framatome

ATWS-I Analysis Methodology for BWRs Using RAMONA5-FA Response to NRC Request for Additional Information

ANP-10346Q1NP
Revision 0

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	All	New Document

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BACKGROUND

This document comprises Framatome's response to the Nuclear Regulatory Commission (NRC's) Request for Additional Information (RAIs) for the Licensing Topical Report (LTR) ANP-10346, "ATWS-I Analysis Methodology for BWRs Using RAMONA5-FA." The RAIs were transmitted in Reference 9.

The specific regulatory requirements associated with anticipated transient without scram (ATWS) events are contained in Title 10 of the Code of Federal Regulations (10 CFR) Part 50.62, "Requirements for reduction of risk from anticipated transients without scram (ATWS) events for light-water-cooled nuclear power plants," and 10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," as well as General Design Criteria (GDC) 12, "Suppression of Reactor Power Oscillations," 14, "Reactor Coolant Pressure Boundary," 16, "Containment Design," 35, "Emergency Core Cooling," 38, "Containment Heat Removal," and 50, "Containment Design Basis," which are contained in Appendix A to 10 CFR 50.

Of those requirements, GDCs 12 and 35 are the most relevant, in that the intent of the ATWS with-instability (ATWS-I) analyses is to demonstrate that: (1) power oscillations that arise due to instability in the core are adequately mitigated by appropriate operator actions and/or automatic system responses, and (2) adequate cooling of the fuel is maintained, such that the maximum cladding temperature does not reach thresholds where significant fuel/cladding damage or metal-water reactions are expected to occur. The NRC guidance related to the boiling water reactor (BWR) ATWS-I event is presented in the Standard Review Plan, Section 15.8. During review of Topical Report (TR), ANP-10346P, Revision 0, "ATWS-I Analysis Methodology for BWRs Using RAMONA5-FA," the NRC staff identified some information that would be necessary to establish adequate technical bases to make a safety determination based on the above

regulatory requirements. In particular, this information directly affects the calculation of the three figures of merit (FoMs) that the demonstration of regulatory compliance are based on-the oscillation inception (i.e., how much time operators have to act), limit cycle amplitude (i.e., worst case oscillation), and post-dryout (i.e., peak cladding temperature (PCT)).

RAI-1

The Framatome 3-dimensional core physics simulator code, MICROBURN-B2, is used to produce data transfer files which pass condensed versions of relevant information for use in the RAMONA5-FA neutron kinetics solution [

]. Therefore, the NRC staff requests the following information:

1. *What [ ] information is passed from MICROBURN-B2 to the RAMONA5-FA ATWS-I calculation? What process and/or criteria, if any, is used to ensure that [*

]?

Framatome Response RAI-1:

[

]. These include:

[

]

[
]

The RAMONA5-FA code incorporates several models to capture specific phenomena of interest for the ATWS-I event. These models are typically constructed from empirical correlations developed based on a combination of theoretical principles and experimental data analysis. In order for the models to capture the phenomena of interest throughout the ranges of interest for key analysis parameters, the appropriate dependencies must be accurately captured in the models. To do so, the models must consider all relevant parameters, and the empirical correlations must be based on an appropriate analysis of the available data (including any gaps or limitations). Therefore, the NRC staff requests the following information

RAI-2

The NRC staff has the following questions regarding the fitting of model parameters to measured data:

a. *For models such as the dryout-rewet model and gap conductance model which contain multiple fitting parameters, how were values for these parameters inferred in cases where direct experimental validation for each parameter is not possible or not available?*

b. *For the gap conductance model, the TR states that [*

]. Describe this approach in additional detail, including how this adjustment was performed and how these values compare to similar values used in other Framatome methodologies.

Framatome Response RAI-2–a:

The fitting of coefficients depends not only on experimental data but also on assumptions that are based on first principles and reasonable engineering judgment. These must be applied on a case by case basis.

[

]

Framatome Response RAI-2–b:

RAI-3

Justify the [ ] used in the TR methodology. Include data for the [ ].

Framatome Response RAI-3:

[
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[

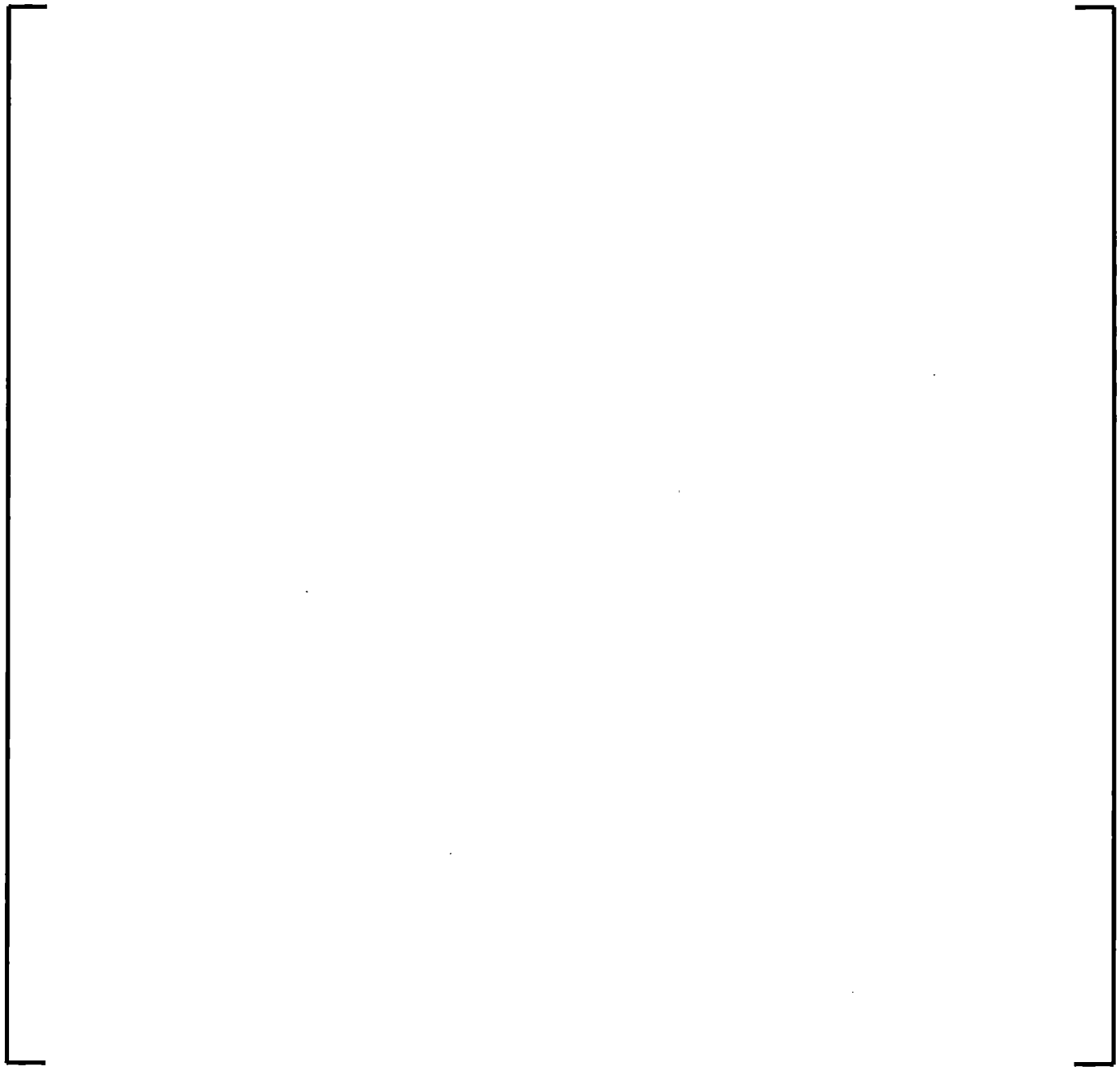

Figure 1 [

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Figure 2 [

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Figure 3 [

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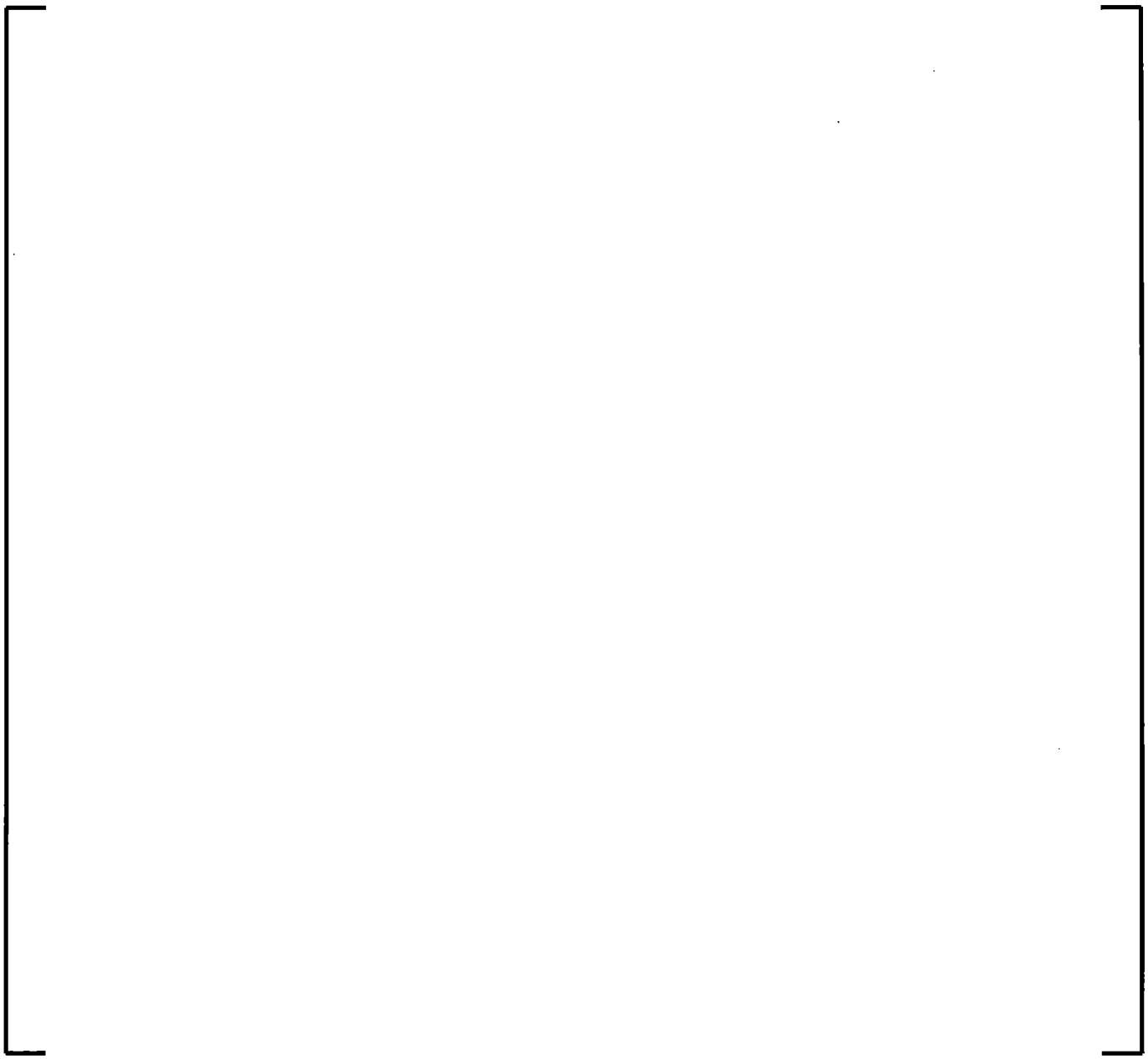
[]

Figure 4 [

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[

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Figure 5 [

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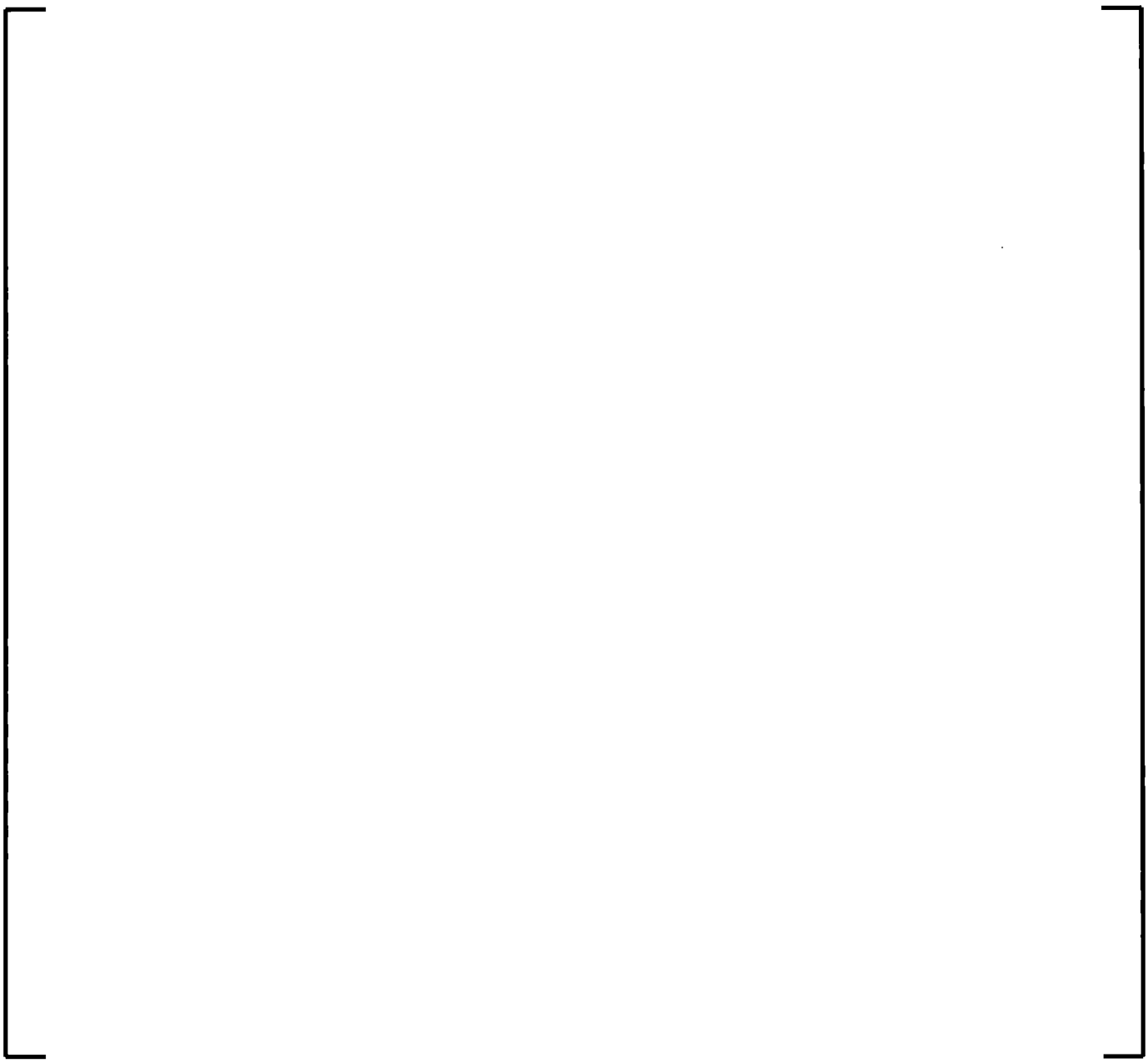

Figure 6 [

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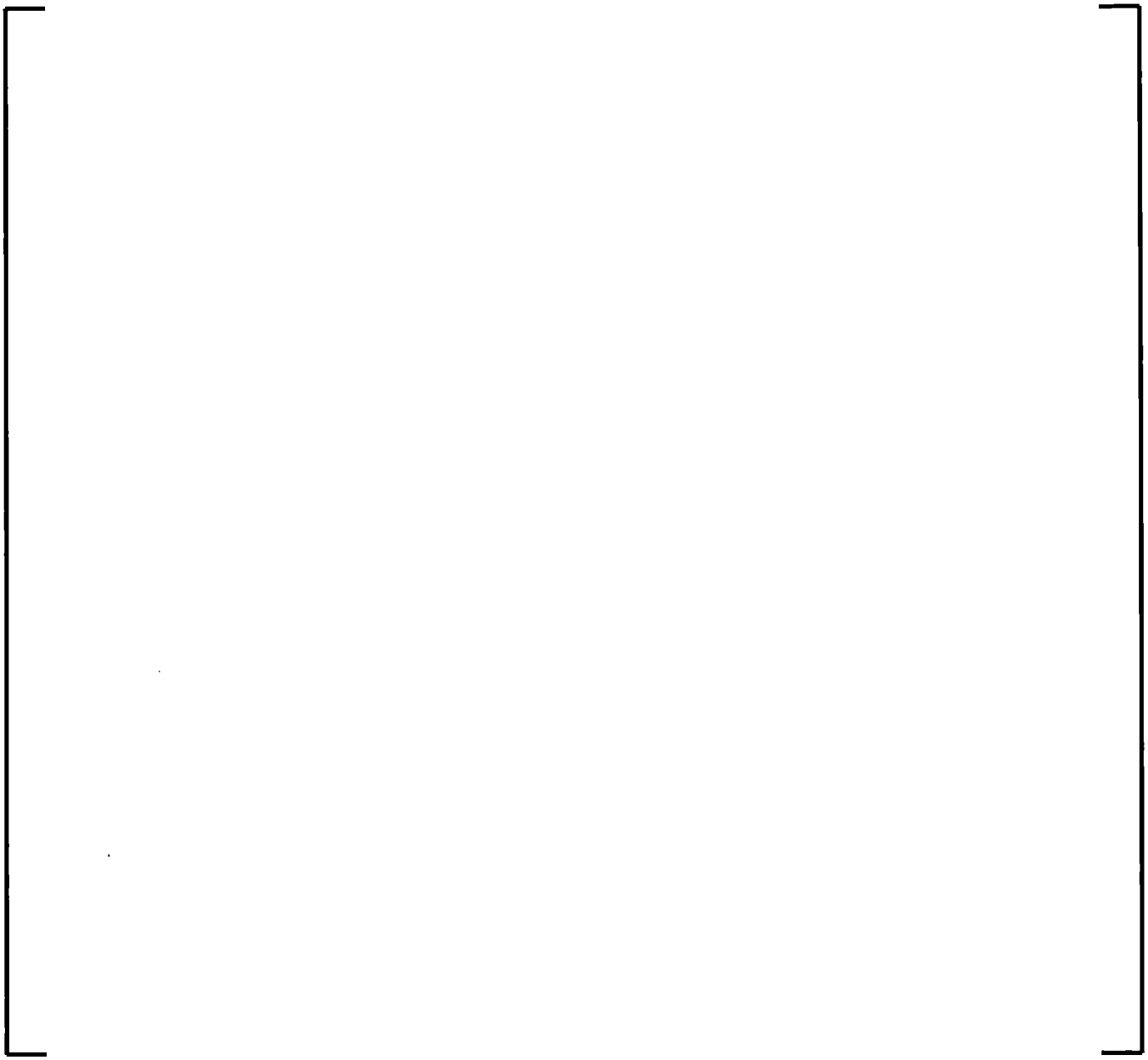

Figure 7 [

]

Figure 8 Dry [ ]

RAI-4

Since the [ ] was not part of the KATHY dryout-rewet experimental validation, justify that the models are a reasonable and accurate representation of [ ] during ATWS-I.

Framatome Response RAI-4:

[
]

RAI-5

The [

]. How is the model ensured to give reasonable and accurate behavior under such conditions during ATWS-I?

Framatome Response RAI-5:

[
]

Figure 9 Illustration of [

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[

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Figure 10 Illustration of [

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Figure 11 Illustration of [

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[

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Figure 12 Illustration of [

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Figure 13 Illustration of the [

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[

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Figure 14 Illustration of [

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[

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Figure 15 Illustration of [

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Once all of the models and coupling equations were combined into an unified analysis methodology within RAMONA5-FA to calculate the thermal hydraulic and neutron kinetics response during an ATWS-I event, Framatome validated the overall methodology by comparing calculational results to independent benchmarks. By demonstrating that RAMONA5-FA can independently reproduce key parameters for applicable benchmarks, reasonable assurance is provided that RAMONA5-FA will reproduce the same parameters for a postulated ATWS-I event. The key comparison results are presented in the TR, but some additional detail is needed to confirm that the benchmarks, and information used in the benchmarking calculations, are applicable to the intended use of RAMONA5-FA. Therefore, the NRC staff requests the following information:

RAI-6

The NRC staff has the following questions regarding the linear stability benchmarks provided in the TR:

a. *Provide a table showing the following operating conditions and calculated conditions for each linear stability benchmark case: core power, core flow rate, core inlet subcooling, axial peaking factor, peak axial power location, and radial peaking factor.*

b. *What fuel type(s) were present in the core for each of the linear stability benchmarks? Were all data and specifications available for these fuel types? What data and specifications required by RAMONA5-FA ATWS-I were not available, if any?*

c. *What neutronic and thermal hydraulic data were used from each plant in these benchmarks?*

Framatome Response RAI-6–a:

The range of operating conditions for the various linear stability reactor benchmarks are shown in Table 1.

Table 1 Operating conditions of the linear reactor benchmarks

[

]

Framatome Response RAI-6–b:

The linear stability benchmarks were all taken from the approved STAIF (Reference 5) and RAMONA5-FA (Reference 6) benchmarking suites. For these benchmarks the majority of fuel inputs were already available. In some cases, [

].

[

].

Framatome Response RAI-6–c:

The neutronics and thermal-hydraulics data for these benchmarks was taken directly from the approved STAIF (Reference 5) and RAMONA5-FA (Reference 6) benchmarking suite. No additional neutronics or thermal-hydraulics data was required.

RAI-7

The NRC staff has the following questions regarding the nonlinear stability benchmarks provided in the TR:

a. *What fuel type(s) were present in the core for each of the nonlinear stability benchmarks? Were all data and specifications available for these fuel types? What data and specifications required by RAMONA5-FA ATWS-I were not available, if any?*

b. *What deviations, if any, were made in the boundary conditions or other modeling assumptions for these cases relative to measured data and/or available benchmark specifications?*

Framatome Response RAI-7–a:

The Oskarshamn-2 benchmark consisted of [

].

Framatome Response RAI-7–b:

For the Oskarshamn-2 benchmark, the initial power, core flow and inlet subcooling were all input as the initial measured conditions. The feedwater flow versus time was decreased from the measured data to ensure reasonable water level calculation. This was necessary to restore correct mass balance as the calculated steam flow underpredicted the measured steam flow which would have led to an upward drift in water level. Modifying the feedwater flow versus time to better control water level is also consistent with the application of the method which utilizes a feedwater control system for the same purpose. The feedwater temperature versus time was taken directly from the benchmark specifications and includes the adjustment to the temperature function that accounts for instrumentation delay due to pipe heat

conduction. The pressure was set to the measured value versus time. The control rod insertions were modeled as they occurred in the event. Two sets of runs were made for pump speed. In one case, the measured pump speed versus time was prescribed. Reviewing the output of this run, it was observed that the core flow just prior to oscillation inception is overpredicted when compared to measurements. To investigate this effect, a second run was made with a pump speed that was modified to provide a core flow close to the measured values. Both cases were presented in the topical report.

[
]

The TR includes guidance for nodalization of the plant models used in executing the RAMONA5-FA ATWS-I calculations. The nodalization selected in a model is generally a balance between managing the time required to complete a calculation, maintaining calculational stability, and resolving the time/spatial distribution of parameters to a sufficiently fine level for accuracy. In general, the testing performed by Framatome can be expected to ensure that the computational time and stability are acceptable, but the NRC staff needs to verify that the nodalization recommendations are adequate to provide reasonable accuracy in the calculations. Therefore, the NRC staff requests the following information:

RAI-8

Justify that the RAMONA5-FA ATWS-I axial nodalization scheme in the core region provides sufficient numerical fidelity for the ATWS-I calculations, including considerations of numerical diffusion and resolution of the axial void distribution. In particular, prior studies by the NRC staff and contractors have shown that the axial void distribution may need to be captured at a sufficiently high resolution to result in an accurate calculation of the axial power profile, and thus accurate calculation of stability behavior (e.g. decay ratio), in some codes. This effect has been shown to be separate from that of numerical diffusion, so provide a discussion regarding whether the average void fraction for each node is accurate enough to correctly capture the axial power distribution for stability calculations. For example, would an increase in the number of thermal hydraulic nodes lead to a significant change in the locally-averaged void fraction across the coupled neutronic nodes due to the higher resolution of the void fraction distribution, and would this significantly affect the RAMONA5-FA ATWSI calculations?

Framatome Response RAI-8:

A theoretical discussion of the numerical fidelity of the algorithms used for BWR stability must come with a disclaimer pointing to the wide opinions promulgated in the nuclear industry where no studies can claim completeness or generality of applicability to all codes. While a discussion is provided here, the ultimate support for the RAMONA5-FA code numerical fidelity rests on the empirical proof afforded by good agreement with a wide variety of experimental data forming a benchmarking database, and stressing the code with numerical experiments and sensitivity studies.

Numerical diffusion and damping

Numerical diffusion results from the residuals of finite differencing (or finite volume) approximations of transport differential equations. Neglected higher order terms resemble diffusion operators acting on the transported property, e.g. temperature moving in a 1-D pipe. In the ideal example of a step change in temperature of a fluid moving through a pipe, the exact solution maintains the same step function shape which moves along the pipe at the flow speed. Physical or numerical diffusion causes the sharp step change to diffuse and the temperature distribution spreads increasingly with time. This numerical diffusion is a kinematic aspect as it does not involve forces or momenta. The effect of diffusion (spread) of various flow variables on the momentum is not discussed in the available literature beyond numerical experiments demonstrating a damping effect of the perturbations as functions of time; the connection between the spatial diffusion and temporal damping is implied but only as a qualitative trend without proof. An attempt to make this dynamic connection in the context of density waves is presented here. [

] Another possible effect of diffusion is increasing the attenuation of the flow perturbations as they travel from the inlet to higher elevations. In this case, the magnitude of the pressure drop near the exit would be reduced relative to that of the inlet which has a dampening effect. A third possible effect is related to how the momentum balance equations are formulated where either nodal momentum equations are used or a single integrated momentum equation is formulated per boiling channel.

The effect of increased attenuation of the flow perturbations as they travel up the boiling channel has been shown [

]

ratio increase is not large, the benchmarking becomes biased. For the large oscillation magnitude cases, the increased nodalization also produced larger oscillations that [

].

Figure 16 Calculated Versus Measured Decay Ratio for [ ]

Figure 17 Calculated Versus Measured Frequency for [ ]

[

].

Table 2 Linear reactor benchmarks [ ]

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[

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Figure 18 [

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Figure 19 [

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Figure 20 [

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Figure 21 [

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Figure 22 [

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Figure 23 [

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Table 3 provides a comparison between the results of the Brunswick ATWS-I sample base case with standard nodalization and the doubled core nodalization case.

Table 3 Comparison between Brunswick sample case results with standard and doubled core nodalization

Parameter	Base Case	Doubled Nodalization
Time of oscillation inception (sec)	113	92
Time of failure to rewet excursion (sec)	117	97
Time of peak bundle power (sec)	117.2	143.3
Peak bundle power (MW)	5.74	5.69
Time of maximum core inlet subcooling (sec)	147.1	151.5
Maximum core inlet subcooling (kJ/kg)	195.8	205.5
Time of peak clad temperature (sec)	140.7	143.5
Peak clad temperature (°C)	656	677

[

].

RAI-9

Justify that the vessel nodalization used for RAMONA5-FA ATWS-I is sufficient to provide a reasonable and accurate prediction of PCT during ATWS-I events.

Framatome Response RAI-9:

The Brunswick test case for ATWS-I was rerun with the nodalization in the vessel
[

].

Figure 24 Brunswick sample problem showing effect on [ ] due to vessel nodalization

Figure 25 Brunswick sample problem showing effect on [ ] due to vessel nodalization

Figure 26 Brunswick sample problem showing effect on [ ] due to vessel nodalization

Figure 27 Brunswick sample problem showing effect on [ ] due to vessel nodalization

For the same calculation where the operator actions are omitted (unmitigated case), the core inlet subcooling varies towards the end of the run due to the effect of the power and flow oscillations in the core which become highly nonlinear and chaotic fluctuations are expected. **[**

].

Table 4 Unmitigated Brunswick sample problem PCT results with different vessel nodalization

[ ]

Figure 28 Unmitigated Brunswick sample problem showing effect on [ ] due to vessel nodalization

Figure 29 Unmitigated Brunswick sample problem showing effect on [ ] due to vessel nodalization

RAI-10

Provide an example(s) of the calculated time-dependent behavior of the [ ] during large-amplitude oscillations with flow reversal. In the cases presented in the TR, did sufficient flow reversal occur such that [ ]? If such a circumstance occurs, justify that the RAMONA5-FA ATWS-I methodology treats this circumstance in a reasonable and/or conservative way, with respect to the ATWS acceptance criteria.

Framatome Response RAI-10:

[
]

Figure 30 [

]

Several inputs to the ATWS-I calculation are described in the TR, with specific recommendations provided. In some cases, the parameters of interest may be determined to be insensitive to specific inputs based on engineering judgment or sensitivity studies. In other cases, the parameters of interest are adjusted to achieve desired results. In all cases, the recommendations must ensure that the results from the ATWS-I calculations are accurate or conservative. In order to verify this, the NRC staff requests the following information:

RAI-11

Provide sensitivity results for one or more linear stability benchmark cases and a simulated ATWS-I event (either a nonlinear benchmark problem or a sample full-core case) by adjusting the gap conductance values. Show time-dependent results for power, PCT, and other relevant results.

Framatome Response RAI-11:

The effect of gap conductance on the reactor benchmarks is given in Table 5, [

]

Table 5 Effect of gap conductance [ ] linear reactor stability benchmarks

In conclusion, it is observed that the best estimate gap conductance is the best practice for performing stability calculations in particular for ATWS-I, where biasing its value in one direction may not be always conservative.

[ ]

Figure 31 [

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Figure 32 [

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Figure 33 [

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[

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Figure 34 [

]

RAI-12

The NRC staff has the following questions regarding time step control:

a. *What input parameters are provided by RAMONA5-FA ATWS-I to control the timestep size? What are the recommended values for use?*

b. *What values for these parameters were used for the nonlinear stability benchmarks and the sample problem provided in the TR?*

c. *Provide a set of sensitivity results for timestep size, similar to the sensitivity study provided for RAI11.*

Framatome Response RAI-12–a:

[

]

Framatome Response RAI-12–b :

The values are provided in Table 6 and are common between the benchmarks and the sample problem.

Table 6 Time Step Criteria

[

]

Framatome Response RAI-12–c:

Time step control parameters were varied to generate the time step sensitivity for several cases including the reactor benchmarks and the sample Brunswick ATWS-I run. [

]. An example of the time step variation will be provided.

Table 7 Control parameters for time step sensitivity

[

]

The reactor benchmarking results using these time step control parameters are provided in Table 8, [

].

Table 8 Linear reactor benchmark results with variations of time step controls listed in Table 7

The results of the Brunswick sample run for different time step controls are plotted together. [

].

Table 9 Peak clad temperature results for the Brunswick sample case with varied time step control parameters

Figure 35 Brunswick sample problem with varied time step control parameters showing [ ]

Figure 36 Brunswick sample problem with varied time step control parameters showing [ ]

Figure 37 Brunswick sample problem with varied time step control parameters showing [ ]

Figure 38 Brunswick sample problem with varied time step control parameters showing [ ]

Figure 39 Brunswick sample problem with varied time step control parameters showing [ ]

RAI-13

What spatial distribution is used for the [ ]? Justify that the modeling approach for [ ].

Framatome Response RAI-13 :

Figure 40 Oskarshamn Core Power Results, [ ]

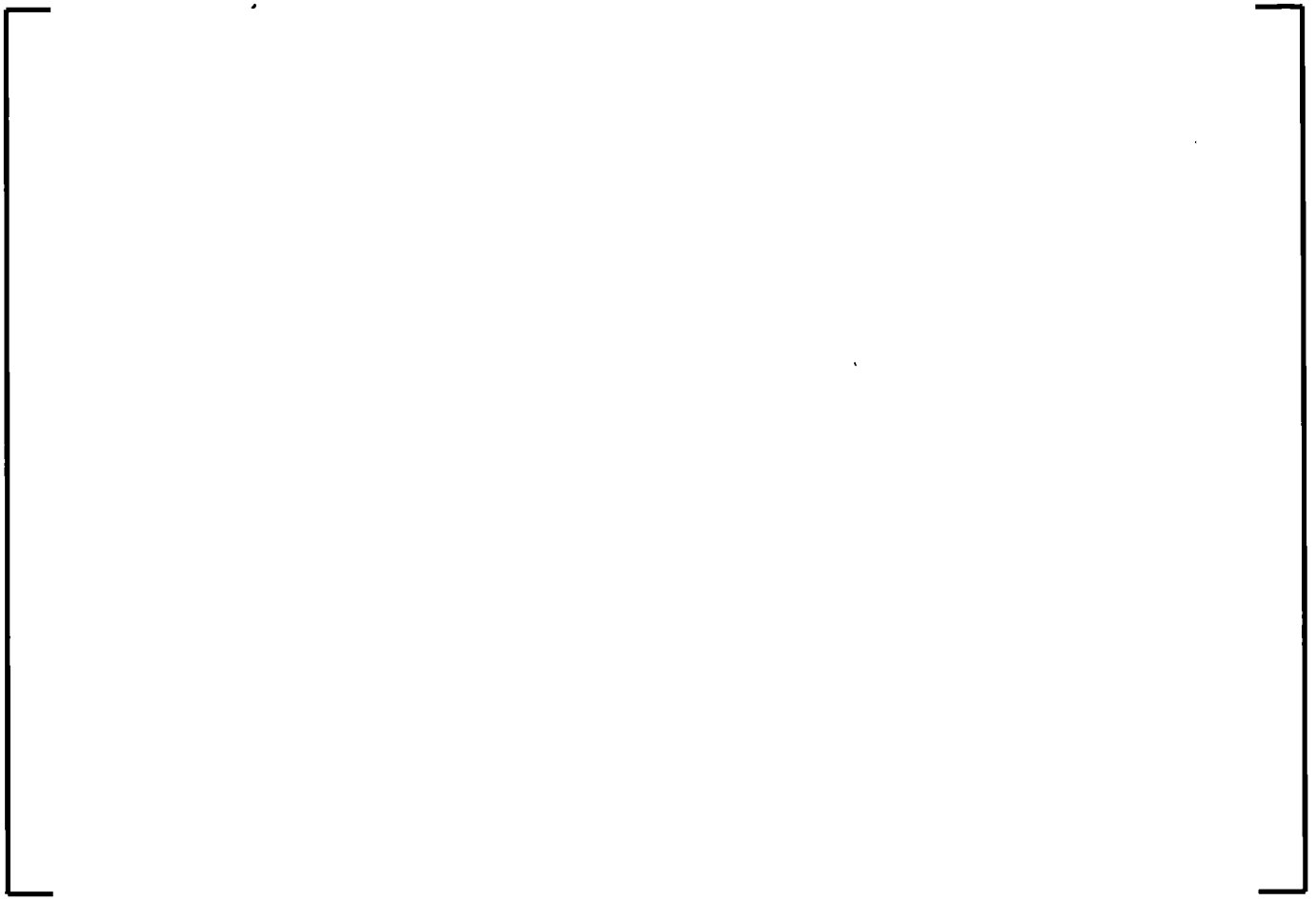

Figure 41 Oskarshamn Core Power Zoomed Results, [ ]

RAI-14

Justify that the [

].

Framatome Response RAI-14:

[
]

The TR provides a brief procedure that would be used to perform the ATWS-I analysis and determine whether acceptance criteria are met. [

]. Therefore, the NRC staff requests the following information:

RAI-15

[

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Framatome Response RAI-15:

[
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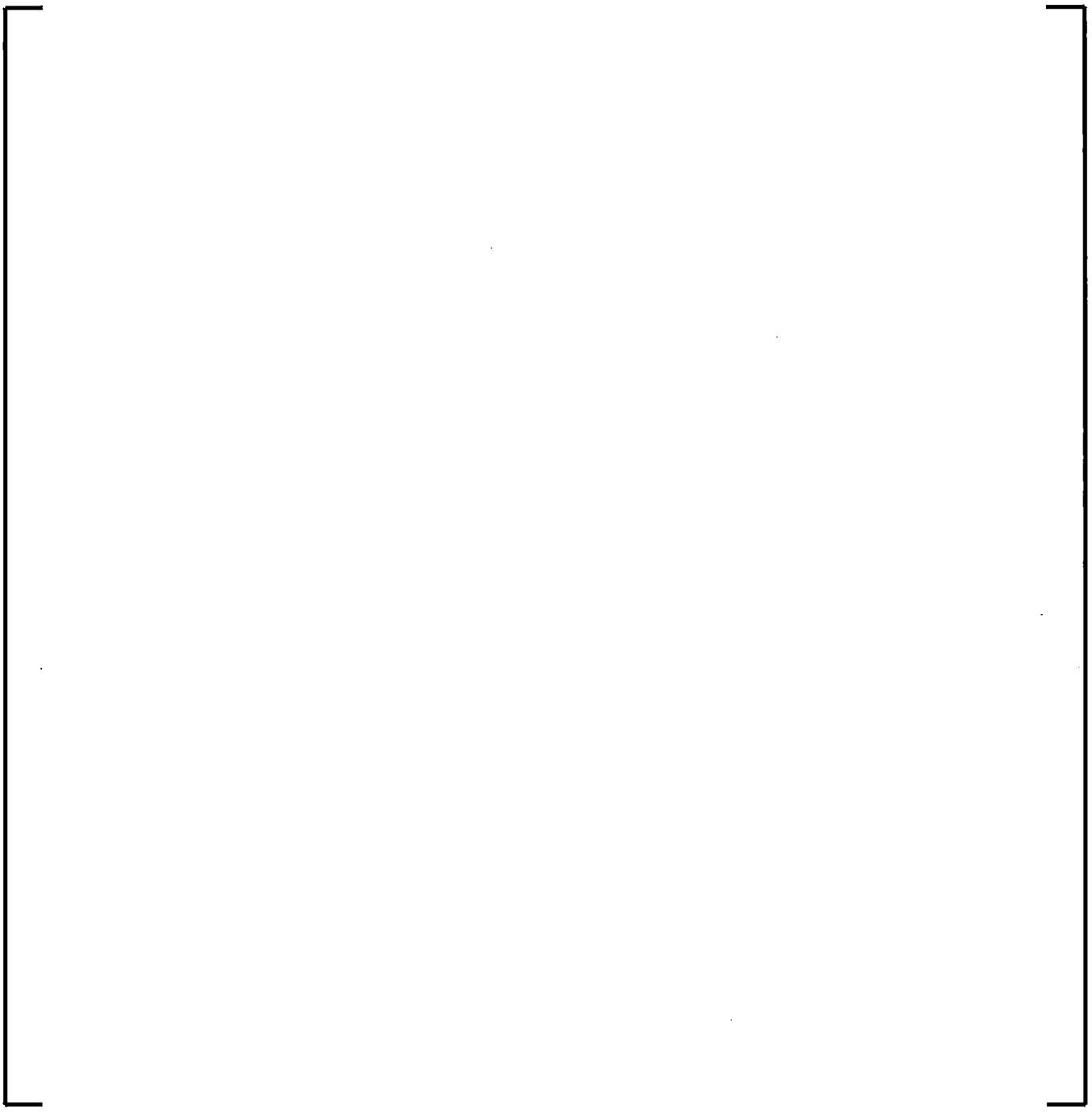

RAI-16

For the process described in RAI 15, discuss how the various modeling and input assumptions remain appropriate when considering their effect on the time of oscillation onset.

Framatome Response RAI-16:

Additional Information

In the topical report ANP-10346P, Section 8.0 (Calculation Procedure), Steps 3a and 3b are inconsistent.

Step 3a contains the following statement:

[

]

A corrected page 8-2 has been added to Appendix A to reflect this change.

References

1. Y. M. Farawila and M. R. Billaux, "XEDOR -- Reduced Order Stress Model for Interactive Maneuvering of Boiling Water Reactors," Proceedings of the International LWR Fuel Performance Top Fuel Meeting, San Francisco, September 30 - October 3 2007, Paper 1059.

2. Y. M. Farawila, K. Wei, and R. G. Grummer, "XEDOR Evaluation of PCI Risk due to Loss of Feedwater Heating in Boiling Water Reactors," Proceedings of the 2008 Water Reactor Fuel Performance Meeting, Seoul Korea, October 19-23, Paper 8142.

3. J. March-Leuba, C. G. Thurston and T. L. Huang, "Time-space nodalization issues in BWR stability calculations," in NURETH-15, Pisa, Italy, 2013.

4. Aaron J. Wysocki, "Investigation of Limit Cycle Behavior in BWRs with Time-Domain Analysis," PhD Thesis, University of Michigan, 2015.

5. EMF-CC-074(P)(A) Volume 4 Revision 0, *BWR Stability Analysis: Assessment of STAIF with Input from MICROBURN-B2*, August 2000.

6. BAW-10255PA Revision 2, *Cycle-Specific DIVOM Methodology Using the RAMONA5-FA Code*, May 2008.

7. P. Yarsky, "Sensitivity to Tmin In Trace/Parcs Analysis of ATWS with Instability," NURETH-16, Chicago, IL, August 30-September 4, 2015

8. Yousef M. Farawila, "Fuel Design Concept to Stabilize Boiling Water Reactors," Top Fuel 2016, Boise, ID, September 11-15, 2016

9. Letter, Jonathan G. Rowley (NRC) to Gary Peters (Framatome), "Request for Additional Information Regarding Framatome Inc. Topical Report ANP-10346P Revision 0, "ATWS-I Analysis Methodology for BWRs Using RAMONA5-FA (EPID: L-2017-TOP-0067)," September 21, 2018.

Appendix A Revised Topical Pages

The following Appendix contains revised topical pages as discussed during the audit held at the Framatome Richland facility on June 11-13, 2018. A revised page is also included to reflect the correction shown in the Additional Information portion of this document. It is intended that these pages replace the current LTR pages in the final approved document.

6.2 *Benchmarking to Void Fraction Tests*

The FRIGG experiments, Reference 32 have been included in the validating database because of the broad industry use of these experiments in benchmarking activities, including TRAC, RETRAN, and S-RELAP5. The experiments include a wide range of pressure, subcooling, and quality from which to validate the general applicability of a void correlation. However, the experiments do not contain features found in modern rod bundles such as part length fuel rods and mixing vane grids. The lack of such features makes the data less useful in validating correlations for modern fuel designs.

Because of its prototypical geometry, the ATRIUM-10 and ATRIUM 10XM void data collected at KATHY was useful in validating void correlation performance in modern rod bundles that include part length fuel rods, mixing vane grids, and prototypic axial/radial power distributions. The characteristics of the void fraction validation database are listed in Table 6-1. For ATWS-I benchmarking the range of data [

]

Figure 6-1 provides comparisons of predicted versus measured void fractions for the AREVA multi-rod void fraction validation database using the [ ] correlation. This figure shows reasonable predictions versus the measured data. The mean predictions fall within [ ] (predicted – measured) error with a mean error of [ ] and a standard deviation of [ ].

[

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6.6.2 [ ]

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6.6.3 [ ]

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* [

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6.6.4 [ ]

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6.7 *Benchmarking to Non-Linear Reactor Benchmarks*

In order to validate the functions and additions to the RAMONA5-FA ATWS-I code, several sets of non-linear stability reactor benchmarks were performed. These benchmarks include:

- Oskarshamn Non-Linear Instability
- BWR A Feedwater Transient with Non-Linear Instability

A description of the benchmark analyses is given in the following sections along with the RAMONA5-FA ATWS-I calculated decay ratios and frequencies.

6.7.1 Oskarshamn Nonlinear Instability

On February 25, 1999 as maintenance work was being performed on a switchyard outside of Oskarshamn Unit 2, the power supply to a bus bar was interrupted for 150 ms. A load rejection signal was sent to the main breaker that connects the unit to the grid. This signal caused the turbine to trip, however due to a failure in the relay circuit, this signal was not transmitted to the reactor protection system. The system continued at power until operators initiated a partial scram. Following the partial scram, power and flow were decreased. The feedwater temperature continued to decrease causing reactor power to further increase until the system crossed the stability boundary. The reactor continued to oscillate until a high power scram was reached.

The Oskarshamn-2 non-linear stability was analyzed with RAMONA5-FA ATWS-I. Two separate scenarios were evaluated. In the first scenario, the measured pump speed was imposed and the recirculation flow was calculated based on the specified pump performance curves. The plots of relevant parameters to actual measured data for this scenario are given in Figure 6-24, Figure 6-25, and Figure 6-26. The results show good agreement with measured values with a small overestimation of the event growth rate. However, Figure 6-26 shows that the code overestimates the final recirculation flow during the final portion of the event. A second scenario was then run in which the pump speed versus time was modified to produce a recirculation flow approximately equal to the measured value. The results of this evaluation are given in Figure 6-27, Figure 6-28, and Figure 6-29. The results of this scenario show a slightly greater overestimation with the measured power results.

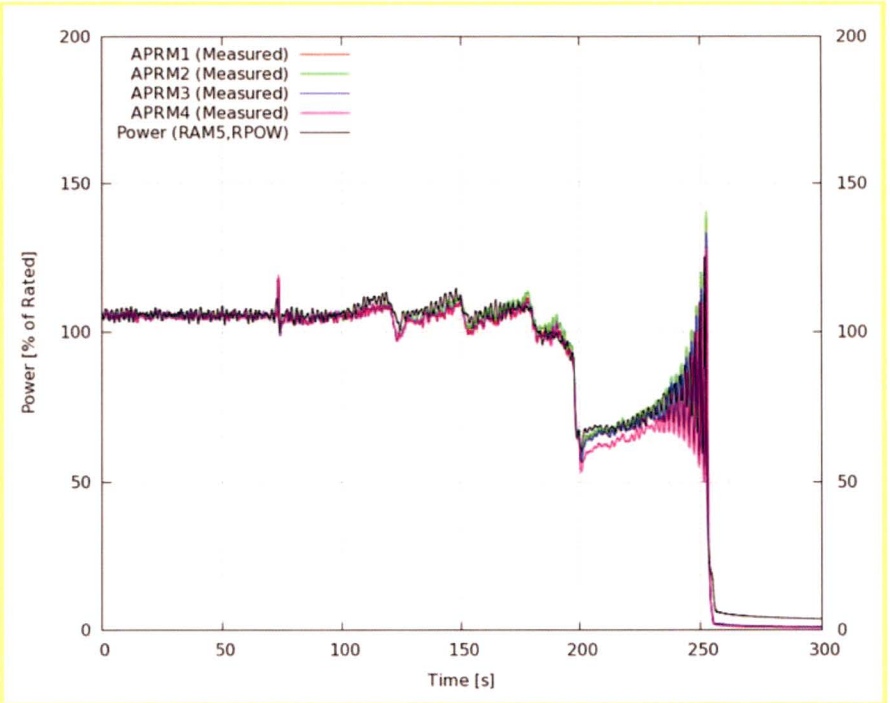


Figure 6-24: Oskarshamn-2 Non-Linear Stability Simulation Core Power, Imposed Pump Speed

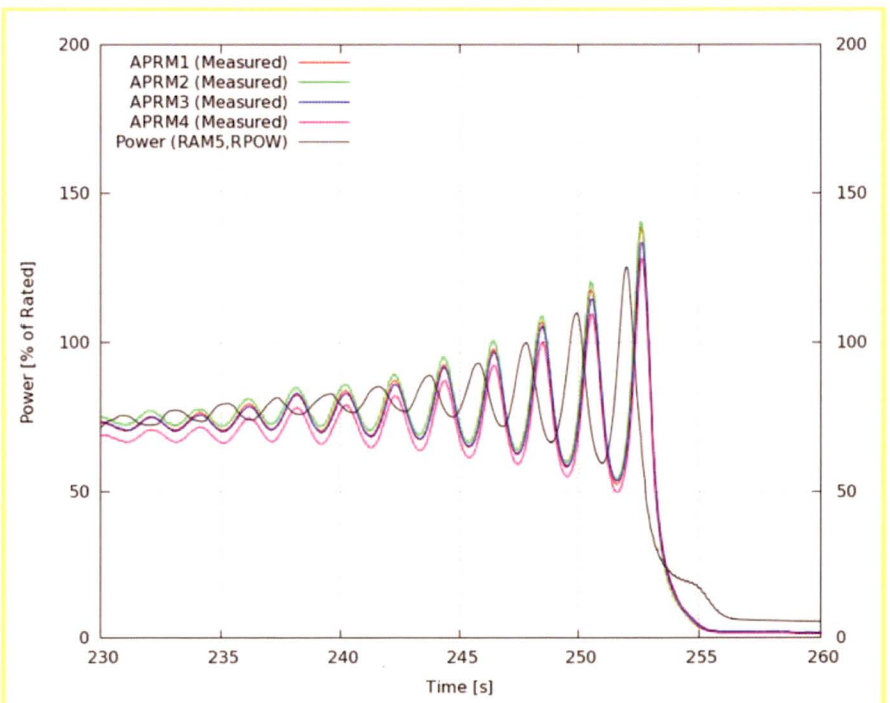


Figure 6-25: Oskarshamn-2 Non-Linear Stability Simulation Core Power - Zoom, Imposed Pump Speed

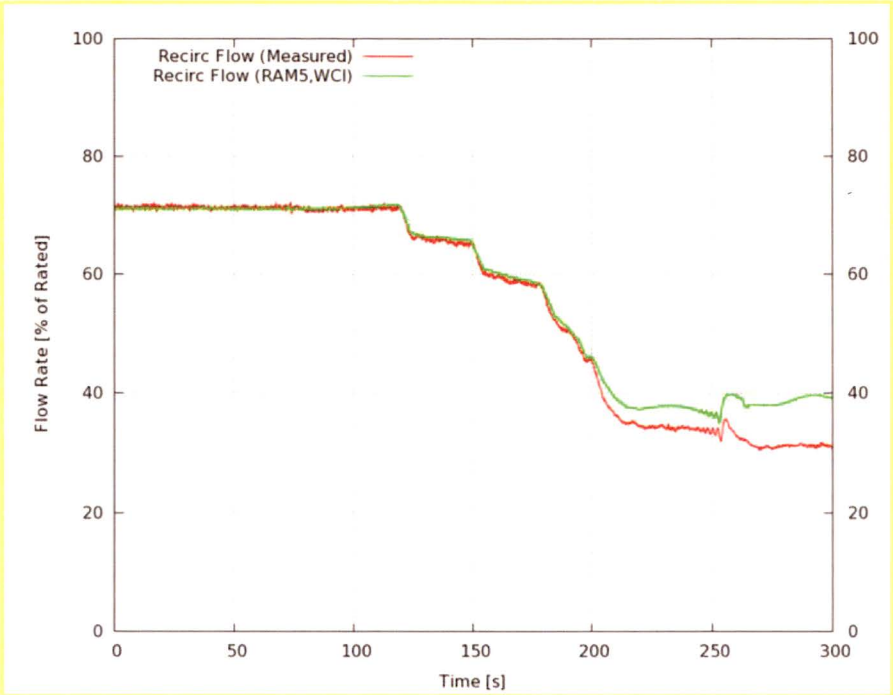


Figure 6-26: Oskarshamn-2 Non-Linear Stability Simulation Recirculation Flow, Imposed Pump Speed

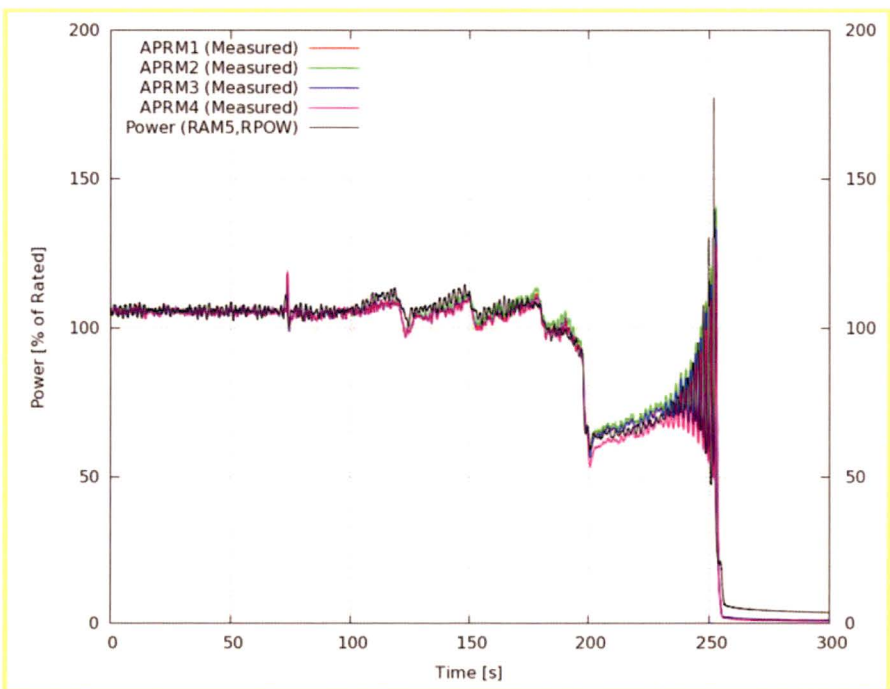


Figure 6-27: Oskarshamn-2 Non-Linear Stability Simulation Core Power, Match Recirculation Flow

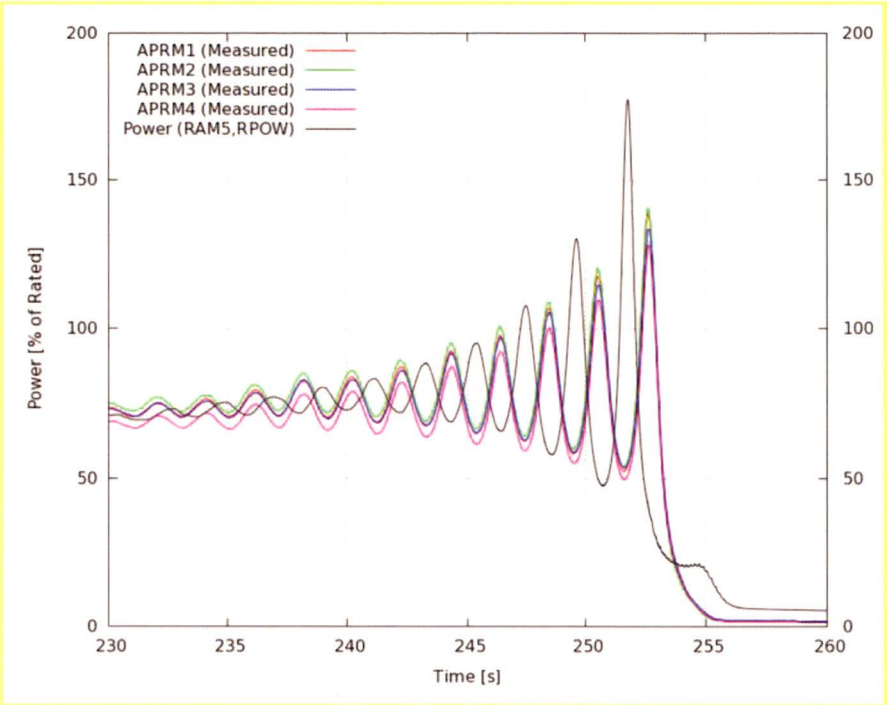


Figure 6-28: Oskarshamn-2 Non-Linear Stability Simulation Core Power - Zoom, Match Recirculation Flow

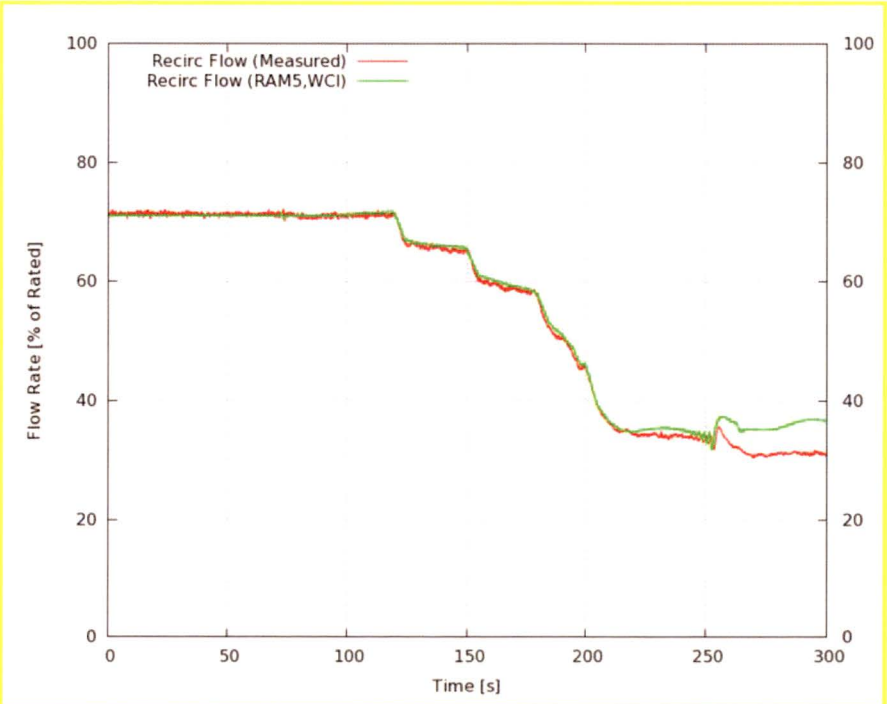


Figure 6-29: Oskarshamn-2 Non-Linear Stability Simulation Recirculation Flow, Match Recirculation Flow

Figure 6-30. The results show very good agreement between the measured and calculated [ ]

Figure 6-30: BWR [ ] Transient Non-Linear Stability Simulation

Table 7-1: TTWB Sensitivity Study Results

[ ]

Figure 7-1: TTWB Base Case Core Power

Figure 7-2: TTWB Base Case Core Inlet Flow

Figure 7-3: TTWB Base Case Core Inlet Subcooling

Figure 7-4: TTWB Base Case Limiting Channel Inlet Flow

Figure 7-5: TTWB Base Case Vessel Water Level

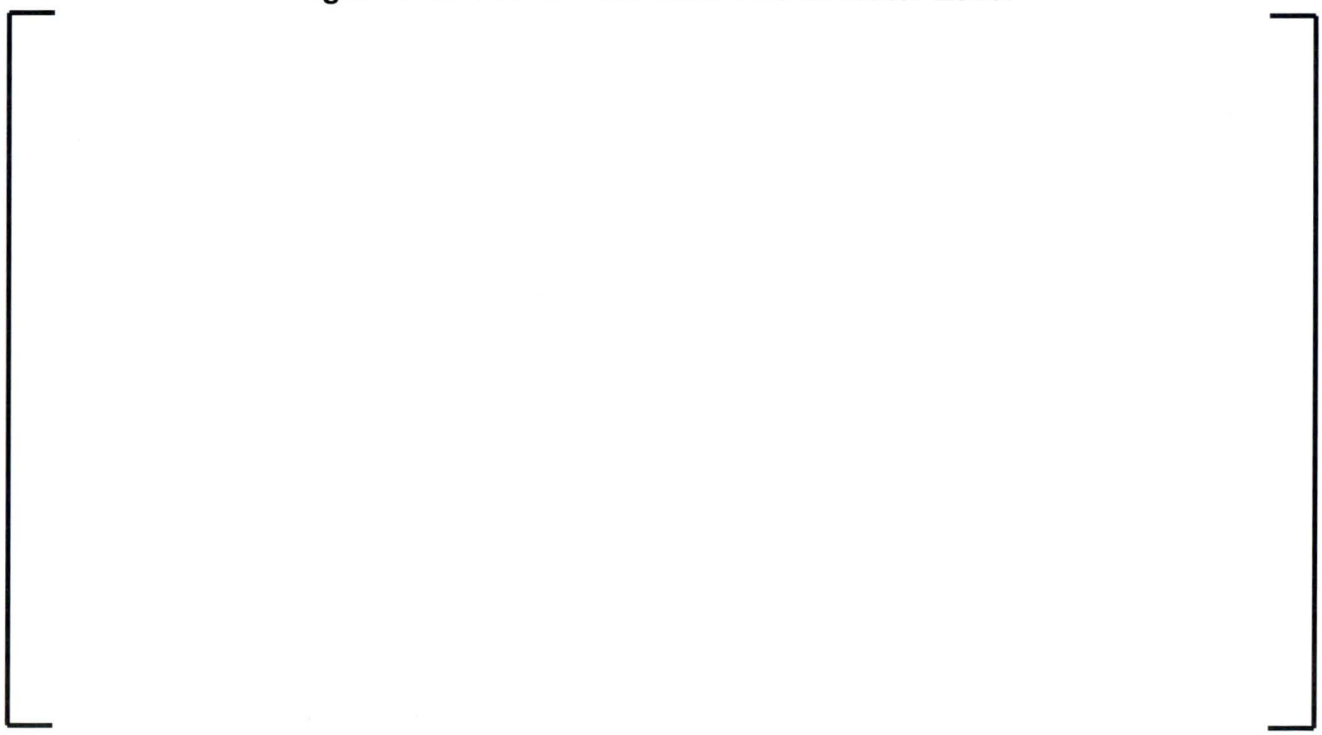


Figure 7-6: TTWB Base Case Limiting Channel PCT

Table 7-2: 2RPT Sensitivity Study Results

Figure 7-7: 2RPT Base Case Core Power

Figure 7-8: 2RPT Base Case Core Inlet Flow

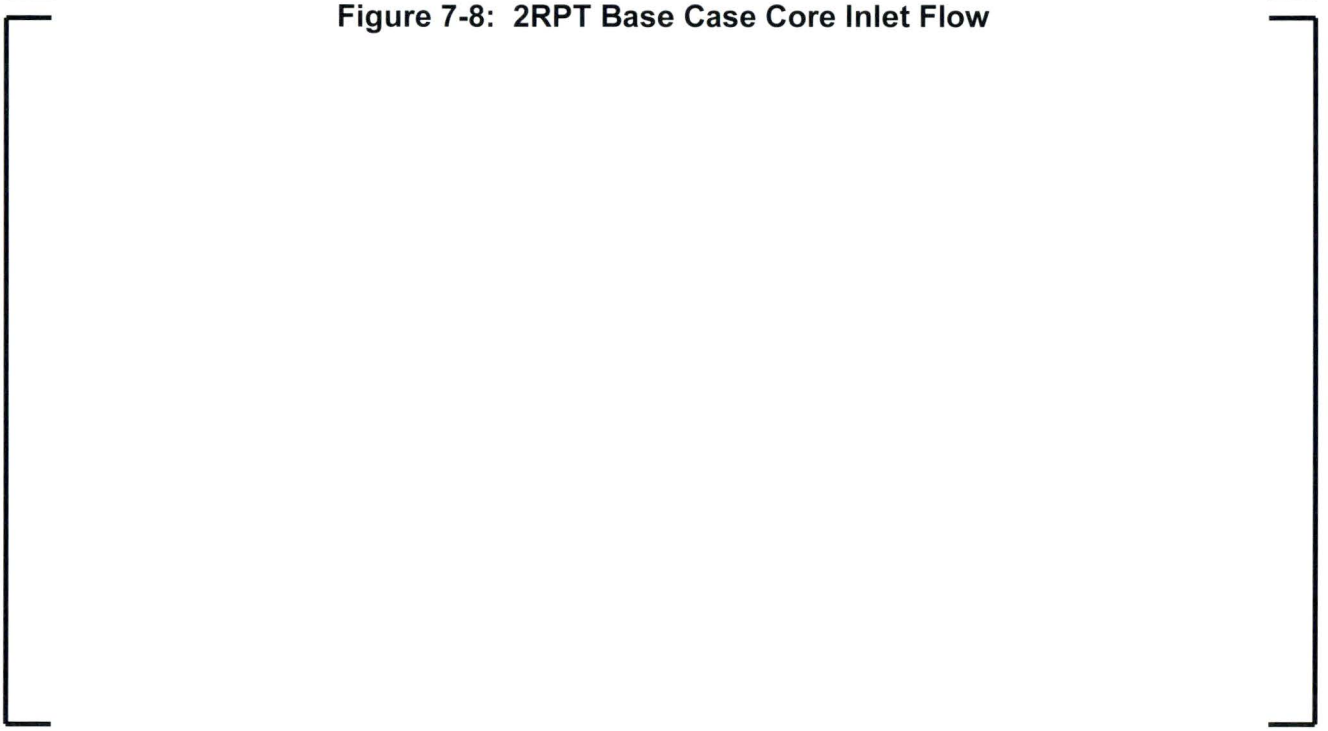


Figure 7-9: 2RPT Base Case Limiting Channel Inlet Flow

Figure 7-10: 2RPT Base Case Core Inlet Subcooling

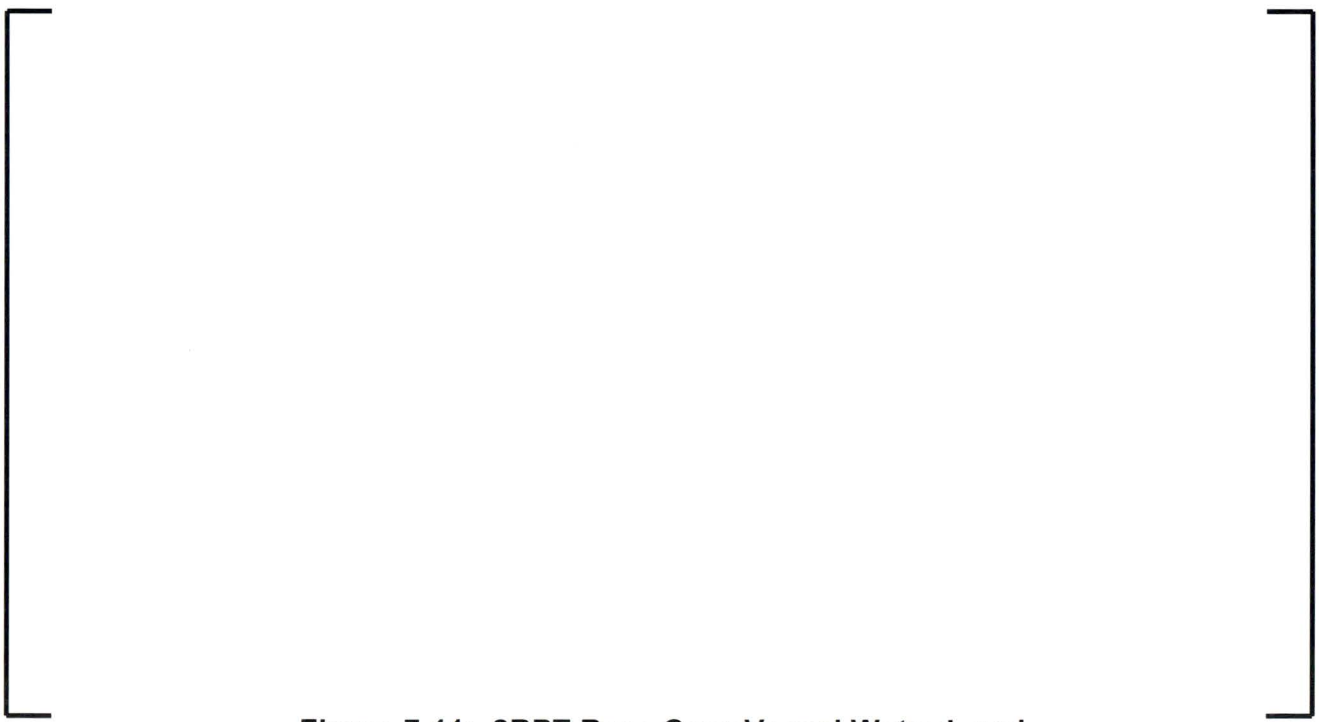
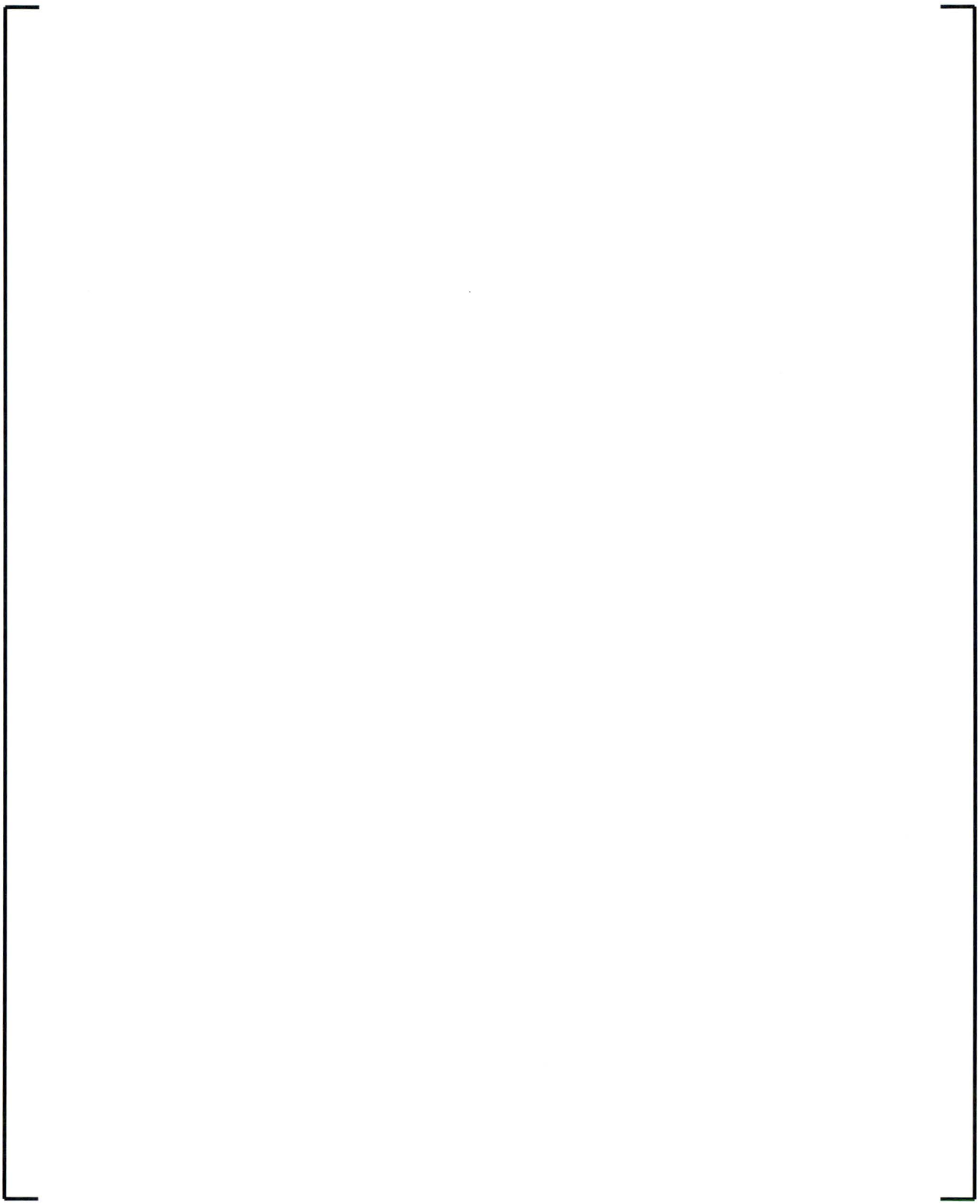


Figure 7-11: 2RPT Base Case Vessel Water Level

Figure 7-12: 2RPT Base Case Limiting Channel PCT



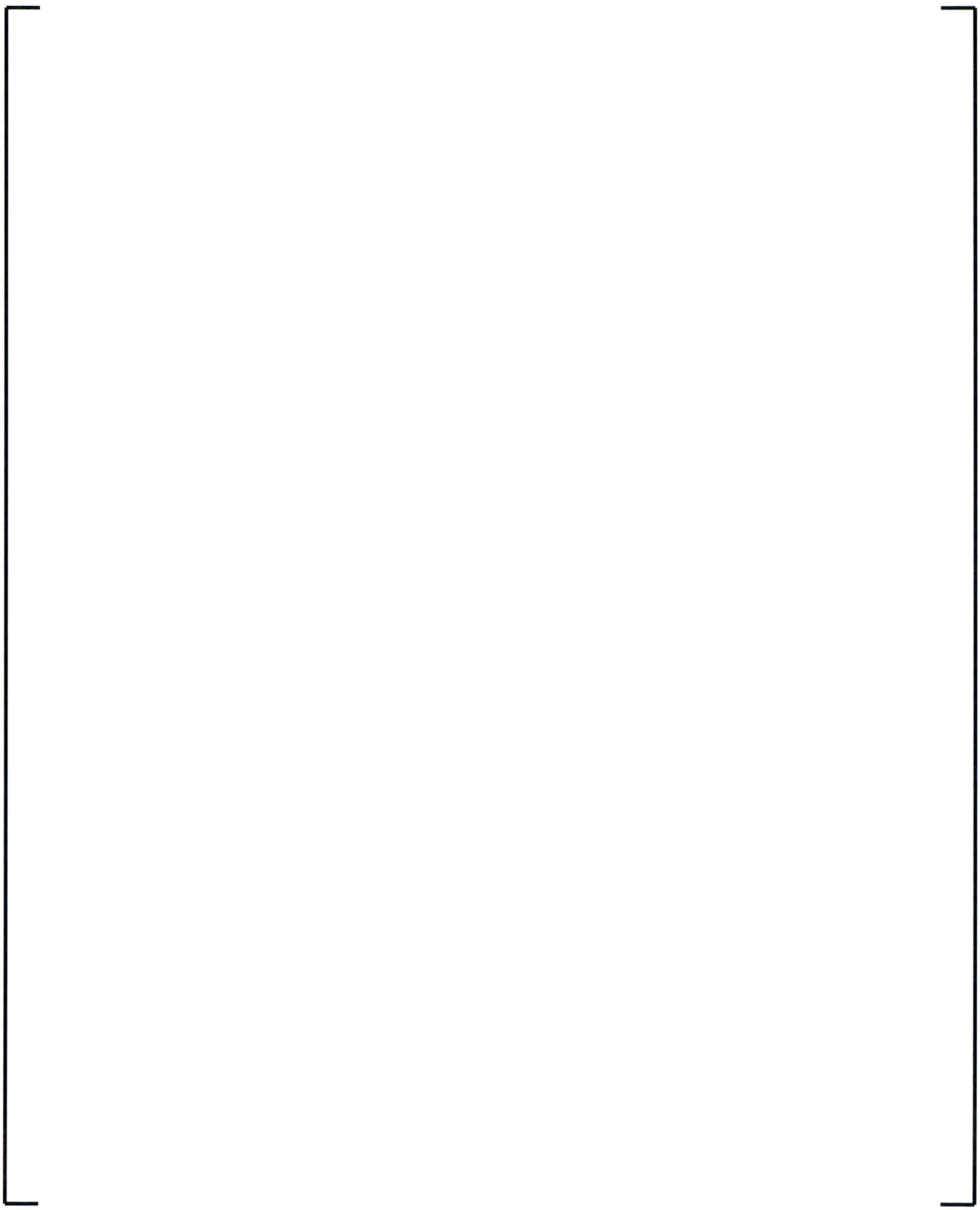


Figure C-1: Oskarshamn Core Power, Interfacial Friction Sensitivity

Figure C-2: BWR A Core Power, Interfacial Friction Sensitivity

Appendix D Chromia Fuel Rod Properties

New RODEX4 based fuel rod properties models are described in Section 5.2.5. These models are intended for use with standard UO_2 pellets. For Chromia doped pellets, modifications to the fuel thermal conductivity and [ ] models will be needed to account for the effects of the Chromia doping. The Chromia doped pellet specific models presented here will be based on the RODEX4 Chromia models described in Reference D.1.

D.1 FUEL CONDUCTIVITY

The fuel thermal conductivity model for Chromia doped fuel is given in Section 7.1.1 of Reference D.1. [

] As such, this correlation forms the basis of the fit for the model shown.

- Fuel conductivity (W/m-K)

[

]

where

[

]

D.2 [ ]

[

]

where

[ ]

D.3 REFERENCES

D.1 ANP-10340P-A Revision 0, "Incorporation of Chromia-Doped Fuel Properties in AREVA Approved Methods," May 2018.