Final Scientific / Technical Report for the Phase 1 NuScale SMR FOAK Nuclear Demonstration Readiness Project

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1.0 Introduction and Executive Summary

The overarching objective of the Phase 1 NuScale SMR First-of-a-Kind (FOAK) Nuclear Demonstration Readiness Project was to enhance competitiveness of the U.S. nuclear industry by enabling timely deployment of the NuScale small modular reactor (SMR). The scope of this Phase 1 project continued to advance the licensing and design maturity, particularly in those areas related to supporting customer readiness, supply chain integration, cost competitiveness, and cost confidence.

This investment provided by the Government has accelerated development of these designs and technologies so that the existing domestic fleet of nuclear power plants remains viable and the most mature in the nuclear industry. The intent is to have the new, advanced U.S. designs be deployed as early 2026, and be globally competitive.

As a part of the First-of-a-Kind Nuclear Demonstration Readiness Project, NuScale has been developing an advanced reactor design, leading the path for other development projects or complex technology advancements for existing plants that have significant technical and licensing risk.

The NuScale Power team (NuScale) is advancing licensing, engineering, supply chain development, testing, and other required activities to enhance the innovation and competitiveness of the U.S. nuclear industry by enabling timely deployment of the NuScale SMR. Specifically, NuScale is performing the following activities in Phase 1:

- Fully supporting the NRC review of the NuScale DCA to ensure approval of a final safety evaluation report by the end of 2020.
- Improving plant cost confidence and cost competitiveness through design and supply chain advancement, incorporation of constructability best practices, and margin recovery to increase plant power output.
- Accelerating design maturity, technology development, and operational program readiness to support a customer commitment for plant deployment.

The Department of Energy (DOE) Office of Scientific and Technical Information (OSTI), a unit of the Office of Science, fulfills agency-wide responsibilities to collect, preserve, and disseminate both unclassified and classified scientific and technical information (STI) emanating from DOE-funded research and development (R&D) activities at DOE national laboratories and facilities and at universities and other institutions nationwide.

This scientific and technical report provides summaries of the analyses and research that was performed by NuScale under this project that achieves the objective of disseminating information to the nuclear industry to ensure the innovations realized are shared for the benefit of the industry at large.

2.0 Scientific and Technical Information (STI)

The following sections provide summarized abstracts, introductions and conclusions for the scientific and technical scopes of work being disseminated in this report. Full references are provided within this report for each STI topic.

2.1 STI Topic 1: Treatment of Heat Loss during Critical Heat Flux Testing

Data from critical heat flux (CHF) and critical power (CP) tests are used for developing CHF and CP (or dryout) correlations to predict the maximum allowable heat flux at points of operational interest. CHF and CP tests are conducted using heater rod arrays representing fuel rods in a partial fuel bundle. Heat is directly generated in these heater rods depicting the axial power distributions of interest. The test rod array is housed in a slender vertical channel of metallic walls that are generally unheated. During testing, part of the heat generated in the heater rods is lost to the environment through the channel walls. Heat loss through the channel wall has the potential to favor channel thermal-hydraulic (T-H) conditions, and thereby make power measurements non-conservative. Typically, a single conservative estimate of the heat loss obtained from a separate isothermal test of the same test configuration is used regardless of the reactor conditions tested during a test campaign. This paper investigates the theoretical basis for the use of a single value for channel heat loss under varying reactor conditions. Results indicate that this practice has sound theoretical bases when applied with appropriate conservatisms.

This paper presented a review of the current regulatory concerns regarding heat loss from a CHF test section and how it is accommodated in the development of CHF correlations. It also provided calculations with the subchannel thermal hydraulic code VIPRE-01 demonstrating that the standard modeling approach assuming an adiabatic test section wall and reduced heat input into the test section results in a conservatively low prediction of local thermodynamic quality at the location of CHF. This is important as thermodynamic quality is one of the primary correlating parameters of nearly all CHF correlations (Reference 1).

2.2 STI Topic 2: Advanced Manufacturing to Enable the Next Generation of Nuclear Plants

Many of the same manufacturing/fabrication technologies that were employed for light water reactors (LWR) plants built 30-50 years ago are also being employed today to build advanced light water reactors (ALWRs). Manufacturing technologies have not changed dramatically for the nuclear industry even though higher quality production processes are available which could be used to significantly reduce overall component manufacturing/fabrication costs. New manufacturing/fabrication technologies that can accelerate production and reduce costs are vital for the next generation of plants (small modular reactors and GEN IV plants) to assure they can be competitive in today's and tomorrow's market.

This project has been assembled to demonstrate and test several of these new manufacturing/fabrication technologies with a goal of producing critical assemblies of a

2/3rds scale SMR reactor pressure vessel (RPV). Through use of technologies including: powder metallurgy-hot isostatic pressing, (PM-HIP), electron beam welding, diode laser cladding, bulk additive manufacturing, advanced machining, and elimination of dissimilar metal welds (DMWs), EPRI, the U.S. Department of Energy, and the UK-based Nuclear-Advanced Manufacturing Research Centre (Nuclear-AMRC) (together with a number of other industrial team members) will seek to demonstrate the hypothesis that critical sections of an SMR reactor can be manufactured/fabricated in a timeframe of less than 12 months and at an overall cost savings of >40% (versus today's technologies). Major components that will be fabricated from PM-HIP include: the lower reactor head, upper reactor head, steam plenum, steam plenum access ports and covers, and upper transition shell.

The project aims to demonstrate and test the impact that each of these technologies would have on future production of SMRs, and explore the relevance of the technologies to the production of ALWRs, SMRs, GEN IV, Ultra-supercritical fossil, and supercritical CO2 plants. The project, if successful, may accelerate deployment of SMRs in both the USA and UK, and ultimately throughout the world for power production.

Two key technologies: PM-HIP and electron beam welding (EBW) have been covered in this paper. Both technologies have the potential to completely change the way industry fabricates reactor vessels today, to rapidly accelerate deployment of SMRs, and to significantly reduced costs and time toward production of a SMR (Reference 2).

2.3 STI Topic 3: Higher Resolution Radial Reflector Modeling Capabilities in MPACT

To provide high fidelity multiphysics simulations of nuclear reactors, the Consortium for Advanced Simulation of Light Water Reactors (CASL) is developing the Virtual Environment for Reactor Applications (VERA). MPACT, which is the primary deterministic neutron transport solver, employs the 2D/1D method to solve 3D problems, leveraging 2D method of characteristics (MOC) for radial transport and 1D-NEM-P3 for axial transport. To this point, full-and quarter-core MPACT cases have used lower fidelity radial reflector models consisting of an explicit baffle representation, an assembly-width of moderator along the core periphery, and pin-wise representations of pad and vessel components. Building off this previous work, higher resolution capabilities have been added by incorporating a Cartesian subgrid to pins in the reflector, allowing for a more faithful representation of the cylindrical structural components.

Two test problems are assessed in this work. The first is a 2D quarter core model of Watts Bar Unit 1 with a representative cycle of depletion. Comparisons are shown to the previous lower fidelity model, where it is shown that the use of higher resolution capabilities do not result in different pin power or eigenvalue results. The use of higher resolution capabilities does not require significantly more memory or computational time resources. The second case shown is a 2D model representative of the NuScale small modular reactor reflector configuration. This design has interesting characteristics, such as coolant channels in the reflector, and assessments are made highlighting the importance of their detailed modelling.

This paper presents recent improvements made to the reflector modelling capabilities in MPACT, resulting in higher resolution reflector modelling. This has been demonstrated on both a Watts Bar Unit 1 2D quarter core and a 2D slice from a model representing the NuScale design. From the Watts Bar core results, which primarily focus on comparing the high and low fidelity options, effectively no difference in solution was observed between the options and they required effectively the same computational resources. The NuScale results included comparisons between high and low resolution reflector options and where minor differences resulted in that were also negligible. The NuScale comparison also included a comparison of explicit modelling of the reflector coolant channels to smearing them into the reflector region. Larger differences in eigenvalue and pin power were observed, justifying the attempts to explicitly model them. The paper demonstrates that the high resolution reflector capabilities in MPACT are working as intended, and even if the solution differences between low and high resolution are low, it resolves concerns over using low resolution models and provides increased confidence in both past and future analyses.

Future work will continue extending the applications of these models and begin focusing on 3D analyses to assess the effect on larger problems. Larger differences have been observed in the comparisons presented, particularly along the core periphery. Fuel shuffling that may place fuel assemblies with larger differences in in the core interior in later cycles may be of further interest. Furthermore, additional efforts will consider the mesh refinement in the high resolution case, as it may be worthwhile to use a lower resolution than was studied in this paper to help reduce the computational burden (Reference 3).

2.4 STI Topic 4: The Dynamical System Scaling Methodology

This paper introduces a Dynamical System Scaling (DSS) method that can be used to scale physical processes from one temporal and spatial scale to another. It can also be used to assess scale distortions over the entire duration of a process. The DSS method proposes that the states of a system can be represented by process curves in a two-dimensional $(x^1 = \beta, x^2 = \omega)$ phase space endowed with a process metric tensor, g_{ij}, and an embedded process time parameter, τ, defined by the metric, $d\tau^2 = g_{ij}dx^i dx^j$. It is demonstrated that the process time scale is emergent; stretching or contracting relative to a constant interval reference time scale as the process evolves. This paper introduces a transformation law that relates process time to reference time and presents a process metric to measure intervals in process phase space. A key finding is that process curves, defined as solutions to the integral balance equations that govern the process, are geodesics in $\beta-\omega$ phase space when parameterized by the process time, τ. Having defined process curves as geodesics in phase space and process time as the natural parameter for parametrizing the curves, the well-known rules for establishing the geometric similarity of curves under coordinate transformation can be readily implemented to develop the scaling laws for physical processes. It is proposed that the process action is the appropriate normalization factor for the process metric. Lastly, the invariance of the normalized process metric under coordinate transformation provides the relativity principle for scaling dynamical processes. The application of a two-parameter affine transformation to the phase space coordinates yields five distinct methodologies for scaling a dynamical process. Applying the DSS method to a coupled mass and energy transport problem highlights its efficacy. By coupling the physics of dynamical processes to geometric objects, the DSS method can be used to describe, analyze, group into classes, and scale processes using the tools of differential geometry (Reference 4).

2.5 STI Topic 5: NuScale Power Plant Resilience Studies

Because nuclear power plants can operate continuously for periods exceeding one year without the need to refuel, nuclear power has always played an important role in providing reliable electricity to the grid. The advent of advanced SMR designs will further enhance the resiliency of nuclear power. In 2015, NuScale Power launched a research initiative to assess and enhance the resiliency of its plant design. The purpose of this summary is to provide a brief overview of the results of the internal and external collaborative research studies that have been completed and the status of resiliency projects that are currently underway. The basis for the studies was the 50 MWe NuScale power modules incorporated in a standard 12-module (600 MWe) nuclear power plant as shown in Figure 1.

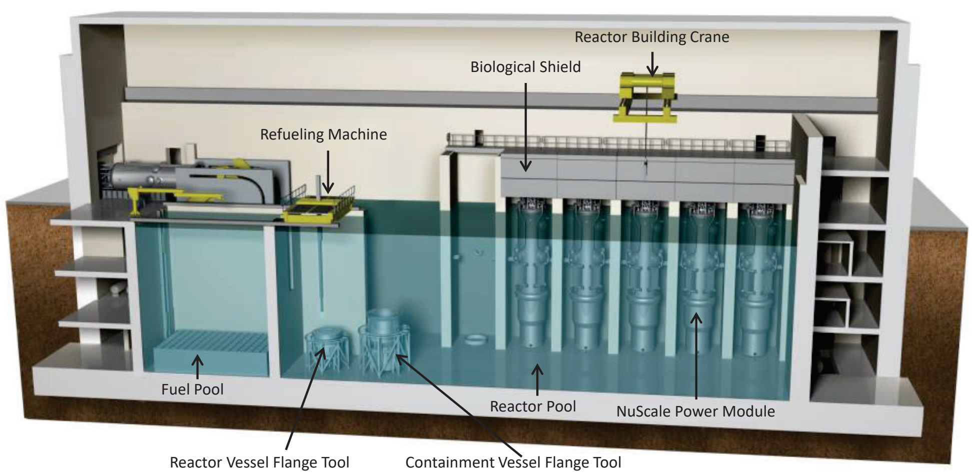

Fig. 1. A 12-Module NuScale reactor building houses the NuScale power modules, fuel pool, and ultimate heat sink for safety.

The table below summarizes the resilience features for a 12-Module NuScale plant.

Table 1. NuScale Plant Resilience Features

Nuclear Safety	A NuScale plant does not require operator or computer actions, or AC/DC power, or additional water to keep the reactors safe for an unlimited period.
Increased Operational Reliability	Eliminated >70% of existing 2015 commercial fleet reactor scrams by design.
Redundant Array of Independent Reactors (RAIR)	RAIR permits staggered refueling so plant continues to produce 550 MWe gross during refueling.
Black-Start Capability	A NuScale Plant can start up from cold conditions without external grid connections using small onsite back-up generators.
Island Mode Power	A single module can supply all house loads for the entire plant to maintain power to a mission critical facility without external grid connection.
Highly Reliable Power for Mission Critical Facilities	A NuScale plant can provide 100 MWe at 99.95% reliability or 50 MWe at 99.98% reliability over the 60-yr lifetime of the plant
First Responder Power with 100% Turbine Bypass	On loss of offsite grid, all 12 modules can remain at full power or be ramped down while rejecting 100% steam to its condensers. Able to provide power to the grid in 50 MWe increments as soon as the grid is restored.
Resilience to Natural Events	The reactor modules and fuel pools are located below grade in a Seismic Category 1 Building; Capable of withstanding a Fukushima type seismic event, hurricanes, tornados, and floods
Resilience to Aircraft Impact	The reactor building is able to withstand aircraft impact as specified by the NRC air-craft impact rule.
Resilience to Catastrophic Loss of Grid and Transportation Infrastructure	A 12 module NuScale plant can provide 100 MWe to a mission critical facility micro-grid for 12 years without new fuel following a catastrophic loss of offsite grid and transportation infrastructure.

NuScale has performed several studies to examine the resilience of its 12-module plant. This includes NuScale plant resiliency to a loss of grid connection, loss of all AC/DC power, reduction of inadvertent reactor scrams, and reliable power for mission critical facilities. A variety of external events, both natural and targeted have also been considered. Three additional studies are underway, *Assessment of Effects of EMP and Geomagnetic Storms on a NuScale Plant* with Oregon State University and EMP expert consultants; *Consequence Evaluations of Cyber-Attacks on Nuclear Power Plants Using Adaptive Sampling of Attack Scenarios* with Brookhaven National Laboratory and DOE; and *Micro-grid Reliability and Resilience* with the Tennessee Valley Authority and University of Tennessee. (Reference 5)

2.6 STI Topic 6: NuScale Power Module Instrumentation

The safe and efficient operation of any nuclear power plant (NPP) depends on accurate and timely measurement of the primary system temperature, pressure, level, flow, and neutron flux. Integral pressurized water reactor (iPWR) or small modular reactors (SMRs) present unique challenges to instrumentation and control (I&C) sensors and their maintenance strategies. More specifically, the calibration and response time of these sensors may have to be verified periodically to ensure that they maintain their required degree of accuracy and speed of response.

A review of technical reports and safety analysis documentation of the NuScale Power Module (NPM) by Analysis and Measurement Services Corporation (AMS), together with NuScale engineers, confirms that the I&C sensors within the NPM will need to be testable as installed to verify their static and dynamic performance at plant operating conditions. Sensor placement and installation as well as the process conditions expected in natural circulation integral SMRs like the NPM are very different from those in large scale NPPs with conventional primary system loop piping. In particular, reactor coolant system (RCS) flows are more complex and flow rates much lower, the average containment temperature is higher, nuclear radiation levels in some areas are greater, and the accessibility of sensors for hands-on maintenance is very limited. These challenges among others related to I&C sensors can be overcome by adapting existing I&C sensor test methods, developing new techniques for non-conventional I&C sensors, and incorporating online monitoring technologies into the I&C architecture of the plant to verify the calibration and response time of sensors within the NPM prior to startup, during operation, and during subsequent refueling outages. These methods and technologies will be demonstrated and validated through a research and development (R&D) grant recently awarded to AMS by the U.S. Department of Energy (DOE) to facilitate timely deployment of the first NuScale SMR in the United States and to enable efficient I&C maintenance strategies during the life of the plant. This paper presents the R&D plan for the DOE project with a focus on temperature measurement needs of NuScale.

2.7 STI Topic 7: Progress of Full-Scale MCNP6™ Model Development of NuScale Small Modular Reactor

This paper presents the recent progress of development of full-scale MCNP6™ small modular reactor within NuScale Power LLC (NuScale) using MCNP6™ version 1.0. This model currently is being used to determine of vessel neutron fluence, nuclear damage, and radiological consequence analysis. The results of the best estimate fluence analysis to support Design Certification Application (DCA) and technical details has been included within a licensing technical report that had been submitted to U.S. NRC for review in 2017. The detailed analysis of using this full-scale NuScale SMR model is focusing on operational radiological external dose exposure, nuclear damage, nuclear heating and neutron activation of SMR components to support optimized design optimizing and supporting request for additional information response activities (Reference 7).

3.0 Contributions to FOAK Nuclear Demonstration Readiness

Over the last 11 years, NuScale has maintained a sustained effort and commitment to SMR deployment in the U.S. to support a first module COD in 2026, and the NuScale SMR FOAK Nuclear Demonstration Readiness Project will ensure readiness and timeliness of new SMR technology introduction to benefit the U.S. nuclear industry. NuScale shares the DOE objective of making nuclear power more affordable and available to a wider range of customers

The NuScale technology will benefit the industry by providing a safer technology that eliminates pumps, valves, and other moving parts while adding safeguards in a design that results in a plant that is virtually impervious to meltdown. The NuScale SMRs have a potential to change the economics of the industry and be cost competitive. The rapid deployment of the NuScale technology is imperative, as we are the only technology that has advanced through the licensing phase to where we are today, with a mature design. With the reduction of nuclear power plants in the U.S. due to end of life, or economic challenges for continued operation, the deployment of NuScale plants in the U.S. is critical to revitalize the industry and ensure the U.S. continues to be a world leader in nuclear power generation. NuScale is developing in-house designs, technologies, and methodologies that have the potential to benefit the current fleet of commercial nuclear reactors, as well as other advanced reactor designs. The NuScale SMR both advances the state of nuclear technology and has significant importance to the nuclear industry. Bringing a new design to market is a monumental undertaking with major challenges in technology, design, financing, licensing, and business acumen. NuScale has achieved significant progress in each of these critical elements, all of which have direct or indirect relevance to future advanced reactor technologies. The benefits of this work will accrue beyond NuScale and its collaborating suppliers. Advances in design, technology, and regulatory elements will extend to other advanced reactor technologies. In turn, this will create more demand for similar products, increase capacity and versatility through manufacturing learning curves, and drive down per-unit costs. Collectively, these advancements will place the U.S. in a strategic position to reclaim international leadership.

3.1 NuScale's Work Benefitting the Industry

NuScale's pioneering work creates benefits beyond the company's bottom line, so investments in NuScale are already helping to advance the industry as a whole. Benefits to multiple industries as a result of NuScale's efforts include:

- Partnering with private business to develop tools and methodologies that build upon the foundational work of NuScale in time-dependent assessments of scale distortions. This work resulted in methodology recommendations and proposed future work to further the topic for use in nuclear applications.
- Providing the small modular reactor industry with a design benchmark for plant resiliency assessments and the types of events and targets that could be overcome.

- Developing creative concepts by collaboration with external entities to develop an approach for configuration, testing, review, and acceptance process definition for equipment qualification.
- Manufacturing and fabrication of equipment for a variety of industrial applications using advanced manufacturing is leveraged by the studies and work NuScale is performing alongside EPRI and international research centers.
- Simplification of display and indication systems by developing field programmable gate arrays (FPGAs) concepts for industries that require platforms to have independence, redundancy, diversity, predictability, and repeatability.
- NuScale advises the Nuclear Energy Institute's advanced reactors working group (ARWG) and the WNA's CORDEL SMR Task Force (chaired by NuScale) by sharing lessons learned from the DCA licensing status. Both these organizations help streamline the design review processes of other advanced technologies. NuScale's Regulatory Affairs team shares its experience with 50 members of the ARWG, including advanced reactor vendors, NEI, DOE, national labs, Platts, and the NRC.
- Working with the U.S. Department of Defense and participation in a study whereby NuScale SMR would provide power to critical national security infrastructure assets.

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5.0 Abbreviations and Acronyms

ALWR	Advanced Light Water Reactor
CHF	Critical Heat Flux
CP	Critical Power
DCA	Design Certification Application
DOE	Department of Energy
DSS	Dynamical Systems Scaling
FOAK	First of a Kind
FPGA	Field Programmable Gate Array
HIPS	Highly Integrated Protection System
I&C	Instrumentation and Control
INL	Idaho National Laboratory
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MPS	Module Protection System
NIST	NuScale's Integral System Test Facility
NPM	NuScale Power Module
NPP	Nuclear Power Plant
OSTI	Office of Scientific and Technical Information
PM-HIP	Powder Metallurgy-Hot Isostatic Pressing
PWR	Pressurized Water Reactor
R&D	Research and Development
RAIR	Redundant Array of Independent Reactors
RPV	Reactor Pressure Vessel

SMR	Small Modular Reactor
STI	Scientific and Technical Information