framatome

Single-Phase CFD Licensing

NRC/Framatome Pre-submittal Tactical Meeting

06/23/2022

FRAMATOME

Gayle Elliott	US Regulatory Affairs
Will Maxson, Benjamin Farges	Fuel Products
Anca Hatman, Ken Greene, TJ Smiley	US Fuels

Agenda

- Objective and Schedule
- Background and Motivation
- Proposed Topical Report Content
- Single-Phase CFD PLC Methodology Highlights
    - Applicability

  [ ]
    - Key CFD Modeling Requirements
- Validation of Pressure Loss CFD Methodology
    - Validation Process
    - PLC Methodology Predictive Performance
- Proposed Sample Problems
- Concluding Remarks
    - Questions, Comments, Feedback

Objectives

- Outline plans for the [ ] submittal of Topical Report: “Single-phase CFD for Fuel Assemblies Characterization” with focus on RANS PLC evaluations
- As previously discussed with the NRC, this submittal represents a FOAK application, for which we request a fee waiver

Proposed Schedule

Informal NRC meeting – September 2020

Pre-submittal tactical meeting (strategy and scope) – June 2022, today

Pre-submittal meeting (technical content) – [ ]

Topical Report submittal to the NRC – [ ]

Audit for understanding – [ ]

Response to RAIs – [ ]

Additional meetings/technical audits – as needed

NRC approval is requested by [ ]

Background

- Framatome CFD methods development and validation has been an exhaustive, decades-long effort. A single-phase CFD methodology has been established and validated for multiple applications, including pressure losses, flow field, thermal mixing, and single-phase heat transfer
- In September 2020, Framatome presented to the NRC the validation status and the predictive performance of the single-phase CFD methodology; it has been concluded the methodology is sufficiently mature for safety applications
- To streamline the review process, this Topical Report is limited to LWR fuel assemblies PLC characterization alone. It will demonstrate the simulation uncertainty is lower than the measurement uncertainty, and the deviation between PLC predictions and test data is within the measurement uncertainty

Motivation: Replace Physical Testing

- Over the years, emerging single-phase CFD methods were validating against available experimental data and perfected by including advanced [ ] modeling features to replace the early in-house coding and solver modifications
- The present fine-tuned methodology is routinely used to support product development, to evaluate non-standard configurations, and to find solutions to field issues; licensing is the logical step towards full industrialization of single-phase CFD to allow direct support to safety applications:
  - Characterize traditional designs and unconventional configurations without testing
  - Generate PLC correlations for safety analysis
  - Answer open questions relating to advanced codes (ARITA) implementation, plant-specific licensing, etc.

A final comprehensive validation effort determined the methodology is in excellent agreement with the experimental data and can replace testing

Motivation: Development and Design Certification of Non-Traditional Fuel and Reactor Designs

- CFD is versatile and can handle unconventional designs (advanced fuels, advanced reactors, SMRs, etc.) and conditions prohibitive to physical testing
- Traditional codes are not suitable for some non-standard applications and cannot match the CFD ability to address FOAK problems
- Licensed CFD is intended to replace testing and help enhance traditional tools for advanced applications
- Framatome will propose Limitations and Conditions that clarify when confirmatory physical testing is required

Proposed Topical Report Content

Introduction

- Purpose of the Report
- PIRT Analysis Summary
- Applicability Range

Compliance with Regulatory Requirements (SRP Sections 4.2 and 4.4)

Single-Phase CFD PLC Methodology

[ ]

Benchmarking

[ ]

Predictive Capability

[ ]

Sample Problems

Methodology Highlights and Key Requirements

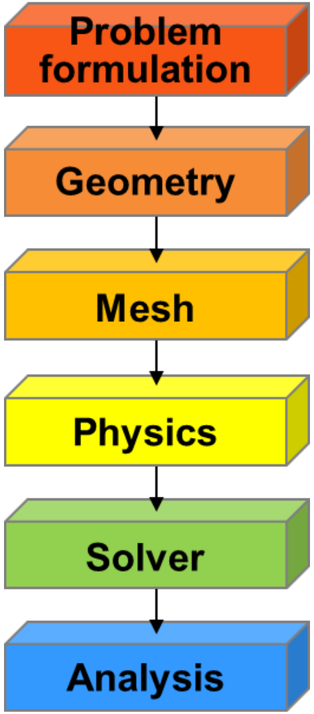
framatome

Applicability

- LWR Designs: [ ]
- Flow conditions: experimental state-points to nominal reactor conditions
- Isothermal: [ ]
- Reynolds numbers: [ ]
- [ ]
- Geometry: high-fidelity 3D representation of actual hardware; not directly applicable to porous media or other major geometry simplifications

  [ ]

CFD Analysis Basic Steps



Define the problem and solving strategy

Create the geometry

Set the coordinate system, determine the interfacing approach for multi-domains problems, generate 3D representation of the computational domain(s) by subtracting the solid CAD geometry from the fluid domain

Generate the volume mesh

Spatial discretization of the computational domain(s)

Define physics

Select physical models for specific applications, specify material properties, initial and boundary conditions, etc.

Run simulation

Select solvers, set solver controls, solve equations, and produce a solution

Results pre-/post- processing tools

Create solution monitors and user functions to analyze and visualize the results

All modeling and analysis steps are rigorously controlled!

CFD Modeling Process Using [ ]

[ ]

[ ] Computer Code Qualification

[ ]

Customized Single-Phase CFD Modeling

[

]

The modeling process is standardized, user-independent, consistent for all fuel/reactor types, automated for routine applications, but flexible enough to accommodate any non-traditional design

Key Modeling Features

Modeling features critical to accurate predictions:

[ ]

The results are right for the right reasons, without outdated custom code modifications or numerical artifacts

Geometry Requirements

- The 3D CAD geometry imported into the CFD code must capture product definition details and the correct relative position of components within the assembly

[ ]

CAD4CFD modeling process is standardized to ensure user-independence and consistency amongst CFD models

framatome

Typical CFD Models for PLC Calculations
Slide 40

Physical Models for PLC Characterization

Single-phase simulations are setup as:

[ ]

The setup is optimized for accurate pressure loss AND flow field results

Spatial Discretization

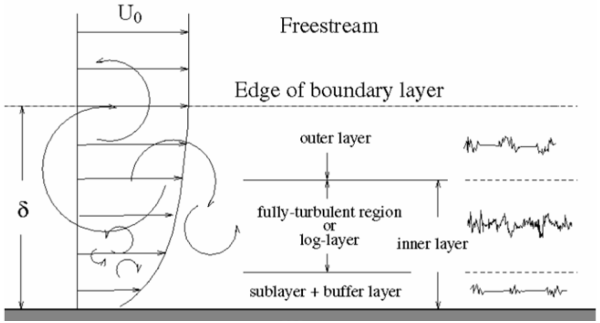
- A unique set of mesh controls guarantees consistent discretization for all spacer types

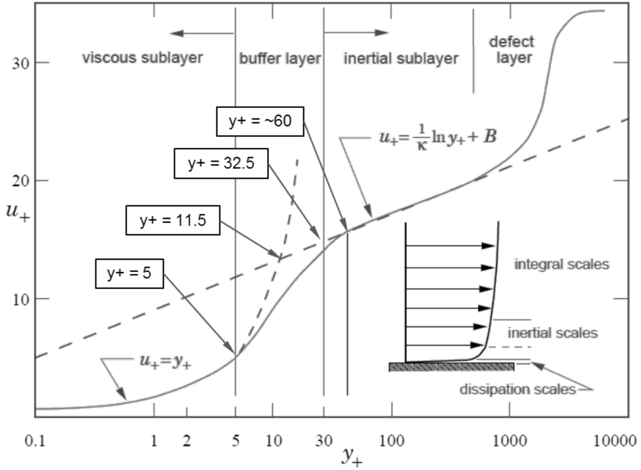
[ ]

Standardized, user-independent meshing process

[ ]

Non-Dimensional Wall Distance y+



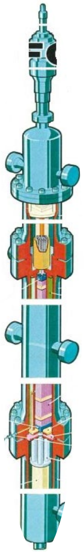


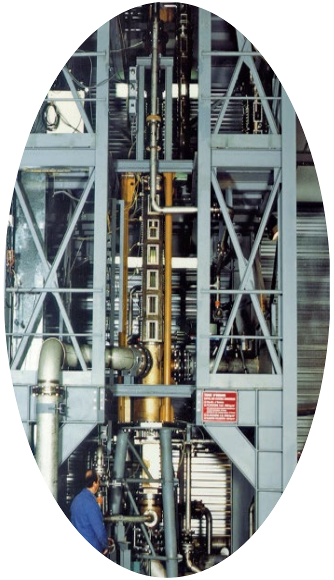
Methodology Validation

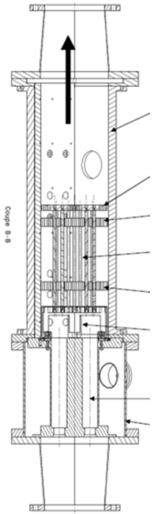
framatome

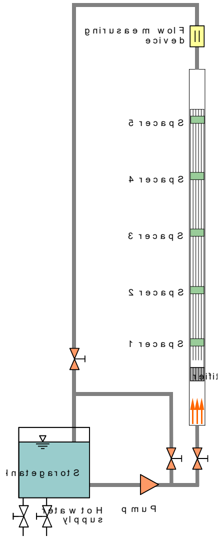
Test Facilities for Pressure Measurements

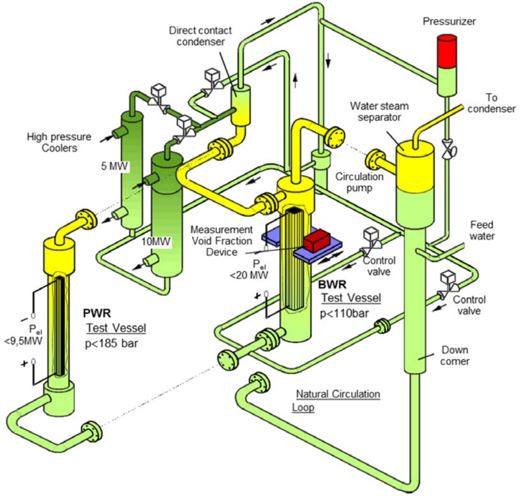
HERMES-P **Le Creusot** **KATHY**











PHTF **MAGALY** **ALAIN**

Validation database comprised of measurements from multiple test loops

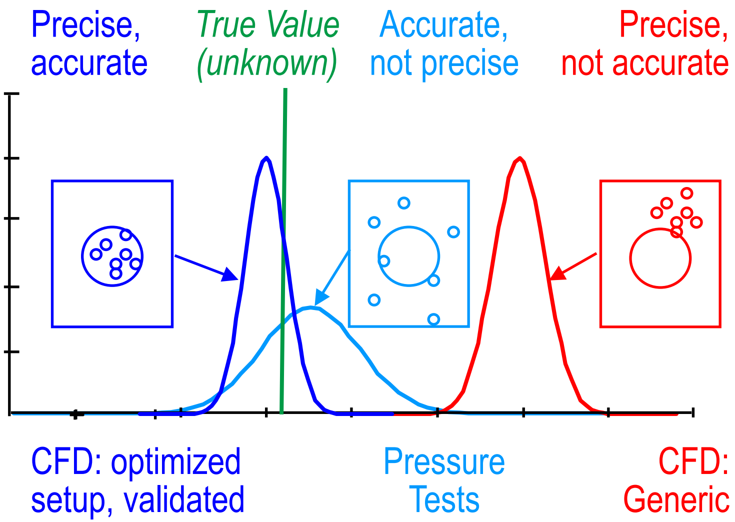
For information only

Brief Description of Test Facilities

PHTF	Portable Hydraulic Test Facility, Richland, US - Operated by Framatome Prototypic full size PWR and BWR Fuel Assemblies; 15 bar; up to 300˚C; Re# up to 300,000; [ ] depending on Re#
HERMES-P	Operated by CEA Prototypic full size (12ft and 14ft) square and hexagonal PWR fuel assemblies; 155 bar; up to 310˚C; Re# up to 500,000; [ ]
MAGALY	Partial bundle, horizontal, prototypic components - Operated by Framatome Up to 10 bar; 80˚C; Re# up to 300,000; [ ]
Le Creusot	Partial bundle, horizontal, prototypic end nozzles - Operated by Framatome Up to 8 bar; 70˚C; Re# up to 200,000; [ ]
ALAIN	Low Pressure Test Facility, Erlangen, Germany - Operated by Framatome Partial bundle, spacers only; 5x5 matrix; 1 bar; up to 80˚C; Re# up to 270,000; [ ]
KATHY	KArlstein Thermal-HYdraulic facility, Karlstein, Germany - Operated by Framatome Full length 5x5 bundle with SSG for CHF tests; up to 172 bar; up to 290˚C; Re# up to 500,000; [ ]

Precision and Accuracy: Experiments vs. CFD

- The experimental data is generally accurate; however, there is significant variability in measurements obtained during different test campaigns, at different test facilities, etc.
- CFD results obtained with a generic setup display less dispersion; however, without systematic benchmarking and modeling optimization, the predicted mean value can deviate from the measured pressure loss by more than15%
- With standardized modeling (geometry, mesh, turbulence) and controlled physical input (properties, state-points), the optimized pressure loss CFD methodology is both precise and accurate



With validated setup, CFD can produce more consistent results than the experiments

Comparative Uncertainty Quantification

[ ]

CFD-based PLC uncertainty evaluation replicates the process established for post-processing test data for safety analysis

PLC Uncertainties - Experimental vs. CFD

The deviation between PLC predictions and measurements is within +/-4% for the entire validation database

Typical CFD Pressure Loss Results

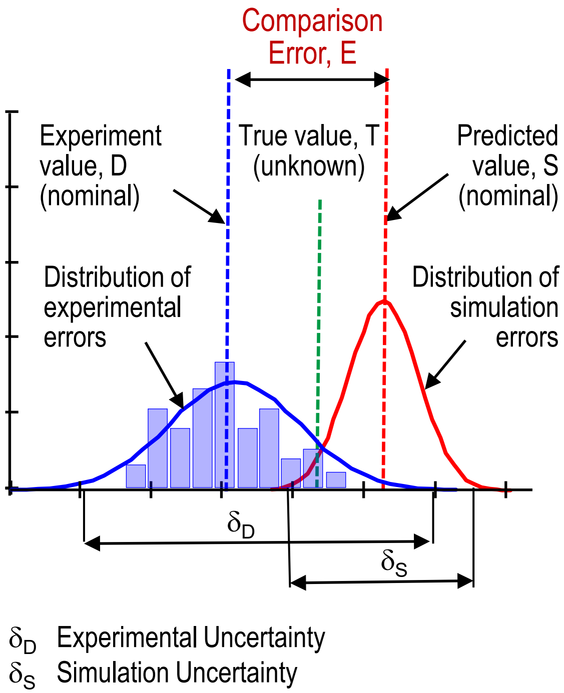
[ ]

Typical Pressure Tap Arrangements
Slide 41

PLC Validation Database

- Single-phase CFD methodology validated for the entire Framatome fuel product line

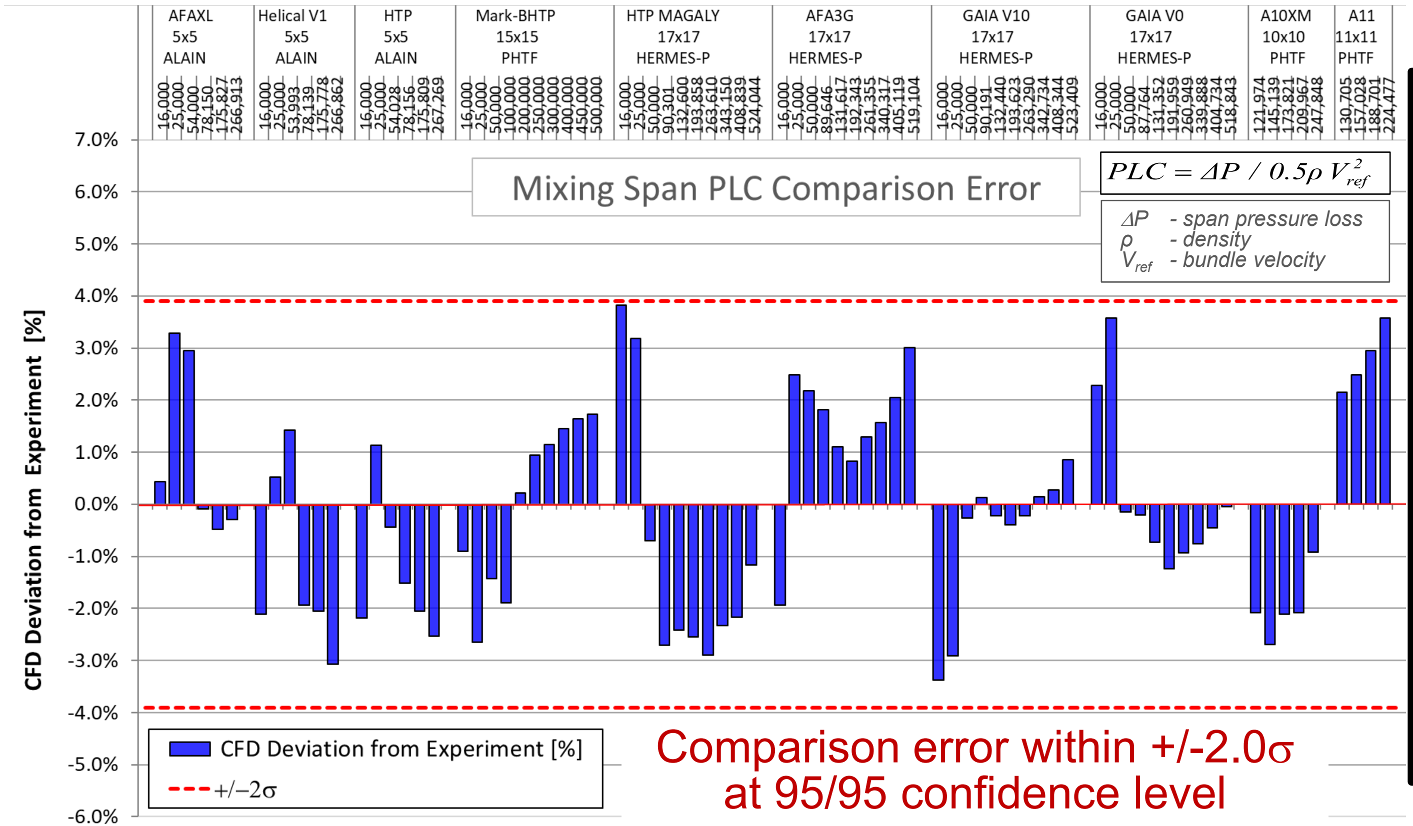
[ ]



CFD prediction deviation from test data evaluated in terms of comparison error, E

PLC Methodology Predictive Performance

Representative cases



Sample Problems

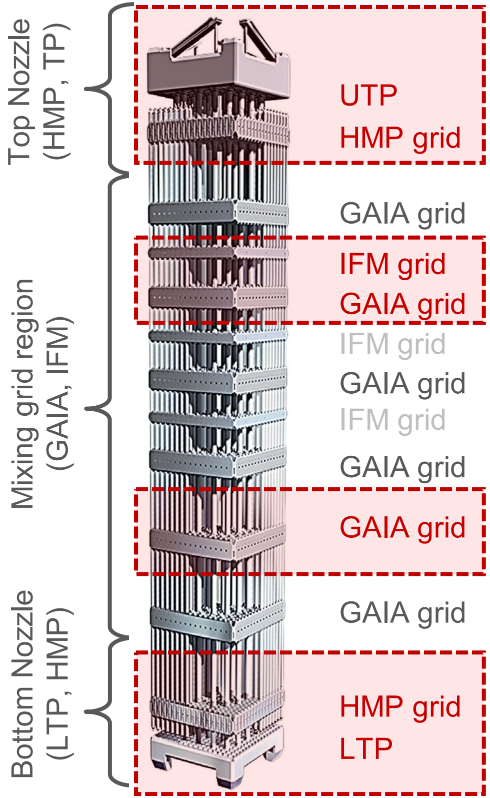
PWR & SMR Sample Problems: GAIA 17x17 FA Components FLC

- The GAIA 17x17 FA will be used to demonstrate ability to determine:

[ ]

- Separate simulations will cover:

[ ]

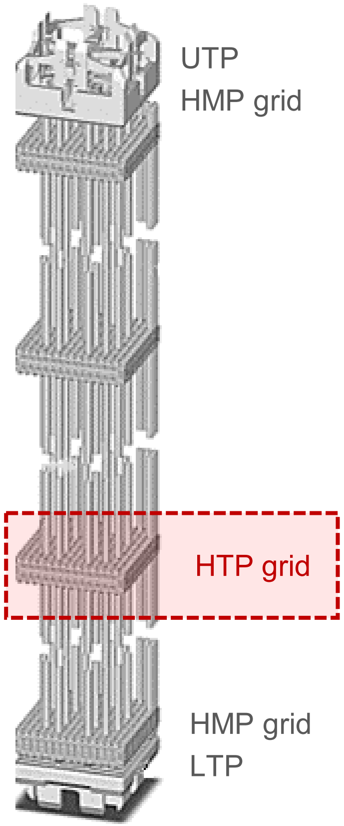


[ ]

framatome

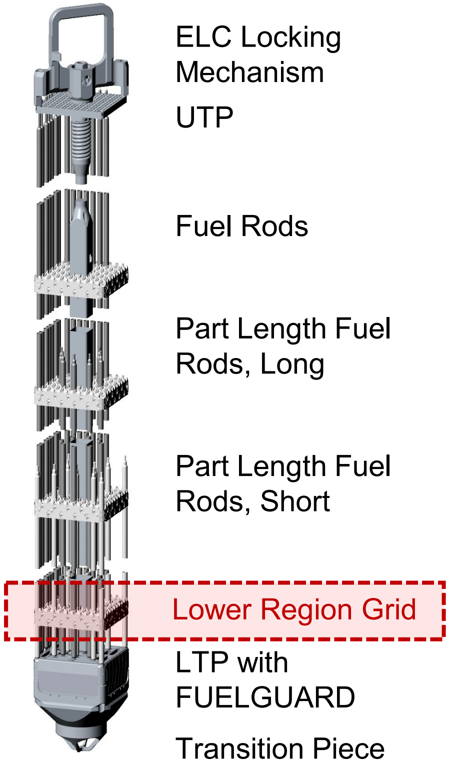
PWR Confirmatory Sample Problem: Mk-BHTP 15x15 Spacer FLC

[ ]



BWR Sample Problem: ATRIUM11 Lower Region Grid PLC

[ ]



Concluding Remarks

framatome

Summary

- Framatome's single-phase CFD methodology is optimized, fully validated against a comprehensive experimental database, and adequate for safety-related applications
  - The maximum deviation between PLC predictions and measurements is ~4.0%, [ ]
  - The comparison error is within +/-2.0σ at 95/95 confidence level for all the cases in the validation database
- The methodology is robust and will be able to accommodate future CFD developments (advances in computing technology, HPC availability, etc.)

CFD pressure loss results can replace experiments for developing FLC correlations for safety analysis in a manner consistent with current practices

Summary - Intended TR Applications

- Replace pressure tests for:
  - Modifications of traditional fuel products
  - New product development and optimization (traditional designs)
  - Non-traditional fuel configurations
- Tool of choice for advanced fuel evaluation and non-traditional designs certification
- Characterization of physics invisible to traditional codes and methods, and not captured by physical testing
- Produce better quality licensing materials and sound engineering justifications for new products, new correlations, etc.

Fee Waiver Request

- The industry is increasingly relying on CFD analysis to support design decisions; and its role will be expanding into safety applications
- Industry and NRC staff acknowledge that guidance on the qualification and application of CFD methods is needed
- Lessons learned from the review of this first-of-a-kind topical report provides valuable insight and bases (e.g., standard requirements, attributes) to assist NRC staff in developing this needed guidance
- 10 CFR 170.11(a)(1)(ii) states that an exemption from fees is warranted if the special project provides information which could assist the NRC in generic regulatory improvements or efforts (e.g., regulatory guides)
- Framatome will request a fee waiver

Questions/Discussion

Questions / Comments / Feedback

Acronyms

ARITA	ARITA–ARTEMIS/RELAP Integrated Transient Analysis Methodology
CFD	Computational Fluid Dynamics
CAD	Computer Aided Design (generic term used to refer to a 3D geometry)
CEA	Commissariat à l’énergie atomique (French Atomic Energy Commission)
CV	Control Volume
FA	Fuel Assembly
FLC	Form Loss Coefficient
FOAK	First-Of-A-Kind
GAIA	Framatome’s advanced PWR fuel assembly design
GT	Guide Tube
HMP	High Mechanical Performance Fuel
HPC	High Power Computing
HTP	High Thermal Performance Fuel
IFM	Intermediate Flow Mixer
LTP	Lower Tie Plate
PLC	Pressure Loss Coefficient
RANS/URANS	Reynolds Averaged Navier-Stokes Equations (steady/unsteady)
Re#	Reynolds Number
SSG	Simple Support Grid
UTP	Upper Tie Plate
y+	Normalized wall distance

Sample CFD Models for Hydraulic Characterization

Typical CFD Models for PLC Calculations

[ ]

Geometry Requirements
Slide 16

Typical Pressure Tap Arrangements

[ ]

CFD-Based PLC
Slide 26

List of Relevant Publications

Single-Phase CFD Evolution: Publications (1)

M. Leberig, N. Alleborn, M. Glück, J. Jones, Ch. Kappes, C. Lascar, G. Sieber, “AREVA NP’s Advanced Thermal Hydraulic Methods for Reactor Core and Fuel Assembly Design”, Top Fuel 2009, Paris, France (2009).

J.H. Jones, M.G. Martin, T.H. Keheley, R.L. Harne, M.G. Pop, C. Lascar, J-P.Simoneau,” AREVA’s Comparative Process for CILC Risk Assessment Using Subchannel and CFD Modeling”, LWR Fuel Performance Meeting, Top Fuel, WRFPM, Orlando, Florida, USA, (2010).

C. Lascar, N. Alleborn, M. Leberig, J. Jones, M. Martin, “Recent developments in CFD and their impact on fuel assembly optimization”, KTG Jahrestagung Kerntechnik, Berlin, Germany, (2010).

T. Keheley, M. Martin, A. Hatman, C. Lascar, N. Alleborn, A. Chatelain, “Counter Current Flow Limitation Prediction Using CFD,” The 14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), Toronto, Canada, (2011).

S. Opel, N. Alleborn, P. Pohl, K. Greene, A. Chatelain, “Advanced CHF Prediction by F-COBRA-TF and CFD Analysis to Support PWR and BWR Fuel Product and Methodology Development,” Proceedings of Top Fuel Reactor Fuel Performance, Charlotte, NC, USA, (2013).

C. Lascar, E. Jan, K. Goodheart, T. Keheley, M. Martin, A. Hatman, A. Chatelain, and E. Baglietto, ”Example of Application of the ASME V&V20 to Predict Uncertainties in CFD Calculations,” Proceeding of the 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-15-070, Pisa, Italy, (2013).

C. Lascar, M. Pierre, K. Goodheart, M. Martin, A. Hatman, and J-P. Simoneau, “Validation of a CFD Methodology to Predict Flow Fields within Rod Bundles with Spacer Grids,” *15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-15*, Pisa, Italy, (2013).

Single-Phase CFD Evolution: Publications (2)

A. Hatman, G. Williams, M. Martin, T. Keheley, C. Lascar, K. Goodheart, and A. Chatelain, "CFD Analysis of Reactor Core Flow Field in Support of FIV Diagnosis," *15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-15*, Pisa, Italy, (2013).

M. Martin, T. Keheley, K. Vogel, K. Goodheart, A. Hatman, A. Chatelain, "Validation of AREVA's Best Practices in the EPRI Round Robin Benchmark," *16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-16* (2015).

A. Hatman, A. Chatelain, K. Goodheart, M. Martin, T. Keheley, *"A Review of AREVA's Experimental Validation of State-of-the-Art Single-Phase CFD Methods with Application to PWR Fuel Analysis and Design," 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-16* (2015).

M. Martin, A. Hatman, A. Chatelain, K. Goodheart, "AREVA NP's industrial CFD single-phase methodology and applications for nuclear fuel", Top Fuel 2016, Boise Centre, Boise, Idaho, USA, (2016).

J. Dumond, V. Marx, M. Rehm, A. Hatman, M. Bezard, B. Farges, E. Mery deMontigny, J. Pacul, L. Charlot "Industrial Applications of Framatome's State-of-the-Art CFD Methods to Nuclear Reactor Analysis", Top Fuel 2018, Prague, Czech Republic, (2018).

A. Hatman, S. Lydzinski, L. Charlot, G. Bache, B. Farges, J. Dumond, M. Rhem, K. Vogel, "Framatome's Unified Single-Phase CFD Methodology for Fuel Design and Analysis", 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics NURETH-18, Portland, OR, USA, (2019).

A. Hatman, M. Rehm, B. Farges, "Implementation of Framatome's Unified Single-Phase CFD Methodology in the Product Improvement and Advanced Fuel Development Process", 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics NURETH-19, Brussels, Belgium, (2022).

Trademarks

HTP, **AFA 3G, HMP**, **GAIA**, **M5**, **M5$_{\text{Framatome}}$**, **Q12**, **AGORA**, **FUELGUARD**, **TRAPPER**, **GRIP**, **MONOBLOC**, and **PROtect** are trademarks or registered trademarks of Framatome or its affiliates in the USA or other countries.

Simcenter STAR-CCM+™ is a trademark or registered trademark of Siemens Industry Software Inc. or its subsidiaries in the United States and in other countries.

framatome