NUSCALE POWER™

RAIO-0518-60030

May 17, 2018

Docket: PROJ0769

U.S. Nuclear Regulatory Commission
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Rockville, MD 20852-2738

SUBJECT: NuScale Power, LLC Response to NRC Request for Additional Information No. 9440 (eRAI No. 9440) on the NuScale Topical Report, "Evaluation Methodology for Stability Analysis of the NuScale Power Module," TR-0516-49417, Revision 0

REFERENCE: U.S. Nuclear Regulatory Commission, "Request for Additional Information No. 9440 (eRAI No. 9440)," dated March 20, 2018

The purpose of this letter is to provide the NuScale Power, LLC (NuScale) response to the referenced NRC Request for Additional Information (RAI).

The Enclosure to this letter contains NuScale's response to the following RAI Questions from NRC eRAI No. 9440:

- 15.09-1
- 15.09-2

This letter and the enclosed response make no new regulatory commitments and no revisions to any existing regulatory commitments.

If you have any questions on this response, please contact Paul Infanger at 541-452-7351 or at pinfanger@nuscalepower.com.

Sincerely,

Zackary W. Rad
Director, Regulatory Affairs
NuScale Power, LLC

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Enclosure 1: NuScale Response to NRC Request for Additional Information eRAI No. 9440

Enclosure 1:

NuScale Response to NRC Request for Additional Information eRAI No. 9440

NuScale Power

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 9440
Date of RAI Issue: 03/20/2018

NRC Question No.: 15.09-1

Title 10 of the Code of Federal Regulations (CFR), Part 50, Appendix A, General Design Criterion (GDC) 10 – Reactor Design, states that the reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits (SAFDLs) are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences (AOOs). Title 10 of the CFR, Appendix A, GDC 12 states that the reactor core and associated coolant, control, and protection system shall be designed to assure that power oscillations which can result in conditions exceeding SAFDLs are not possible or can be reliably and readily detected and suppressed. The SRP 15.0.2 acceptance criteria with respect to evaluation models states that the chosen mathematical models and the numerical solution of those models must be able to predict the important physical phenomena reasonably well from both qualitative and quantitative points of view.

The staff reviewed the response to the original RAI, RAI 8808 Question 29740, and found that the response was insufficient for the staff to reach a conclusion regarding the adequacy of the stability analysis methodology. Specifically, the applicant responded that a quasi-steady state model is sufficient to model fuel heat conduction, presumably for performing stability analysis with PIM. The applicant's response also states that consideration for the conduction dynamics in the licensing methodology is used but not required for stability calculation accuracy.
In order to make an affirmative finding associated with the above regulatory requirement important to safety, NRC staff requests NuScale to provide the following supplemental information:

1. If the intent of the RAI 8808 response is to apply a quasi-steady heat conduction model in place of the conduction dynamics model currently described in section 5.6.4.1 of the NuScale Topical Report (TR) TR-0516-49417, "Evaluation Methodology for Stability Analysis of the NuScale Power Module" then:
    - Revise the stability TR accordingly, and
    - Justify the quasi-steady approximation using quantitative arguments
2. If the intent of the RAI response is to apply PIM's dynamic conduction model as currently discussed in section 5.6.4.1 of the stability TR then:
    - Provide the technical basis for the fuel thermal time constant correlation. It

is acceptable to respond by providing a technical reference, such as a peer reviewed scientific paper.

- Confirm that the correlation is not fuel-design specific.
- Clarify which terms in Equation 5-92 are exposure dependent.
- Because density, heat capacity, conductivity, and diameter change with exposure, explain what values are used if the exposure dependence is ignored.
- Confirm that the core average exposure is used to evaluate exposure dependent quantities.

NuScale Response:

Item 1

NuScale confirms that the PIM dynamic pin conduction model as described in TR-0516-49417-P is used in the applications. The response to RAI 8808 merely posits that a quasi-steady model would be a valid approximation given that the pin conduction time constant is much smaller than the oscillation period, and therefore the model parameters do not represent a non-conservative design basis.

Item 2

The intent of the response to RAI 8808 is to affirm the dynamic model applicability. The responses to individual bullet items are given below.

- The thermal time constant is not a correlation but a formula obtained from first principles with simplifying approximations. A derivation is presented as follows.

An effective time constant is sought for use in the first order equation:

$$\tau \frac{dq(t)}{dt} + q(t) = Q(t) \quad (1)$$

Where

t Time

q Rate of heat transfer at the outer rod surface (per unit length)

Q Energy generated inside the fuel rod (per unit length)

τ Conduction (thermal) time constant

An approximate solution is obtained by assuming radially uniform heat generation and an invariant temperature profile. The effect of these assumptions is addressed later.

Since the temperature profile is assumed invariant, therefore it can be obtained from steady state. This is obtained from the text book by Incropera and De Witt (Reference 1) as:

$$T(r)=T_s+\frac{q}{4\pi k}\left(1-\frac{r^2}{R^2}\right)=T_s+\left(T_0-T_s\right)\left(1-\frac{r^2}{R^2}\right) \tag{2}$$

where

k Thermal conductivity

r Radial distance

R Outer pellet radius

T_S Outer pellet (surface) temperature, at r = R

T_0 Center pellet temperature, at r = 0

T Temperature, function of radial distance

The average temperature is obtained from

$$\dot{T}=\frac{1}{\pi R^2}\int_0^R T(r)2\pi r dr=T_s+\frac{1}{2}\left(T_0-T_s\right) \tag{3}$$

Taking the sink coolant temperature as a reference, Eqn. (3) can be written as:

$$\dot{T}=T_s+\frac{1}{2}\left(T_0-T_s\right)=T_{cool}+\left(T_s-T_{cool}\right)+\frac{1}{2}\left(T_0-T_s\right) \tag{4}$$

where

T_{cool} Coolant (sink) temperature

The pellet surface temperature is related to the heat transfer coefficient as:

$$q=2\pi R h\left(T_s-T_{cool}\right) \tag{5}$$

where

h Effective heat transfer coefficient from pellet surface to coolant.

Using,

$$(T_0 - T_s) = \frac{q}{4\pi k} \tag{6}$$

The average temperature is obtained from combining Eqs. (4), (5), and (6) to get:

$$\dot{T} = T_{cool} + \frac{q}{2\pi Rh} + \frac{q}{8\pi k} \tag{7}$$

Energy balance yields the change in stored energy as the difference between the generated heat and the heat loss at the outer rod surface. Thus,

$$\rho c V \frac{d\dot{T}}{dt} = Q(t) - q(t) \tag{8}$$

where

ρ Pellet density

c Pellet heat capacity

$V = \pi R^2$ Pellet volume (per unit length)

Using Eqn. (7) to calculate the average temperature time derivative and substituting into Eqn. (8) we get:

$$\rho c \pi R^2 \left(\frac{1}{2\pi Rh} + \frac{1}{8\pi k} \right) \frac{dq(t)}{dt} = Q(t) - q(t) \tag{9}$$

Comparing Eqns. (1) and (9), we get the time constant as:

$$\tau = \rho c \pi R^2 \left(\frac{1}{2\pi Rh} + \frac{1}{8\pi k} \right) \tag{10}$$

which is simplified to get:

$$\tau = \frac{\rho c D^2}{32k} + \frac{\rho c D}{4Rh} \tag{11}$$

where

$D=2R$ Rod diameter

Eqn. (11) is the same formula as given in (Lassmann 1977, Reference 2) as quoted by Elenkov et al. (Reference 3). The derivation of the formula in Eqn. (11) is provided here because Ref. 2 is not readily available and is apparently in German.

The assumptions used to derive the idealized time constant of Eqn. (11) are examined qualitatively. First, when more energy is generated near the outer rod surface than the average (due to neutron flux dip), the effective average temperature is reduced. Second, if the heat generation is oscillating in time, the heat conduction wave does not penetrate as effectively when the oscillation frequency is high. These combined effects result in a reduced effective time constant. A factor of 2 reduction in the first term of Eqn. (11) results in:

$$\tau=\frac{\rho c D^2}{64k}+\frac{\rho c D}{4Rh} \tag{12}$$

Notice that different applications may adopt Eqn. (11) or Eqn. (12) depending on specifics of the transient and coupling to other models. For example, the heat transfer coefficient can be taken as the pellet-clad gap conductance. In the PIM model, only the pellet is represented by the time constant method, while the thermal resistance of the pellet-clad gap and the clad wall and the coolant are modeled separately and coupled to the pellet conduction equation. For this reason, the pellet conduction time constant is reduced to the first term of Eqn. (12), thus:

$$\tau=\frac{\rho c D^2}{64k} \tag{13}$$

- The pellet conduction time constant formula is confirmed as applicable to cylindrical fuel pellets with no other limitations related to fuel design.
- The only physical parameter that is considered exposure dependent in the TR equation 5-92 is the pellet thermal conductivity per the TR Eqn. 5-108.
- The values of the parameters that enter in the time constant formula used as input to the analysis reported in the TR are: pellet heat capacity of 293 J/kg/C, density of 10522 kg/m3, and pellet diameter of 0.00812 m.
- The average exposure is used to determine the pellet conductivity. Finer resolution would be inconsistent with the point-kinetics model for which the pellet conduction provides the pellet temperature for the purpose of calculating Doppler reactivity.

It should be emphasized that the solution of the transient equation using a finite time constant that is much less than the oscillation period is nearly equivalent to the quasi-steady state solution. The transient model in PIM has been selected since it was not known *a priori* that the oscillation period is much larger than the fuel rod thermal time constant. Therefore, the approximations used or implied in the time constant have insignificant effect on the NuScale module stability calculations. This is demonstrated by performing a PIM calculation at 20% of rated power and BOC using the best estimate pellet conduction time constant and a sensitivity case where the time constant is forced to be zero (quasi-steady-state). The two solutions are plotted together in Figure 1, and the difference is shown to be negligible.

In conclusion, the NuScale stability methodology and code apply a dynamic pin conduction model, however a quasi-steady state model can be imposed by input and produces similar and equally valid results due to the insensitivity of the NPM stability to the dynamic pin conduction phenomena.

References:

1. Frank P. Incropera and David P. De Witt, "Introduction to Heat Transfer," John Wiley & Sons, Second Edition 1990, ISBN 0-471-61247-2
2. K. Lassmann, "Die transiente Version des Rechenprogramms URANUS, Internationale Zeitschrift für Kernenergie (ATW) XXII (1977) (in German, quoted in Ref. 3)
3. D. Elenkov, K. Lassmann, A. Schubert, and J. van de Laar, "Dependence of the Time-Constant of a Fuel Rod on Different Design and Operational Parameters," IAEA-TECDOC-1233, Nuclear Fuel Behavious Modelling at High Burnup and its Experimental Support, Proceedings of a Technical Committee Meeting held in Windermere, UK, 19-23 June 2000.

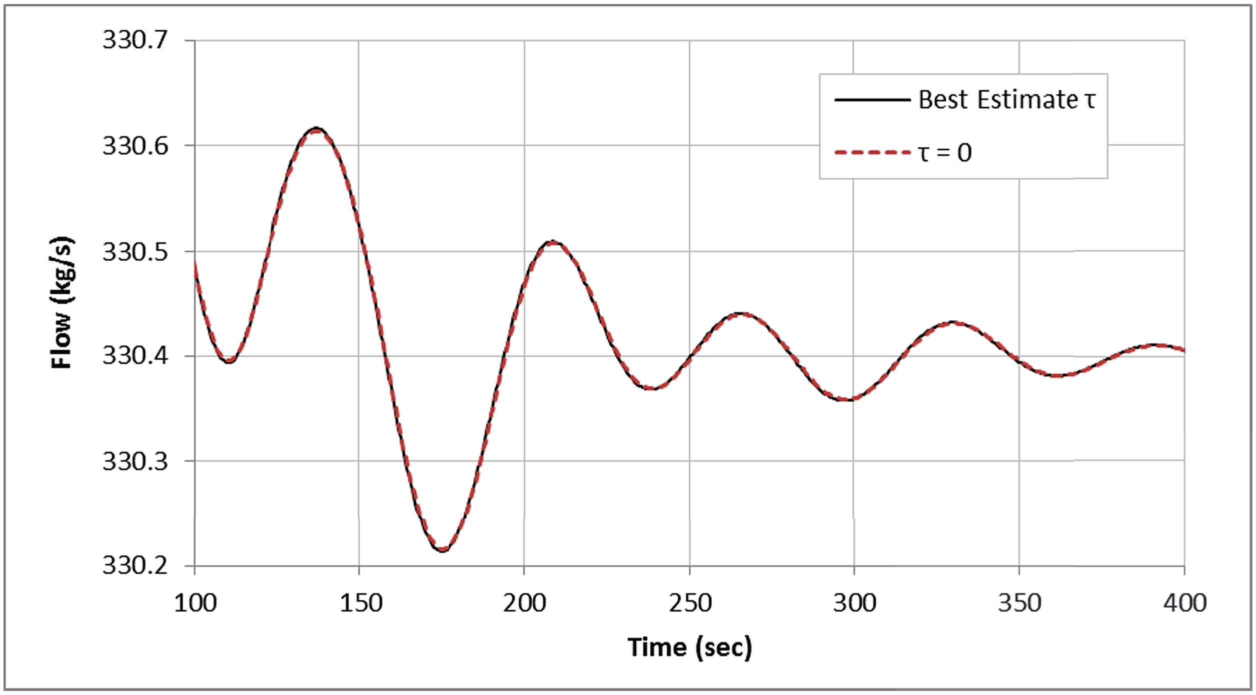

Figure 1. Effect of Pellet Conduction Time Constant.

Impact on Topical Report:

There are no impacts to the Topical Report TR-0516-49417, Evaluation Methodology for Stability Analysis of the NuScale Power Module, as a result of this response.

Response to Request for Additional Information
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eRAI No.: 9440
Date of RAI Issue: 03/20/2018

NRC Question No.: 15.09-2

Title 10 of the Code of Federal Regulations (CFR), Part 50, Appendix A, General Design Criterion (GDC) 10 – Reactor Design, states that the reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits (SAFDLs) are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences (AOOs). GDC 12 – Suppression of reactor power oscillations, states that the reactor core and associated coolant, control, and protection system shall be designed to assure that power oscillation which can result in conditions exceeding SAFDLs are not possible or can be reliably and readily detected and suppressed. The Standard Review Plan 15.0.2 acceptance criteria with respect to evaluation models states that the chosen mathematical models and the numerical solution of those models must be able to predict the important physical phenomena reasonably well from both qualitative and quantitative points of view.

The staff reviewed the response to the original RAI, RAI 8808 Question 29741, and found that the response was insufficient for the staff to reach a conclusion regarding the adequacy of the stability analysis methodology in NuScale Topical Report (TR) TR-0516-49417, "Evaluation Methodology for Stability Analysis of the NuScale Power Module".

In order to make an affirmative finding with regard to the above regulatory requirement important to safety, the NRC staff requests the following supplemental information:

1. Provide the temperature weighting factor (ω) from Equation 5-102 of the stability TR.
2. Explain why the value of the temperature weighting factor is appropriate.
3. Explain why the burnup-dependent factor (a) from Equation 5-109 of the stability TR is appropriate for stability analysis, generically.

It is acceptable to respond by either:

- Providing a technical reference that forms the basis for the burnup-dependent factor, such as a peer-reviewed scientific paper, or such as a peer-reviewed scientific paper, or
- Providing validation of the model against applicable experimental data and demonstrating that the model provides reasonable agreement with the data.

NuScale Response:

Item 1

As stated in the TR, the temperature weighting factor, ω, accounts for the distribution of neutron flux inside fuel pellets where a flux dip reduces the reactivity importance of the pellet center. An example of fission power distribution in pellets for different exposure is given in Fig. 2 of Ref. 1 where the surface value is higher than the average value. The TR recommends a weighting factor in the range of ω = 0.85 to 1.0 where the PIM code user specifies the value as input. In the analysis reported in the TR, the weighting factor value of ω = 0.85 has been used in all runs.

Item 2

The open literature contains several estimates of the weighting factor, which is of interest in transients where Doppler reactivity plays an important role, such as reactivity initiated accidents with control rod ejection in PWRs or control rod drop in BWRs where the temperature distribution changes significantly and the transient outcome is sensitive to the Doppler effect. It should be noted that the authors of Ref. 1 reported the lack of sensitivity to the choice of the Doppler temperature definition on the enthalpy rise in a reactivity initiated accident. In Ref. 1, the authors recommend ω = 0.92 (Equation 4 of Ref. 1).

Reference 1 also cites NEA study by Kozlowski and Downar (Ref. 2), where another weighting factor is given. Notice that the NEA formula (Equation 2 of Ref. 1) presents the Doppler effective temperature as a weighted average of pellet center temperature (T_0) and surface temperature (T_S) as:

$$T_{Doppler} = 0.7\,T_s + 0.3\,T_0 \tag{1}$$

Upon converting to the form used in the LTR equation 5-102 using the average pellet temperature, $T_{avg} = (T_0 - T_s)/2$, the resulting relationship becomes:

$$T_{Doppler} = 0.6\,T_{avg} + 0.4\,T_s \tag{2}$$

Thus, the NEA Doppler temperature weighting factor of the average and surface pellet temperatures is ω = 0.6.

Reference 3 (Equation 30) presents Rowland's effective Doppler temperature (Ref. 4) as:

$$T_{Doppler} = T_s + \frac{4}{9}(T_o - T_s) \tag{3}$$

which is the same as given by Reference 5 (Equation 3) presented as:

$$T_{Doppler} = T_{avg} + \frac{1}{18}(T_o - T_s) \tag{4}$$

Both forms (References 3 and 5) are transformed to the average and surface temperature weighting to get:

$$T_{Doppler} = \frac{8}{9}T_{avg} - \frac{1}{8}T_s \tag{5}$$

which results in the weighting factor of:

$$\omega = \frac{8}{9} = 0.89 \tag{6}$$

Other estimates of the effective Doppler temperature are given in the Ph.D. thesis of De Kruijf (Ref. 6), where (Eqn. 6.24 of Ref. 6)

$$T_{Doppler} = T_s + 04(T_o - T_s) \tag{7}$$

and (Eqn. 6.25 of Ref. 6)

$$T_{Doppler} = T_s + 0.35(T_o - T_s) \tag{8}$$

which correspond to ω = 0.8 and ω = 0.7, respectively.

The estimates of the weighting factor from the cited literature are ω = 0.92, 0.6, 0.89, 0.8 and 0.7 which indicates that the value used in PIM analysis of ω = 0.85 is reasonable. No sensitivity was observed in PIM analysis due to the variation of the weighting factor within the recommended range. See Figure 1 which shows two cases with ω = 0.85 and ω = 1.0 where the results are very close.

Item 3

The UO_2 thermal conductivity correlation and its dependence on exposure (degradation) have been addressed in the response to RAI 9104 Q47. It can be added here that the correlation does not include the electronic term responsible for increasing the conductivity at high temperatures; thus the correlation is applicable to stability calculations but not applicable (too conservative) for severe accident analysis, outside the scope of the PIM code, where very high pellet temperatures are expected.

References:

1. Gerardo Grandi, Kord Smith, Zhiwen Xu and Joel Rhodes, "Effect Of CASMO-5 Cross-Section Data and Doppler Temperature Definitions on LWR Reactivity Initiated Accidents," PHYSOR 2010 - Advances in Reactor Physics to Power the Nuclear Renaissance, Pittsburgh, Pennsylvania, USA, May 9-14, 2010, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2010)
2. T. Kozlowski, T. J. Downar, "The PWR MOX/UO_2 Core Transient Benchmark, Final Report", NEA/NSC/DOC(2006)20.
3. W. J. M. de Kruijf and A. J. Janssen, "The Effective Fuel Temperature to be Used for Calculating Resonance Absorption in a $^{238}UO_2$ Lump with a Nonuniform Temperature Profile," Nuclear Science and Engineering: 123. 121-135 (1996).
4. G. Rowlands, "Resonance Absorption and Non-Uniform Temperature Distributions," J. Nucl. Energy Parts A/B, Vol. 16, pp. 235-236 (1962).
5. D. Bernard, A. Calame, and J-M. Palau, "LWR-UO_2 Doppler Reactivity Coefficient: Best Estimate Plus (nuclear and atomic sources of) Uncertainties, International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017
6. W. J. M. De Kruijf, "Reactor Physics Analysis of the PIN-Cell Doppler Effect in a Thermal Nuclear Reactor," ECN-R-94-033, January 1995.

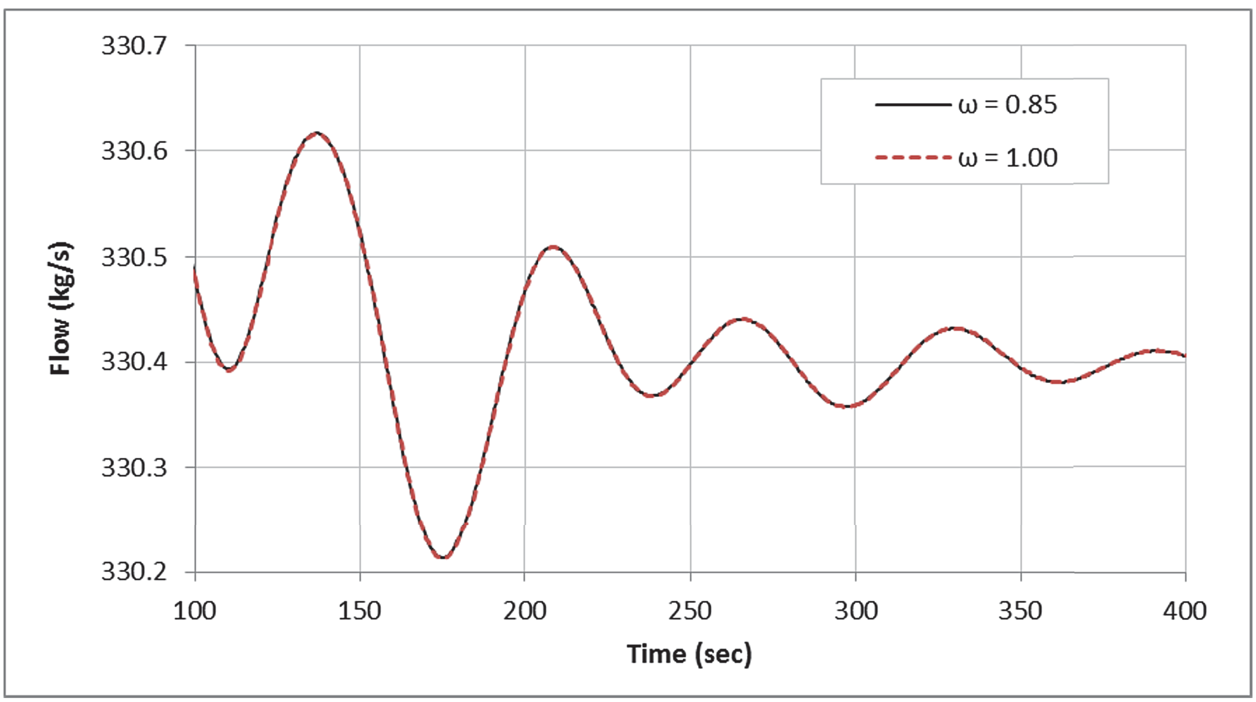

Figure 1. Effect of Doppler Effective Fuel Temperature Weighting Factor.

Impact on Topical Report:

There are no impacts to the Topical Report TR-0516-49417, Evaluation Methodology for Stability Analysis of the NuScale Power Module, as a result of this response.