USE OF WHITE NOISE IN TRACE/PARCS ANALYSIS OF ATWS WITH INSTABILITY

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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. In that analysis, instability onset was observed in response to changing plant conditions of power, flow, and feedwater temperature. The baseline calculations were performed without using a PARCS feature to simulate "noise" in the reactor.

When a simulated reactor is unstable but in a steady-state condition, an analytical tool may not show the onset of instability because there would not be a perturbation to excite oscillation. Such a condition of artificial stability could not persist in an actual reactor where subtle variation of local conditions (e.g. void fraction) would provide a constant source of perturbation, or "noise." The regulatory purpose of the current work is to study the reliability of the TRACE/PARCS prediction of instability onset and oscillation growth during ATWS-I by providing a source of noise in the simulation. In addition, the results of this study support a generic methodology recommendation for any future studies.

PARCS has a feature that can simulate the reactivity effect of perturbations in local void fraction. This feature, referred to as the white noise feature, is used to provide an artificial source of constant, local perturbation that would more closely mimic the actual reactor condition where local void fractions are constantly changing. Sensitivity of the onset timing and growth was studied by varying the magnitude, frequency, and contour of the perturbations applied by the white noise feature.

The study concludes that onset timing and growth of both the initial core-wide and subsequent bi-modal oscillation stabilized at a certain combination of perturbation magnitude, frequency range, and frequency resolution. With the appropriate range of these parameters, the instability onset occurs approximately 20 seconds earlier, and peak oscillation amplitude is achieved approximately 15 seconds earlier when compared to the baseline calculations. Given the importance of oscillation onset and growth on potential fuel damage, this study recommends a specific methodology with respect to white noise so as to ensure a reliable prediction with TRACE/PARCS for future studies.

KEYWORDS
ATWS BWR MELLLA+ PARCS TRACE Instability

1. INTRODUCTION

It is expected that when a reactor is unstable but in a steady state condition, an analytical time-domain tool would not show the onset of instability because there would not be a perturbation to excite oscillation. Therefore, there were some open questions about the reliability of the predicted instability onset timing and growth ratio in the TRACE/PARCS ATWS-I analyses.

For ATWS-I analyses, the plant is presumed to undergo a transient with varying core boundary conditions. These variations in core boundary conditions (e.g. pressure) were expected to be sufficient to perturb an unstable core configuration into instability. However, since the ATWS-I transient progression is driven by somewhat slowly evolving conditions (e.g. slow reduction in feedwater temperature) it was deemed appropriate to study the sensitivity of the transient response to simulated noise. The purpose of this study is to understand the effect of artificial noise on instability onset timing and growth ratio in the early development stage of unstable power oscillations for ATWS-I analyses. In addition, the results of this sensitivity study are intended to form the basis for generic guidelines for future work in the area of ATWS-I.

For the current purpose it is desirable to apply noise with the intent of a specific magnitude and modal excitation, as opposed to random noise. The specific noise option applied should not result in power oscillations greater than the uncertainty in average core power. Further, application of noise along a specific mode achieves the objective of investigating the onset and growth of an instability in that mode. Applying any driving function to a stable configuration will not incite growth; however, providing targeted modal excitation as a perturbation to an unstable configuration will incite growth. In other words, there is no noise application that would cause oscillation growth for a stable configuration; however, untargeted noise may not achieve the goal of inciting growth in unstable modes of interest. For this reason, the current work does not utilize random noise.

Section 2 of this report describes the methodology and the basis for the selection of noise input parameters. Section 3 describes the case matrix and the different PARCS noise parameters that were used for each case. Section 4 presents and discusses the calculation results for the pertinent parameters, namely the instability onset timing and the growth ratio. Section 5 provides a conclusion and recommendations for future work in the area of ATWS-I.

2. METHODOLOGY

This study starts with a baseline ATWS-I calculation similar to that described in the companion paper [1]. The specific case selected is the peak hot excess (PHE) ATWS-I case except that no noise is simulated. Sensitivity studies are then performed by activating the noise feature with different specifications.

To activate the noise feature it is necessary to specify various aspects of the noise signal. For the current work, the noise feature was used with the fundamental and harmonic contours to provide perturbations to these modes. To exploit this feature, it is necessary to supply the harmonic shape file (HAR) to the transient calculation. The HAR is generated by a separate PARCS stand-alone calculation.

The PARCS stand-alone calculation was performed using the TRACE/PARCS coupled steadystate calculation DEP file. This file supplies the instantaneous moderator density, temperature, fuel temperature, and xenon/samarium distributions. By adjusting the INP_OPT card it is possible to disable thermal-hydraulic feedback, provide the static distributions from the DEP file, and calculate the fundamental mode power shape and eigenvalue as well as the first harmonic mode shape and eigenvalue. These calculations generally require a large number of iterations to converge the harmonic shape; therefore, the number of PARCS iterations was increased to 7500. The staff confirmed that the PARCS stand-alone calculation was performed correctly by verifying that the fundamental mode power shape and eigenvalue was consistent with the predicted values from the coupled TRACE/PARCS steady-state calculation and that the harmonic calculation converged with fewer than the maximum number of iterations.

The output of the PARCS stand-alone calculation includes the HAR file necessary for the modal excitation in the transient calculation. The transient input deck TRAN block was modified to include noise. This requires additional input for the EXCI_MOD, WHIT_NOI, DM_AMPLM, TF_AMPLM, and HARMON_F cards. The last card, HARMON_F, merely specifies the location of the HAR file.

The EXCI_MOD controls the number of spatial modes considered in the distribution of noise in the reactor core. The first spatial mode indicates random noise, the second spatial mode applies noise along the fundamental mode contour, and the third spatial mode applies noise along the harmonic mode contour. In the current work, three modes are specified in the input; however, the random component is suppressed.

The WHIT_NOI entry controls the noise start and stop times as well as the range of frequencies. The WHIT_NOI entry was set to initiate noise at 5 seconds. This allows a period of 5 seconds of pure null transient in advance of noise activation in the transient calculation. Since the null transient duration is 10 seconds, the initial 10 second period can be used to verify that the noise option is activated correctly and that the magnitude of the noise in terms of power perturbation is appropriate. The end time for the noise was initially selected to coincide with the end of the simulation time. However, additional runs were made to investigate the possibility of ending the noise earlier, after it had achieved its purpose, so that it would not interfere with the rest of the simulation.

The remaining WHIT_NOI entries represent the minimum and maximum frequency as well as the step size in frequency between these limits. The noise is reconstructed from these inputs by performing an inverse Fourier transform based on the finite frequencies between the minimum and maximum at each step. A random phase shift is applied in the inverse Fourier transform.

The expected oscillation frequency is between 0.3 and 0.7 Hz for typical BWR density wave oscillation driven instability [4]. Initial runs indicated that the natural frequency of the reactor under ATWS-I conditions is within the range of 0.35 Hz to 0.5 Hz [1]. However, In order to capture the full effect of both core-wide (CW) and out-of-phase (OOP) oscillation, the options in PARCS were set to specify a wider frequency range of 0.3 Hz to 1.2 Hz with a very small frequency step size of 0.000001 Hz.

The DM_AMPLM and TF_AMPLM specify the mode-specific noise amplitude for moderator density and fuel temperature, respectively. Since the void reactivity feedback is typically much stronger than the Doppler feedback, the fuel temperature noise was fully suppressed in favor of a noise perturbation based purely on moderator density. Therefore, the TF_AMPLM entry is null. The moderator density noise amplitude for the first mode was set to zero. This means that no random noise is applied. The amplitudes were set for both the fundamental (or CW) and first harmonic (or OOP) modes iteratively in the current work.

3. CASE MATRIX

The purpose of this study is to determine the optimal combination of CW and OOP noise amplitudes that would consistently result in the earliest instability onset timing while not introducing any non-physical perturbations to the overall plant response. In order to achieve this goal, a large number of runs were made, the results were analyzed, a narrow range of CW and OOP noise amplitude combinations was determined, and a specific combination was recommended for future work in the area of ATWS-I. Only the most relevant cases are included in this paper; those are listed in Table I.

All 12 calculations listed in Table I are performed using TRACE Version 5 Patch 3. The first is the baseline analysis without the inclusion of noise. Cases 2 through 5 specify only CW noise and no OOP noise. Cases 6 through 9 specify only OOP noise and no CW noise. Cases 10 through 12 specify both CW and OOP noise. All noise sensitivity cases are based on the same transient TRACE input deck but with modifications made to the PARCS transient input deck TRAN block, per Section 2..

The baseline (Case 1) was executed for 300 seconds. All other cases were executed for 200 seconds, which provided sufficient data to compare transient power responses. For all cases that included noise, the noise was initiated at 5 seconds. This allows a period of 5 seconds of pure null transient in advance of noise activation in the transient calculation. Since the null transient duration is 10 seconds, the initial 10 second period was used to verify that the noise option is activated correctly and that the magnitude of the noise in terms of power perturbation is appropriate (i.e. less than 2 percent). The end time for the noise was initially selected to coincide with the end of the simulation time. However, preliminary results showed the benefit of ending the noise earlier, at around 115 seconds after it had achieved its purpose, so that it wouldn't interfere with the rest of the simulation. This was also verified later by comparing the results of Cases 10 and 12. Therefore, noise was terminated at 115 seconds for most cases.

The magnitude of the moderator density noise amplitude was iteratively determined to achieve an approximate power perturbation on the order of 0.5 to 1.0 percent. A value of 0.0001 for CW noise amplitude was found to generate an approximate 0.5 percent variation in core power level during the last 5 seconds of the null transient. Therefore, this value was used as a starting point for CW noise analysis. Although a wide range of noise amplitude was investigated during the CW analysis, the most relevant range of 0.00005 to 0.0005 is documented in this study. Similarly, a wide range of noise amplitude was investigated during the OOP analysis. However, only the most relevant range of 0.000001 to 0.00005 is documented in this study. The specific cases are listed in Table I.

Table I. Case matrix

Case Number	Case Name	CW Noise Amplitude	OOP Noise Amplitude	Noise Start-End Time (sec)	Frequency Range (Hz)	Frequency Step Size (Hz)
1	Base	0	0	N/A	N/A	N/A
2	C/5E-5	5.00E-05	0	5-115	0.3-1.2	1.00E-06
3	C/1E-4	1.00E-04	0	5-115	0.3-1.2	1.00E-06
4	C/2E-4	2.00E-04	0	5-115	0.3-1.2	1.00E-06
5	C/5E-4	5.00E-04	0	5-115	0.3-1.2	1.00E-06
6	P/1E-6	0	1.00E-06	5-115	0.3-1.2	1.00E-06
7	P/5E-6	0	5.00E-06	5-115	0.3-1.2	1.00E-06
8	P/1E-5	0	1.00E-05	5-115	0.3-1.2	1.00E-06
9	P/5E-5	0	5.00E-05	5-115	0.3-1.2	1.00E-06
10	CP/1E-4/5E-6	1.00E-04	5.00E-06	5-115	0.3-1.2	1.00E-06
11	CP/2E-4/1E-5	2.00E-04	1.00E-05	5-115	0.3-1.2	1.00E-06
12	CP/1E-4/5E-6/200	1.00E-04	5.00E-06	5-200	0.3-1.2	1.00E-06

4. CALCULATION RESULTS AND ANALYSIS

Figure 1 depicts the core power transient during ATWS-I for the baseline (Case 1). The key period of interest is the onset and normal growth of the power oscillations. This stage is marked by a growing oscillation magnitude. In the baseline case, this period of the transient starts at approximately 100 seconds and the initial peak oscillation magnitude is achieved at approximately 125 seconds. Another period of interest includes the bi-modal power oscillations which peak at approximately 160 seconds.

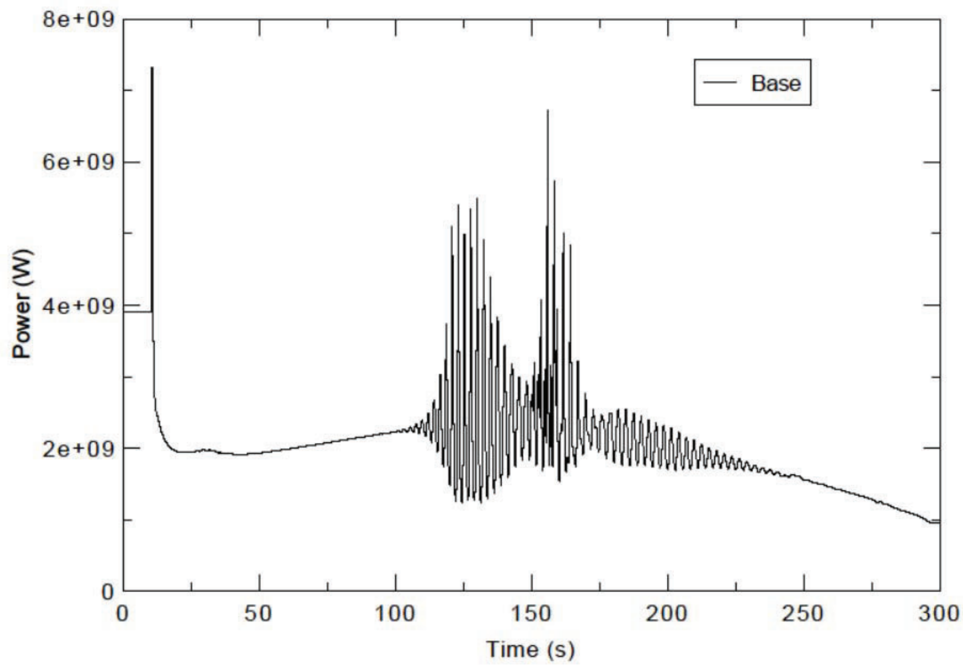

Figure 1. Baseline Core Power Response.

Figures 2, 3 and 4 depict the core power transients during ATWS-I for the 4 cases which include only CW noise and no OOP noise (Cases 2 through 5), and compares them to the baseline power transient. It can be seen that for all cases the onset of the power oscillations starts at approximately 80 seconds; however, its growth rate and peak oscillation magnitude and timing vary from case to case.

It can be seen that the growth rate increases with increasing noise amplitude until the noise amplitude reaches 1E-4; at which point the response appears to "saturate." In other words, not much is gained by increasing the noise amplitude from 1E-4 to 2E-4. Increasing the noise amplitude beyond 2E-4 introduces a larger power perturbation during the null transient with no benefit in terms of predicted onset timing and growth. Therefore, a reasonable range for CW noise amplitude would be 1E-4 to 2E-4. A CW noise amplitude of 1E-4 is preferred since it accomplishes the goal with minimal power perturbation.

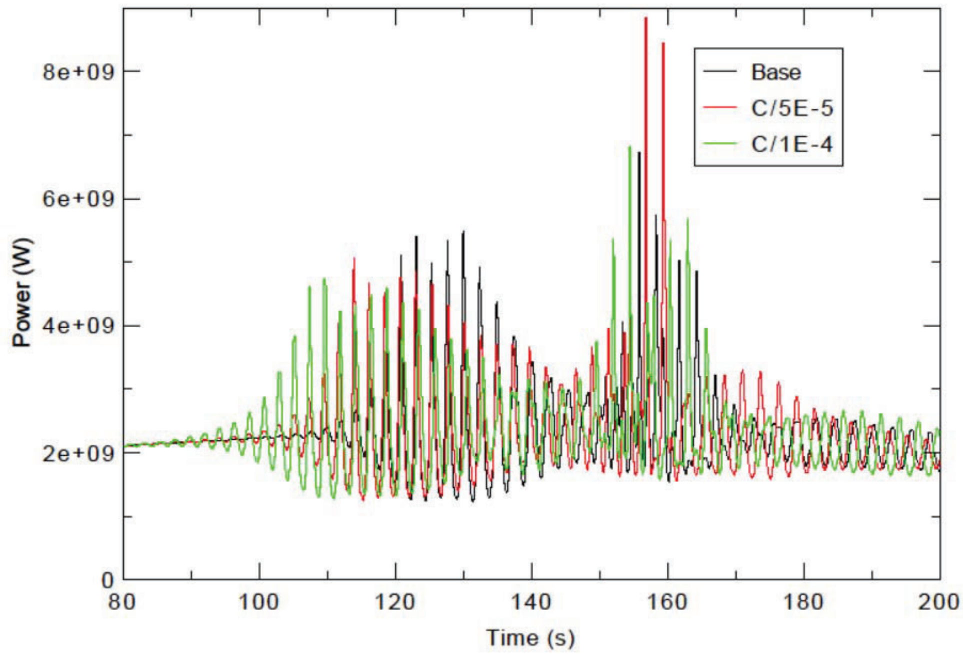

Figure 2. Core Power Responses Cases 1, 2 and 3.

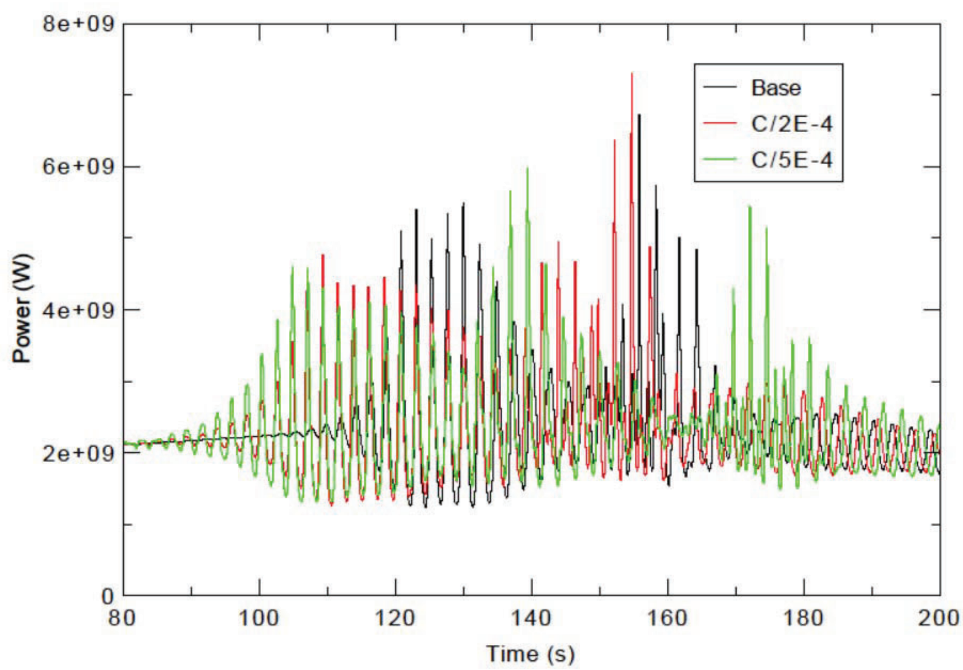

Figure 3. Core Power Responses Cases 1, 4, and 5.

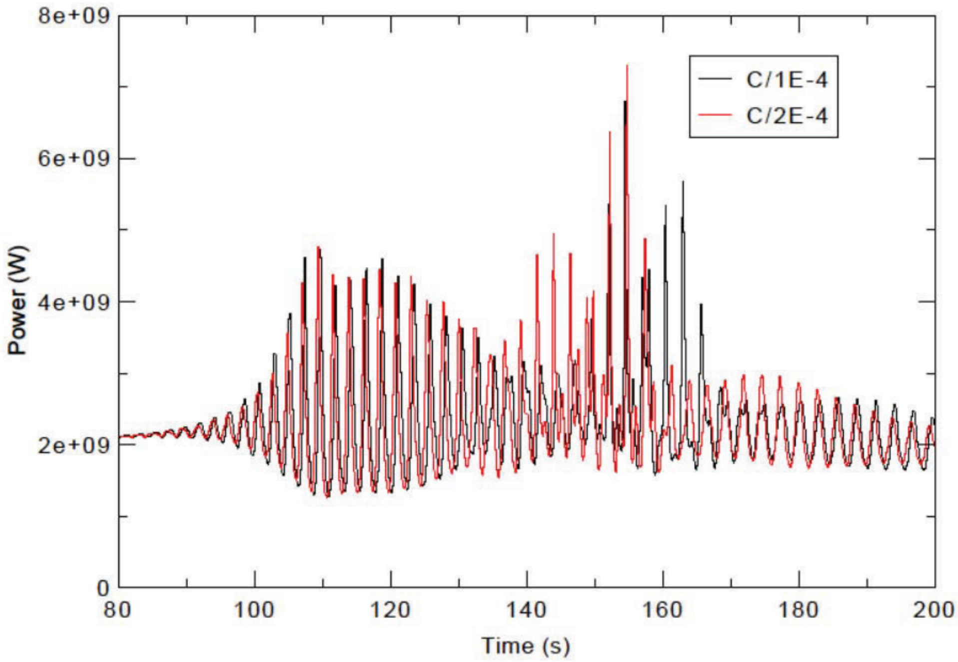

Figure 4. Core Power Responses Cases 3 and 4.

Figures 5, 6 and 7 depict the core power transients during ATWS-I for the 4 cases which include only OOP noise and no CW noise (Cases 6 through 9), and compares them to the baseline power transient. The analogous goal of introducing the OOP noise is subtly different from, and a little more complicated than, that for the CW noise. This is because OOP instability is not directly observable in the total core power response. When the core is unstable in the OOP mode, power oscillates between two halves of the core, so total core power can remain largely unchanged. However, when the OOP mode is highly unstable, there is non-linear coupling to the CW mode. When this non-linear, bi-modal coupling occurs, a frequency doubling is observed in to the total core power response. Figure 1 depicts the onset of the bi-modal instability shortly before 150 seconds and is evidenced by the frequency doubling along with the large amplitude power oscillation. In the current work, the bi-modal oscillation apparent in the total core power response is an indication of the unstable nature of the OOP mode.

Therefore, the goal of assigning OOP noise is to bring the bi-modal oscillations (observed in the baseline within the range of approximately 150 to 170 seconds) as early as possible while not exciting the system in a way that introduces any unrelated, non-physical, CW oscillations.

It can be seen that Cases 6 and 9, for example, were unable to achieve that goal, Cases 7 and 8 do. Therefore, a reasonable range for OOP noise amplitude would be 5E-6 to 1E-5. It would appear from the calculation results that the bi-modal onset timing “saturates” around an OOP noise amplitude of 5E-6. An OOP noise amplitude of 5E-6 is preferred since it accomplishes the goal with minimal perturbation.

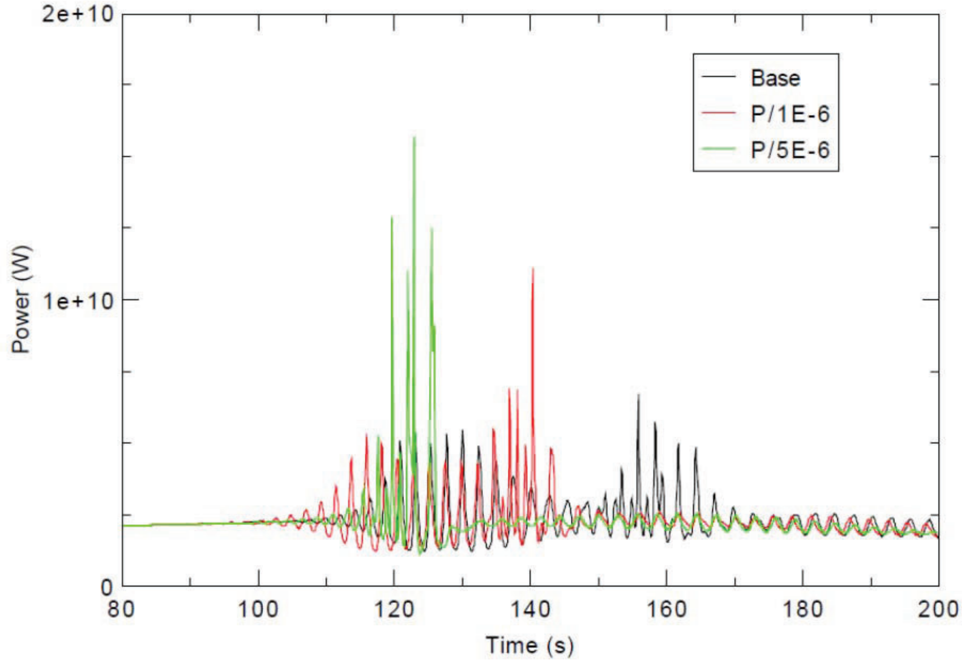

Figure 5. Core Power Responses Cases 1, 6, and 7.

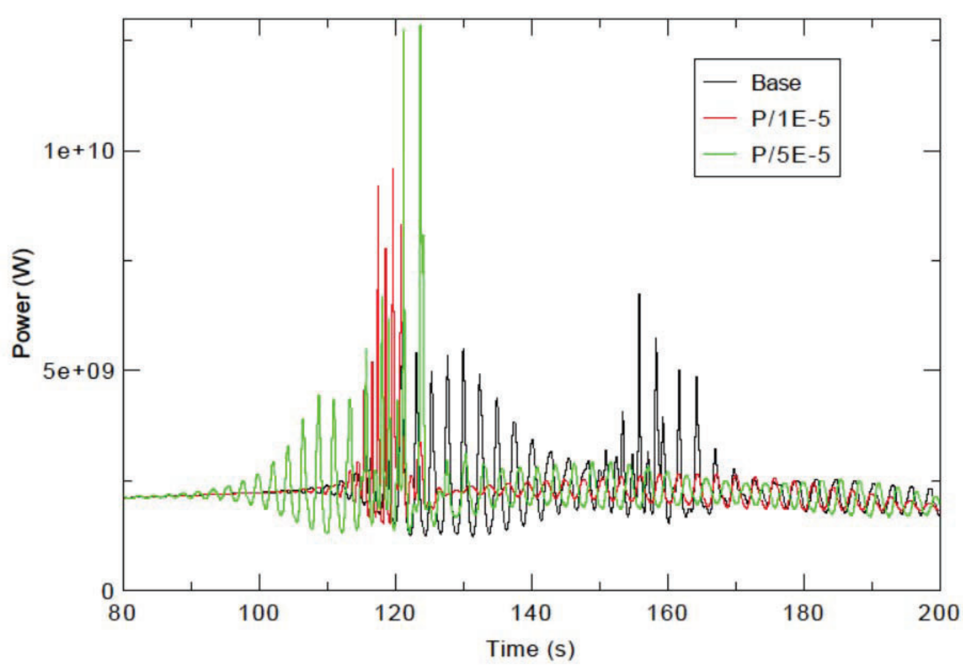

Figure 6. Core Power Responses Cases 1, 8, and 9.

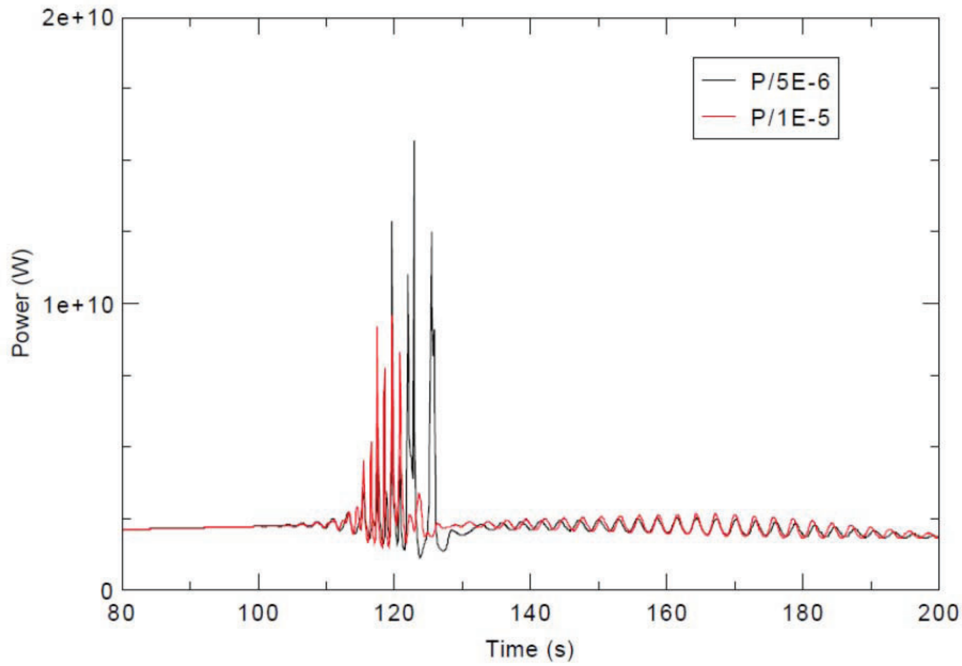

Figure 7. Core Power Responses Cases 7 and 8.

For completeness, and to ensure a full understanding of any unforeseen synergy effects, a combination of the recommended CW noise range (1E-4 to 2E-4) and OOP noise range (5E-6 to 1E-5) was considered and analyzed. As expected, the results were very close for all cases analyzed within that range. The two limiting CW/OOP combinations (i.e., 1E-4/5E-6 and 2E-4/1E-5) within that range are shown in Figure 8 for demonstration purposes. It can be seen how closely the results agree. Therefore, a reasonable range for a combined CW/OOP noise amplitude would be 1E-4/5E-6 to 2E-4/1E-5. A combined CW/OOP noise amplitude of 1E-4/5E-6 is preferred since it accomplishes the goal with minimal perturbation.

In this case, the onset of the power oscillations starts at approximately 80 seconds (20 seconds earlier than that for the baseline), and the peak oscillation magnitude is achieved at approximately 110 seconds (15 seconds earlier than that for the baseline). The power oscillation growth rate is slightly larger than that for the baseline; however, its peak magnitude is similar to that of the baseline.

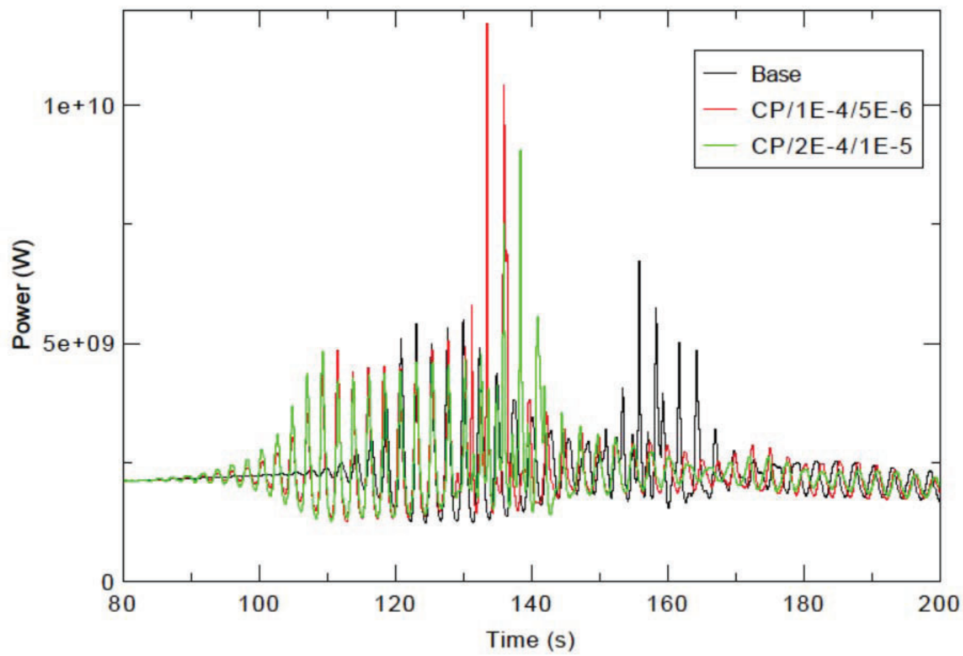

Figure 8. Core Power Responses Cases 1, 10 and 11.

As mentioned above, noise was terminated at 115 seconds for all cases since preliminary results showed the benefit of ending the noise earlier so that it would not interfere with the rest of the simulation. This was also verified by comparing the results of Cases 10 and 12; the comparison is shown in Figure 9. It can be seen that ending the noise earlier, after it had accomplished its goal, does not alter the results at the beginning of the transient. However, it ensures minimal interference with the rest of the simulation. Therefore, it is recommended to terminate noise as early as possible, after the power oscillation would have reached its peak.

For future work in this area, it would be ideal to specify a generic noise signal. However, our current work demonstrates the advantage of disabling the noise once the instability has been excited. To this end, any generic methodology would require an additional run to determine the appropriate time to terminate noise as the onset timing cannot be known a priori.

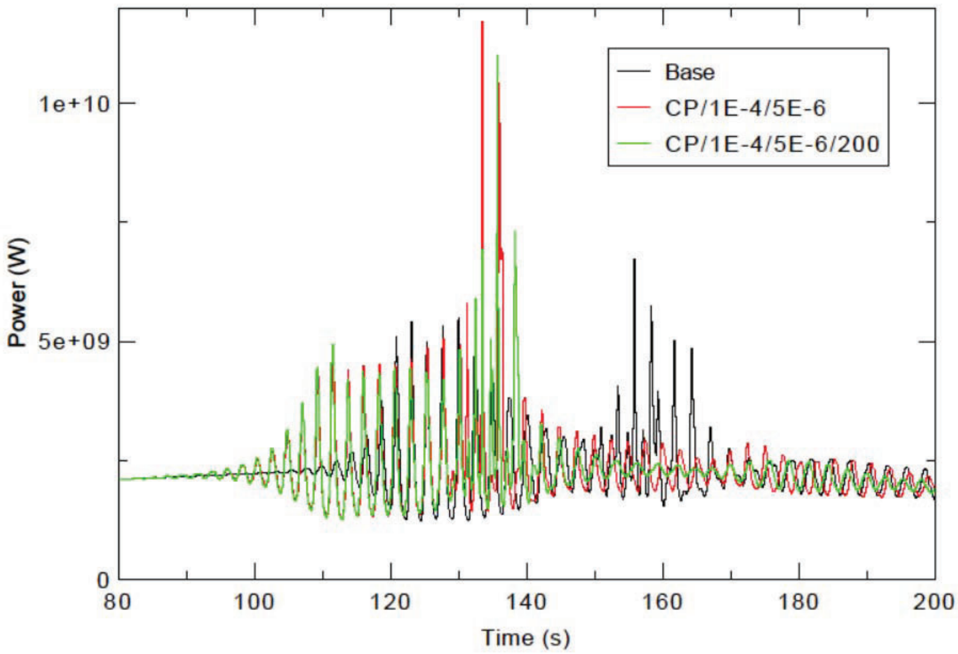

Figure 8. Core Power Responses Cases 1, 10 and 12.

5. CONCLUSIONS

This study has demonstrated the importance of inclusion of noise in predictions of ATWS-I events. In particular the current work illustrates the sensitivity of the instability onset timing and growth rate to the application of white noise. A large number of runs were made and analyzed in order to determine the optimal combination of CW and OOP noise that would consistently result in the earliest instability onset timing while not introducing non-physical perturbations to the plant response in the simulation. First, the effects of inclusion of CW noise and OOP noise were separately analyzed. The effect of inclusion of a combined CW and OOP noise was then evaluated and a determination was made regarding the appropriate noise range for future work in the area of ATWS-I.

For all CW noise only cases, the onset of the power oscillations starts at approximately 80 seconds; however, its growth rate and peak oscillation magnitude and timing vary from case to case. The results show that the growth ratio and onset timing saturate at a CW noise amplitude of 1E-4. Not much is gained by increasing the noise amplitude from 1E-4 to 2E-4. Increasing the noise amplitude beyond 2E-4 introduces a significant power perturbation with no benefit in terms of growth rate. Therefore, a reasonable range for CW noise amplitude would be 1E-4 to 2E-4. A CW noise amplitude of 1E-4 is preferred since it accomplishes the goal with minimal power perturbation.

Similarly, the results show that a reasonable range for OOP noise amplitude would be 5E-6 to 1E-5. An OOP noise amplitude of 5E-6 is preferred since it accomplishes the goal with minimal perturbation. Finally, the results show that a reasonable range for a combined CW/OOP noise amplitude would be 1E-4/5E-6 to 2E-4/1E-5. A combined CW/OOP noise amplitude of 1E-4/5E-6 is preferred since it accomplishes the goal with minimal perturbation. In this particular case, the onset of the power oscillations starts at approximately 80 seconds (20 seconds earlier than that for the baseline), and the peak oscillation magnitude is achieved at approximately 110 seconds (15 seconds earlier than that for the baseline). The power oscillation growth rate is slightly larger than that for the baseline; however, its peak magnitude is similar to that of the baseline.

For future TRACE analyses of this type, this work supports the inclusion of a combined CW and OOP noise within the above recommended range and consistent with the input parameters provided in Table I for that range.

For future ATWS-I analysis, this report recommends the following methodology to ensure reliable prediction of instability onset and growth:

1. Perform a baseline transient calculation; this step determines the time range of interest for providing the noise by providing the time of the instability onset.
2. Given the instability onset time, perform a second calculation with noise active in both the CW and OOP modes that persists to the time of instability onset plus 15 seconds.
3. The moderator density amplitude of the CW noise should be set to a magnitude of 1E-4 and the moderator density amplitude of the OOP noise should be set to a magnitude of 5E-6.
4. If no change in instability onset timing is observed increase the CW noise moderator density amplitude to 2E-4 and the OOP noise moderator density amplitude to 1E-5.

It should also be noted that RES has added high resolution numerical methods to TRACE since the start of the ATWS-I work. The reduction in numerical damping has been shown to have an impact on BWR stability calculations that did not include noise. The reduction in numerical damping may also lead to earlier onset and faster growth of the unstable power and flow oscillations, even when noise has been introduced. Therefore, it is recommended that future work be performed that examines the impact of using the high resolution methods on the predicted onset and growth of power oscillations

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