December 30, 2021 Docket No. 99902078

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
One White Flint North
11555 Rockville Pike
Rockville, MD 20852-2738

SUBJECT: NuScale Power, LLC Submittal of Supplemental Topical Report “Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2,” TR-108601, Revision 0

REFERENCE: Letter from NuScale Power to the NRC, “NuScale Power, LLC Submittal of Approved Version of ‘Subchannel Analysis Methodology,’ TR-0915-17564, Revision 2,” submitted March 8, 2019 (ML19067A256)

NuScale Power, LLC (NuScale) hereby submits Revision 0 of “Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2,” (TR-108601). The purpose of this submittal is to request that the NRC review and approve the subchannel methodology for calculating margin to fuel thermal limits. NuScale respectfully requests that the acceptance review be completed in 60 days from the date of transmittal, and the review schedule be transmitted within the same period.

Enclosure 1 contains the proprietary version of the report entitled “Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2,” TR-108601, Revision 0. NuScale requests that the proprietary version be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavit (Enclosure 3) supports this request. Enclosure 1 has also been determined to contain Export Controlled Information. This information must be protected from disclosure per the requirements of 10 CFR § 810. Enclosure 2 contains the nonproprietary version of the report.

This letter makes no regulatory commitments and no revisions to any existing regulatory commitments.

If you have any questions, please contact Rebecca Norris at 541-452-7539 or at RNorris@nuscalepower.com

Sincerely,

Mark W. Shaver

Mark W. Shaver
Manager, Licensing
NuScale Power, LLC

Distribution: Michael Dudek, NRC
Getachew Tesfaye, NRC
Bruce Bavol, NRC

Enclosure 1: "Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2," TR-108601-P, Revision 0, proprietary version

Enclosure 2: "Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2," TR-108601-NP, Revision 0, nonproprietary version

Enclosure 3: Affidavit of Mark W. Shaver, AF-111193

NuScale Power, LLC
1100 NE Circle Blvd., Suite 200 Corvallis, Oregon 97330 Office 541.360-0500 Fax 541.207.3928
www.nuscalepower.com

Enclosure 1:

"Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2, TR-108601-P," Revision 0, proprietary version

NuScale Power, LLC
1100 NE Circle Blvd., Suite 200 Corvallis, Oregon 97330 Office 541.360-0500 Fax 541.207.3928
www.nuscalepower.com

Enclosure 2:

"Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2," TR-108601-NP, Revision 0, nonproprietary version

Licensing Topical Report

Statistical Subchannel Analysis Methodology

Supplement 1 to TR-0915-17564-P-A, Revision 2, Subchannel Analysis Methodology

December 2021

Revision 0

Docket: 99902078

NuScale Power, LLC
1100 NE Circle Blvd., Suite 200
Corvallis, Oregon 97330
www.nuscalepower.com

Licensing Topical Report

Department of Energy Acknowledgement and Disclaimer

This material is based upon work supported by the Department of Energy under Award Number DE-NE0008928.

List of Affected Pages

Revision Number	Page Number	Explanation
0	All	Initial Issue

Table of Contents

Table of Contents

Table of Contents

List of Tables

List of Figures

Abstract

This report documents the NuScale statistical subchannel analysis methodology using the VIPRE-01 computer code. This methodology is used to calculate margin to fuel thermal limits, such as critical heat flux ratio and fuel centerline temperature.

This report discusses how NuScale meets the NRC requirements for use of VIPRE-01, the modeling methodology for performing steady-state and transient subchannel analyses, and the qualification of the code for application to the NuScale design. NuScale intends to use this methodology for thermal-hydraulic analysis in support of future design work for NuScale reactors.

NuScale requests NRC approval to utilize this methodology, with the noted limitations described herein, for the NuScale thermal-hydraulic design and supporting analysis.

Executive Summary

The purpose of this topical report supplement is to define and justify a statistical based methodology for steady-state and transient subchannel analysis, including justification for the acceptability of the updated VIPRE-01 radial and axial nodalization for NuScale applications. The bases for how the subchannel model is developed and utilized, as well as its application is discussed. The core is modeled with a one-pass approach, meaning all the characteristics of the hot channel are captured, including inter-channel feedback. This approach allows the use of a fully-detailed model as well as lumped channel models to resolve the desired enthalpy and flow field. For CHF SAFDL applications, the core is analyzed via progressively-lumped radial nodalization with a detailed hot subchannel.

This methodology will be utilized to evaluate thermal margin and demonstrate adequate heat removal capability in design applications of the NuScale Power Module (NPM). NuScale requests NRC review and approval of the statistical treatment of uncertainties presented in this supplement.

The specific elements of the requested approval are:

- The VIPRE-01 modeling approach applied in NuScale steady-state and transient subchannel analysis
- The methodology for treatment of uncertainties in the NuScale statistical subchannel methodology

1.0 Introduction

1.1 Purpose

The purpose of this topical report supplement is to define and justify a statistical based methodology for steady-state and transient subchannel analysis, including justification for the acceptability of the updated VIPRE-01 radial and axial nodalization for NuScale applications. This methodology will be utilized to evaluate thermal margin and demonstrate adequate heat removal capability in design applications of the NuScale Power Module (NPM). NuScale requests NRC review and approval of the statistical treatment of uncertainties presented in this supplement to the Subchannel Analysis Methodology topical report TR-0915-17564-P-A, Revision 2 (Reference 8.1.1).

The specific elements of the requested approval are:

- The VIPRE-01 modeling approach applied in NuScale steady-state and transient subchannel analysis.
- The treatment of uncertainties in the NuScale statistical subchannel methodology.

1.2 Scope

This report describes the assumptions, codes, and methodology utilized to perform steady-state and transient subchannel analysis for design-basis accidents. This topical report focuses on the NuScale statistical subchannel methodology and is not intended to provide final detailed reactor core design or final values of any other associated accident evaluations.

1.3 Abbreviations and Definitions

Table 1-1 Abbreviations

Term	Definition
A/Q	assurance-to-quality
CDF	cumulative distribution function
K_{BN}	loss coefficient of the bottom nozzle
K_{HMP}	loss coefficient of the HMP™ spacer grid
K_{HTP}	loss coefficient of the HTP™ grid
K_{LCP}	loss coefficient of the lower core plate
K_{TN}	loss coefficient of the top nozzle
K_{UCP}	loss coefficient of the upper core plate
M/P	measured-to-predicted
NPM	NuScale Power Module
SCHFAL	statistical critical heat flux analysis limit
WRS	Wilcoxon Rank Sum

1.4 Topical Report Supplement Format and Layout

This topical report supplement provides an alternative methodology and modeling approach compared to Reference 8.1.1. The layout of this supplement follows the layout of the original topical report in Reference 8.1.1. Section titles and content are analogous to that presented in the base topical report, unless new content is provided, and then the new content is labeled with the next available section or subsection numbering. Figures, tables, and equations are numbered such that they use the corresponding figure, table, or equation number in Reference 8.1.1. Figures, tables, and equations that are new, in that there was not analogous content in Reference 8.1.1, are provided the next sequential number in that section, to avoid confusion with the table, figure, and equation numbering in Reference 8.1.1.

2.0 Background

This section is unchanged relative to the corresponding section of Reference 8.1.1. The CHF correlations approved for use in VIPRE-01 are documented in Reference 8.1.2 and Reference 8.1.3.

2.1 VIPRE-01

This section is unchanged relative to the corresponding section of Reference 8.1.1.

2.2 As-Approved Use

This section is unchanged relative to the corresponding section of Reference 8.1.1. The CHF correlations approved for use in VIPRE-01 are documented in Reference 8.1.2. Additionally, an extension of the range of applicability for the NSP4 CHF correlation has been submitted to the NRC for approval in Reference 8.1.3. Additional NRC approved CHF correlations may be used with the code in the future.

2.3 VIPRE-01 Safety Evaluation Report Requirements

NuScale continues to fulfill the requirements of the VIPRE-01 Safety Evaluation Report requirements as detailed in the corresponding section of Reference 8.1.1.

2.4 Regulatory Requirements

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.0 General Application Methodology

This section describes an overview of the statistical thermal design analysis methodology used for NuScale subchannel analysis. The bases for how the subchannel model is developed and utilized, as well as its application, is discussed. The core is modeled with a one-pass approach, meaning all the characteristics of the hot channel are captured, including inter-channel feedback. The one-pass approach allows the use of a fully-detailed model as well as lumped channel models to resolve the desired enthalpy and flow field. For CHF SAFDL applications, the core is analyzed via progressively-lumped radial nodalization with a detailed hot subchannel. The specific radial nodalization applied must have at least one detailed subchannel, follow generic VIPRE-01 manual guidance, and include sensitivity analysis that supports the implemented nodalization. Independent uncertainties are applied in a statistical manner.

3.1 Nuclear Safety Engineering Disciplines

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.2 Core Design Limits

The only change to the corresponding section of Reference 8.1.1 is to the basemodel. Additional details of the subchannel basemodel are provided in Section 3.7 of this supplement report.

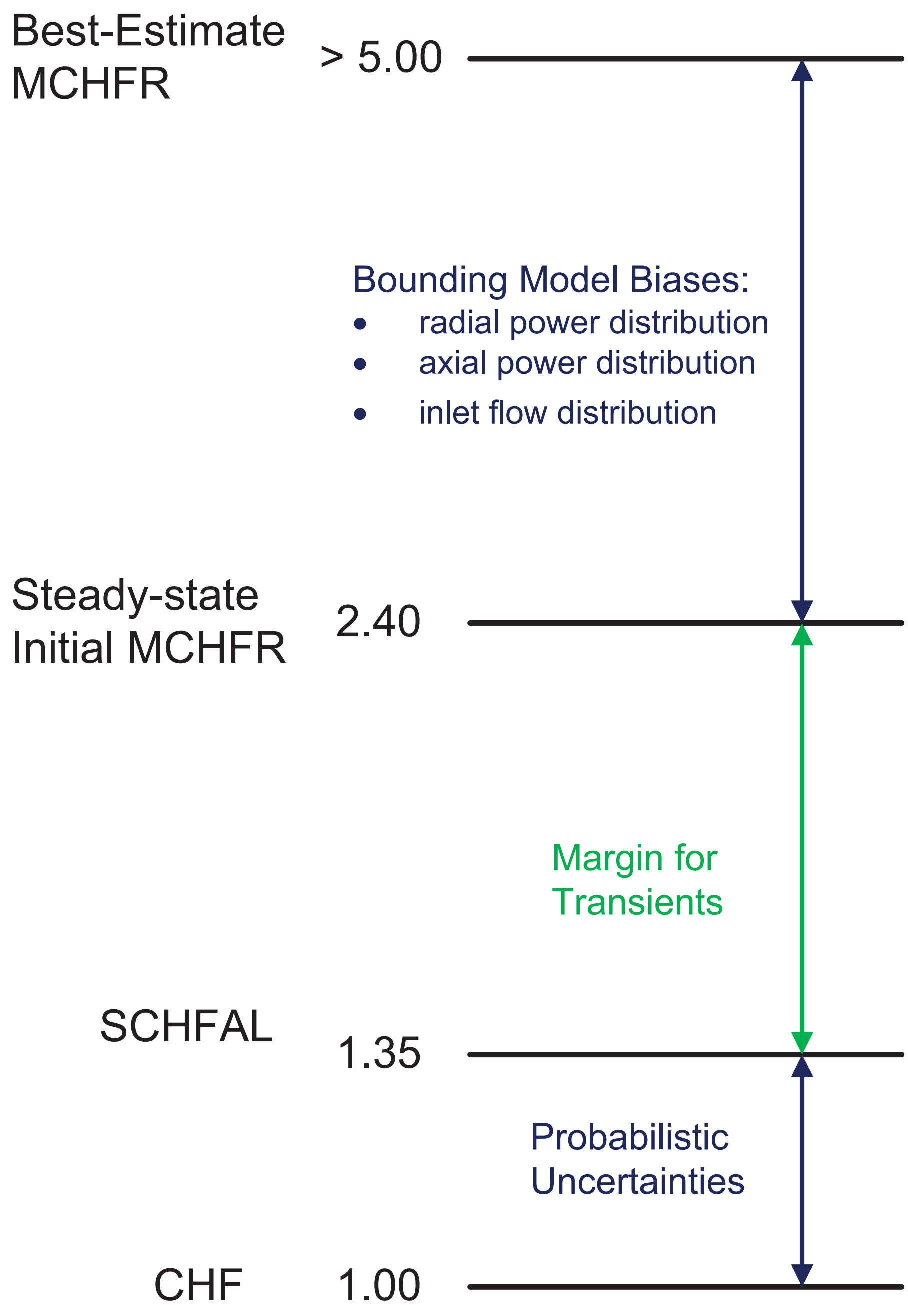
3.3 Critical Heat Flux Correlation

An NRC-approved CHF correlation is required for reporting thermal margin with the subchannel analysis methodology. The 5 conditions listed in Section 3.3 of Reference 8.1.1 remain applicable to the statistical subchannel analysis methodology.

3.4 Thermal Margin Results Reporting

The corresponding section of Reference 8.1.1 is updated to provide additional clarification for the penalty fractions in Equation 3-4 of Reference 8.1.1. These penalty fractions may be determined either deterministically or statistically to calculate the CHF analysis limit. Additionally, Figure 3-2 shows the MCHFR limits and the example margins in the MCHFR calculation in the statistical subchannel analysis methodology.

Figure 3-2 Example Thermal Margin Pictorial



3.5 Geometry Design Input

This section is unchanged relative to the corresponding section of Reference 8.1.1.

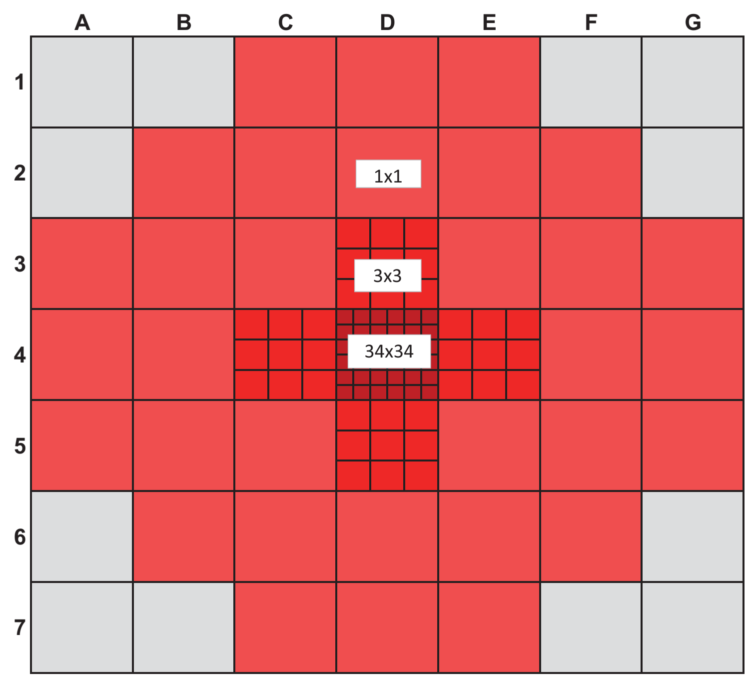
3.6 Fuel Design Specific Inputs

This section is unchanged relative to the corresponding section of Reference 8.1.1 with respect to the application of the spacer grid form loss coefficients. The axial model domain changes from Reference 8.1.1 are discussed in Section 3.7.2. With the change in the modeled axial domain, all fuel assembly form loss coefficients are applied at their respective centerline elevations.

3.7 Basemodel

The NuScale core contains 37 fuel assemblies as shown in the red squares of Figure 3-3. The methodology for statistical subchannel analysis utilizes a radial nodalization that models the full core and contains at least one detailed subchannel surrounded by progressively-lumped channels. An example of this is shown in the red squares of Figure 3-3. The basemodel is developed in a conservative manner and it does not represent a cycle-specific core; it is constructed in a way to preserve the limiting core conditions along with the operational envelope specified in the Technical Specifications. It is established based on the design peaking factors in combination with the limiting reactor coolant system global parameters. With this method, an artificial and bounding subchannel analysis model is appropriate, because the methodology ensures the limiting conditions of the cycle-specific core are captured by the basemodel.

Figure 3-3 VIPRE-01 Radial Nodalization



3.7.1 Radial Nodalization

The radial nodalization for the subchannel VIPRE-01 model represents the core at the level of detailed required for the analysis. VIPRE-01 defines channels based on flow area, wetted perimeters, and heated perimeters, with subchannel communications modeled through gaps and centroid distances. The core radial nodalization must have at least one detailed subchannel with progression of lumped subchannels a few rod rows away from the hot subchannel, supported by sensitivity studies; these studies provide assurance that the hot rod and hot subchannel are able to resolve the local conditions while not significantly impacting MCHFR.

As an example, the NuScale core is modeled with one fully detailed assembly, where all fuel rods and subchannels are modeled explicitly, and the remaining fuel assemblies progressively lumping several subchannels into a single "lumped channel". Specifically, assemblies directly adjacent to a fully detailed assembly are represented by nine lumped flow channels while all other assemblies are lumped into a single flow channel. This allows VIPRE-01 to be efficient in performing calculations, while the limiting subchannel local conditions fidelity is maintained. This example modeling approach is used for all steady-state calculations and most transients. However, some transients result in significant changes to the generic power distribution (discussed in Section 3.10.1) and may use a more modified power distribution.

In addition to the nodalization described, as well as that of Reference 8.1.1, limited flexibility is allowed. The following items must be satisfied in order for the radial nodalization to be acceptable:

- Reliable and converged solution
- Sufficient detail to resolve the dependent variables of CHF and CHF location (i.e., local flow, enthalpy, quality, and power)
- Hot rod and immediately adjacent fuel rods must be explicitly modeled in full detail
- At locations of node size changes, the relative difference in size (aspect ratio) must be sized in order to preserve fundamental assumptions of the numerical method
- Each unique nodalization requires a set of sensitivity studies comparing it to more detailed nodalizations with no significant non-conservative impacts on calculated MCHFR

Justification for this example progressive-lumping approach is provided in Section 6.4.1.

3.7.1.1 Peripheral Assembly Geometry Modeling

The area of the core that is beyond the assembly pitch boundaries is not considered core flow that is available for heat transfer. Therefore, any area that is outside of the assembly pitch boundary line is considered bypass flow. This bypass fraction is reduced from the total primary system flow rate.

3.7.2 Axial Nodalization

The axial nodalization for the subchannel model is critical to capture the variance of the flow field throughout the height of the fuel assembly. Axial node size directly impacts the calculated MCHFR. The axial node size is selected to capture the flow field accurately while providing the numerical solution.

The following items must be considered and balanced in order to determine the axial nodalization:

- Reliable and converged solution
- Sufficient detail to resolve the dependent variables of CHF and CHF location (i.e., local flow, enthalpy, quality, and power)
- Ensuring that losses are applied in the model near their appropriate locations
- At locations of node size changes, the relative difference in heights (aspect ratio) is roughly similar in order to preserve fundamental assumptions of the numerical method
- Smaller level heights in which flow diversions or asymmetric flow distributions may occur, such as just before the uppermost grid or at the core inlet, respectively
- Reasonable run times

Sensitivity studies are shown in Section 6.4.3 that look at different uniform axial node heights within the active fuel region. The sensitivities demonstrate the flow and enthalpy distribution can be sufficiently resolved with a variety of node lengths.

The axial domain analyzed with the subchannel model is from the bottom of lower core plate to above the upper core plate. While VIPRE-01 inherently applies drag losses for the entire model, it can over-account for frictional losses. This is a negligible and acceptable modeling simplification. An alternate modeling approach is to adjust the form loss for components outside of the fuel assembly to compensate for the additional drag losses modeled. Figure 3-6 is a graphical representation of the axial nodalization scheme for the subchannel basemodel.

This modeling method is justified based on a parametric sensitivity analysis in Section 6.0 in which different axial node sizes in the active fuel region are assessed. This sensitivity analysis demonstrates that the nodalization increments are appropriate to calculate the flow field and the MCHFR.

Figure 3-6 Axial Nodalization Diagram for Subchannel Basemodel (Not to Scale)

{{

}}2(a),(c),ECI

3.8 Boundary Conditions

This section and subsequent subsections are unchanged relative to the corresponding section of Reference 8.1.1.

3.9 Turbulent Mixing

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.10 Radial Power Distribution

The subchannel analysis uses a progressively-lumped basemodel as discussed in Section 3.7. To decouple the dependency of using a cycle-specific or time-in-life dependent radial power distribution, a conservative radial power distribution for a NuScale core that accounts for the worst distribution throughout the cycle is used. The limiting radial power distribution is bounding of the technical specifications limit on radial peaking factor. This must be confirmed for each fuel cycle loading pattern.

The radial power distribution is held constant throughout the transient for subchannel analyses.

3.10.1 Static Standard Review Plan Section 15.4 Analyses

For the Chapter 15 events where the radial power distribution can change during the event, particularly those that involve control rod movement, a modified radial distribution is used.

An augmentation factor is utilized to address this modification to the power distribution. It is defined in Equation 3-6 as the ratio of the maximum $F_{\Delta H}$ during the event to the initial condition. The augmentation factor is applied to the limiting assembly while a lower power assembly far away is reduced to preserve normalization of core power.

$$F_{\Delta H}^{Aug} = \frac{F_{\Delta H}^{Max}}{F_{\Delta H}^{Initial}} \qquad \text{Equation 3-6}$$

where:

$F_{\Delta H}^{Aug}$ = radial peaking augmentation factor

$F_{\Delta H}^{Initial}$ = maximum radial peaking at the beginning of the event

$F_{\Delta H}^{Max}$ = maximum radial peaking during the event

3.10.2 Time-Dependent Standard Review Plan Section 15.4 Analyses

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.10.3 Enthalpy Rise Hot Channel Factor

The core design has imposed a design limitation on the peak value of $F_{\Delta H}$, and therefore the highest value for any fuel rod throughout the full range of power, time in life, and allowed control rod positions. These values are defined in the development of the cycle design to allow the core operating limit peaking factor to increase for lower power level, in the form of Equation 3-8:

$$F_{\Delta H}^{SA} = A + [1 + B * (1 - P)] \qquad \text{Equation 3-8}$$

where:

$F_{\Delta H}^{SA}$ = Max. hot rod radial peaking analysis limit for safety analysis

P = Fraction of rated thermal power

A, B = Coefficients defined during core cycle design

The subchannel methodology bounds any radial power distribution that occurs in the core prior to any AOO, infrequent event, or accident. The hot rod for the radial power distribution is set to the core operating limit peaking factor (or design limit) dependent upon the initial condition.

Uncertainties associated with $F_{\Delta H}$ are accounted for in the subchannel analysis as an increase on the core operating limit value. The uncertainties accounted for are measurement uncertainty related to the instrumentation used for monitoring, which is detailed in Section 3.12.2, and engineering hot channel uncertainty, which is detailed in Section 3.12.4. Increases in $F_{\Delta H}$ peaking for rodded configurations are also included as detailed in Section 3.10.5.

For cases evaluated at partial power levels, the $F_{\Delta H}$ distribution for the entire limiting assembly is scaled by Equation 3-8. The limiting assembly is peaked using Equation 3-8 and the lower power assembly is reduced by the necessary factor to maintain normalization of the core power.

3.10.3.1 Assembly Peripheral Row Peaking

In the subchannel methodology in Reference 8.1.1, a requirement is imposed on the core design that the peak $F_{\Delta H}$ rod for any assembly is not allowed to occur on the peripheral row. This requirement forces the hot subchannel to not occur on the outer row, as the outer row would be influenced by direct crossflow from the annulus channel between assemblies. While this channel is not truly simulated in the CHF tests, it is consistent with the CHF testing basis, therefore it was conservatively chosen to impose this design constraint.

However, for the statistical subchannel methodology described in this supplement, this restriction is no longer maintained.

It is acceptable for the peak $F_{\Delta H}$ rod in an actual core design to occur on a peripheral fuel rod in the assembly. The ratio of the flow area to heated area associated with a peripheral fuel rod location is larger, which results in a higher calculated MCHFR as compared to the smaller flow area to heated area ratio of a fuel rod channel in the interior of the assembly. The radial power distribution is determined as described in Section 3.10.6, which conservatively forces the analyzed hot rod location to occur in the limiting interior fuel rod location. This occurs either in a channel surrounded by four fuel rods, or a smaller flow area of the channel surrounded by three fuel rods and one unpowered guide tube rod.

3.10.4 Radial Flux Tilt

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.10.5 All Rods Out Power Dependent Insertion Limit Enthalpy Rise Hot Channel Factor

As described in Section 3.10.3, the power dependent radial peaking factor analysis limit inherently includes allowed control rod insertions. The deterministic methods in Reference 8.1.1 did not account for this allowed operational flexibility in this manner, and thus a specific PDIL-ARO factor was defined and accounted for in the subchannel method. In the method defined in this supplement, to avoid double counting, this factor is not applied.

3.10.6 Determining the Bounding Radial Power Distribution

The radial power distribution for the subchannel basemodel is a bounding distribution expected to be used for future core designs that maintain a similar shuffle or loading pattern. This modeling method is justified from parametric sensitivity analysis in Section 6.4.2 of Reference 8.1.1, which confirms that the radial power distribution far removed from the hot subchannel has a negligible impact on the MCHFR results. Therefore, the use of a radial power distribution with the hot rod at the design peaking limit is sufficient for any distribution in a cycle-specific core.

The bounding radial power distribution used in the basemodel and most transients is not representative of the actual core conditions, and as a result, the determination of MCHFR for meeting the acceptance criterion is only applicable for the hot rod and subchannel. Thus, the purpose of the bounding radial power distribution is to capture the hot subchannel flow conditions, which are dependent upon the surrounding crossflow neighbor channels. A "flat" power distribution is one in which nearly all the rods provide similar power, and therefore, flow conditions and this power distribution limit the amount of turbulent mixing and diversion crossflow in the hot subchannel. This is conservative for thermal margin calculations.

The power distribution for an assembly may be characterized by its "peak-to-average" ratio, which is the maximum $F_{\Delta H}$ rod in an assembly divided by the average $F_{\Delta H}$ for the assembly. A value closer to unity denotes a flat power distribution. A spectrum of peak-to-average values for each assembly throughout the cycle burnup in the equilibrium cycle design is utilized to determine a bounding distribution.

For each core design, each rod has a unique radial peak-to-average ratio. In evaluating these ratios, assembly average relative power fraction values below a reasonable threshold (~1.1) are filtered out because the hot rod power is too low to be considered limiting for MCHFR. For example, when a core loading pattern contains fresh fuel on the periphery of the core, assemblies with a high $F_{\Delta H}$ rod have a large peak-to-average ratio due to the average $F_{\Delta H}$ rod being reduced by core leakage. These assemblies are considered non-limiting because of the enhanced inner-assembly crossflow that will be induced. For higher average-powered assemblies, the ratio of the peak-to-average ratio is flatter, because all the $F_{\Delta H}$ values are not far from the mean. These configurations are of interest because they work to reduce inner-assembly crossflow. The flattest peak-to-average ratio for assemblies of interest occur at high burnup steps where the maximum $F_{\Delta H}$ is quite small and thus considered non-limiting. Thus, a $F_{\Delta H}$ is required to be above a threshold (i.e., 1.25) for consideration in the peak-to-average ratio. Maximum $F_{\Delta H}$ values below this threshold are far below the analysis limit described in Section 3.9.1 and are excluded.

{{

}}2(a),(c),ECI

4. {{

}}2(a),(c),ECI

An example radial power distribution utilizing the example values and implementing the defined steps is presented in Figure 3-7.

Figure 3-7 Example Radial Power Distribution for Core (Top) and Hot Assembly (Bottom)

{{

}}2(a),(c),ECI

3.10.7 Deterministic Radial Power Distribution

This section is no longer applicable to the statistical subchannel analysis methodology as the $F_{\Delta H}$ measurement uncertainty and $F_{\Delta H}$ engineering uncertainty are applied in the determination of the statistical CHF analysis limit (SCHFAL) as described in Section 3.12.

3.10.8 Axial Power Distribution

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.10.9 Standard Review Plan Section 15.4 Analyses

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.11 Numerical Solution

This section and associated subsections are unchanged relative to the corresponding section of Reference 8.1.1.

3.12 Statistical Method and Treatment of Uncertainties

There are several biases and uncertainties that are accounted for in subchannel safety analysis calculations, including those from analysis method, physical manufacturing design inputs to the model, and operating conditions. Each of these will be discussed in more detail to inform what each is composed of and how each is accounted for within the subchannel analysis methodology.

All of the uncertainties described in the sections below are summarized in Table 3-4 with a description of how each is applied and what distribution is recommended for use in generating random samples. The uncertainty distribution utilized in generating the statistical CHF analysis limit is justified in the implementing analysis. A normal distribution is applied when there are no firm bounds on the value or where the uncertainty is known to come from a stochastic process. For instance, measurement uncertainty for a thermocouple comes from the manufacturer and is generally based on sample testing, which naturally lends itself to a normal distribution. A uniform distribution is applied when well defined bounds are available and the probability of a particular value occurring is no greater than that of any other value (e.g., a measurement dead band or rod bow factor). There may be cases where neither of these distributions are ideal; engineering judgment will determine the most appropriate or conservative distribution.

3.12.1 Uncertainty in Analysis Method

The uncertainties in the analysis method consist of computer code uncertainty and CHF correlation uncertainty.

3.12.1.1 Computer Code Uncertainty

The computer code uncertainty pertains to the effects from using distinct discretization in axial and radial nodalization and also the approximations in the governing constitutive equations. Comparisons of code predictions to actual data for the condition ranges of application will usually eliminate the need for an explicit penalty on code and model uncertainties when the models used in the application are consistent with the models used in the development of the analysis limit. Most of this test validation work has been performed in VIPRE-01 already in

Reference 8.1.5. Additional validation work is performed in benchmarking VIPRE-01 to COBRA-FLX, an approved subchannel analysis code owned by Framatome with an approved SER, as described in Section 5.8 of Reference 8.1.1. The results of the benchmarks demonstrate that VIPRE-01 results are in good agreement with the AREVA COBRA-FLX code for conditions anticipated for NuScale applications. This includes various specific configurations of the NPM design concept at different powers, pressures, and temperatures, as well as axial and radial nodalizations that have been demonstrated to be acceptable.

3.12.1.2 Critical Heat Flux Correlation Uncertainty

The CHF correlation uncertainty is measureable and is included as part of the total CHF analysis limit. CHF correlations are developed from the local conditions derived from a simulated subchannel model of the CHF test, using the subchannel software.

Generally, a CHF correlation limit is determined in the process of correlation development. This limit prevents the occurrence of CHF on the hot rod with 95% probability at the 95-percent confidence level (95/95 level). The CHF measured-to-predicted (M/P) samples used to set this limit have a distribution that may or may not be parametric.

The measured-to-predicted cumulative distribution function (CDF) can be used directly to select random samples for Σ_{CHF} (i). Although this CDF has discrete points and a continuous distribution, it is necessary for random sampling that some method of interpolation be used. As long as the CDF is constituted of a reasonably large sample size (greater than ~50), linear interpolation provides an acceptable prediction, but the sample CDF should always be compared to the underlying CHF to verify that the two match. It is also necessary to adjust the CDF to account for any round-up in the approved 95/95 CHF limit {{

}}2(a),(c),ECI

It is also possible to create a normal distribution, bounding the measured-to-predicted CDF to use in the random normal distribution sampling method. The CHF correlation limit is based on a one-sided tolerance limit. For a normal distribution, the method for determining a one-sided upper tolerance limit is discussed in Section 9.12 of Ref. 8.1.4. The upper tolerance limit for CHF, L_{CHF}, is determined with:

$$L_{CHF} = \mu_s + k_1 \sigma_s \qquad \text{Equation 3-10}$$

where:

μ_s is the sample mean,

σ_s is the sample standard deviation, and

k_1 is the one-sided tolerance factor based on the confidence level and the number of sample data.

The one-sided tolerance factor is determined using tables found in various statistical references such as Table T-11b of Ref. 8.1.4.

To create a bounding normal distribution for the CHF M/P data, the one-sided upper tolerance limit sets the CHF correlation limit. A standard deviation based on the CHF correlation limit, σ_{lim}, is determined based on a rearrangement of Equation 3-10 to calculate σ_{lim}:

$$\sigma_{lim} = \frac{(L_{CHF} - \mu_s)}{k_1} \qquad \text{Equation 3-11}$$

where:

L_{CHF} is the CHF correlation limit,

μ_s is the mean of the sample data, and

k_1 is the tolerance factor.

3.12.2 Uncertainty in Operating Conditions

The operating boundary conditions that are input into the subchannel analysis must account for all sources of margin and uncertainties related to them. Operating uncertainties account for process variable uncertainty, sensor accuracy and drift, and control deviation. The values for these uncertainties will be based on the instrumentation used for monitoring, and therefore are plant specific. Engineering judgement is made to incorporate reasonable uncertainties for the measured parameters.

The measurement uncertainties consist of those related to

- core thermal power (Σ_{CAL})
- core inlet flow (Σ_G)
- core inlet temperature (Σ_T)
- core exit pressure (Σ_P)
- enthalpy rise measurement uncertainty ($F^U_{\Delta H}$)

The correct accounting for uncertainties will be consistent between the system code and subchannel methodology, and care is taken to ensure the uncertainty is applied once to either the systems or subchannel calculations. Additional information on each of the operating boundary conditions and how they are applied in the statistical subchannel methodology is described in the following subsections.

3.12.2.1 Core Thermal Power

Core thermal power is a function of the core calorimetric calculation and uncertainty. The core calorimetric calculation deduces core power from the temperature differential between cold-side and hot-side temperatures, the flow rate, and core fluid properties. The core thermal power Q_C is expressed as:

$$Q_C = Q_{CAL}\left(1 + \frac{\Sigma_{CAL}}{100}\right) \qquad \text{Equation 3-12}$$

where:

Q_{CAL} is the calorimetric calculation of core power, and

Σ_{CAL} is the calorimetric measurement and calculation uncertainty (%).

3.12.2.2 Core Inlet Flow

The core inlet flow boundary condition must account for the appropriate bypass flow that is not available for heat transfer. The system-code transmitted flow boundary condition information will be that of RCS system flow to maintain compatibility with the systems transient methodology. The bypass values used for safety analysis are determined as analytical maximums rather than best-estimate values. The type of bypass mechanisms applicable for NuScale core subchannel analyses are described throughout Section 3.8.4 of Reference 8.1.1, with exact values defined in the core parameters report for a given core design. Core inlet flow is a function of the system flow and bypass flows, as well as flow measurement uncertainty. The core inlet flow G_{IN} is expressed as:

$$G_{IN} = G_{SYS} \cdot \left(1 + \Sigma_G - \frac{G_{RB}}{100} - \frac{G_{GT}}{100}\right) \qquad \text{Equation 3-13}$$

where:

G_{SYS} is system flow,

G_{RB} is reflector bypass (%),

G_{GT} is bypass (%) in the fuel assembly guide thimbles/tubes, and

Σ_G is flow measurement uncertainty.

3.12.2.3 Core Inlet Temperature

Core inlet temperature uncertainty is a function of the cold-side temperature, temperature control dead band, and measurement uncertainty. The core inlet temperature T_{IN} is expressed as:

$$T_{IN} = T_{COLD} + \Sigma_T + T_{DB} \qquad \text{Equation 3-14}$$

where:

T_{COLD} is cold-side temperature,

T_{DB} is the temperature controller dead band, and

Σ_T is the temperature measurement uncertainty.

The temperature dead band may be applied to a temperature other than T_{COLD} depending on the control system (i.e., T_{HOT} or T_{AVE}) and core inlet temperature distribution is considered to be flat per Section 3.8.6 of Reference 8.1.1.

3.12.2.4 Core Exit Pressure

Core exit pressure is a function of the pressurizer pressure, pressure control dead band, measurement uncertainty, and the static head pressure drop between the pressurizer and the core exit. The core exit pressure P_{OUT} is expressed as:

$$P_{OUT} = P_{PRZ} + \Sigma_P + P_{DB} \qquad \text{Equation 3-15}$$

where:

P_{PRZ} is pressurizer pressure,

P_{DB} is the pressure controller dead band, and

Σ_P is the pressure measurement uncertainty.

The hydrostatic head from the core exit to the pressurizer should be determined and provided as a boundary condition from a systems code such as NRELAP5.

3.12.2.5 Enthalpy Rise Measurement Uncertainty

The $F_{\Delta H}$ measurement uncertainty ($F^U_{\Delta H}$) accounts for uncertainties in the instrumentation for protecting Technical Specification limits. The default method accounts for this in the SCHFAL, but when the radial peaking factor is defined as an analytical limit (as opposed to an operating limit), no additional uncertainty is incorporated.

The enthalpy rise measurement uncertainty is applied to the SCHFAL.

3.12.3 Uncertainty in Physical Data Inputs

Physical data that is used in the VIPRE-01 subchannel analysis has an uncertainty and must be accounted for in thermal margins analysis because small deviations from nominal are allowed. The items that are generally applicable to VIPRE-01 and subchannel calculation methods are related to initial manufacturing tolerances and changes to dimensions throughout the life of fuel:

- enthalpy rise engineering uncertainty ($F_{\Delta H}^{E}$)
- heat flux engineering uncertainty (F_{Q}^{E})
- LHGR engineering uncertainty (F_{LHGR}^{E})
- radial power distribution uncertainty ($F_{\Delta H}^{NRF}$)
- fuel rod bowing and assembly bowing uncertainties ($F_{\Delta H}^{RB}$)
- core inlet flow distribution uncertainty
- core exit pressure distribution uncertainty

The treatment, in the VIPRE-01 inputs or post-processing thermal margin determination, for each above uncertainties is described in the follow sections.

3.12.4 Enthalpy Rise Engineering Uncertainty

The enthalpy rise engineering uncertainty ($F_{\Delta H}^{E}$) is a penalty factor that is applied on the hot channel to account for fabrication uncertainties related to allowable manufacturing tolerances. This factor is also referred to as the enthalpy rise hot channel factor. The enthalpy rise hot channel factor accounts for variations in pellet diameter, pellet density, enrichment, fuel rod diameter, fuel rod pitch, rod bowing, inlet flow distribution, flow redistribution, and flow mixing.

The fuel vendor divides this into two factors, $F_{\Delta H1}^{E}$, referred to as the pin power effect, and $F_{\Delta H2}^{E}$, which is the flow area factor impact on enthalpy rise. The fuel vendor provides the $F^{E}_{\Delta H1}$ channel factor while $F^{E}_{\Delta H2}$ is dependent upon the subchannel modeling and methodology applied.

The rod power part of the hot channel factor, $F^{E}_{\Delta H1}$, accounts for fuel stack length and uranium loading uncertainties. The $F^{E}_{\Delta H2}$ hot channel factor is dependent upon the VIPRE-01 modeling and two phase flow correlations when used in combination with accounting for uncertainties in the subchannel flow area due to fuel rod pitch and outer diameter variations.

Both sources of enthalpy rise engineering uncertainty are applied to the SCHFAL.

3.12.5 Heat Flux Engineering Uncertainty

The heat flux engineering uncertainty factor (F^{E}_{Q}) is a penalty factor that accounts for the small manufacturing uncertainties that affect the local heat flux. This factor is often referred to as the heat flux hot channel factor. The heat flux hot channel factor is affected by variations in fuel enrichment, pellet density, pellet diameter, and fuel rod surface area. The value of this uncertainty parameter is provided by the fuel vendor.

The use of a non-uniform axial factor on the critical heat flux value is sufficient to account for any reasonable non-uniformities that develop in the heat flux distribution. NuScale CHF correlations use a non-uniform axial factor, referred to as the F-Factor, to account for non-uniform axial heating. However, the heat flux engineering uncertainty is included in the SCHFAL for conservatism.

The heat flux is intended to be penalized so that the local heat flux uncertainty does not affect the channel enthalpy rise. There is no method to directly account for this in VIPRE-01, therefore this uncertainty is applied to the CHFAL in the SCHFAL methodology. Heat flux engineering uncertainty samples, $P_{HF}(i)$, are taken on the range of 0% to the maximum heat flux engineering factor for a one-sided distribution. Using a one-sided distribution is appropriate because the heat flux engineering factor always provides a CHF penalty. The sample heat flux engineering penalty factor, $F^{E}_{Q}(i)$, is calculated with:

$$F^{E}_{Q}(i) = 1 + \frac{P_{HF}(i)}{100} \qquad \text{Equation 3-16}$$

where:

$P_{HF}(i)$ is sample heat flux engineering penalty in %.

The heat flux engineering uncertainty is sampled and applied to the SCHFAL.

3.12.6 Linear Heat Generation Rate Engineering Uncertainty

The F_{LHGR}^{E} hot channel factor remains applicable for PLHGR FCM calculations. This is not applied to the CHFR calculations because it is accounted for in the heat flux hot channel factor (F_{Q}^{E}).

The linear heat generation rate engineering uncertainty factor is applied as a penalty on the peak LHGR (Section 4.5.1 of Reference 8.1.1).

3.12.7 Radial Power Distribution (SIMULATE5) Uncertainty

The radial power distribution uncertainty is related to the neutronics code that is used for the radial power distribution inputs. A sensitivity study for different power distributions of the NuScale core in Section 6.0 of Reference 8.1.1 showed that rod powers a few rod rows beyond the limiting hot rod/channel have a negligible impact on the MCHFR. The hot rod in the subchannel model is placed at the radial peaking analysis limit (see Section 3.10.3) and the neutronic code uncertainty is accounted for in the check of the core design to the analysis limit.

No radial power distribution penalty is applied to the subchannel analysis evaluation model or SCHFAL.

3.12.8 Fuel Rod and Assembly Bow Uncertainty

3.12.8.1 Fuel Rod Bow Uncertainty

Rod bow penalty samples, P_{RB} (i), are taken from a uniform distribution on the range of 0% to the maximum rod bow penalty. The rod bow penalty is conservatively assumed to only provide a CHF penalty. The sample rod bow penalty factor, $F_{\Delta H}^{RB}(i)$, is calculated with:

$$F_{\Delta H}^{RB}(i) = 1 + \frac{P_{RB}(i)}{100} \qquad \text{Equation 3-17}$$

where P_{RB} (i) is sample rod bow penalty in %.

The fuel rod bow uncertainty is applied to the SCHFAL.

3.12.8.2 Assembly Bow Uncertainty

Assembly bow is a complex phenomenon that results in axial distortions of the fuel assembly. The large flux gradients along the outer assemblies, if higher reactivity fuel is loaded there, increases the potential for assembly bow to occur. As defined in Reference 8.1.6, CHF penalties are only applied for rod bow and not assembly bowing because bowing of a full assembly will preserve the flow area. No penalties for assembly bowing are considered in CHF calculations.

3.12.9 Core Inlet Flow Distribution Uncertainty

This section is unchanged relative to the corresponding section of Reference 8.1.1.

The core inlet flow distribution uncertainty is applied to the limiting channels in the basemodel.

3.12.10 Core Exit Pressure Distribution Uncertainty

This section is unchanged relative to the corresponding section of Reference 8.1.1.

No uncertainty for core exit pressure distribution is applied.

3.13 Bias and Uncertainty Application within Analysis Methodology

In the NuScale statistical subchannel methodology, random uncertainties are combined together statistically and accounted for within the statistical CHF analysis limit (SCHFAL). A summary of the uncertainties discussed throughout this section is provided in Table 3-4. Figure 3-2 visually represents the MCHF limits and presents a pictorial meaning to the margins.

3.13.1 Statistical Methods

The statistical methods utilized are predominantly based on Reference 8.1.4, which include, but are not limited to:

- Tests for independence
- Non-parametric confidence intervals
- Assurance-to-quality (A/Q) of 95/95

For all statistical tests and processes the level of significance, α, is 0.05. For all parameters used, a justification must be provided for the distribution used. Evidence or theoretical reasoning must be provided for parameters that sample from a uniform distribution. Parameters that are directly measured will typically utilize a normal distribution with proper justification.

3.13.1.1 Uniform Distribution

A uniform distribution models situations where a random variable takes on a value from a specified interval with equal probability. The density function for a uniform distribution is illustrated in Figure 3-10. This demonstrates that on the range a to b, all points have the same probability of occurring. More information regarding the uniform distribution may be found in Section 7.2 of Reference 8.1.4. A randomly generated value from a uniform distribution on the range a to b, U(a,b), is determined with:

$$U(a,b) = RND(0,1) \cdot (b - a) + a \qquad \text{Equation 3-18}$$

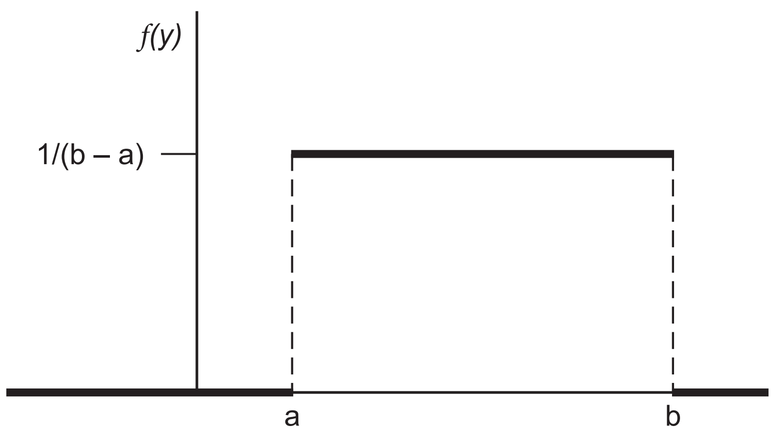
where:

RND(0,1) is a randomly generated value on the range **0** to **1**,

a is the lower bound of the range, and

b is the upper bound of the range.

Figure 3-10 Density Function of the Uniform Distribution



3.13.1.2 Normal Distribution

The use of the normal distribution is ubiquitous in statistics as it provides a model for many natural phenomena. The density function for the normal distribution is illustrated in Figure 3-11 below. Two randomly generated values from a normal distribution, Z_1 and Z_2, are determined with the Box-Muller transformation (Section 27.5 of Reference 8.1.4).

$$Z_1 = \sqrt{-2\ln(U_1)}\cos(2\pi U_2)$$

$$Z_2 = \sqrt{-2\ln(U_1)}\sin(2\pi U_2) \qquad \text{Equation 3-19}$$

where U_1 and U_2 are randomly generated values from a uniform distribution, U(0,1), using Equation 3-18 above. The two z values calculated with the Box-Muller transformation can both be shown to belong to the normal distribution given enough samples. Uncertainty values N1 and N2 may be determined from the two samples above with:

$$N_1(\mu,\sigma) = \sigma Z_1 + \mu$$

$$N_2(\mu,\sigma) = \sigma Z_2 + \mu$$

Equation 3-20

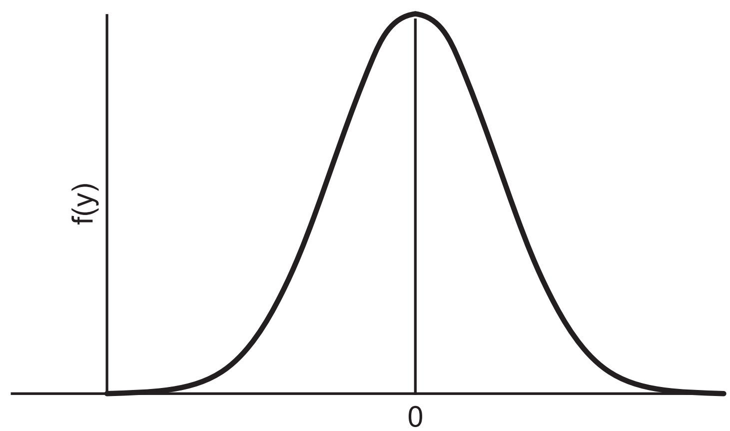
where:

σ is standard deviation, and

μ is the mean value.

In most cases μ is considered to be 0, unless some bias is noted.

Figure 3-11 Density Function of the Normal Distribution



3.13.1.3 Tests of Variable Independence

When exercising a probabilistic model it is crucial to assure that the sampled parameters are independent. To test independence between two sample means the Wilcoxon Rank Sum (WRS) test from Section 25.8 of Reference 8.1.4 is used. To test the independence between two sample variances the Squared Ranks test from Section 25.13 of Reference 8.1.4 is used. If the null hypothesis of either test is invalid then the two samples are considered independent.

3.13.1.3.1 Wilcoxon Rank Sum Test of Means

Let $\{y_{11},y_{12},\ldots,y_{1n}\}$ be a sample of size n from a population with median ζ_1, and $\{y_{21},y_{22},\ldots,y_{2m}\}$ be an independent sample of size m from a population with median ζ_2. If the sample is symmetric then the test of equality of the medians is a test of quality of the means. The null and alternative hypothesis against a two-sided alternative hypothesis are:

H_0: $\zeta_1 = \zeta_2$

H_1: $\zeta_1 \neq \zeta_2$

The *m* + *n* observations are combined and ranked from 1 to *m* + *n*. For tied values each is assigned the average of the ranks that would otherwise have been assigned. Let $R(y_{1i})$ denote the rank assigned to y_{1i} for *i* = 1,2,…,*n* and $R(y_{2i})$ denote the rank assigned to y_{2i} for *i* = 1,2,…,*m* the WRS test statistic is then:

$$W = \sum_{1}^{n} R(y_{1i}) \qquad \text{Equation 3-21}$$

Critical values $w_q(n,m)$ of the test statistic are given in Table T-17 of Ref. 8.1.4 for $n \leq 20$ and $m \leq 20$. Critical values for the corresponding upper quantiles for $n > 20$ and $m > 20$ are given by:

$$w_q(n,m) = \frac{n(n+m+1)}{2} + z_q\sqrt{\frac{n \cdot m(n+m+1)}{12}}$$

where z_q is the q^{th} quantile of the standard normal distribution given in Table T-1 of Ref. 8.1.4. α is the significance level. Critical values for H_1: $\zeta_1 \neq \zeta_2$, reject H_0 if $W > w_{1-\alpha/2}(n,m)$ or if $W < w_{\alpha/2}(n,m)$.

3.13.1.3.2 Squared Ranks Test of Variance

Let $\{y_{11}, y_{12}, \ldots, y_{1n}\}$ be population with variance σ_1^2 and $\{y_{21}, y_{22}, \ldots, y_{2m}\}$ be a population with variance σ_2^2 with independent random samples of size *n* and *m*, respectively, from the two populations. The null and alternative hypothesis against a two-sided alternative hypothesis are:

H_0: $\sigma_1 = \sigma_2$

H_1: $\sigma_1 \neq \sigma_2$

Sample variances for the observations of each sample are calculated with:

$$u_i = |y_{1i} - \mu_1|,\ i = 1,2,\ldots,n$$

$$v_j = |y_{2j} - \mu_2|,\ j = 1,2,\ldots,m$$

where μ_1 and μ_2 are the mean of populations 1 and 2. If μ_1 and μ_2 are unknown then the sample means $\overline{y_1}$ and $\overline{y_2}$ may be used instead. The *m* + *n* observations are combined and ranked from 1 to *m* + *n* with $R(u_i)$ and $R(v_i)$ denoting the resulting ranks. For tied values each is assigned the average of the ranks would otherwise have been assigned. The resulting ranks are denoted as $R(u_i)$ and $R(v_j)$. If there are no ties, the test statistic is:

$$T_1 = \sum_{\mathrm{i}=1}^{n} R(u_i)^2 \qquad \text{Equation 3-22}$$

If there are ties, the test statistic is:

$$T_1^* = \frac{T_1 - n\bar{R}^2}{\sqrt{\frac{n \cdot m}{(n+m)(n+m-1)}\sum_{k=1}^{n+m} R_k^4 - \left(\frac{n \cdot m}{n+m-1} \cdot \bar{R}^2\right)^2}} \qquad \text{Equation 3-23}$$

where:

$$\bar{R}^2 = \frac{1}{n+m}\left\{\sum_{i=1}^{n} R(u_i)^2 + \sum_{j=1}^{m} R(v_j)^2\right\}$$

and

$$\sum_{k=1}^{n+m} R_k^4 = \sum_{i=1}^{n} R(u_i)^4 + \sum_{j=1}^{m} R(v_j)^4$$

When either *n* or *m* are greater than 10 (the predominant situation) the quantiles for the Squared Rank test are obtained with:

$$w_q = \frac{n(n+m+1)(2n+2m+1)}{6} + z_q\sqrt{\frac{n \cdot m(n+m+1)(2n+2m+1)(8n+8m+1)}{180}}$$

where z_q is the qth quantile of the normal distribution. For H_1: $\sigma_1 \neq \sigma_2$, reject H_0 if $T_1\left(or\ T_1^*\right) < w_{\alpha/2}$ or if $T_1\left(or\ T_1^*\right) > w_{1-\alpha/2}$.

3.13.1.4 Quality Assurance Sampling

The specific criteria necessary to meet the requirements of GDC 10 are that "*there should be a 95-percent probability at the 95-percent confidence level that the hot rod in the core does not experience a boiling crisis during normal operation or AOOs.*" This amounts to a quality assurance statement equivalent to an A/Q of 95/95. Quality assurance is discussed in detail in Section 24.8, 24.9, 24.10, and 24.11 of Reference 8.1.4. Some general rules for A/Q sampling are:

- Sample size shall be determined before sampling begins and the entire set will be either accepted or rejected
- The set shall be unequivocally defined before sampling begins
- The set is made up of similar items that are treated alike
- If the set is comprised of several sub-sets, each sub-set must be addressed separately

While A/Q sampling is more generally used in manufacturing to determine whether a lot is acceptable based on statistically sampling of the lot, the concept may be extended to the determination of data bounds. For instance, if the lot is considered to be all occurrences of CHF then statistical sampling is performed on a subset of CHF, namely the CHF test results. Once a CHF correlation is developed it is imperative to create a limit that assures an A/Q of 95/95 to meet GDC 10. In this example, the limit is set to be greater than or equal to 95% of the data with 95% confidence. This same principle can be applied to any data subset that is representative of a larger set.

The sample size is fixed in advance, and should be informed by the number of failures, or in the CHF example above the number of data above the limit, that are deemed acceptable. Using the framework set forth in Section 24.10 of Reference 8.1.4 for determining the allowable number of failures for a given sample size n, utilizing a binomial distribution, Table 3-3 is created. This table provides the number of samples required to meet a particular number of allowable failures, up to 99.

Table 3-3 Sample Size versus Number of Allowable Failures

fail	n	fail	n	fail	n	fail	n
0	59	25	694	50	1260	75	1810
1	93	26	717	51	1282	76	1832
2	124	27	740	52	1305	77	1854
3	153	28	763	53	1326	78	1876
4	181	29	786	54	1348	79	1898
5	208	30	809	55	1371	80	1919
6	234	31	832	56	1393	81	1941
7	260	32	855	57	1415	82	1963
8	286	33	877	58	1437	83	1985
9	311	34	900	59	1460	84	2006
10	336	35	923	60	1481	85	2029

Table 3-3 Sample Size versus Number of Allowable Failures (Continued)

fail	n	fail	n	fail	n	fail	n
11	361	36	945	61	1503	86	2050
12	386	37	968	62	1525	87	2071
13	410	38	991	63	1547	88	2093
14	434	39	1013	64	1569	89	2115
15	458	40	1036	65	1591	90	2138
16	482	41	1058	66	1613	91	2158
17	506	42	1081	67	1635	92	2180
18	530	43	1103	68	1657	93	2202
19	554	44	1126	69	1679	94	2223
20	577	45	1148	70	1701	95	2245
21	601	46	1170	71	1723	96	2267
22	624	47	1193	72	1745	97	2288
23	647	48	1215	73	1766	98	2310
24	671	49	1237	74	1788	99	2331

3.13.2 Statistical CHF Analysis Limit

When not considering uncertainties, a fuel rod is considered to fail when MCHFR reaches 1.0. {{

}}2(a),(c),ECI

{{

}}2(a),(c),ECI

Figure 3-12 CHF Analysis Limit Calculation Flow Chart

{{

}}2(a),(c),ECI

3.13.2.1 Best-Estimate Model Reference State-Point

Determining the overall uncertainty of the SCHFAL requires comparing the difference in MCHFR values between a best-estimate model and the perturbed model for numerous sampled state-points (i.e., core power, temperature, pressure, mass flows, axial power profiles). The range of the sampled state-points should be constructed such that it is ensured that the time of MCHFR and the associated state-point within a given transient are bounded by the domain of which the SCHFAL was developed. Figure 3-13 provides a sample of this for conceptual purposes. The red shaded regions represent the applicability domain for the current NSP4 CHF correlation. The red-hatched regions represent the domain that may be of interest for the transient space to which the SCHFAL may be appropriately applied. If the transient domain is discovered to go outside the SCHFAL applicability range then the limit must be re-derived considering the wider range.

Figure 3-13 Example Sample SCHFAL Domain

{{

}}2(a),(c),ECI

3.13.3 ΔMCHFR Calculation Process

{{

}}2(a),(c),ECI Equation 3-25

{{

}}2(a),(c),ECI Equation 3-26

3.13.4 Calculating the Statistical CHF Analysis Limit

The SCHFAL is a value determined to ensure that a sufficient number of probabilistic samples of the CHFAL fall below the SCHFAL at the 95/95 level. A non-parametric statistical method is used to determine the SCHFAL, so the CHFAL samples are ranked in ascending order and the number of allowable values above the SCHFAL are determined based on the number of overall converged CHFAL samples using Table 3-3. For a sample size of 500 CHFAL samples, the number of acceptable values above the SCHFAL would fall between 16 and 17 values. The lower value is chosen to ensure compliance with the 95/95 criterion. From the 500 ordered samples the 484th (500-16) ordered value sets the SCHFAL.

Assessments of the complete sample and subsets of the sample are performed to ensure that the SCHFAL is sufficient to cover all subregions of the data. As an example, five subsets of the CHFAL samples are created by binning the CHFAL samples by pressure. These bins are sized to achieve as close to an even distribution of data in each subset as possible. Each bin is processed with the non-parametric method described above and a SCHFAL for each bin is calculated. The maximum SCHFAL of the five bins is considered the limiting SCHFAL because it covers all of the bins. This same process is performed for mass flux, temperature, power, and other relevant parameters.

3.13.5 Summary of Bias and Uncertainty Treatment

To summarize the uncertainties and biases applied in the statistical subchannel methodology, Table 3-4 is provided. The uncertainty bias for the boundary conditions are listed as being accounted for in the system transient analysis boundary conditions provided using systems transient methodology. As an example, these may also be included in the SCHFAL. When performing steady-state analyses for CHF evaluation or analyses that don't explicitly involve system transient methodology, these uncertainties should be applied explicitly in the subchannel application.

Table 3-4 Summary of Example Subchannel Methodology Parameter Treatment

Symbol	Description	Application	Example Distribution
{{			
			}}2(a),(c),ECI

3.14 Mixed Core Analysis

This section is unchanged relative to the corresponding section of Reference 8.1.1.

3.15 Methodology-Specific Acceptance Criteria

This section is unchanged relative to the corresponding section of Reference 8.1.1, with one exception. The MCHFR may occur on a peripheral subchannel of the assembly, as discussed in Section 3.10.3.1

4.0 Transient-Specific Applications Methodologies

This section is unchanged relative to the corresponding section of Reference 8.1.1.

5.0 VIPRE-01 Qualification

This section is unchanged relative to the corresponding section of Reference 8.1.1.

6.0 Example Calculation Results

The example calculation analyses and results presented in Reference 8.1.1 are presented to demonstrate the applicability of the subchannel methodology. A subset of the parameteric sensitivity analysis have been performed for the updated radial nodalization (Section 6.4.1) and axial nodalization (Section 6.4.3) discussed in Section 3.7. No additional changes are needed in the corresponding section of Reference 8.1.1.

6.4 Parametric Sensitivity Analysis

Various sensitives are performed comparing the linear heat generation rate to determine input and modeling impacts. Results from specific sensitivities are compared to a reference basemodel to quantify the impacts.

6.4.1 Radial Geometry Nodalization

A sensitivity analysis is performed to demonstrate that the radial nodalization outside the hot channel does not have significant impact on the local hot channel results. To demonstrate this, the sensitives in Table 6-17 are performed considering various levels of resolution of the subchannels outside the modeled hot assembly.

Table 6-17 Radial Nodalization Sensitivities

Case	Description
{{	
	}}2(a),(c),ECI

Figure 6-15 Single Fully Detailed Hot Assembly Model

{{

}}2(a),(c),ECI

Figure 6-16 Nine Detailed Assemblies Model

{{

}}2(a),(c),ECI

Figure 6-17 Twenty-Five Detailed Assemblies Model

{{

}}2(a),(c),ECI

Figure 6-18 Fully Detailed Core Model

{{

}}2(a),(c),ECI

Figure 6-19 Full Core Lumped Model

{{

}}2(a),(c),ECI

The results are presented in Table 6-18.

{{

}}2(a),(c),ECI

Table 6-18 Radial Geometry Nodalization Linear Heat Generation Rate Sensitivity Results

Case ID	Critical LHGR (kW/ft)	Axial Location (in)	Local Heat Flux (Mbtu/(hr-ft^2))	Mass Flux (Mlbm/(hr-ft^2))	Equilibrium Quality (-)
{{					
					}}2(a),(c),ECI

{{

}}2(a),(c),ECI

6.4.3 Axial Geometry Nodalization

A sensitivity analysis is performed to demonstrate that within a specified range of axial node sizes, a reasonable and consistent solution can be obtained considering both accuracy and performance characteristics.

These sensitivities are performed to help inform the appropriate axial nodalization resolution to:

- Ensure a reliable and converged solution.
- Ensure sufficient nodalization to resolve the dependent variables of CHF and CHF location (i.e., local flow, enthalpy, quality, and power).
- Ensure that losses are applied in the model near their appropriate locations.
- Obtain efficient runtimes.

To determine the appropriate axial node size, the sensitivities identified in Table 6-19 are performed.

Table 6-19 Axial Nodalization Sensitivities

Case	Sensitivity
{{	
	}}2(a),(c),ECI

The results are presented in Table 6-20.

Table 6-20 Axial Geometry Nodalization Linear Heat Generation Rate Sensitivity Results

Case ID	Critical LHGR (kW/ft)	Axial Location (in)	Heat Flux (Mbtu/(hr-ft^2))	Mass Flux (Mlbm/(hr-ft^2))	Equilibrium Quality (-)
{{					
					}}2(a),(c),ECI

{{

}}2(a),(c),ECI

7.0 Summary and Conclusions

An overview of the statistical methodology utilized for steady-state and transient subchannel analysis has been presented. Design calculations will use this methodology for assessing thermal margin and to determine if fuel failure will occur due to inadequate heat removal capability through evaluation of the critical heat flux ratio and fuel centerline melt. The methodology is developed to meet relevant acceptance criteria of Section 4.4 and Chapter 15 of the SRP.

The thermal design analysis methodology for NuScale subchannel analysis has been presented with the basis for the subchannel model development and application. A progressively lumped channel model is used to resolve the desired enthalpy and flow field, with focus on the hot channel. This methodology is applied as a standard technique for modeling steady-state calculations and transients. Sensitivity analysis is provided to demonstrate applicability of the methodology. Descriptions of the model nodalization, boundary conditions, radial power distributions, and uncertainties and biases are provided.

An extension of the qualification of VIPRE-01 previously approved in Reference 8.1.1 to NuScale applications is presented. This includes additional parametric sensitivity studies to understand input and method dependencies and to justify the overall methodology. This ensures that the VIPRE-01 model, with the applied methodology, appropriately models the NuScale reactor core and conservatively predicts the minimum critical heat flux ratio (MCHFR).

7.1 VIPRE-01 Safety Evaluation Report Requirements

This section is unchanged relative to the corresponding section of Reference 8.1.1.

The NuScale application of VIPRE-01 continues to fulfill the requirements specified in the generic VIPRE-01 SER (Reference 8.1.7).

7.2 Criteria for Establishing Applicability of Methodology

The generalized methodology presented in this topical report supplement is based upon modeling assumptions. The following set of criteria for establishing the applicability of this methodology is provided. An applicant or licensee that uses the methodology of this supplement must satisfy these criteria in order to establish applicability. Any deviation from these criteria must be defined and justified.

7.2.1 General Criteria

The following criteria are required for a valid MCHFR calculation:

- The local mass flux, equilibrium quality, and pressure at the location and time of MCHFR must be within the correlation applicability range.
- The hot rod from the VIPRE-01 MCHFR calculation must be the rod with the highest $F_{\Delta H}$ peaking factor.

- The VIPRE-01 calculation must satisfy all selected convergence criteria for the results to be considered valid. If convergence cannot be met with the selected default values or methods, justification must be provided to ensure that the relaxed acceptance criterion does not result in incorrect or premature results. If the calculation still does not converge, an assessment of the calculated results needs to be provided to prove acceptability.
- Axial nodalization within the region in which MCHFR is predicted to occur must be sufficiently small to resolve the flow field such that parametric sensitivity analysis results in a change of less than five CHF points for a halving of the nodalization size. Additionally, an aspect ratio (ratio of adjacent cell heights) of less than three must be maintained.
- The RECIRC numerical solution must be used.
- Heat transfer and two-phase flow correlation options defined in Table 5-7 of Reference 8.1.1 must be used.
- Rate of depressurization must be below 20 psi/second.
- Fast transients require that simulations are performed in sufficiently small time steps to capture the CHFR behavior adequately.
- Water properties for temperature and specific volume must be valid within the VIPRE-01 application range.
- Fuel pressure drop must be significantly less (by a factor of 10) than the minimum system pressure evaluated with the uniform pressure option or the local pressure drop option must be used.

7.2.2 Critical Heat Flux Correlation

The methodology presented in this report is independent of a specific CHF correlation. However, any application of the subchannel methodology is limited by the following restrictions:

- The application must explicitly state that an approved CHF correlation is used.
- The CHF correlation must be used within its applicable parameter ranges.
- Simulated local conditions in the subchannel analysis must be consistent with or bounded by the local conditions for CHF testing, CHF correlation development, and CHFR analysis limit development.
- The same two-phase flow model options must be used for CHF correlation and analysis limit development.
- CHF correlation and corresponding inputs must be those which are applicable to the fuel design (including spacer grids) being analyzed.
- Fuel design and CHF correlation dependent (or bounding) turbulent mixing coefficient (ABETA) must be defined and utilized in the analysis.

7.2.3 Nuclear Analysis Discipline Interface

The nuclear analysis interfaces are:

- Cycle-specific confirmations of all bounding analysis limits must be defined in the core parameter report for a specific core design.

7.2.4 Transients Discipline Interface

The transient analysis interfaces are:

- For events in which one or more parameters are outside the CHF correlation range applicability, such as low flow rate after reactor trip, the transients discipline calculation must ensure all SAFDLs are satisfied via long term cooling methodology.
- Either the system transients analysis or the subchannel analysis must account for operating parameter measurement uncertainties in core power, system flow, inlet temperature, and core exit pressure.
- The flow boundary condition must be provided as system flow (as opposed to core flow) such that the subchannel analysis accounts for all components of bypass flow consistent with methodology.

7.3 Cycle-Specific Confirmations

In general, the subchannel method presented is generic to a given core design (i.e., not cycle-specific) and specific analyses utilizing the methods do not need to be repeated each cycle if the cycle remains within evaluated bounds. However, each unique core design is checked to ensure the subchannel analysis remains applicable. As a result, the following cycle-specific confirmations with respect to subchannel analysis only (i.e., other confirmations may be required) are performed for each cycle:

- Cycle-specific axial power shapes are bounded by those used in the generic bounding analysis
- Radial nodalization appropriately treats the symmetry of the core design
- Hot full power $F_{\Delta H}$ at all exposures is less than analysis limit $F_{\Delta H}$
- Changes to radial peaking as a result of allowed control rod insertion is appropriately treated in an analysis limit or subchannel input
- Fission product (i.e., xenon) transients that disturb symmetric power peaking preserve radial tilt less than allowed by Technical Specifications
- Asymmetric reactivity anomaly events analyses confirm that the maximum cycle-specific augmentation factor calculated is bounded by that used in the generic bounding analysis

7.4 Key Fuel Design Interface Requirements

The subchannel analysis methodology presented is generic to a given fuel design, and does not need to be reformulated for a different design. However, each unique fuel design requires significant inputs into the subchannel analysis. The following is a minimum list of required fuel design inputs that must be provided for each fuel design evaluated with this methodology:

- An approved CHF correlation valid for the fuel design
- Basic geometry, flow loss coefficients, and friction factors
- Guide tube bypass flow
- Heat flux engineering uncertainty factor
- Linear heat generation rate engineering uncertainty factor
- Assembly and rod bow uncertainty factors
- Calibration of the VIPRE-01 fuel rod conduction model to a fuel performance code
- Melting temperature equation to calculate fast transient FCM safety limit

7.5 Unique Features of the NuScale Design

This section is unchanged relative to the corresponding section of Reference 8.1.1, with the exception of Table 7-2, which is updated.

Table 7-2 Comparison of NuScale Reactor Core Design to Conventional PWR

Parameter	Units	NuScale	Typical 4-Loop PWR (Ref. 8.2.39)
Core Thermal Output	MW	160-250	3565
System pressure	psia	1850-2000	2250
Thermal design flow rate	Mlbm/hr	5-6	139.4
Core average coolant mass velocity	Mlbm/hr-ft^2	0.5-0.6	2.41
Core inlet coolant temperature	°F	470-500	556.8
Core average rise in reactor core	°F	90-125	63.2
Core average heat flux	MBtu/hr-ft^2	0.02-0.03	0.206
Local peak heat flux	MBtu/hr-ft^2	0.03-0.05	0.515
Min. CHFR at nominal conditions	Ratio	>5	2.47

8.0 References

8.1 Referenced Documents

8.1.1 NuScale Power, LLC, "Subchannel Analysis Methodology," TR-0915-17564-P-A, Revision 2.

8.1.2 NuScale Power, LLC, "NuScale Power Critical Heat Flux Correlations," TR-0116-21012-P-A, Revision 1.

8.1.3 NuScale Power, LLC, "Applicability Range Extension of NSP4 Critical Heat Flux Correlation, Supplement 1 to TR-0116-21012-P-A, Revision 1," TR-107522-P, Revision 0.

8.1.4 U.S. Nuclear Regulatory Commission, “Applying Statistics,” NUREG-1475, Revision 1, March 2011.

8.1.5 C.W. Stewart et al., NP-2511-CCM-A, Volume 2, User's Manual, Revision 4.5, "VIPRE-01 A Thermal-Hydraulic Code for Reactor Cores," Computer Code Manual, February 2014.

8.1.6 NuScale Power, LLC, "Applicability of AREVA Fuel Methodology for the NuScale Design," TR-0116-20825-P-A, Revision 1.

8.1.7 "Safety Evaluation by the Office of Nuclear Reactor Regulation Relating to VIPRE-01 Mod 02 for PWR and BWR Applications," EPRI-NP-2511-CCM-A, Revision 3, October 30, 1993.

Enclosure 3:

Affidavit of Mark W. Shaver, AF-111193

NuScale Power, LLC

AFFIDAVIT of Mark W. Shaver

I, Mark W. Shaver, state as follows:

(1) I am the Licensing Manager of NuScale Power, LLC (NuScale), and as such, I have been specifically delegated the function of reviewing the information described in this Affidavit that NuScale seeks to have withheld from public disclosure, and am authorized to apply for its withholding on behalf of NuScale

(2) I am knowledgeable of the criteria and procedures used by NuScale in designating information as a trade secret, privileged, or as confidential commercial or financial information. This request to withhold information from public disclosure is driven by one or more of the following:

(a) The information requested to be withheld reveals distinguishing aspects of a process (or component, structure, tool, method, etc.) whose use by NuScale competitors, without a license from NuScale, would constitute a competitive economic disadvantage to NuScale.

(b) The information requested to be withheld consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), and the application of the data secures a competitive economic advantage, as described more fully in paragraph 3 of this Affidavit.

(c) Use by a competitor of the information requested to be withheld would reduce the competitor's expenditure of resources, or improve its competitive position, in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.

(d) The information requested to be withheld reveals cost or price information, production capabilities, budget levels, or commercial strategies of NuScale.

(e) The information requested to be withheld consists of patentable ideas.

(3) Public disclosure of the information sought to be withheld is likely to cause substantial harm to NuScale's competitive position and foreclose or reduce the availability of profit-making opportunities. The accompanying topical report reveals distinguishing aspects about the method by which NuScale develops its Statistical Subchannel Analysis Methodology.

NuScale has performed significant research and evaluation to develop a basis for this method and has invested significant resources, including the expenditure of a considerable sum of money.

The precise financial value of the information is difficult to quantify, but it is a key element of the design basis for a NuScale plant and, therefore, has substantial value to NuScale.

If the information were disclosed to the public, NuScale's competitors would have access to the information without purchasing the right to use it or having been required to undertake a similar expenditure of resources. Such disclosure would constitute a misappropriation of NuScale's intellectual property, and would deprive NuScale of the opportunity to exercise its competitive advantage to seek an adequate return on its investment.

(4) The information sought to be withheld is in the enclosed topical report entitled “Statistical Subchannel Analysis Methodology, Supplement 1 to TR-0915-17564-P-A, Revision 2,” TR-108601, Revision 0. The enclosure contains the designation “Proprietary" at the top of each page containing proprietary information. The information considered by NuScale to be proprietary is identified within double braces, "{{ }}" in the document.

(5) The basis for proposing that the information be withheld is that NuScale treats the information as a trade secret, privileged, or as confidential commercial or financial information. NuScale relies upon

the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC § 552(b)(4), as well as exemptions applicable to the NRC under 10 CFR §§ 2.390(a)(4) and 9.17(a)(4).

(6) Pursuant to the provisions set forth in 10 CFR § 2.390(b)(4), the following is provided for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld:

(a) The information sought to be withheld is owned and has been held in confidence by NuScale.

(b) The information is of a sort customarily held in confidence by NuScale and, to the best of my knowledge and belief, consistently has been held in confidence by NuScale. The procedure for approval of external release of such information typically requires review by the staff manager, project manager, chief technology officer or other equivalent authority, or the manager of the cognizant marketing function (or his delegate), for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside NuScale are limited to regulatory bodies, customers and potential customers and their agents, suppliers, licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or contractual agreements to maintain confidentiality.

(c) The information is being transmitted to and received by the NRC in confidence.

(d) No public disclosure of the information has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or contractual agreements that provide for maintenance of the information in confidence.

(e) Public disclosure of the information is likely to cause substantial harm to the competitive position of NuScale, taking into account the value of the information to NuScale, the amount of effort and money expended by NuScale in developing the information, and the difficulty others would have in acquiring or duplicating the information. The information sought to be withheld is part of NuScale's technology that provides NuScale with a competitive advantage over other firms in the industry. NuScale has invested significant human and financial capital in developing this technology and NuScale believes it would be difficult for others to duplicate the technology without access to the information sought to be withheld.

I declare under penalty of perjury that the foregoing is true and correct. Executed on 12/30/2021.

Mark W. Shaver

Mark W. Shaver