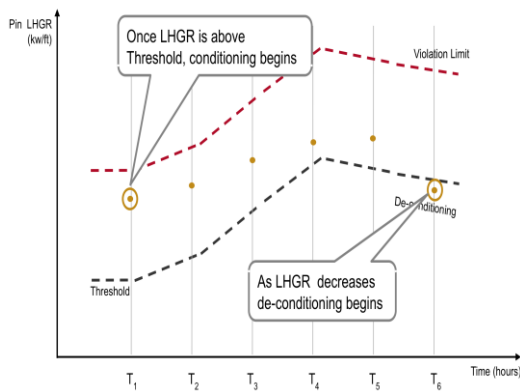


Fig. 2. Threshold PCI Model using LHGR data

Conversely, once the LHGR is above the threshold and then begins to decrease, the threshold and PCI violation limits begin to decrease or de-condition.

The drawback with this particular model for PWRs is that the threshold level, the PCI violation limit delta, and the conditioning & de-conditioning rates are not typically supplied from the fuel vendor. They can be determined from detailed thermo-mechanical fuel performance calculations or via experimental data. Additionally, detailed neutronic data of the actual LHGR's during operation has previously been difficult to obtain.

II. C. Detailed Thermo-Mechanical Fuel Performance Analysis

When the LHGR of a fuel pin increases, the fuel pin becomes prone to a failure mechanism known as PCI. The specific mechanism is referred to as stress corrosion cracking (SCC) and occurs at the inner wall of the fuel pin cladding. Although the power increase causes a differential thermal expansion in the fuel clad, which in turn generates a tensile stress in the cladding (hoop stress), a certain final power level is also necessary for failure to occur.

This behavior implies that a high temperature in the fuel, leading to the release of chemically aggressive fission products (such as iodine), is also required for PCI. The failure is not immediate, suggesting that the crack has to develop and propagate until the crack length is greater than the cladding thickness, requiring that the fuel pin be at power for a certain period of time.

Therefore, in order to properly assess vulnerability to PCI due to local power changes, the key indicators from a

fuel performance perspective are maximum local concentrated clad hoop stress and maximum local clad crack length.

Clad Hoop Stress - is the stress that forces a crack in the clad wall to "open up" and propagate through the cladding. Formation of a crack is a prerequisite to PCI and is therefore an ideal indication of the susceptibility of a fuel pin to PCI failure. However, PCI failure will not necessarily occur only by formation of the crack by itself.

Clad Yield Stress - the point at which the material moves from elastic to plastic deformation, i.e., does not "recover" when the stress is removed. In this analysis the difference in the calculated clad hoop stress to clad yield stress, or margin to clad failure, is used. The clad yield stress limit is dependent on the fuel design and conditions during plant operation.

Clad Crack Length - Once a crack has formed in the clad wall, the length and growth of the crack is a direct indication of the potential for a PCI failure. However, the failure threshold occurs when the calculated crack length exceeds the clad wall thickness.

It is important to note that the clad hoop stress and clad crack length are very much dependent on the irradiation history (LHGR vs. exposure) as well as the local LHGR of every fuel pin. Therefore, a full power history (LHGR vs. time) of every fuel pin for the entire time it has been in the reactor core must be modeled as part of the PCI assessment. (Note this is for Zircaloy clad fuel and is not necessarily applicable for other cladding material.)

The deficiency with this approach has been in its application; typically only the most limiting pins from a core neutronic simulation are selected for this more thorough fuel performance analysis. This brings into question the criteria used to select the candidate pins. During an actual operational transient it is very difficult to set inclusive criteria to ensure the most limiting pins are correctly chosen. As with the other methods, until now, there has not been an efficient way to perform this more robust assessment during plant operations.

III. OPEN VALVE TEST EVENT DESCRIPTION

To demonstrate the application of the various PCI evaluation methods to actual operating data, a specific event from an operating PWR in Southern Nuclear's fleet was selected. The event is called an open valve test. The test itself should result in fairly mild changes in LHGR values. However, upon completion of the test in the actual plant, coolant off-gas activity increased indicating fuel failure. The analysis was motivated by the need to eliminate PCI as a possible cause.

In an open valve test the reactor core inlet coolant temperature is reduced to facilitate testing on the secondary side. The temperature reduction is mild, on the order of a few degrees.

This particular event was conducted near BOC at full reactor power (HFP). The MTC for the core at this condition was slightly negative in value (meaning as temperature decreases positive reactivity is inserted). In order for the reactor to remain critical this positive reactivity insertion must be balanced with the insertion of negative reactivity by partially inserting the lead control bank. During this event, the lead bank was partially inserted approximately 10% into the core.

Once the testing on the secondary side is complete, the lead control bank is withdrawn to a full out position as the inlet coolant temperature is slowly raised back to nominal.

During this movement of the lead control bank at HFP LHGR is redistributed axially and radially within the core. Since PCI is dependent on changes in LHGR vs. time, this event was chosen to apply the various PCI methods previously discussed.

IV. ANALYSIS MODELS OF SPECIFIC OPERATING EVENTS DESCRIPTION

In order to assess PCI during operating events, several calculational components are necessary: an accurate three-dimensional, cycle-specific core neutronic model, detailed core follow data for the actual transients, an accurate thermo-mechanical fuel performance code, a system coupling these models together, and a data management system to digest and resolve all the data points into a succinct summary for the events. This section describes these analysis models.

IV. A. CMS Model Description

A cycle-specific CMS neutronics model, comprised of Studsvik's CASMO¹ and SIMULATE² codes, has been used for several cycles at Southern Nuclear for fuel vendor oversight, operational support, and operator simulator training. These models employ CASMO as the cross-section lattice code and SIMULATE as the steady-state nodal simulator.

IV. B. CMSOps Model Description

Studsvik's CMSOps³ was used to integrate detailed plant operational data during the events analyzed within this paper⁴. CMSOps manages the high-fidelity CMS neutronics model for reactivity management, including a threshold based PCI assessment.

CMSOps ensures the CMS core neutronics model accurately reflects the plant's actual detailed operating history by automating core follow. CMSOps reads plant measured signals on a minute-by-minute frequency and detects any changes in the values of these signals. Based on certain change criteria being met (e.g., changes in power level, lead control bank position, inlet temperature change, etc.), CMSOps automatically activates execution and updating of the cycle-specific SIMULATE model.

CMSOps is built on a very efficient database that archives all of the measured signals and all calculated neutronic parameters, making it easy to assess PCI using other techniques, such as the delta-kW/ft and the threshold models.

Studsvik, with assistance from Southern's engineers, implemented CMSOps for the plant in which the operating event (open valve test) was conducted. This event resulted in several SIMULATE calculations over a small amount of time (~8 hours), each of which produced detailed three-dimensional LHGR pin-maps.

IV. C. ENIGMA Thermo-Mechanical Fuel Performance Model Description

The UK National Nuclear Laboratory (NNL) participated in the analysis by evaluating the CMS data from the operational event using their fuel performance code, ENIGMA⁵.

ENIGMA is a fully validated fuel performance code that has been used for several definitive design and licensing assessments for both UO₂ and MOX fuel, including licensing UO₂ and gadolinia-doped UO₂ in Sizewell B (the UK's only PWR) and the Finnish Loviisa VVER-440 reactor, and mixed oxide (MOX) fuel in the Swiss Beznau-1 PWR. ENIGMA is also used in support of MOX production in the Sellafield MOX Plant (SMP) and to perform feasibility studies for advanced fuel concepts.

Recently NNL and Studsvik have coupled the CMS core neutronics model and ENIGMA's fuel performance analysis capabilities, producing ONUS^{6,7} to perform thermo-mechanical analysis of every fuel pin in the core.

Since CMSOps automatically generates CMS cases for the entire operational event, detailed LHGR's generated are available for every fuel pin and axial pin node in the core. This data was coupled directly with ENIGMA to perform PCI evaluation for every pin in the core, using its detailed power history. ONUS is also then used to display the 3-D pin-by-pin data available following the analysis.

V. PCI RESULTS FROM OPEN VALVE TEST

This event provided an opportunity to explore the various ways of monitoring PCI limits in order to mitigate PCI violations. The three various methods explained previously are applied.

Fig.3. presents a graphical result from ONUS (ENIGMA/CMS), of the normalized, axially integrated (radial) pin-by-pin LHGR at the point of deepest insertion of the lead control bank. The core loading pattern is easily recognized as a contemporary low-leakage one.

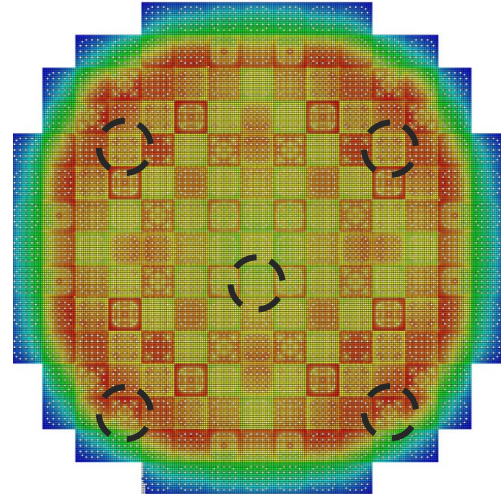


Fig.3. Relative Power Density Distribution and Lead Control Bank Locations during Event (Circles)

Note also the locations of the lead control bank, which is partially inserted during the open valve test. Since the locations are in relatively high-powered regions, the concern of PCI during the event is warranted.

V. A. Delta-kW/ft Results for Open Valve Test

Using data from the open valve test event, the delta-kW/ft analysis was applied to assess margin to PCI limit. This analysis calculated delta-kW/ft/hr, as compared to the immediately previous case, calculated with data for every node in the core, as shown in Fig. 4. and Fig. 5.

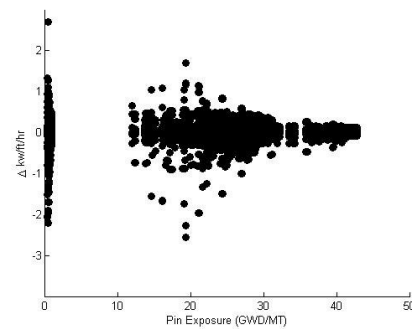


Fig. 4. Nodal delta-kW/ft/hr during Open Valve Test vs. Exposure.

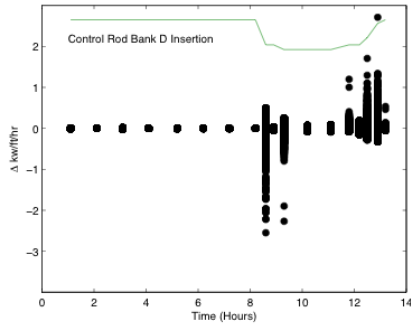


Fig. 5. Nodal delta-kW/ft/hr during Open Valve Test vs. Time

The nodal delta-kW/ft/hr values presented in the figure coincide with the expected behavior. During the event nodes where power is being suppressed as the lead control bank is inserted experience a negative delta-kW/ft/hr. Conversely, nodes where power is being increased as the lead control bank is withdrawn experience a positive delta-kW/ft/hr. The magnitude of the changes (in delta-kW/ft/hr) are consistent with the expected increase in clad strain – a key component of PCI – given that the lead control bank movement occurs over a relatively short time.

The event was also evaluated with the delta-kW/ft approach by using data for each fuel *pin* in the core (data which is typically not available during operational transients).

Exploring the same plot of delta-kW/ft/hr with data for every pin in every node in the core (Fig. 6.) highlights one major inadequacy of this monitoring method – namely that it ignores local (pin-level) changes, which can be significantly larger in magnitude than more coarse node-wise data.

This pin data is compared with the nodal results and presented as Fig.6. Note that in the following plot, the data in red is pin-by-pin delta-kw/ft/hr, while the data in black is the nodal delta-kw/ft/hr.

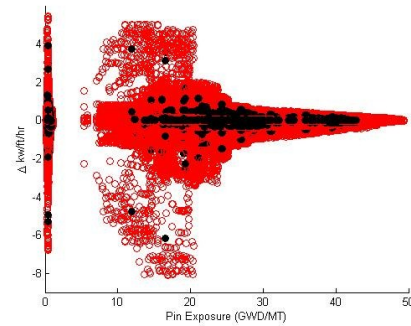


Fig. 6. Pin-by-Pin Margin-to-PCI during Open Valve Test

The results demonstrate that using nodal data vs. detailed pin information does not show the significantly higher changes in LHGR that individual pins could experience during a power transient. (Even though for this particular case there is not sufficient evidence, even with thermo-mechanical fuel performance analysis to support PCI failure.)

Finally, neither the nodal data based delta-kW/ft/hr model nor the pin-by-pin delta-kW/ft/hr models are sufficient for diagnosing PCI. PCI is predicated not only in changes in kW/ft but also a time component (e.g., how quickly the changes have occurred, has the fuel cladding been conditioned to the higher LHGR, etc.).

V. B. Threshold LHGR Results for Results for Open Valve Test

Using the same detailed pin-by-pin LHGR data generated from CMSOps during the open valve test, the alternative threshold model⁸ was applied. As previously mentioned, this model requires certain constants for the components for monitoring (e.g., conditioning/de-conditioning rates, etc.).

The results presented in Fig. 7. indicates similar margin for the most limiting pin during the transient using the threshold model and empirical data from Studsvik Nuclear⁹.

In the figure the inlet temperature vs. time during the event is plotted against the right-side y-axis and the lead control bank position on the left-side y-axis.

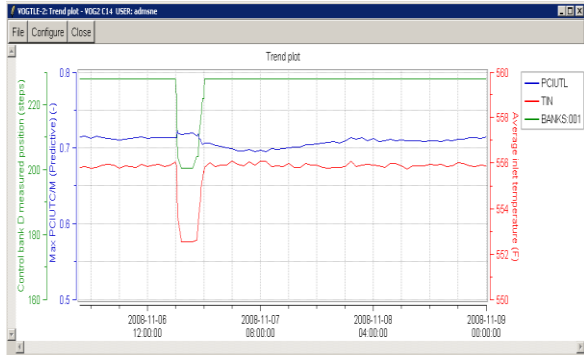


Fig. 7. Margin to PCI During Open Valve Test from Threshold Model

Although every pin was evaluated for susceptibility to PCI, a simple way to summarize the event is shown in the figure as PCIUTL (shown in blue). PCIUTL is defined as the margin to PCI for the most limiting *pin* per time step during the event. The model accommodates the situation where the limiting pin location is changing from time step to time step. Basically, the margin is calculated for every pin and only the most limiting margin value is presented in the figure. The results show that there was sufficient margin during the event to PCI failure.

V. C. Thermo-Mechanical Fuel Performance Analysis Results

The last PCI analysis conducted for the open valve test was to analyze every pin via the ONUS integrated fuel performance analysis (ENIGMA and CMS using detailed operational histories from CMSOps CMSOps)¹⁰.

The most limiting parameter analyzed was the margin to maximum clad yield stress during the open valve test. The result is summarized here as Fig. 8. The ENIGMA analysis assumed a failure yield stress of 93.5 kPSI. (The actual limit is fuel design type- and exposure-dependent, but the variation is insignificant with the amount of margin that exists for the fuel during this test.)

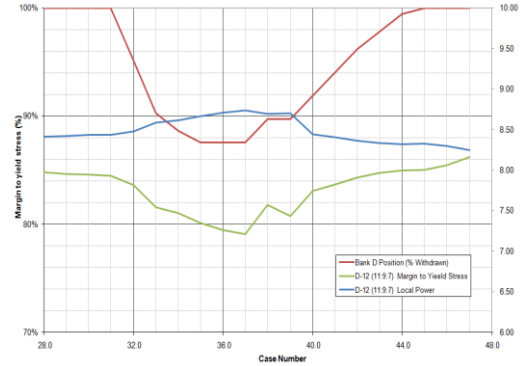


Fig. 8. Margin to Yield Stress Limit of Most Limiting Pin During Open Valve Test

The cases shown in the figure's x-axis correspond to the time during which the open valve test was conducted, (approximately 8 hours). In the figure, the most limiting pin – in terms of smallest margin to yield stress (clad failure) – was in one of the assemblies which the lead control bank was partially inserted/withdrawn. The minimum margin occurred axially near the core mid-plane.

The figure also shows the lead control bank position during the test and the LHGR of the limiting pin. The minimum margin (highest stress) occurs at the deepest insertion of the lead control bank, most probably due to the LHGR being redistributed as the lead control bank suppresses power in the upper axial region of the assemblies into which they are inserted.

Other findings from the ONUS results are that the pins with the highest crack lengths (albeit with crack lengths only a fraction of 1% of the total clad thickness) are from higher depleted assemblies (pin-average exposures of about 45 GWd/T) where pellet clad gap closure will have already occurred. However, because the higher depleted assemblies were located on the periphery of the core, the pin LHGRs before, during, and after the event were relatively low and consequently SCC propagation negligible.

Detailed pin-by-pin results for minimum margin yield stress during the event are presented in Fig. 9. The axial location where the minimum margin occurs is in the bottom half of the core. When the lead control bank is partially inserted, the power in this lower region of the core increases leading to a systematic increase in stress on the clad (margin decrease). When this lead control bank is fully withdrawn, the power in this lower region decreases again and the stress on the clad relaxes (margin increase).

Pins with the lowest margin during the event are from the same assembly locations in which the lead control bank was partially inserted during the event. These assemblies have pin exposures high enough that the fuel/clad gap is expected to have closed prior to the event.

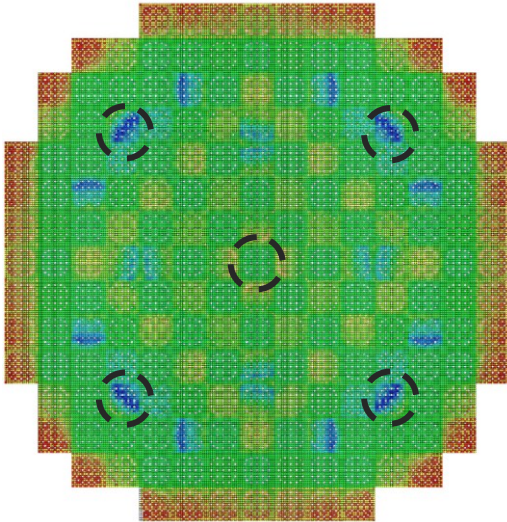


Fig. 9. Minimum margin to clad yield stress (lead control bank partially inserted)

The results indicate there is still a large degree of margin before fuel failure would occur, even for the most limiting pin locations during this event. (Fuel failure might still be possible due to prior mechanical damage that could have been exacerbated during this event; missing pellet surface, introduction of foreign material hitting the fuel pin, hydriding, etc.)

VI. CONCLUSION

Three different methodologies to evaluate fuel performance in terms of PCI were applied to an actual transient from operating PWR. The methods range from examining changes in coarse nodal LHGR's (delta-kW/ft model) during the transient as an indicator of PCI susceptibility, to a threshold-based pin-by-pin model, to thermo-mechanical fuel performance analysis for every pin in the entire core.

The work here demonstrates that all three approaches are computationally feasible and that limitations of performing coarse analysis using nodal LHGR data (in which the margin to PCI is underestimated) can be replaced with explicit pin-by-pin thermo-mechanical fuel performance evaluation during plant operation.

Furthermore, using these thorough and rigorous methods, it has provided confidence that the fuel failure experienced during the open valve test in the Southern Nuclear PWR was not caused by PCI. This analysis helped eliminated this potential cause from any further investigation and has allowed Southern Nuclear to focus resources onto other potential sources of fuel failure. (Root cause analysis results based on poolside inspections conducted by Southern at the end of cycle turned out to be consistent with results from these studies.)

The techniques presented in this study were applied to analyze a past operating event, but they can also easily be applied to the simulation of a future power maneuvers to assess margin to fuel performance parameters (such as clad stress, strain) before the event actually occurs. The results could then be used to alter the power maneuver, if necessary, to ensure sufficient margin and help reduce potential fuel failures.

The coupled CMS-ENIGMA analysis has demonstrated how an explicit pin-by-pin PCI analysis can be applied during actual operating events for fuel performance assessment.

NOMENCLATURE

- PCI – Pellet Clad Interaction
- LHGR – Linear Heat Generation Rate
- PWR – Pressurized Water Reactor
- Delta-kW/ft – delta kilowatt per foot (energy)
- SCC - Stress Corrosion Cracking
- BOC – Beginning of Cycle
- HFP – Hot Full Power
- MTC – Moderator Temperature Coefficient
- CMS – Studsvik Core Management System
- kPSI – kilo-pounds per square inch (pressure)
- MPa – mega Pascals (pressure)
- GWd/T – gigawatt days per metric ton (exposure)

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