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Improvement of Fuel Product TH Performance

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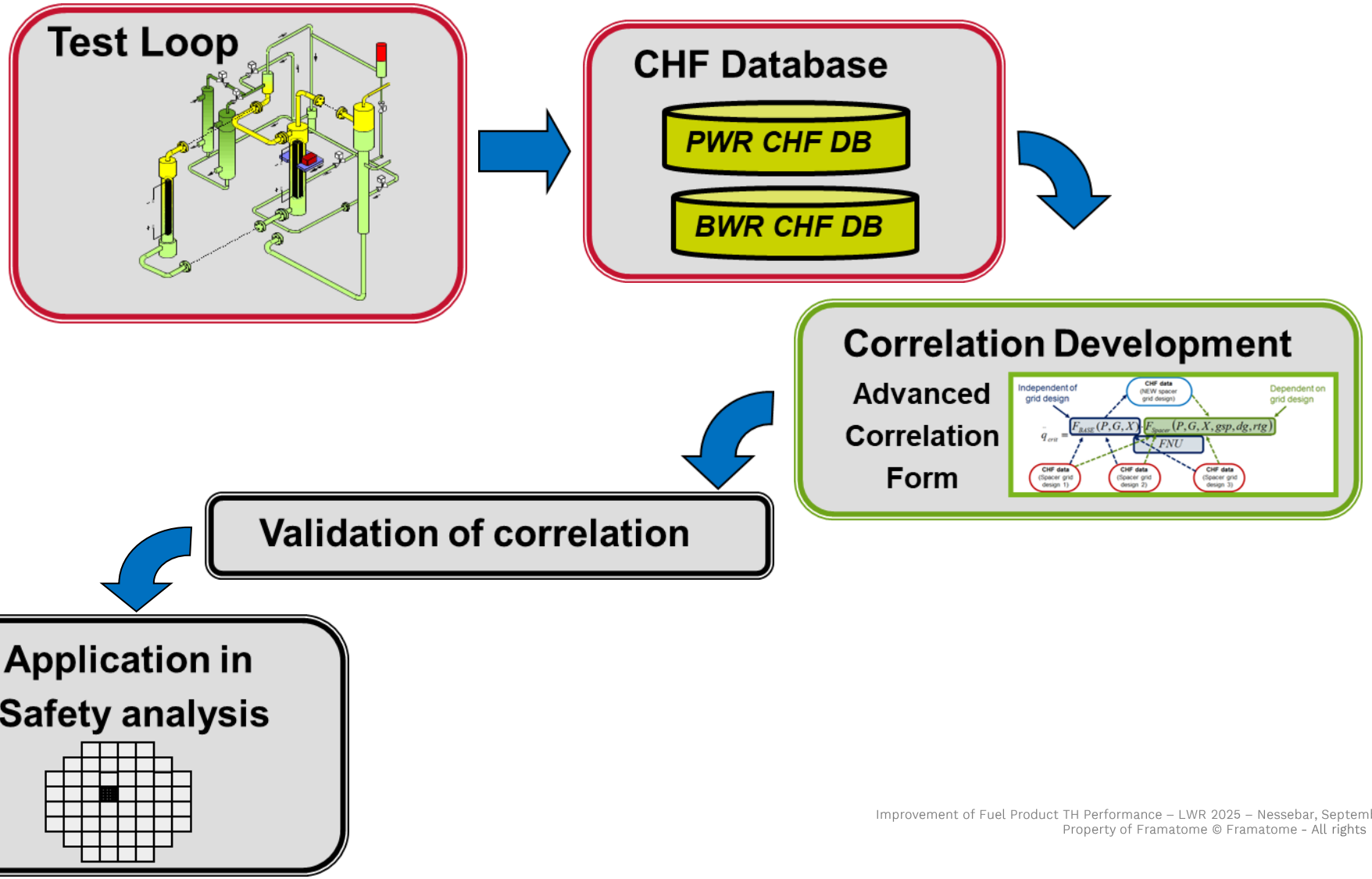
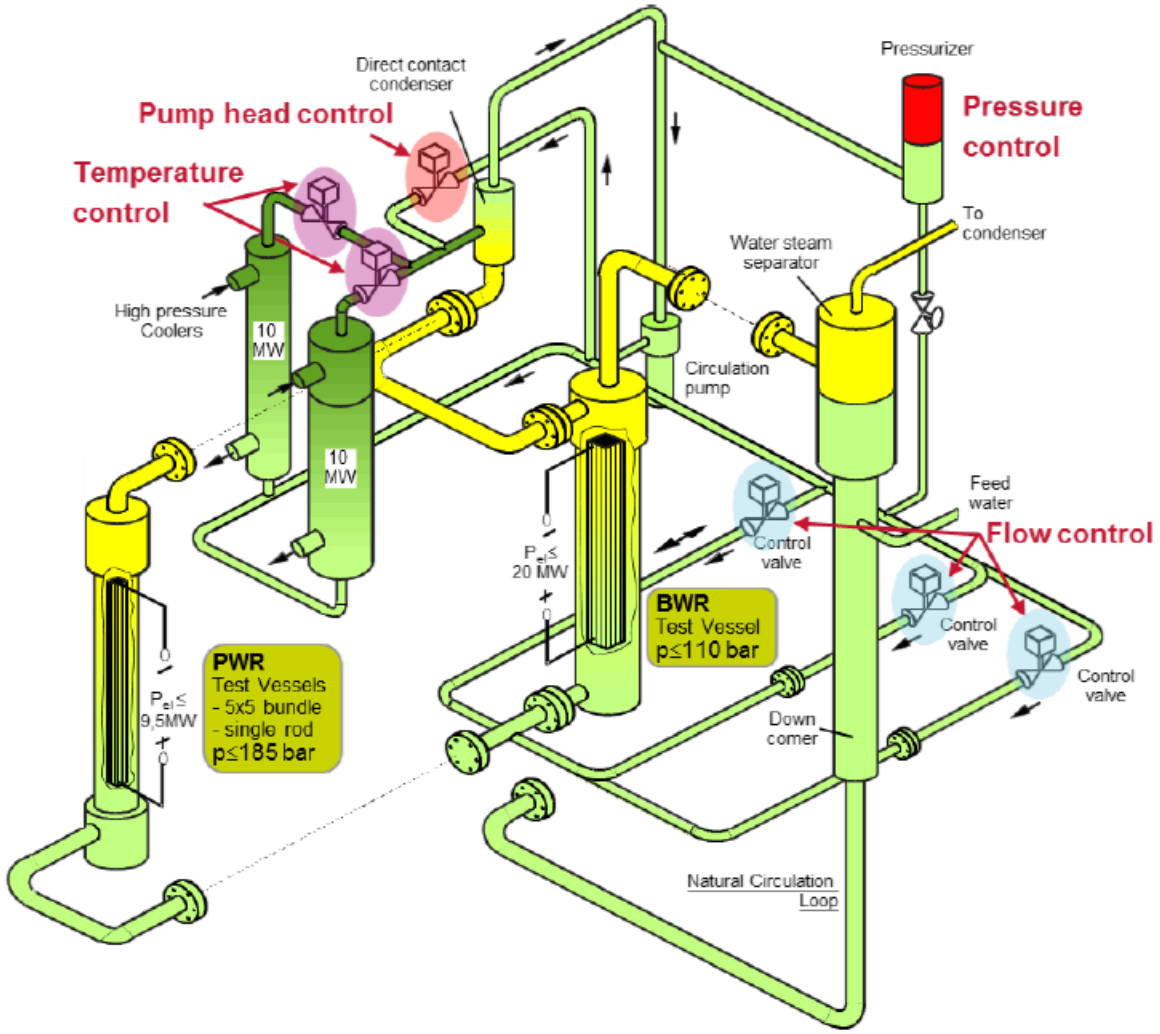
1

KATHY CHF Testing

CHF Correlation Development Process at FRAMATOME



KATHY Test Loop



- KArlstein Thermal-HYdraulic test facility operated by FRAMATOME
- Facility start-up: 1986
- Extended Qualification in 2002/3 for PWR Measurements
- >80 PWR CHF Tests
- >500 BWR CHF Tests
- > 10 VVER-1000 CHF Tests

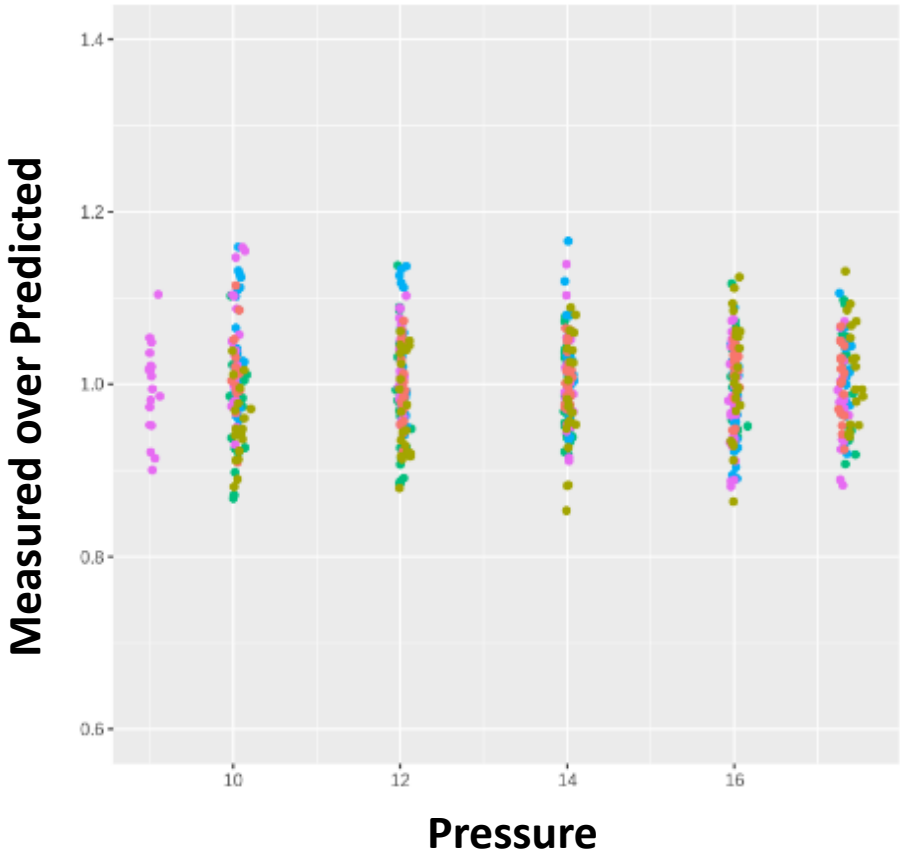
KATHY provides high quality CHF measurements

Range of Test Programs

- More than 80 PWR + 10 VVER CHF tests performed at KATHY since 2000:
  - Wide range of spacer grid designs
    (HTP, AFA 2G / AFA 3G, GAIA, VVER-1000 non-mixing and mixing grids, etc.)
  - Wide range of radial and axial geometries
    (axial power profiles, heated lengths, grid spacings, etc.)
- Extensive Database
  - PWR/VVER: approximately ~25000 data points
    - Pressures: 15 bar to 180 bar
    - Mass flux: 400 kg/m²s to 5700 kg/m²s
    - Quality: -0.25 to 0.80
    - Various core designs: 14x14, 15x15, 16x16, 17x17 and 18x18 plus VVER-1000
    - Plus single rod experiments.

This comprehensive database provides a well founded starting point for correlation and model development

Development of a Preliminary CHF Correlation for VVER-1000



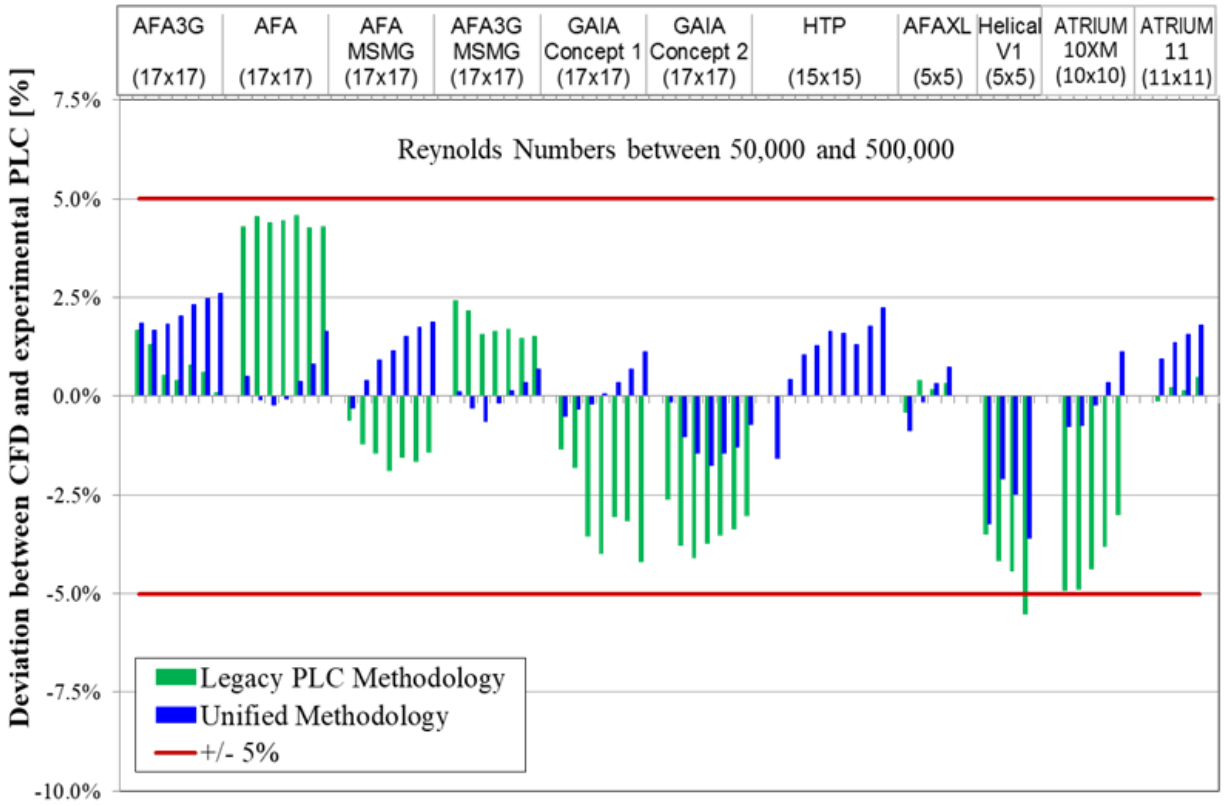
- Framatome has developed a preliminary non-mixing grid correlation FC-VVER-NMGRID with excellent statistics that can be used for LTAs
- Non-Mixing grid correlation implemented in Framatome's sub-channel TH code COBRA-FLX

2

CFD at Framatome: Use and Validation

CFD at Framatome: Use and Validation

- Framatome uses high-fidelity tools like computational fluid dynamics (CFD) to develop and verify new spacer designs.
- Design simulations are conducted early to assess concepts and extract detailed subchannel flow data for improved modeling.
- Intermediate validation compares simulation results with measured data to ensure consistency between testing and modeling.
- A comprehensive validation database, covering multiple reactor types and scales, underpins these methodologies.

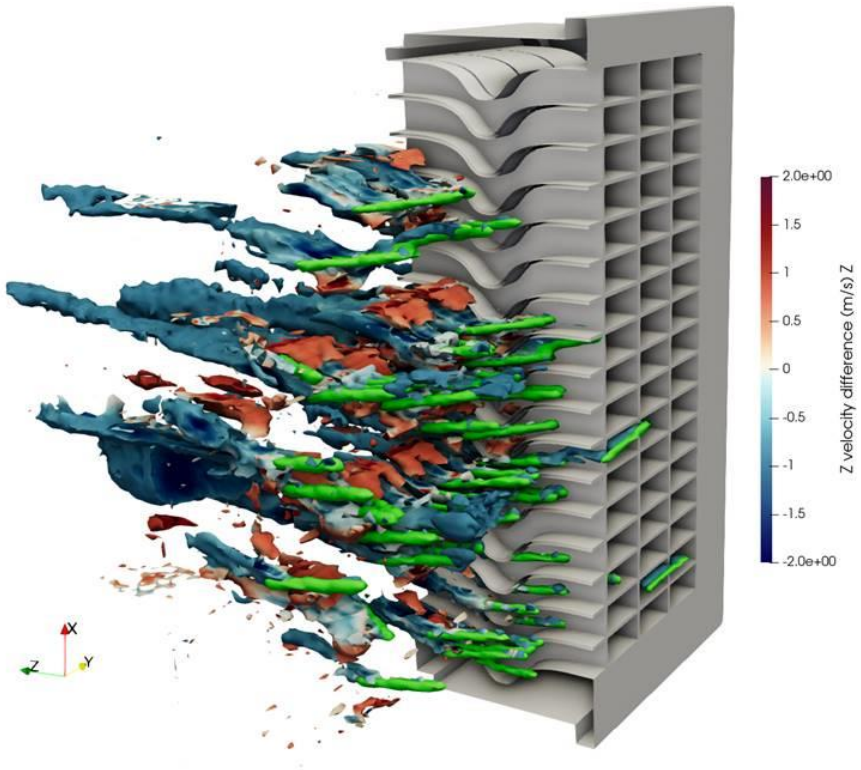


Evolution of Framatome CFD modeling approaches [1]

[1] Rehm, M., A. Hatman, and B. Farges. "Framatome's unified single-phase CFD methodology for fuel design and analysis." *Proceedings of the CFD4NRS-8, Virtual Conference*. 2020.

Advanced Measurements for CFD Validation

- High-fidelity 2D and 3D measurement data, obtained through innovative techniques like Magnetic Resonance Imaging (MRI), enhance the accuracy of CFD models—providing detailed insights into velocity, turbulence, and particle deposition.
- MRI enables non-invasive, high-resolution mapping of complex flow fields and particle behavior within fuel assembly filters, supporting the development of optimized debris filters that minimize pressure loss and clogging risk [2].
- These validated CFD methodologies and experimental techniques contribute to safer and more reliable reactor operation by improving the understanding of coolant flow, debris capture, and filter performance in nuclear fuel assemblies.



MRI measurement of the particle deposition and its impact on the flow velocity [2].

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[2] Vincent Klempau, Kristine John, Sven Grundmann, Martin Bruschewski, Markus Rehm, Elmar Rieder: "CFD-Grade Characterization of Debris Capture and Flow Dynamics in PWR Filters with MRI", NURETH-21, Busan (Korea), Aug. 31-Sep. 5 2025 (Honored with NURETH-21 Best Paper Award).

Advanced Measurements for CFD Validation

Siemens Tim Trio scanner [3]

- Medical scanner
- 3 Tesla
- Max. gradient 40 mT/m

Measureable quantities [3]

- Void fraction of water
- Velocity
  - 3 dimensions
  - 3 components
- Reynolds stress tensor
  - 3 dimensions
  - 6 components
- Time-averaged
- Uncertainty <5%

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[3] John, K., Bruschewski, M., Rehm, M., Hadžić, H., Pohl, P., & Grundmann, S. CFD-Grade Experimental Data of the 3D Mean Velocity Vector and 2D Reynolds Stress Tensor Obtained with Magnetic Resonance Velocimetry: Single-Phase Flow Through a 5 x 5 Rod Bundle at Re=50,250. ETMM14, 6-8 September 2023, 14th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements.

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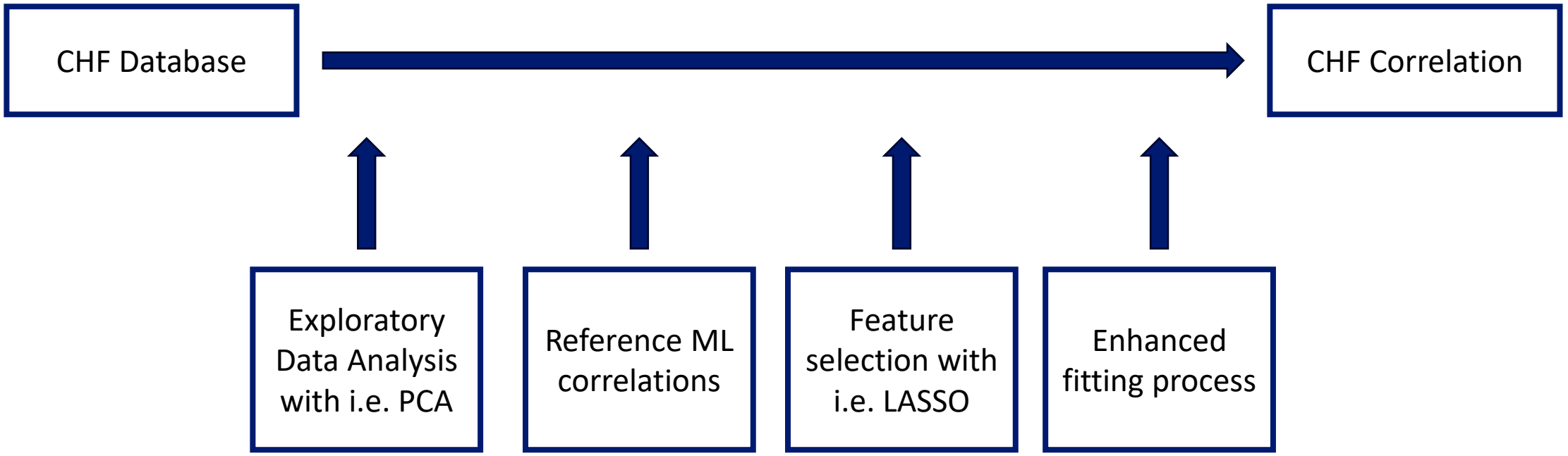
Machine Learning Enhancements of CHF Correlation Development

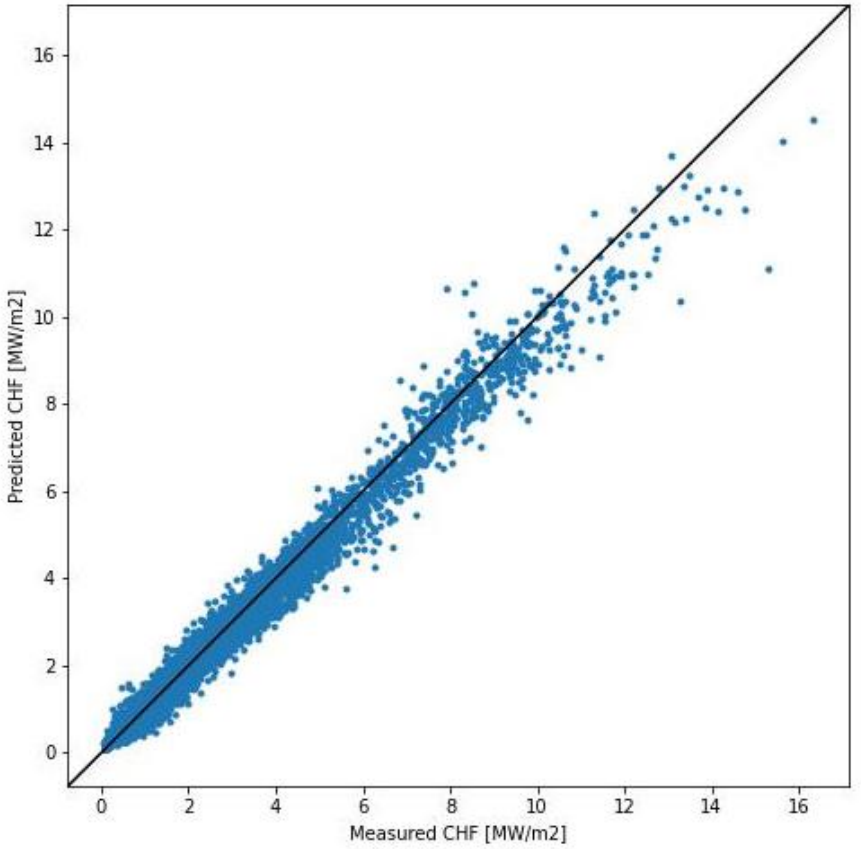
Machine Learning application in Classical CHF Correlation Development



Framatome already incorporated multiple Machine Learning tools to the classical CHF correlation development process to enhance efficiency of processes and improve product performance robustness

Machine Learning CHF Prediction – OECD Benchmark Activities

- OECD CHF AI ML benchmark: applying AI and ML CHF in a controlled manner
- The Benchmark consists of two phases: phase 1 with single rod data (finalized August 2024), phase 2: bundle data, start to be determined.
- Framatome's contribution:
  - Best estimate Neural Network model with PCA based feature engineering and state-of-the-art hyperparameter optimization and overfitting prevention
  - Novel Bayesian Additive Regression Trees model for new and improved uncertainty quantification
- Can we apply it in COBRA-FLX ? Yes, we can



Neural Network based CHF prediction

4

Conclusions

Conclusions

- **KATHY:** High-Quality CHF Measurements
- **Extensive Test Data**: A large inventory of PWR and increasing VVER test data supports our findings.
- **Effective CFD Methodologies**: Framatome's CFD methodologies are in productive use, notably for pressure loss coefficient analysis, with excellent experimental validation.
- **Enhanced CFD Quality**: High-fidelity MRI data is utilized to further improve CFD quality.
- **Machine Learning Integration**: Machine Learning techniques are assisting in the development of Framatome’s CHF correlation.
- **Collaboration with Scientific Community**: Framatome works with the scientific community to advance Artificial Intelligence (AI) in CHF prediction.

Acknowledgements

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Universität Rostock Traditio et Innovatio

The project is done in cooperation with the MRI Flow Lab of Rostock University

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Thank you

Благодаря!
Köszönöm!
Děkuji!
Kiitos!
Ďakujem!
Дякую!
Tack!
Merci !
Danke!

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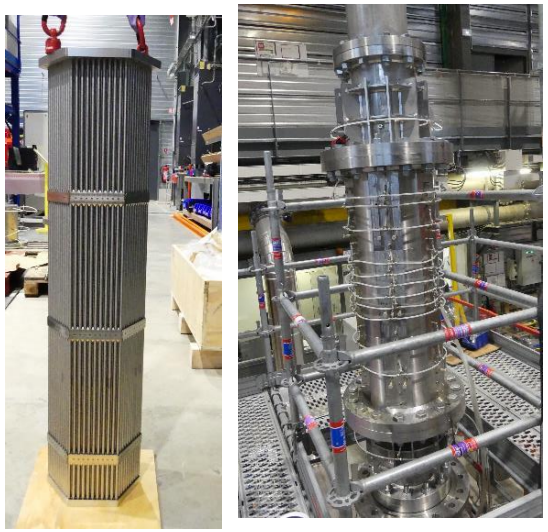
Backup slides

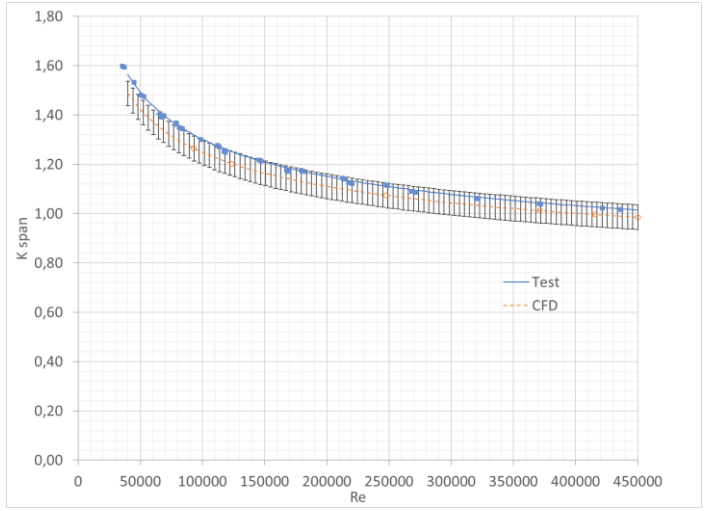
Framatome testing facilities adaptation

Hydraulic testing facilities:

- In addition to numerical evaluation, Framatome considers as mandatory a validation PLC by hydraulic testing.
- Thus, Framatome launched the adaptation of its hydraulic loop (FQH test facility – [1]).



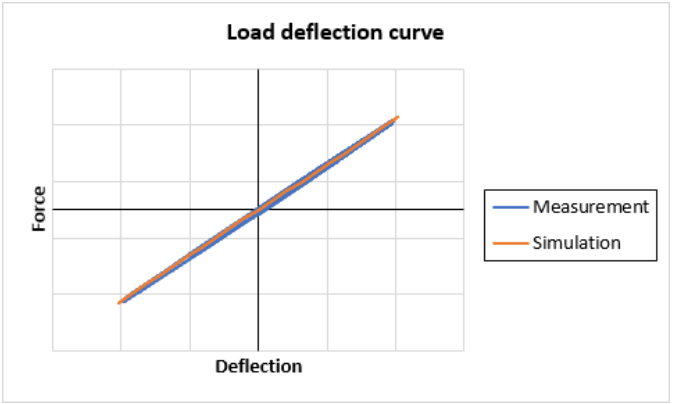
Mock-up and FQH facility



Sized PLC versus Reynolds number

Mechanical testing (cage stiffness):

- After preliminary evaluation using FEM analysis, a mock-up is manufactured and the stiffness bench is adapted at the top and bottom part to comply with the VVER design – [2]



Stiffness test

[1] M. DENIS, J.F. DESSEIGNES, "FQH - A new Framatome accurate and innovative test loop to support mastering of Fuel Assembly hydraulics – C2024-09-01" – Top Fuel 2024

[2] B. MIGLIERINI et al., "Development of VVER fuel engineering services at Framatome- C2024-09-01"- Top Fuel 2024.