ASME VVUQ 30.1-2024

Scaling Methodologies for Nuclear Power Systems Responses

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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FOREWORD

The ASME Codes and Standards Committee for verification, validation, and uncertainty quantification in computational modeling and simulation (VVUQ Committee) is responsible for coordinating, promoting, and fostering the development of standards that provide procedures for verification, validation, and uncertainty quantification of computational models and simulations. One of the subcommittees of the VVUQ Committee is the VVUQ 30 Subcommittee, which is focused on verification, validation, and uncertainty quantification in computational simulation of nuclear system thermal fluids behavior. The VVUQ 30 Subcommittee's charter is to provide the practices and procedures for verification and validation of software* used to calculate nuclear system thermal fluids behavior. While a single model may have many uses, complex systems such as nuclear power plants require a collection of multiple models to be adequately represented. Thus, the focus of the VVUQ 30 Subcommittee is not on a single model, but a specific collection of coupled models (CCM).

Historically, one of the most challenging aspects of determining the credibility of the software* has been ensuring that the validation is applicable to the particular scenario in the real-world system. Many features including size, operating conditions, and a heating source from fission often make it infeasible to obtain prototypical experimental data for nuclear system thermal fluid behavior. Due to cost and safety reasons, experimental facilities are usually scaled down from the real-world plant. Thus, performing validation based on such facilities has the additional complexity (and task) of needing to ensure that the results from validation are applicable to the real-world system. ASME VVUQ 1 defines "applicability" as the relevance of the evidence from the verification, validation, and uncertainty quantification activities to support the use of the computational model for a context of use. However, this is a relativity new definition. In the nuclear industry, applicability, specifically as it relates to ensuring the experimental data is relevant with respect to the behavior of the real-world system, has been called scaling analysis. Scaling has been a major focus in the nuclear industry almost since its inception and has major ramifications in determining if the computational models used to simulate nuclear system thermal fluids behavior can be useful or useless. One of the challenges in obtaining appropriate experimental data for nuclear reactor systems is ensuring that the experiment contains the appropriate physical behavior. Such behavior is often directly impacted by pressures and temperatures, heat fluxes, local geometries (e.g., lengths, areas, volumes), and local fluid properties. However, it is impossible to perform an experiment where all factors can be maintained exactly as would be found in a real-world nuclear reactor.

This Standard, in its first edition, is intended to provide practices and procedures for scaling analysis methodologies. Future revisions will be published as necessary.

Following approval by the ASME VVUQ Standards Committee, ASME VVUQ 30.1-2024 was approved by the American National Standards Institute on June 12, 2024.

* In many other engineering communities, "software" is often used to refer to generic packages, such as commercial off-the-shelf programs, and a specific collection of coupled models used to simulate a specific system would still be considered a model. However, the term "software" is used here to mean the specific collection of couple models (CCM) in order to distinguish between the entire collection of models and a specific model (SM), providing a solution based on geometric configurations and initial and boundary conditions.

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Verification, Validation, and Uncertainty Quantification in Computational Modeling and Simulation

(The following is the roster of the committee at the time of approval of this Standard.)

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In addition, the committee may post errata on the committee web page. Errata become effective on the date posted. Users can register on the committee web page to receive e-mail notifications of posted errata.

This Standard is always open for comment, and the committee welcomes proposals for revisions. Such proposals should be as specific as possible, citing the paragraph number, the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent background information and supporting documentation.

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(a) The most common applications for cases are

(1) to permit early implementation of a revision based on an urgent need

(2) to provide alternative requirements

(3) to allow users to gain experience with alternative or potential additional requirements prior to incorporation directly into the Standard

(4) to permit the use of a new material or process

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(2) the urgency of the case (e.g., the case concerns a project that is underway or imminent)

(3) the Standard and the paragraph, figure, or table number

(4) the editions of the Standard to which the proposed case applies

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SCALING METHODOLOGIES FOR NUCLEAR POWER SYSTEMS RESPONSES

1 PURPOSE, SCOPE, INTRODUCTION, AND NOMENCLATURE

1.1 Purpose

When determining the credibility of a model, a key question is what the accuracy of the computational model is for the real-world conditions where the system will operate. This accuracy is called predicative capability and is often based on the model validation. To estimate the model's predictive capability, first the error of the model needs to be determined under conditions where empirical data is available. This is referred to as the validation error. Often, based on the similarity of the test facilities and real-world systems, the validation error is used as an estimate of the model's error when making predictions on the real-world system. Thus, a key assumption is that the model's predictive capability of the real-world system is similar to the model's accuracy in predicting the empirical (experimental) data. If both systems have similar physical behavior, it is expected that the model's accuracy will be similar in both systems (the real-world system and the experiment).

There can be many reasons why the model's validation error may be very different from the model's predictive capability. While experimentalists strive to ensure that the experiment is similar to the real-world system, some sacrifices often need to be made. For example, due to the large size and inherent complexity, experimental facilities used to provide data to validate models for nuclear power plant scenarios often must be scaled down from the true nuclear power plant dimensions and operational conditions (such as pressure, temperature, and flow rates). This may include operating the experiment at lower powers and pressures, at a reduced size, or using other fluid. While these changes may not directly impact the model validation (since validation is based on the comparison of the empirical data to the model's predictions), these changes certainly impact the applicability of the model for the real-world system. For example, if a specific system was influenced by behavior that was sensitive to a characteristic length (e.g., hydraulic diameter), area (e.g., flow area), and volume, the scaled system (e.g., experiment) could not be scaled in all three values at once. Consider liquid flow through a tube. If the diameter is reduced by a factor of 2, the flow cross-section area and volume must be reduced by a factor of 4 while the wall heat transfer area is still decreased (as diameter) by a factor of 2. Thus, a phenomenon such as boiling, in which all of these geometry factors could be important, requires a method to determine if the scaled system can provide useful data, or if the scaled system is not similar to the particular scenario in the real-world system. In nuclear thermal fluid systems, the relevance of the empirical (experimental) data to the real-world system is determined through scaling analysis. Scaling is not focused on how well the computational model predicts the empirical data (i.e., validation). Instead, scaling is focused on if a model validated with the empirical data will be relevant to the real-world system. In other words, scaling formalizes the connection between the test facility and real-world system.

This Standard provides practices and procedures for determining if experimental data (used to validate models) is applicable to the real-world system. Historically, such analysis has been unique for nuclear reactor applications where conditions of fluid, both single- and two-phase, are highly size dependent due to surface-to-volume ratio, size-dependent interfacial shape (flow regimes), and interfacial area density. However, it is hoped that the presented scaling analyses methodologies developed for the nuclear community can be used to benefit other fields of engineering and science or combined with other methodologies already developed.

1.2 Scope

This Standard is focused on the scaling analysis that is used to evaluate the effects of differences (e.g., distortions) in the phenomenological behavior of experimental facilities compared to the phenomenological behavior of the real-world system. This includes scaling analysis methodologies for supporting the design of facilities and experiments capable of generating data that characterize the phenomena present in an entire system [such facilities are known as integral effects test (IET) facilities] and in components of the system (e.g., the nuclear core or the steam generator) [such facilities are known as separate effects test (SET) facilities].