December 19, 2018 Docket No. 52-048

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 the Approved Version of NuScale Topical Report TR-0116-21012, “NuScale Power Critical Heat Flux Correlations,” Revision 1

REFERENCE: Letter from Robert Taylor (NRC) to Thomas Bergman (NuScale), “Final Safety Evaluation for NuScale Power, LLC Topical report-0116-21012, Revision 1, ‘NuScale Power Critical Heat Flux Correlations,” dated August 8, 2018 (ML18214A478)

By the referenced letter dated August 8, 2018, the NRC issued a final safety evaluation report documenting the NRC staff conclusion that NuScale Topical Report TR-0116-21012, “NuScale Power Critical Heat Flux Correlations,” Revision 1, is acceptable for referencing in licensing applications for the NuScale design. The referenced letter requested that NuScale publish the approved version of TR-0116-21012, Revision 1.

Accordingly, Enclosure 1 to this letter provides the approved version of the topical report, designated TR-0116-21012-P-A, Revision 1. The approved version includes the August 8, 2018 NRC letter and its final safety evaluation report, the NuScale responses to NRC requests for additional information, and the final topical report submittal (Revision 1).

Enclosure 1 contains proprietary information. NuScale requests that the proprietary enclosure be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavit (Enclosure 3 and Enclosure 4) support this request. Enclosure 3 pertains to the NuScale proprietary information, denoted by double braces (i.e., “{{ }}”). Enclosure 4 pertains to Framatome Inc. (formerly AREVA Inc) proprietary information, denoted by brackets (i.e., “[ ]”). 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 is the nonproprietary version of the approved topical report package.

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

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

Sincerely,

Thomas A. Bergman
Vice President, Regulatory Affairs
NuScale Power, LLC

Distribution: Robert Taylor, NRC, OWFN-8G9A
Samuel Lee, NRC, OWFN-8G9A
Gregory Cranston, NRC, OWFN-8G9A
Bruce Bavol, NRC, OWFN-8G9A

Enclosure 1: NuScale Topical Report, TR-0116-21012-P-A, “NuScale Power Critical Heat Flux Correlations,” Revision 1, proprietary version
Enclosure 2: NuScale Topical Report, TR-0116-21012-P-A, “NuScale Power Critical Heat Flux Correlations,” Revision 1, nonproprietary version
Enclosure 3: Affidavit of Thomas A. Bergman, AF-1118-62427
Enclosure 4: Affidavit of Nathan E. Hottle

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:

NuScale Topical Report, TR-0116-21012-P-A, “NuScale Power Critical Heat Flux Correlations,” Revision 1, proprietary version

Enclosure 2:

NuScale Topical Report, TR-0116-21012-P-A, “NuScale Power Critical Heat Flux Correlations,” Revision 1, nonproprietary version

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Section A

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

Mr. Thomas Bergman
Vice President, Regulatory Affairs
NuScale Power, LLC
1100 NE Circle Boulevard, Suite 200
Corvallis, OR 97330

SUBJECT: FINAL SAFETY EVALUATION FOR NUSCALE POWER, LLC TOPICAL REPORT-0116-21012, REVISION 1, "NUSCALE POWER CRITICAL HEAT FLUX CORRELATIONS"

Dear Mr. Bergman:

By letter dated November 30, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17335A089), NuScale Power, LLC (NuScale), submitted Topical Report (TR)-0116-21012, Revision 1, "Critical Heat Flux Correlations," to the U.S. Nuclear Regulatory Commission (NRC) staff for review. This revision replaced the submittal dated October 5, 2016 (ADAMS Accession No. ML16279A363), "NuScale Power Critical Heat Flux Correlation NSP2." The revised submittal implemented an additional NSP4 critical heat flux (CHF) correlation and incorporated changes associated with NRC requests for additional information (RAIs).

The NRC staff has found that the TR-0116-21012, Revision 1, "Critical Heat Flux Correlations," is acceptable for referencing in licensing applications for the NuScale small modular reactor design to the extent specified and under the conditions and limitations delineated in the enclosed safety evaluation report (SER). The SER defines the basis for acceptance of the TR.

The NRC staff requests that NuScale publish the applicable version(s) of the SER listed above within three months of receipt of this letter. The accepted version of the TR shall incorporate this letter and the enclosed SER and add "-A" (designated accepted) following the report identification number.

Document transmitted herewith contains sensitive unclassified information. When separated from the enclosure, this document is "DECONTROLLED."

CONTACT: Bruce M. Bavol, NRO/DLSE
301-415-6715

If the NRC staff's criteria or regulations change, so that its conclusion that the SER is acceptable is invalidated, NuScale and/or the applicant referencing the SER will be expected to revise and resubmit its respective documentation, or submit justification for continued applicability of the SER without revision of the respective documentation.

Prior to placing the public version of this document in the publicly available records component of NRC's ADAMS, the NRC staff requests that NuScale perform a final review of the SER for proprietary or security related information not previously identified. If you believe that any additional information meets the criteria, please identify such information line by line and define the basis pursuant to the criteria established in Title 10 of the *Code of Federal Regulations,* Part 2, Section 390.

If after a 10-day period, you do not request that all or portions of the SER be withheld from public disclosure, the SER will be made available for public inspection through the publicly available records component of NRC's ADAMS.

If you have any questions or comments concerning this matter, please contact Bruce Bavol at 301-415-6715 or via e-mail address at Bruce.Bavol@nrc.gov.

Sincerely,

Robert Taylor, Director
Division of Licensing, Siting,
and Environmental Analysis
Office of New Reactors

Project No. 0769

Enclosures:
1. CHF SER (Non-Proprietary)
2. CHF SER (Proprietary)

cc: DC NuScale Power, LLC Listserv (w/o Enclosure 2)

SUBJECT: FINAL SAFETY EVALUATION FOR NUSCALE POWER, LLC TOPICAL REPORT-0116-21012, REVISION 1, "NUSCALE POWER CRITICAL HEAT FLUX CORRELATIONS" DATED:

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Letter: ML18214479
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SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS

TOPICAL REPORT - 0116-21012, REVISION 1

"NUSCALE POWER CRITICAL HEAT FLUX CORRELATIONS"

NUSCALE POWER, LLC

PROJECT NO. PROJ0769

Enclosure 1

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1.0 INTRODUCTION

By letter dated November 30, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17335A089), NuScale Power, LLC (NuScale), submitted Topical Report (TR)-0116-21012, Revision 1, “Critical Heat Flux Correlations,” to the U.S. Nuclear Regulatory Commission (NRC) staff for review. This revision replaced the submittal dated October 5, 2016 (ADAMS Accession No. ML16279A363), “NuScale Power Critical Heat Flux Correlation NSP2.” The revised submittal implements an additional NSP4 critical heat flux (CHF) correlation and incorporates changes associated with NRC requests for additional information (RAIs). The purpose of TR-0116-21012 is to provide the bases for NRC approval to use the NSP2 and NSP4 CHF correlations in VIPRE-01, within their range of applicability, along with their associated correlation limits for the NuScale design certification application and safety analysis of the NuScale Power Module (NPM) with NuFuel-HTP2^{TM} fuel.

Table 1, “List of Key Correspondence,” contains the key correspondence between the NRC and NuScale. This includes preapplication correspondence, RAIs, responses to RAIs, audit documentation, and other correspondence relevant to this review.

Table 1. List of Key Correspondence

Sender	Document	Document Date	Reference
NuScale	Critical Heat Flux Test Program Technical Report	January 24, 2014	1
NRC	NuScale Critical Heat Flux Correlation Topical Report Preapplication Engagement with NRC	December 10, 2015	2
NRC	Audit Plan for NuScale Critical Heat Flux Testing at KATHY	May 2, 2016	3
NRC	Audit Report for NuScale Critical Heat Flux Testing at KATHY	August 12, 2016	4
NuScale	Topical Report	October 5, 2016	5
NRC	Request for Supplemental Information	December 5, 2016	6
NuScale	Supplemental Information	December 29, 2016	7
NRC	Acceptance Letter	February 2, 2017	8
NRC	Request for Additional Information (eRAI 8795)	May 8, 2017	9
NRC	Audit Plan for Regulatory Audit of NuScale Topical Report TR-0116-21012, Revision 0	May 30, 2017	10
NuScale	Response to Request for Additional Information (eRAI 8795)	July 7, 2017	11

Sender	Document	Document Date	Reference
NRC	Request for Additional Information (eRAI 8931)	August 21, 2017	12
NuScale	Response to Request for Additional Information (eRAI 8931)	September 25, 2017	13
NRC	Audit Summary for NuScale CHF	November 27, 2017	14
NuScale	Topical Report Revision	November 30, 2017	15

2.0 REGULATORY EVALUATION

Title 10 of the *Code of Federal Regulations* (10 CFR), Sections 52.47, "Contents of Applications; Technical Information," and 10 CFR 52.79, "Contents of Applications; Technical Information in Final Safety Analysis Report," require a final safety analysis report (FSAR) to describe and analyze the design and performance of the structures, systems, and components. Safety evaluations (SEs) performed to support the FSAR include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with CHF that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing an SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," which refer to the general design criteria (GDC) of Appendix A, "General Design Criteria for Nuclear Power Plants."

- GDC 10, "Reactor Design," which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

- GDC 12, "Suppression of reactor power oscillations," which requires that the reactor core and associated coolant, control, and protection systems be designed to assure that power oscillation which can result in conditions exceeding SAFDLs are not possible or can be reliably detected and suppressed.

- 10 CFR 52.47(a)(2)(iv) and GDC 19, "Control Room," as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 4.4, "Thermal and Hydraulic Design," describes an acceptable approach for a CHF correlation to meet GDC 10 and GDC 12 as establishing a 95-percent probability at the 95-percent confidence level that the hot rod in the core does not experience a boiling transition condition during normal operation and AOOs.

The scope of the NRC staff's review addresses the applicability of the NSP2 and NSP4 CHF correlations, and their associated CHF ratio (CHFR) limits, for use in performing safety analyses of the NPM with NuFuel-HTP2™ fuel.

3.0 TECHNICAL EVALUATION

The purpose of TR-0116-21012 is to provide the bases for NRC approval to use the NSP2 and NSP4 CHF correlations in VIPRE-01, within their range of applicability, along with their associated correlation limits for the NuScale design certification application and safety analysis of the NPM with NuFuel-HTP2™ fuel. The NRC staff used the critical boiling transition model assessment framework summarized in Table 2, "List of All Goals," which considers the framework presented in Appendix A of this SE. For brevity, Table 2 only contains the goals (G). The sections below provide the evidence.

Table 2. List of All Goals

GOAL			The critical boiling transition model can be trusted in reactor safety analyses.
G1			The experimental data supporting the critical boiling transition model are appropriate.
	G1.1		The experimental data have been collected at a credible test facility.
		G1.1.1	The test facility is well understood.
		G1.1.2	The test facility has been verified by comparison to an outside source.
	G1.2		The experimental data have been accurately measured.
		G1.2.1	The test facility has an appropriate quality assurance program.
		G1.2.2	The experiment has been appropriately statistically designed (i.e., the value of a system parameter from any test was completely independent from its value in the test before and after the test).
		G1.2.3	The method used to obtain critical boiling transition data results in an accurate measurement.
		G1.2.4	The instrumentation uncertainties have been demonstrated to have a minimal impact on the measured critical heat flux or critical power.
		G1.2.5	The uncertainty in the critical heat flux or critical power is quantified through repeated tests at the same state points.
		G1.2.6	The heat losses from the test section are quantified, appropriately low, and duly accounted for in the measured data.
	G1.3		The test bundle reproduced the local conditions in the reactor fuel bundle.
		G1.3.1	The test bundle used in the experiment should have geometric dimensions equivalent to those of the fuel bundle used in the reactor for all major components.
		G1.3.2	The grid spacers used in the test bundle should be prototypical of the grid spacers used in the reactor assembly.

GOAL			The critical boiling transition model can be trusted in reactor safety analyses.
		G1.3.3	The axial power shapes in the test bundle should reflect the expected or limiting axial power shapes in the reactor bundle.
		G1.3.4	The radial power peaking in the test bundle should reflect the expected or limiting radial powers in the reactor bundle.
		G1.3.5	Any differences between the test bundle and the reactor bundle should have a minimal impact on the flow field. This includes components that are not in the reactor bundle but that are needed for testing purposes.
G2			The model was generated in a logical fashion.
	G2.1		The mathematical form of the model is appropriate.
		G2.1.1	The mathematical form of the model contains all the necessary parameters.
		G2.1.2	The reasoning for choosing the mathematical form of the model should be discussed and should be logical.
	G2.2		The process for determining the model's coefficients was appropriate.
		G2.2.1	The training data (i.e., the data used to generate the coefficients of the model) should be identified.
		G2.2.2	The method for calculating the model's coefficients should be described.
		G2.2.3	The method for calculating the R- or K-factor and the additive constants (for both full-length and part-length rods) should be described. Further, a description of how such values are calculated if dryout is not measured on the rod under consideration should be provided (boiling-water reactors only).
G3			The model has sufficient validation as demonstrated through appropriate quantification of its error.
	G3.1		The correct validation error has been calculated.
	G3.2		The validation error is appropriately distributed throughout the application domain.
		G3.2.1	The validation data (i.e., the data used to quantify the model's error) should be identified.
		G3.2.2	The application domain of the model should be mathematically defined.
		G3.2.3	The expected domain of the model should be understood.
		G3.2.4	There should be adequate validation error data density throughout the expected and application domains.
		G3.2.5	Sparse regions (i.e., regions of low data density) in the expected and application domains should be identified and justified to be appropriate.

GOAL			The critical boiling transition model can be trusted in reactor safety analyses.
		G3.2.6	The model should be restricted to its application domain.
	G3.3		Any inconsistencies in the validation error have been accounted for appropriately.
		G3.3.1	The validation error should be investigated to ensure that it does not contain any subgroups that are obviously not from the same population (i.e., non-poolable).
		G3.3.2	The expected domain should be investigated to determine if it contains any non-conservative subregions which would impact the predictive capability of the model.
		G3.3.3	The model is trending as expected in each of the various model parameters.
	G3.4		The model's uncertainty has been appropriately calculated from the validation error.
		G3.4.1	The validation error statistics should be calculated from an appropriate database.
		G3.4.2	The validation error statistics should be calculated using an appropriate method.
		G3.4.3	The model's uncertainty should be appropriately biased.
	G3.5		The model has been correctly implemented.
		G3.5.1	The model has been implemented in the same computer code that was used to generate the validation error.
		G3.5.2	The model's prediction of the critical boiling transition (CBT) is being applied using the same evaluation methodology as it was when predicting the validation data set for determining the validation error.
		G3.5.3	The model results in an accurate or conservative prediction when it is used to predict transient behavior.

In addition to the NSP2 and NSP4 CHF correlations, TR-0116-21012 discusses a third CHF correlation, NSP1. Section 5.3 of the TR explains that the NSP2 CHF correlation is simply the NSP1 CHF correlation with an additional NSPX factor. Therefore, anything that affects the NSP1 CHF correlation also affects the NSP2 CHF correlation.

3.1 Experiential Data

3.1.1 Credible Test Facility

3.1.1.1 Test Facility Description

Test Facility Description
The test facility is well understood.
G1.1.1, Review Framework for Critical Boiling Transition Models

Section 3.1 of the TR describes the facilities used to obtain the data in the development and validation of the NSP2 and NSP4 CHF correlations, which includes Stern Laboratories in Hamilton, Ontario, Canada, and the KArlstein Thermal HYdraulic test loop (KATHY) in Karlstein, Germany. In addition to using these facility descriptions, the NRC staff conducted an inspection at Stern Laboratories (References 16-19) and an audit at the KATHY test loop (Reference 4). Based on the descriptions provided by NuScale and the information obtained by the staff during the inspection and audit activities, the NRC staff finds that the test facilities NuScale used to develop the NSP2 and NSP4 CHF correlations are well understood.

3.1.1.2 Test Facility Comparison

Test Facility Comparison
The test facility has been verified by comparison to an outside source.
G1.1.2, Review Framework for Critical Boiling Transition Models

Benchmarking tests were conducted at the CHF testing facilities of Stern Laboratories, the KATHY test loop, and the Heat Transfer Research Facility at Columbia University (Reference 20). The results of these benchmarking activities demonstrated that the variation of test data obtained from these facilities was within a reasonable range, and that a comparison of CHF data among the three facilities showed consistent results from all three facilities (Reference 20). Based on the existence of a benchmarking study involving Stern Laboratories and the KATHY test loop in the literature and the results presented in that study, the NRC staff finds that the test facilities NuScale used to develop the NSP2 and NSP4 CHF correlations have been adequately compared to outside sources.

3.1.2 Accurate Data

3.1.2.1 Test Procedures

Facility Quality Assurance
The test facility has an appropriate quality assurance program.
G1.2.1, Review Framework for Critical Boiling Transition Models

Section 3.1.1.3 and Section 3.1.2.7 of the TR provide a high-level description of the data collection process at Stern Laboratories and the KATHY test loop, respectively. These sections describe the instrumentation used to measure heater power, coolant flow, pressure, and temperature. The TR describes the heater power, coolant temperature, and pressure measurements as redundant and diverse at both facilities. The TR describes the flow measurement at Stern Laboratories as redundant and diverse but did not provide similar information for flow measurement at the KATHY facility. Accordingly, the NRC staff issued RAI 8795, Question 29725 (Reference 9), asking the applicant to describe how flow measurement redundancy and diversity were treated for the KATHY test loop. The applicant's response, provided in a letter dated July 7, 2017 (Reference 11), stated that the flow measurement [ ]. The NRC staff finds this response acceptable because it describes [ ] instrumentation capable of providing a check against instrument malfunction. The NRC summarized the redundancy and diversity capabilities for the power, flow, pressure, and temperature measurements at Stern Laboratories and the KATHY test loop in Table 3, "Instrumentation Redundancy and Diversity."

Table 3. Instrumentation Redundancy and Diversity

	Stern	**KATHY**
Power	Current and voltage at power supply [ ]	Two independent and diverse methods for measuring electric current through the test bundle: a Faraday effect meter and shunts
Flow	[ ]	Orifice with [ ]
Pressure	Pressure taps installed [ ]	Two pressure transducers at the outlet of the test section
Temperature	Resistance temperature detectors for [ ]	Two independent, calibrated resistance temperature detectors

In addition to reviewing the information in the TR, the NRC staff conducted an inspection at Stern Laboratories (Reference 17) and an audit at the KATHY test loop (Reference 4). During the inspection and audit activities, the NRC staff determined that the test procedures appropriately incorporated the testing requirements, that all of the instrumentation is routinely calibrated, and that the calibration records were up to date at the time of testing. Based on the instrumentation redundancy and diversity, the NRC staff's inspection findings, and the staff's audit observations, the staff finds that the test facilities used to collect CHF data maintained appropriate quality assurance programs.

3.1.2.2 Statistical Design of Experiment

Statistical Design of Experiment

The experiment has been appropriately statistically designed (i.e., the value of a system parameter from any test was completely independent from its value in the test before and after it).

G1.2.2, Review Framework for Critical Boiling Transition Models

Section 3.1 of TR-0116-21012 describes the data sources used to develop the CHF correlation and provides the test matrices used for testing at Stern Laboratories and the KATHY test loop. The NRC staff was not able to identify any discussion regarding the statistical design of the experiments. Accordingly, it issued RAI 8795, Question 29724 (Reference 9) asking the applicant to describe how the statistical design of experiments was treated during testing at Stern Laboratories and the KATHY test loop. The applicant's response, provided in its letter dated July 7, 2017 (Reference 11), stated that data were taken for each combination of pressure, mass-flux, and subcooling with no particular state point emphasized. The applicant stated that taking data at each state point combination allows for a systematic evaluation of trends with regard to pressure, mass flux, and subcooling. The NRC staff finds that this method of collecting data is consistent with existing precedent (Reference 21 and Reference 22). Based on the consistency with precedent and the repeatability tests, discussed in Section 3.1.2.5 of this SE, the NRC staff finds the experiment has been appropriately statistically designed.

3.1.2.3 Accurate Method

Accurate Method

The method used to obtain critical boiling transition data results in an accurate measurement.

G1.2.3, Review Framework for Critical Boiling Transition Models

Section 3.1.1.3 and Section 3.1.2.7 of the TR provide a high-level description of the data collection process at Stern Laboratories and the KATHY test loop, respectively. These sections describe the method used to obtain steady-state CHF data points by first establishing the desired conditions (i.e., pressure, temperature, and flow) and then increasing heater power until a CHF event is detected. The NRC staff's audit summary (Reference 4) describes additional details about this process. The NRC staff finds this process produces an accurate measurement of CHF because it results in the direct observation of critical boiling transition at a known heat flux, and is therefore acceptable.

3.1.2.4 Instrumentation Uncertainties

Instrumentation Uncertainties

The instrumentation uncertainties have been demonstrated to have a minimal impact on the measured heat flux or critical power.

G1.2.4, Review Framework for Critical Boiling Transition Models

The TR provides the instrument uncertainties for measuring system pressure, mass flux, inlet coolant temperature, and bundle power in Table 3-3 and Table 3-12 of the TR for the tests at Stern Laboratories and the KATHY test loop, respectively. The NRC staff inquired about the impact of instrument uncertainty during the audit of the KATHY test loop (Reference 4) and was informed that sufficient test data are taken such that the standard deviation of the measured-to-predicted values for the CHF correlation encompass uncertainties associated with instrumentation measurement, test repeatability, and test reproducibility. Section 3.2.2 of Revision 1 of the TR incorporates this information. The NRC staff performed calculations to further investigate the impact of instrument uncertainty on the NSP2 and NSP4 CHF correlations. These calculations determined sensitivity derivatives of the CHF correlations with respect to pressure, temperature, mass flux, and power, and then used these sensitivity derivatives and the instrument uncertainties provided in the TR to estimate the resulting uncertainty in the calculated CHFR. The results of the calculations showed that the CHFR limits account for much more uncertainty (approximately a factor of 5) than what can be attributed to instrument error. Therefore, the NRC staff concluded that instrument uncertainty is not the major contributor to the uncertainty in the NSP2 and NSP4 CHF correlations.

3.1.2.5 Repeated Test Points

Repeated Test Points

The uncertainty in the critical heat flux or critical power is quantified through repeated tests at the same state points.

G1.2.5, Review Framework for Critical Boiling Transition Models

Section 3.1.2.7 of the TR discusses the use of "reference points" at the KATHY test loop that are used to verify test repeatability. Additionally, the NRC staff conducted an audit of the KATHY test loop and noted that, "Test repeatability at the KATHY test loop is verified by [ ]. This is in contrast to CHF testing at Stern, where random state points within the testing domain are rerun" (Reference 4). The NRC staff issued RAI 8795, Question 29726, asking NuScale to provide evidence to show that the variability in the repeatability tests was sufficiently low (Reference 9).

The applicant's response, provided in its letter dated July 7, 2017 (Reference 11), stated the following:

- CHF testing, at both Stern Laboratories and the KATHY test loop, had established acceptance criteria on test repeatability of [

  ].

- [

  ].

- [

  ].

The NRC staff notes that the repeat test points that [ ] occur for state points that are outside the requested range of applicability for the CHF correlations. The NRC staff finds the applicant's response acceptable because the stated acceptance criteria are sufficient to demonstrate low variance in test repeatability (i.e., uncertainty associated with test repeatability is much less than the uncertainty accounted for in the CHFR limits), and the test repeatability criteria are satisfied in the ranges of applicability for the CHF correlations. Based on the number of repeat test points collected, and the acceptance criteria used for these tests, the NRC staff finds that the applicant has appropriately quantified the uncertainty in CHF through repeated tests.

3.1.2.6 Quantified Heat Losses

Quantified Heat Losses

The heat losses from the test section are quantified, appropriately low, and duly accounted for in the measured data.

G1.2.6, Review Framework for Critical Boiling Transition Models

Section 3.1.1.3 of the TR states that the heat losses at Stern [

] and are accounted for in the CHF correlation validation. Based on the heat losses being accounted for in the KATHY test loop data, which is used to establish the 95/95 CHFR limits for both the NSP2 and NPS4 CHF correlations, the NRC staff finds that the treatment of heat losses is acceptable.

3.1.3 Reproduced Local Conditions

3.1.3.1 Equivalent Geometries

Equivalent Geometries
The test bundle used in the experiment should have equivalent geometric dimensions to that of the fuel bundle used in the reactor for all major components.
G1.3.1, Review Framework for Critical Boiling Transition Models

Sections 3.1.2.2 to 3.1.2.5 of the TR describe test sections used to obtain data from the KATHY test loop for prototypical NuFuel-HTP2^{TM} fuel (K9000, K9100, K9200, and K9300). The TR describes the K9000, K9100, K9200, and K9300 test bundles as representing the NuFuel-HTP2^{TM} design. NRC staff compared the geometric dimensions of the these test sections (provided in TR Table 3-6, 3-7, 3-8, and 3-10 for the K9000, K9100, K9200, and K9300, respectively) against the geometric dimensions for NuFuel HTP2^{TM} fuel assemblies (provided in TR Table 2-1). This comparison showed that the simulated fuel used in the test sections used equivalent rod diameter, gap pitch, guide tube diameter, grid spacer heights, and grid spacer locations (grid spacer locations were within [ ]). Based on this comparison between the NuFuel-HTP2^{TM} design and the simulated fuel used to develop validation data, NRC staff finds that these test bundles have equivalent dimensions to those of the fuel bundle in the reactor for all major components.

In addition to the data collected from the K9000 – K9300 test sections, the TR describes two other categories of experimental data. Section 3.1.1.1 of the TR describes the Stern test sections used to obtain data for a preliminary fuel design (U1, U2, and C1); this data was used to develop the NSP1 CHF correlation (note that NSP1 is included in the NSP2 CHF correlation, however, separate approval is not being sought for the application of NSP1 to NuFuel-HTP2^{TM} fuel). Section 3.1.2.1 of the TR describes a test section used to obtain legacy data from the KATHY test loop for a design that used HMP^{TM} grids (K8500 HMP^{TM}); this data was used to develop the NSPX factor and NSP2 CHF correlation. The geometric dimensions associated with these test sections are provided in TR Table 3-2 and TR Table 3-5 for the Stern tests and K8500 tests, respectively. NRC staff notes that [ ]. However, NRC staff finds the use of this data to develop the NSP1 and NSP2 CHF correlations acceptable because this data is not used for validation (note that the K9000 – K9300 test data is used to validate the NSP2 and NSP4 CHF correlations).

3.1.3.2 Equivalent Grid Spacers

> **Equivalent Grid Spacers**
>
> *The grid spacers used in the test bundle should be prototypical of the grid spacers used in the reactor assembly.*
>
> G1.3.2, Review Framework for Critical Boiling Transition Models

Section 3.1.2 of the TR describes the grid spacers used in the testing to obtain validation data as the HMP™ and HTP™ that are prototypical of the NuFuel-HTP2™ fuel design. In addition, NRC staff performed an audit of the CHF testing at the KATHY test loop and observed that HMP™ and HTP™ mixing grids used in the testing are consistent with the prototypical design and are located at the same axial locations as the prototypical design (Reference 4). Based on the discussion in this paragraph, the NRC staff finds that the grid spacers used in the test bundles for obtaining validation data are prototypical of the grid spacers used in the NuFuel-HTP2™ fuel design.

3.1.3.3 Axial Power Shapes

> **Axial Power Shapes**
>
> *The axial power shapes in the test bundle should reflect the expected or limiting axial power shapes in the reactor bundle.*
>
> G1.3.3, Review Framework for Critical Boiling Transition Models

Section 3.1.1 and Section 3.1.2 of the TR describe the experiments at Stern Laboratories and the KATHY test loop, respectively. The description of the experiments at Stern Laboratories show that data were obtained using uniform and symmetric cosine axial power profiles. Additionally, as described in Section 4.3 of the TR, the applicant uses a nonuniform flux factor to adjust CHF predictions for the effect of variations of axial power profiles and demonstrated that this factor adequately adjusts data obtained for a uniform power profile to nonuniform shapes. Based on the testing performed with uniform and nonuniform power shapes and the development of a nonuniform flux factor, the NRC staff finds that the axial power shapes used in the test bundles at Stern Laboratories are suitably representative of the expected or limiting axial power shapes used in the reactor bundle.

The description of the experiments at the KATHY test loop show that data [ ]. Additionally, as described in Section 7.5 of the TR, the applicant uses a nonuniform flux factor to adjust CHF predictions for the effect of variations of axial power profiles and demonstrated that this factor adequately adjusts [ ]. Based on the testing performed with [ ] and the development of a nonuniform flux factor, the NRC staff finds that the axial power shapes used in the test bundles at the KATHY test loop are suitably representative of the expected or limiting axial power shapes used in the reactor bundle.

3.1.3.4 Radial Power Shapes

Radial Power Shapes
The radial power peaking in the test bundle should reflect the expected or limiting radial power in the reactor bundle.
G1.3.4, Review Framework for Critical Boiling Transition Models

The TR Figures 3-4, 3-5, and 3-11 to 3-15 show the radial power distribution used in the tests. As described in the NRC staff's audit report of the KATHY test facility, the radial power distribution is selected to produce CHF in the interior rods to negate the impact of the wall effect. The radial power distributions in the TR show power distributions that (1) produce peak heat flux values within the interior rods and (2) produce a subchannel surrounded by peaked rods such that it is expected to result in a hot or limiting subchannel. Based on these observations, the NRC staff finds the radial power distributions used in the TR reflect a limiting radial power distribution for developing and validating the NSP2 and NSP4 CHF correlations.

3.1.3.5 Differences between Test and Reactor

Differences between Test and Reactor
Any differences between the test bundle and the reactor bundle should be addressed. This includes components that are not in the reactor bundle but are needed for testing purposes.
G1.3.5, Review Framework for Critical Boiling Transition Models

The NRC staff found the following differences between the K9000, K9100, K9200, and K9300 test bundles, which are used to develop validation data, and the NuFuel-HTP2™: (1) the test bundles used a 5x5 grid as compared to the 17x17 grid used in the prototype, and (2) the test bundles used intermediate support grids to counteract the electromagnetic forces on the heater rods. During an audit of the KATHY test loop, the NRC staff inquired about these differences and noted that (1) early CHF testing at the Columbia University Heat Transfer Research Facility loop demonstrated that a 5x5 grid layout is sufficiently large to negate the impact of the wall effect, and (2) based on the results of previous tests, Areva, Inc. has determined that the intermediate support grids produce a small flow resistance and have a negligible contribution to mixing (Reference 4). The NRC finds these differences acceptable because they have a negligible impact on the test results and are consistent with established practice.

3.2 Model Generation

3.2.1 Appropriate Mathematical Model

3.2.1.1 Necessary Parameters

> **Necessary Parameters**
>
> *The mathematical form of the model contains all necessary parameters.*
>
> G2.1.1, Review Framework for Critical Boiling Transition Models

Sections 4.2 and 5.2 of the TR discuss the form of the NSP2 CHF, while Section 7.4 discusses the form of the NSP4 CHF correlation. The NSP4 correlation includes pressure, local mass flux, local equilibrium quality, boiling length, [ ], and hydraulic diameter as correlation parameters. The NSP2 CHF correlation includes these same parameters plus the [ ]. The NRC staff finds the parameters chosen for the NSP2 and NSP4 correlations are consistent with parameters used in previously approved CHF correlations (Reference 21 and Reference 22). Additionally, the coefficient generation process, described in Section 3.2.2 of this SE, checks that statistically significant parameters are captured by the correlation; and the correlation validation process, described in Section 3.3 of this SE, verifies adequate performance of the correlation (i.e., the final correlation includes the necessary parameters). Based on the use of correlation parameters that are consistent with previously approved CHF correlations, the coefficient generation process, and the validation process, the NRC staff finds that the NSP2 and NSP4 CHF correlations contain the necessary parameters.

3.2.1.2 Model Form

> **Model Form**
>
> *The reasoning for choosing the mathematical form of the model should be discussed and be logical.*
>
> G2.1.2, Review Framework for Critical Boiling Transition Models

Section 4.2 and Section 7.4 of the TR discuss the form of the base CHF correlation for NSP2 and the form of the NSP4 CHF correlation, respectively. These correlations are quadratic equations consisting of the parameters discussed in Section 3.2.1.1 of this SE. During an audit, the NRC staff reviewed engineering calculations associated with correlation development and noted that (1) NuScale considered several forms of the CHF correlation, (2) global sensitivity analyses were performed for each form of the CHF correlation to confirm consistency with known physical trends, and (3) the quadratic formulation was selected as the final form based on the results of the global sensitivity analyses (Reference 4). Additionally, the correlation validation process, described in Section 3.3 of this SE, verifies adequate performance of the correlation. Based on the description of the CHF correlation forms in Sections 4.2 and 7.4 of the TR, the information obtained by the NRC staff during an audit, and the correlation validation process, the staff finds that the mathematical form of the NSP2 CHF correlation and the NSP4 correlations are adequately described and logical.

The final NSP2 CHF correlation, Equation 5-2 of the TR, includes an NSPX factor. Section 5.2 of the TR describes the NSPX factor as an adjustment to the base CHF correlation for analyzing the thermal performance of NuFuel-HTP2™ fuel. The NSPX factor is applied because the base CHF correlation is developed using data from the Stern tests, which did not use prototypical NuFuel-HTP2™ geometry (see Section 3.1.3.1 of this SE). Section 5.2 of the TR explains that the NSPX factor imposes a mean predicted-to-measured ratio of [ ] when the NSP2 CHF correlation is applied to the K8500 data. Additionally, during an audit, the NRC staff observed that the K8500 data, which use a heater rod longer than the NuFuel-HTP2™ fuel, showed reduced thermal performance than the data collected for NuFuel-HTP2™ fuel (Reference 4). Therefore, the NRC staff recognizes that the NSPX factor, which is derived from the K8500 data, introduces conservative bias into the NSP2 correlation (Reference 4). Furthermore, the NRC staff recognizes that the correlation validation process, described in Section 3.3 of this SE, uses data that are independent of the K8500 data and addresses uncertainties associated with any lack of fit that may be introduced by the NSPX factor. Based on the conservative development of the NSPX factor and the use of a validation process over the correlations' range of applicability, the NRC staff finds the NSPX factor acceptable.

A nonuniform flux factor, described in Section 4.3 of the TR, is applied to adjust NSP2 CHF predictions for the effect of variations of axial power profiles. As described in Section 4.3 of the TR, the nonuniform flux factor is based on the original Tong factor (Reference 23). The parameters in the original Tong factor, which are carried over into the nonuniform flux factor for the NSP2 CHF correlation, are based on test parameters that do not bound the range of applicability for the NSP2 CHF correlation. However, as described in Section 4.3 of the TR, the applicant [ ]. Additionally, the correlation validation process, described in Section 3.3 of this SE, verifies adequate performance of the correlation over its range of applicability. Appendix A of the TR contains the local conditions used to develop the CHF correlations and shows that the Tong factors are always applied as a penalty. Accordingly, the NRC staff established Limitation 1 on the application of the NSP2 and NSP4 correlations. Based on the use of Stern test data to modify the base Tong factor, the validation process that covers the correlation range of applicability, and pursuant to Limitation 1, the NRC staff finds the applicant's use of the Tong factor in the NSP2 CHF correlation acceptable.

The final NSP4 CHF correlation is provided as Equation 7-1 of the TR and is developed using data obtained from experiments that are consistent with NuFuel-HTP2™ fuel. A nonuniform flux factor, described in Section 7.5 of the TR, is applied to adjust NSP4 CHF predictions for the effect of variations of axial power profiles. Unlike the approach taken for the NSP2 nonuniform flux factor, the applicant refit the parameters used in the original Tong factor using data obtained from experiments that are consistent with NuFuel-HTP2™ fuel. Additionally, the correlation validation process, described in Section 3.3 of this SE, verifies adequate performance of the correlation over its range of applicability. Based on the use of prototypical test data to develop a nonuniform flux factor, as well as the validation process that covers the correlation range of applicability, and subject to Limitation 1, the NRC staff finds the applicant's nonuniform flux factor for the NSP4 CHF correlation acceptable.

3.2.2 Model Coefficient Generation

3.2.2.1 Training Data

> **Training Data**
>
> *The training data (i.e., the data used to generate the coefficients of the model) should be identified.*
>
> G2.2.1, Review Framework for Critical Boiling Transition Models

Section 4.4 and Section 7.6 of the TR describe the statistical technique used in the CHF correlation coefficient generation process for the NSP1 (which is incorporated into NSP2) and NSP4 CHF correlations, respectively. Section 4.4 of the TR states that a five-fold cross-validation process is used in generating the NSP1 coefficients, and Section 7.6 states that a three-fold cross-validation process is used in generating the NSP4 coefficients. Section 4.1 of the TR describes the *k*-fold process as randomly portioning the data into *k* subsets, then holding one subset for validation testing and using the remaining data to train the correlation (i.e., obtain correlation coefficients). This process is repeated *k* times (i.e., until all of the data have been used in validation). The NRC staff finds the *k*-folds process for selecting training data acceptable because it is an established statistical technique for training correlations.

Additionally, Section 7.1 of the TR states that the difference between a five-fold and three-fold cross validation is small. During an audit, the NRC staff noted that NuScale performed sensitivity studies on the number of groups used in the *k*-folds cross-validation process and that the results of the sensitivity study showed negligible differences between three and five groups (Reference 4). Based on the information provided in Section 7.1 of the TR, and the NRC staff's audit observations, the staff finds the number of subsets used in the cross-validation process for the NSP1 and NSP4 CHF correlations acceptable.

In addition to the Stern data used in the development of the NSP1 CHF correlation and the prototypical NuFuel-HTP2™ data used in the development of the NSP4 CHF correlation, NuScale uses legacy data obtain from the KATHY test loop, K8500 data, to develop the NSPX factor. The NRC staff recognizes that the correlation validation process, described in Section 3.3 of this SE, uses data that are independent of the K8500 data. Based on the independence of the NSP2 validation data, the NRC staff finds the use of K8500 data to develop the NSPX factor acceptable.

3.2.2.2 Coefficient Generation

> **Coefficient Generation**
>
> *The method for calculating the model's coefficients should be described.*
>
> G2.2.2, Review Framework for Critical Boiling Transition Models

Sections 4.2 and 7.4 of the TR describe the process used to develop the NSP1 and NSP4 CHF correlations. The TR describes the iterative process that removes noncorrelating parameters from the quadratic form discussed in Section 3.2.1.2 of this SE. Once the final form of the correlation is obtained, NuScale performs the *k*-fold cross-validation process described in Section 3.2.2.1 of this SE. NuScale performs a linear least squares fit, which is an established technique for performing linear regression, to obtain correlation coefficients *k* times during the *k*-folds process. NuScale averaged the coefficients obtained from the cross-validation process to obtain the final coefficients. During an audit, the NRC staff independently replicated the NSP1 CHF correlation using the group structure and data provided by NuScale (Reference 14). Additionally, the correlation validation process, described in Section 3.3 of this SE, verifies adequate performance of the correlation over its range of applicability. Based on the use of an established technique to fit the CHF correlations and a validation process that covers the correlation range of applicability, the NRC staff finds the coefficient generation process for the NSP1 (which is included in NSP2) and NSP4 CHF correlations acceptable.

3.3 Model Validation

3.3.1 Validation Error

Validation Error
The validation error has been correctly calculated.
G3.1, Review Framework for Critical Boiling Transition Models

NuScale uses a database to develop and validate the NSP2 and NSP4 CHF correlations that depends upon reduced data (i.e., the raw data from CHF testing are further processed by calculation). Section 3.3.2 of the TR describes this data reduction process as using VIPRE-01 to [ ]. The TR explains that the Stern data [ ], and the data collected from the KATHY test loop [ ]. The validation data for the NSP2 and NSP4 CHF correlations are obtained from testing the NuFuel-HTP2™ simulated fuel.

Section 3.3.2 of the TR explains that, to obtain local conditions from the NuFuel-HTP2™ testing data for validation of the NSP2 CHF correlation, NuScale took the local conditions [ ]. The NRC staff finds this approach acceptable because it results in a conservative CHFR limit.

Section 3.3.2 of the TR explains that, to obtain local conditions from the NuFuel-HTP2™ testing data to develop and validate the NSP4 CHF correlation, NuScale took the local conditions [ ]. The local conditions, provided in Appendix A of the TR, show that CHF [ ]. Therefore, the NRC staff finds that it is reasonable to select local conditions [ ] for developing and validating the NSP4 CHF correlation.

Based on the acceptable identification of the CHF location for obtaining validation data, the NRC staff finds that the validation error is calculated using an acceptable measured value.

3.3.2 Data Distribution

3.3.2.1 Validation Data

Validation Data
The validation data (i.e., the data used to quantify the model's error) should be identified.
G3.2.1, Review Framework for Critical Boiling Transition Models

Section 4.5, Section 6.3, and Section 7.7 describe the validation process used to establish the CHF correlation limits for the NSP1, NSP2, and NSP4 CHF correlations, respectively. These sections of the TR explain that [

]. Based on the use of the *k*-folds method and the [ ], the NRC staff finds the use of all the data to perform validation and to determine the CHFR limit acceptable.

3.3.2.2 Application Domain

Application Domain
The application domain of the model should be mathematically defined.
G3.2.2, Review Framework for Critical Boiling Transition Models

Table 8-2 and Table 8-4 of the TR provide the application domains for the NSP2 and NSP4 CHF correlations, respectively. The NRC staff identifies the application domains provided in the TR as hyper-rectangles and finds that defining the application domain as a hyper-rectangle is consistent with current practice. NRC staff finds the definition of the application domain acceptable because it is (1) consistent with current practice, and (2) regions within the application that are not supported by data (e.g., low flow with low quality, and high flow with high quality) are not observed in testing and are not realistically expected to occur during normal operation, including AOOs.

3.3.2.3 Expected Domain

Expected Domain
The expected domain of the model should be understood.
G3.2.3, Review Framework for Critical Boiling Transition Models

As described in Section 2.5 of Reference 1, the applicant performed preliminary analyses of the NPM to develop conditions covering normal operation and AOOs. The NRC staff compared the range of test conditions, identified in Table 2-5 of Reference 1, with the range of applicability of the NSP2 and NSP4 CHF correlations, provided in Table 8-2 and Table 8-4 of the TR, and determined that the range of test conditions encompasses the range of applicability for both the NSP2 and NSP4 CHF correlations. Based on the performance studies of the NPM presented in Reference 1, the NRC staff finds the expected range acceptable.

3.3.2.4 Data Density

Data Density
There should be an appropriate data density throughout the expected domain.
G3.2.4, Review Framework for Critical Boiling Transition Models

Table 8-2 and Table 8-4 of the TR mathematically define the application domains for the NSP2 and NSP4 CHF correlations, respectively. Based on prior experience with CHF correlation reviews, the NRC staff recognizes that the defined application domain of a CHF correlation contains regions where there are no underlying experimental data and where the correlation will not be used. Accordingly, on August 21, 2017, the NRC staff issued RAI 8931, Question 30134 (Reference 12), requesting that NuScale demonstrate adequate data density throughout the expected domain of application. NuScale’s response, provided in a letter dated September 25, 2017 (Reference 13), included several plots that show the data collection within the expected domain. These plots show that the expected mass flux and pressure regions are densely populated with data. These plots also show that the local equilibrium quality data fall mostly outside the expected domain. The NRC staff finds these results acceptable because CHF data are collected by driving test rods into CHF, which results in much higher thermodynamic qualities than are expected to occur. Based on the information provided by NuScale in response to RAI 8931, Question 30134, the NRC finds that there is appropriate data density throughout the expected domain.

3.3.2.5 Sparse Regions

> **Sparse Regions**
>
> *Sparse regions (i.e., regions of low data density) in the expected domain should be identified and justified to be appropriate.*
>
> G3.2.5, Review Framework for Critical Boiling Transition Models

As described in Section 3.3.2.4 of this SE, the expected mass flux and pressure regions are densely populated with data, but the local equilibrium quality observed in the data mostly falls outside the expected domain. The NRC staff recognizes that this occurs because CHF data are collected by driving test rods into CHF, which results in much higher equilibrium qualities than are expected to occur in the actual plant (i.e., CHF testing forces CHF to occur, but CHF is not expected to actually occur in the plant during normal operation and AOOs). However, NRC staff recognizes that if reactor power was increased substantially, due to an unexpected and unforeseen event, such that thermal margin to CHF was challenged, the increased energy added to the coolant would result in equilibrium qualities in the region where CHF data was collected. Accordingly, the NRC staff finds that the sparse regions in the expected domain are identified and appropriately justified.

3.3.2.6 Restricted Domain

> **Restricted Domain**
>
> *The model should be restricted to its application domain.*
>
> G3.2.6, Review Framework for Critical Boiling Transition Models

Table 8-2 and Table 8-4 of the TR mathematically define the application domains for the NSP2 and NSP4 CHF correlations, respectively. Additionally, Section 1.1 of the TR states that approval of the NSP2 and NSP4 CHF correlations is requested within the domain of applicability defined in these tables. The NRC staff finds that this is consistent with established precedent and is sufficient for restricting the domain of applicability.

3.3.3 Consistent Model Error

3.3.3.1 Poolability

> **Poolability**
>
> *The validation error should be investigated to ensure that it does not contain any subgroups that are obviously not from the same population (i.e., non-poolable).*
>
> G3.3.1, Review Framework for Critical Boiling Transition Models

Section 3.3.2.1 of this SE explains the process of splitting up the validation data. The NRC staff further investigated this process during an audit, where it observed that the NuScale process for developing the CHFR limit involved several statistical tests to determine (1) whether subregions can be combined (i.e., pooled), and (2) whether the data can be treated as normally distributed. The NRC staff developed a flow chart, provided in Figure 1, to clarify the NuScale process for developing the CHFR limit. The statistical tests used by NuScale, and shown in Figure 1, are consistent with those described in NUREG-1475, Revision 1, “Applying Statistics” (Reference 24). Based on the description of these methods in NUREG-1475, the NRC staff finds that these statistical tests are consistent with established practice and are therefore acceptable. Additionally, based on NuScale [ ], the NRC staff finds the process used to select the CHFR limit acceptable.

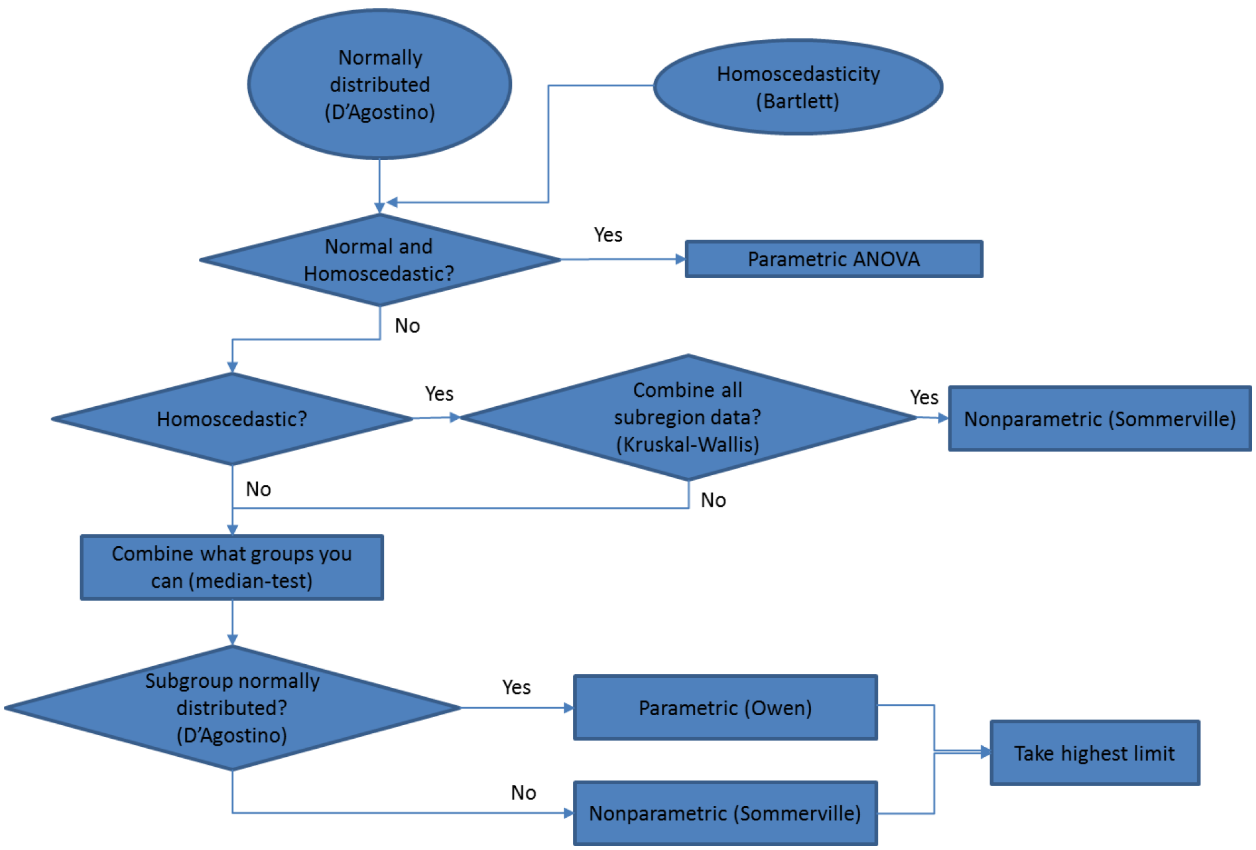

Figure 1. [ ]

3.3.3.2 Nonconservative Subregions

Nonconservative Subregions

The expected domain should be investigated to determine if it contains any non-conservative subregions which would impact the predictive capability of the model.

G3.3.2, Review Framework for Critical Boiling Transition Models

The NRC staff analyzed the measured-to-predicted performance of the NSP2 CHF correlation. This analysis showed that a subregion of reduced margin existed within the application domain of the NSP2 CHF correlation (at low mass flux and high quality), which caused the NRC staff to question whether the NSP2 correlation limit, proposed in Revision 0 of TR-0116-21012, is suitable for application within this subregion. Accordingly, on August 21, 2017, the NRC staff issued RAI 8931, Question 4.4-6 (Reference 12), asking NuScale to provide a means to address the low-margin subregion to ensure that CHF will not be experienced at the CHFR limit at the 95/95 level. NuScale's response, provided in its letter dated September 25, 2017 (Reference 13), proposed to reduce the application domain to remove the subregion in question. The NuScale response further demonstrated the efficacy of this approach by plotting the most limiting points and showing that, by restricting the application domain, the clustered region of low margin is eliminated. The NRC staff finds this response acceptable because it eliminates the region of reduced margin. Based on the NuScale response to RAI 8931, Question 4.4-6, the NRC staff finds that the NSP2 CHFR limit is suitably conservative over the revised application domain. The NRC staff has confirmed that NuScale has incorporated the changes associated with this RAI response into Revision 1 of TR-0116-21012.

Figures 7-4 and 7-5 of the TR show that the predicted-to-measured data points exceeding the NSP4 CHFR limit occur at low mass fluxes and high qualities. Further analysis by the NRC staff showed that three data points, exceeding the NSP4 CHFR limit, occur in close proximity to each other in the low mass flux, high-quality region. However, Table 7-3 of the TR shows that the low mass flux, high-quality region is captured by the CHFR limit calculation process by partitioning the data by mass flux and local quality. Additionally, Table 3-1 of TR-0915-17564, "Subchannel Analysis Methodology," dated February 15, 2017 (Reference 25), shows that normal and off-normal conditions, encountered for the NPM, are not expected to occur in the low mass flux, high-quality region. Based on the analyses presented in Section 7.7 of the TR, the NRC staff finds that the NSP4 CHFR limit is suitably conservative over the application domain established by Table 8-4 of the TR.

3.3.3.3 Model Trends

Model Trends

The model is trending as expected in each of the various model parameters.

G3.3.3, Review Framework for Critical Boiling Transition Models

Sections 4.7 and 7.9 of the TR show the results of global sensitivity analyses for the NSP1 (which is included in the NSP2 CHF correlation) and the NSP4 CHF correlations. These studies show that the [ ]. The NRC staff recognizes that these trends are consistent with previously reviewed CHF correlations. NuScale's sensitivity studies also show that the CHF [ ]. Data collected at Stern Laboratories (shown in Figure 4-1 of the TR) and the KATHY test loop (shown in Figure 7-10 of the TR) support this trend in the NSP2 and NSP4 CHF correlations. The NRC staff recognizes that this trend differs from the trend observed in previously reviewed CHF correlations. The NRC staff further investigated this trend through the comparison with historical CHF data provided in the 2006 CHF lookup table (Reference 26). The NRC staff found that the trend of increasing pressure resulting in lower CHF is observed in the Groeneveld CHF lookup table. Based on the consistency in physical trends observed between the physical data and the CHF correlation, and [ ], the NRC staff finds that the NSP2 and NSP4 CHF correlations trend as expected in each of the various model parameters.

Section 4.4 and Section 7.6 of the TR show the measured-to-predicted performance of the NSP1 and NSP4 CHF correlations, respectively. The plots provided show that the measured-to-predicted performance of the NSP1 and NSP4 CHF correlations is consistent over the domain of applicability, [

] Section 3.3.3.2 of this SE presents the NRC staff's evaluation of this region.

Section 6.3 of the TR shows the measured-to-predicted performance of the NSP2 CHF correlation. The plots provided show that the accuracy of the NSP2 CHF correlation is dependent upon the location within the application domain. Because this trend was not observed in the NSP1 CHF correlation, which is included in the NSP2 correlation, the NRC staff recognizes that this trend is attributed to the NSPX factor (discussed in Section 3.2.1.2 of this SE). Section 5.2 of the TR describes the NSPX factor as a conservative multiplier that assures that the mean predicted-to-measured CHF value is conservatively biased [ ]. The NRC staff finds the measured-to-predicted trend for the NSP2 CHF correlation acceptable because, as described in Section 3.3.2.1 of this SE, the limiting region sets the CHFR limit.

3.3.4 Quantified Model Error

3.3.4.1 Error Data Base

Error Data Base
The model's error should be calculated from an appropriate data base.
G3.4.1, Review Framework for Critical Boiling Transition Models

As described in Section 3.3.2.1 of this SE, NuScale [
] to establish the CHFR limit for the NSP2 and NSP4 CHF correlations. Based on the use of the [ ] to set the CHFR limits, the NRC staff finds that the error data base used to determine the CHFR limits for the NSP2 and NSP4 CHF correlations acceptable.

3.3.4.2 Statistical Method

Statistical Method
The model's error should be calculated using an appropriate statistical method.
G3.4.2, Review Framework for Critical Boiling Transition Models

Section 3.2.5 of the TR describes the statistics used to develop the correlation limit. As evaluated in Section 3.3.3.1 of this SE, the statistical tests for poolability and normality are consistent with established practice and are therefore acceptable. If normality testing determines that the data are normally distributed, NuScale determines the CHFR limit by adding the standard deviation times an appropriate tolerance factor (i.e., sufficient to establish a 95/95 CHFR limit) to the predicted-to-mean distribution average. If normality testing determines that

the data are not normally distributed, then NuScale uses nonparametric statistics to establish a 95/95 CHFR limit. The NRC staff finds NuScale's statistical methodology acceptable because it is consistent with established practice.

3.3.4.3 Appropriate Bias for Model Uncertainty

Appropriate Bias
The model's error should be appropriately biased in generating the model uncertainty.
G3.4.3, Review Framework for Critical Boiling Transition Models

Section 4.5, Section 6.3, and Section 7.7 of the TR develop the CHFR limits for the NSP1, NSP2, and NSP4 CHF correlations, respectively. The CHFR limit of 1.17 for the NSP1 correlation, presented in Section 4.5 of the TR, is based on Stern data and is selected from the value obtained for the limiting subset of data. NuScale uses the NSP1 limit of 1.17 for the NSP2 correlation and shows that this limit is bounding in Table 6-2 of the TR. NuScale selected a CHFR limit of 1.21 for the NSP4 correlation, which conservatively rounds up and bounds the value obtained for the most limiting subset of data presented in Table 7-4 of the TR. Based on the use of bounding values the CHFR limit, the NRC staff finds that the CHFR limits for the NSP2 and NSP4 CHF correlations are appropriately biased.

3.3.5 Model Implementation

3.3.5.1 Same Computer Code

Same Computer Code
The model has been implemented in the same computer code that was used to generate the validation data.
G3.5.1, Review Framework for Critical Boiling Transition Models

Section 3.3.1 and Section 3.3.2 of the TR show that the VIPRE-01 models are used to perform the data reduction calculations in accordance with TR-0915-17594, "Subchannel Analysis Methodology" (Reference 25). To ensure that the NSP2 and NSP4 CHF correlations are used in a manner consistent with their validation, the NRC staff established Limitation 2 on the use of VIPRE-01 calculations using the NSP2 and NSP4 CHF correlations. Based on the description in Section 3.3.1 and Section 3.3.2 of the TR, and pursuant to Limitation 2, the NRC staff finds that the NSP2 and NSP4 CHF correlations are implemented using the same computer code used to generate validation data.

3.3.5.2 Same Methodology

Same Methodology

The model's prediction of critical boiling transition is being applied in the same manner as it was when predicting the validation data set.

G3.5.2, Review Framework for Critical Boiling Transition Models

As described in Section 3.3.5.1 of this SE, the NRC staff established Limitation 2 to ensure that the NSP2 and NSP4 CHF correlations are used in a manner consistent with their validation. Based on the description in Section 3.3.1 and Section 3.3.2 of the TR, and pursuant to Limitation 2, the NRC staff finds that the NSP2 and NSP4 CHF correlations are being applied in the same manner as when predicting the validation data set.

3.3.5.3 Transient Behavior

Prediction of Transient Behavior

The model results in an accurate or conservative prediction when it is used to predict transient behavior.

G3.5.3, Review Framework for Critical Boiling Transition Models

During an audit, the NRC staff observed that NuScale performed [

] Based on the results of these tests, the NRC staff finds that the NSP2 and NSP4 CHF correlations provide suitably conservative predictions for CHF when used to predict transient behavior.

4.0 LIMITATIONS

The NRC staff's conclusions about TR-0116-21012 are subject to the following limitations:

Limitation 1 — The nonuniform flux factors used in the NSP2 and NSP4 CHF correlations must always be greater than or equal to one. Section 3.2.1.2 of this SE describes the basis for this limitation.

Limitation 2 — Analyses using the NSP2 and NSP4 CHF correlations must be performed in accordance with TR-0915-17564. Section 3.3.5.1 of this SE provides the basis for this limitation.

5.0 CONCLUSIONS

The NRC staff approves the use of NuScale TR-0116-21012, Revision 1, subject to the limitations identified in Section 4.0 of this SE. In particular, the NRC staff finds that (1) the

NSP2 CHF correlation is acceptable for use in performing safety analyses of the NPM with NuFuel-HTP2™ fuel, with a CHFR limit of 1.17, over the range of applicability provided in Table 8-2 of the TR, and (2) the NSP4 CHF correlation is acceptable for use in performing safety analyses of the NPM with NuFuel-HTP2™ fuel, with a CHFR limit of 1.21, over the range of applicability provided in Table 8-4 of the TR. These findings are based on the following three observations:

1. The experimental data supporting the NSP2 and NSP4 CHF correlations are appropriate as evidenced by meeting all the supporting goals discussed in Section 3.1 of this SE.

2. The NSP2 and NSP4 CHF correlations were generated in a logical fashion as evidenced by meeting all the supporting goals discussed in Section 3.2 of this SE.

3. The NSP2 and NSP4 CHF correlations have sufficient validation, demonstrated through appropriate quantification of their error, as evidenced by meeting all the supporting goals discussed in Section 3.3 of this SE.

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A. CRITICAL BOILING TRANSITION MODEL ASSESSMENT FRAMEWORK

A.1 Introduction

Critical boiling transition (CBT) is defined as a transition from a flow regime that has a higher heat transfer rate to a flow regime that has a significantly lower heat transfer rate. In scenarios where the heat transfer is controlled by the heat flux (such as in nuclear fuel bundles), the reduction in heat transfer rate results in an increase in the surface temperature such that the heat flux can be maintained. If the reduction in the heat transfer rate and resulting increase in surface temperature is large enough, the surface may weaken or melt. In a nuclear power plant, this condition could result in fuel damage. The term CBT is meant to encompass many other terms that have been used to describe this phenomena including critical heat flux, departure from nuclear boiling, and dryout.

To ensure that the fuel is not damaged during normal operation or AOOs, computer simulations of the fuel are conducted to predict the thermal-hydraulic conditions that would occur in the fuel during various scenarios. The resulting thermal-hydraulic conditions are then input to a CBT model that determines whether a CBT has occurred and, if not, the margin to a CBT occurrence (i.e., the additional power that would be required to initiate a CBT). The NRC has historically accepted that one way to demonstrate the avoidance of fuel damage during all normal operation and AOOs is to demonstrate that there is margin to a CBT.

Because of the importance of CBT models, a major focus in reactor safety analysis is to determine that they are trustworthy. The NRC has reviewed many CBT models over the years and has documented why each model was found acceptable in the corresponding safety evaluation.

A.2 Existing CHF Correlations

The NRC staff has reviewed several CBT models throughout its history. Table A-1 provides a list of several correlations that have been used in the safety analyses of light water reactors, both boiling water reactors and pressurized water reactors (note that Table A-1 is not comprehensive).

Table A-1. List of CBT Models

	CBT Model	Date	ML
1	B&W-2	1970	ML082490748
2	CE-1	1976	ML083010357
3	XNB DNB	1983	-
4	WRB-1	1984	ML080630433
5	WRB-2	1985	ML092430561
6	CE-1 modified)	1985	-
7	ANFP DNB	1990	-
8	WRB-2M	1999	ML081610106
9	ABB-NV and ABB-TV	2004	ML042610371
10	BHTP	2004	ML052500092
11	HTP	2005	ML051020019
12	WSSV and WSSV-T	2007	ML072570633
13	ABB-NV (extended) and WLOP	2008	ML081280713
14	WNG-1	2010	ML100850532
15	WRB-1 and WRB-2	2013	ML13284A071
16	KCE-1	2012	ML130180119
17	ORFEO	2016	ML16238A082
18	GE transient CHF	1971	-
19	GEXL	1977	ML092820214
20	ANFB	1990	ML081820434
21	D2	1999	ML993470286
22	D1	1999	ML003767392
23	GEXL96	2001	ML003755947
24	GEXL10	2001	ML012760512
25	GEXL80	2004	ML043210062
26	D4	2005	ML051260213
27	GEXL97	2008	ML082070090
28	GEXL17	2009	ML091830641
29	SPCB	2009	ML093650230
30	GEXL14	2011	ML111290535
31	ACE/ATRIUM-10	2014	ML14175A228
32	ACE/ATRIUM-10 XM	2014	ML14183A748
33	D5	2013	ML13333A276

A.3 CBT Assessment Framework

The CBT assessment framework was developed by NRC staff based on engineering judgement. This engineering judgement is informed by the NRC staff's experience conducting CHF reviews as described in Section A.2 of this SE, and uses a top-down approach. This top-down approach starts with a high level goal (G) that the CBT model can be trusted in reactor safety analyses. This high level goal is decomposed into lower level sub-goals, which are further decomposed until each sub-goal is sufficiently precise as to be satisfied directly by evidence. The top level of this framework is provided in Figure A-1 and is further decomposed in Sections A.3.1, A.3.2, and A.3.3 of this SE.

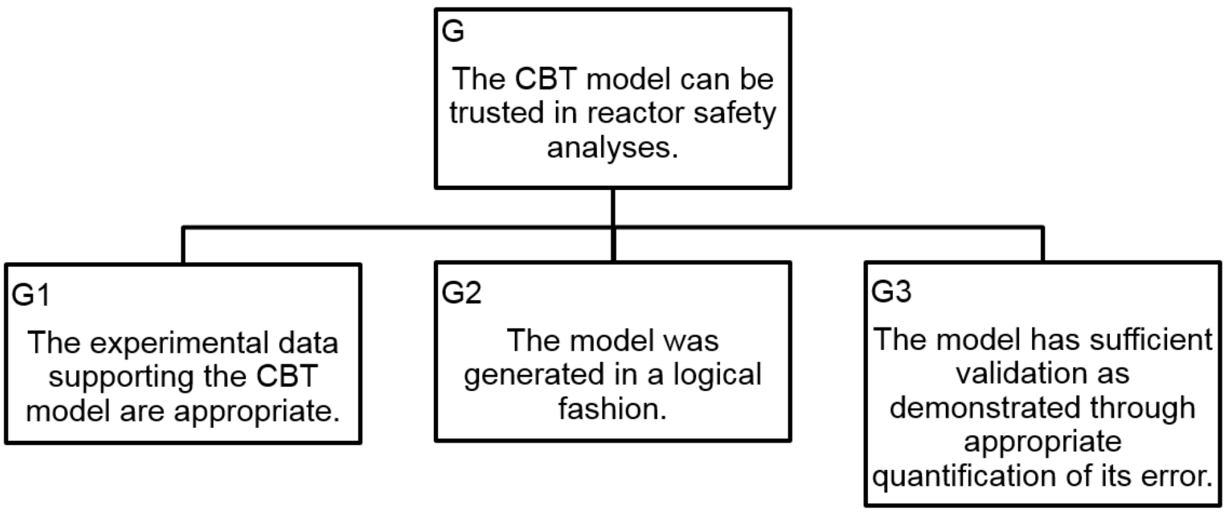

Figure A-1. Decomposition of G —Main Goal

A.3.1 G1 Experimental Data

Experimental data are the cornerstone of a CBT model. The data are used to generate the coefficients of the model and validate the model. Additionally previous data are often used to generate the form of the model. Therefore, it is essential that the experimental data are appropriate. The three subgoals in Figure A-2 are used to demonstrate that the experimental data are appropriate.

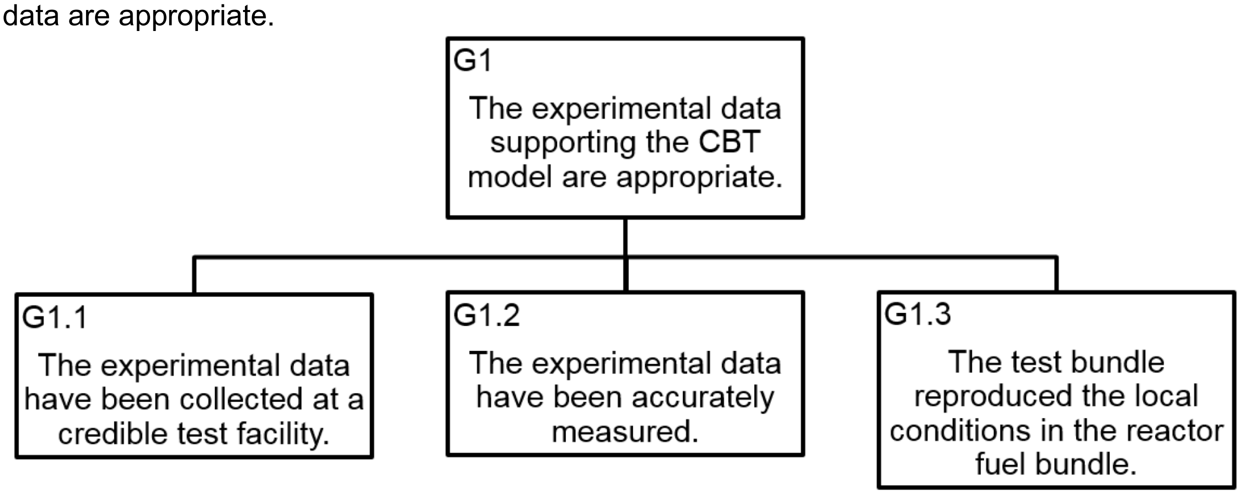

Figure A-2. Decomposition of G1—Experimental Data

A.3.1.1 G1.1 Credible Test Facility

Test facilities that are used to measure the CBT primarily focus on measuring key flow parameters which occur during the CBT event. Although such experimental data could be collected at many facilities, the time, effort, and resources needed to set up a credible facility are quite significant; therefore, most CBT data come from one of the following facilities:

- Columbia University's Heat Transfer Research Facility (closed in 2003).
- General Electric Company's ATLAS test loop facility in San Jose, CA (closed).
- Stern Laboratories in Hamilton, Ontario (still in use).
- AREVA's KATHY loop in Karlstein, Germany (still in use).
- Westinghouse Electric Corporation's FRIGG and ODEN loops in Västerås, Sweden, for BWRs and PWRs (still in use).

The two subgoals in Figure A-3 are used to demonstrate the credibility of the test facility. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

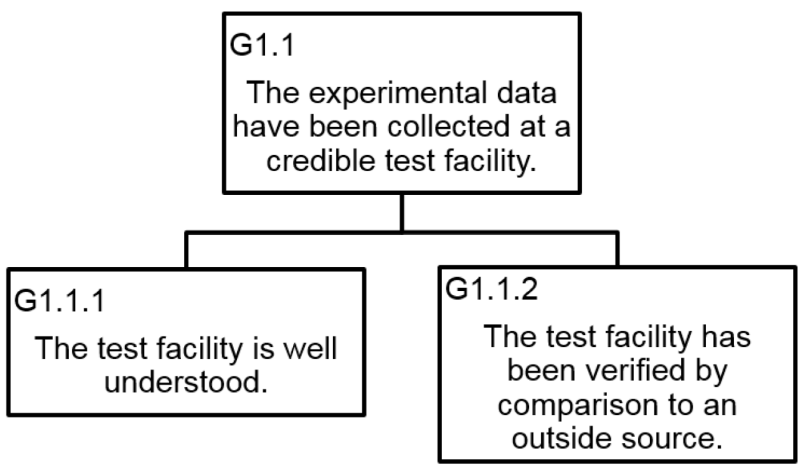

Figure A-3. Decomposition of G1.1—Credible Test Facility

A.3.1.2 G1.2 Accurate Measurements

The test facility should provide accurate measurements of all important experimental parameters, including the measurement of critical heat flux or critical power. It is important to note that the critical heat flux or critical power is not a directly measured parameter (like flow rate or pressure); instead, it is inferred from the power, axial and radial power peaking, and a determination that a CBT has occurred. The six subgoals provided in Figure A-4 are used to demonstrate the accuracy of the measurements. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

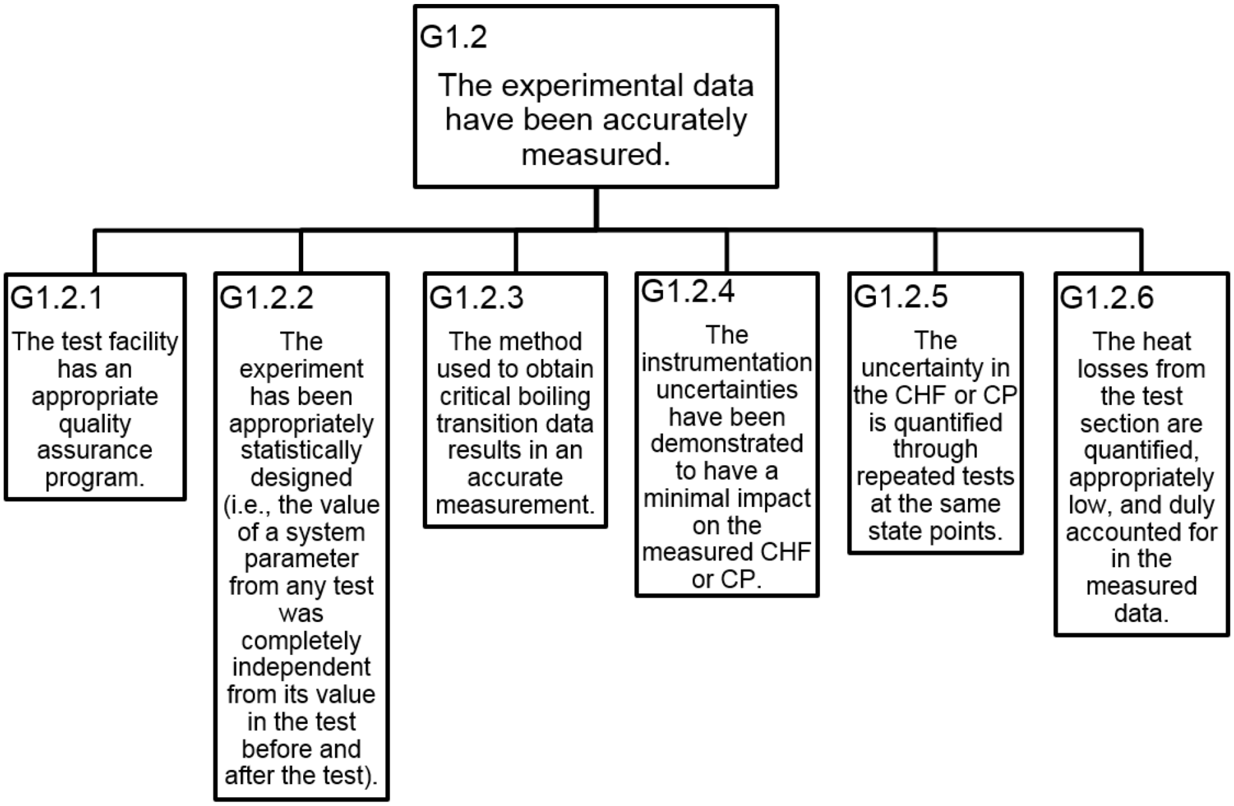

Figure A-4. Decomposition of G1.2—Accurate Measurements

A.3.1.3 G1.3 Reproduction of Local Conditions

The local conditions in the reactor fuel bundle should be reproduced in the test bundle to ensure that experimental data taken in the laboratory apply to the reactor fuel bundle placed in the reactor. The five subgoals in Figure A-5 are used to demonstrate the reproduction of local conditions. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

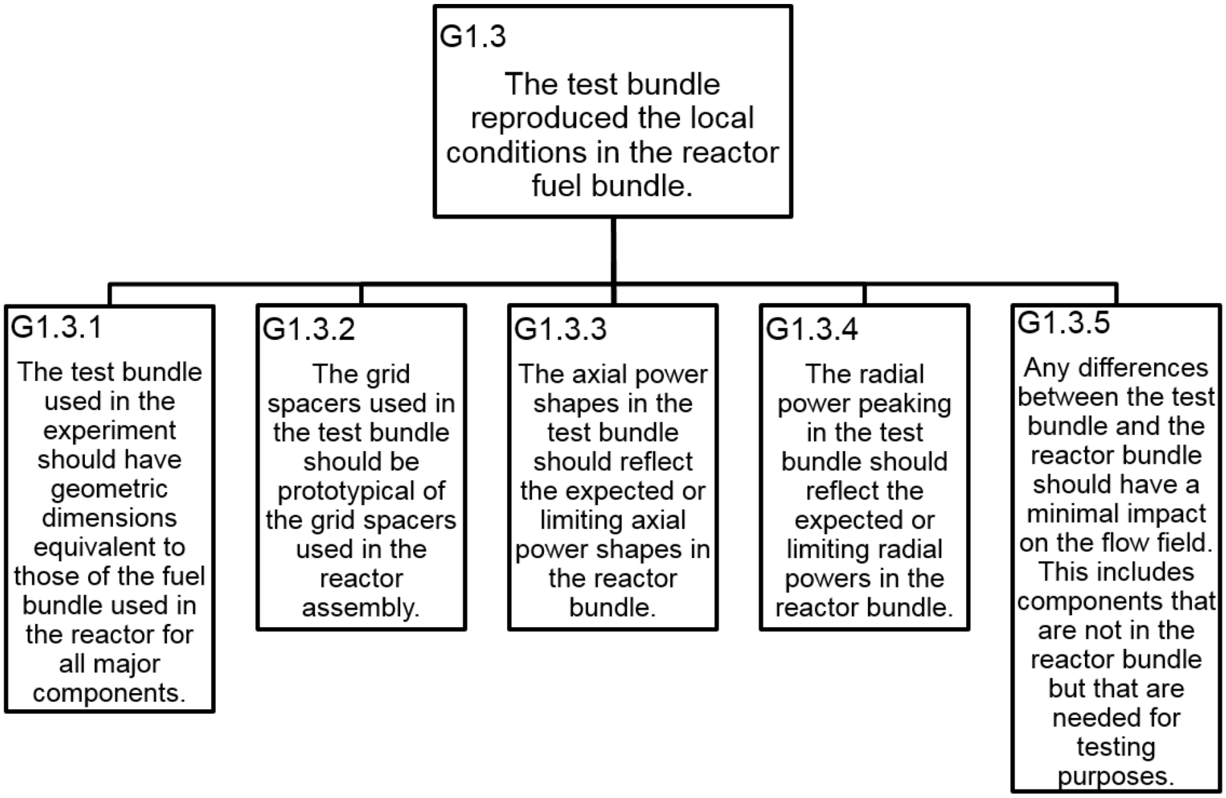

Figure A-5. Decomposition of G1.3—Reproduction of Local Conditions

A.3.2 G2 Model Generation

A CBT model should be generated in a logical fashion. This statement is intentionally broad because the decision to trust the model rests mostly on the validation data.
Although any number of methods could be used to generate a CBT model, understanding what method was used and the reasoning behind that method is helpful. The two subgoals in Figure A-6 are used to demonstrate that the model was generated in a logical fashion.

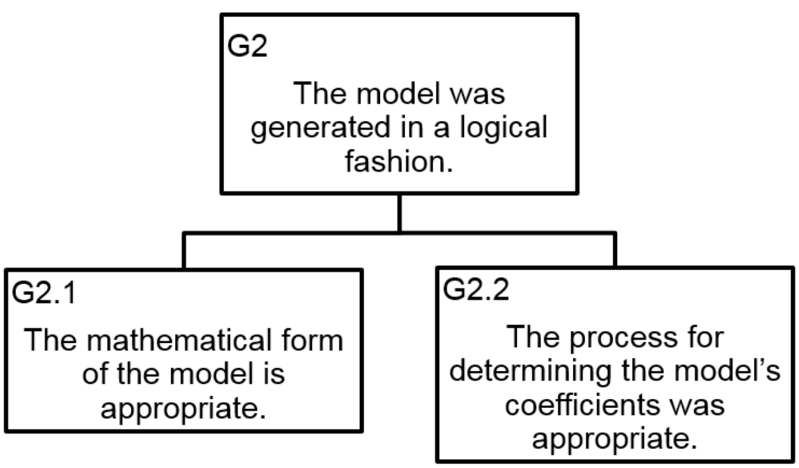

Figure A-6. Decomposition of G2—Model Generation

A.3.2.1 G2.1 The Mathematical Form

The mathematical form of the model should be appropriate in that all relevant parameters appear as variables in the model and the general mathematical behavior of each variable is consistent with known physical behavior. Typically, the mathematical form of the model is chosen based on an organization's past experience. The two subgoals in Figure A-7 are used to demonstrate that the mathematical form of the model is appropriate. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

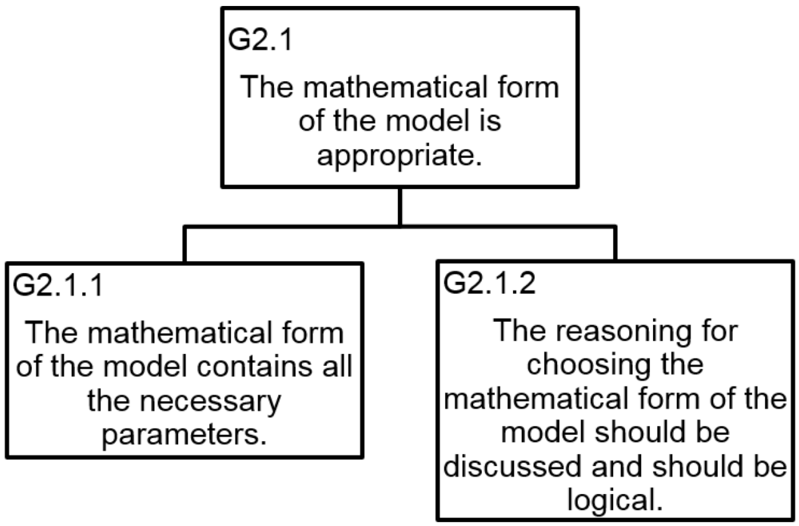

Figure A-7. Decomposition of G2.1—The Mathematical Form

A.3.2.2 G2.2 Method for Determining Coefficients

The process for determining the values of the model's coefficients should be appropriate. Again, as with the choice of the model's mathematical form, the values of the coefficients can be chosen in a number of ways. Although only a single set of the coefficients would result in the lowest error, as judged by some norm (e.g., the Euclidian norm), minimizing this error is often not the most important criteria when determining the coefficient values. Instead, great care is usually taken to ensure that the model reflects appropriate physical behavior rather than simply minimizing the error. Thus, many of the coefficients for a model are chosen to ensure that the model has certain desired trends. The three subgoals in Figure A-8 are used demonstrate that the method for determining the coefficients is appropriate. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

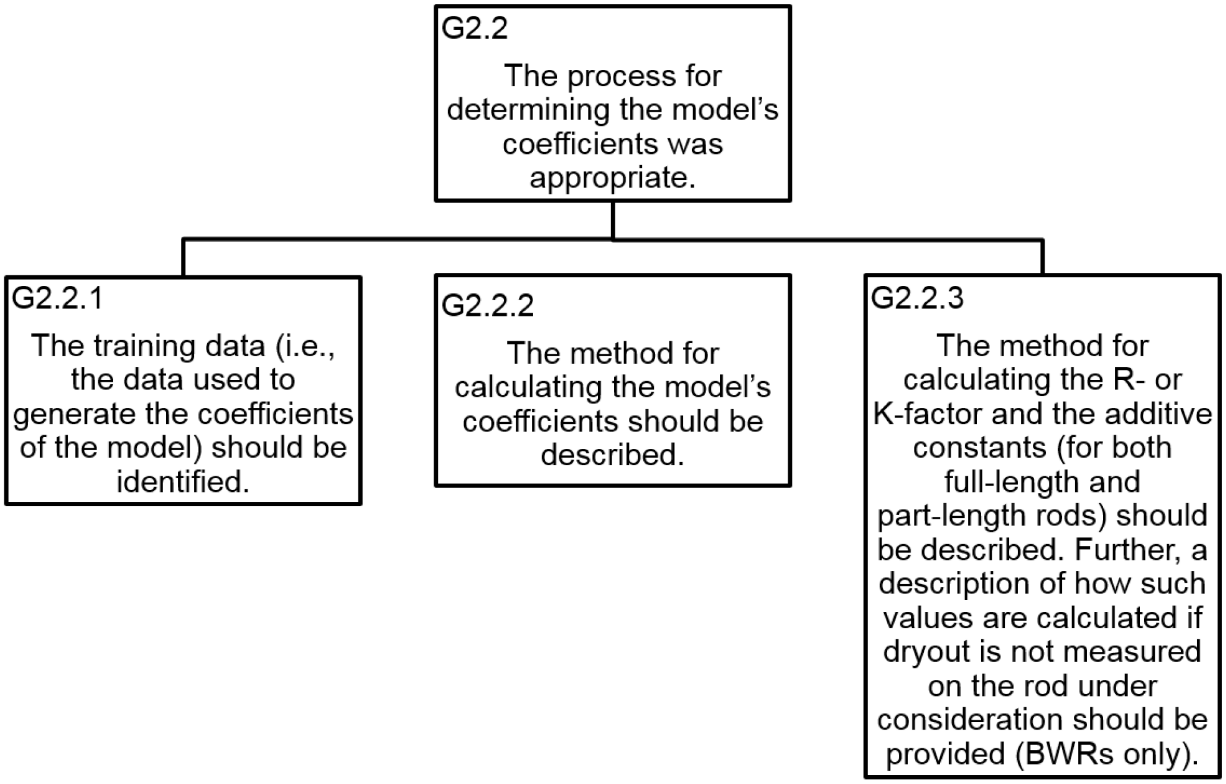

Figure A-8. Decomposition of G2.2—Method for Determining Coefficients

A.3.3 G3 Validation through Error Quantification

Because of the desire to ensure that the model's prediction is conservative, any bias or uncertainty, or both, in the model's prediction of CBT should be adequately quantified such that safety analyses can account for it. This process is uncertainty quantification. The first step in this process is to use the experimental data (i.e., the validation data) along with the model's prediction of that experimental data to calculate the validation error. If the validation error is appropriately distributed through the model's application domain and if any inconsistencies in the validation error are accounted for, statistics from the validation error can be used to determine the model's uncertainty. The five subgoals in Figure A-9 are used to demonstrate that the model has sufficient validation through the quantification of its error.

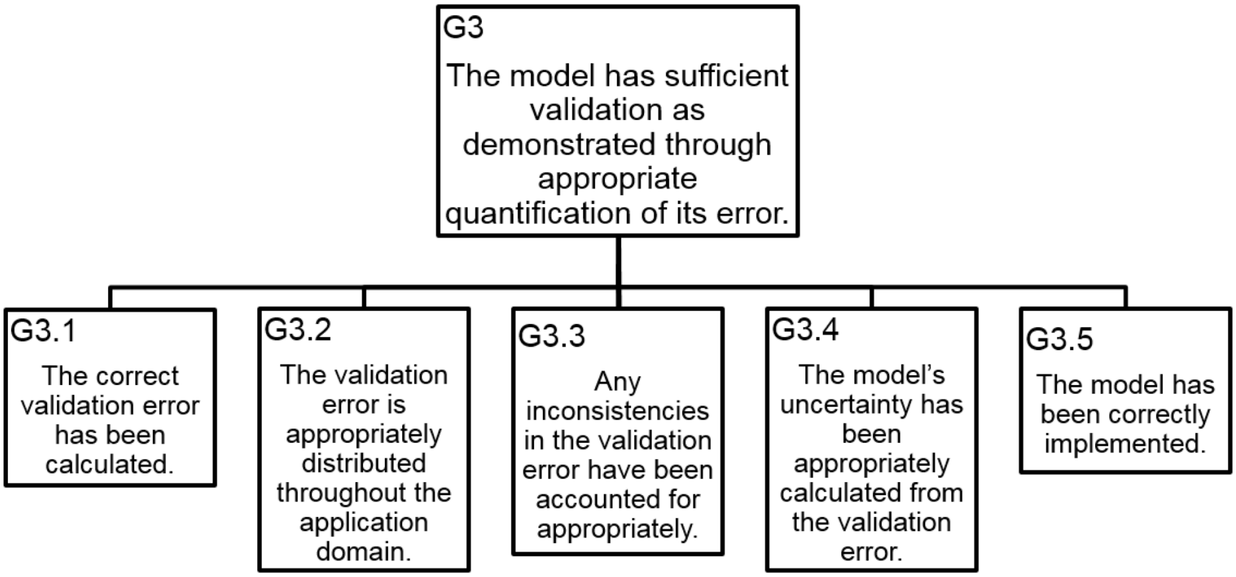

Figure A-9. Decomposition of G3—Validation through Error Quantification

A.3.3.1 G3.1 Calculating Validation Error

Base on prior experience, NRC staff determined that G3.1 can be supported directly by evidence and no further decomposition is necessary.

A.3.3.2 G3.2 Data Distribution in the Application Domain

The validation error data should be appropriately distributed throughout the application domain. The six subgoals in Figure A-10 are used to demonstrate that the validation error is appropriately distributed throughout the application domain. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

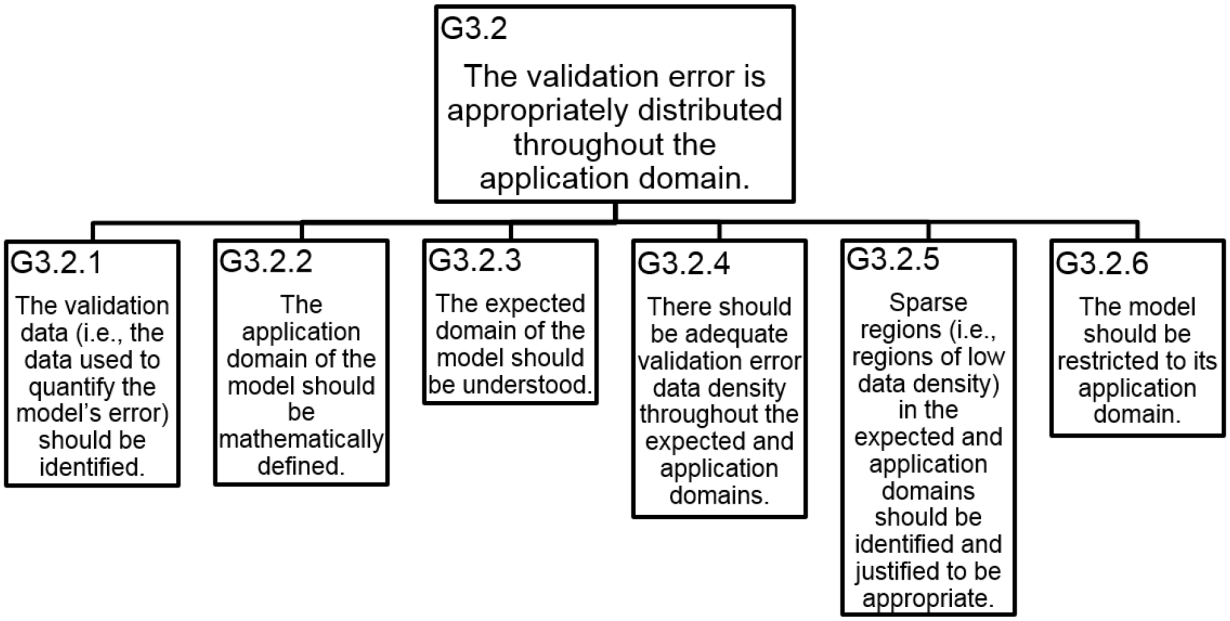

Figure A-10. Decomposition of G3.2—Data Distribution in the Application Domain

A.3.3.3 G3.3 Inconsistency in the Validation Error

Statistics from the validation error is used as estimates of parameters from the population of the model application error in order to quantify the uncertainty of the CBT model. This assumes that the model application error can be described as a single population with the same distribution and parameters (e.g., mean, variance) over the entire application domain and that the validation error is a representative sample of this distribution. The three subgoals in Figure A-11 are used to demonstrate that any inconsistencies in the validation error have been appropriately addressed. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

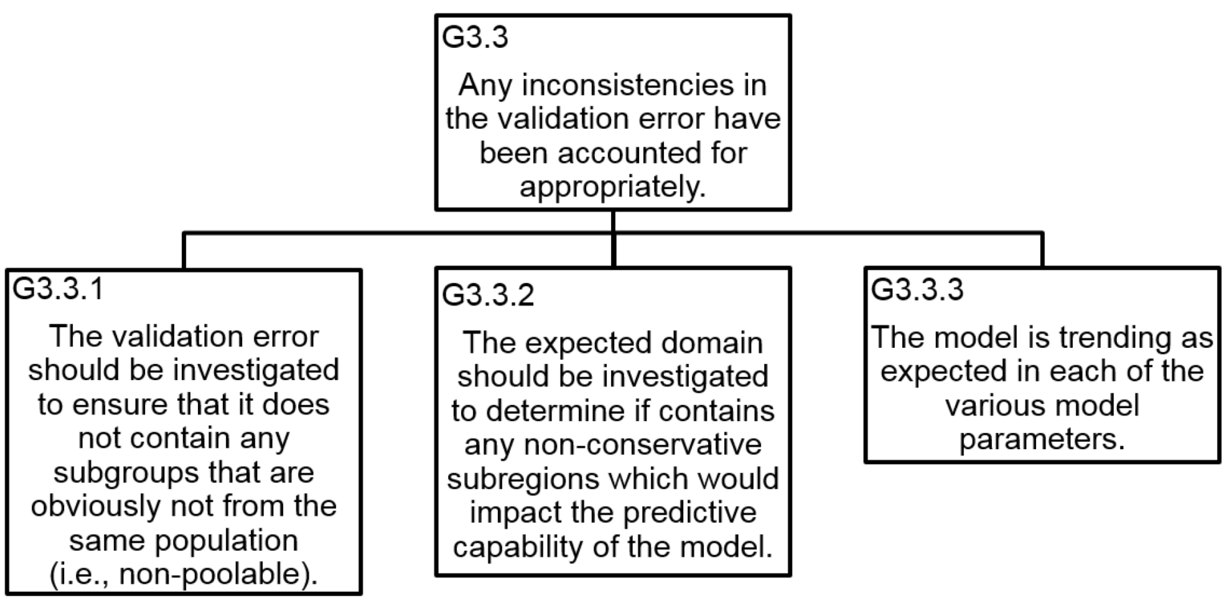

Figure A-11. Decomposition of G3.3—Inconsistencies in the Validation Error

A.3.3.4 G3.4 Calculating Model Uncertainty

The CBT model's uncertainty is quantified using statistics from the validation error as estimates of the parameters of the population of the model application error. Thus, the calculation of those statistics is a major focus and should be appropriate and conservative such that an uncertainty that is greater than or equal to the model's actual application uncertainty is calculated. The three subgoals in Figure A-12 are used to demonstrate that the validation error has been appropriately quantified. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

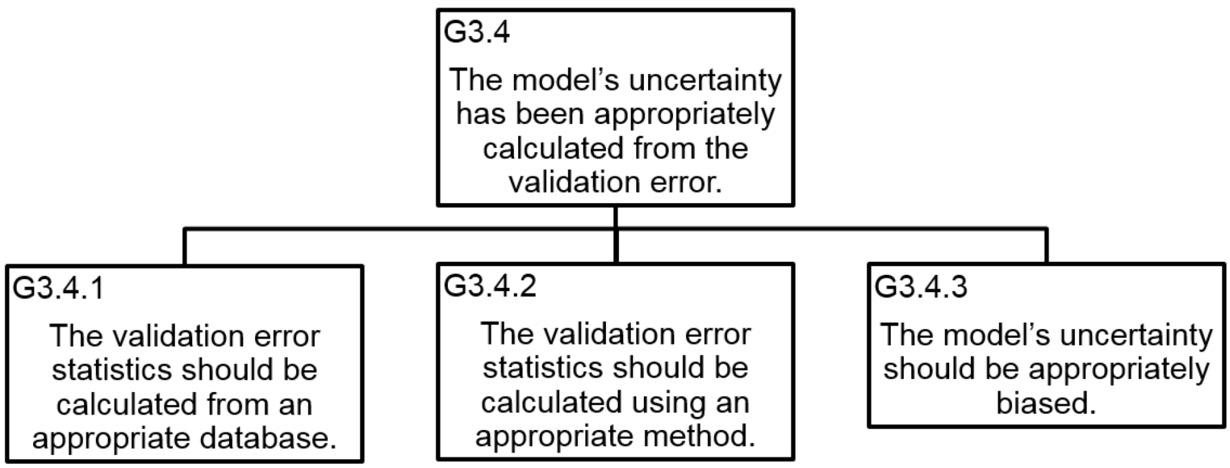

Figure A-12. Decomposition of G3.4—Quantification of the Model's Error

A.3.3.5 G3.5 Model Implementation

Once the model's uncertainty has been quantified by experimental data, the model can be applied in a reactor safety analysis. However, the implementation of the model in the analysis should be consistent with its use during validation. The three subgoals in Figure A-13 are used to demonstrate that the model has been correctly implemented. NRC staff determined, based on prior experience, that this level of decomposition is sufficient, such that each subgoal could be supported directly by evidence.

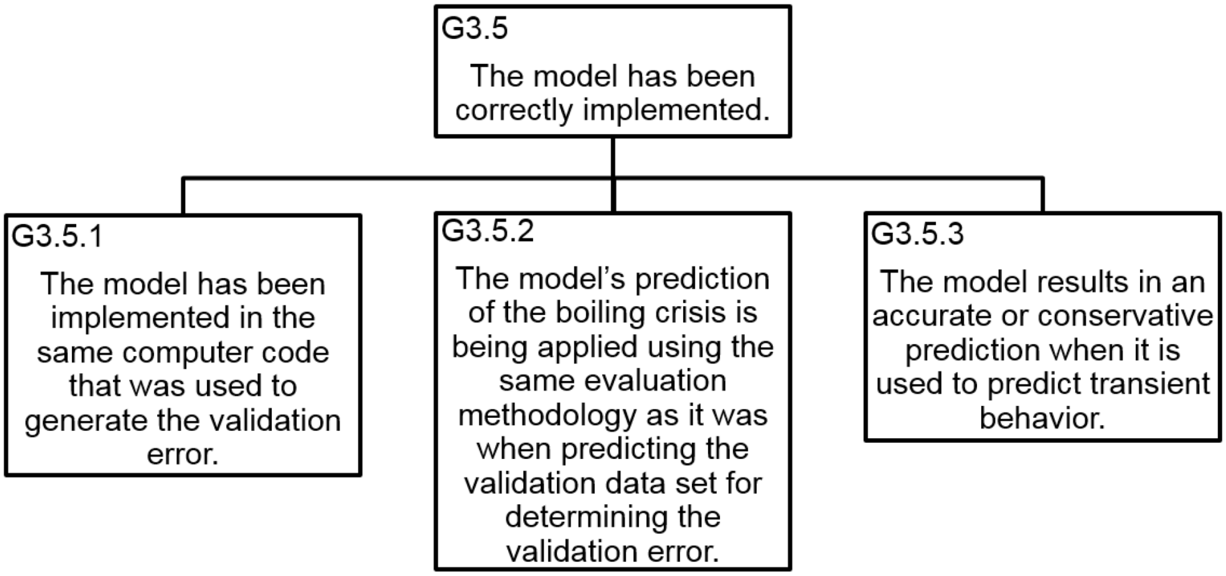

Figure A-13. Decomposition of G3.5—Model Implementation

Section B

NuScale Power Critical Heat Flux Correlations

December 2018

Revision 1

Docket: PROJ0769

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CONTENTS

TABLES

FIGURES

Abstract

The purpose of this report is to provide the bases for Nuclear Regulatory Commission approval to use the NSP2 critical heat flux (CHF) correlation in VIPRE-01, within its range of applicability in Table 8-2, along with its associated correlation limit of 1.17, for the NuScale Power, LLC, Design Certification Application (DCA) and safety analysis of the NuScale Power Module (NPM) with NuFuel-HTP2™ fuel. This report also provides the bases for Nuclear Regulatory Commission approval to use the NSP4 CHF correlation in VIPRE-01, within its range of applicability in Table 8-4 along with its associated correlation limit of 1.21, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel.

These correlations conform to acceptance criteria given by the NuScale Design-Specific Review Standard (DSRS), Section 4.4 (Reference 9.1.3), and the requirements of 10 CFR 50, Appendix A, General Design Criterion (GDC) 10.

This topical report describes the development of the NuScale NSP2 and NSP4 CHF correlations for the NPM. The figure of merit for preventing the occurrence of CHF in the NPM is critical heat flux ratio (CHFR), rather than departure from nucleate boiling ratio that is traditionally used for pressurized water reactor (PWR) applications.

The CHF tests for a preliminary prototypical fuel assembly design for NuScale, performed at Stern Laboratories, Inc. in Ontario, Canada, are used to develop the NSP1 CHF correlation. This preliminary prototypical assembly design uses a different spacer grid design than that used on the NuFuel-HTP2™ fuel design referenced in the NuScale DCA. A set of CHF data from AREVA testing of an assembly design that includes the HMP™ spacer grids used in the NuFuel-HTP2™ design is used to develop an “NSPX factor” for the NSP1 correlation that conservatively predicts NuFuel-HTP2™ CHF performance. The NSP2 CHF correlation is based on the combination of the NSP1 CHF correlation and this NSPX factor and is validated with data from design specific CHF testing for the NuFuel-HTP2™ fuel design performed at AREVA’s Karlstein, Germany, thermal-hydraulic (KATHY) test facility. The NSP4 CHF correlation is developed from the design specific CHF testing for the NuFuel-HTP2™ fuel design performed at AREVA’s Karlstein, Germany, thermal-hydraulic (KATHY) test facility. This report describes the tests, test facilities, statistical methods, NSP1 CHF correlation development, NSPX factor development, and final validation for the NSP2 CHF correlation along with the NSP4 CHF correlation development and validation.

Executive Summary

The purpose of this report is to provide the bases for Nuclear Regulatory Commission approval to use the NSP2 CHF correlation in VIPRE-01, within its range of applicability in Table 8-2, along with its associated correlation limit of 1.17, for the NuScale Design Certification Application (DCA) and safety analysis of the NuScale Power Module (NPM) with NuFuel-HTP2™ fuel. This report also provides the bases for Nuclear Regulatory Commission approval to use the NSP4 CHF correlation in VIPRE-01, within its range of applicability in Table 8-4, along with its associated correlation limit 1.21, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel.

These correlations conform to acceptance criteria given by the NuScale Design-Specific Review Standard (DSRS) and the requirements of 10 CFR 50, Appendix A, General Design Criterion (GDC) 10.

This topical report presents the NSP2 and NSP4 critical heat flux (CHF) correlations developed by NuScale to assess CHF performance for normal operation and anticipated operational occurrences (AOOs) in the NPM with NuFuel-HTP2™ fuel. Described in this report are the tests, test facilities, statistical methods, correlation development process, and resultant NSP2 and NSP4 CHF correlations.

The NPM will use the NuFuel-HTP2™ fuel assembly design for the DCA. This fuel assembly is a half-height, standard 17x17 design that includes AREVA's HMP™ and HTP™ spacer grids. The NSP2 and NSP4 CHF correlations developed within this report are used with this fuel design.

The CHF tests for NuScale were performed at Stern Laboratories, Inc. in Ontario, Canada, and at AREVA's Karlstein, Germany, thermal-hydraulic (KATHY) test facility to obtain steady-state CHF data used in the derivation and validation of the NSP2 CHF correlation. The Stern tests were performed on a preliminary prototypical bundle geometrically comparable to the NuFuel-HTP2™ design, but with generic, simple non-mixing spacer grids rather than the HMP™ and HTP™ spacer grids. The Stern preliminary prototypical bundle tests provide data over wide parameter ranges, which encompass the NPM operating parameter values that are analyzed with the VIPRE-01 code, to develop a NSP1 CHF correlation. A set of existing CHF data for an HMP™ spacer grid (KATHY K8500 HMP™), which is utilized in the NuFuel-HTP2™ design, is used to develop an "NSPX factor" that conservatively predicts the NuFuel-HTP2™ CHF performance. The NSP2 CHF correlation combines the NSP1 CHF correlation and this NSPX factor.

The CHF tests of the reference NuFuel-HTP2™ design were conducted by AREVA at the KATHY test facility (KATHY NuFuel-HTP2™) to provide data used to validate the NSP2 CHF correlation and to develop the NSP4 CHF correlation for the NPM application. Overall, data were obtained from eight separate CHF tests including **[** **]** along with both unit and guide tube layouts. A total of {{ }}$^{2(a),(c)}$ data points are used to develop the NSP1 CHF correlation form, coefficients and NSPX factor while {{ }}$^{2(a),(c)}$ data points are used to validate the NSP2 CHF correlation, and to develop the NSP4 CHF correlation, for NuFuel-HTP2™ fuel. The figure of merit for preventing the occurrence of

CHF in the NPM is critical heat flux ratio (CHFR), rather than departure from nucleate boiling ratio that is traditionally used for pressurized water reactor (PWR) applications. The CHFR is used for consistency in modeling the range of NuScale specific phenomena, and is defined as the ratio of CHF to local heat flux. The NSP2 and NSP4 CHF correlations are empirically based correlations that account for fuel geometry and local fluid conditions, properties, and heat flux. They include a non-uniform flux factor (F-factor) that accommodates variability in axial power profiles in the NPM. The NSP2 CHF correlation conservatively predicts CHF for the Stern preliminary prototypic test data and the KATHY HMP™ and KATHY NuFuel-HTP2™ fuel. The NSP4 CHF correlation adequately predicts CHF for the KATHY NuFuel-HTP2™ fuel. Therefore, the NSP2 and NSP 4 CHF correlations conservatively predict CHF for the NuFuel-HTP2™ application in the NPM, when used in conjunction with the applicable statistically derived correlation limit. Application of a CHFR limit determined with the NSP2 and NSP4 CHF correlations ensures with a 95 percent probability at the 95 percent confidence level (95/95 level), that the hot fuel rod in the core does not experience CHF during normal operation or AOOs in conformance with the acceptance criteria given by the NuScale DSRS, Section 4.4 (Reference 9.1.3). The application of these CHF correlations to safety analysis, including development of safety analysis design limits, application of uncertainties or fuel failure methods, is outside of the scope of this report.

The NSP2 and NSP4 CHF correlations are used in safety analysis evaluations of the NPM using the NuFuel-HTP2™ fuel design with local conditions calculated by the VIPRE-01 subchannel thermal-hydraulic code. Qualification of VIPRE-01 for use in NPM calculations is addressed in the NuScale Subchannel Analysis Methodology topical report (Reference 9.2.3).

1.0 Introduction

1.1 Purpose

This report presents the NSP2 and NSP4 critical heat flux (CHF) correlations that have been developed by NuScale to assess CHF performance for normal operation and anticipated operational occurrences (AOOs) in the NuScale Power Module (NPM) with NuFuel-HTP2™ fuel. This report describes the tests, test facilities, statistical methods, and CHF correlation development process. NuScale requests NRC approval of the NSP2 CHF correlation in VIPRE-01 for NuFuel-HTP2™ fuel, within its range of applicability in Table 8-2, along with its associated correlation limit of 1.17, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel. NuScale also requests NRC approval of the NSP4 CHF correlation in VIPRE-01, within its range of applicability in Table 8-4, along with its associated correlation limit 1.21, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel.

1.2 Scope

This report presents descriptions of the NuScale CHF testing, and the development and validation of the NSP2 and NSP4 CHF correlations. The overall process flow for developing the NSP2 CHF correlation is illustrated in Figure 1-1. The process for developing the NSP4 CHF correlation is simpler, relying only on the NuFuel-HTP2™ CHF test data, as illustrated in Figure 1-2. The facilities and test descriptions are provided in Section 3.1 along with methods for obtaining data. The development of the NSP1 CHF correlation and NSPX factor that make up the NSP2 CHF correlation are presented in Section 4.0 and 5.0, respectively. Development of a {{

}}2(a),(c) is discussed in Section 4.3 for the NSP2 CHF correlation. Validation of the NSP2 CHF correlation with NuFuel-HTP2™ design specific CHF test data is presented in Section 6.0. The development and validation of the NSP4 CHF correlation is presented in Section 7.0

The application of these CHF correlations to safety analysis, including the development of safety analysis design limits, application of uncertainties or fuel failure survey methods, is outside of the scope of this report.

The CHF correlations are based upon local thermal-hydraulic conditions calculated with the VIPRE-01 subchannel thermal-hydraulic code. Qualification of VIPRE-01 for use in NPM calculations is outside of the scope of this report and is addressed in the NuScale Subchannel Analysis Methodology Topical Report (Reference 9.2.3). The two-phase and heat transfer correlations used for deriving local conditions (refer to Section 3.3.1) in this report are consistent with those in Reference 9.2.3. Use of the CHF correlation developed in this report requires consistency with the VIPRE-01 two-phase and heat transfer correlations in Section 3.3.1 of this report and Reference 9.2.3.

{{

}}2(a),(c)

Figure 1-1. NSP2 CHF correlation development flow chart

{{

}}2(a),(c)

Figure 1-2. NSP4 CHF correlation development flow chart

1.3 Abbreviations

Table 1-1. Abbreviations

Term	Definition
AOO	anticipated operational occurrence
BOHL	beginning of heated length
BWR	boiling water reactor
CHF	critical heat flux
CHFR	critical heat flux ratio

Term	Definition
DAS	data acquisition system
DCA	Design Certification Application
DSRS	Design Specific Review Standard
EOHL	end of heated length
F-factor (F_{Tong})	non-uniform flux factor
GDC	General Design Criterion
M/P	measured-to-predicted ratio
NRC	U.S. Nuclear Regulatory Commission
NPM	NuScale Power Module
P/M	predicted-to-measured ratio
PWR	pressurized water reactor
RTD	resistance temperature detectors

Table 1-2. Definitions

Term	Definition
95/95 Level	95% probability at the 95% confidence level
Bartlett Test	The *Bartlett test* is used for testing the homoscedasticity of several populations.
C1	CHF unit test with cosine axial power profile conducted at Stern Laboratories for preliminary prototypical bundle design
Boiling length	{{ }}2(a),(c)
{{ }}2(a),(c)	{{ }}2(a),(c)
D'Agostino (*D'*) Test	The *D'Agostino test*, or *D'* test, tests whether the distribution from which a sample is taken is a normal distribution (Reference 9.2.1, Section 11.10). This test may be used for sample sizes of 50 or more.
Guide Tube Test	Test section where the four central subchannels are surrounded by 3 heated rods and 1 guide tube while the remaining subchannels are surrounded by 4 heated rods except the wall subchannels
K8500	CHF **[ ]** conducted by AREVA
K9000	CHF guide tube test with **[ ]** conducted by AREVA
K9100	CHF unit test with **[ ]** conducted by AREVA
K9200	CHF guide tube test with **[ ]** conducted by AREVA
K9300	CHF **[ ]** conducted by AREVA
KATHY	Areva's Karlstein thermal-hydraulic test facility

Term	Definition
Kruskal-Wallis Test	The *Kruskal-Wallis test* is a non-parametric method for testing whether two or more independent samples of equal or different sizes originate from the same distribution. This test has an underlying assumption of equal variances.
Level of Significance	Level of significance is the acceptable level of risk of rejecting the null hypothesis when the null hypothesis is actually correct.
Median Test	The *Median test* is a non-parametric method for testing whether two or more independent samples of equal or different sizes originate from the same distribution. This test has no assumption of equal variances.
Null Hypothesis	The null hypothesis is a statement describing a populations parameters that can be tested.
NuScale Power Module	The NPM is a self-contained nuclear steam supply system composed of a reactor core, a pressurizer, and two steam generators integrated within the reactor pressure vessel and housed in a compact steel containment vessel.
Parametric and Non-parametric	A distribution (Reference 9.2.1, Section 25.2) is considered parametric if the form of the distribution is known (e.g. belongs to a normal distribution or another with known parameters). If the form of the distribution is not known, and the central limit theorem is not applicable, then the distribution is considered non-parametric.
Population	A population (Reference 9.2.1, Section 1.6) is a collection of measurements made on items defined by some characteristic of the items. At least a single observation (e.g. pressure, mass flux, CHF) is associated with each item (or statistic).
Shapiro-Wilks (*W*) Test	The *Shapiro Wilk test*, or *W-test*, tests whether the distribution from which a sample is taken is a normal distribution (Reference 9.2.1, Section 11.9). This test may be used for sample sizes below 50.
Tolerance Limits	Statistical tolerance limits have the property that a specified percentage of the population is expected to fall within them (Reference 9.2.1, Section 9.12) with a specified confidence.
U1	CHF unit test with uniform axial power profile conducted at Stern Laboratories for preliminary prototypical bundle design.
U2	CHF guide tube test with uniform axial power profile conducted at Stern Laboratories for preliminary prototypical bundle design.
Unit Test	Test section where all of the subchannels are surrounded by four heated rods except the wall subchannels.

2.0 Background

In a pressurized water reactor (PWR), the majority of heat generated in the fuel pellets is conducted through the fuel rod materials to be removed by convective heat transfer to the water coolant. Reactors are designed to operate at a point where this heat transfer to the coolant occurs in either sub-cooled or nucleate boiling conditions, both of which provide efficient means of heat transfer. The condition of the coolant adjacent to the cladding surface may transition to a condition where a continuous vapor layer separates the fuel rod surfaces from the coolant in off-nominal conditions, such as AOOs and postulated accidents. Under these conditions, heat transfer to the coolant is degraded due to the decreased heat transfer coefficient. The rod surface heat flux corresponding to the point of transition to boiling crisis is referred to as the CHF. The reduction in heat transfer to the coolant at these conditions results in an increase in fuel rod temperatures that could challenge fuel rod cladding integrity. A design specific CHF correlation is developed for use in safety analyses of the NPM to assure that this will not occur.

The NPM is a self-contained nuclear steam supply system composed of an integral reactor core, two helical-coil steam generators and pressurizer within the reactor pressure vessel and housed in a compact steel containment. It is designed to operate under natural circulation to provide primary coolant flow, which eliminates the need for reactor coolant pumps. This reactor design results in significantly lower core coolant flow rates than conventional PWR designs, and also operates at a lower system pressure than conventional PWR designs. The NPM relies on the NuFuel-HTP2™ fuel design, which uses AREVA's HTP™ and HMP™ spacer grid technology. Development of a fuel assembly design specific CHF correlation is required to characterize these design and operating conditions and to provide a correlation for analyzing the thermal performance of the NPM.

A CHF correlation is dependent on the fuel assembly design: fuel and guide tube diameters, rod pitch, spacer grid design, spacer grid pitch, etc. It is also dependent on its application: pressures, mass fluxes, inlet subcooling, etc. The CHF is typically predicted with a correlation based on empirical data from design-specific CHF testing that addresses these dependencies. Such testing generally models the fuel designs in full axial scale with a scaled radial lattice (i.e. 5x5 in testing rather than 15x15 or 17x17 in production). The CHF testing is conducted over a wide range of operating conditions, generally encompassing the ranges experienced during normal reactor operation and AOOs.

Initial CHF testing for the NPM at Stern Laboratories was performed on a preliminary prototypical design that was geometrically similar to the NuFuel-HTP2™ design, but was equipped with generic, simple, non-mixing, spacer grids. These tests were performed at fluid conditions appropriate for the NPM and were used to develop the NSP1 CHF correlation. The "NSPX factor" is developed using data from an existing AREVA CHF test using HMP™ spacer grids at fluid conditions appropriate for the NPM, in order to apply the NSP1 correlation to the NuFuel-HTP2™ design while providing conservatism to the CHF predictions. The NSP1 correlation combined with the NSPX factor forms the basis of the NSP2 CHF correlation. Adequacy of the NSP2 CHF correlation is assessed with NuFuel-HTP2™ design specific CHF test data from AREVA's KATHY test facility. The NSP2 CHF correlation is applicable to the NuFuel-HTP2™ fuel design.

A second correlation, the NSP4 CHF correlation, is developed directly from the NuFuel-HTP2™ CHF database and is directly applicable to the NuFuel-HTP2™ fuel design.

2.1 Regulatory Requirements

Failure of nuclear fuel rods must be precluded in accordance with 10 CFR 50, Appendix A, GDC 10 (Reference 9.1.1).

Specified acceptable fuel design limits based on CHF conditions are established to prevent degradation of heat transfer from the fuel rod surface, which could cause an increase in temperatures that may ultimately lead to the failure of the fuel rod cladding. As discussed above, the NPM design is required to assure that these limits are not exceeded during normal operation or AOOs.

The NuScale Design Specific Review Standard (DSRS) (Reference 9.1.3), Section 4.4, provides specific criteria necessary to meet the requirements of GDC 10. For CHF correlations, there should be a 95-percent probability at the 95-percent confidence level (95/95 level) that the hot rod in the core does not experience a boiling crisis during normal operation or AOOs.

2.2 NuScale Power Module Fuel Assembly Design

The NPM uses the NuFuel-HTP2™ fuel assembly, illustrated in Figure 2-1, which includes AREVA's HMP™ and HTP™ spacer grids. The spacer grids, illustrated in Figure 2-2 and Figure 2-3, are located axially at locations indicated in Table 2-1. Principle fuel assembly parameters are tabulated in Table 2-1.

Table 2-1. NuFuel-HTP2™ fuel assembly parameters

Parameter	Value
Fuel assembly layout	17 x 17
Fuel rod outer diameter	0.374 in.
Fuel rod pitch	0.496 in.
Guide tube outer diameter	0.482 in.
Number of fuel rods per bundle	264
Number of guide tubes per bundle	24
Number of instrument tubes per bundle	1
Length of total active fuel stack	78.74 in.
Grid spacer height	1.750 in.
Axial spacing from bottom of heated length to centerline of grid spacer	{{ }}2(a),(c),ECI {{ }}2(a),(c),ECI {{ }}2(a),(c),ECI {{ }}2(a),(c),ECI {{ }}2(a),(c),ECI

[1] Note that {{ }}2(a),(c)

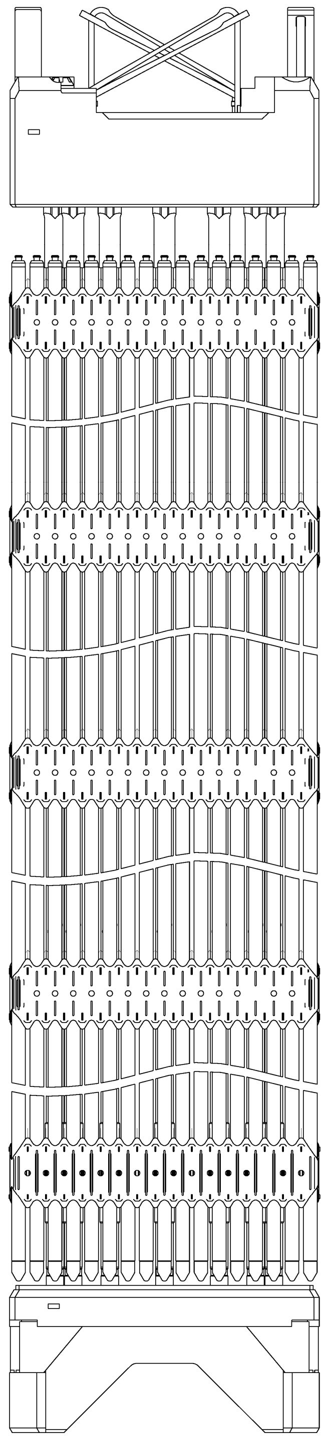

Figure 2-1. NuFuel-HTP2™ fuel assembly

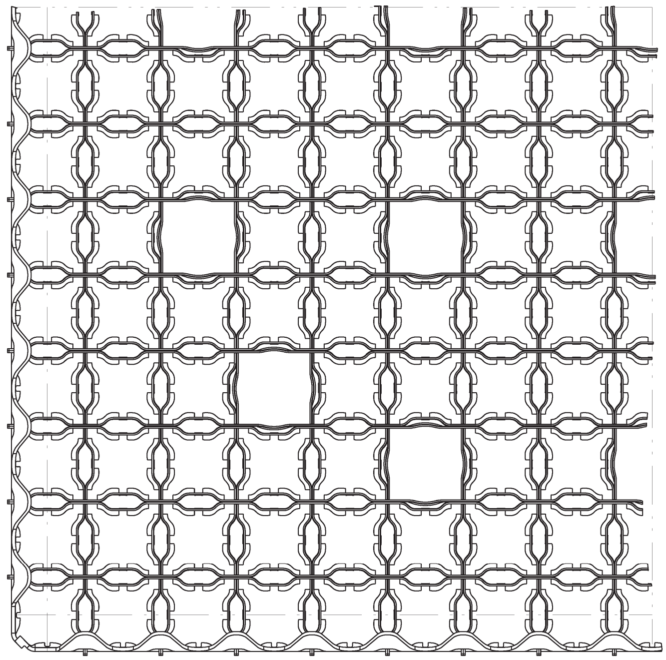

Figure 2-2. HMP™ spacer grid ($^{1}/_{4}$ of grid shown)

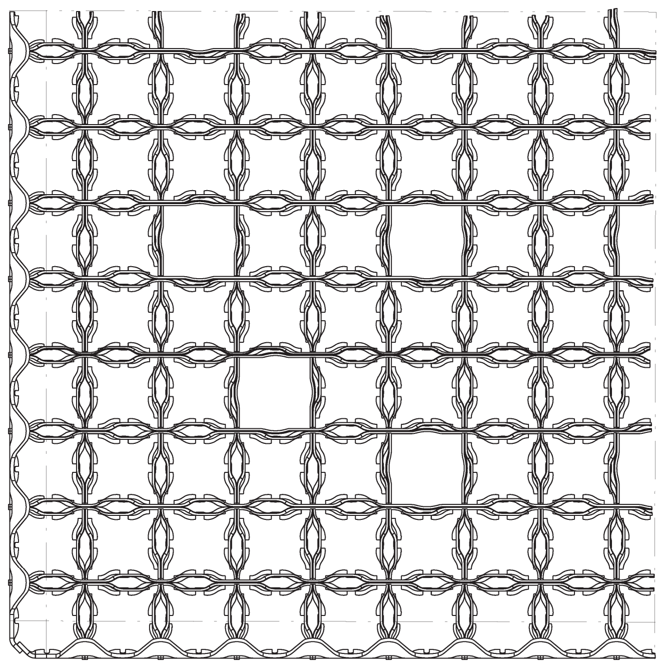

Figure 2-3. HTP™ spacer grid ($^{1}/_{4}$ of grid shown)

3.0 Analysis and Experimentation

3.1 Data Sources

3.1.1 Stern Laboratories

The CHF testing was performed on a preliminary prototypical design for NuScale by Stern Laboratories in Ontario, Canada, between September 2012 and March 2013. Three tests, referenced as U1, U2, and C1, were performed. The U1 test is a unit test with uniform axial power profile. The U2 test is a guide tube test with uniform axial power. The C1 test is a unit test with a symmetric cosine axial power profile. These tests are discussed in the NuScale Critical Heat Flux Test Program Technical Report (Reference 9.2.2). The following sections describe the test section, the test loop, and the instrumentation utilized in the test campaign. The test matrix corresponding to the tests performed at Stern Laboratories for the test campaign is tabulated in Table 3-1.

Table 3-1. Stern preliminary prototypical test matrix

{{

}}2(a),(c)

{{

}}2(a),(c)

3.1.1.1 Stern Preliminary Prototypic Test Section

The test section, illustrated schematically in Figure 3-1, consists of pressure housing, flow channel of square cross section, the fuel simulation, and instrumentation. The fuel simulation is a 5x5 array of electrically heated rods with parameters described in Table 3-2. The pressure housing is designed for 20.8 MPa (3017 psia) and 371 degrees Celsius (700 degrees Fahrenheit). The pressure housing is 125.197 in. long and has re-entrant geometries at the inlet and outlet of the test section to provide calming regions to minimize potential flow maldistribution. The simulated fuel rods are fastened in a manner that allows for thermal expansion. The flow channel design allows for thermal expansion and reduces mixing of the main flow stream with the water in the annulus formed between the flow channel and the pressure housing.

The fuel simulation uses twenty-five fuel simulators (or twenty-four plus a central unheated tube in guide tube tests) assembled into a 5x5 square array with rods positioned using spacer grids. The spacer grids, illustrated in Figure 3-2 and Figure 3-3, are located axially at locations indicated in Table 3-2. The axial positioning of the grid spacers, illustrated in Figure 3-1, indicates that the distance between grid spacers varies between 20.0 and 20.5 in. The indirectly heated fuel simulators in the U1 and U2 test series have a uniform axial power distribution while those in the C1 test series have a symmetric cosine axial power distribution. The symmetric cosine power distribution is defined by:

{{

}}2(a),(c)

where,

{{ }}2(a),(c)

{{ }}2(a),(c)

{{ }}2(a),(c)

z = axial location relative to the beginning of the heated length, in.

HL = heated length, in.

The radial peaking distribution for the U1, C1, and U2 tests are illustrated in Figure 3-4 and Figure 3-5.

Table 3-2. Stern Laboratories test section physical parameters

Parameter	U1	U2	C1
Flow channel width	{{ }}2(a),(c)		
Fuel simulator diameter	0.374 in.		
Guide tube diameter	-	0.482 in.	-
Grid heater rod pitch	0.496 in.		
Heated length	78.740 in.		
Axial power distribution	Uniform	Uniform	Cosine
Grid spacer height	2.500 in.		
Axial spacing from BOHL to bottom of grid spacer[2]	Grid #1: {{ }}2(a),(c) Grid #2: {{ }}2(a),(c) Grid #3: {{ }}2(a),(c) Grid #4: {{ }}2(a),(c) Grid #5: {{ }}2(a),(c)		
{{ }}2(a),(c)	{{ }}2(a),(c) {{ }}2(a),(c) {{ }}2(a),(c) {{ }}2(a),(c) {{ }}2(a),(c)		

Note: All dimensions are cold dimensions. Use of cold dimensions is consistent with subchannel analysis methods using VIPRE-01 in Reference 9.2.3.

[2] Note that {{ }}2(a),(c)

{{

}}2(a),(c)

Figure 3-1. Stern Laboratories test section axial schematic

{{

}}2(a),(c)

Figure 3-2. Stern Laboratories U1 and C1 grid spacer

{{

}}2(a),(c)

Figure 3-3. Stern Laboratories U2 grid spacer

{{

}}2(a),(c)

Figure 3-4. Stern Laboratories U1 and C1 test radial schematic

{{

}}2(a),(c)

Figure 3-5. Stern Laboratories U2 test radial schematic

3.1.1.2 Stern Laboratories Test Loop

The Stern Laboratories test facility is used for collecting thermal-hydraulic test data for pressurized water and boiling water reactors. The test loop schematic is illustrated in Figure 3-6.

The Stern Laboratories loop design pressure and temperature are 208 bar (3017 psia) and 371 degrees Celsius (700 degrees Fahrenheit), respectively. Loop coolant circulation flow is provided by a high-head, high-capacity pump with flow adjusted by control valves at the inlet to the test section. The pressure is maintained at the test section outlet (downstream end of heated length) using a pressurizer.

The Stern Laboratories test loop's electric power supply has a maximum power of approximately 16.75 MW (five 2500 kW, three 1000 kW, and five 250 kW power supplies). Three of the 2500 kW power supplies can be used in reversed polarity to minimize the magnetic forces due to electric current. The power supplies are low ripple, twelve pulse design and employ current feedback for stable control.

{{

}}2(a),(c)

Note: Figure provided for illustration purposes only. Illegible text is not pertinent.

Figure 3-6. Stern Laboratories PWR test loop schematic

3.1.1.3 Stern Laboratories Instrumentation and Data Acquisition System

The test section and loop are instrumented to measure power, flow rates, absolute pressures, differential pressures, and coolant and fuel simulator temperatures during testing. Pressure transmitters are used to measure absolute and differential pressures. Pressure taps are installed {{ }}2(a),(c). Resistance temperature detectors (RTDs) are used to measure {{ }}2(a),(c) of the test section. Thermal wells are installed into the piping for the RTDs to measure the coolant temperature. The flow rate is measured using {{ }}2(a),(c). The flow, pressure, differential pressure, and temperature measurement devices used during the experiments were in current calibration.

The fuel simulators are instrumented with {{ }}2(a),(c). The axial locations of the {{ }}2(a),(c) are illustrated in Figure 3-1. The {{ }}2(a),(c) for each test series are illustrated in Figure 3-7 and Figure 3-8.

{{ }}2(a),(c) during the thermal mixing tests. The identification and location of the {{ }}2(a),(c) for each test series are illustrated in Figure 3-9 and Figure 3-10.

Current and voltage transducers are used to measure the amperage and voltage {{ }}2(a),(c). These measurements are used to calculate the actual fuel simulator power and peaking factors.

The laboratory data acquisition system (DAS) is used to scan the instruments and convert the signals to engineering units and perform various calculations. A list of the DAS measurements and calculations and their associated uncertainties are tabulated in Table 3-3. The instrument signals are scanned continuously at the rate of 10 Hz per channel and selected channels are displayed on video monitors. For steady-state tests, signals are recorded for a period of 30 seconds and the averages are calculated in engineering units. For critical power tests, when the operator initiates a data recording event, a 20 second pre-event data buffer and a 20 second post-event data recording are stored. If the power control program initiates a power step down due to a {{ }}2(a),(c) the data are automatically stored by the DAS in the same manner as the critical power data recording.

The data acquisition program continuously scans the {{ }}2(a),(c) and utilizes various software algorithms and graphical techniques to ensure that the first occurrence of CHF is detected.

A calculated {{ }}2(a),(c) is used for predicting the occurrence of CHF. Routinely during testing, a user-initiated software procedure (normalization) estimates {{ }}2(a),(c). Using the {{ }}2(a),(c) ensures a discernible and consistent CHF criterion is applied. Following the normalization procedure described above just prior to CHF, the {{ }}2(a),(c) throughout a given axial plane of the fuel simulation are all within {{ }}2(a),(c) of each other. At the onset of CHF, when the heat transfer coefficient intermittently begins to deteriorate, small perturbations {{ }}2(a),(c) are observed. As the power is increased {{ }}2(a),(c) as the mechanism of heat transfer approaches film boiling. The CHF criterion is met when any of the {{ }}2(a),(c), which experience has shown to be sufficient to differentiate from noise and still below the boiling crisis when rapid excursions occur.

Heat balance tests were performed to check the consistency of the primary measurements and assure that the test equipment was operating within the expected parameters. The heat balance is expressed in terms of heat loss and was typically less than {{ }}2(a),(c). Therefore, for development of the NSP1 CHF correlation these heat losses are ignored.

Table 3-3. Stern Laboratories DAS variables and uncertainties

Measurement / Calculation	Units	Method	Uncertainty
Test section inlet temperature	°C	{{ }}2(a),(c)	{{ }}2(a),(c)
Test section outlet pressure	kPa	{{ }}2(a),(c)	{{ }}2(a),(c)
Test section mass flux	kg/s-m^2	{{ }}2(a),(c)	{{ }}2(a),(c)
Total measured power	kW	{{ }}2(a),(c)	{{ }}2(a),(c)

{{

}}2(a),(c)

Figure 3-7. Stern preliminary prototypic U1 and U2 test sections thermocouple layout

{{

}}2(a),(c)

Figure 3-8. Stern preliminary prototypic C1 test section thermocouple layout

{{

}}2(a),(c)

Figure 3-9. Stern preliminary prototypic U1 and C1 thermal mixing thermocouples

{{

}}2(a),(c)

Figure 3-10. Stern preliminary prototypic U2 thermal mixing thermocouples

3.1.2 AREVA

AREVA provided NuScale with CHF data from testing at the KATHY test facility in Karlstein, Germany. Data are provided for the HMP™ spacer grid design from the KATHY K8500 test **[** **]** conducted in December of 2014. The test assembly has similar geometry to that of the NuFuel-HTP2™ fuel design {{ }}2(a),(c),ECI and thermal-hydraulic conditions that fall within the range of pressure and mass flux tested for the Stern preliminary prototypical bundle. The KATHY K8500 HMP™ test provides representative data to assess the NSP1 CHF correlation for the NuFuel-HTP2™ fuel design and develop the NSPX factor (refer to Section 5.2). While the KATHY K8500 HMP™ test data are based on HMP™ spacer grids and the NuFuel-HTP2™ design relies on both HMP™ and HTP™ spacer grids, the data are considered applicable because at low flows, such as those of the NPM, any mixing benefits provided by the HTP™ design decrease.

Testing of the reference NuFuel-HTP2™ fuel design was performed by AREVA at the KATHY test facility between March and July of 2016. Four tests, referenced as K9000, K9100, K9200, and K9300, were performed during this campaign.

- K9000 is a guide tube test with **[** **]**
- K9100 is a unit test with uniform **[** **]**
- K9200 is a guide tube test with a **[** **]**
- K9300 is a unit test with a symmetric **[** **]**

The test matrix performed for the KATHY NuFuel-HTP2™ tests is tabulated in Table 3-4. Unlike testing for the Stern preliminary prototypical design, data (refer to Table 3-1) are not taken at every statepoint in the test matrix for each of the tests. Instead, data points are spread out among the four tests. In the end each statepoint is covered by at least one test. The test matrix is designed so that there is overlap between **[** **]** tests, allowing for {{ }}2(a),(c). There is also overlap between guide tube and unit tests.

Table 3-4. Test matrix for KATHY NuFuel-HTP2™ testing

{{

}}2(a),(b),(c)

3.1.2.1 KATHY K8500 HMP™ Test Section

The KATHY K8500 HMP™ test section is comprised of twenty-five fuel simulators assembled into a 5x5 square array with HMP™ spacer grids. The spacer grids are located axially at locations indicated in Table 3-5. {{

}}2(a),(c). The number and locations of the spacer grids are tabulated in Table 3-5 and illustrated in Figure 3-11. The fuel simulators in the KATHY K8500 HMP™ test have a **[ ]**. The radial power distribution is illustrated in Figure 3-11. The number and location of the **[ ]** are also tabulated in Table 3-5 and illustrated in Figure 3-11.

Table 3-5. KATHY K8500 HMP™ test section physical parameters

Parameter	Value
Flow channel width	**[ ]**
Fuel simulator diameter	**[ ]**
Grid heater rod pitch	**[ ]**
Heated length	**[ ]**
Axial power distribution	**[ ]**
Grid spacer height	**[ ]**
Axial spacing from BOHL to bottom of HMP™ spacer grid[3]	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]** Grid #5: **[ ]**
Axial spacing from BOHL to bottom of support grid	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]**
[ ]	**[ ]** **[ ]** **[ ]** **[ ]** **[ ]** **[ ]** **[ ]**

[3] Only spacer grids {{ }}2(a),(c) are modeled in VIPRE-01

[

]

Figure 3-11. KATHY K8500 HMP™ test section schematic

3.1.2.2 KATHY NuFuel-HTP2™ K9000 Test Section

The K9000 test section represents the NuFuel-HTP2™ fuel design and is comprised of twenty-four fuel simulators and a central guide tube assembled into a 5x5 square array with HMP™ and HTP™ spacer grids. The spacer grids are located axially at locations indicated in Table 3-6. {{ }}2(a),(c). The number and locations of the spacer grids are tabulated in Table 3-6 and illustrated in Figure 3-12. The fuel simulators in the K9000 test have a **[ ]**. The radial power distribution is illustrated in Figure 3-12. The number and location of the **[ ]** are also tabulated in Table 3-6 and illustrated in Figure 3-12.

Table 3-6. KATHY NuFuel-HTP2™ K9000 test section physical parameters

Parameter	Value
Flow channel width	**[ ]**
Fuel simulator diameter	0.374 in.
Guide tube diameter	0.482 in.
Grid heater rod pitch	0.496 in.
Heated length	78.740 in.
Axial power distribution	**[ ]**
HTP™ spacer grid height	1.750 in.
HMP™ spacer grid height	1.750 in.
{{ }}2(a),(c),ECI	**[ ]**
Axial spacing from BOHL to bottom of HTP™ grid spacer[4]	Grid #1: {{ }}2(a),(c) Grid #2: {{ }}2(a),(c) Grid #3: {{ }}2(a),(c)
Axial spacing from BOHL to bottom of support grid	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]**
[ ]	**[ ]** **[ ]** **[ ]** **[ ]**

[4] Only spacer grids {{ }}2(a),(c) are modeled in VIPRE-01

[

]

Figure 3-12. KATHY NuFuel-HTP2™ K9000 test section schematic

3.1.2.3 KATHY NuFuel-HTP2™ K9100 Test Section

The K9100 test section represents the NuFuel-HTP2™ fuel design and is comprised of twenty-five fuel simulators assembled into a 5x5 square array with HMP™ and HTP™ spacer grids. The spacer grids are located axially at locations indicated in Table 3-7. As with other KATHY tests, {{ }}2(a),(c). The number and locations of the spacer grids are tabulated in Table 3-7 and illustrated in Figure 3-13. The fuel simulators in the K9100 test have a **[ ]**. The radial power distribution is illustrated in Figure 3-13. The number and location of the **[ ]** are also tabulated in Table 3-7 and illustrated in Figure 3-13.

Table 3-7. KATHY NuFuel-HTP2™ K9100 test section physical parameters

Parameter	**Nominal Value**
Flow channel width	**[ ]**
Fuel simulator diameter	0.374 in.
Grid heater rod pitch	0.496 in.
Heated length	78.740 in.
Axial power distribution	**[ ]**
HTP™ spacer grid height	1.750 in.
HMP™ spacer grid height	1.750 in.
{{ }}2(a),(c),ECI	**[ ]**
Axial spacing from BOHL to bottom of HTP™ grid spacer[5]	Grid #1: {{ }}2(a),(c) Grid #2: {{ }}2(a),(c) Grid #3: {{ }}2(a),(c)
Axial spacing from BOHL to bottom of support grid	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]**
[ ]	**[ ]** **[ ]** **[ ]** **[ ]**

[5] Only spacer grids {{ }}2(a),(c) are modeled in VIPRE-01

[

]

Figure 3-13. KATHY NuFuel-HTP2™ K9100 test section schematic

3.1.2.4 KATHY NuFuel-HTP2™ K9200 Test Section

The K9200 test section represents the NuFuel-HTP2™ fuel design and is comprised of twenty-four fuel simulators and a central guide tube assembled into a 5x5 square array with HMP™ and HTP™ spacer grids. The spacer grids are located axially at locations indicated in Table 3-8. As with other KATHY tests, {{ }}[2(a),(c)]. The number and locations of the spacer grids are tabulated in Table 3-8 and illustrated in Figure 3-14. The fuel simulators in the K9200 test have a **[ ]**, which is described in Table 3-9. The radial power distribution is illustrated in Figure 3-14. The number and location of the **[ ]** are also tabulated in Table 3-8 and illustrated in Figure 3-14.

Table 3-8. KATHY NuFuel-HTP2™ K9200 test section physical parameters

Parameter	Value
Flow channel width	**[ ]**
Fuel simulator diameter	0.374 in.
Guide tube diameter	0.482 in.
Grid heater rod pitch	0.496 in.
Heated length	78.740 in.
Axial power distribution	**[ ]**
HTP™ spacer grid height	1.750 in.
HMP™ spacer grid height	1.750 in.
{{ }}[2(a),(c),ECI]	**[ ]**
Axial spacing from BOHL to bottom of HTP™ grid spacer[6]	Grid #1: {{ }}[2(a),(c)] Grid #2: {{ }}[2(a),(c)] Grid #3: {{ }}[2(a),(c)] Grid #4: {{ }}[2(a),(c)]
Axial spacing from BOHL to bottom of support grid	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]**
[ ]	**[ ]** **[ ]** **[ ]** **[ ]** **[ ]** **[ ]**

[6] Only spacer grids {{ }}[2(a),(c)] are modeled in VIPRE-01

Table 3-9. KATHY NuFuel-HTP2™ K9200 axial power profile

[

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[

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Figure 3-14. KATHY NuFuel-HTP2™ K9200 test section schematic

3.1.2.5 KATHY NuFuel-HTP2™ K9300 Test Section

The K9300 test section represents the NuFuel-HTP2™ fuel design and is comprised of twenty-five fuel simulators assembled into a 5x5 square array with HMP™ and HTP™ spacer grids. The spacer grids are located axially at locations indicated in Table 3-10. As with other KATHY tests, {{ }}2(a),(c). The number and locations of the spacer grids are tabulated in Table 3-10 and illustrated in Figure 3-15. The fuel simulators in the K9300 test have a **[ ]**, which is described in Table 3-9. The radial power distribution is illustrated in Figure 3-15. The number and location of the **[ ]** are also tabulated in Table 3-10 and illustrated in Figure 3-15.

Table 3-10. KATHY NuFuel-HTP2™ K9300 test section physical parameters

Parameter	**Value**
Flow channel width	**[ ]**
Fuel simulator diameter	0.374 in.
Grid heater rod pitch	0.496 in.
Heated length	78.740 in.
Axial power distribution	**[ ]**
HTP™ spacer grid height	1.750 in.
HMP™ spacer grid height	1.750 in.
{{ }}2(a),(c),ECI	**[ ]**
Axial spacing from BOHL to bottom of HTP™ grid spacer[7]	Grid #1: {{ }}2(a),(c) Grid #2: {{ }}2(a),(c) Grid #3: {{ }}2(a),(c) Grid #4: {{ }}2(a),(c)
Axial spacing from BOHL to bottom of support grid	Grid #1: **[ ]** Grid #2: **[ ]** Grid #3: **[ ]** Grid #4: **[ ]**
[ ]	**[ ]** **[ ]** **[ ]** **[ ]** **[ ]** **[ ]**

[7] Only spacer grids {{ }}2(a),(c) are modeled in VIPRE-01

[

]

Figure 3-15. KATHY NuFuel-HTP2™ K9300 test section schematic

3.1.2.6 AREVA Test Loop

The AREVA KATHY test facility, has been in operation since 1986 and can be used for a variety of thermal-hydraulic tests for pressurized water and boiling water reactors. The KATHY test loop is illustrated in Figure 3-16 and its design conditions are tabulated in Table 3-11. The PWR test loop is utilized for the NuFuel-HTP2™ CHF tests.

The KATHY loop's 300 kW pressurizer has a volume of 1.0 m^3 and a design pressure and temperature consistent with the test vessel. The circulation pump has a design maximum pressure of 210 bar (3046 psia) and a design maximum temperature of 370 degrees Celsius (698 degrees Fahrenheit). The loop's electric power supply has a maximum (gross) power of 20 MW and a maximum current of 80 kA at 230V.

[

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Table 3-11. KATHY loop design conditions

Parameter	Value
Design pressure	185 bar (2683 psia)
Design temperature	360 °C (680 °F)

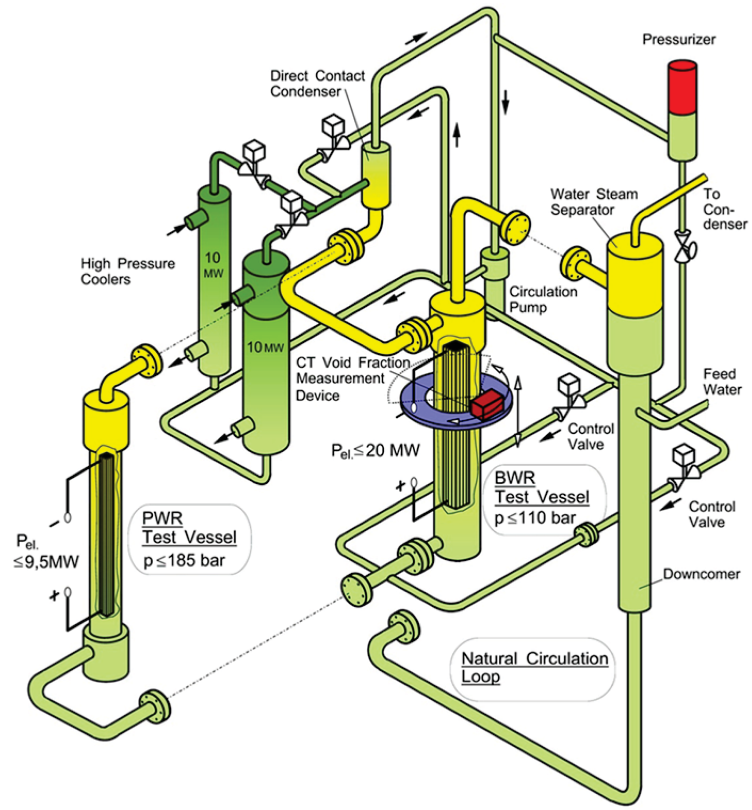

Figure 3-16. AREVA's KATHY facility layout

3.1.2.7 AREVA Instrumentation and Data Acquisition System

The test section and loop are instrumented to measure power, flow rates, absolute pressures, and coolant and fuel simulator temperatures during testing. System pressure is measured by two pressure transducers at the outlet of the test section (flow channel). The inlet temperature is measured at the test vessel inlet by two independent, calibrated RTDs. The outlet temperature is measured by three RTDs. The flow is determined using the measured pressure drop across the orifices using a pressure transducer. All measurement devices used during the experiments were in current calibration.

[

]. The installed heater rod thermocouples are checked for acceptable operation prior to the heater rod installation into the test bundle.

Two independent and diverse methods are applied to measure the electric current through the test bundle: the first is based on the Faraday effect and, the second is based on four high precision fast response shunts. At least one heater rod is equipped with voltage taps across the heated length. This measurement is used to determine the electric power to the test bundle. The voltage between the busbars is also measured as a backup measurement. The measured current and voltage is used to calculate the total bundle power.

The DAS is used to scan the instrumentation and convert the signals to engineering units and perform calculations. A list of the primary DAS variables and their associated uncertainties are tabulated in Table 3-12. Analog signals of the loop instrumentation are sampled by digital converter and stored to hard disk at a sampling rate per channel of 20 Hz. All data from the test run are retained and available for engineering assessment. Select data channels are displayed on a bank of three displays with particular attention paid to visualization of the **[ ]**. The evaluation software transfers the measured values into physical values (e.g., pressure, temperature and mass flow rate).

During testing, power is slowly ramped when approaching CHF. A CHF event is characterized by an increase in the measured temperatures of thermocouples positioned inside the heater rods. **[ ]** are used to check for the occurrence of onset of CHF: **[ ]**. Two “reference points” are selected to allow a more efficient transition from anywhere in the testing range to a nearby “reference point” to determine if the measured performance level is maintained for the test bundle and loop operation. Periodically the test loop is taken back to one of the “reference points” to verify integrity of the test bundle. A check is repeated during the test series each day or if there are any indications of abnormalities in testing. The test repeatability at these “reference points” is acceptable and is within past testing experience.

During CHF testing, loop stability is controlled by monitoring the pressure, inlet flow and inlet temperature. Nominal values for these three parameters for each statepoint are prescribed and the values are not allowed to deviate from the nominal values beyond the ranges specified in Table 3-13. During the test run the parameter values are not allowed **[ ]** specified in Table 3-13. During the last **[ ]** prior to CHF the **[ ]** specified in Table 3-13. This graded approach to assuring loop stability is illustrated in Figure 3-17.

The test loop heat loss is the amount of energy lost from the test vessel that does not contribute to the enthalpy increase of the fluid flowing through the test channel. Heat losses have been characterized at KATHY and concluded to be **[ ]**. This value is accounted for in the validation of the NSP2 CHF correlation.

Table 3-12. KATHY DAS variables and estimated uncertainties

Variable	Uncertainty
System pressure	**[ ]**
Mass flux	**[ ]** **[ ]**
Inlet temperature	**[ ]**
Bundle Power	**[ ]**

Table 3-13. KATHY maximum deviations of CHF test parameters

Parameter	Pressure	Inlet Mass Flux	Inlet Temperature
Max. deviation from nominal value	[ ]	[ ] [ ]	[ ]
Max. deviation from [ ]	[ ]	[ ] [ ] [ ]	[ ]
Max. deviation from [ ]	[ ]	[ ] [ ] [ ]	[ ]

[ ]

Figure 3-17. Monitoring of loop stability during CHF testing

3.2 Statistical Evaluation Methods

The following sections describe the statistical methods employed in the development of the NuScale NSP2 and NSP4 CHF correlations. In order to meet the regulatory criteria outlined in Section 2.1 CHF must be avoided at the 95/95 level, which implies a required level of significance, α, of 0.05. Therefore, the level of significance is considered to be 0.05 for all statistical processes involved in the development of the CHF correlations.

3.2.1 Treatment of Outliers

An outlier is considered to be an “apparently erroneous observation that has been identified by some statistical procedure as due to error or some cause rather than randomness in the data" (refer to Reference 9.2.1, Section 26.2). In the traditional sense, an outlier would tend to be measured data, such as a test measurement, that could be affected by unknown outside influences. When this concept is applied to a correlation of data, which is a mathematical rather than physical process, external factors that are spurious in nature are excluded. While it is possible to justify the removal of outliers from a correlation in this manner, this is not the approach employed in the development or assessment of the CHF correlations. The methodology encompasses the complete population of constituent data and the uncertainty of the correlation in its entirety in deriving the correlation limit.

3.2.2 Critical Heat Flux Test Uncertainties

The measured test values of bundle inlet temperature, average mass flux, pressure, and power are used as boundary conditions for determining {{ }}[2(a),(c)] for each CHF statepoint tested. The overall test uncertainty, including measurement and repeatability uncertainties, is included in this measured test data based on the premise that sufficient test data are taken such that the standard deviation or cumulative distribution function of the measured-to-predicted ratio (M/P) values encompass these uncertainties. Therefore, the CHF correlation limit accounts for these uncertainties. Furthermore, system biases and uncertainties are applied in the subchannel methodology to conservatively account for plant uncertainties associated with these same parameters, which are of the same order of magnitude as the CHF test uncertainties.

3.2.3 Tests for Normality

It is important to establish whether a particular population may be considered to be from a normal distribution, because this test determines whether to employ parametric or non-parametric statistical methods. One of two statistical normality tests is applied to test whether a population belongs to a normal distribution:

1. Shapiro-Wilks' *W*-test if there are fifty (50) or less data (Reference 9.2.1, Section 11.9), or

2. D'Agostino's D' test if there are more than fifty (50) data (Reference 9.2.1, Section 11.10).

3.2.4 Comparisons of Data Sets

The complete data set is {{

}}2(a),(c).

For parametric data, the Bartlett test of homoscedasticity (Reference 9.2.1, Section 14.7) is performed on data subsets to test whether the variances are considered equal. For non-parametric data, the k-Sample Squared Ranks test (Reference 9.2.1, Section 25.14) is performed to test equality of variances. If the null hypothesis that the variances are equal is rejected, then the median test of locations (Reference 9.2.1, Section 25.9) is used to determine whether data subsets can be combined. Otherwise, the Kruskal-Wallis test of locations (Reference 9.2.1, Section 25.10) is used because the Kruskal-Wallis test assumes that variances are equal. If it can be statistically shown that data subsets have equal means then they are combined into larger data groups. When combining data into groups it is possible that some data subsets can belong to multiple groups. For example, consider a simple case with three subsets: α, β, and γ; it is possible that α can be combined with β, and γ, but that β cannot be combined with γ. In this case α, β, and γ cannot be combined into a single group, but α can be combined with β to make one group and α can be combined with γ to make a second group.

3.2.5 Correlation Limit

The CHF correlation limit is equivalent to a one-sided tolerance limit of the predicted-to-measured ratio (P/M) CHF values. If the P/M sample can be shown to belong to a normal distribution then a parametric statistical tolerance limit method (Reference 9.2.1; Section 9.12) is used. If the sample cannot be shown to belong to the normal distribution then a non-parametric statistical tolerance limit method using order statistics is used. If a random sample n is taken from a population having a continuous distribution function $F(x)$ the samples are ordered ascendingly as $x_1, x_2, \dots, x_i, \dots, x_n$, as illustrated in Figure 3-18. The fraction β of the population that lie between the i^{th} and j^{th} values (i.e., x_i and x_j) in the sample is $F(x_j) - F(x_i)$. This quantity is referred to as the population coverage of the interval (x_i, x_j) and has the probability element:

$$\frac{\Gamma(n+1)}{\Gamma(k)\Gamma(n-k+1)}\, u^{k-1}(1-u)^{n-k}du \qquad \text{Eq. 3-2}$$

where u is the probability of the statistic falling in the interval. The probability α that the coverage is at least β is given as:

$$\alpha = \int_{\beta}^{1} \frac{\Gamma(n+1)}{\Gamma(k)\Gamma(n-k+1)} u^{k-1}(1-u)^{n-k} du \qquad \text{Eq. 3-3}$$

where $k = n - j + i$ and α is referred to as the tolerance level. The above equation is simplified and the value of k is maximized so that:

$$\alpha \leq 1 - I_{\beta}(n-k+1, \mathrm{k}) \qquad \text{Eq. 3-4}$$

Where $I_x(A, B)$ is the incomplete beta distribution:

$$I_x(A,B) = \frac{\Gamma(A+B)}{\Gamma(A)\Gamma(B)} \int_0^x z^{A-1}(1-z)^{B-1}\, dz, \qquad \text{Eq. 3-5}$$

For all variations of A and B the following equality holds:

$$I_{1-\beta}(k, n-k+1) = 1 - I_{\beta}(n-k+1, k) \qquad \text{Eq. 3-6}$$

Therefore, Eq. 3-3 can be expressed as:

$$\alpha \leq I_{1-\beta}(k, n-k+1) \qquad \text{Eq. 3-7}$$

Tolerance limits are calculated for each data subset grouping discussed in Section 3.2.4. The maximum tolerance limit for all of the groups is adopted as the correlation limit, because this limit conservatively bounds all of the groups.

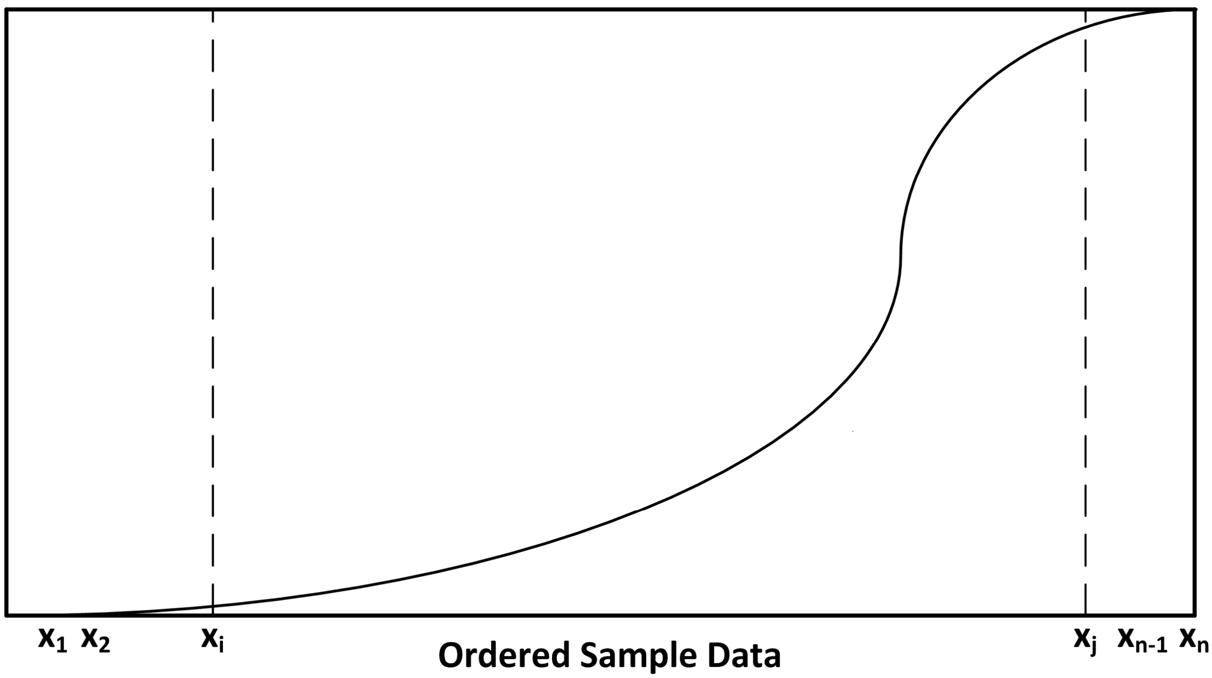

Figure 3-18. Illustrative non-parametric probability distribution function

3.3 Local Conditions

The CHF test data provide global parameter values such as system pressure, inlet temperature, and total bundle power. The NSP2 and NSP4 CHF correlations, however, are based on thermal-hydraulic conditions {{ }}$^{2(a),(c)}$. These parameters include, but are not limited to, local mass flux, local equilibrium quality, and local heat flux. The local thermal-hydraulic conditions are calculated with the VIPRE-01 subchannel code (Reference 9.2.3). The following sections describe the generic and test specific modeling options selected.

3.3.1 VIPRE-01 Models

The radial geometry of the Stern preliminary prototypic U1, U2, and C1 tests is represented by a 36-channel model of the test assembly in full radial detail, as illustrated in Figure 3-4 for the U1 and C1 tests and Figure 3-5 for the U2 test. The model represents the heated length of the test section with grid spacers represented with discrete nodes to capture the diversion crossflow at appropriate locations. Maximum axial node size is {{ }}$^{2(a),(c)}$ The axial power distribution is uniform for the U1 and U2 tests and symmetric cosine for the C1 test, as discussed in Section 3.1.1.1. The cosine axial power shape of C1 is defined by Eq. 3-1. Operating conditions are based on the measured exit pressure, inlet temperature, inlet mass flux, and average linear heat generation rate, which vary for each test point.

The radial geometry of the KATHY K8500 HMP™ and KATHY NuFuel-HTP2™ K9000, K9100, K9200, and K9300 tests are also represented by similar 36-channel models of the test assembly in full radial detail. The models cover the heated length of the test section with spacer grids represented with discrete nodes. Maximum axial node size for any of the KATHY models is {{ }}2(a),(c) The **[** **]** for the **[** **]** tests, and **[** **]** for the **[** **]** tests. Operating conditions are based on the measured exit pressure, inlet temperature, inlet mass flux, and average linear heat generation rate, which vary for each test point.

Each of the VIPRE-01 models, for the Stern preliminary prototypic, KATHY K8500 HMP™ and KATHY NuFuel-HTP2™ tests for development and validation of the NSP2 CHF correlation, use the same VIPRE-01 two-phase, heat transfer and mixing correlation inputs. For the NSP4 CHF correlation, the turbulent mixing (β) value is increased from {{**[** **]**}}2(a),(c),ECI consistent with improved mixing with the HTP2™ grid as demonstrated by the NuFuel-HTP2™ thermal mixing test data. The two-phase and heat transfer correlation models are tabulated in Table 3-14 and the mixing models are tabulated in Table 3-15. The models in these two tables are identical to those identified for safety analysis of the NPM per the subchannel analysis methodology topical report (Reference 9.2.3). Justification for the selection of these models is discussed in the subchannel analysis methodology topical report (Reference 9.2.3). Therefore, the two-phase and heat transfer correlations listed in Table 3-14 and Table 3-15 must be used in any safety analysis of the NPM that uses the NSP2 or NSP4 CHF correlations.

Table 3-14. Two-phase and heat transfer correlations

Correlation	VIPRE-01 Model	Notes
Two-phase friction multiplier	EPRI	The EPRI correlations are recommend in the guidelines for two-phase models because they provided the best overall benchmark to data. (VIPRE-01 default option)
Two-phase subcooled void	EPRI	
Two-phase bulk void	EPRI	
Hot wall friction correction	NONE	
Single-phase forced convection heat transfer	EPRI	The EPRI correlation is the Dittus-Boelter correlation with the leading coefficients defined to correspond to the EPRI void models (VIPRE-01 default option)
Subcooled boiling heat transfer	THSP	The Thom correlation (VIPRE-01 default option)
Saturated boiling heat transfer	THSP	The Thom correlation (VIPRE-01 default option)
Transition boiling heat transfer	COND	The Condie-Bengtson correlation (VIPRE-01 default option)
Film boiling heat transfer	G5.7	The Groeneveld 5.7 correlation (VIPRE-01 default option)

Table 3-15. Turbulent mixing factors

Correlation	Value	Notes
Turbulent momentum factor	0.8	This is the default recommended value for VIPRE-01 and it has been determined that the sensitivity of this parameter ranging from 0 to 1 is negligible
Single-phase mixing coefficient correlation	$w' = \beta S\bar{G}$	Use a standard Rowe & Angle type model
β value for NSP2 CHF correlation	{{[ ]}}2(a),(c),ECI	Based on single-phase data from Stern Laboratories thermal mixing tests
β value for NSP4 CHF correlation	{{[ ]}}2(a),(c),ECI	Based on single-phase data from NuFuel-HTP2™ thermal mixing tests
Two-phase mixing coefficient correlation	-	Treated the same as single-phase mixing, which has been found to be conservative

3.3.2 VIPRE-01 Data Reduction

VIPRE-01 {{ }}2(a),(c). For the Stern preliminary prototypic tests, {{ }}2(a),(c). The [ ]. Local conditions for KATHY NuFuel-HTP2™ K9000 through K9300 are {{ }}2(a),(c). These data are used to validate the NSP2 CHF correlation. Using the highest predicted CHF in the P/M CHF value calculation increases the P/M values. Higher P/M values are more challenging relative to validating that the NSP2 CHF correlation can conservatively predict NuFuel-HTP2™ fuel CHF. Therefore, the NSP2 CHF correlation can be shown to provide conservative predictions of CHF for the KATHY NuFuel-HTP2™ data without concerns that there are other more challenging local thermal-hydraulic conditions. For the NSP4 CHF correlation local conditions are taken from the {{ }}2(a), (c).

The local conditions obtained from VIPRE-01 include:

- local mass flux, 10^6 lbm/hr-ft^2
- local enthalpy, Btu/lbm

Global parameters obtained from VIPRE-01 include:

- boiling length, in.

- saturated liquid enthalpy, Btu/lbm
- saturated vapor enthalpy, Btu/lbm

Other parameters considered for the CHF development include:

- exit pressure, psia (CHF test boundary condition)
- {{ }}2(a),(c)
- local equilibrium quality (calculated from local enthalpy)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)

All of these parameters are considered in one way or another for the NSP1 CHF correlation. For reference, the primary parameters common to most CHF correlations are pressure, local mass flux, and local quality.

4.0 NSP1 Critical Heat Flux Correlation Development

The NSP1 CHF correlation is based upon Stern preliminary prototypical CHF test data. This data meets general behavioral expectations. The measured uniform CHF is found to {{

}}2(a),(b),(c). Therefore, the trends in Figure 4-1 are consistent with expectations considering the combined effect of {{ }}2(a),(c). This trend is consistent with that of the KATHY K8500 HMP™ data in Figure 5-1. The linear fit of the data demonstrates a trend of {{ }}2(a),(b),(c), as illustrated in Figure 4-2. This trend meets expectations, as the {{ }}2(a),(c) aid in the removal of heat from the heater rods. Also, the linear fit of the data demonstrate a trend of {{ }}2(a),(b),(c), as illustrated in Figure 4-3. This trend meets expectations, as the increased quality signifies a greater level of overall vapor in the channels that inhibits heat removal from the heater rods.

{{

}}2(a),(b),(c)

Figure 4-1. Measured uniform CHF vs. pressure (Stern preliminary prototypic)

{{

}}2(a),(b),(c)

Figure 4-2. Measured uniform CHF vs. local mass flux (Stern preliminary prototypic)

{{

}}2(a),(b),(c)

Figure 4-3. Measured uniform CHF vs. local quality (Stern preliminary prototypic)

4.1 Correlating Technique

The ultimate goal of the CHF correlation is to provide a tool to predict CHF for safety analysis and provide a correlation limit that assures the guidance given by acceptance criterion 1 of Reference 9.1.3 is met. The Stern preliminary prototypic tests encompass a range of thermal-hydraulic conditions necessary to establish the CHF-based safety analysis protection measures for the NPM, but do not provide a continuous database where all applicable operating conditions are included. A cross-validation process is employed to optimize and validate the final correlation. A five-fold cross-validation is employed in evaluating the NSP1 CHF correlation. Cross-validation is a technique for assessing how accurately a predictive model performs in its actual application. This process minimizes "over-fitting" of the correlation to data along with other undesirable biases. The complete data population (all local condition data) is randomly partitioned into five equal-sized sub-populations, or subsets. Of these five subsets, one is held aside for validation testing, while the other four are used to train the correlation. This process is repeated five times (five-fold) until all five subsets have been used for validation testing. The correlation coefficients derived from {{ }}$^{2(a),(c)}$ to produce the final correlation coefficients. The coefficients and statistical results of validation testing are compared between the five-folds to assure that each predicts similar values. The coefficients and statistical results are also determined for the full data set and compared to the results of the five-fold cross-validation.

4.2 Correlation Form

The NSP1 CHF correlation is determined using an additive linear least squares regression. The linear terms include the following:

- pressure
- local mass flux
- local equilibrium quality
- {{ }}$^{2(a),(c)}$
- cold wall factor
- boiling length

The {{ }}$^{2(a),(c)}$ is defined by:

{{

}}$^{2(a),(c)}$

where,

{{ }}2(a),(c)

{{ }}2(a),(c)

{{ }}2(a),(c)

The cold wall factor is defined as {{ }}2(a),(c).

The boiling length is defined as {{ }}2(a),(c).

{{ }}2(a)(c). Once the form is set, the five-fold cross-validation from Section 4.1 is employed to determine the final coefficients. Through this process, the NSP1 CHF correlation is found to have the form:

{{ Eq. 4-2 }}2(a),(c)

The critical heat flux ratio (CHFR) is defined as:

$$CHFR = q''_{C,u}/\left(q''_L \times F_{Tong}\right) \quad \text{Eq. 4-3}$$

where,

{{ }}2(a),(c)

$B = 1/G$

$C = X$

{{ }}2(a),(c)

{{ }}2(a),(c) (cold wall factor)

{{ }}2(a),(c)

$q''_{C,u}$ = uniform CHF, 10^6 Btu/hr-ft^2

q''_L = local heat flux, 10^6 Btu/hr-ft^2

P = pressure, psia

P_{crit} = critical pressure: 3204 psia

G = local mass flux, 10^6 lbm/hr-ft^2

X = local equilibrium quality

{{ }}2(a),(c)

{{ }}2(a),(c)

{{ }}2(a),(c)

Z_{bo} = boiling length, in.

{{ }}2(a),(c)

F_{Tong} = non-uniform flux factor (F-Factor) discussed in Section 4.3

c_x = CHF correlation coefficients (see Table 4-1)

Table 4-1. NSP1 CHF correlation coefficients

Coefficient	Value	Coefficient	Value
c_0	{{ }}2(a),(c)	c_8	{{ }}2(a),(c)
c_1	{{ }}2(a),(c)	c_9	{{ }}2(a),(c)
c_2	{{ }}2(a),(c)	c_{10}	{{ }}2(a),(c)
c_3	{{ }}2(a),(c)	c_{11}	{{ }}2(a),(c)
c_4	{{ }}2(a),(c)	c_{12}	{{ }}2(a),(c)
c_5	{{ }}2(a),(c)	c_{13}	{{ }}2(a),(c)
c_6	{{ }}2(a),(c)	c_{14}	{{ }}2(a),(c)
c_7	{{ }}2(a),(c)	c_{15}	{{ }}2(a),(c)

4.3 Non-Uniform Flux Factor Development

An F-factor, Tong (Reference 9.2.4), is used to adjust CHF predictions for the effect of variations of axial power profiles. The Tong F-factor is based on a wide variety of axial power shapes and has been previously employed to account for axial power shape variations. The Tong F-factor is given as:

$$F_{Tong} = \frac{C \int_0^{l_{CHF}} q''(z) e^{-C(l_{CHF}-z)} dz}{q''_{(l_{CHF})} \times (1 - e^{-C \cdot l_{CHF}})} \qquad \text{Eq. 4-4}$$

where,

{{ }}2(a),(c)

G = mass flux at CHF location, 10^6 Btu/hr-ft^2

l_{CHF} = elevation of CHF from bottom of heated length

$q''(z)$ = heat flux at elevation z, 10^6 Btu/hr-ft^2

$q''(l_{CHF})$ = heat flux at CHF location, 10^6 Btu/hr-ft^2

X = equilibrium quality at CHF location

This factor is applied to capture the effect of non-uniform axial power profiles as follows:

$$q''_{C,n} = q''_{C,u}/F_{Tong} \qquad \text{Eq. 4-5}$$

where,

$q''_{C,u}$ = uniform CHF, 10^6 Btu/hr-ft^2

$q''_{C,n}$ = non-uniform heat flux, 10^6 Btu/hr-ft^2

F_{Tong} = Tong non-uniform flux factor

When the {{

}}2(a),(c) is necessary. By comparing the {{

}}2(a),(c), a multiplicative factor of 1.11 adequately adjusts the Tong F-factor, as depicted by Figure 4-4. Thus the F-factor term is finally expressed as:

{{

}}2(a),(c)

The effect of applying this multiplier is illustrated in Figure 4-4.

{{

}}2(a),(b),(c)

Figure 4-4. Stern Preliminary Prototypic U1 and C1 CHF

4.4 Statistical Evaluation

The mean and root mean square error of the M/P CHF values for the five-fold cross validation and the final coefficients are tabulated in Table 4-2. For the five-folds of the cross-validation, the mean M/P is within {{ }}2(a),(c) of unity, and using the {{ }}2(a),(c) results in a mean M/P of {{ }}2(a),(c), which represents a negligible bias. The root mean square error values fall within a range of {{ }}2(a),(c). The predicted versus measured heat flux values are illustrated in Figure 4-5. The majority of data falls along the ideal 45 degree line and {{ }}2(a),(c) of this ideal line. Biases with respect to the correlating parameters are evaluated by examining plots of M/P CHF versus each parameter. There is no distinct bias for any of the correlating parameters as illustrated in Figure 4-6 for pressure, Figure 4-7 for mass flux, Figure 4-8 for quality, Figure 4-9 for boiling length, and Figure 4-10 for the cold wall factor {{ }}2(a),(c). With no distinct bias in M/P CHF values or with regards to the correlating parameters, the NSP1 CHF correlation predicts the Stern Laboratories test data in an acceptable manner.

Table 4-2. NSP1 CHF correlation M/P mean and RMS error

Coefficient	Mean M/P CHF	M/P CHF Root Mean Square Error
Cross-validation 1 coefficient	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
Cross-validation 2 coefficient	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
Cross-validation 3 coefficient	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
Cross-validation 4 coefficient	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
Cross-validation 5 coefficient	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
{{ }}2(a),(c)	{{ }}2(a),(b),(c)	{{ }}2(a),(c)
Coefficients based on full data	{{ }}2(a),(b),(c)	{{ }}2(a),(c)

{{

}}2(a),(b),(c)

Figure 4-5. Predicted vs. measured CHF for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Figure 4-6. M/P CHF vs. pressure for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Figure 4-7. M/P CHF vs. local mass flux for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Figure 4-8. M/P CHF vs. local equilibrium quality for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Figure 4-9. M/P CHF vs. boiling length for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Figure 4-10. M/P CHF vs. cold wall factor for Stern preliminary prototypic data

4.5 Correlation Limit

While many discussions in this report are based on the M/P, when it comes to determining the correlation limit, the P/M is more appropriate. When considering the definition of CHFR, the CHF calculated with the correlation is the same whether being compared to test data or applied to safety analyses and the local heat flux in operation can be considered analogous to the measured heat flux from the CHF test. Thus:

$$CHFR = \frac{q''_{CHF}}{q''_L} \approx \frac{PREDICTED}{MEASURED} \qquad \text{Eq. 4-7}$$

The Stern preliminary prototypic data is {{ }}2(a),(c) as tabulated in Table 4-3. These {{ }}2(a),(c) from the Stern preliminary prototypic CHF test matrix (see Table 3-1) for {{ }}2(a),(c). For {{ }}2(a),(c). Tolerance limits, at the 95/95 level, for {{ }}2(a),(c) in Table 4-3 are calculated and tabulated in Table 4-4. The maximum tolerance limit is {{ }}2(a),(c). Therefore, the NSP1 CHF correlation limit is found to be 1.17 to prevent CHF at the 95/95 level.

Table 4-3. Data subsets for Stern preliminary prototypic data

{{

}}2(a),(b),(c)

Table 4-4. Tolerance limits for Stern preliminary prototypic data

{{

}}2(a),(c)

4.6 Range of Applicability

The range of applicability in Table 4-5 is determined from the data points used in the development of the NSP1 CHF correlation. The values for the most significant parameters are tabulated in Table 4-5. The range of data listed covers the data at the 95/95 level (using non-parametric two-sided tolerance limit methods). There is no lower limit on local quality because the trends with regards to quality indicate reasonable and predictable behavior at low qualities.

Table 4-5. Parameter ranges of applicability for NSP1 CHF correlation

Parameter	Range of Applicability
pressure, psia	300 to 2300
local mass flux, 10^6 lbm/hr-ft^2	0.110 to 0.700
local equilibrium quality, %	≤ 90.0%
inlet equilibrium quality, %	≤ 0.0%

4.7 NSP1 Correlation Performance

The performance of the NSP1 uniform CHF correlation is assessed with a global sensitivity analysis. A large set of statepoints {{ }}2(a),(c) is generated randomly within the ranges of the correlating parameters describing bundle boundary conditions. Pressure, mass flux, inlet subcooling, and boiling length corresponding to these statepoints are randomly selected. The {{

}}2(a),(c). The predicted CHF {{ }}2(a),(b),(c), as illustrated in Figure 4-11, is consistent with the data trend established in Figure 4-1. The predicted CHF {{ }}2(a),(b),(c), as illustrated in Figure 4-12, is consistent with the data trend established in Figure 4-2. The predicted CHF {{ }}2(a),(b),(c), as illustrated in Figure 4-13, is consistent with the data trend established in Figure 4-3. Therefore, the NSP1 CHF correlation predicts CHF values in a manner that is consistent with the measured Stern preliminary prototypic data.

{{

}}2(a),(b),(c)

Figure 4-11. Global sensitivity – predicted uniform CHF vs. pressure

{{

}}2(a),(b),(c)

Figure 4-12. Global sensitivity – predicted uniform CHF vs. mass flux

{{

}}2(a),(b),(c)

Figure 4-13. Global sensitivity – predicted uniform CHF vs. quality

5.0 NSP2 Critical Heat Flux Correlation Development

5.1 Assessment of KATHY K8500 HMP™ Test with NSP1 Critical Heat Flux Correlation

Stern preliminary prototypic CHF tests are designed specifically for the operating conditions needed to support the CHF-based safety analysis protection for the NPM using the VIPRE-01 code. The Stern preliminary prototypic tests use a generic, simple, non-mixing spacer grid design, while the NuFuel-HTP2™ fuel design includes AREVA's HTP™ and HMP™ spacer grid technology. Data are obtained for fluid conditions similar to the Stern preliminary prototypic tests for a bundle of comparable geometry with HMP™ spacer grids from the KATHY K8500 HMP™ test. Comparisons of significant test parameters from the Stern preliminary prototypic and KATHY K8500 HMP™ tests are tabulated in Table 5-1. **[**

]. The grid spacers {{

}}$^{2(a),(c)}$. Therefore, the HTP™ grid spacer employed in the NuFuel-HTP2™ fuel design produces **[**

] than either the Stern preliminary prototypic or KATHY K8500 HMP™ tests as it is designed to **[**

]. This conclusion is validated with testing of the NuFuel-HTP2™ fuel design as discussed in Section 6.0. The KATHY K8500 HMP™ local conditions fall within the Stern preliminary prototypic test local condition ranges for pressure, mass flux, and equilibrium quality, as illustrated in Figure 5-1 through Figure 5-3. **[**

].

The NSP1 correlation predictions of CHF values for KATHY K8500 HMP™ data are illustrated in Figure 5-4. **[**

].

Table 5-1. Stern preliminary prototypic and KATHY K8500 HMP™ parameters

Parameter	Stern Preliminary Prototypic	KATHY K8500 HMP™
Heater rod diameter, in.	0.374	[ ]
Heater rod pitch, in.	0.496	[ ]
Channel width, in.	{{ }}2(a),(c)	[ ]
Heated length, in.	78.740	[ ]
Grid spacer design	Simple non-mixing	HMP™
Distance between grid spacers, in.	20.5	[ ]
Radial powers (max/min)	{{ }}2(a),(c)	[ ]
Axial power profile	uniform & cosine	[ ]
Average mass flux, 10^6 lbm/hr-ft^2	{{ }}2(a),(c)	[ ]
Pressure, psia	{{ }}2(a),(c)	[ ]
Local quality	{{ }}2(a),(c)	[ ]

[

]

Figure 5-1. CHF vs. pressure for Stern preliminary prototypic and KATHY K8500 HMP™

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Figure 5-2. CHF vs. mass flux for Stern preliminary prototypic and KATHY K8500 HMP™

[

]

Figure 5-3. CHF vs. quality for Stern preliminary prototypic and KATHY K8500 HMP™

[

]

Figure 5-4. NSP1 P/M CHF for Stern preliminary prototypic and KATHY K8500 HMP™

5.2 NSPX factor

The NSPX factor is used to adjust CHF predictions using the NSP1 CHF correlation to provide conservative predictions of the KATHY K8500 HMP™ data. **[**

]. The NSPX factor has the form:

{{**[**

]}}2(a),(c)

where,

P = pressure, psia

P_{crit} = critical pressure (3204 psia)

[

]

Figure 5-5. NSP1 CHF Correlation M/P CHF vs. pressure for KATHY K8500 HMP™

5.3 NSP2 Critical Heat Flux Correlation

The NSP2 CHF correlation combines the CHF prediction of the NSP1 CHF correlation with the NSPX factor:

{{[

]}}2(a),(c)

where,

$q''_{C,u}$ = uniform CHF from NSP1 correlation, 10^6 Btu/hr-ft^2

F_{NSPX} = NSPX factor

{{ }}2(a),(c)

$B = 1/G$

$C = X$

{{ }}2(a),(c)

{{ }}2(a),(c) (cold wall factor)

{{ }}2(a),(c)

$P =$ pressure, psia

P_{crit} = critical pressure: 3204 psia

$G =$ local mass flux, 10^6 lbm/hr-ft^2

$X =$ local equilibrium quality

{{ }}2(a),(c)

{{ }}2(a),(c)

{{ }}2(a),(c)

Z_{boil} = boiling length, in.

{{ }}2(a),(c)

c_x = CHF correlation coefficients (see Table 4-1)

The effect of the NSPX factor is illustrated with the M/P heat flux values for both the NSP1 and final NSP2 CHF correlations in Figure 5-6. With the NSPX factor applied, the KATHY K8500 HMP™ and Stern preliminary prototypic data are conservatively predicted.

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Figure 5-6. NSP1 and NSP2 predicted vs. measured CHF for KATHY K8500 HMP™

6.0 Validation of NSP2 CHF Correlation

The NSP2 correlation is developed using test data from test bundles that are geometrically comparable, but have different spacer grids than the NuFuel-HTP2™ design used for the NuScale DCA. Therefore, it is imperative to validate that the correlation adequately predicts CHF performance for the NuFuel-HTP2™ design used in the NPM. In order to validate the correlation, the following are considered:

- Compare raw test data between Stern preliminary prototypic and KATHY NuFuel-HTP2™ tests.
- Predict CHF for KATHY NuFuel-HTP2™ test data with the NSP2 correlation and verify that it is conservatively predicted.
- Determine the applicable tolerance limit for the KATHY NuFuel-HTP2™ P/M data, assuring that the correlation limit determined for the NSP1 CHF correlation (Section 4.5) remains conservative, or determining a more conservative limit specific to the KATHY NuFuel-HTP2™ data.

The KATHY NuFuel-HTP2™ data are from a test bundle design consistent with the NuFuel-HTP2™ fuel bundle considered in the NuScale DCA. The KATHY NuFuel-HTP2™ data were obtained using HTP™ and HMP™ spacer grids and the grid spacing is consistent with the NuFuel-HTP2™ design considered in the NuScale DCA.

6.1 Comparison of Stern Preliminary Prototypic to KATHY NuFuel-HTP2™ Test Data

The test matrix for KATHY NuFuel-HTP2™ testing is designed to have some direct overlap with the conditions tested with the Stern preliminary prototypic bundle design so that comparisons can be made between data from the two designs. This approach accounts for {{ }}$^{2(a),(c)}$. Overlap with regards to {{ }}$^{2(a),(c)}$ and with regards to {{ }}$^{2(a),(c)}$ (refer to Table 3-1 and Table 3-4). Comparisons for the K9000, K9100, and K9300 tests are addressed in the following sections.

6.1.1 KATHY NuFuel-HTP2™ K9000 versus Stern Preliminary Prototypic U2

Data from KATHY NuFuel-HTP2™ K9000 and Stern preliminary prototypical U2 tests are compared qualitatively by plotting the measured hot rod average heat flux as a function of test matrix mass flux for the corresponding levels of test matrix inlet subcooling in Figure 6-1 through Figure 6-4. **[**

] as described in Section 5.1.

Note: The y-axis values are omitted in Figure 6-1 through Figure 6-4 due to NuScale requirements for the handling of proprietary test data. All four plots use an identical y-axis range.

[

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Figure 6-1. U2 vs. K9000 measured heat flux at 7.0 MPa

[

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Figure 6-2. U2 vs. K9000 measured heat flux at 10.0 MPa

[

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Figure 6-3. U2 vs. K9000 measured heat flux at 13.0 MPa

[

]

Figure 6-4. U2 vs. K9000 measured heat flux at 16.0 MPa

6.1.2 KATHY NuFuel-HTP2™ K9100 versus Stern Preliminary Prototypic U1

Data from KATHY NuFuel-HTP2™ K9100 and Stern preliminary prototypical U1 tests are compared qualitatively by plotting the measured hot rod average heat flux as a function of test matrix mass flux for corresponding levels of test matrix inlet subcooling in Figure 6-5 through Figure 6-8. **[**

].

Note: The y-axis values are omitted in Figure 6-5 through Figure 6-8 due to NuScale requirements for the handling of proprietary test data. All four plots use an identical y-axis range.

[

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Figure 6-5. U1 vs. K9100 measured heat flux at 7.0 MPa

[

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Figure 6-6. U1 vs. K9100 measured heat flux at 10.0 MPa

[

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Figure 6-7. U1 vs. K9100 measured heat flux at 13.0 MPa

[

]

Figure 6-8. U1 vs. K9100 measured heat flux at 16.0 MPa

6.1.3 KATHY NuFuel-HTP2™ K9300 versus Stern Preliminary Prototypic C1

Data from KATHY NuFuel-HTP2™ K9300 and Stern preliminary prototypical C1 tests are compared qualitatively by plotting the hot rod average heat flux as a function of test matrix mass flux for corresponding levels of test matrix inlet subcooling in Figure 6-9 through Figure 6-12. **[**

].

Note: The y-axis values are omitted in Figure 6-9 through Figure 6-12 due to NuScale requirements for the handling of proprietary test data. All four plots use an identical y-axis range.

[

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Figure 6-9. C1 vs. K9300 measured heat flux at 7.0 MPa

[

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Figure 6-10. C1 vs. K9300 measured heat flux at 10.0 MPa

[

]

Figure 6-11. C1 vs. K9300 measured heat flux at 13.0 MPa

[

]

Figure 6-12. C1 vs. K9300 measured heat flux at 16.0 MPa

6.1.4 Summary of KATHY to Stern Laboratories Data Comparisons

Comparisons between Stern preliminary prototypic and KATHY NuFuel-HTP2™ data demonstrate that the NuFuel-HTP2™ assembly design performs **[** **]** with regards to CHF. The measured CHF for the KATHY NuFuel-HTP2™ test is, **[** **]**. The trend demonstrated by Figure 6-1 through Figure 6-12 is expected because the HTP™ spacer grid **[** **]**. Overall, the **[** **]** and supports the use of the KATHY NuFuel-HTP2™ data as a validation set for the NSP2 CHF correlation.

6.2 NuFuel-HTP2™ Critical Heat Flux Predictions with NSP2 Critical Heat Flux Correlation

The NSP2 CHF correlation predicts conservative CHF values for the NuFuel-HTP2™ design as demonstrated **[** **]**. This conclusion is also demonstrated by the statistical mean values of P/M CHF for the four tests, which are **[** **]**. In Figure 6-14 the P/M CHF values are broken out by mass flux range. This figure illustrates that the NSP2 CHF correlation is **[** **]**. These results do not diminish the overall conservatism of the method, because the P/M CHF values that are above 1.0 are addressed by the final CHF correlation limit. **[** **]**.

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Figure 6-13. NSP2 P/M CHF for KATHY NuFuel-HTP2™ tests

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Figure 6-14. NSP2 P/M CHF for KATHY NuFuel-HTP2™ mass flux ranges

6.3 Correlation Limit for NSP2

In order to develop a CHF correlation limit that meets regulatory requirements across the correlation applicability range, the CHF data is {{

}}2(a),(c). Tolerance limits, at the 95/95 level, for {{

}}2(a),(c). Furthermore, {{

}}2(a),(c). Therefore, the NSP2 CHF correlation limit is 1.17, which is conservative, to prevent CHF at the 95/95 level. Bias plots for pressure, mass flux, quality, boiling length, cold wall factor, and inlet enthalpy are illustrated in Figure 6-15 through Figure 6-20, respectively. From these figures it is evident that there is distinct conservative bias (i.e. under-predicting data) and the vast majority of M/P data lies above the correlation limit. The M/P limit is calculated from the correlation limit with:

$$LIMIT_{M/P} = \frac{1}{LIMIT_{P/M}} = \frac{1}{LIMIT_{correlation}}$$

The trends of a linear fit to the data are not flat (flat is preferable) but this is expected because neither the NSP1 CHF correlation nor the NSPX factor were directly correlated to the NuFuel-HTP2™ CHF data. Overall, the NSP2 CHF correlation provides generally conservative predictions of CHF for the NuFuel-HTP2™ design.

Table 6-1. Data subsets for KATHY NuFuel-HTP2™ data

{{

}}2(a),(b),(c)

Table 6-2. Tolerance limits for subset groupings of KATHY NuFuel-HTP2™ data

{{

}}2(a),(c)

[

]

Figure 6-15. M/P CHF versus pressure for NuFuel-HTP2™ with NSP2

[

]

Figure 6-16. M/P CHF versus mass flux for NuFuel-HTP2™ with NSP2

[

]

Figure 6-17. M/P CHF versus quality for NuFuel-HTP2™ with NSP2

[

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Figure 6-18. M/P CHF versus boiling length for NuFuel-HTP2™ with NSP2

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Figure 6-19. M/P CHF versus cold wall factor for NuFuel-HTP2™ with NSP2

[

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Figure 6-20. M/P CHF versus inlet enthalpy for NuFuel-HTP2™ with NSP2

6.4 Validation Conclusions

Comparison between KATHY NuFuel-HTP2™ and Stern preliminary prototypic test data demonstrates that the NuFuel-HTP2™ design has **[ ]**. For the majority of points the KATHY NuFuel-HTP2™ measured CHF values **[ ]** comparable Stern preliminary prototypic values. **[ ]**. All non-conservative predictions are conservatively addressed by appropriately setting the CHF correlation limit, which ensures that CHF will not be experienced by the limiting fuel rod at the 95/95 level. The correlation limit determined for sub-regions of the KATHY NuFuel-HTP2™ test data (refer to Section 6.3) is {{ }}[2(a),(c)] determined for the NSP1 CHF correlation. Therefore, the NSP2 CHF correlation is found to conservatively predict CHF for the NuFuel-HTP2™ fuel design and the correlation limit determined for the NSP1 CHF correlation (1.17) is applicable.

7.0 NSP4 CHF Correlation for NuFuel-HTP2™

7.1 NSP4 Correlating Technique

A cross-validation process is employed to optimize and validate the NSP4 CHF correlation using the NuFuel-HTP2™ CHF test data. A three-fold cross-validation is employed in evaluating the NSP4 CHF correlation rather than the five-fold used for the NSP1 CHF correlation in Section 4.1, consistent with the quantity of data available. It has been demonstrated, with the Stern Laboratories data, that the difference between using a five-fold and three-fold cross-validation is small. The correlation coefficients derived from the three results are {{ }}2(a),(c) NSP4 correlation coefficients. The coefficients and statistical results of validation testing are compared between the three-folds to assure that each predicts similar values.

7.2 NSP4 VIPRE-01 Calculations

Local thermal hydraulic conditions for NSP4 are calculated using VIPRE-01 with boundary conditions from the NuFuel-HTP2™ CHF data. VIPRE-01 inputs are generally identical to those used to validate the NSP2 CHF correlation in Section 6.0, except that the turbulent mixing term in the single-phase thermal mixing coefficient correlation is increased from {{**[** **]**}}2(a),(c), ECI. This increased value is based on an assessment of the NuFuel-HTP2™ thermal mixing data from the K9200 and K9300 CHF tests. The increase in turbulent mixing is consistent with improved thermal mixing produced by the HTP™ grids and provides better thermal mixing between channels.

7.3 NSP4 Local Conditions

VIPRE-01 local conditions are extracted from locations {{ }}2(a),(c). **[** **]**. Local conditions for KATHY NuFuel-HTP2™ K9000 through K9300 are {{ }}2(a),(c).

Local conditions obtained from VIPRE-01 for NSP4 include:

- local mass flux, 10^6 lbm/hr-ft^2
- local enthalpy, Btu/lbm

Global parameters obtained from VIPRE-01 include:

- exit pressure, psia (CHF test boundary condition)
- boiling length, in.
- saturated liquid enthalpy, Btu/lbm
- saturated vapor enthalpy, Btu/lbm

Other parameters considered for the CHF development include:

- {{ }}2(a),(c)
- local equilibrium quality (calculated from local enthalpy)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)

All of these parameters are considered for the NSP4 CHF correlation.

7.4 NSP4 Correlation Form

The NSP4 CHF correlation is created using an additive linear least squares regression. The linear terms include the following:

- pressure
- local mass flux
- local equilibrium quality
- cold wall factor
- boiling length

The cold wall factor is defined as {{ }}2(a),(c).

The boiling length is defined as {{ }}2(a),(c).

{{ }}2(a),(c). Once the form is set, the three-fold cross-validation is employed to determine the final coefficients. Through this process, the NSP4 CHF correlation is found to have the form:

{{

}}2(a),(c)

where,

q''_u is the uniform CHF calculated in 10^6 Btu/hr-ft^2
g is the local mass flux in 10^6 lb/hr-ft^2
x is the local equilibrium quality
p is the system pressure in psia
p_c is critical pressure in psia: 3,204 psia
z_b is the boiling length {{ }}2(a),(c) in inches
{{ }}2(a),(c)
{{ }}2(a),(c)
{{
}}2(a),(c)
c_x are the correlation coefficients from regression in Table 8-1

A non-uniform CHF value is calculated with the uniform NSP4 CHF and the Tong F-factor with Eq. 4-5.

Table 7-1. NSP4 CHF correlation coefficients

Coefficient	Value	Coefficient	Value
c_0	{{ }}2(a),(c)	c_7	{{ }}2(a),(c)
c_1	{{ }}2(a),(c)	c_8	{{ }}2(a),(c)
c_2	{{ }}2(a),(c)	c_9	{{ }}2(a),(c)
c_3	{{ }}2(a),(c)	c_{10}	{{ }}2(a),(c)
c_4	{{ }}2(a),(c)	c_{11}	{{ }}2(a),(c)
c_5	{{ }}2(a),(c)	c_{12}	{{ }}2(a),(c)
c_6	{{ }}2(a),(c)		

7.5 NSP4 Tong Non-uniform Flux Factor

A new, non-uniform flux factor is developed for the NSP4 CHF correlation, based on the NuFuel-HTP2™ CHF data, using the Tong F-Factor formulation (Eq. 4-4). Rather than apply a simple multiplicative factor to the F-factor, as in Eq. 4-6, the coefficients of the *C* term are adjusted to better fit the NuFuel-HTP2™ CHF data for the NSP4 CHF correlation.

The NuFuel-HTP2™ CHF data is based on **[** **]**. The **[** **]** tests can be used to determine the coefficients for the F-factor using the uniform tests as a baseline. The **[** **]** tests are related by:

$$q_u^{''} \cong F_{Tong} \cdot q_n^{''} \qquad \text{Eq. 7-2}$$

where q_u'' is uniform CHF,
q_n'' is non-uniform CHF, and
F_{Tong} is the Tong F-factor

This equation requires that the local conditions at CHF be the same and that the inlet temperatures be comparable **[** **]**. The local mass flux, quality, and corresponding inlet temperature for each data point in K9200 is compared to the conditions for all of the test points in K9000. The same procedure is also performed with K9300 and K9100. Using this approach, 144 points are found to correlate the *C* term coefficients. The *C* term is: {{

}}2(a)(c)

The Tong F-factor for the NSP4 CHF correlation is:

$$FNU = \frac{C\int_0^{l_{CHF}} q''(z)e^{-C(l_{CHF}-z)}dz}{q''(l_{CHF}) \cdot (1-e^{-C \cdot l_{CHF}})} \qquad \text{Eq. 7-4}$$

where,

$C =$ {{ }}2(a)(c)

$G =$ local mass flux, 10^6 lbm/hr-ft^2

$X =$ local equilibrium quality

$l_{CHF} =$ elevation of the CHF location, in,

$q''^{(z)} =$ heat flux at elevation z in MBtu/hr-ft^2, and

$q''(l_{CHF}) =$ heat flux at the CHF location in MBtu/hr-^{ft2}

In Figure 7-1, the predicted uniform CHF is plotted versus the measured uniform CHF for NSP4 F-factor form. The data fall along the ideal 45° line with minimal scatter.

{{

}}[2(a),(b),(c)]

Figure 7-1. Predicted vs. measured uniform feat flux for Tong F-factor

7.6 NSP4 Statistical Evaluation

The mean and standard deviation of the CHF P/M values for the three-fold cross validation and the final coefficients are tabulated in Table 7-2. For the three-folds of the cross-validation, the mean M/P is within {{ }}[2(a),(c)] of unity, and using the {{ }}[2(a),(c)] results in a mean P/M of {{ }}[2(a),(c)], which represents a negligible bias. The standard deviation values are less than {{ }}[2(a),(c)]. The predicted versus measured heat flux values are illustrated in Figure 7-2. The majority of data falls along the ideal 45 degree line and {{ }}[2(a),(c)] of this ideal line. Biases with respect to the correlating parameters are evaluated by examining plots of P/M CHF versus each parameter. There is no distinct bias for any of the correlating parameters as illustrated in Figure 7-3 for pressure, Figure 7-4 for mass flux, Figure 7-5 for quality, Figure 7-6 for boiling length, and Figure 7-7 for the cold wall factor {{ }}[2(a),(c)]. The bias with regards to inlet enthalpy, illustrated in Figure 7-8, is consistent with inlet enthalpy not being a correlating parameter. Nevertheless, the slope of a line fit to the P/M data is fairly small, and the extremes of the inlet enthalpy are not expected to be reached. With no distinct bias in P/M CHF values or with regards to the correlating parameters, the NSP4 CHF correlation predicts the NuFuel-HTP2™ test data in an acceptable manner.

Table 7-2. NSP4 CHF correlation P/M mean and standard deviation

Coefficient	CHF P/M Mean	CHF P/M Standard Deviation
Cross-validation 1 coefficients	{{ }}2(a),(c)	{{ }}2(a),(c)
Cross-validation 2 coefficients	{{ }}2(a),(c)	{{ }}2(a),(c)
Cross-validation 3 coefficients	{{ }}2(a),(c)	{{ }}2(a),(c)
{{ }}2(a),(c)	{{ }}2(a),(c)	{{ }}2(a),(c)

{{

}}2(a),(b),(c)

Figure 7-2. Predicted vs. measured CHF for NSP4

{{

}}2(a),(b),(c)

Figure 7-3. P/M CHF vs. pressure for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(b),(c)

Figure 7-4. P/M CHF vs. mass flux for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(b),(c)

Figure 7-5. P/M CHF vs. quality for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(b),(c)

Figure 7-6. P/M CHF vs. boiling length for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(b),(c)

Figure 7-7. P/M CHF vs. cold wall factor for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(b),(c)

Figure 7-8. P/M CHF vs. inlet enthalpy for NuFuel-HTP2™ data with NSP4

7.7 NSP4 Correlation Limit

The NuFuel-HTP2™ CHF data is {{ }}2(a),(c) as tabulated in Table 7-3. The {{ }}2(a),(c) from the NuFuel-HTP2™ CHF test matrix (see Table 3-4) for {{ }}2(a),(c). For {{ }}2(a),(c). {{ }}2(a),(c). The former are randomly chosen validation data while the latter are tied to the NuFuel-HTP2™ CHF test matrix. Tolerance limits at the 95/95 level, for {{ }}2(a),(c) in Table 7-3, are calculated and tabulated in Table 7-4. The maximum tolerance limit is {{ }}2(a),(c). Therefore, the base CHF correlation limit is found to be 1.21 to prevent CHF at the 95/95 level.

Table 7-3. Subsets of NuFuel-HTP2™ data for NSP4

{{

}}2(a),(b),(c)

Table 7-4. Tolerance limits for NuFuel-HTP2™ data with NSP4

{{

}}2(a),(c)

7.8 NSP4 Range of Applicability

The range of applicability in Table 7-5 is determined from the data points used in the development of the NSP4 CHF correlation. The range of applicability listed covers the data at the 95/95 level (using non-parametric, two-sided tolerance limit methods). There is no lower limit on local quality because the trends with regards to quality indicate reasonable and predictable behavior at low qualities.

Table 7-5. Parameter ranges of applicability for NSP4 CHF correlation

Parameter	Range of Applicability
Pressure	500 to 2,300 psia
Mass flux	0.110 to 0.635 Mlb/hr-ft^2
Local quality	< 95%
Inlet quality	≤ 0%

7.9 NSP4 Correlation Performance

The performance of the NSP4 CHF correlation is assessed with a global sensitivity analysis that is performed by randomly selecting 2,500 values for the parameters pressure, mass flux, inlet subcooling, and power. Nodal conditions and boiling length are calculated with a one-dimensional heat balance calculation, using the axial power shapes in Figure 7-9.

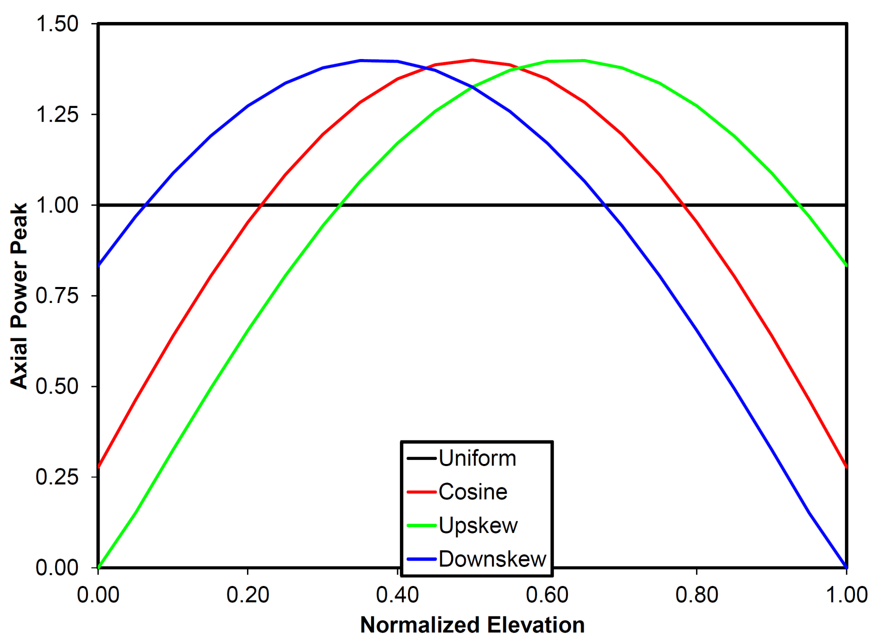

Figure 7-9. Axial flux shapes for NSP4 global sensitivity

The trends of CHF relative to pressure, mass flux, and quality are illustrated in Figure 7-10 through Figure 7-12, respectively, for both the global sensitivity and the underlying NuFuel-HTP2™ data. The CHF demonstrates a {{
}}2(a),(b),(c) in Figure 7-10. The CHF demonstrates a {{
}}2(a),(b),(c) in Figure 7-11. The CHF demonstrates a {{
}}2(a),(b),(c) in Figure 7-12. All of these trends are expected from previous experience and from the trends of the underlying NuFuel-HTP2™ CHF test data.

[

]

Figure 7-10. Global sensitivity – predicted uniform CHF vs. pressure for NSP4

[

]

Figure 7-11. Global sensitivity – predicted uniform CHF vs. mass flux for NSP4

[

]

Figure 7-12. Global sensitivity – predicted uniform CHF vs. quality for NSP4

8.0 Summary and Conclusions

The CHF tests for NuScale were conducted at Stern Laboratories and at AREVA's KATHY test facility to obtain steady-state CHF data used in the derivation and validation of the NSP2 and NSP4 CHF correlations used for NPM safety analysis involving the NuFuel-HTP2™ fuel design.

8.1 The NSP2 CHF Correlation

The NSP2 CHF correlation is developed in two parts. The NSP1 CHF correlation is developed using the data from Stern Laboratories for a preliminary prototypical assembly design that is similar, but not identical to, the NuFuel-HTP2™ design. These data encompass the operating range of the NPM to be analyzed with the VIPRE-01 code for the NuScale DCA. An NSPX factor is separately developed from data obtained from existing KATHY testing {{ }}2(a),(c). The NSPX factor conservatively adjusts the NSP1 correlation such that it conservatively predicts the Stern preliminary prototypic and KATHY K8500 HMP™ test data. The combination of the NSP1 CHF correlation and the NSPX factor forms the basis for the NSP2 CHF correlation that is used for safety analysis performed in support of the NuScale DCA. The NSP2 CHF correlation has the form:

{{[

]}}2(a)(c)

where,

$A = P/P_{crit}$

$B = 1/G$

$C = X$

{{ }}2(a),(c)

{{ }}2(a),(c) (cold wall factor)

{{ }}2(a),(c)

P = pressure, psia

P_{crit} = critical pressure: 3204 psia

G = local mass flux, 10^6 lbm/hr-ft^2

X = local equilibrium quality

{{ }}2(a),(c)

{{ }}2(a),(c)

{{ }}2(a),(c)

Z_{boil} boiling length, in.

{{ }}2(a),(c)

c_x = CHF correlation coefficients from regression (see Table 8-1)

Table 8-1. NSP2 CHF correlation coefficients

Coefficient	Value	Coefficient	Value
c_0	{{ }}2(a),(c)	c_8	{{ }}2(a),(c)
c_1	{{ }}2(a),(c)	c_9	{{ }}2(a),(c)
c_2	{{ }}2(a),(c)	c_{10}	{{ }}2(a),(c)
c_3	{{ }}2(a),(c)	c_{11}	{{ }}2(a),(c)
c_4	{{ }}2(a),(c)	c_{12}	{{ }}2(a),(c)
c_5	{{ }}2(a),(c)	c_{13}	{{ }}2(a),(c)
c_6	{{ }}2(a),(c)	c_{14}	{{ }}2(a),(c)
c_7	{{ }}2(a),(c)	c_{15}	{{ }}2(a),(c)

An F-factor is used to account for the effect of non-uniform axial power profiles, and is defined as:

$$F_{Tong} = \frac{1.11 \times C \int_0^{l_{CHF}} q''(z) e^{-C(l_{CHF}-z)} dz}{q''_{(l_{CHF})} \times (1 - e^{-C \cdot l_{CHF}})}$$ Eq. 8-2

where,

{{ }}2(a),(c)

G = mass flux at CHF location, 10^6 Btu/hr-ft^2

l_{CHF} = elevation of CHF

$q''(z)$ = heat flux at elevation z, 10^6 Btu/hr-ft^2

$q''(l_{CHF})$ = heat flux at CHF location, 10^6 Btu/hr-ft^2

X = equilibrium quality at CHF location

The F-factor is applied to convert the uniform NSP2 CHF to a non-uniform CHF with:

$$q''_{NSP2,n} = q''_{NSP2}/F_{Tong} \quad \text{Eq. 8-3}$$

where,

q''_{NSP2} = uniform CHF, 10^6 Btu/hr-ft^2

$q''_{NSP2,n}$ = non-uniform heat flux, 10^6 Btu/hr-ft^2

F_{Tong} = Tong non-uniform flux factor

The NSP2 CHF correlation is validated against NuFuel-HTP2™ design-specific CHF data obtained for NuScale at AREVA's KATHY test facility. The validation demonstrates that measured CHF values for KATHY NuFuel-HTP2™ data **[ ]** the Stern preliminary prototypic design for comparable operating conditions.

Evaluation of the NSP2 CHF correlation indicates that the correlation provides a conservative prediction **[ ]** KATHY NuFuel-HTP2™ test data. A correlation limit of 1.17 ensures at the 95/95 level that CHF will not be experienced on a rod demonstrating a limiting value, which meets acceptance criterion 1 of Reference 9.1.3, demonstrating compliance with the requirements of 10 CFR 50, GDC 10. The NSP2 CHF correlation must be used in conjunction with local condition calculations from the VIPRE-01 subchannel code (Reference 9.2.3). Qualification of VIPRE-01 for use in NPM calculations is outside of the scope of this report and is addressed in the NuScale Subchannel Analysis Methodology topical report (Reference 9.2.3). The ranges of applicability for the NSP2 CHF correlation are tabulated in Table 8-2.

NuScale requests NRC approval to use the NSP2 CHF correlation in VIPRE-01, within its range of applicability in Table 8-2, along with its associated correlation limit of 1.17, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel. This correlation conforms to acceptance criteria given by the NuScale DSRS, Section 4.4, and the requirements of 10 CFR 50, Appendix A, GDC 10.

Table 8-2. Parameter ranges of applicability for NSP2 CHF correlation

Parameter	Range of Applicability
pressure, psia	300 to 2300
local mass flux, 10^6 lbm/hr-ft^2	0.110 to 0.700
local equilibrium quality, %	≤ 90.0%
inlet equilibrium quality, %	≤ 0.0%

8.2 The NSP4 CHF Correlation

The NSP4 CHF correlation is developed using NuFuel-HTP2™ CHF test data. These data encompass the operating range of the NPM to be analyzed with the VIPRE-01 code for the NuScale DCA. The NSP4 CHF correlation has the form:

{{

}}2(a),(c)

where,

q''_u is the uniform CHF calculated in 10^6 Btu/hr-ft^2
g is the local mass flux in 10^6 lb/hr-ft^2
x is the local equilibrium quality
p is the system pressure in psia
p_c is critical pressure in psia: 3,204 psia
z_b is the boiling length {{ }}2(a),(c) in inches
{{ }}2(a),(c)
{{ }}2(a),(c)
{{
}}2(a),(c)
c_x are the correlation coefficients from regression in Table 8-3

Table 8-3. NSP4 CHF correlation coefficients

Coefficient	Value	Coefficient	Value
c_0	{{ }}2(a),(c)	c_7	{{ }}2(a),(c)
c_1	{{ }}2(a),(c)	c_8	{{ }}2(a),(c)
c_2	{{ }}2(a),(c)	c_9	{{ }}2(a),(c)
c_3	{{ }}2(a),(c)	c_{10}	{{ }}2(a),(c)
c_4	{{ }}2(a),(c)	c_{11}	{{ }}2(a),(c)
c_5	{{ }}2(a),(c)	c_{12}	{{ }}2(a),(c)
c_6	{{ }}2(a),(c)		

A non-uniform flux factor is used to account for the effect of non-uniform axial power profiles, and is defined as:

$$F_{Tong} = \frac{C\int_0^{l_{CHF}} q''(z)e^{-C(l_{CHF}-z)}dz}{q''_{(l_{CHF})} \times (1 - e^{-C \cdot l_{CHF}})} \qquad \text{Eq. 8-5}$$

where,

{{ }}2(a),(c)

G = mass flux at CHF location, 10^6 Btu/hr-ft^2

l_{CHF} = elevation of CHF

$q''(z)$ = heat flux at elevation z, 10^6 Btu/hr-ft^2

$q''(l_{CHF})$ = heat flux at CHF location, 10^6 Btu/hr-ft^2

X = equilibrium quality at CHF location

The F-factor is applied to convert the uniform NSP4 CHF to a non-uniform CHF with:

$$q''_{NSP4,n} = q''_{NSP4,u}/F_{Tong} \qquad \text{Eq. 8-6}$$

where,

$q''_{NSP4,u}$ = uniform CHF, 10^6 Btu/hr-ft^2

$q''_{NSP4,n}$ = non-uniform heat flux, 10^6 Btu/hr-ft^2

F_{Tong} = non-uniform flux factor

Evaluation of the NSP4 CHF correlation indicates that on the average the correlation provides an accurate prediction of NuFuel-HTP2™ test data. A correlation limit of 1.21 ensures at the 95/95 level that CHF will not be experienced on a rod demonstrating a limiting value, which meets Acceptance Criterion 1 of Reference 9.1.3, demonstrating compliance with the requirements of 10 CFR 50, General Design Requirement 10. The NSP4 CHF correlation must be used in conjunction with local condition calculations from the VIPRE-01 subchannel code (Reference 9.2.3). Qualification of VIPRE-01 for use in NPM calculations is outside of the scope of this report and is addressed in the NuScale Subchannel Analysis Methodology topical report (Reference 9.2.3). The ranges of applicability for the NSP4 CHF correlation are tabulated in Table 8-4.

NuScale requests NRC approval to use the NSP4 CHF correlation in VIPRE-01, within its range of applicability in Table 8-4, along with its associated correlation limit of 1.21, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel downstream of HTP™ spacer grids. This correlation conforms to acceptance criteria given by the NuScale DSRS, Section 4.4, and the requirements of 10 CFR 50, Appendix A, GDC 10.

Table 8-4. Parameter ranges of applicability for NSP4 CHF correlation

Parameter	Range of Applicability
pressure, psia	500 to 2300
local mass flux, 10^6 lbm/hr-ft^2	0.116 to 0.635
local equilibrium quality, %	≤ 95%
Inlet equilibrium quality, %	≤ 0%

9.0 References

9.1 Source Documents

9.1.1 *U.S. Code of Federal Regulations*, “Appendix A to Part 50 – General Design Criteria for Nuclear Power Plants,” (10 CFR 50, Appendix A).

9.1.2 *U.S. Code of Federal Regulations*, “Part 50 – Domestic Licensing of Production and Utilization Facilities,” (10 CFR 50).

9.1.3 U.S. Nuclear Regulatory Commission, “Design-Specific Review Standard for NuScale SMR Design,” Section 4.4, June 2016.

9.1.4 NuScale Power, LLC, “Quality Assurance Program Description for the NuScale Power Plant,” NP-TR-1010-859-NP-A, Rev. 3, December 2016, ML16347A405.

9.2 Referenced Documents

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

9.2.2 NuScale Power, LLC, "Critical Heat Flux Test Program Technical Report," TR-1113-5374, January 2014, Rev. 0, ML14024A452.

9.2.3 NuScale Power, LLC, "Subchannel Analysis Methodology," TR-0915-17564, Rev. 1, February 2017.

9.2.4 Tong, L.S., et al., “Influence of Axially Non-uniform Heat Flux on DNB,” AIChE Chemical Engineering Progress Symposium, Series 62, (1966), 64:35-40.

Appendix A. Local Conditions

Definitions:

TEST	Test identifier
POINT	Test point
Z	Elevation of CHF detection from bottom of heated length, in.
P	Pressure, psia
G_{in}	Approximate inlet mass flux (test matrix value), kg/s-m^2
ΔT_{sub}	Approximate inlet subcooling (test matrix value), °C
G	Local mass flux, Ml/hr-ft^2
X	Local equilibrium quality
Z_{boil}	Boiling length {{ }}$^{2(a),(c)}$, in.
{{	}}$^{2(a),(c)}$
{{	}}$^{2(a),(c)}$
q"(l_{chf})	Measured CHF, MBtu/hr-ft^2
F-factor	Modified Tong F-factor
M/P	Measured-to-predicted CHF ratio

Notes:

1) Stern and K8500 M/P values are for NSP1 correlation while NuFuel includes the NSPX factor

Table A-1. Local Conditions for Stern U1, U2 and C1 Tests

{{

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

{{

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

{{

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

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

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

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

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

{{

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

{{

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

{{

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

Table A-2. Local Conditions for AREVA K8500 Test

{{[

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

{{[

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

{{[

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

Table A-3. Local Conditions for AREVA K9000, K9100, K9200 and K9300 Tests (NSP2)

{{[

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

{{[

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

{{[

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{{[

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

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

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

Table A-4. Local Conditions for AREVA K9000, K9100, K9200 and K9300 Tests (NSP4)

{{[

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

{{[

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

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

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

{{[

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

Section C

RAI Number	eRAI Number	NuScale Letter Number
13	8795	RAIO-0717-54798
8931	8931	RAIO-0917-56096
8931	8931	RAIO-1117-57350

July 7, 2017

Docket No. PROJ0769

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

SUBJECT: NuScale Power, LLC Response to NRC Request for Additional Information No. 13 (eRAI No. 8795) on NuScale Topical Report TR-0116-21012, “NuScale Power Critical Heat Flux Correlation NSP2,” Revision 0

REFERENCES:
1. U.S. Nuclear Regulatory Commission, “Request for Additional Information No. 13 (eRAI 8795),” dated May 8, 2017.
2. NuScale Topical Report, “NuScale Power Critical Heat Flux Correlation NSP2,” TR-0116-21012, Revision 0, dated October 2016

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. 8795:

- 29724
- 29725
- 29726

Enclosure 1 is the proprietary version of the NuScale Response to NRC RAI No. 13 (eRAI No. 8795). NuScale requests that this enclosure be withheld from public disclosure pursuant to 10 CFR § 2.390. The enclosed affidavits (Enclosures 3 and 4) support this request. Enclosure 3 pertains to the AREVA proprietary information to be withheld from the public while Enclosure 4 pertains to the NuScale proprietary information to be withheld from the public. AREVA proprietary information is denoted by straight brackets (i.e., “[ ]”) while NuScale proprietary information is denoted by double curly brackets (i.e., “{{ }}”).

Enclosure 2 is the nonproprietary version of the NuScale Response to NRC RAI No. 13 (eRAI No. 8795).

Please feel free to contact Darrell Gardner at 980-349-4829 or at dgardner@nuscalepower.com if you have any questions.

Sincerely,

Jennie Wike
Manager, Licensing
NuScale Power, LLC

Distribution: Gregory Cranston, NRC, TWFN-6E55
Samuel Lee, NRC, TWFN-6C20
Bruce Bavol, NRC, TWFN-6C20

Enclosure 1: NuScale Response to NRC Request for Additional Information eRAI No. 8795, proprietary
Enclosure 2: NuScale Response to NRC Request for Additional Information eRAI No. 8795, nonproprietary
Enclosure 3: AREVA Affidavit
Enclosure 4: Affidavit of Zackary W. Rad, AF-0717-54799

Enclosure 2:

NuScale Response to NRC Request for Additional Information eRAI No. 8795, nonproprietary

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8795
Date of RAI Issue: 05/08/2017

NRC Question No.: 29724

Title 10 of the Code of Federal Regulations (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, Reactor design, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

Section 3.1 of TR-0116-21012 describes the data sources used to develop the CHF correlation and provides the test matrices used for testing at Stern Laboratories and the KATHY test loop. NRC staff was not able to identify any discussion regarding the statistical design of the experiments. In particular, NRC staff is questioning whether randomization of the test points was conducted in an effort to preclude the potential for introducing bias into the figure of merit (i.e., CHF). As part of the review of TR-0116-21012, NRC staff needs to establish a finding that the statistical design of the experiment is acceptable. Accordingly, NRC staff requests that NuScale describe how the statisctical design of experiments was treated during testing at Stern Laboratories and the KATHY test loop.

NuScale Response:

The test matrix for the NuScale Power critical heat flux (CHF) testing at Stern Laboratories was designed to include state points distributed across a large range of conditions of pressure, average mass flux, and inlet sub-cooling for all three test bundle designs (unit and guide tube tests with uniform axial power profile, and unit test with cosine axial power profile). Data are taken for each combination of pressure, mass flux, and sub-cooling with no particular state point emphasized more than the others, other than the inclusion of repeat points taken throughout the test campaign, to assure that the test results remain consistent from beginning to end of the a test campaign. This approach is consistent with historical precedent. Taking data at each state point combination allows for a systematic evaluation of trends with regards to pressure, mass flux, and sub-cooling, and a comparison to the expected rod bundle behavior during testing. This approach is preferred over selecting test points to satisfy a particular statistical test design, since a test campaign is comprised of a very large number of test points. The distribution of test points across the envisioned operating space is structured, eliminating any concerns of test design bias.

The test matrices at AREVA's KATHY facility were based on the following guidance:

- {{ }}2(a)(c)
- {{ }}2(a)(c)
- {{ }}2(a)(c)
- {{ }}2(a)(c)

The state points for the KATHY test are distributed across the envisioned operating space, although the state point density is not identical to that of Stern testing. There are a large number of data measured from the four tests that cover the operating space fairly evenly. At low pressures and low mass fluxes an increased amount of data was taken because these test conditions tend to be more challenging.

Impact on Topical Report:
There are no impacts to the Topical Report as a result of this response.

NuScale Power

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8795
Date of RAI Issue: 05/08/2017

NRC Question No.: 29725

Title 10 of the Code of Federal Regulations (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, Reactor design, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

Section 3.1.1.3 and Section 3.1.2.7 of TR-0116-21012 describe the data acquisition systems at Stern Laboratories and the KATHY test loop, respectively. These sections describe the instrumentation used to measure heater power, coolant flow, pressure, and temperature. The measurements for heater power are described as redundant and diverse at both facilities. The coolant pressure and temperature measurements are described as redundant at both facilities. The flow measurement at Stern Laboratories is described as redundant and diverse. However, from the description of the flow measurement at the KATHY test loop, it is unclear to the NRC staff whether measurement redundancy and diversity were considered. NRC staff relies upon adequate measurement redundancy and diversity to support a finding that the experimental data has been accurately measured. Accordingly, NRC staff requests that NuScale describe how flow measurement redundancy and diversity were treated for the testing at the KATHY test loop, and describe how this treatment is assessed to support application of the KATHY test loop results.

NuScale Response:

The three step process used for ensuring the accuracy of flow measurements for the KATHY test loop is:

1. the utilization of calibrated **[** **]** that conform with the NQA-1 quality assurance program requirements,
2. an extensive loop commissioning, performed prior to CHF test data acquisition, where the flow measurements of **[** **]** and
3. the use of **[** **]**

This process was applied for the CHF tests K8500, K9000, K9100, K9200, and K9300 to ensure the accuracy of the flow measurements. The K8500 CHF test was performed in 2014 for the HMP spacer grid design and the K9000-K9300 CHF tests were performed in 2016 specifically for the NuScale fuel design. The flow measurement devices used for the determination of the flow values in the CHF test results are shown in Figure A.

The KATHY loop flow measurements for the K8500 CHF testing were performed using **[** **]**

During the loop commissioning effort for test K8500, prior to the CHF test data acquisition, the flow measurements from the **[** **]**

During the course of CHF data acquisition for K8500, the flow measurements **[** **]** to detect if deviations higher than the tolerance value were present.

The KATHY loop flow measurements for the K9000-K9300 CHF testing for the NuScale Power fuel design were performed using **[** **]**

[

]

[

]

During the loop commissioning effort for K9000-K9300 CHF testing, the flow measurements from the **[**

]

During the course of CHF data acquisition, the flow measurements from **[**

]

Therefore, the accuracy of the flow measurements for CHF testing at the KATHY loop is assured through strict adherence to NQA-1 requirements for instrumentation and calibration, as well as redundant and diverse flow measurement during loop commissioning and data collection:

- **[**

]

Figure A: Flow Measurement Devices used for the Determination of the Flow Value in the CHF Test Data

Figure B: Comparison of [ ] during the KATHY Test Loop Commissioning for K9000-K9300 CHF Testing [ ]

Impact on Topical Report:
There are no impacts to the Topical Report as a result of this response.

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8795
Date of RAI Issue: 05/08/2017

NRC Question No.: 29726

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

Section 3.1.2.7 of TR-0116-21012 provides a high level discussion on the use of “reference points” at the KATHY test loop, which are used to verify test repeatability. There is no similar description of repeatability testing at Stern Laboratories within TR-0116-21012. During an audit of the KATHY test loop, NRC staff noted that, “Test repeatability [at the KATHY test loop] is verified by returning the test loop to pre-defined points and repeating tests at these points. This is in contrast to CHF testing at Stern where random state points within the testing domain are rerun.” NRC staff has not obtained sufficiently detailed information (e.g., repeatability test results, acceptance criteria) to demonstrate acceptable test repeatability for either Stern Laboratories or the KATHY test loop. As part of the review of TR-0116-21012, NRC staff needs to establish a finding that the variability in the CHF measured at repeated test points is acceptably low. Accordingly, NRC requests that NuScale provide evidence to show that repeatability tests were conducted at both Stern Laboratories and the KATHY test loop, and that the variability in the results are acceptably low.

NuScale Response:

For the NuScale Power critical heat flux (CHF) testing at Stern Laboratories, several different state points throughout the range of conditions are repeated in pairs. For each of these, the error is calculated with:

$$error = \frac{|Power_{initial} - Power_{repeat}|}{|Power_{initial}|} \; x\ 100\%$$

The purpose of the repeat points is to assure that the testing is consistent and that nothing has occurred that could skew the overall test results. To this end an acceptance criterion of less than {{

}}2(a)(c)

For the NuFuel-HTP2™ CHF testing at AREVA's KATHY facility, {{

}}2(a)(c)

Impact on Topical Report:
There are no impacts to the Topical Report as a result of this response.

September 25, 2017 Docket: PROJ0769

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

SUBJECT: NuScale Power, LLC Response to NRC Request for Additional Information No. 8931 (eRAI No. 8931) on the NuScale Topical Report, "NuScale Power Critical Heat Flux Correlation NSP2," TR-0116-21012, Revision 0

REFERENCES:
1. U.S. Nuclear Regulatory Commission, "Request for Additional Information No. 8931 (eRAI No. 8931)," dated July 30, 2017
2. NuScale Topical Report, "NuScale Power Critical Heat Flux Correlation NSP2," TR-0116-21012, Revision 0, dated October 2016

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

The Enclosures to this letter contain NuScale's response to the following RAI Questions from NRC eRAI No. 8931:

- 04.04-4
- 04.04-5
- 04.04-6
- 04.04-7
- 04.04-8
- 04.04-9

Enclosure 1 is the proprietary version of the NuScale Response to NRC RAI No. 8931 (eRAI No. 8931). NuScale requests that the proprietary version be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavits (Enclosures 3 and 4) support this request. Enclosure 3 pertains to the NuScale proprietary information to be withheld from the public. Encosure 4 pertains to the AREVA proprietary information to be withheld from the public. NuScale proprietary is denoted by double braces (i.e., "{{ }}) while AREVA proprietary is denoted by brackets (i.e., "[ ]"). Enclosure 1 has also been determined to contain Export Controlled Information. This information must be protected from disclosure per the requirements of 10 CFR Part 810.

Enclosure 2 is the nonproprietary version of the NuScale Response to NRC RAI No. 8931 (eRAI No. 8931).

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

If you have any questions on this response, please contact Darrell Gardner at 980-349-4829 or at dgardner@nuscalepower.com.

Sincerely,

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

Distribution: Gregory Cranston, NRC, OWFN-8G9A
Samuel Lee, NRC, OWFN-8G9A
Bruce Bavol, NRC, OWFN-8G9A

Enclosure 1: NuScale Response to NRC Request for Additional Information eRAI No. 8931, proprietary

Enclosure 2: NuScale Response to NRC Request for Additional Information eRAI No. 8931, nonproprietary

Enclosure 3: Affidavit of Zackary W. Rad, AF-0917-56097
Enclosure 4: Affidavit of Nathan E. Hottle

Enclosure 2:

NuScale Response to NRC Request for Additional Information eRAI No. 8931, nonproprietary

NuScale Power, LLC
1100 NE Circle Blvd., Suite 200 Corvalis, Oregon 97330, Office: 541.360.0500, Fax: 541.207.3928
www.nuscalepower.com

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-4

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

NRC staff conducted an audit of the calculations supporting the development of the NSP2 CHF correlation at the NuScale office in Rockville, MD on June 13-15, 2017 (ML17138A113). During the audit NRC staff identified additional information that needed to be added to Appendix A of TR-0116-21012. This information is necessary for NRC staff to establish a finding that the correlation coefficients and limit were calculated from an appropriate database using appropriate methods. Accordingly, NRC staff request that NuScale update Appendix A of TR-0116- 21012 to include columns for (1) the Tong Factor, (2) measured-to-predicted values, and (3) inlet subcooling temperature.

NuScale Response:

TR-0116-21012, Appendix A has been updated to include columns for the Tong factor, measured-to-predicted values and the inlet subcooling. Additionally, the inlet flow and subcooling data columns are for test matrix specifications and are not measured test data. The revised Appendix A has been incorporated into the topical report as depicted by the markup included in the RAI response.

Impact on Topical Report:
Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, has been revised as described in the response above and as shown in the markup provided with the response to question 04.04-9.

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-5

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

TR-0116-21012 does not contain plots to demonstrate the measured-to-predicted performance of the CHF correlation. NRC staff relies upon such information to support a finding that the CHF correlation and limit establish a 95/95 limit. Accordingly, NRC staff request that NuScale provide the following plots:

a. Measured-to-Predicted vs Pressure
b. Measured-to-Predicted vs Mass Flux
c. Measured-to-Predicted vs Quality
d. Measured-to-Predicted vs Boiling Length
e. Measured-to-Predicted vs Inlet Enthalpy
f. Measured-to-Predicted vs Hydraulic Diameter Ratio

NuScale Response:

Measured-to-predicted (M/P) bias plots for pressure, mass flux, quality, boiling length, hydraulic-to-heated diameter ratio, and inlet enthalpy are illustrated below in Figures 1 through 6, respectively, for NuFuel-HTP2™ data (K9000 - K9300 tests) using the NSP2 CHF correlation within the range of applicability from Table 7-2 of TR-0116-21012:

Parameter	Range of Applicability
pressure, psia	300 to 2,300
local mass flux, $Mlb/hr\text{-}ft^2$	0.110 to 0.700
local equilibrium quality, %	≤ 90%
inlet equilibrium quality, %	< 0%

1. The upper limit for the correlation quality range has been revised from 0.95% to 0.90% in response to eRAI 8931, Question 04.04.06 .

These figures indicate that there is distinct conservative bias (i.e. under-predicting data) and the M/P data lie above the correlation limit. The M/P limit is calculated from the correlation limit with:

$$LIMIT_{M/P} = \frac{1}{LIMIT_{P/M}} = \frac{1}{LIMIT_{correlation}} = \frac{1}{1.17}$$

The trends of a linear fit to the data are not flat, but this trend is expected because the NSP2 CHF correlation was not directly correlated to the NuFuel-HTP2™ CHF data. Overall, the NSP2 CHF correlation provides conservative predictions of CHF.

{{[

]}}2(a),(c)

Figure 1. NSP2 Measured-to-Predicted CHF vs. Pressure for NuFuel-HTP2™ Data

{{[

]}}2(a),(c)

Figure 2. NSP2 Measured-to-Predicted CHF vs. Mass Flux for NuFuel-HTP2™ Data

{{[

]}}2(a),(c)

Figure 3. NSP2 Measured-to-Predicted CHF vs. Quality for NuFuel-HTP2™ Data

{{[

]}}2(a),(c)

Figure 4. NSP2 Measured-to-Predicted CHF vs. Boiling Length for NuFuel-HTP2™ Data

{{[

]}}2(a),(c)

Figure 5. NSP2 Measured-to-Predicted CHF vs. Cold Wall Factor for NuFuel-HTP2™ Data

{{[

]}}2(a),(c)

Figure 6. NSP2 Measured-to-Predicted CHF vs. Inlet Enthalpy for NuFuel-HTP2™ Data

Impact on Topical Report:
There are no impacts to the Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, as a result of this response.

NuScale Power

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-6

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

NRC staff conducted an audit of the calculations supporting the development of the NSP2 CHF correlation at the NuScale office in Rockville, MD on June 13-15, 2017 (ML17138A113). An analysis of the measured-to-predicted data, conducted during the audit, showed a subregion of reduced margin exists within the application domain of the NSP2 CHF correlation. This caused NRC staff to question whether the NSP2 correlation limit, proposed in Rev. 0 of TR-0116-21012, is suitable for application within this subregion. Accordingly, NRC staff is requesting that NuScale provide a means for adequate treatment of the low-margin subregion such that the correlation will ensure at the 95/95 level that CHF will not be experienced at the CHF correlation limit.

NuScale Response:

A 3D plot of pressure, mass flux and quality is illustrated in Figure 1 for the NuFuel-HTP2™ data (K9000 - K9300) using the NSP2 CHF correlation. The red points represent the lowest 5% of M/P values and the black points represent the remaining 95% of M/P values. In Figure 1 it is evident that the red points are predominantly clustered in a limited location of the domain (i.e. intermediate pressure, low mass flux, and high quality). This observation is consistent with the issue raised by the RAI question. This same issue is not evident in the Stern CHF data with the NSP1 CHF correlation as illustrated in Figure 2. When the upper quality limit is reduced from 95% to 90% the red points spread out again as illustrated in Figure 3. Therefore, the upper limit on the quality range of applicability has been lowered to 90% and Tables 4-5 and 7-2 of TR-0116-21012 have been revised as follows:

Parameter	Range of Applicability
pressure, psia	300 to 2,300
local mass flux, $Mlb/hr\text{-}ft^2$	0.110 to 0.700
local equilibrium quality, %	$\leq$ 90%
inlet equilibrium quality, %	< 0.0%

{{

}}2(a),(c)

Figure 1. 3D plot of P, G, and X for NuFuel-HTP2™ Data with NSP2

{{

}}2(a),(c)

Figure 2. 3D Plot of P, G, and X for Stern Data with NSP1

{{

}}2(a),(c)

Figure 3. 3D plot of P, G, and X for NuFuel-HTP2™ Data with NSP2 (90% Quality limit)

Impact on Topical Report:
Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, has been revised as described in the response above and as shown in the markup provided with the response to question 04.04-9.

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-7

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

TR-0116-21012 mathematically defined the application domain of the NSP2 correlation. As with all application domains, the NSP2 application domain contains regions which contain no data and regions in which the correlation wil not be used. Therefore, NuScale should identify the expected domain and ensure that the expected domain contains an adequate number of data points. NRC staff needs to establish a finding that there is adequate data density throughout the expected domain. Accordingly, NRC staff request that NuScale provide, at a minimum, the following plots to identify the expected domain of the NSP2 correlation (i.e., the region on each plot where the NSP2 correlation is expected to be used during steady state and transient analysis):

a. Pressure vs Mass Flux
b. Pressure vs Quality

---

c. Mass Flux vs Quality

NuScale Response:

Subchannel analyses of transient events, including anticipated operation occurrences, infrequent events and accidents are expected to remain in the domain defined by:

Pressure: 1,700 to 2,200 psia

Mass Flux: 0.11 to 0.5 Mlb/hr-ft^2

Quality: -40% to 20%

This operation domain is compared to the NuFuel-HTP2™ (K9000 through K9300 tests) and Stern CHF data in Figures 1 through 6. Although Figures 2 and 3 indicate that the operation domain occurs at local quality levels below the majority of the CHF test data, the data density is sufficient to perform all statistical assessments within operation domain and therefore the number of data points is adequate.

In CHF testing the inlet subcooling, mass flux and pressure are fixed and the power is increased until CHF is detected by one of the heated rod thermocouples. In this framework the power is independent of the mass flux. In the NuScale Power Module (NPM) the mass flux increases primarily with core power due to the operating characteristics of the natural circulation reactor coolant system. Therefore, low mass flux values occur in conjunction with low core power in the NPM and conversely high mass flux values occur in conjunction with high core power. This operating characteristic is not evident in the CHF testing since CHF data are only obtained at qualities much greater than would be expected in application domain. This inherent margin to CHF is demonstrated by the figures.

Due to the unique operating characteristics of the NPM design, an additional comparison, based on inlet conditions, is presented. Figures 4, 5 and 6 demonstrate that the test boundary conditions for both Stern and NuFuel-HTP2™ are consistent with the operational domain of the NPM.

{{

}}2(a),(c)

Figure 1. Local Mass Flux vs. Pressure with Mass Flux and Pressure Operation Domain

{{

}}2(a),(c)

Figure 2. Local Quality vs. Pressure with Quality and Pressure Operation Domain

{{

}}2(a)(c)

Figure 3. Local Quality vs. Local Mass Flux with Quality and Mass Flux Operation Domain

{{

}}2(a),(c)

Figure 4. Inlet Mass Flux vs. Pressure with Mass Flux and Pressure Operation Domain

{{

}}2(a),(c)

Figure 5. Inlet Quality vs. Pressure with Quality and Pressure Operation Domain

{{

}}2(a),(c)

Figure 6. Inlet Quality vs. Inlet Mass Flux with Quality and Mass Flux Operation Domain

Impact on Topical Report:
There are no impacts to the Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, as a result of this response.

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-8

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

TR-0116-21012 mathematically defined the application domain of the NSP2 correlation. Based on past experience reviewing CHF correlations, NRC staff is concerned about the potential for regions within the application domain, where non-physical CHF behavior could be exhibited. A “Corner-to-Corner” analysis consists of predicting the CHF value at extreme locations within the application domain of the CHF correlation, and is used to identify regions where the CHF correlation is not applicable. NRC staff relies upon such analyses to identify limitations in the application of a CHF correlation. Accordingly, NRC staff requests that NuScale perform a “Corner-to-Corner” analysis of the NSP2 correlation over it application domain.

NuScale Response:

A corner-to-corner analysis demonstrates performance of the critical heat flux (CHF) correlation at the extremes of its applicable domain. The minimum and maximum points are:

Pressure: 300 and 2300 psia

Mass Flux: 0.11 and 0.70 Mlb/hr-ft^2

Quality: -60 and 90%

Boiling Length: 0.0 and 78.74 in.

Cold Wall Factor: {{ }}$^{2(a)(c)}$

The NSP2 CHF values at all combinations of the above are tabulated in Table 1. There are six cases that have high NSP2 CHF values where the predicted CHF value is greater than 2.0 MBtu/hr-ft^2 and is considered unreliable. Cases 9 and 10 have a boiling length and quality that are mutually exclusive, because a boiling length of 0.0 in. suggests quality must be above 0% for entire length, so -60% quality is not possible. Similarly, cases 15 and 16 have a boiling length and quality that are mutually exclusive, because a boiling length of 78.74 in. suggests quality must be below 0% for entire length, so 90% quality is not possible. The remaining two cases (cases 11 and 12) occur at low pressure (300 psia) and high mass flux (0.7 Mlb/hr-ft^2), which is also not a condition that will be reached in the NuScale power module (NPM). A pressure of 300 psia corresponds to a saturation temperature of 417 °F. In order to be at a temperature of 417 °F the NPM must be in Mode 3 (safe shutdown), at which point the flow must be low due to its first order relationship with power. Therefore, a high flow (greater than that of full operating conditions) is not feasible at such a low pressure. Since these six points are not truly feasible, they are not considered, and the remaining points behave in a predictable manner.

Table 1. Corner-to-Corner points with NSP2 CHF Values

Case	Pressure *psia*	Mass Flux *Mlb/hr-ft^2*	Quality	Boiling Length *in.*	Cold Wall Factor	NSPX Factor	NSP2 *MBtu/hr-ft^2*
1	300	0.110	-0.600	0.000	{{	{{	{{
2	300	0.110	-0.600	0.000			
3	300	0.110	-0.600	78.740			
4	300	0.110	-0.600	78.740			
5	300	0.110	0.900	0.000			
6	300	0.110	0.900	0.000			
7	300	0.110	0.900	78.740			
8	300	0.110	0.900	78.740			
9	300	0.700	-0.600	0.00			
10	300	0.700	-0.600	0.000			
11	300	0.700	-0.600	78.740			
12	300	0.700	-0.600	78.740			
13	300	0.700	0.900	0.000			
14	300	0.700	0.900	0.000			
15	300	0.700	0.900	78.740			
16	300	0.700	0.900	78.740			
17	2300	0.110	-0.600	0.000			
18	2300	0.110	-0.600	0.000			
19	2300	0.110	-0.600	78.740			
20	2300	0.110	-0.600	78.740			
21	2300	0.110	0.900	0.000			
22	2300	0.110	0.900	0.000			
23	2300	0.110	0.900	78.740			
24	2300	0.110	0.900	78.740			
25	2300	0.700	-0.600	0.000			
26	2300	0.700	-0.600	0.000			
27	2300	0.700	-0.600	78.740			
28	2300	0.700	-0.600	78.740			
29	2300	0.700	0.900	0.000			
30	2300	0.700	0.900	0.000			
31	2300	0.700	0.900	78.740			
32	2300	0.700	0.900	78.740	}}2(a),(c)	}}2(a),(c)	}}2(a),(c)

Impact on Topical Report:
There are no impacts to the Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, as a result of this response.

Response to Request for Additional Information
Docket: PROJ0769

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-9

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

The NSP2 CHF correlation uses boiling length as one of the correlation parameters. The parameter ranges, provided in Table 4-5 and Table 7-2 of TR-0116-21012, Rev. 0, do not specify a requirement on inlet subcooling. Based on the use of boiling length in the NSP2 CHF correlation and {{
}}[2(a),(c)], the application range for the NSP2 correlation should be restricted to an application domain with inlet subcooling. Accordingly, NRC staff requests that NuScale update the parameter range in TR-0116-21012 to require inlet subcooling.

NuScale Response:

The parameter range tables (TR-0116-21012; Table 4-5 and Table 7-2) were updated to include a limit on inlet equilibrium quality as depicted by Table 1.

Table 1. Parameter ranges of applicability for NSP2 CHF correlation

Parameter	Range of Applicability
pressure, psia	300 to 2,300
local mass flux, Mlb/hr-ft^2	0.110 to 0.700
local equilibrium quality, %	≤ 90%
inlet equilibrium quality, %	< 0%

Impact on Topical Report:
Topical Report TR-0116-21012, NuScale Power Critical Heat Flux Correlation NSP2, has been revised as described in the response above and as shown in the markup provided in this response.

TABLES

FIGURES

Table 4-3. Data subsets for Stern preliminary prototypic data

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}}2(a),(b),(c)

Table 4-4. Tolerance limits for Stern preliminary prototypic data

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}}2(a),(c)

4.6 Range of Applicability

The range of applicability in Table 4-5 is determined from the data points used in the development of the base CHF correlation. The values for the most significant parameters are tabulated in Table 4-5. The range of data listed covers the data at the 95/95 level (using non-parametric two-sided tolerance limit methods). There is no lower limit on local quality because the trends with regards to quality indicate reasonable and predictable behavior at low qualities.

Table 4-5. Parameter ranges of applicability for base CHF correlation

Parameter	Range of Applicability
pressure, psia	300 to 2300
local mass flux, 10^6 lbm/hr-ft^2	0.110 to 0.700
local equilibrium quality, %	≤ 9590.0%
inlet equilibrium quality, %	< 0.0%

$q''_{NSP2,n}$ = non-uniform heat flux, 10^6 Btu/hr-ft^2

FNU = non-uniform flux factor

The NSP2 CHF correlation is validated against NuFuel-HTP2™ design specific CHF data obtained for NuScale at AREVA's KATHY test facility. The validation demonstrates that measured CHF values for KATHY NuFuel-HTP2™ data **[** **]** the Stern preliminary prototypic design for comparable operating conditions.

Evaluation of the NSP2 CHF correlation indicates that the correlation provides a conservative prediction **[** **]** KATHY NuFuel-HTP2™ test data. A correlation limit of 1.17 ensures at the 95/95 level that CHF will not be experienced on a rod demonstrating a limiting value, which meets acceptance criterion 1 of Reference 8.1.3 demonstrating compliance with the requirements of 10 CFR 50, GDC 10. The NSP2 CHF correlation must be used in conjunction with local condition calculations from the VIPRE-01 subchannel code (Reference 8.2.3). Qualification of VIPRE-01 for use in NPM calculations is outside of the scope of this report and is addressed in the NuScale Subchannel Analysis Methodology topical report (Reference 8.2.3). The ranges of applicability for the NSP2 CHF correlation are tabulated in Table 7-2.

NuScale requests NRC approval to use the NSP2 CHF correlation in VIPRE-01, within its range of applicability in Table 7-2, along with its associated correlation limit of 1.17, for the NuScale DCA and safety analysis of the NPM with NuFuel-HTP2™ fuel. This correlation conforms to acceptance criteria given by the NuScale DSRS, Section 4.4, and the requirements of 10 CFR 50, Appendix A, GDC 10.

Table 7-2. Parameter ranges of applicability for NSP2 CHF correlation

Parameter	**Range of Applicability**
pressure, psia	300 to 2300
local mass flux, 10^6 lbm/hr-ft^2	0.110 to 0.700
local equilibrium quality, %	≤ 9590.0%
inlet equilibrium quality, %	< 0.0%

Appendix A. Local Conditions

Definitions:

TEST	Test identifier
POINT	Test point
Z	Elevation of CHF detection from bottom of heated length, in.
P	Pressure, psia
G_{in}	Approximate inlet mass flux (test matrix value), kg/s-m^2
ΔT_{sub}	Approximate inlet subcooling (test matrix value), °C
G	Local mass flux, Ml/hr-ft^2
X	Local equilibrium quality
Z_{boil}	Boiling length (elevation at which quality is 0.0), in.
{{	}}2(a),(c)
{{	}}2(a),(c)
q"(I_{chf})	Measured CHF, MBtu/hr-ft^2
F-factor	Modified Tong F-factor
M/P	Measured-to-predicted CHF ratio

Notes:

1) Stern and K8500 M/P values are for NSP1 correlation while NuFuel includes the NSPX factor

Table A-1. Local Conditions for Stern U1, U2 and C1 Tests

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

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

Table A-2. Local Conditions for AREVA K8500 Test

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

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

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

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

Table A-3. Local Conditions for AREVA K9000, K9100, K9200 and K9300 Tests

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

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

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

RAIO-1117-57350

November 30, 2017

Docket: PROJ0769

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

SUBJECT: NuScale Power, LLC Supplemental Response to NRC Request for Additional Information No. 8931 (eRAI No. 8931) on the NuScale Topical Report, "NuScale Power Critical Heat Flux Correlation NSP2," TR-0116-21012, Revision 0

REFERENCES:
1. U.S. Nuclear Regulatory Commission, "Request for Additional Information No. 8931 (eRAI No. 8931)," dated July 30, 2017
2. NuScale Power, LLC Response to NRC "Request for Additional Information No. 8931 (eRAI No.8931)," dated September 25, 2017
3. NuScale Topical Report, "NuScale Power Critical Heat Flux Correlation NSP2," TR-0116-21012, Revision 1, dated November 2017

The purpose of this letter is to provide the NuScale Power, LLC (NuScale) supplemental response to the referenced NRC Request for Additional Information (RAI) resulting from the revision of the topical report submitted in Reference 3.

The Enclosures to this letter contain NuScale's supplemental response to the following RAI Questions from NRC eRAI No. 8931:

- 04.04-4
- 04.04-5
- 04.04-6
- 04.04-7

Enclosure 1 is the proprietary version of the NuScale Supplemental Response to NRC RAI No. 8931 (eRAI No. 8931). 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 2 is the nonproprietary version of the NuScale response.

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

If you have any questions on this response, please contact Darrell Gardner at 980-349-4829 or at dgardner@nuscalepower.com.

Sincerely,

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

Distribution: Gregory Cranston, NRC, OWFN-8G9A
Samuel Lee, NRC, OWFN-8G9A
Bruce Bavol, NRC, OWFN-8G9A

Enclosure 1: NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8931, proprietary

Enclosure 2: NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8931, nonproprietary

Enclosure 3: Affidavit of Zackary W. Rad, AF-1117-57351

Enclosure 2:

NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8931, nonproprietary

NuScale Power™

Response to Request for Additional Information

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-4

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

NRC staff conducted an audit of the calculations supporting the development of the NSP2 CHF correlation at the NuScale office in Rockville, MD on June 13-15, 2017 (ML17138A113). During the audit NRC staff identified additional information that needed to be added to Appendix A of TR-0116-21012. This information is necessary for NRC staff to establish a finding that the correlation coefficients and limit were calculated from an appropriate database using appropriate methods. Accordingly, NRC staff request that NuScale update Appendix A of TR-0116- 21012 to include columns for (1) the Tong Factor, (2) measured-to-predicted values, and (3) inlet subcooling temperature.

NuScale Response:

This response revises the changes to the topical report previously provided in the response to this RAI. TR-0116-21012, Table A-3, "Local Conditions for AREVA K9000, K9100, K9200 and K9300 Tests (NSP2)" has been revised to correct local condition values for the K9100 data and new Table A-4, "Local Conditions for AREVA K9000, K9100, K9200 and K9300 Tests (NSP4)" has been added to provide the local conditions used in development of the NSP4 correlation. These changes are reflected in TR-0115-21102, Revision 1 (submitted by separate letter), and are not duplicated in this supplementary response. Revised Table A-3 and new Table A-4 include columns for the Tong factor, measured-to-predicted values and inlet subcooling temperature.

Impact on DCA:

TR-0116-21012 has been revised as described in the response above. The revised TR-0116-21012, Revision 1 was transmitted by a separate letter.

Response to Request for Additional Information

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-5

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

TR-0116-21012 does not contain plots to demonstrate the measured-to-predicted performance of the CHF correlation. NRC staff relies upon such information to support a finding that the CHF correlation and limit establish a 95/95 limit. Accordingly, NRC staff request that NuScale provide the following plots:

a. Measured-to-Predicted vs Pressure
b. Measured-to-Predicted vs Mass Flux
c. Measured-to-Predicted vs Quality
d. Measured-to-Predicted vs Boiling Length
e. Measured-to-Predicted vs Inlet Enthalpy
f. Measured-to-Predicted vs Hydraulic Diameter Ratio

NuScale Response:

This response supplements and revises the original response previously provided by NuScale. The previously provided measured-to-predicted (M/P) bias plots for pressure, mass flux, quality, boiling length, hydraulic-to heated diameter ratio and inlet enthalpy have been revised to address an error concerning the K9100 local condition data used for validation of the NSP2 correlation, as depicted by Figures 6-15 through 6-20 of TR-0116-21012, Revision 1. Additionally, new M/P bias plots for these parameters have been developed to demonstrate the lack of bias associated with the NSP4 correlation, as depicted by Figures 7-3 through 7-8 of TR-0116-21012, Revision 1.

Impact on DCA:

TR-0116-21012 has been revised as described in the response above. The revised TR-0116-21012, Revision 1 was transmitted by a separate letter.

NuScale Power

Response to Request for Additional Information

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-6

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

NRC staff conducted an audit of the calculations supporting the development of the NSP2 CHF correlation at the NuScale office in Rockville, MD on June 13-15, 2017 (ML17138A113). An analysis of the measured-to-predicted data, conducted during the audit, showed a subregion of reduced margin exists within the application domain of the NSP2 CHF correlation. This caused NRC staff to question whether the NSP2 correlation limit, proposed in Rev. 0 of TR-0116-21012, is suitable for application within this subregion. Accordingly, NRC staff is requesting that NuScale provide a means for adequate treatment of the low-margin subregion such that the correlation will ensure at the 95/95 level that CHF will not be experienced at the CHF correlation limit.

NuScale Response:

This supplemental response revises figures in the original response previously provided by NuScale as a result of Revision 1 to the topical report. A revised 3D plot of pressure, mass flux, and quality is illustrated in Figure 1 for the NuFuel-HTP2™ data (K9000 - K9300 tests) using the NSP2 CHF correlation, reflecting corrections of the K9100 HTP2™ data. A 3D plot of pressure, mass flux, and quality is illustrated in Figure 2 for the NuFuel-HTP2™ data (K9000 - K9300 tests) using the NSP4 CHF correlation. The red points in both figures represent the lowest 5% of M/P values and the black and blue points represent the remaining 95% of M/P values. From these figures it is evident that the lowest M/P values are not clustered in one particular subregion, so the current correlation limit is reasonable and acceptable.

{{

}}2(a),(c)

Figure 1- 3D Plot of P, G, and X for NuFuel-HTP2™ Data with NSP2

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}}2(a),(c)

Figure 2- 3D Plot of P, G, and X for NuFuel-HTP2™ Data with NSP4

Impact on DCA:

There is no impact on TR-0116-21012 as a result of this response.

Response to Request for Additional Information

eRAI No.: 8931
Date of RAI Issue: 07/30/2017

NRC Question No.: 04.04-7

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, Section 47 and Section 79 require a final safety analysis report (FSAR) to analyze the design and performance of the structures, systems, and components (SSCs). Safety evaluations, performed to support the FSAR, include accident analyses to (1) demonstrate that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation, including the effects of anticipated operational occurrences (AOOs), and (2) determine the number of fuel failures associated with critical heat flux (CHF) that need to be included in the radiological consequences for postulated accidents. An approved CHF correlation is used in establishing a SAFDL for use in such analyses. Thus, an approved CHF correlation is used to establish a partial basis for demonstrating compliance with the following applicable regulations from Title 10 of the Code of Federal Regulations (10 CFR) which include the General Design Criteria (GDCs) of Appendix A to 10 CFR Part 50:

GDC 10, *Reactor design*, which requires that the reactor core and associated coolant, control, and protection systems be designed with appropriate margin to assure that SAFDLs are not exceeded during any condition of normal operation, including the effects of AOOs.

10 CFR 52.47(a)(2)(iv)(A), 10 CFR 52.47(a)(2)(iv)(B), and GDC 19 as they relate to the evaluation and analysis of the radiological consequences of postulated accidents.

TR-0116-21012 mathematically defined the application domain of the NSP2 correlation. As with all application domains, the NSP2 application domain contains regions which contain no data and regions in which the correlation wil not be used. Therefore, NuScale should identify the expected domain and ensure that the expected domain contains an adequate number of data points. NRC staff needs to establish a finding that there is adequate data density throughout the expected domain. Accordingly, NRC staff request that NuScale provide, at a minimum, the following plots to identify the expected domain of the NSP2 correlation (i.e., the region on each plot where the NSP2 correlation is expected to be used during steady state and transient analysis):

a. Pressure vs Mass Flux
b. Pressure vs Quality

c. Mass Flux vs Quality

NuScale Response:

This response revises figures in the original response previously provided by NuScale. Updated comparisons between the NuFuel-HTP2™ data (K9000 through K9300 tests) and the anticipated operation domain are illustrated in Figures 1 through 6. These updates address a minor error in the K9100 data and do not significantly change the comparisons for NuFuel-HTP2™ data. Stern data is not included in these figures because there was no change to the Stern data. Figures 1 through 3 have been revised to illustrate local condition comparisons, while Figures 4 through 6 are revised to illustrate inlet condition comparisons.

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}}2(a),(c)

Figure 1. NuFuel-HTP2™ local mass flux vs. pressure data with operating domain

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}}2(a),(c)

Figure 2. NuFuel-HTP2™ local quality vs. pressure data with operating domain

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}}2(a),(c)

Figure 3. NuFuel-HTP2™ local quality vs. local mass flux data with operating domain

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}}2(a),(c)

Figure 4. NuFuel-HTP2™ inlet mass flux vs. pressure data with operating domain

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}}2(a),(c)

Figure 5. NuFuel-HTP2™ inlet quality vs. pressure data with operating domain

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}}2(a),(c)

Figure 6. NuFuel-HTP2™ inlet quality vs. inlet mass flux data with operating domain

Impact on DCA:

There is no impact to TR-0116-21012 as a result of this response.

Section D

LO-1117-57378

November 30, 2017

Docket No. PROJ0769

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 Topical Report "Critical Heat Flux Correlations," TR-0116-21012, Revision 1

REFERENCES: 1. Letter from NuScale Power, LLC to U.S. Nuclear Regulatory Commission, "NuScale Power, LLC Submittal of Topical Report TR-0116-21012 'NuScale Power Critical Heat Flux Correlation NSP2,' Revision 0 (NRC Project No. 0769)", Dated October 5, 2016 (ML16279A363)

2. Letter from NuScale Power, LLC to U.S. Nuclear Regulatory Commission, "NuScale Power, LLC Submittal of "Critical Heat Flux (CHF), Topical Report TR-0116-21012, Revision 0, Topical Update, Dated October 13, 2017 (ML17286A89)

NuScale Power, LLC (NuScale) submitted Revision 0 of the licensing topical report "Critical Heat Flux Correlation NSP2", TR-0116-21012 to the NRC for review and approval (Reference 1). The purpose of this letter is to submit Revision 1 of the licensing topical report for NRC review and approval, replacing Revision 0. Revision 1 of the topical report implements the NSP4 CHF correlation and corrects local condition data errors as discussed in Reference 2, and incorporates changes to the topical report associated with NRC requests for additional information.

Enclosure 1 is the proprietary version of the topical report entitled "Critical Heat Flux Correlations", TR-0116-21012, Revision 1. NuScale requests that the proprietary version be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavits (Enclosures 3 and 4) support this request. Enclosure 3 pertains to the NuScale proprietary information to be withheld from the public while Enclosure 4 pertains to the AREVA proprietary information to be withheld from the public. NuScale proprietary is denoted by double braces (i.e., "{{ }}") while AREVA proprietary is denoted by straight brackets (i.e., "[ ]"). Enclosure 2 is the nonproprietary version of the topical report entitled "Critical Heat Flux Correlations", TR-0116-21012, Revision 1.

The proprietary enclosures have been deemed to contain Export Controlled Information. This information must be protected from disclosure per the requirements of 10 CFR § 810.

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

Please feel free to contact Darrell Gardner at 980-349-4829 or at dgardner@nuscalepower.com if you have any questions.

Sincerely,

Thomas A. Bergman
Vice President, Regulatory Affairs
NuScale Power, LLC

Distribution: Gregory Cranston, NRC, OWFN-8G9A
Samuel Lee, NRC, OWFN-8G9A
Bruce Bavol, NRC, OWFN-8G9A

Enclosure 1: "Critical Heat Flux Correlations", TR-0116-21012, Revision 1, proprietary version
Enclosure 2: "Critical Heat Flux Correlations", TR-0116-21012, Revision 1, nonproprietary version
Enclosure 3: Affidavit of Thomas A. Bergman, AF-1117-57385
Enclosure 4: Affidavit of Nathan E. Hottle, AREVA Inc.

LO-1117-57378

Enclosure 2:

"Critical Heat Flux Correlations", TR-0116-21012, Revision 1, nonproprietary version

Note: this enclosure to NuScsale's November 30, 2017 letter to the NRC is Identical to the topical report included in Section B of the current NuScale Letter with two exceptions: the Section B version includes "-A" in the document identification number and the date was updated on the cover page.

Enclosure 3:

Affidavit of Thomas A. Bergman, AF-1118-62427

NuScale Power, LLC

AFFIDAVIT of Thomas A. Bergman

I, Thomas A. Bergman, state as follows:

(1) I am the Vice President of Regulatory Affairs 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 report reveals distinguishing aspects about the process and method by which NuScale develops its critical heat flux correlations.

NuScale has performed significant research and evaluation to develop a basis for this process and 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 Enclosure 1 to the "NuScale Power, LLC Submittal of the Approved Version of NuScale Topical Report TR-0116-21012, 'NuScale Power Critical heat Flux Correlations,' Revision 1".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. – ("[ ]" in the NRC Safety Evaluation Report).

(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 December 19, 2018.

Thomas A. Bergman

Enclosure 3:

Affidavit of Nathan E. Hottle

AFFIDAVIT

COMMONWEALTH OF VIRGINIA)
) ss.
CITY OF LYNCHBURG)

1. My name is Nathan E. Hottle. I am Manager, Product Licensing, for Framatome Inc. (Framatome) and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by Framatome to determine whether certain Framatome information is proprietary. I am familiar with the policies established by Framatome to ensure the proper application of these criteria.

3. I am familiar with the Framatome information contained in the following document: TR-0116-21012-P-A Rev.1, "NuScale Power Critical Heat Flux Correlations," referred to herein as "Document." Information contained in this Document has been classified by Framatome as proprietary in accordance with the policies established by Framatome Inc. for the control and protection of proprietary and confidential information.

4. This Document contains information of a proprietary and confidential nature and is of the type customarily held in confidence by Framatome and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in this Document as proprietary and confidential.

5. This Document has been made available to the U.S. Nuclear Regulatory Commission in confidence with the request that the information contained in this Document be withheld from public disclosure. The request for withholding of proprietary information is made in accordance with 10 CFR 2.390. The information for which withholding from disclosure is

requested qualifies under 10 CFR 2.390(a)(4) "Trade secrets and commercial or financial information."

6. The following criteria are customarily applied by Framatome to determine whether information should be classified as proprietary:

(a) The information reveals details of Framatome's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for Framatome.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for Framatome in product optimization or marketability.

(e) The information is vital to a competitive advantage held by Framatome, would be helpful to competitors to Framatome, and would likely cause substantial harm to the competitive position of Framatome.

The information in this Document is considered proprietary for the reasons set forth in paragraphs 6(b), 6(c) and 6(d) above.

7. In accordance with Framatome's policies governing the protection and control of information, proprietary information contained in this Document has been made available, on a limited basis, to others outside Framatome only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. Framatome policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

SUBSCRIBED before me this 12th

day of December, 2018.

Heidi Hamilton Elder
NOTARY PUBLIC, COMMONWEALTH OF VIRGINIA
MY COMMISSION EXPIRES: 12/31/2022
Reg. # 7777873

HEIDI HAMILTON ELDER
COMMONWEALTH
REGISTRATION NO.
7777873
MY COMM. EXPIRES:
12/31/2022
OF VIRGINIA
NOTARY PUBLIC