PEGASUS™: An Advanced Tool for Assessing Pellet-Cladding Interaction

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ABSTRACT

PEGASUS™ has been developed by Structural Integrity Associates, Inc., as a generalized fuel cycle code built upon a robust finite element computational framework. PEGASUS is designed to calculate fuel response throughout the entire fuel cycle including in-core fuel behavior during normal operation and transient events as well as back-end events associated with dry storage and transportation.

This paper describes the application of PEGASUS to PCI margin analysis. The history of PCI failures and the current industry-standard methodology are summarized. Discussion is then provided of a unique methodology under development combining 2D and 3D finite element models within one analysis (i.e., 'hybrid model') to balance run time of the full length model with the needed fidelity in the PCI-susceptible region to assess margin. Discussion is also provided of high-fidelity 3D models and results for PCI-type analyses.

INTRODUCTION

In the current economic environment where nuclear plants compete with less costly energy sources, a quicker return to full power correlates to more power generated and increased operating efficiency. This may be achieved, for example, with a shorter startup post-refueling or a quicker return-to-power following any number of plant evolutions including load follow, control blade repositioning, equipment outage or maintenance, extended low power operation, scram, etc. Furthermore, efforts are underway to extend operating cycles through increased enrichment and discharge burnups. Such strategies to increase operating efficiency may increase the risk of pellet-cladding interaction (PCI), a failure mechanism that can occur under conditions of high local cladding stress in conjunction with aggressive chemical species at the cladding inner surface. These conditions can occur during rapid and extensive local power changes and can be further aggravated by the presence of fuel pellet defects such as missing pellet surface (MPS). Several commercial reactor fuel failure events in the recent past, the latest in 2019, suggest a PCI-type failure cause. To safely manage changes in core operation, the margin to conditions promoting PCI-type failures must be assessed prior to implementation of such operational changes.

While PCI is not a high visibility issue under current operating strategies (i.e., utilities are managing the issue well), the industry is moving towards a) flexible operation (e.g., load follow, extended low power operation), b) higher burnup and higher energy core designs for longer operating cycles, and c) higher operating efficiencies. These and other changes have the potential to reduce margin to PCI-type failures.

Technical aspects of the PCI failure mechanism are quite complex and require performance of high-fidelity simulations using an advanced fuel performance code validated by applicable experimental data to be a predictive tool used to compute the integral thermal, mechanical and chemical aspects of the failure mechanism. Structural Integrity (SI) Nuclear Fuel Technology (NFT) staff, formerly ANATECH, have, for several decades, been at the forefront of this development and, working as a contractor to the Electric Power Research Institute (EPRI), developed EPRI's 2D fuel performance code Falcon, which is regarded in the industry as the most advanced tool for the modeling and simulation of the PCI mechanism [1]. Using Falcon, SI-NFT have developed expert systems in the form of operational guidelines [2] to avoid PCI failures, and have worked closely with a number of utilities individually to 1) assess margin to failure under their particular operating strategies and provide guidance on ways to ensure adequate margin to PCI-type failures, and 2) provide a thorough understanding of the PCI failure mechanism, contributing factors, remedies and means of assessing margin to PCI-type failures through training of utility staff.

The Falcon 2D finite-element methodology treats the 3D PCI problem in a two-step process: a global analysis utilizing 2D R-Z geometry, with one-way coupling to a local 2D R-θ geometry. Aside from the obvious limitations of this approach, the fidelity of the analysis results is highly dependent on the skill and depth of knowledge of the analyst. The PEGASUS nuclear behavior code [3-5] advances the 2D PCI modeling methodology to a full 3D finite-element modeling capability, featuring a computationally robust thermo-mechanics simulation platform. Coupled to the requisite nuclear material constitutive models, PEGASUS provides the high fidelity analysis tool required for PCI margin assessment.

A brief overview of the PCI failure mechanism and its impacts on the nuclear industry is first described. Next, an overview of methods currently available to the nuclear industry for evaluating PCI margin is outlined. We conclude the discussion with an overview of the advanced capabilities of PEGASUS for evaluating PCI margin.

PCI FAILURE MECHANISM AND INDUSTRY EXPERIENCE

Under conditions of increasing power, the fuel pellet thermally expands outward and cracks due to thermal stresses resulting from differential thermal expansion and the significant thermal gradient generated across the pellet radius. The increased pellet temperatures enhance fission product release from the fuel matrix while the pellet cracks allow their transport to the fuel-cladding gap and direct contact with the cladding inner surface. High cladding stresses are generated by the friction forces at the pellet-cladding interface due to radial cracks opening and stretching the cladding in the hoop direction. This loading mechanism, termed Pellet-Cladding Mechanical Interaction (PCMI), in the presence of aggressive chemical species such as iodine, can lead to cladding failure by stress corrosion cracking (SCC). This so-called "classic" PCI is known as PCI-SCC, which can be aggravated by the presence of a pellet chip described as missing pellet surface (MPS). This failure mechanism is referred to as PCI-MPS.

As PCI failures were not uncommon in the 1970s and 1980s, fuel vendors revised fuel pellet and fuel rod design and reactor operation in an attempt to mitigate this failure mechanism. However, in the early 2000s, a number of duty-related failures occurred in high-energy US PWRs during reactor startup and restarts. Hot cell examination of several of the failures confirmed the presence of fuel pellet MPS. While the affected fuel vendor revised manufacturing and inspection to minimize the occurrence of large MPS features, affected utilities implemented one or more of the following remedial actions:

- reduced power ramp rates on startup,
- added constant power holds to allow cladding stress relaxation as the reactor approached full power conditions,
- implemented core design changes to reduce local power peaking,
- performed cycle-specific startup analyses to explicitly evaluate margin to PCI failure in limiting rods, and
- limited extent and/or duration of coast downs.

These remedies have proven effective in limiting the occurrence of PCI-type failures in the affected US plants. However, these remedies have the effect of reducing operating efficiency through lost generation and enhanced staff workload.

TRADITIONAL PCI MARGIN EVALUATION METHODOLOGY

The current, industry-standard fuel performance code for the evaluation of PCMI is Falcon, a 2D finite element steady-state and transient fuel performance code developed by ANATECH Corp. (now SI-NFT) for EPRI [6]. The code has been used quite extensively over the last ~17 years for the evaluation of PCI-type failures, assessment of PCI margin under various operating strategies, and remedies to preclude PCI failure. The current methodology is a two-stage process. First, the integral rod is modeled through its full irradiation history, including the power ramping event of interest, using the R-Z model shown in Figure 1. Moving from the centerline outward at a given elevation, the central elements represent the fuel pellets, the dark grey elements represent the cladding, and the lighter grey elements represent the coolant channel. Though not shown, fuel-cladding elements model the annular region between the pellet outer surface and the cladding inner surface. Plena are shown above and below the fuel stack. The full-length model captures rod integral effects and allows the code user to select the axial station of interest from a PCMI perspective.

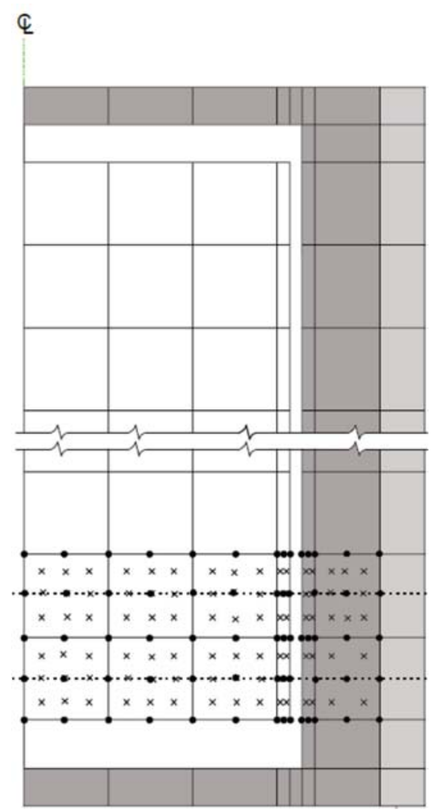

Figure 1: Falcon 2D full-length model [6]

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The second stage uses a slice model to capture the local effects of pellet radial cracks and, if present, MPS defects, on the cladding stress distribution (Falcon uses a stress-based criterion to determine failure probability). This model, the R-θ model, is shown in Figure 2. Moving in a radial direction at any azimuthal position, the center region represents the fuel pellet, the next elements represent the cladding, and the light gray elements represent the coolant channel. Fuel-cladding gap elements are not shown. The model can implement radial cracks in the pellet and/or an MPS.

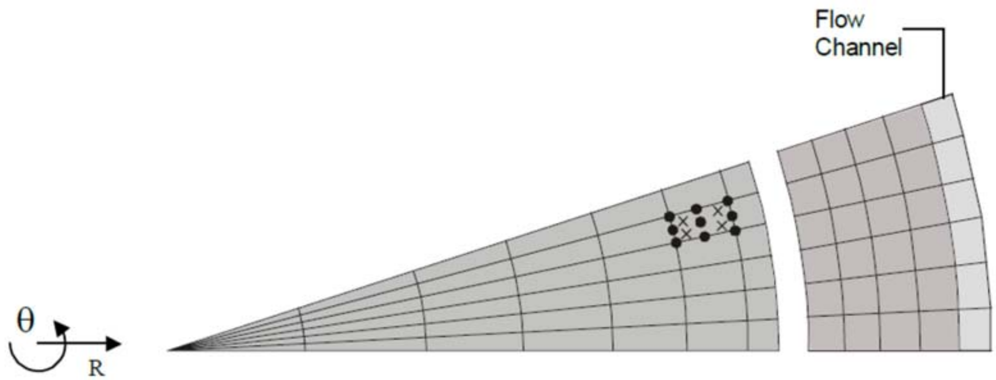

Figure 2: Falcon 2D plane strain slice model [6]

There are a number of conservatisms and limitations in this methodology:

1) The R-θ model implements plane strain boundary conditions. As such, this constrains any axial motion of the fuel and cladding due, for example, to thermal expansion.
2) The R-θ analysis models only one of the axial stations as a single entity out of 24 or 25 total.
3) The model inherently assumes that any pellet defect explicitly modeled, for example an MPS, as an infinite length feature. Correction factors can be used to reflect stress reduction for finite-length MPS defects to account for additional cladding support provided by the pellet away from the MPS (i.e., by intact pellet surfaces).
4) The R-θ model must be initialized using integral variables (e.g., rod internal pressure, fission gas composition and burnup) and local variables (e.g., fuel displacements, power, cladding temperature and fast flux) captured from the full-length model.
5) The code user manually or automatically selects times from the R-Z full-length analysis for evaluation of cold fuel-cladding gap, the start of the power ramp of interest, and the analysis end time.

It is important to note that Falcon has served industry well for the prediction and simulation of PCI-type failures and effects of rapid power changes.

ADVANCED METHODOLOGY WITH PEGASUS

PEGASUS moves PCI margin analysis to a new simulation level with full 3D analysis capabilities that allow explicit modeling of the fuel pellet, with cracks and MPS defects in a single model that evaluates the very local pellet-cladding mechanical interaction.

Figure 3 provides a schematic of the conceptual model currently under development. Main features of this hybrid model include:

1) A 3D region with explicit fuel pellet and cladding meshes for the detailed local analysis of PCMI (i.e., classic PCI and MPS-induced PCI). This is shown as Zone C in the figure. Fuel pellet cracks will be explicitly modeled. This high-definition region need only be ~10 cm in length to capture the PCI phenomenon.
2) On either side of the central zone, a simplified 3D region will be modeled as smeared pellets with the smeared-cracking model. Shown as Zone B in the figure, meshing will be detailed enough to capture the 3D pellet response yet reduce overall computational requirements. A 20 cm region should be adequate for Zone B.
3) For the remainder of the rod, a more simplified 2D axisymmetric mesh will be used (i.e., Zone A in the figure). The smeared cracking model will be implemented. This will ensure that rod integral effects are accurately modeled.

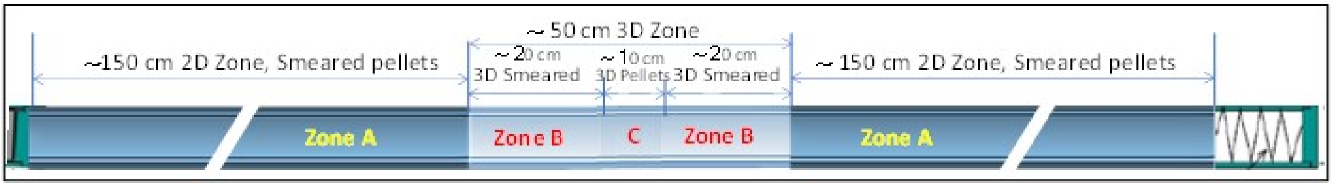

Figure 3: Conceptual model of full-length rod [7]

Such a model moves from a very detailed region where PCMI is modeled in high fidelity to coarser meshed regions where less detail is needed yet allow rod global and integral effects to be accurately evaluated and captured. This precludes 1) the need to transmit rod global and local characteristics from one model to the next, and 2) initializing dimensions in the local model based on a snapshot in time in the full-length model. Note that the high fidelity region Zone C can be moved axially within the mesh to capture PCI-susceptible regions anywhere along the length of the fuel rod, for example at the peak power or minimum fuel-cladding gap size position . The hybrid model helps to optimize run time yet still capture integral rod effects and the local PCMI effects.

Figure 4 provides the temperature distribution as envisioned with the hybrid model when an MPS is modeled. The power level is 35 kW/m. The figure superimposes the 3D distribution on a full length 2D axisymmetric model to show the expected temperature distribution. The MPS is modeled mid-span in Zone C at the upper surface of the pellet. Since a larger fuel-cladding gap is present with an MPS, the temperature is skewed outward from the MPS.

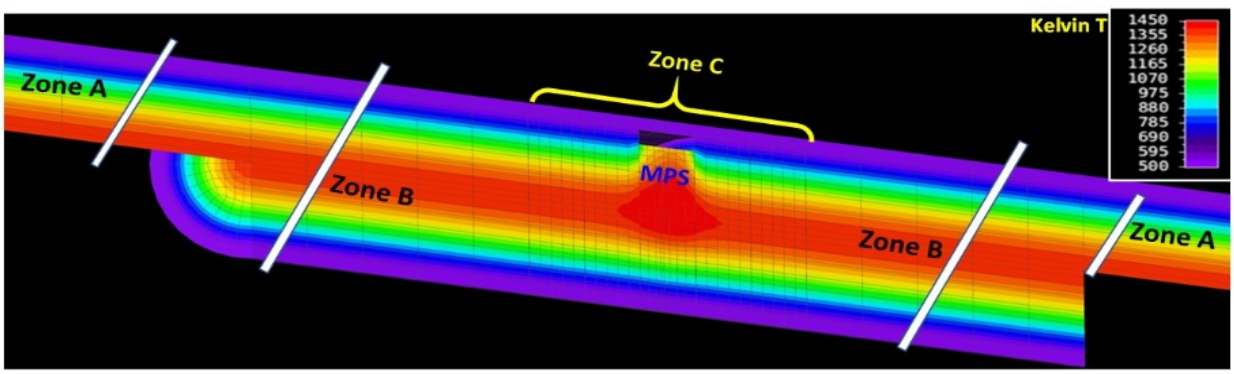

Figure 4: Temperature distribution in hybrid model (2D distribution superimposed on 3D distribution to show concept) [7]

The strategy adopted in constructing the hybrid model is to develop the 3D detailed model first then link this to the 2D portion. Figure 5 provides an example of a 3D fuel pellet and cladding mesh for an MPS case. A single pellet mesh is shown with the MPS located at the right-hand side of the pellet mesh (additional adjacent pellets complete the model). The MPS is assumed to be the full height of the pellet. A partial length radial crack in the pellet is shown as the cross-hatched region.

Figure 5 also shows the resultant cladding hoop stress distribution along the pellet height. The distribution is as expected. The hoop stress is tensile at the cladding inner surface with peak stress observed at the mid-height of the MPS due to inward deformation of the cladding in response to the coolant overpressure. The maximum compressive stress is observed on the cladding outer surface also due to the inward bending of the cladding. Stresses tend to decrease at the top and bottom of the MPS due to cladding support provided by pellets above and below this central pellet. One also observes compressive stresses at the cladding inner surface, and tensile stresses at the outer surface, where the edge of the MPS contacts the cladding inner surface, a consequence of the pellet stretching the cladding at the point of contact.

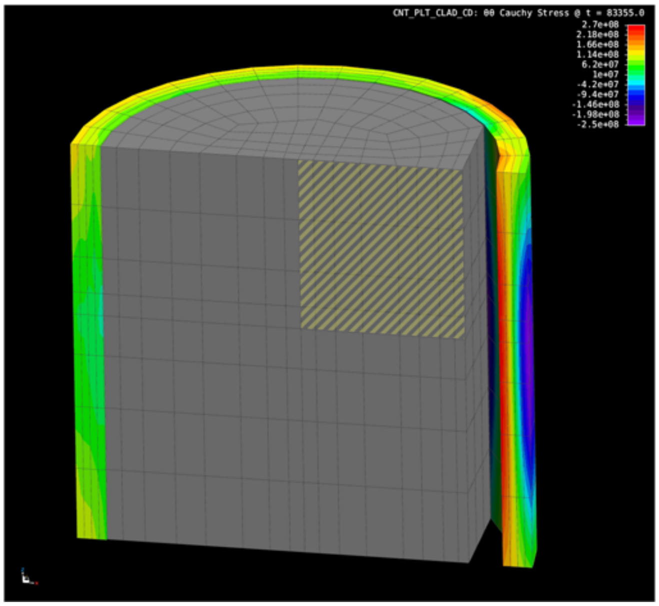

Figure 5: Cladding hoop stress distribution for the case of an MPS (right-hand side of pellet) and pellet radial crack (cross-hatched region).

Figure 6 provides the 3D hoop stress distributions in the fuel pellets and cladding. Pellet hoop stresses are relatively high along the bottom half of the MPS and decrease in the upper region where the radial crack is present. High cladding stresses occur at the inner surface of the cladding immediately adjacent to the MPS with high compressive stresses occurring on the cladding outer surface, again in the shape of the MPS. High tensile stresses also occur on the cladding outer surface where the MPS contacts the cladding inner surface. The effect of pellet support adjacent to the MPS is observed by way of higher stress about the MPS on the cladding outer surface. Additionally, stress risers at the pellet interfaces are apparent in the cladding stress distribution.

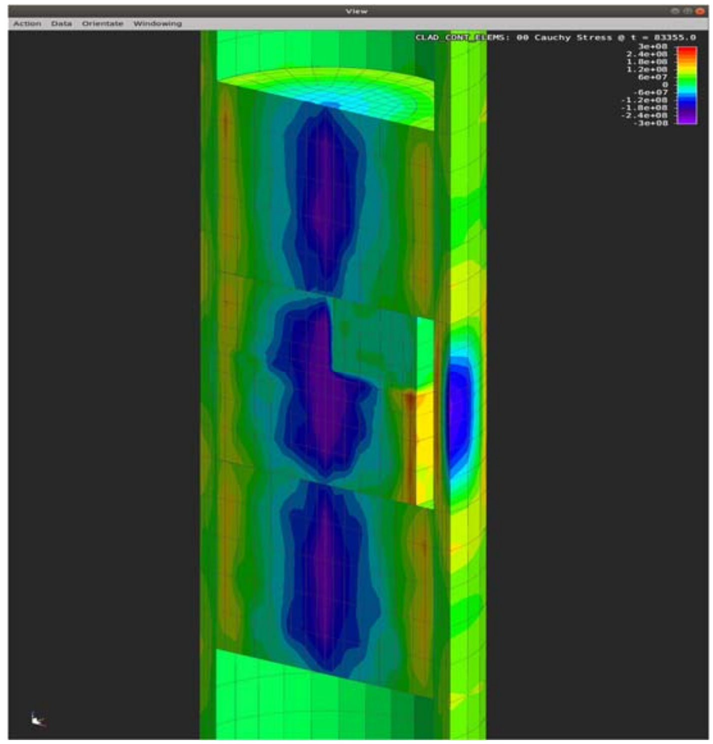

Figure 6: Hoop stress distribution in pellets and cladding. An MPS is modeled on the center pellet with a pellet radial crack from the top of the pellet intersecting the MPS mid-width. This is a vertical slice through the fueled region with only three pellets shown.

Figures 7 and 8 clearly show the 3D effects of an MPS and radial crack on the cladding hoop stress distribution: Figure 7 shows the distribution from the inside of the cladding while Figure 8 shows the distribution from the outside of the cladding. In both figures, the mesh has been cut through the mid-width of the MPS. The MPS itself generates high tensile stresses on the inside of the cladding and compressive stresses on the outside – the opposite is observed where the MPS contacts the cladding inner surface. Slight stress enhancement is observed at pellet-pellet interfaces and in regions about the MPS where the cladding is supported by the intact pellet surfaces.

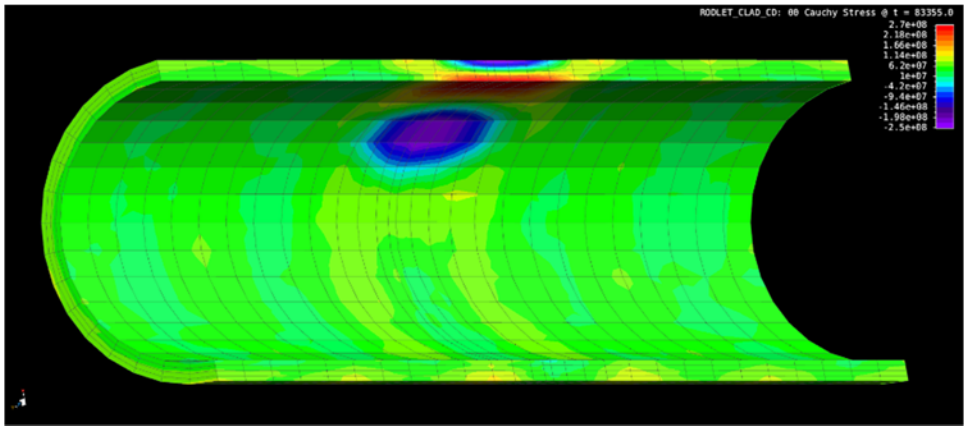

Figure 7: Cladding hoop stress distribution for case with pellet MPS and radial crack.

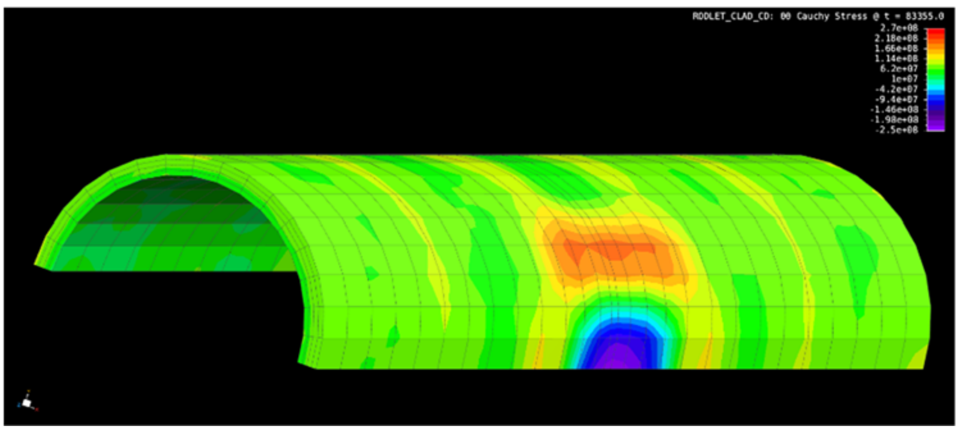

Figure 8: Cladding outer surface hoop stress distribution

PERSPECTIVES

The following perspectives regarding PCI margin analyses are worth noting.

PCI as a Failure Mechanism

The nuclear industry has managed PCI-type failures quite well for currently employed operating strategies. As the industry moves to higher energy and longer cycles, adopts alternate strategies such as load follow, and more efficient operating strategies to enhance competitiveness, the risk of PCI-type failures is increased. It is prudent to evaluate PCI margin prior to implementation of these more advanced strategies.

Use of 2D Methodologies

The vendor-independent methodology described in this paper for the evaluation of margin to PCI failure rely on 2D methods in a stepped approach. While this method has proven critical in assessing and simulating PCMI and PCI margin and has limited the occurrence of PCI-type failures, it has inherent conservatisms that lead to more restrictive operation.

Use of 3D Methodology

The use of 3D methodology allows the complex thermal, mechanical, and chemical environment necessary for PCI-type failures to be modeled in high fidelity. SI-NFT is developing PEGASUS as an advanced hybrid methodology for PCI evaluation without high computational requirements.

The model simulates the fuel rod using a 2D mesh for much of the rod but integrates two levels of 3D meshes to capture the detail necessary for PCI margin evaluation. Rod integral effects are seamlessly captured with this model.

NOMENCLATURE

BWR	*Boiling Water Reactor*
MPS	*Missing Pellet Surface*
PCI	*Pellet-Cladding Interaction*
PCMI	*Pellet-Cladding Mechanical Interaction*
PWR	*Pressurized Water Reactor*
SCC	*Stress Corrosion Cracking*
US	*United States*

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