AXIAL CONDUCTION NODALIZATION FOR TRACE/PARCS ANALYSIS OF ATWS WITH INSTABILITY

P. Yarsky
Nuclear Regulatory Commission Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission, MS CSB-3A07M, Washington, DC 20555-0001
peter.yarsky@nrc.gov

M. Hardgrove
Nuclear Regulatory Commission Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission, MS OWFN 10-A1, Washington, DC 20555-0001
matthew.hardgrove@nrc.gov

ABSTRACT

In a companion paper [1], the results of TRACE/PARCS [2, 3] calculations for representative anticipated transient without SCRAM (ATWS) events leading to core instability (ATWS-I) were presented. A conclusion of that work indicates that the fuel damage consequences of an ATWS-I scenario for a boiling water reactor (BWR) operating at maximum extended load line limit analysis-plus (MELLLA+) conditions are sensitive to the predictions of heat transfer under oscillatory power/flow conditions.

In simulating these events with TRACE/PARCS it is important to treat the highly important heat transfer phenomena; including dryout, rewet, and quench. This includes accurate representation of axial heat conduction and the effect of such conduction on quench front propagation. Original calculations were performed without use of the dynamic fine-mesh axial conduction model [1]; however, they indicated that fuel heat-up could occur. Therefore, the prediction of the peak cladding temperature could be sensitive to more robust modeling of the axial conduction behavior. While general guidelines exist for the use of the TRACE dynamic fine-mesh axial conduction model for loss-of-coolant-accident applications [4], the current work focuses on the use of the model for ATWS-I scenarios. The regulatory purpose of the current work is to study the effect of axial nodalization, or "meshing," in TRACE/PARCS models for ATWS-I simulation and to establish recommendations for meshing with respect to axial conduction.

Axial conduction controlled quenching is treated in TRACE/PARCS through a fine mesh option that subdivides the heat structure nodes representing the fuel rod into finer meshes. The fine mesh treatment allows for accurate representation of steep temperature gradients that occur near quench fronts.

A simple analytical approach was developed to suggest a range of mesh sizes of interest to a typical ATWS-I scenario where fuel heat-up occurs. On the basis of that suggested range of mesh sizes, a series of sensitivity calculations were performed with TRACE/PARCS to study the influence of mesh size on plant response and fuel temperature during an ATWS-I event. The analysis of the results indicates that highly detailed meshing of the axial conduction in the fuel does not have a significant impact on the prediction of the peak cladding temperature, but does subtly influence the plant response in terms of the onset timing of bi-modal oscillation and the timing of the hot spot quench. The results of the current sensitivity calculations support a recommendation for fine mesh options in future TRACE/PARCS analyses.

KEYWORDS
ATWS BWR PARCS TRACE Quench Fine-mesh

1. INTRODUCTION

During the analysis of ATWS-I events, it was found that the predicted peak cladding temperature (PCT) exceeded 1478 K [2200 °F] [1] and exceeded the values predicted for similar analyses conducted by GE Hitachi using the TRACG code [5]. The regulatory purpose of the current work is to study the influence of quench modeling on PCT during ATWS-I by increasing the resolution of the fine mesh axial conduction model. In addition, the sensitivity studies are intended to form the basis for generic guidelines for axial conduction solution nodalization for any future work in the area of ATWS-I.

According to the results of [1], it is possible during an ATWS-I scenario for the cladding to undergo relatively rapid transition between dryout and rewet. Once there is a failure to rewet, large amplitude oscillations of the flow persist and the cladding undergoes oscillation between the inverted annular film boiling and dispersed flow film boiling regimes. The current work evaluates the sensitivity of the predicted PCT under these conditions to treatment of the axial conduction phenomenon using the TRACE dynamic fine mesh methodology. Since ATWS is a beyond design basis event, this paper did not consider the treatment of uncertainty.

Section 2 of this report describes the basis for the selection of conduction node sizes. Section 3 describes the case matrix and the different TRACE variables that were adjusted for the current studies relative to the base case analysis. Section 4 provides the calculation results for pertinent parameters, namely transient minimum critical power ratio and PCT. Section 5 summarizes the conclusions.

The results of the current studies demonstrate that the findings documented in [1] remain applicable. Further, this paper contains recommendations for generic guidelines when utilizing the TRACE axial conduction controlled quenching model for future work in the simulation of ATWS-I events for MELLLA+ BWRs.

2. CONSIDERATION OF APPROPRIATE AXIAL NODE SIZE

The initial ATWS-I studies were performed by specifying a permanent coarse mesh for the axial conduction problem that was the same as the thermal-hydraulic mesh (NFAX=1) [1]. Additionally, the dynamic fine mesh options were set to allow only the insertion of additional nodes greater than 1.0 mm in size, this was selected based on generic user guidance for the fine mesh model [4]. Therefore, in the current work, the adequacy of this nodalization was studied further to establish ranges for the fine mesh node size applicable to the analysis of ATWS-I.

As a first step an analytical problem of conduction through a semi-infinite slab of zircaloy was considered. The purpose of studying the analytical solution is to determine the projected temperature gradient downstream of a quench front as a function of distance and time for zircaloy properties. The solution of the transient heat conduction equation for an unpowered semi-infinite slab is:

$$\frac{T(z,t)-T_s}{T_0-T_s} = erf\left(\frac{z}{2\sqrt{\alpha t}}\right) \tag{1}$$

Where: T(z,t) is the transient temperature downstream a distance z from the quench at time t,
T_s is the temperature imposed at the quench location,
T_0 is the initial temperature downstream of the quench, and
α is the thermal diffusivity

The imposed surface temperature is set to the minimum stable film boiling temperature (T_{min}), which when predicted by TRACE for conditions typical of ATWS-I would be approximately 700 K. The initial temperature was set to a value above the T_{min} to an initial value of 1000 K, which is in the range of interest for ATWS-I simulations. The thermal diffusivity was calculated for zircaloy properties. At higher temperatures (~1000 K), the thermal conductivity is ~ 22 W/m-K, the density is ~6500 kg/m^3, and the heat capacity is ~300 J/kg-K. Given these properties, a representative thermal diffusivity is ~1.13 x 10^{-5} m^2/sec. The exact value is not as important for this analysis as the "ball-park" value since the objective is to gauge the steepness of the gradient temperature downstream of the quench.

Given these initial conditions and material properties, Figure 1 shows a solution of the transient heat conduction problem after 0.01 and 0.02 seconds. These times were selected since they correspond roughly with the Courant limited time step size used in the TRACE simulation of ATWS-I. The temperature profiles are shown just downstream of the quench point. The most important aspect of this figure is the sharpness of the temperature profile downstream of the quench. The results indicate that axial conduction contributes to a rapid and sharp decline in temperature immediately downstream of the front. The figure indicates that the temperature gradient is steep, ranging between 1000 K (assumed initial temperature) and 700 K (assumed value of T_{min}) over a distance of ~0.001m during the first 0.01 sec.

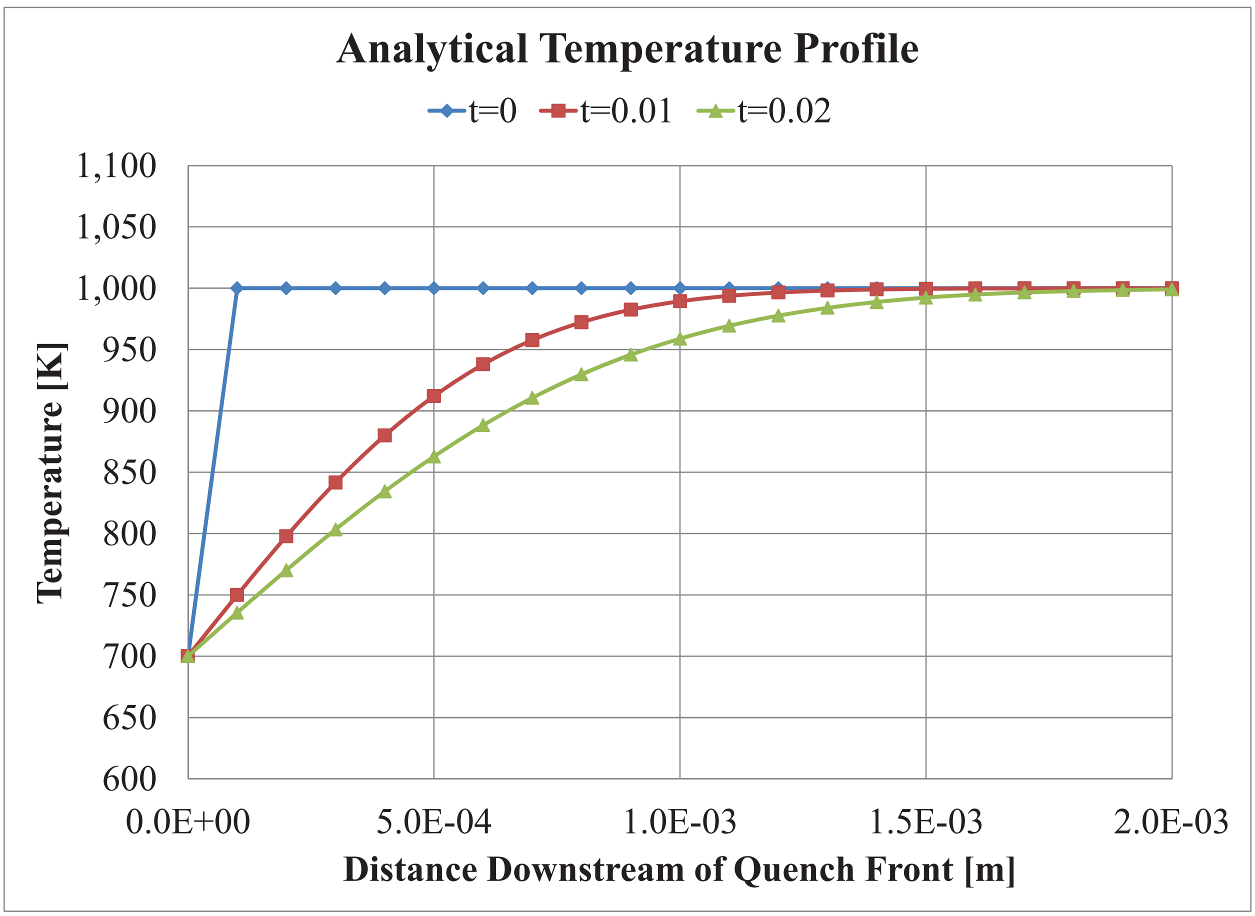

Figure 1. Analytical Temperature Gradient Downstream of Quench.

In order to resolve this gradient in TRACE, it is recommended that the fine mesh nodalization incorporate sufficient nodes such that the temperature difference between nodes is ~ 20-30 K [6]. Therefore, to fully resolve this gradient, at least 10 nodes would be required in the space between 0.0 and 0.001 m. This indicates that node sizes of 0.1 mm or smaller should be used in the transient calculations.

These studies indicate that 1.0 mm fine mesh node sizes may be too large to resolve the axial temperature gradient near the quench front. The simple analysis indicates that 0.1 mm nodes should be appropriate, but a node size of 0.01 mm is also worth consideration as the simple analysis did not account for rod power.

3. CASE MATRIX

The intent of the current work is to determine an appropriate level of resolution in the calculation of the axial conduction (i.e. meshing) to demonstrate that the predicted PCT becomes insensitive to increased nodal resolution. A variety of increased nodalziation cases are described in Table I for comparison to a base case. The base case uses a minimum node size of 1.0 mm, consistent with the recommendation of [4] and specifies a permanent fine mesh consistent with the coarse mesh. The sensitivity cases are labeled "Renode" followed by a number. The number indicates the minimum axial conduction node size considered. In the case matrix, the column heading NZMAX(W) refers to the maximum number of nodes that may be present in the fuel and channel box. DZNHT(W) refers to the minimum node size that may be dynamically inserted by TRACE during the calculation. NFAX is a ratio that specifies a permanent number of fine-mesh axial conduction nodes per each coarse node.

Table I. Case matrix

Case Name	NZMAX(W)	DZNHT(W)	NFAX
Base	900	1.00E-03	1
Renode1E-2	4000	1.00E-02	10
Renode1E-3	4000	1.00E-03	10
Renode1E-4	4000	1.00E-04	10
Renode1E-5	6000	1.00E-05	10

Dynamic renodalization inserts additional nodes when cladding temperature gradients exceed a threshold internally evaluated by TRACE (approximately 50 K between nodes). Nominally the fuel is modeled with 38.1 mm nodes near the channel inlet and 152.4 mm nodes through-out the remainder of the fuel assembly. This results in 37 coarse nodes. NFAX controls the permanent fine mesh, that is, sub-coarse-nodal resolution that is not affected by dynamic renodalization. For a value of NFAX of 10, each of the 37 coarse nodes will be represented with a minimum of 10 axial conduction nodes; yielding a total of 370 permanent fine mesh nodes representing the fuel.

During the calculation if high temperature gradients are predicted, TRACE will dynamically insert additional conduction nodes up to certain limits. The first limit is the cap on the total number of nodes (controlled by NZMAX). For a value of 4000, this would allow TRACE to dynamically remesh the entire fuel assembly with about 10 additional nodes inside each permanent fine mesh node. Considering that the hot spot is likely to occur near the channel inlet in a 38.1 mm node, TRACE certainly would allow node sizes below 0.381 mm, assuming that the entire channel is subject to dynamic renodalization. Since the entire channel is not likely to experience the same degree of dynamic renodalization, the 0.381 mm size represents a sort of upper limit to the resolution. In practice the hot spot is expected to occur in a single coarse node. If the hot spot is in a single coarse node, a value of NZMAX of 4000 would allow 4000-

370, or 3630 nodes to be dynamically inserted. For a large node (6 inches) this supports axial conduction nodal resolution of ~0.04 mm. In cases where the hot spot occurs in a 38.1 mm node, NZMAX of 4000 supports roughly a 0.01 mm node size.

The second limit is the minimum node size, specified by DZNHT for the fuel and DZNHTW for the channel box. TRACE will not insert additional nodes if the node size would be smaller than the limit applied by this variable in the input deck. Values ranging from 10 mm to 0.01 mm were considered.

The input decks were developed by modifying the existing decks by changing the values in the steady-state TRACE stand-alone input deck according to Table I. The coupled steady-state and transient input decks are essentially the same as the previous decks with the exception that the coupled steady-state calculation is prolonged for an additional 100 seconds of problem time running at a time-step size consistent with Courant limit of 1.0.

Run times were compared for steady-state calculations of the base case, the Renode1E-2 case, and the Renode1E-5 case. The comparison is presented in Table II. These results are presented to inform any future engineering implementations of the recommended guidance of this paper. For the run time comparison, the calculations were performed on a workstation with 64 GB of RAM and 3.10 GHz processors.

Table II. Run Time Comparison

Case	Run Time (hours)	Relative Run Time
Base	30.25	1.0
Renode1E-2	75.25	2.5
Renode1E-5	86.25	2.9

4. CALCULATION RESULTS AND ANALYSIS

The Renode cases explore the sensitivity of predicted transient response to increased resolution of the axial conduction solution. Figure 2 illustrates the difference in reactor power oscillation magnitude given differences between the base case and the Renode cases. In the Renode cases the oscillation onset, growth and peak oscillation magnitudes are in relatively good agreement with the base case. For a few periods around 120 seconds, the base case demonstrates a slightly larger peak oscillation magnitude relative to a representative Renode case. However, there is a more stark difference in the results after 150 seconds. The Renode cases appear to demonstrate a larger core wide oscillation magnitude for a period of about 30 seconds relative to the base case.

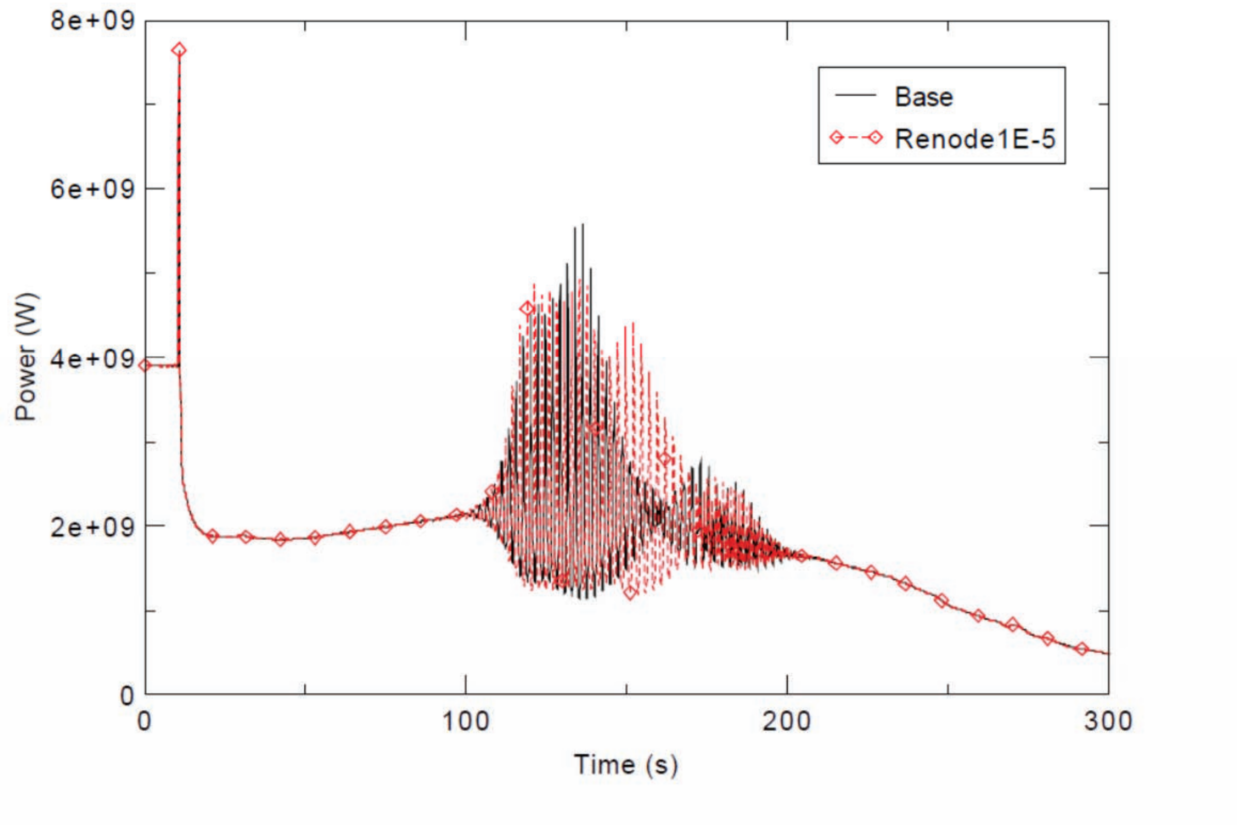

Figure 2. Transient Power Responses for Base Case and Renode1E-5 Case.

The results from the comparison in Figure 2 carry over to all Renode cases. Figure 3 provides a similar plot comparing the results from every Renode sensitivity case. The results of the Renode cases are all essentially identical. This indicates that the likely cause for the difference is a change in the permanent fine mesh (NFAX=10 compared to NFAX=1 in the base case). This occurs at a point in the base case calculation where the oscillation develops a distinctive regional mode contour. Frequency doubling is an indicator of this occurrence, and is not observed until a later part in the transient for the Renode cases. On this basis, it would appear that the finer permanent fine mesh contributes to a delay in the onset of the bi-modal, coupled oscillation. This may be attributed to differences in the heat up of fuel at various sub-nodal axial levels. Fuel heat up contributes to local reactivity reduction and can have a pronounced effect on modal kinetic behavior, so the differences are likely due to this. A method for evaluating and editing the modal kinetic parameters directly would be instrumental in demonstrating this effect, but no such method is currently implemented in TRACE/PARCS.

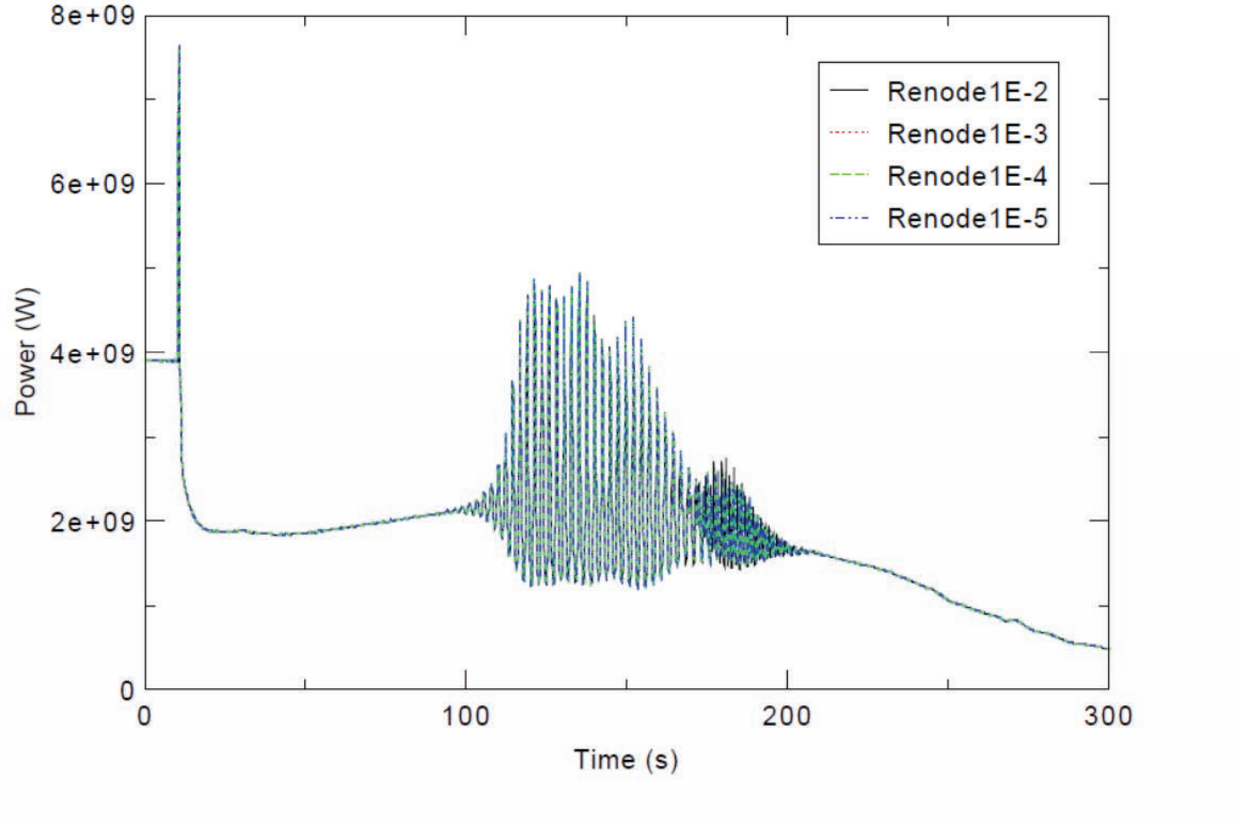

Figure 3. Transient Power Response for All Renode Cases.

Despite some differences in the transition of the oscillation magnitude during the transient to a bi-modal oscillatory response, the event consequences in terms of peak cladding temperature are largely dominated by the occurrence of dryout and failure to rewet during the early part of the transient when core wide oscillation magnitude is at its largest. Figure 4 provides a plot comparing the PCT response for all Renode cases and the base case. As one can see from the figure, the PCT trajectory is essentially identical in all cases. There is a subtle difference in the timing of quench late in the transient between the Renode1E-2 case and the other Renode cases. This indicates that at dynamic node sizes smaller than 1E-2 m, there is an effect on the quench time, but this effect appears to be quite small (a difference in quench timing of about 2 or 3 seconds). There is also a subtle difference in the PCT around 200 seconds, but overall the responses are essentially the same.

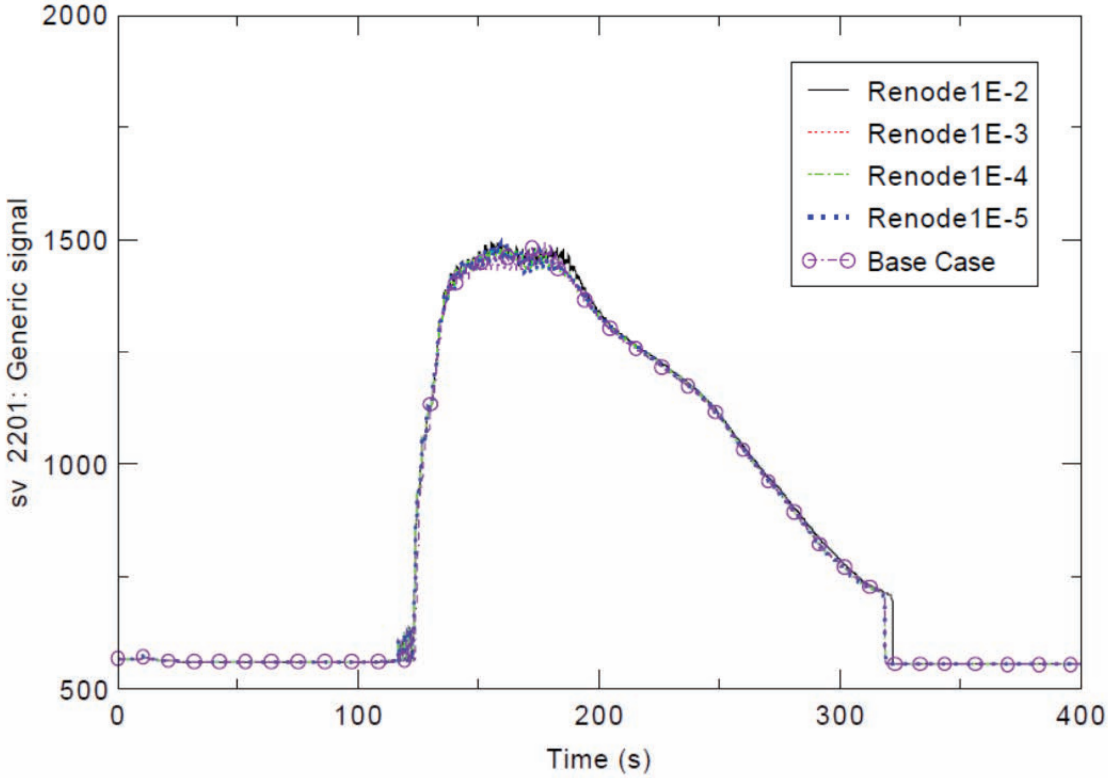

Figure 4. PCT Response for Base and Renode Cases.

The similarity in PCT response can be further explained in terms of the similarity in the predicted critical power ratio response. Figure 5 provides a plot comparing representative Renode cases. Fewer cases are shown on this graph to more clearly illustrate the similarity in the responses. The other case (Renode1E-5) is indistinguishable. The results show that for the same power oscillation magnitude, regardless of the minimum dynamic mesh node size, the minimum critical power ratio (MCPR) response is essentially identical.

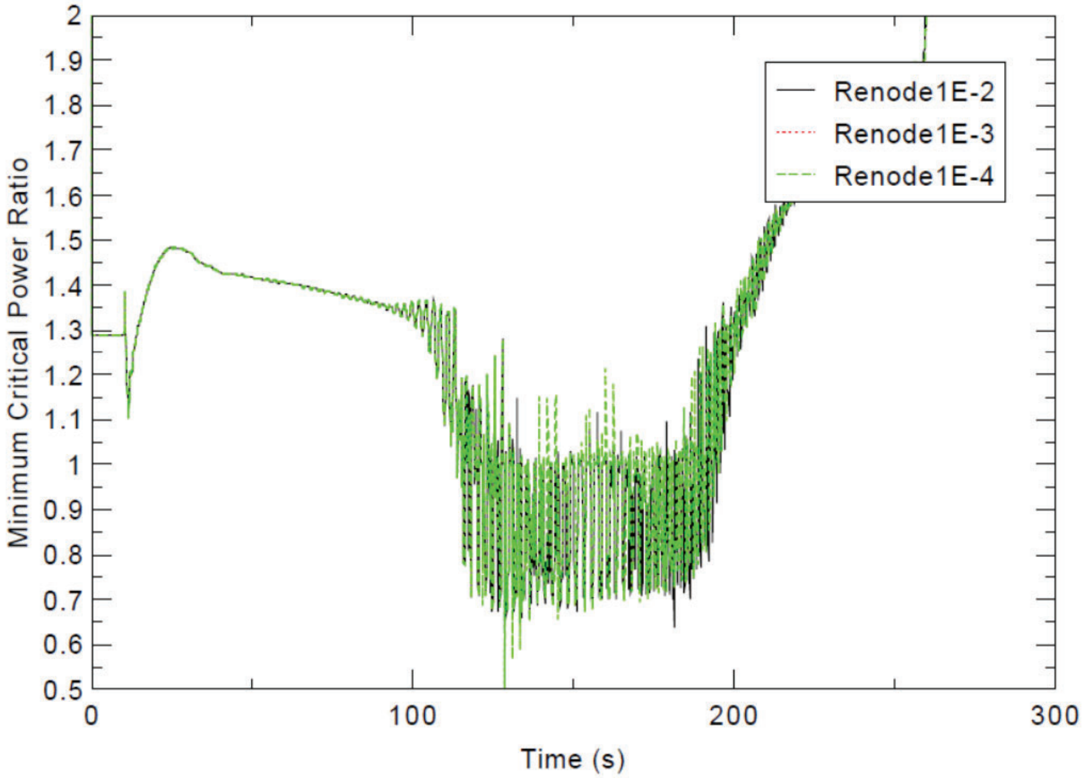

Figure 5. MCPR Response for Representative Renode Cases.

Overall, the sensitivity study calculations indicate that dynamic node sizes below 1E-3 meters (1.0 mm) show no appreciable change in the transient behavior in terms of power and PCT. Slightly larger node sizes (1E-2 m) indicate essentially no change in predicted PCT, but do indicate some more subtle differences, such as a minor difference (2-3 seconds) in the timing of fuel rod quench. In light of these results, it would appear that 1E-3 m node size is acceptable. This provides further justification for the results presented in [1]. However, the analytical result in Section 2 indicates that 0.1 mm node sizes (DZNHT=1E-4) should be appropriate to maintain temperature axial gradients within acceptable limits (~20-30 K per node). Therefore, the current work recommends that future analyses consider 1E-4 m minimum node sizes for the dynamic fine mesh.

The results also indicate a subtle sensitivity to the permanent fine mesh option (controlled by NFAX input). In the Renode cases, there was an observed change in the timing of frequency doubling in the core power response when the NFAX was increased from 1 to 10. NFAX controls the number of permanent fine mesh axial conduction nodes within each thermal-hydraulic cell. Even though the results did not indicate a substantive change in PCT behavior, it is recommended that NFAX of 10 be used for future analyses since a higher resolution can better capture the subtle effects that fuel temperature seems to have on the dynamic behavior of the bi-modal oscillation.

5. CONCLUSIONS

The Renode cases have demonstrated the importance of axial heat structure nodalization and demonstrated subtle variations in PCT and quenching behavior with variation in the input for the axial conduction model in TRACE. The results indicate that PCT is not largely sensitive to changes in this nodalization, but some subtle effects were observed that impact prediction of bi-modal oscillation onset timing and the timing of final fuel rod quench. Neither effect, with highly detailed nodalization, invalidates the previous results and conclusions documented in the companion paper [1].

For future TRACE analyses of this type, the current work supports the selection of 10:1 permanent fine mesh axial conduction nodalization (NFAX=10) and 0.1 mm dynamic fine mesh minimum node size (DZNHT=1E-4).

REFERENCES

1. L. Cheng, et al., "TRACE/PARCS Analysis of ATWS with Instability for a MELLLA+ BWR/5," *Proceedings of 2016 Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, Illinois, August 30-September 4, 2016 (2016).
2. "TRACE V5.0 Theory Manual," U.S. Nuclear Regulatory Commission, June 4, 2010 (ADAMS Accession No. ML120060218).
3. T. Downar, et al., "PARCS: Purdue Advanced Reactor Core Simulator," *Proceedings of Reactor Physics Topical Meeting (PHYSOR 2002)*, Seoul, Korea, October 7-10, 2002 (2002).
4. "TRACE Pressurized Water Reactor Modeling Guidance," U.S. Nuclear Regulatory Commission, Rev. 1, July 2014.
5. J. Harrison, GE Hitachi, letter to U.S. Nuclear Regulatory Commission, "Accepted Version of GE Licensing Topical Report NEDC-33006P-A, Revision 3 (TAC No. MD0277)," MFN 09-362, June 19, 2009, (ADAMS Accession No. ML091800512).
6. "TRACE V5.0 User's Manual," U.S. Nuclear Regulatory Commission, June 18, 2008 (ADAMS Accession No. ML120060218).