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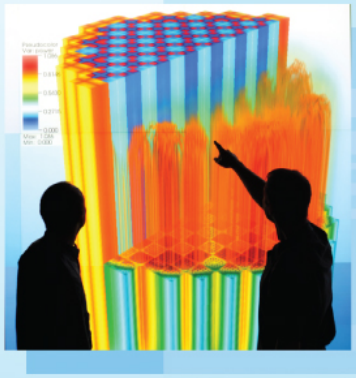
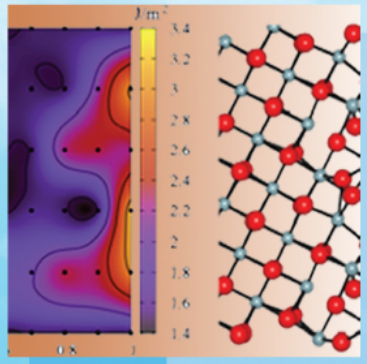
Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



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Perspectives on Nuclear Reactor Thermal Hydraulics

North Carolina State University and Idaho National Laboratory

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Perspectives on Nuclear Reactor Thermal Hydraulics

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ABSTRACT

Over the second half of the 20th century, nuclear reactor thermal-hydraulics was developed vigorously and successfully to meet pressing needs of engineering practice in nuclear reactor design and safety analysis. Along this developmental path, the body of knowledge and capabilities evolved and established itself as a cutting-edge engineering science discipline that benefitted nuclear and other industries. While new opportunities emerged during the past two decades that have potential to enrich the discipline, nuclear thermal-hydraulics as a field has become sluggish, making only incremental, if not marginal, advancements in models and methods used to address the new and emerging needs in nuclear reactor design and safety analysis, despite the critical challenges, e.g., nuclear reactor safety, nuclear proliferation, spent fuel disposition and fuel cycle issues and implications of climate change, facing the nuclear power industry in the 21st century.

This paper argues that conditions have changed and the time is ripe to bring nuclear thermal-hydraulics to a next phase, renewing its intellectual content and technical approaches, to once again serve as the engine for nuclear power developments. In particular, it is envisioned that in the future, the complex and varied issues of nuclear reactor thermal-hydraulic processes could be addressed effectively and efficiently by developing and implementing a data-driven framework for modeling and simulation that brings together and allows for all relevant data and knowledge to be utilized together to enable synergistically predictive tools and processes for nuclear thermal-hydraulics such that "the whole is greater than the sum of its parts." Necessarily, such a change and transition will happen over time and could only succeed if the community works together, leveraging collaborative efforts and sharing of resources and knowledge.

Observation #1: Data Deficit Myth

Contrary to a commonly held belief that there is a lack of data for use in nuclear reactor thermal-hydraulics, the last 10 to 15 years in thermal-hydraulics research has produced an amount of experimental data measured in petabytes, perhaps several orders of

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magnitude more data than all the accumulated data of the previous history of thermal-hydraulics. However, it is true that there is not enough data to adequately support a wide range of continuing efforts in calibration and validation of advanced models and codes. It is, thus, more appropriate to characterize the current situation as an insufficient amount of data available for use with the existing modeling and simulation frameworks. Nevertheless, remarkably large amounts of data have been generated. For instance, each new test run of an integral-test facility could muster from hundreds to a thousand measurement channels. However, it is noted that simulation code benchmarks performed on such integral-effect tests, using existing modeling and simulation frameworks, often used or use as few as four to five plots of data for "by-hand" parameters tuning and a simple "viewgraph norm" assessment to declare the code-to-data comparison a success.

Similarly remarkable is the amount of data generated, for example, in a fundamental boiling heat transfer experiment that uses advanced diagnostics such as infrared thermometry and optical imaging, each at a micron-scale spatial resolution (typically, 5-10 megabytes per image) and acquired at a high speed (1000 to 30000 frames per second). A single test run with one such diagnostics could create up to 300 gigabytes per second of images of a boiling process. Other data-intensive techniques, from PIV (Particle Image Velocimetry) to X-ray radiographic (XR) computer tomography (CT), have become mature and are used increasingly to make routine measurements.

Colorful and impressive as these image-based measurements and data are, the vast amount of data generated in the past and being obtained in current experiments have not made the commensurate impact on either the basic understanding or engineering analysis of nuclear thermal-hydraulics. This present situation with physical experiments is parallel to that of computational experiments using high-fidelity numerical simulation methods and tools to study separate-effects physics under controlled conditions. There, too, petabytes of data are being generated from high-resolution numerical solutions in computationally expensive simulations at "high performance-computing" speed, but with no clear approach or means for effectively utilizing the high-resolution, computational data in nuclear thermal-hydraulics.

For practitioners in nuclear thermal-hydraulics, it becomes critical that the field moves forward from the current "***data-rich, knowledge-poor***" situation.

The first question that emerged is: What are fundamental obstacles on the path to efficient use of the multi-dimensional, high-resolution data, including physical experimental and numerical simulation data, to reduce a prediction's uncertainty in nuclear reactor thermal-hydraulics?

Observation #2: Noise and Pattern

In an era of immense data flows, the biggest challenge is the human limited capacity to digest and process these complex and content rich datasets. A decade into the 21st

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century, the field of nuclear thermal-hydraulics continues to be dominated by investigation methods established and practiced over the past "data-poor" century. Today's researchers and graduate students pore over multi-dimensional, high-resolution datasets to make sense out of its complexity to come up with plausible mechanisms and correlations. However, to make their task on data analysis humanly possible, detailed time- and space-resolved measurements are processed into plots, averaged-out in time and space! This practice largely throws away the physics-originated "noise" content of the data and the value of information associated with it (think of "turbulence").

Equally important is the deficiency of the traditional analysis methods in extracting pattern information and making use of knowledge about collective dynamics as these types of information now are available thanks to the modern imaging techniques. For instance, instead of single-point temperature measurements via thermocouples embedded in a heater block, infrared thermometry (IR) imaging can provide thermal patterns of boiling heat transfer over the entire heater surface. Not only active sites of bubble nucleation and local heat transfer can be measured, but also the complex patterns of bubble-to-bubble interactions (dynamics) are observed in unprecedented details. The complex behaviors evidenced in these data cannot be captured by simplistic models, correlations and flow regime maps based on rudimentary measurements and visual observations dated over five decades ago and still used in today's nuclear reactor thermal-hydraulics codes.

Theoretically, ***two-phase flow patterns and collective behaviors with their long-range signatures appear intrinsically incompatible with the <u>current</u> partial differential equation (PDE)-centric continuum mechanics treatment*** that incorporates interaction physics as a local action and limiting behavior (the nature of continuum mechanics PDEs).

Practically, high-resolution datasets on flow/thermal/phasic patterns obtained by modern diagnostic techniques (e.g., PIV/IR/XR-CT) have not found their use within the current modeling and simulation frameworks.

Observation #3: Expanding Needs vs. Sluggish Developments

Advancement of nuclear thermal-hydraulics is much needed at this stage of nuclear power development, both in breadth and in depth. In breadth, a paradigm shift toward risk-informed decision-making significantly expands the range of scenarios (including beyond-design-basis-events), for which plant system behaviors must be analyzed. Generation III+ plants and small modular reactors also put new requirements, particularly on passive safety system performance and tightly coupled reactor-containment system behaviors. In depth, the analysis must also be more comprehensive, required to provide a quantitative assessment of calculations, i.e., verification and validation (V&V) and uncertainty quantification (UQ). As the demand for predictive capability increases in response to increasing need for reduced uncertainty in plant safety and operational margins, the system becomes more complex, requiring

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considerations of tightly coupled nonlinear multi-physics and multi-scale interactions. Furthermore, traditionally-not-thermal-hydraulics physics, e.g., coolant chemistry, surface materials and microstructures, are known to exert their influence on thermal-hydraulics through microscopic phenomena, e.g., nucleation and wettability.

Over the past 30 years, since the release of RELAP5 code (1979) and equivalent codes, the progress in nuclear thermal-hydraulics – despite isolated successes – has been incremental, even marginal, with respect to a practical impact in nuclear system design and safety analysis. During this period, a significant number of research and development (R&D) efforts were conducted on important topics in nuclear thermal-hydraulics, e.g., boiling heat transfer, flow regimes, interfacial interactions and dynamics. While greatly contributing to the science of multi-phase flow and the training of a new generation of engineers and scientists in nuclear thermal-hydraulics, the R&D activity, its results and publications, remains primarily in the academic realm. The process involves graduate researchers who, after having stared tirelessly at experimental images and records, and increasingly often, also animated results of numerical simulations, come up with correlations that incorporate their "mechanistic understanding" of the observed phenomena or physical process. These new correlations and models developed in academia, however, rarely find their way into nuclear system design and safety analysis codes. By and large, nuclear industry and regulators continue to use legacy codes, with traditional flow regime maps, and empirical/semi-empirical closure laws.

The past three decades were also a period when theory, methods, and tools in Computational Fluid Dynamics (CFD) experienced rapid developments, both for single-phase and multi-phase flow (CMFD). Yet, to date CFD/CMFD applications for nuclear thermal-hydraulics have been limited, in most cases, exploratory in nature or as a complementary tool. A major deficiency for CFD in nuclear applications stems from the fact that processes of importance for nuclear reactor design and safety are complex even when it is a single-phase flow. For instance, thermal mixing, stable and unstable stratification, and boundary layer flows may all be present in a given single-phase flow in a reactor. Developed for non-nuclear applications, CFD codes with a set of turbulence models adjusted for certain flow patterns and conditions are fundamentally incapable of, and inappropriate for capturing complex flow patterns with significant variations in space and time found during reactor transients and accidents.

The challenge is even more formidable in CMFD for two-phase thermal-hydraulics. To date, robust, accurate and efficient methods for computation of multi-dimensional, multi-phase flow with phase changes have been elusive. Research on closure relationships, constitutive models or various separate effects physics had proved to be *ad hoc*, costly, and open-ended. Uncertainty quantification is beyond current reach, but generally the level of confidence in CMFD predictive capability for complex two-phase thermal-hydraulics (e.g., subcooled flow boiling) has not improved adequately given broad efforts and investments over the past twenty years. Notably, the now-legacy mechanistic modeling framework appears not conducive for incorporating these new aforementioned rich content datasets. Once again, the progress relies on graduate researchers to analyze

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these high-resolution, rich content datasets and come up with models. The physics of multi-dimensional, multi-phase interactions and patterns are so complex that it is beyond the capacity of unassisted eyes and minds to discern the nonlinear spatio-temporal dependencies and construct simple, characteristically local, linear and yet physics-accurate correlations.

When a need arises for reducing uncertainty in prediction of a design-, operation-, or safety-significant parameter in nuclear thermal-hydraulics, it takes no less than a decade, more likely two, to carry out the development, from experimental design, development and implementation of diagnostics, to experimental execution, data acquisition, processing, and analysis, to development of models and model parameters calibration, and finally to model implementation in industry-usable software for engineering calculations. Over 20 years have passed since the Rensselaer Polytechnic Institute's foundational works in CMFD; the community today, however, has more "work in progress" and plans to showcase than success stories to tell.

The questions that one must consider are: Is complexity of nuclear reactor thermal-hydraulics the underpinning and unavoidable reason for this sluggish progress (while the research approach has been adequate), or is this indicative of needs for new investigation methods, a new modeling and simulation framework, or both?

One thing that is certain is that it is time to encourage our graduate researchers to think outside-of-the-box of traditional methods in nuclear thermal-hydraulics, and to equip them with new tools and methods to deal with and make use of increasingly rich thermal-hydraulics datasets.

The Opportunities

"The real voyage of discovery consists not in seeking
new landscapes but in having *new eyes*."
— *Marcel Proust*

The past three decades also witnessed an extraordinary progress in science and technology in many related fields that bring opportunities to the advancement of nuclear reactor thermal-hydraulics. This includes an array of unprecedented capabilities enabled by:

(i) Increasing affordability of ***advanced experimental and diagnostic techniques***, e.g., for high-resolution imaging, combination of different flow/thermal/phasic diagnostics, including experimentation under high-pressure, high-temperature conditions of interest to reactor applications;

(ii) Advancement of "***data science,***" including statistical analysis methods and tools for processing of multi-field, multi-dimensional heterogeneous datasets, data mining, pattern recognition, data aggregation, and data assimilation;

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(iii) Methods and tools for ***sensitivity analysis, uncertainty quantification***, model calibration and validation, and design of experiments to maximize the data's informative value;

(iv) Advanced methods in ***computational physics*** that enable effective and accurate solutions for complex non-linear multi-physics, multi-scale problems

- "Old" problems (model equations) can now be approached with new methods and tools, reducing/removing the need to make many simplifying assumptions in physical description and numerical treatment. This enables both more faithfully conserving the underpinning system complexity and more accurate (and robust) numerical solution algorithms (particularly, in tightly coupled thermo-fluid problems with heat transfer and phase changes);

(v) Advancement in ***computer science and software engineering*** that provides methods and tools to accommodate increasingly and necessarily sophisticated software architectural and functional requirements in a new modeling framework (e.g., flexible data-model integration);

(vi) Affordable ***data storage and computational power*** needed for data processing, sensitivity and uncertainty analysis, model calibration, and time- and space-resolved high-fidelity simulations;

(vii) Successes and insights from developments in ***theory and application of computational fluid dynamics*** in broad areas outside nuclear thermal-hydraulics, including multi-phase flow CFD (e.g., chemical reactors, particulate flow, interface tracking);

(viii) ***Community-wide experience***, shared best practice, standards development and accumulative knowledge base from using, innovating, and pushing existing methods and tools in nuclear thermal-hydraulics to the limit, particularly driven by common goals in nuclear reactor safety.

Perspective #1 (Diagnosis): Reductionism vs. Complexity

"It ain't what you don't *know* that gets you into trouble.
It's what you *know for sure* that just ain't so."
— *Mark Twain*

This section argues that the principal issue in understanding and predicting nuclear reactor two-phase thermal-hydraulics lies in complexity of multi-phase flow patterns whose governing physics is not reducible within traditional continuum mechanics framework. Practical multi-phase thermal-hydraulics is complex. Atop a formidable challenge in predicting turbulent flows are effects of microscopic physical processes at interfaces. Interactions between fluid turbulence and multi-scale interfacial dynamics govern macroscopic flow patterns.

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Historically, the practice of multi-phase thermal-hydraulics emerged at the time when the centuries-tested reductionist tradition had led to great successes in continuum mechanics, including methods and tools in theoretical, experimental and computational fluid dynamics. Consequently, it was "natural" that the "divide-and-conquer" strategy's decomposition-quantification-integration dominated the study of multi-phase flow. [1] The continuum mechanics formulation such as two-fluid effective-field models stems from a ***scale separation assumption***. Similar to turbulence modeling, the two-fluid model leaves flow patterns as an afterthought implemented through sub-grid-scale constitutive relations. This scale-separation mindset then focuses significant research efforts on translating measurements, observations and insights about behaviors at all scales into local, instantaneous closure relationships ("mechanistic models") that fit within the PDE-governed framework.

Experimental observations and analyses were carried out to build phenomenological models of interaction(s). Model parameters are calibrated on data from relevant separate-effect tests (SET). The modeling framework then brings together the models to adjust their parameters against data in integral-effect tests (IET). This process of sequential calibration and validation is prone to generating conflicting model parameters tuned, sequentially, on different datasets from SETs and IETs.

In the spirit of reductionism, multi-phase flow interactions at the entity level (e.g., bubbles, droplets, interfaces) are local and instantaneous, and, as such, can be studied in isolation from other interactions and effects of neighboring entities. Theoretically, this assumption is consistent with the PDE framework that does not consider the effect of long-range interactions, memory effects and collective behaviors. Experimentally, the strategy implementation requires that conditions in which elementary entity-level interactions occur are known, well characterized, and can be appropriately reproduced and controlled in a separate-effect study. These requirements are not plausible for two-phase flows; perhaps an exception is low-Reynolds-number dilute monodispersed particulate flow, for which the two-fluid (Eulerian-Eulerian, Eulerian-Lagrangian) theory was developed.

There are other implications. On the one hand, in order to achieve well-characterized behaviors at entity level, efforts in theory, experiments, analyses and computations are focused on simple/simplified flow patterns/configurations, typically in low Reynolds-number, dilute or isolated bubble regimes, e.g., low heat-flux nucleate boiling. The motto "seeing is believing" incentivizes this legacy while ignoring questions about relevancy and

[1] Retrospectively, the approach formulated and adopted four to five decades ago was consistent with the lack of knowledge and data about detailed multi-phase interactions at the time. The level of data/evidence-based uncertainty was so high that physics/intuition-based modeling assumptions deemed more reliable. This led to the state-of-the-art comprehensive and consistent framework that establishes the two-phase flow prediction's credibility.

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scaling of observed ("seen") behaviors to reactor prototypic conditions of interest.[2] On the other hand, the goal for appropriately reproducing conditions is driven into a belief that models developed for entity-level interactions are usable broadly because they are elementary, separate-effect. Further, stove piping between researches on entity-level dynamics (fluid physicists) and system-level dynamics (nuclear engineers) contributed to misconception/misuse of mechanistic models, particularly due to (lack of) treatment and deficient communication about relevance, scaling, applicability, and uncertainty of the models.

Another provision of reductionism is that each and every physics interaction at all scales can be studied in detail, experimentally measured, and eventually quantitatively described. When this is achieved, the model becomes a mature predictive capability. In practice, this is not a reachable goal because of the complexity of multi-phase flow, a sizable number of interactions (constitutive models on mass, momentum, and energy exchanges), and practical impossibility to study individual interactions over a broad range of system and local conditions. In other words, the existing framework is idealistic about implementation, which often comes with pragmatic and programmatic constraints in time and resources.

Finally, it is noted that, existing frameworks for two-phase flow modeling founded on traditional continuum-mechanics-originated averaging principles are deterministic. ***In such frameworks, quantification of uncertainty is added on as an afterthought.*** Input model parameter uncertainties are determined individually, characteristically treated as Gaussian, and computationally propagated towards calculation's output parameters (e.g., figures of merits). Such a treatment may have oversimplified the complex nonlinear interactions between uncertainty sources. Thus, in this respect, the "divide-and-conquer" strategy's impact goes beyond the prediction of system parameters into the realm of uncertainty quantification.

Perspective #2 (Solution): Data-Driven Modeling and Simulation Framework

"*The whole* is greater *than* the *sum* of its *parts*."
— *Aristotle*

The above-discussed perspective explains why existing multi-phase flow modeling and simulation frameworks appear perpetually "data-hungry." This perception also needs to be put in a proper context of existing practice where the increasingly rich and heterogeneous datasets generated by advanced flow diagnostics techniques used in present-day experiments cannot be utilized effectively or incorporated into two-phase flow models based on continuum mechanics frameworks. The resulting situation inhibits

[2] Research on boiling heat transfer and crisis gives strong evidences that physics of high heat-flux boiling and burnout is in a starkly different regime than bubble-centric behaviors observed in boiling at low heat fluxes. A "unified" mechanistic model would unlikely be operational over a range of heat fluxes.

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a positive feedback between experimental research and applications much needed for innovation in multi-phase thermal-hydraulics. It is argued that the underpinning obstacle is the multi-scale nature in multi-phase flow systems. For this reason, it is a daunting task to extract insights and dependencies from multi-dimensional datasets and translate them into "mechanistic models" (constitutive relations). Not only the rich information would be lost in these extractions/translations, but also the process necessarily introduces creative and often strongly simplifying assumptions that are then wired into the ***theory-driven modeling and simulation framework***. Note that hard-wired model-form uncertainties cannot be reduced even by a systematic model parameter calibration. These model-form uncertainties are very hard to discern under limited data (usage) with the state-of-the-practice "viewgraph-based tuning" approach to data analysis in nuclear thermal-hydraulics.

As described, the now-legacy theory-driven framework for two-phase flow modeling has increasingly shown its lack of flexibility for accommodating new data and adapting to new variations in flow configuration and variability of hydrodynamic and physic-chemical parameters. In support of innovation and emerging needs, this variety/variability characteristically grows at a pace that is much faster than the conception and maturation of "mechanistic models." Arguably, this might have been a major contributor to the sluggish progress in nuclear reactor two-phase thermal-hydraulics over the past decades.

For the field to move forward, it appears prudent to encourage explorations into alternative, data-consistent, ***data-driven modeling and simulation frameworks***. A premise of this vision is that high-resolution data is expected to grow even more rapidly and significantly faster than the pace by which mechanistic models and correlations could be developed. Consequently, it could become more cost-effective for the simulation code to have direct access to relevant data (similar to materials or thermo-fluids property databases) and apply pattern recognition and statistical analysis algorithms to extract the required closure information "on-line." For conditions where directly applicable data is absent, the information can be approximated from that of near-by measured conditions. As new experimental data become available, they fill the parameter space and reduce the uncertainty. Such an approach to data fusion/data assimilation is a natural fit for a Bayesian inference framework. The approach is timely, particularly considering the potential of affordable data storage and high-performance-computing data processing power. [*see Opportunity (vi)]*

Not intended to prescribe, the following discussion outlines expectations and implications for a prospective sought-after data-driven framework.

First, the sought-after framework would incorporate a representation of uncertainties in the conservation-law-based system dynamics formulation, possibly in as a system of stochastic integro-differential equations where solvable variables are data-adjustable, imprecise probability density functions that take into account *data uncertainty*. The so-designed UQ-inherent framework would be capable of making use of "raw" and

increasingly rich datasets, minimizing "loss in translation" and time delay (measured in years) from experimental work to "mechanistic models." Specifically, a predictive capability of turbulent multi-phase flow must utilize better the value of a growing body of experimental data about interfacial dynamics, both collective dynamics and elementary interactions (e.g., bubble breakup, coalescence). [*see Opportunity (i)*]

Second, from the UQ point of view, this data-assimilating framework minimizes model-form uncertainty impact in dealing with complex systems. Notably, it reduces reliance on, and the need to wait for, "mechanistic models". The later, once conceived and calibrated on some data, often have their own life detached from the original modeling assumptions and insights, easily misused for conditions outside the model's applicability domain.

Third, the proposed data-centric treatment requires changes in approach to experimentation, modeling, and analysis. On the experimental side, the concept will rely on having experiments that are reconfigurable to enable effective experimentation over a range of conditions. This would be aided by advances in hardware (design, construction, and operation) and software (quantitative PIRT, design-of-experiments) [*see Opportunity (iii)*]. The phasic and flow data can then be processed, stored, and formatted for future mining. That is, the data will be analyzed using pattern recognition and clustering techniques so that the huge amount of data can be condensed into some sort of "tabulated" storage of flow patterns (that may or may not cause breakup and coalescence). When a CFD-based (e.g., two-fluid model) code needs information about flow pattern, or the effect of flow on bubble break-up and coalescence, it "looks up" the databases and calibrates its model/closure laws/flow patterns. Such "on-line" operation is within reach given that computer memory and storage are becoming more affordable with each passing day and effective clustering/recognition techniques that support database searches are now being developed [*see Opportunity (ii, vi)*]. In addition, to support on-line operation, there will be a need for "interpolation" between finite numbers of experimental datasets (and in the future, also data generated by numerical experiments). The more tests/data one could perform and include in the "lookup" database, the more accurate interpolation could become. This way, addition of new physical and numerical experiments would further reduce the overall prediction uncertainty.

One main advantage of this data-driven concept is it will assimilate new multi-dimensional, heterogeneous datasets without having to hard-wire changes of the underlying architectures and models. This becomes achievable by building on advances in methods and tools in software engineering that support intelligent systems [*see Opportunity (v)*] Also, it is suitable for multi-parameters/multi-outputs problems, when processes include other physics (e.g., chemistry/materials effects). It makes use of full richness of time- and space-resolved data, instead of having to "average" the data to a bare bone. In a Bayesian inference spirit, data and models are used in tandem to support specific engineering applications and decisions, in contrast to general-purpose, deterministic equations-based simulation tools.

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In summary, multi-phase flow is a multi-scale (multi-physics) problem. The existing framework (of continuum mechanics) recognizes and addresses this multi-scale nature by providing a multi-scale treatment based on scale separation assumption (***physics decomposition***). As discussed above, such a physics decomposition is not valid for a broad range of complex flow patterns. As a result, in the big picture, efforts in getting experimental data for developing separate-effect, sub-grid-scale/constitutive models are not cost-effective, and, by and large, data obtained are not effectively used. Other multi-scale treatments (e.g., "domain decomposition" in space and "gap-tooth" scheme in time) similarly introduce modeling assumptions that have limited validity in complex, evolving flow patterns of interest to nuclear reactor thermal-hydraulics.

The sought-after data-driven framework with ability to integrate data at all levels should avoid pitfalls of the previous framework. Namely, it would redirect, reduce, and eliminate intermediate steps (and associated with them epistemic uncertainties), including design and performance of experiments to generate data on entity-level interactions, and deduction of the data obtained in such experiments into local, instantaneous mechanistic models (correlations).

Perspective #3 (Implementation): Collaborative Development

"If a problem cannot be solved, *enlarge it*."
- Dwight D. Eisenhower

In an increasingly stringent, global and transparent engineering decision-making and practice, verification and validation and uncertainty quantification (V&V-UQ) become a dominant factor in implementation. Formidable challenges in V&V-UQ come from the multi-scale and multi-physics nature of advanced nuclear reactor simulations, while data heterogeneity and deficit of expertise and information needed to characterize them add to the difficulty in implementing V&V-UQ processes in nuclear reactor engineering applications. In meeting these challenges, the sought-after data-driven predictive capability would use an open knowledge management framework for incorporating relevant data and insights as they become available. At the core of this framework are methods and tools for ***Total Data-Model Integration*** (TDMI) that bring together data, models and simulations to effectively support decision-making in engineering applications. Because of its open, integrative, and practical character, the proposed "total data-model integration" can only succeed when the nuclear reactor thermal-hydraulics community comes together in a community-wide ***knowledge management*** platform, including best practice, standards development and shared knowledge base [*see Opportunity (viii)*]. First and foremost, this is concerned with experimental data (including separate-effect tests, integral-effect tests, and plant measurements) for model calibration and uncertainty quantification in advanced simulation of nuclear reactor thermal-hydraulics. While several TDMI-relevant VUQ methods have emerged and others are under development, their implementation puts a burden on a systematic approach to

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data collection, a consistent framework for data characterization, storage, and management, and making the data available for V&V-UQ processing [*see Opportunity (iii)*]. Furthermore, the TDMI knowledge management nature requires that the raw data and related insights are documented and warehoused, conserving their intrinsic value for use in new applications or for applying new modeling and UQ techniques to known applications.

Undoubtedly, the TDMI would be computationally demanding, particularly due to extreme-scale data processing and large-scale iterative computation as required in optimization and inverse UQ tasks (e.g., calibration of model parameters in multi-variate, multi-response, and multi-dimensional problems against data from multiple types of experiments). The TDMI scope requires that numerical solutions (e.g., of the CFD-based models) are computationally robust, accurate, and efficient, and that software architecture is agile and amenable for dealing with a wide range of data. Development of such TDMI-appropriate methods and tools presents formidable theoretical and algorithmic challenges, requiring selective approaches to different application classes instead of the "one-shoe-fit-all" approach. In an initial phase, an array of practically useful case studies with an increasing level of complexity and coupling can help focus the research and development, while bringing together practitioners, theorists and tool developers. A community-scale coordinated effort is a must in this area too because of a wide range of expertise (from mathematics, fluid physics, experimentalists, data scientist, to software engineer and nuclear/application engineer) needed in implementation of a relevant TDMI application for nuclear reactor thermal-hydraulics.

Education and training of a next generation of nuclear thermal-hydraulics engineers and researchers ought to reflect the above-discussed paradigm shift. In fact, the students should be encouraged to think critically and outside the traditional box of the 20th century's nuclear thermal-hydraulics. Their education must expose them to concepts in complexity, uncertainty quantification, and risk-informed decision-making, in addition to the mechanistic thinking and skills in computer simulations. The next-generation thermal-hydraulics training must be increasingly rich in data science, computational science, and system science, even when their research domain lies primarily in thermal-hydraulics experimentation, modeling, or analysis. So trained young researchers would have the quality needed to face the challenges of the 21st century's nuclear reactor thermal-hydraulics, becoming the driving force. In this respect, it is necessary and timely that nuclear thermal-hydraulics educators themselves get retrained, conceptualizing and implementing a forward-looking educational program in nuclear thermal-hydraulics.

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