Single-Phase CFD Licensing

NRC/Framatome Pre-Submittal Meeting

FRAMATOME

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Agenda

- Objective
- Schedule
- Topical Report Content
- Intended Applications
- Introduction, Background, Outlook
- V&V, PIRT, UQ
- Summary, Discussions, Feedback
- Next Steps

Objective

- Discuss the content and schedule for the upcoming topical report: Single-phase CFD for Fuel Assemblies Characterization (ANP-10354).
- Provide an opportunity for NRC feedback.
- Framatome requests approval for a CFD methodology that constitutes an alternative “virtual” pressure testing platform for LWR fuel assemblies:
  - The methodology accurately predicts the pressure distribution through fuel assemblies, with an uncertainty less than or equal to that of the “physical” experimental platform; the “virtual” data can replace the “physical” data to generate pressure loss correlations for safety analysis in a manner consistent with current reload methods.
  - The methodology can be used to determine the pressure distribution through fuel assemblies placed at various locations inside the core bundle.

Schedule

Informal NRC meeting – September 2020

Pre-submittal technical meeting – June 26th, 2022

Review fee waiver granted – March 29th, 2023

Pre-submittal tactical meeting – June 7th, 2023, today's meeting

Topical Report submittal to the NRC – September 2023

Audit for understanding – 1st quarter 2024

Response to RAIs – 3rd quarter 2024

Additional meetings/technical audits – as needed

NRC approval is requested by 3rd quarter of 2025

Topical Report Content

1. Introduction
    - Purpose and intended applications
    - Regulatory requirements
    - CFD methodology key requirements
2. High-level overview of single-phase CFD methodology development
    - Description of current CFD technology and modeling options
    - Reasoning behind the selection of the most appropriate models
3. Phenomena Identification and Ranking Table (PIRT)
    - Identify of all plausible phenomena (generic CFD)
    - Importance ranking of sources of variability
    - Sensitivity analyses: enhance knowledge, down-select modeling features

Topical Report Content (Continued)

4. Methodology Description
    - Key requirements: geometry, discretization, physical modeling
    - Code qualification, version control, user independence
5. V&V Process
    - Validation database, data evaluation, methodology predictive capability
    - Range of applicability
6. Sample Problems
    - Applications: GAIA FA components, HTP mixing span, ATRIUM 11 fully and partially rodded spans
7. Uncertainty Quantification
    - Parameters that can vary (pressure field prediction methodology)

Intended Application

- Framatome developed a general single-phase CFD methodology for fuel performance evaluation; the methodology is well established and validated for multiple applications, including pressure losses, flow field variables, thermal mixing, and single-phase heat transfer.
- In September 2020 and June 2022, Framatome presented to the NRC the methodology validation status and the predictive performance; it has been concluded the methodology is mature for safety applications.
- To facilitate the review process, it has been decided to proceed with a topical report limited to <u>characterization of pressure fields within LWR fuel assemblies</u>.
- The report will summarize generic requirements to facilitate future licensing of separate CFD applications.

Start of Closed Meeting

Designated Commercial Code

- The single-phase CFD methodology has been validated for the commercial code [ ] ; however, the principles and key elements of the CFD methodology are generic.
- The topical report will document the requirements for establishing a solid foundation for future CFD applications; however, Framatome requests approval for the pressure field prediction methodology in conjunction with the [ ] code.
- The [ ] code is NQA1 qualified; the code vendor performs the code verification before releasing a new version.
- Internally, Framatome controls the code version change through an automated non-regression test process that qualifies the code version and portability to a specific platform in compliance with ASME NQA1 2.7, Section 302. A qualified code version is typically frozen for several years.

“Virtual” Experimental Platform

- It has been proven the single-phase CFD methodology can replicate physical pressure tests, regardless of the test facility and fuel assembly design, with the pressure loss predictions within [ ] of all the data in the validation database, with 95% confidence level.
- The CFD methodology provides a “virtual” experimental platform; once approved, it will be used to generate pressure field data that can be used for developing PLC correlations for safety analysis in a manner consistent with current reload methods that rely on “physical” test data.
- CFD “virtual” testing offers flexible and economical means of sampling the data continuum to extract discrete information at a higher resolution than “physical” testing. “Virtual” testing can provide additional insight into product performance, improve accuracy and consistency between tests, and cover regions within the fuel assemblies, such as end nozzles, that are physically difficult to measure.

Typical CFD Pressure Field Results

Typical CFD Models

Applicability

- LWR Designs: PWR, BWR, SMR
- Geometry: high-fidelity 3D representation of actual hardware:
  - Explicit details of spacers, upper and lower nozzles,
  - Single span, multiple spans, complete inlet/outlet sections, full bundles,
  - Single or multiple fuel assemblies.
- Reynolds numbers: 16,000 to 550,000
- Flow conditions: experimental state-points to nominal reactor conditions

Anticipated Classes of Problems

- Pressure tests for:
  - Modifications of traditional fuel products,
  - New product development and optimization (traditional designs),
  - Non-traditional fuel configurations
- Complement present codes and methods: characterize physics invisible to sub-channel and system tools and not easily measured in physical testing.
- Tool of choice for advanced fuels evaluation and unconventional designs certification; enhance/calibrate current tools for advanced applications.
- Produce quality data to support sound engineering justifications for licensing new products, developing new correlations, etc.
- Address steady and unsteady FOAK problems for which the traditional tools are not suitable.

Continuous Improvement

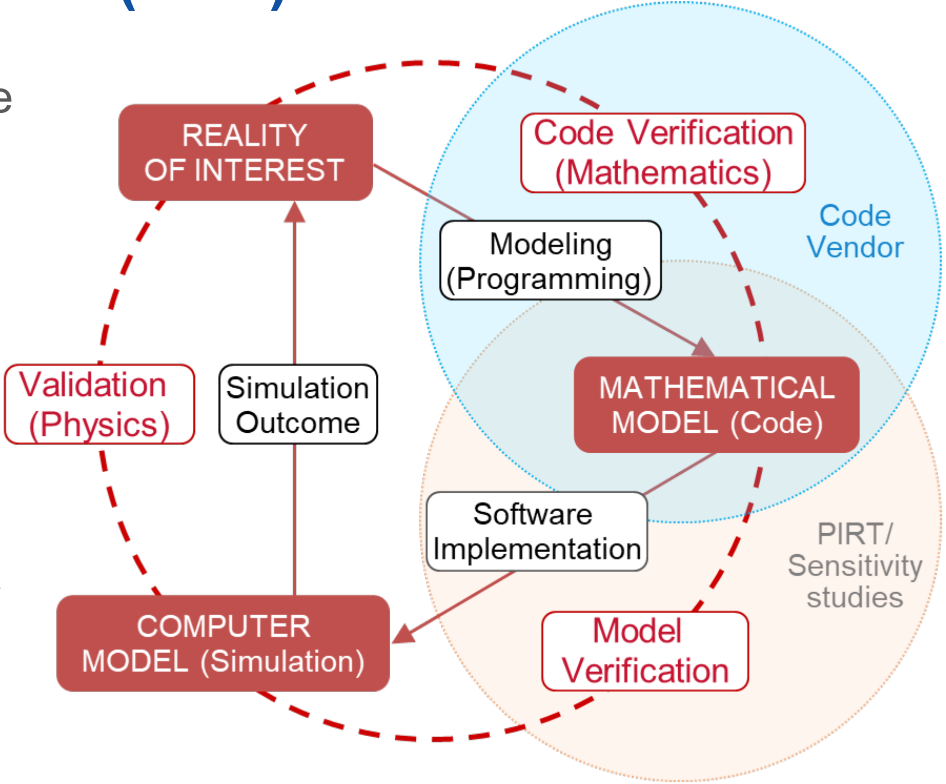
- The methodology is robust and will be able to accommodate future developments such as progresses in computing technology and higher availability of computing resources, without affecting the licensing space.
- The topical report will define the minimum modeling requirements that guarantee the results are accurate. The current lower bound is dictated by pragmatism as a trade-off between accuracy and computing cost.
  - Further mesh refinement, increased number of prism layers, etc., following the meshing rules, can benefit the flow field predictions but only marginally improve PLC predictions.
  - The modeling setup was tuned through iterative validation; the report summarizes the final validation results.
  - Whenever possible, the topical report defines the acceptance criteria in terms of nondimensional parameters.
- Future upgrades shall be controlled by strict guidelines and accompanied by full validation against the existing database.

Verification and Validation (V&V) Process

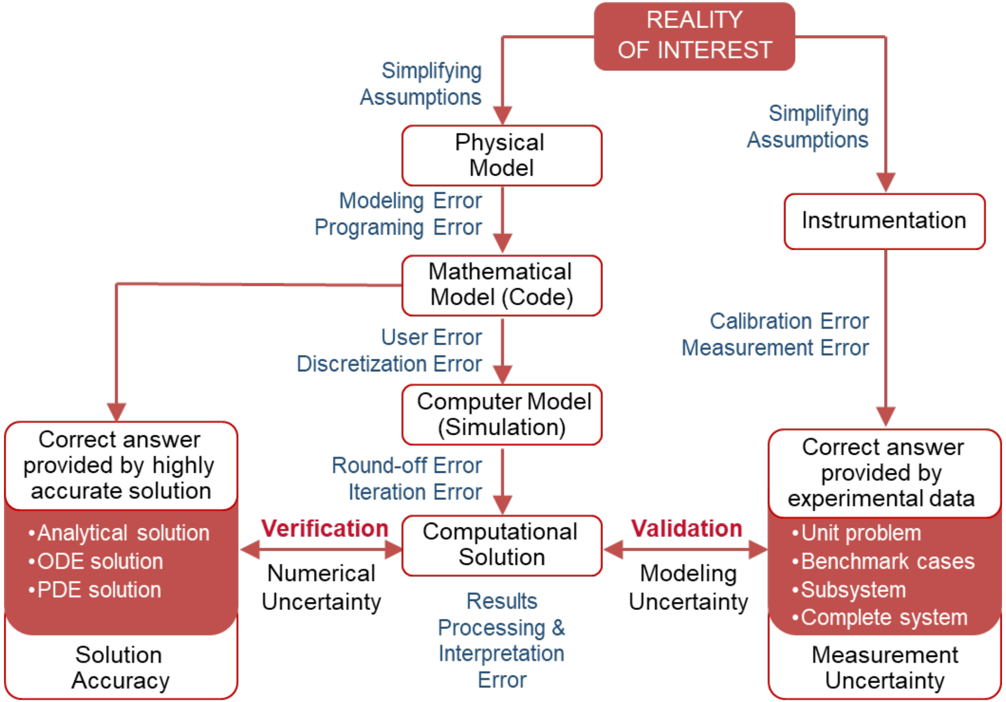
Code Verification: performed by the code vendor/developer through appropriate software engineering practices. (Code Vendor)

Solution/Model Verification: estimates the numerical errors in the simulation due to models' implementation. (Framatome)

Validation: determines the degree to which a model is an accurate representation of the real world, by determining the accuracy of a calculation in terms of deviation from measurements. (Framatome)



V&V Process Map and Sources of Error



REALITY OF INTEREST

Simplifying Assumptions

Physical Model

Modeling Error
Programing Error

Mathematical Model (Code)

User Error
Discretization Error

Computer Model (Simulation)

Round-off Error
Iteration Error

Computational Solution

Results Processing & Interpretation Error

Simplifying Assumptions

Instrumentation

Calibration Error
Measurement Error

Correct answer provided by highly accurate solution

- Analytical solution
- ODE solution
- PDE solution

Solution Accuracy

Verification

Numerical Uncertainty

Validation

Modeling Uncertainty

Correct answer provided by experimental data

- Unit problem
- Benchmark cases
- Subsystem
- Complete system

Measurement Uncertainty

Methodology development and evaluation steps:

1. PIRT: identify potential sources of error.
2. Sensitivity studies: down-select modeling options.
3. Validation: methodology iterative assessment and fine tuning.
4. UQ: quantify variability within final methodology.

PIRT Assessment - Sources of Error

Methodology Validation

- Single-phase CFD methodology is validated for the current Framatome fuel product line,
- 16,000 < Re < 550,000 representative for PWR and BWR conditions and low Re# natural circulation SMRs,
- Experimental data from dissimilar test facilities,
- Test matrix ranging from prototypical 17x17 FA to reduced, wall-confined 5x5 configurations,
- Developmental and prototypical vaned/vaneless spacer designs and end nozzles.

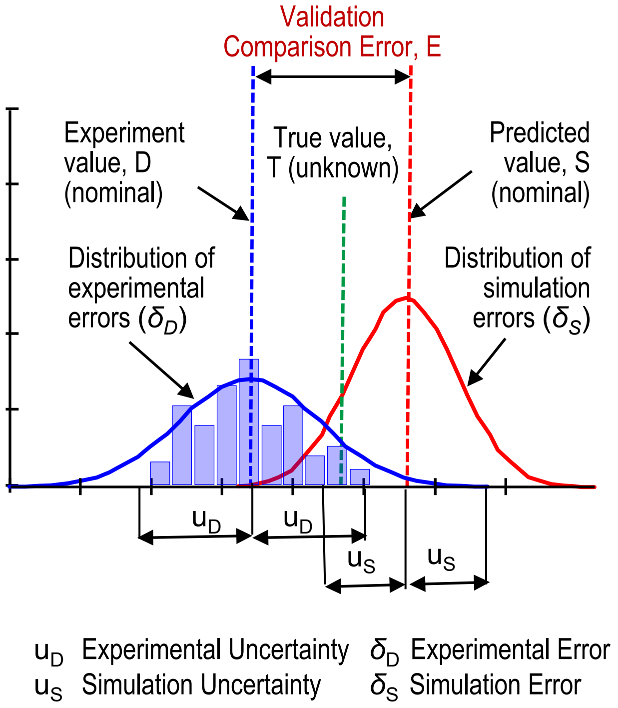
CFD predictive performance is evaluated in terms of validation comparison error, as defined by the ASME V&V20 Standard:

$E = (PLC_{CFD}) - (PLC_{Test})$

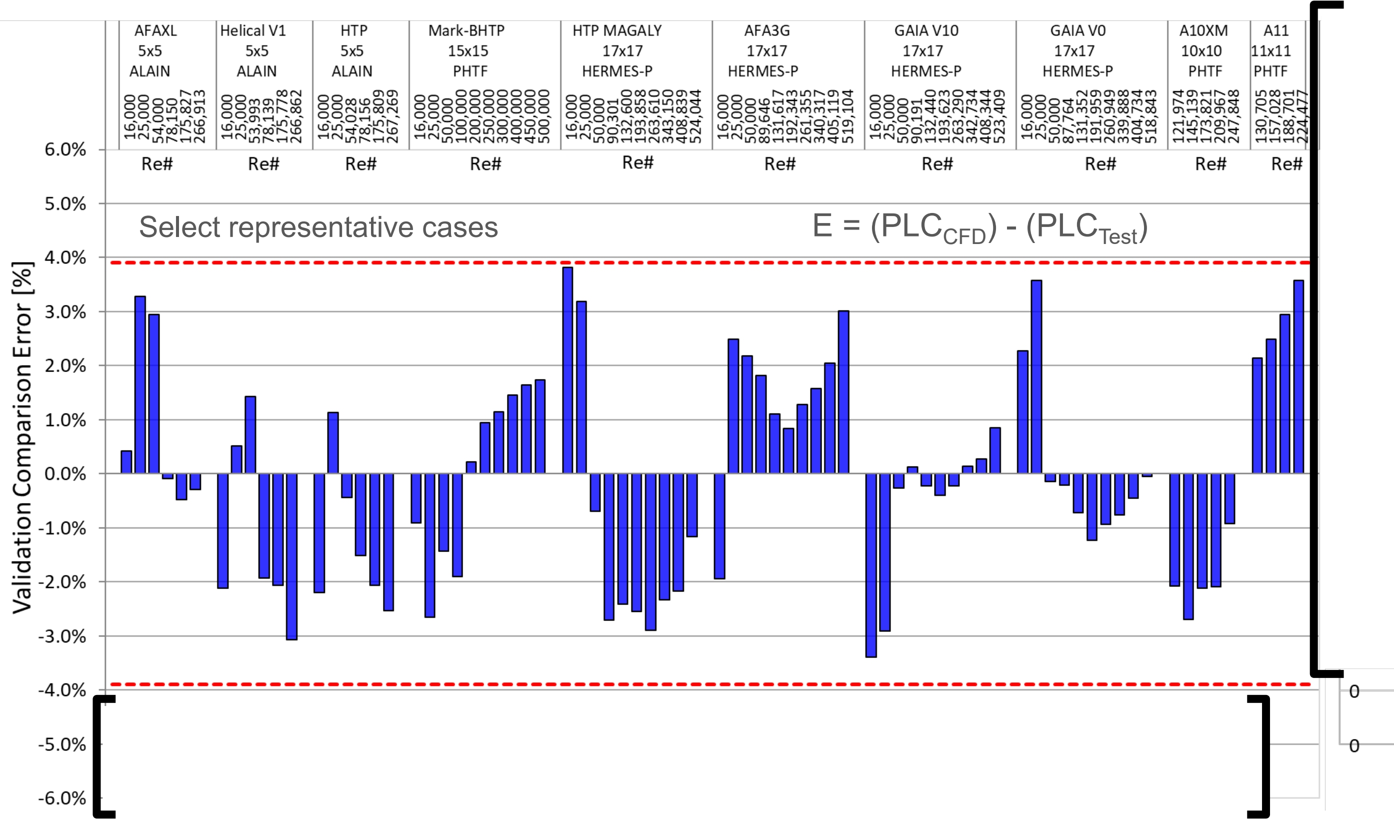
where: PLC_{CFD} – is based on CFD pressure predictions

PLC_{Test} – is based on as-measured test data

ASME V&V 20 Definitions



PLC Methodology Predictive Performance



$$PLC = \Delta P \ / \ 0.5\rho \ V_{ref}^{2}$$

ΔP - pressure drop
ρ - density
V_{ref} - bundle velocity

Summary

- The single-phase CFD methodology is optimized, validated against a complete set of experiments, and applied in a strictly controlled manner.
- The methodology performance has been assessed objectively. The pressure field predictions are accurate; the maximum deviation between the predicted and measured pressure values is lower than the measurement uncertainty. The validation comparison error for all the cases in the validation database is within [ ] with 95% confidence level.
- The methodology has been in use successfully for several years. The [ ] code version for production analyses and the computing platforms are fully qualified. Modeling templates and guideline documents are used to minimize human errors and bias in results interpretation.
- A framework for rigorous CFD analysis is already in place; NRC approval is prerequisite to formal implementation into fuel performance evaluation process for safety applications.

Discussions

Questions / Comments / Feedback

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Nomenclature

ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
FA	Fuel Assembly
FLC, K	Form Loss Coefficient, Pressure Loss Coefficient derived for reload analyses
FOAK	First-Of-A-Kind
GAIA	Framatome’s advanced PWR fuel assembly design
HMP	High Mechanical Performance Fuel
HPC	High Power Computing
HTP	High Thermal Performance Fuel
IGM	Intermediate GAIA Mixer
LWR, PWR, BWR	Light, Pressurized, Boiling Water Reactor
NQA-1	ASME Nuclear Quality Assurance – 1
NRC	US Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
PLC_{CFD}	Pressure Loss Coefficient, based on CFD pressure data
PLC_{Test}	Pressure Loss Coefficient, based on as-measured test pressure data
RAI	Request for Additional Information
SMR	Small Modular Reactor
σ	Standard deviation
V&V	Verification and Validation
y+	Dimensionless distance from the wall

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