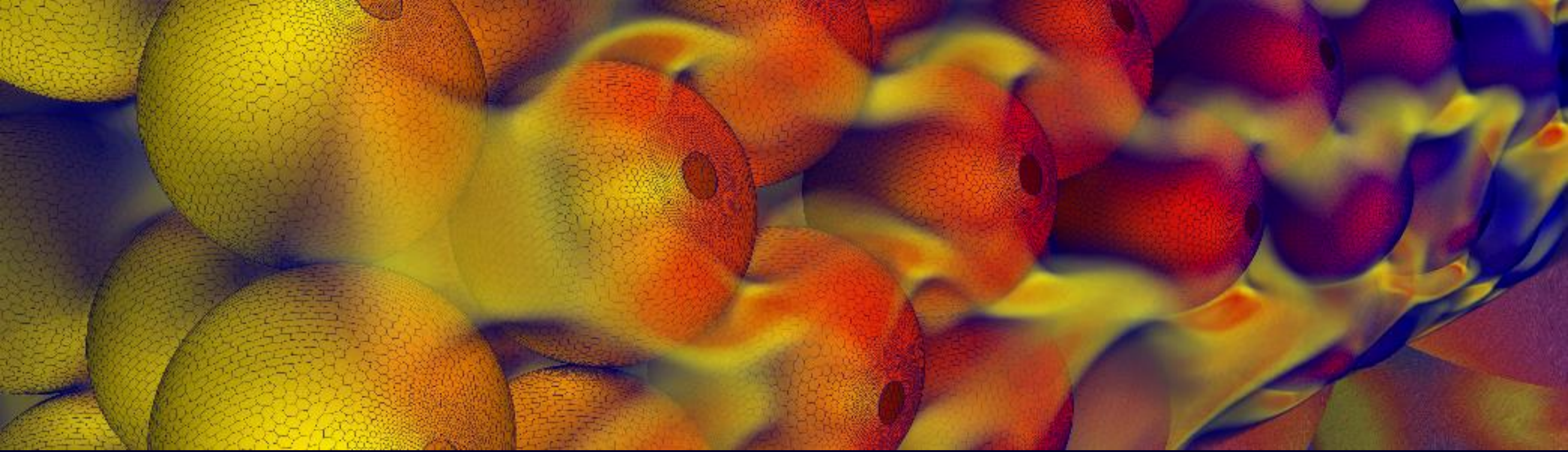

Performance Engineering for Nuclear Applications

Emilio Baglietto

Associate Professor of Nuclear Science and Engineering, Massachusetts Institute of Technology

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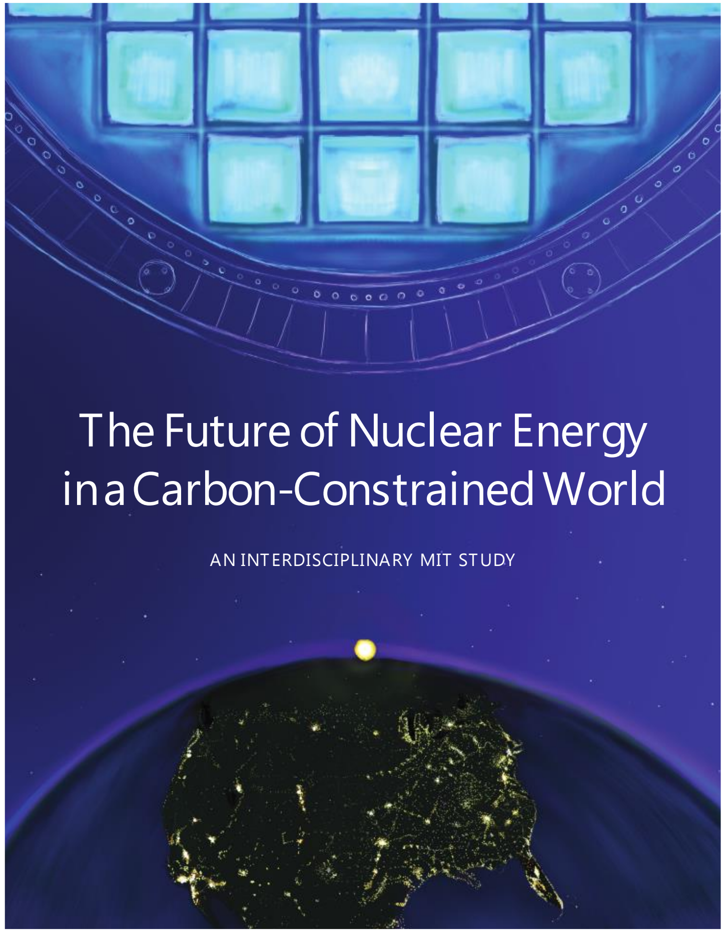
The Need to Rethink Design and Licensing of NPPS
Insights from the interdisciplinary MIT study



Source: http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/

FoN Report Key Messages

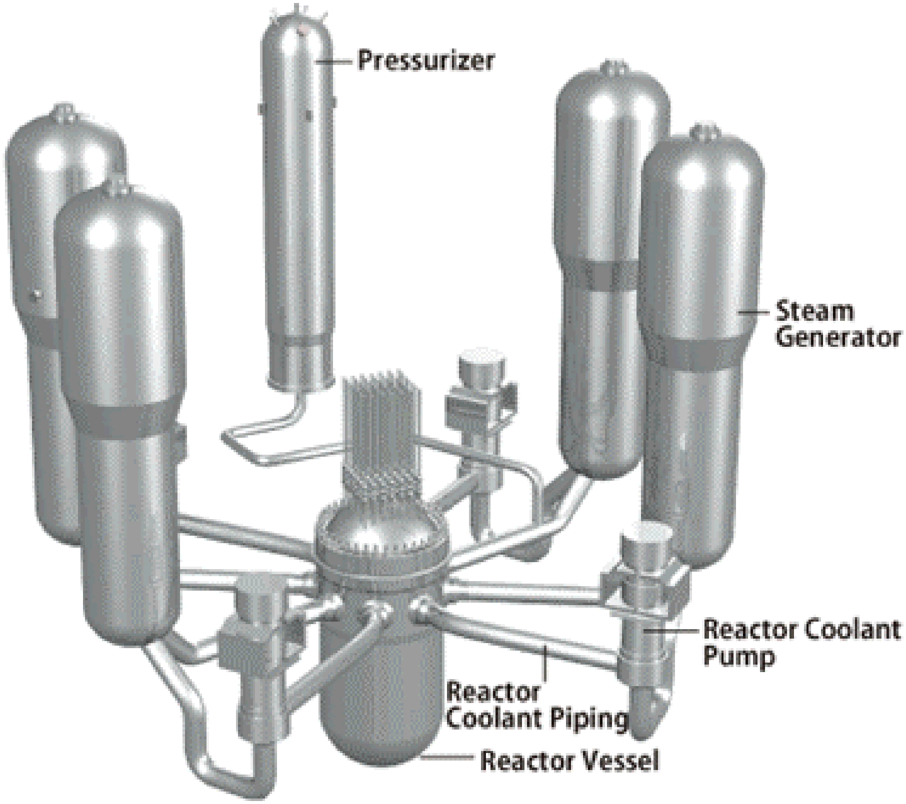
- Open need for cheap zero-carbon energy
- The problem for nuclear is cost
- There are ways to reduce cost
- Government’s help is needed to make it happen

Solution: Digital twin enabled by predictive physical modeling

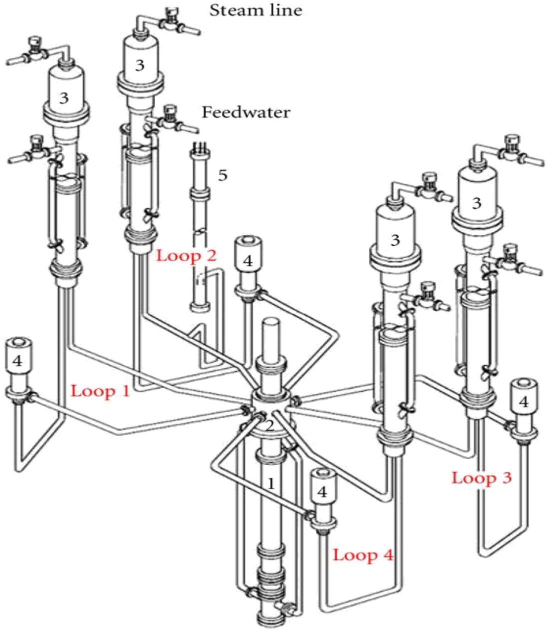
- Focus on physical representation validation and uncertainty qualification
- Cut design cycles in half by reducing testing to support licensing

Legacy methods do not support “cost competitiveness”

4 Loop PWR Layout

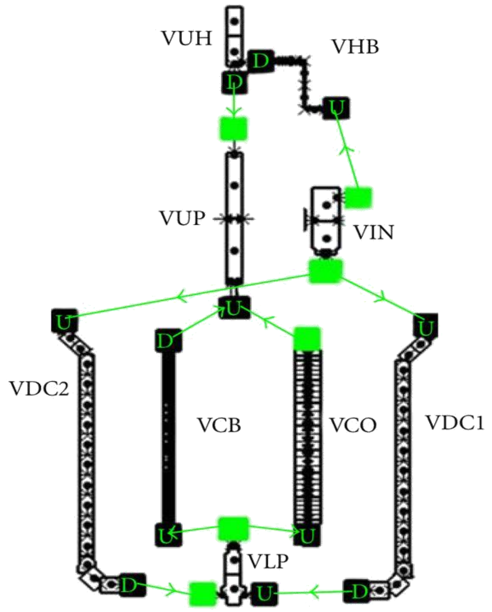


Layout of the PKL test facility



1 Reactor pressure vessel
2 Downcomer
3 Steam generator
4 Pump
5 Pressurizer

CATHARE modelling
PKL reactor vessel components



Anis Bousbia Salah and Jacques Vlassenbroeck, “CATHARE Assessment of Natural Circulation in the PKL Test Facility during Asymmetric Cooldown Transients,” Science and Technology of Nuclear Installations, vol. 2012.

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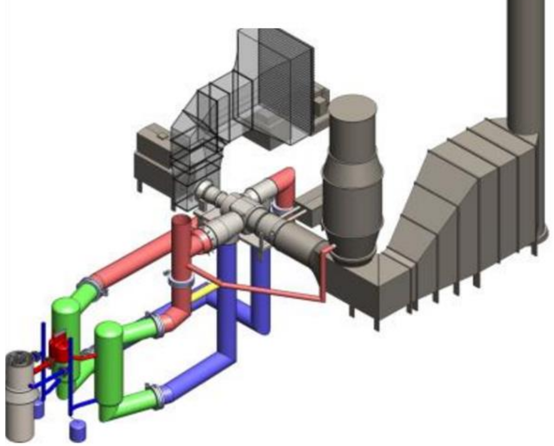
Xenergy

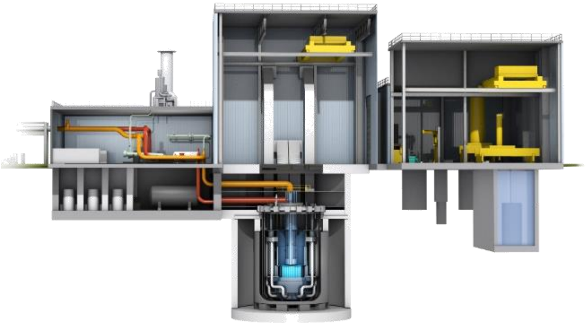
75/300MWe Helium coolant, TRISO fuel 650-700C

Kairos Power



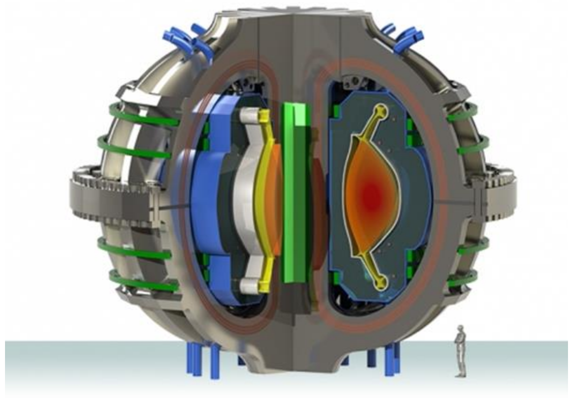
140 MWe - TRISO fuel FLiBe coolant 585C outlet

TerraPower
A nuclear innovation company



NATRIUM Sodium Fast Reactor with integrated SALT storage

MIT PSFC



ARC Fusion Reactor

Rapidly evolving landscape in both Fission and Fusion

- **SUCCESS!** We are finally working on delivering next generation nuclear systems.
- **OPTIMIZATION** drives the need to rely heavily on simulation to accelerate the technology deployment

Design Optimization is necessary to guarantee cost competitiveness. All designs adopt:

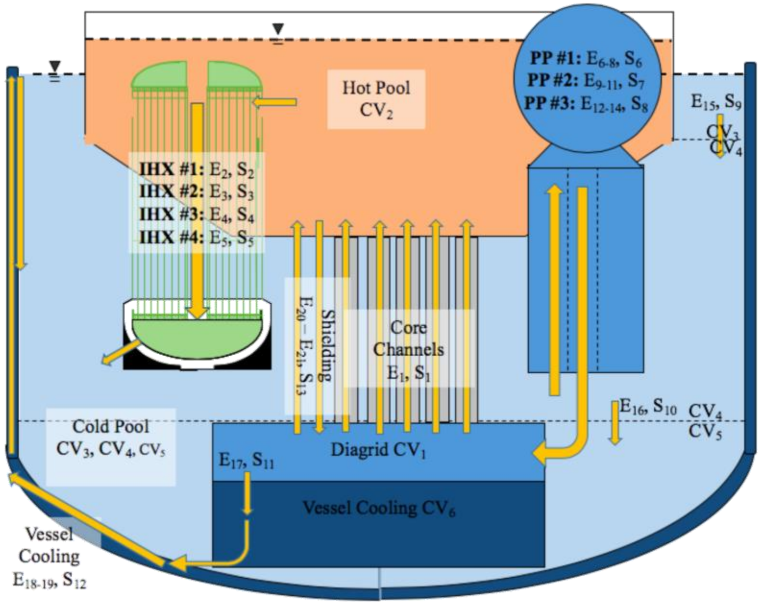
- **Compact/Integral Configurations**
- **High operating temperatures**

Rapidly evolving landscape in both Fission and Fusion

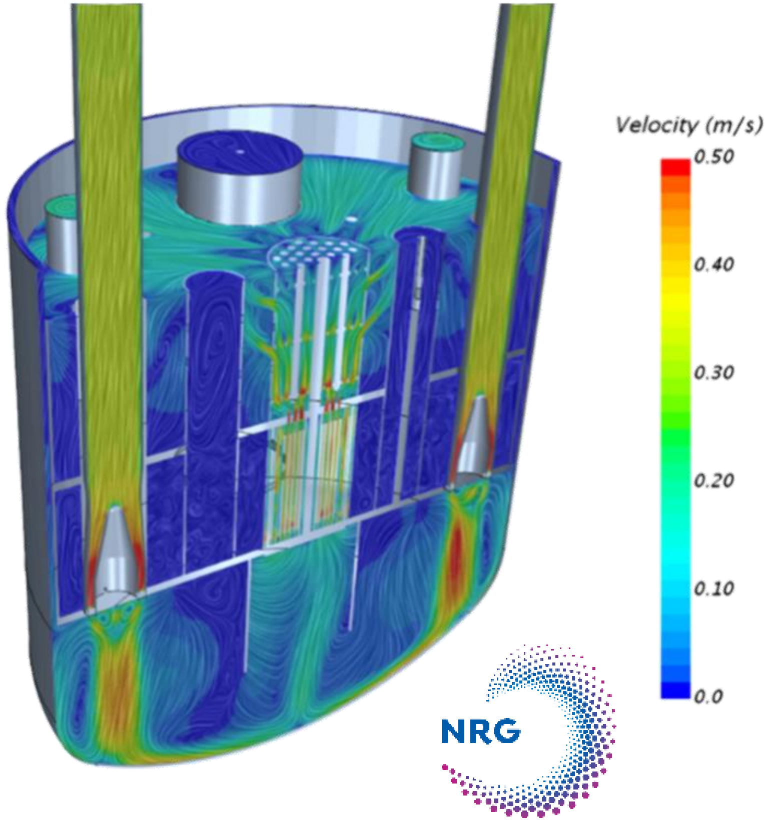
- **SUCCESS!** We are finally working on delivering next generation nuclear systems.
- **OPTIMIZATION** drives the need to rely heavily on simulation to accelerate the technology deployment

A (correctly) biased viewpoint

- Legacy methods must be **strongly augmented** by the use of 3-dimensional modeling



Schematic of SAS4A/SASSYS-1 Model of the Phénix Primary Coolant System, from: V. Narcisi et al. System thermal-hydraulic modelling of the phénix dissymmetric test benchmark, Nuclear Engineering and Design, Volume 353, 2019.



Visser et al. (2020) Nuclear Engineering and Design

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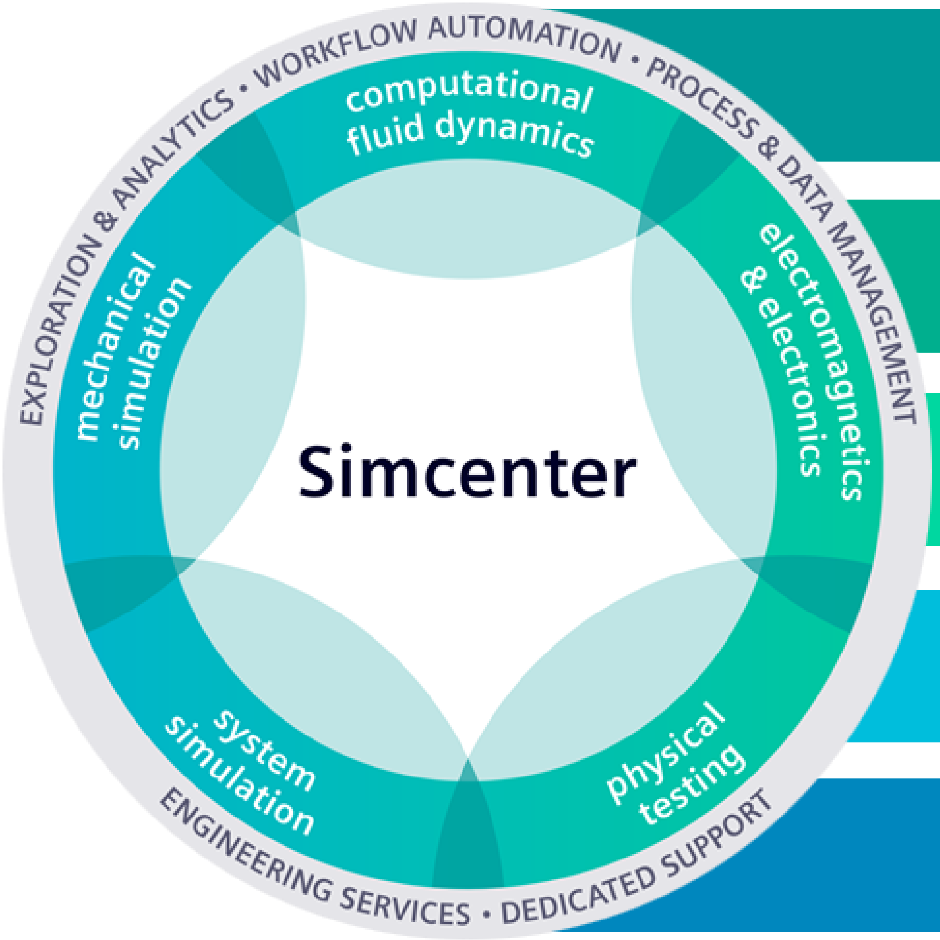
Simcenter Portfolio
Engineer innovation for nuclear energy performance



Fuel Performance
Hydraulic and thermal, Vibration, Bowing, CILC, Refueling

Plant Performance
TASCS, FSI, mixing, outages, containment performance

Advanced Reactors
Core, transients, conversion, metal/salts/gas/water designs

Back-end
Pools, dry-storage, transportation, reprocessing, long term

Integration, Verification & Certification
Virtual & Physical Testing, Component & Integration Testing

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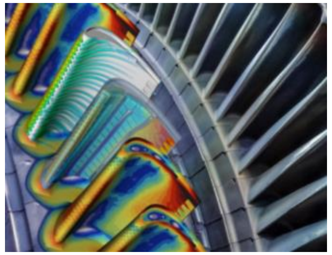
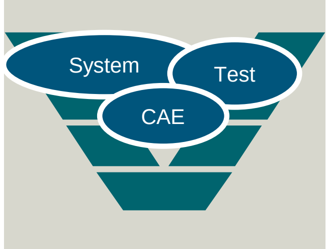
Simcenter™ Portfolio
Investment focus areas

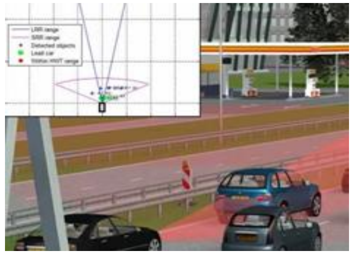
Increasing confidence



Multiphysics

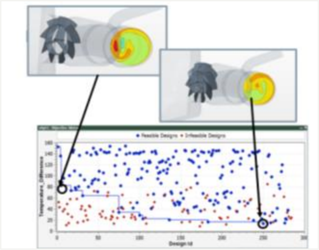


Multifidelity

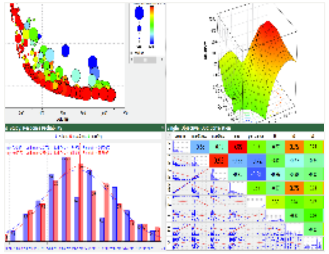


Industry Expertise

Delivering insight



Intelligent Design Exploration



Data Analytics

Visualization

Enabling enterprise collaboration

Openness

IOT & Cloud

Data & Process Management

Saving engineering time and accelerating ROI

Deployment Flexibility

Services & Support

Workflow & User Experience

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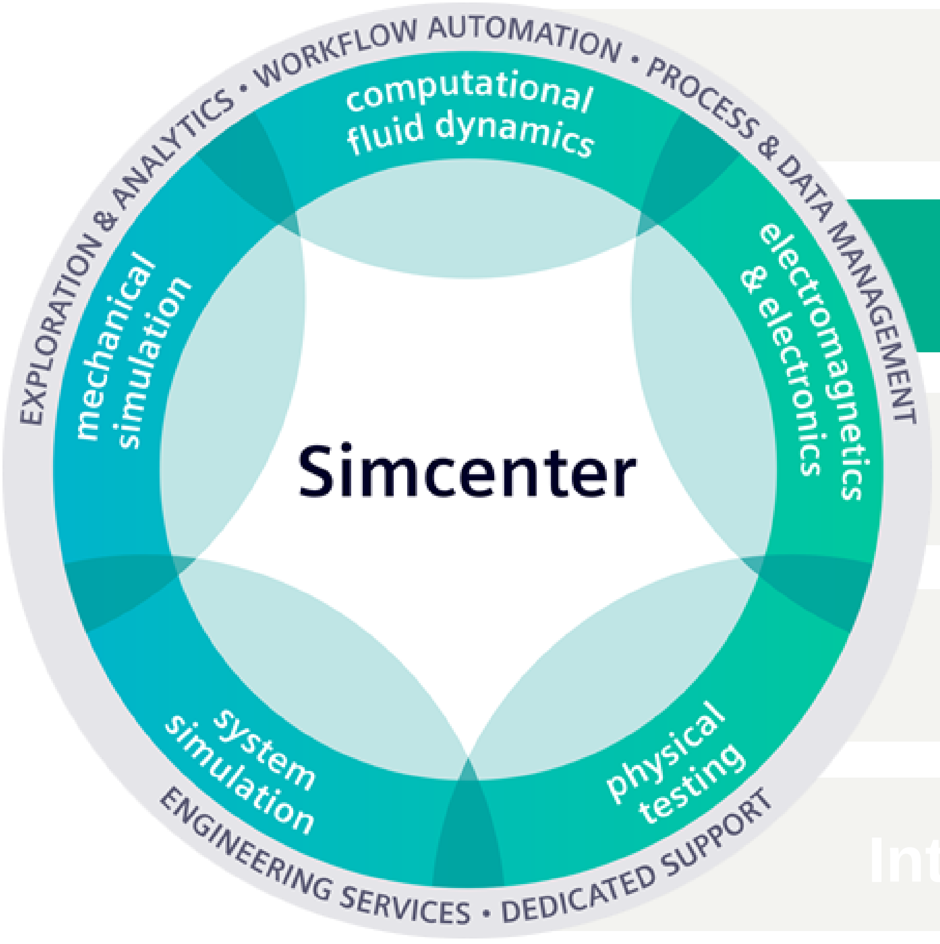
Simcenter Portfolio
Engineer innovation for nuclear energy performance



- Fuel Performance ✓
- **Plant Performance** ✓
- Advanced Reactors ✓
- Back-end ✓
- Integration, Verification & Certification ✓

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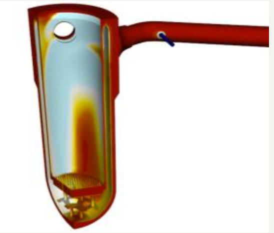
Simcenter for Plant Performance
Improving plant economics with an efficient end-to-end process

Plant Systems Assessment

Thousands of analysis to perform in a context of global engineering team

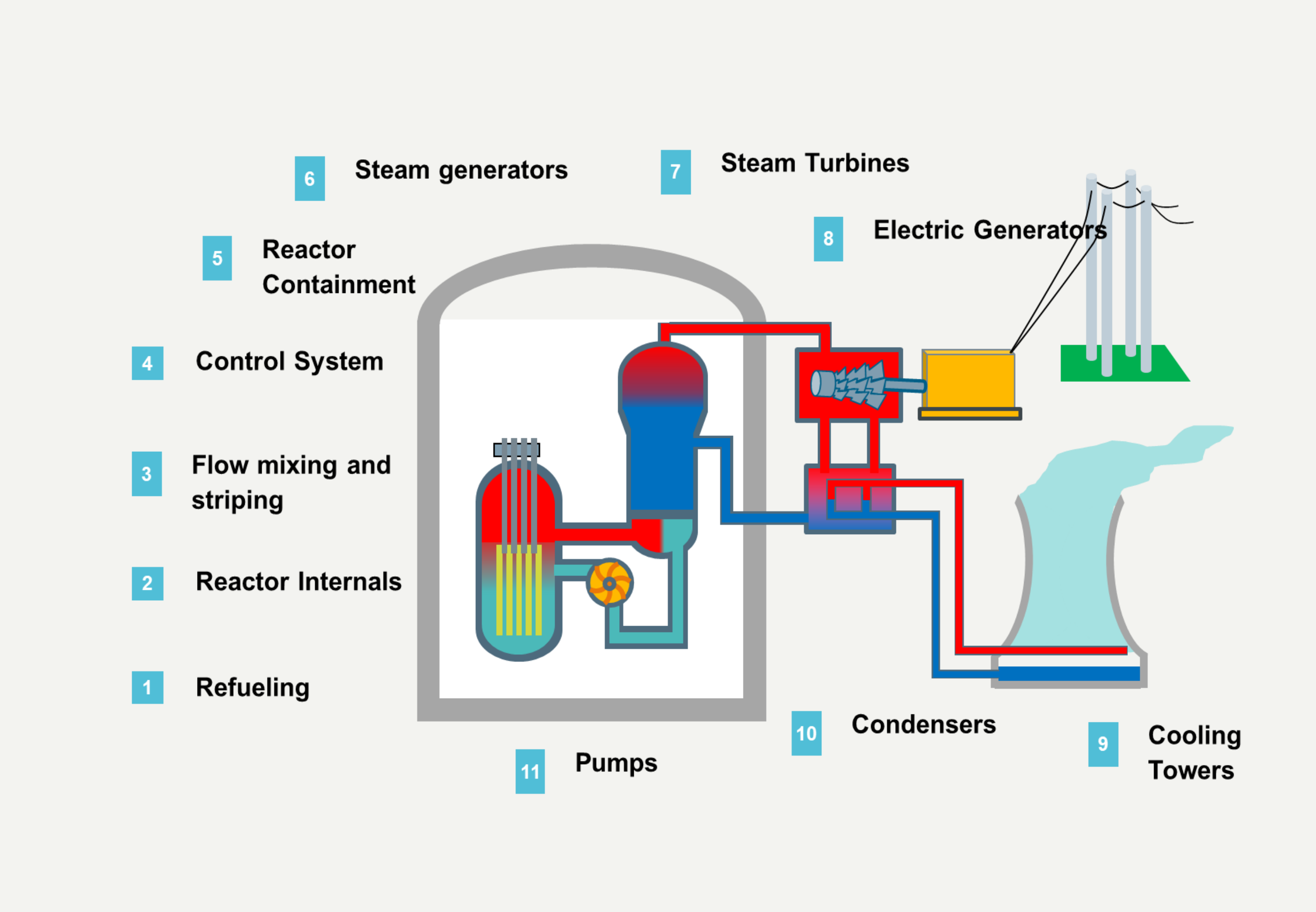
Automation and traceability is key for licensing

Digital Aging/Failure Monitoring



Extend life beyond 60 years

Reduced failures and outage costs are key to keep up with cost pressures



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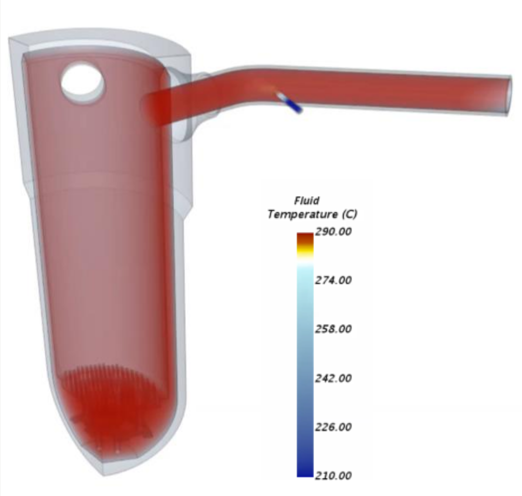
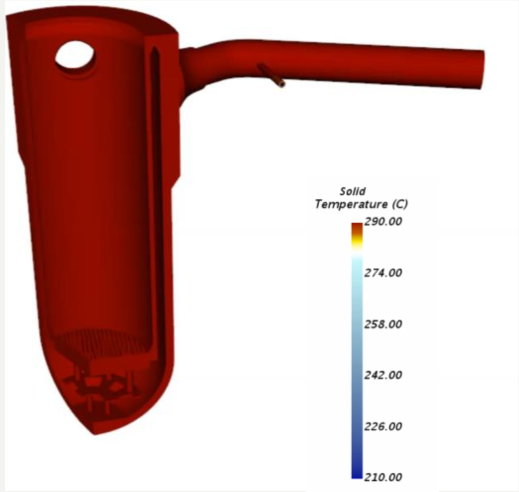
Simcenter for Plant Performance

Leveraging simulation with design exploration for reactor design

Multi-Disciplinary Simulation

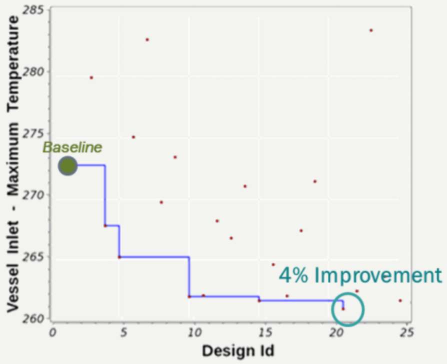
- Better insight into performance with complete flow-thermal-stress analyses
- Streamlined Multi-Disciplinary capabilities include interfacing with nuclear industry tools
- Full automation for faster design

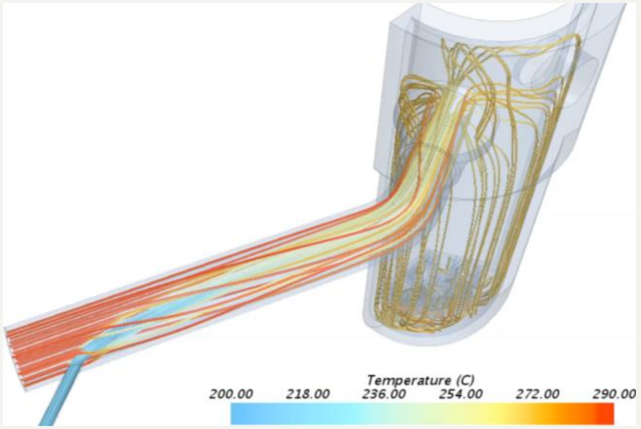




Design Exploration

- More efficient reactor designs
  - Reduce pressure drops
  - Improve thermal and boron mixing
- Optimize reactor operation
  - Eliminate flow anomalies
  - Incorporate load-following effects





Example of Design Exploration for Pipe Connection

- Critical Connection, design exploration must balance tradeoff or requirements
- CFD solution was confirmed by testing

- Analyses performed using STAR- CCM+ v11.04.012 CFD software
- All geometries and results shown are full-scale
- Includes hot leg piping and portions of the ADS and RNS lines attached to the hot leg piping

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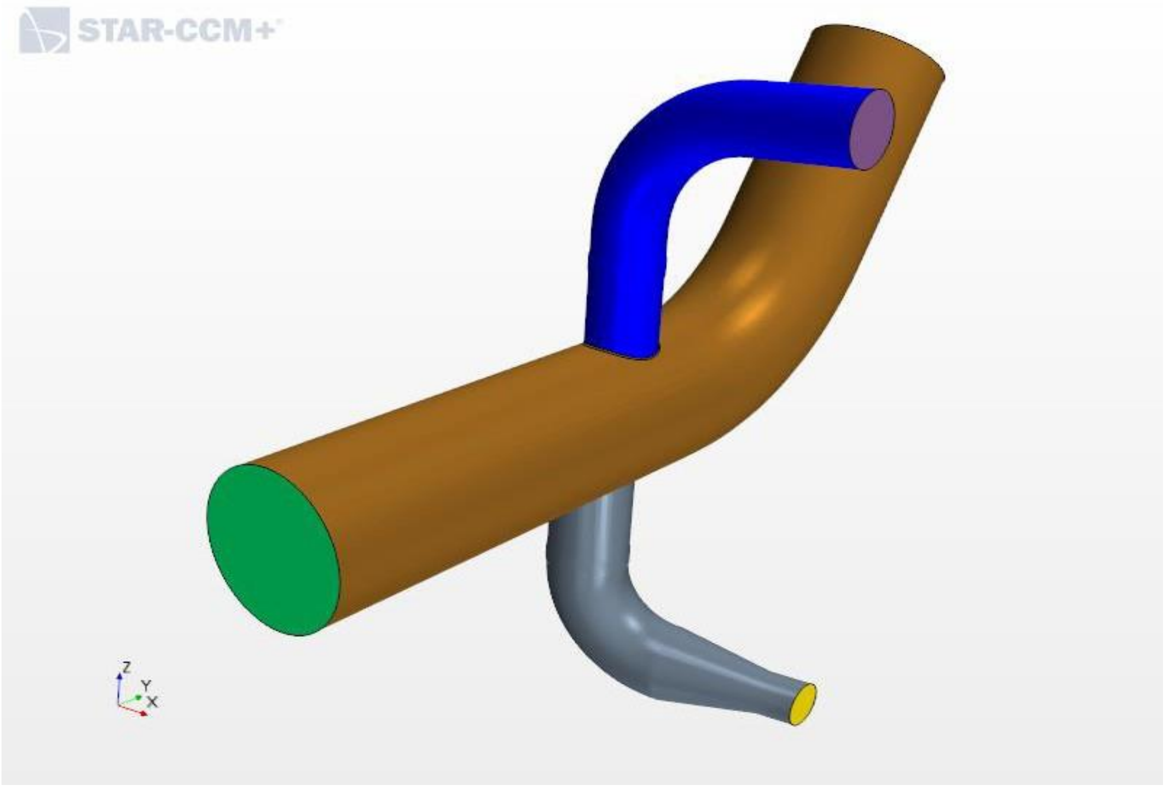
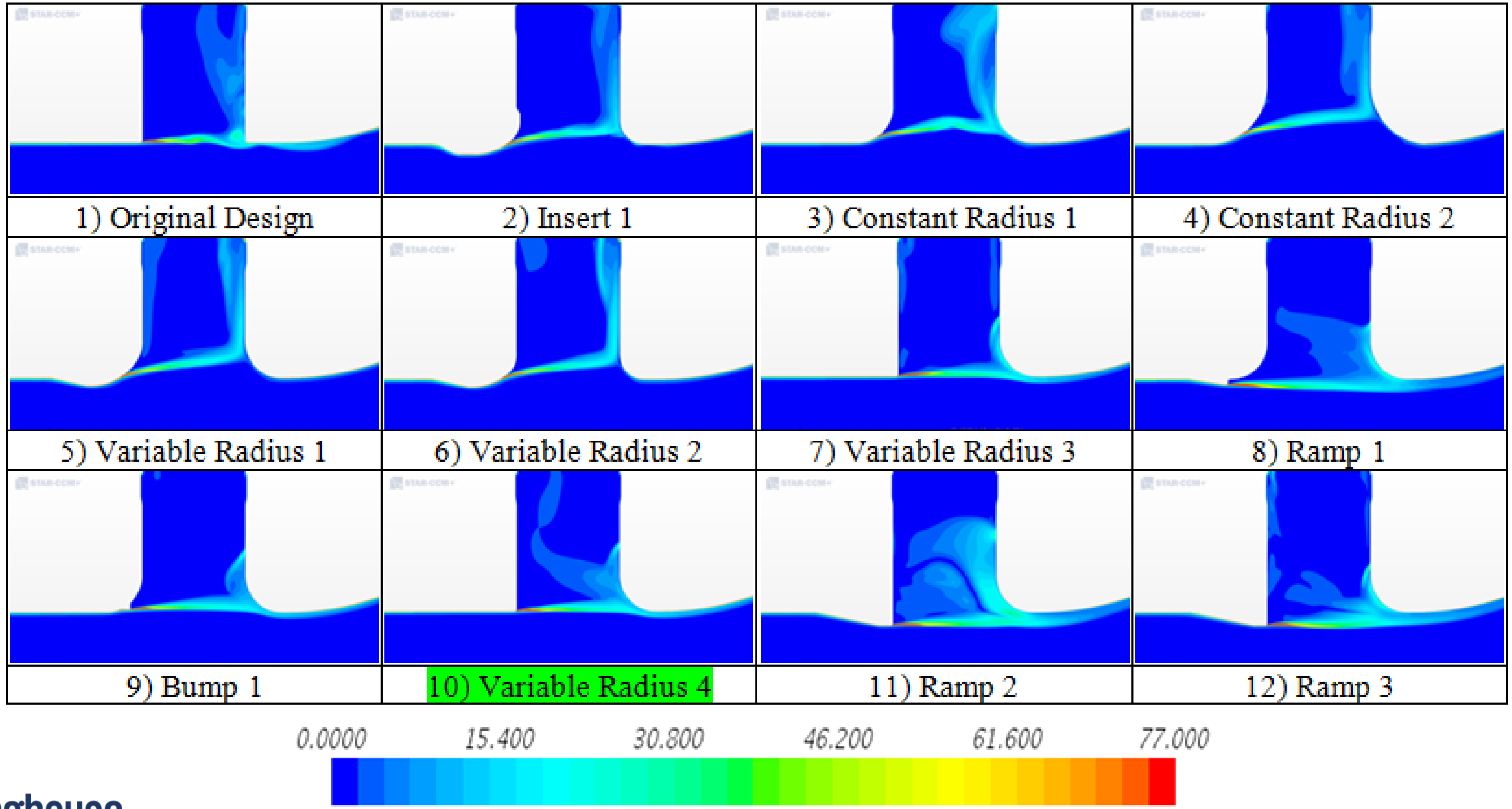
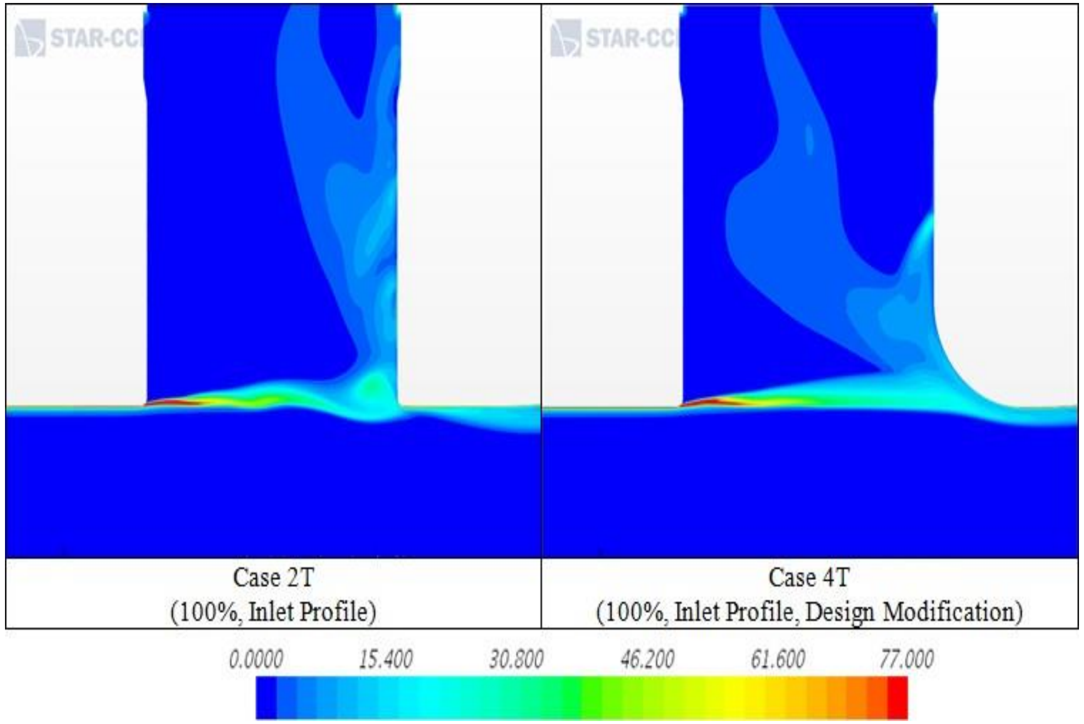
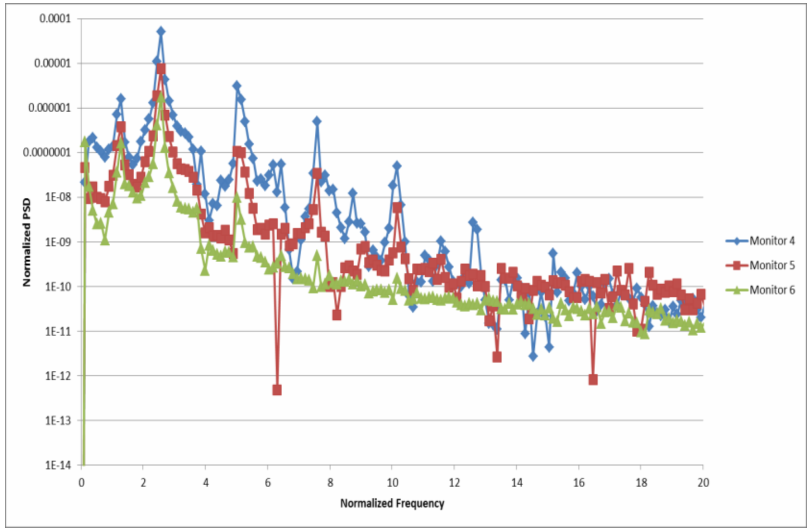


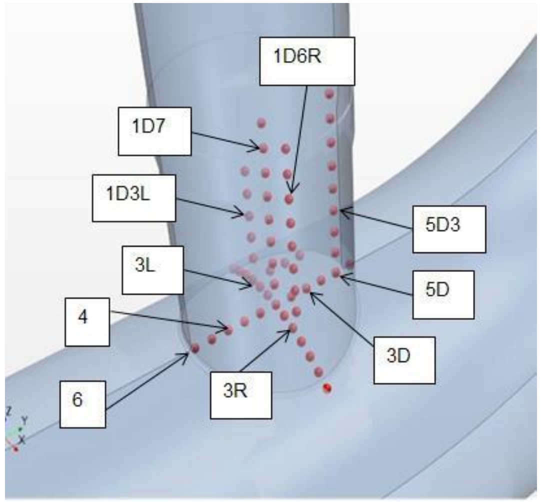
Design Exploration for Pipe Connection

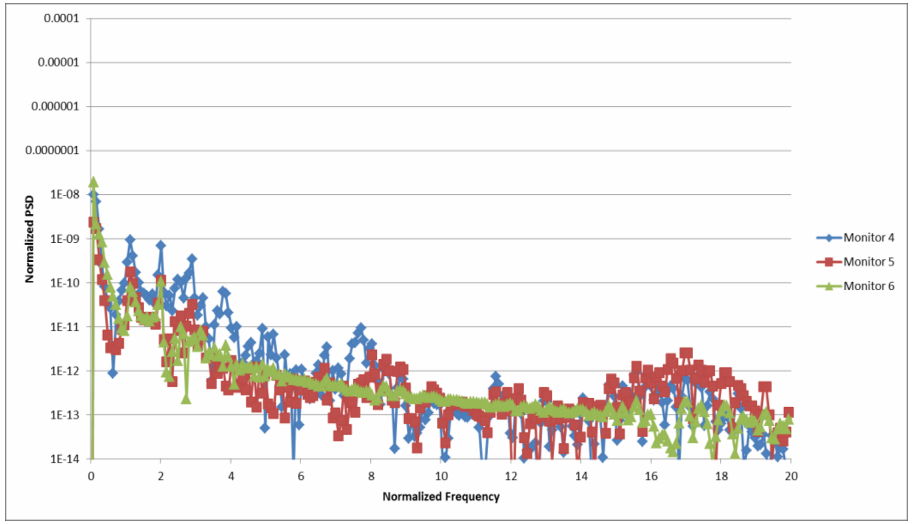


Design Exploration for Pipe Connection









- The CFD analysis is confirmed by testing
- New design provides considerable improvement

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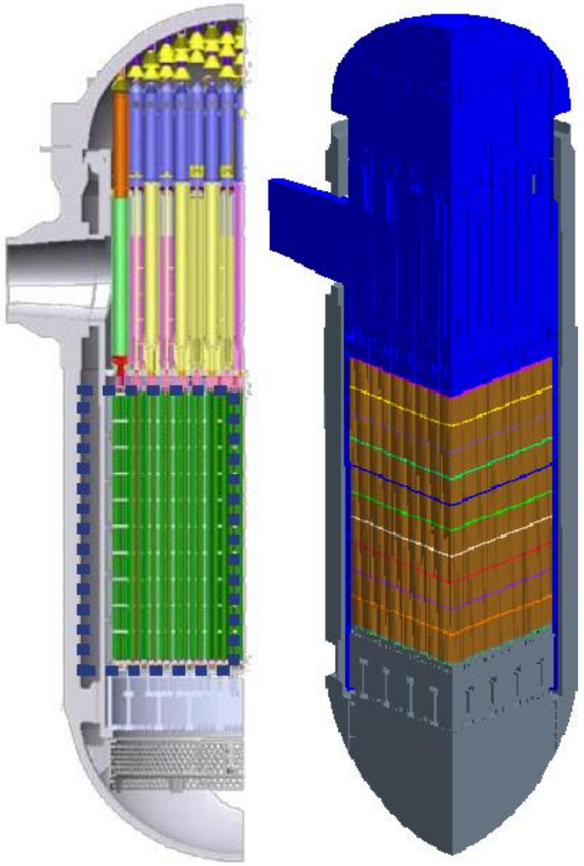
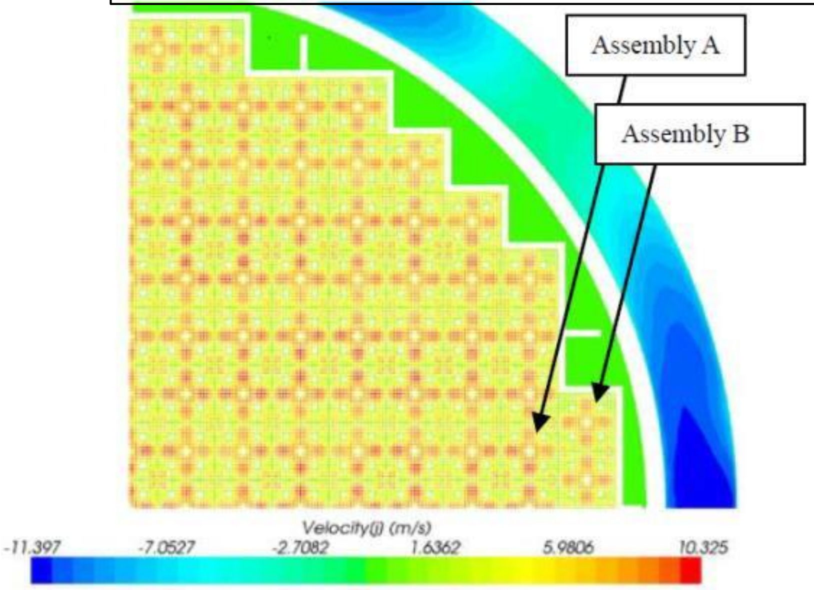
Simcenter for Plant Performance
Improving plant economics with Digital Twin



Phenomena of interest include:
- Hot Leg Thermal Striping
- Flow-induced vibrations
- 3-D flow under abnormal conditions
- Asymmetrical effects
- Core inlet flow distribution
- Lower plenum flow anomaly



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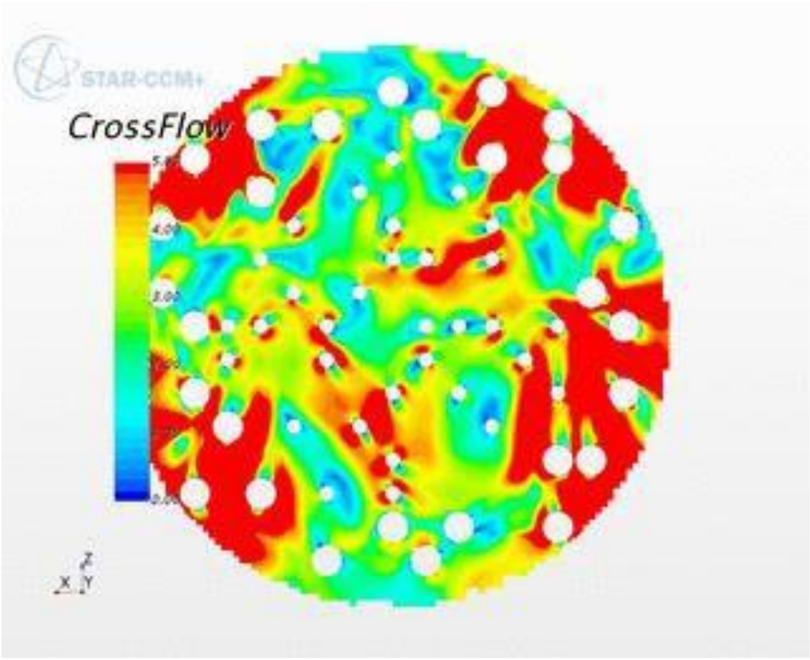
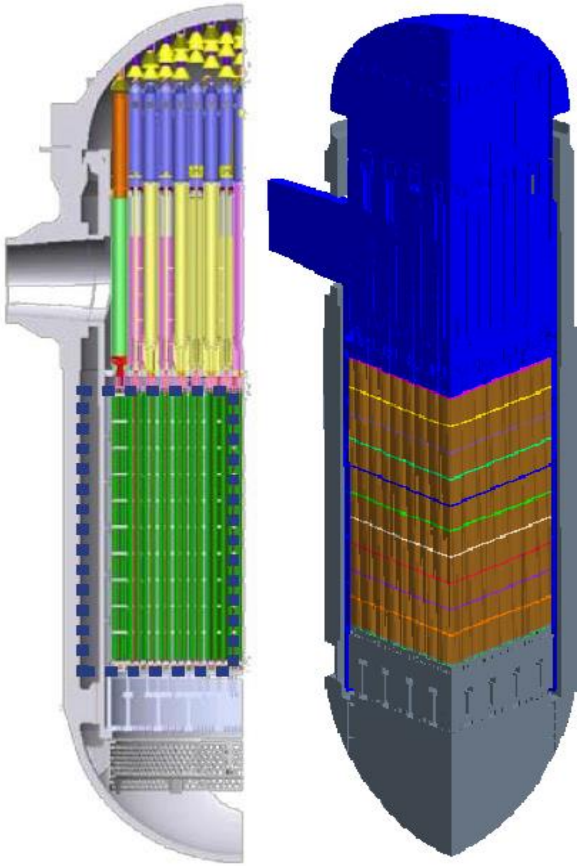


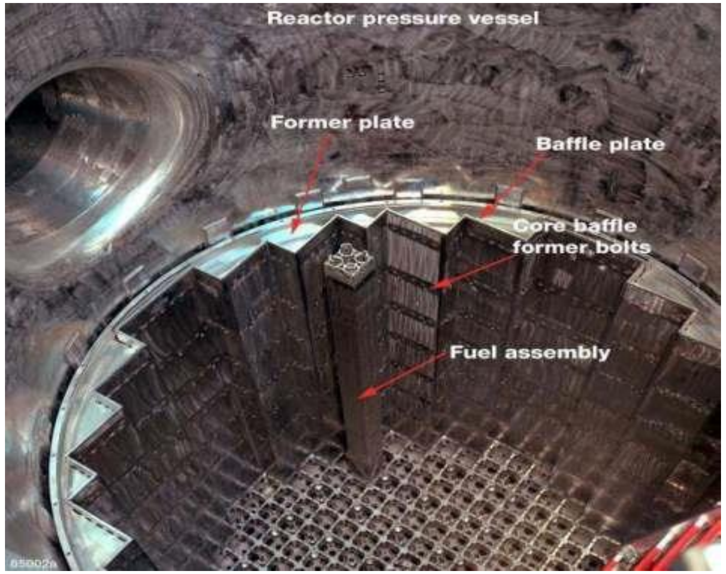
CFD simulations provide detailed information on core inlet flow uniformity, mixing in lower plenum, flow induced vibrations forcing functions, etc.

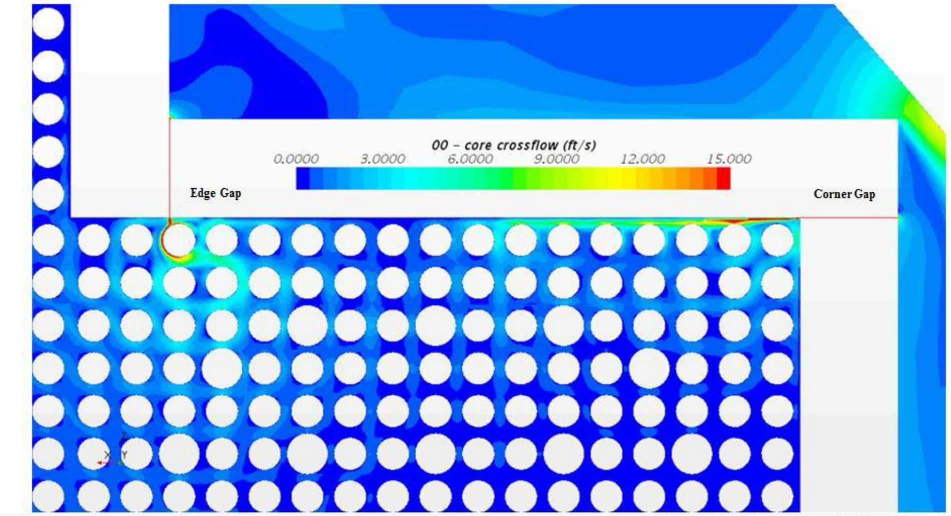
Simcenter for Plant Performance

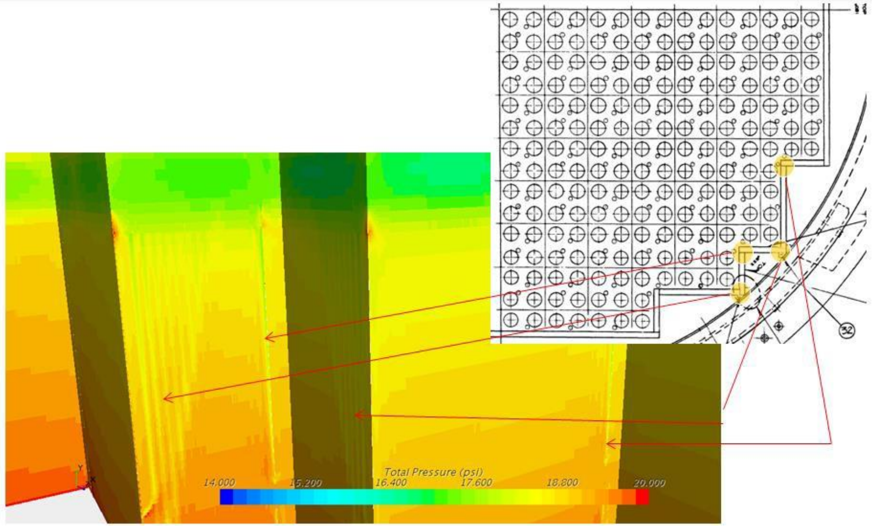
Improving plant economics with Digital Twin



- Flow leakage through gaps between baffle plates can be important in aging plants since baffle bolts can stretch over time
- Virtual model used to examine effects of baffleflow leakage on flow into core
  - Does reduced flow into lower plenum create non-uniformities in core inlet flow distribution or instabilities in the lower plenum?
  - Could these or other flow effects contribute to the development of fuel rod leakers?







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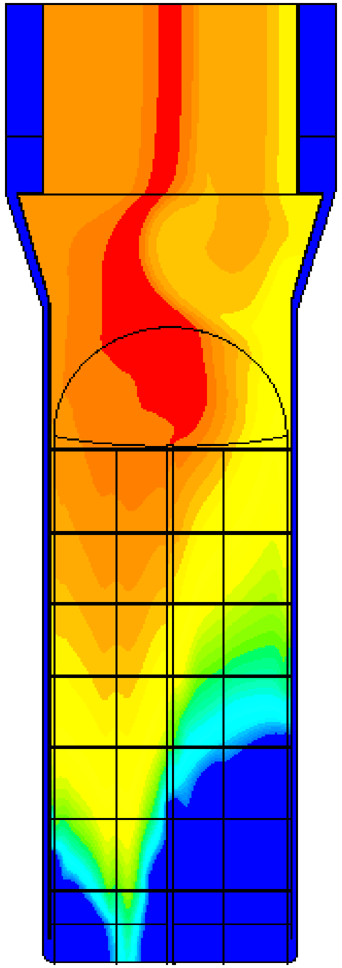
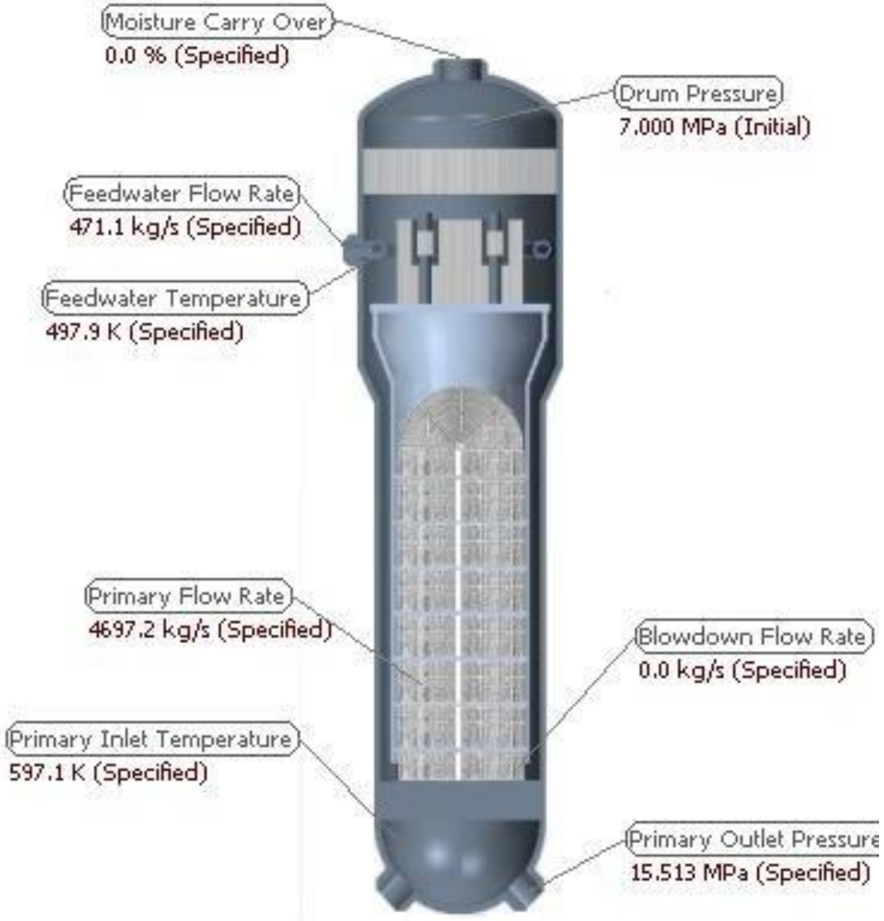
SIEMENS Footprint

Next Generation Steam Generator Tools

- SIEMENS selected by EPRI to develop the Next Generation SG Simulator.
- Targeting the replacement of ATHOS with a predictive tool.
- Code name TRITON, solver STAR-CCM+.
- True CFD solution: To enable special analyses to be performed.
- Detailed information in regions of interest.





Sources EPRI Electric Power Research Institute, Westinghouse

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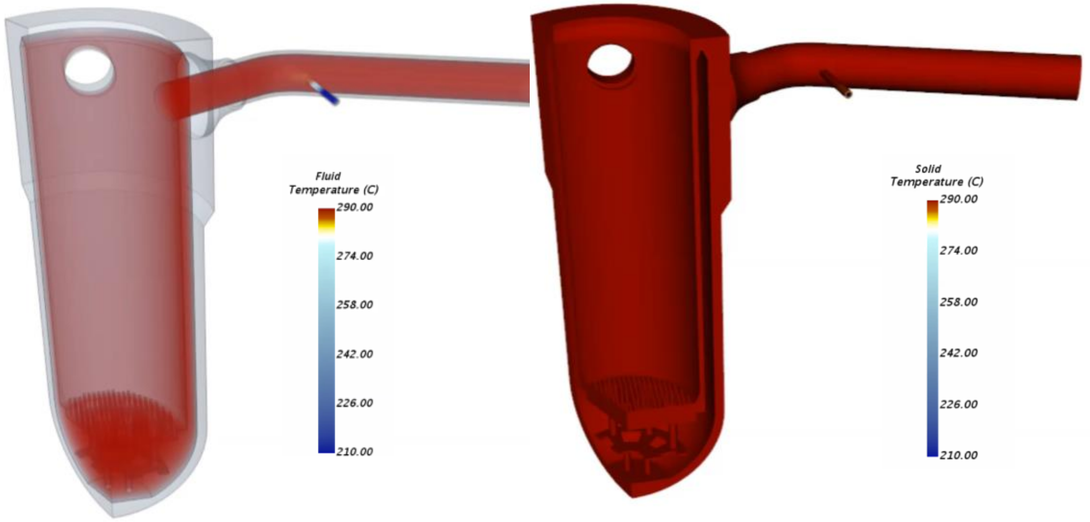
Digital Aging/Failure Monitoring

Operational excellence for complex systems

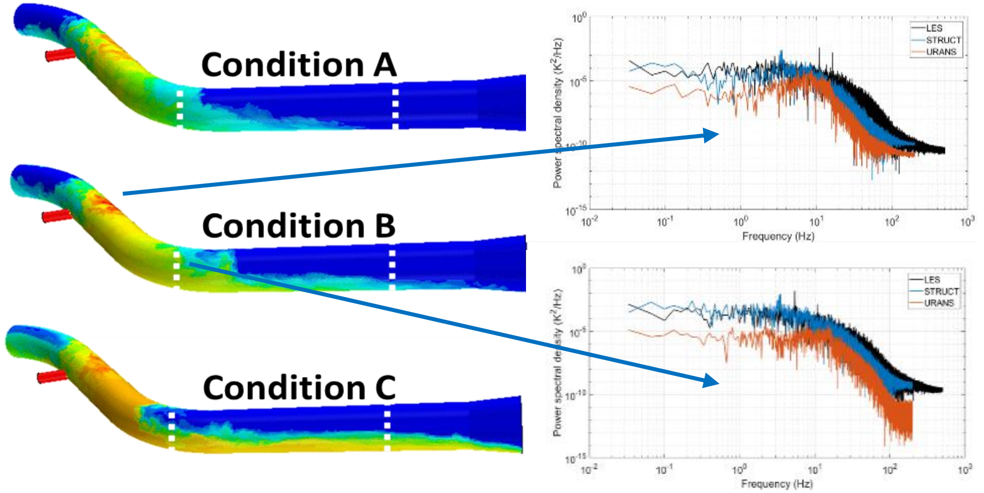
Multi-Disciplinary Simulation

- Better insight into performance with complete flow-thermal-stress analyses
- Streamlined multi-disciplinary capabilities include interfacing with nuclear industry tools
- Full automation for faster design



Digital Aging / Failure Monitoring

- Design exploration capabilities can be used to drive DT of aging
- Example: striping induced thermal fatigue accumulation → Digital Aging

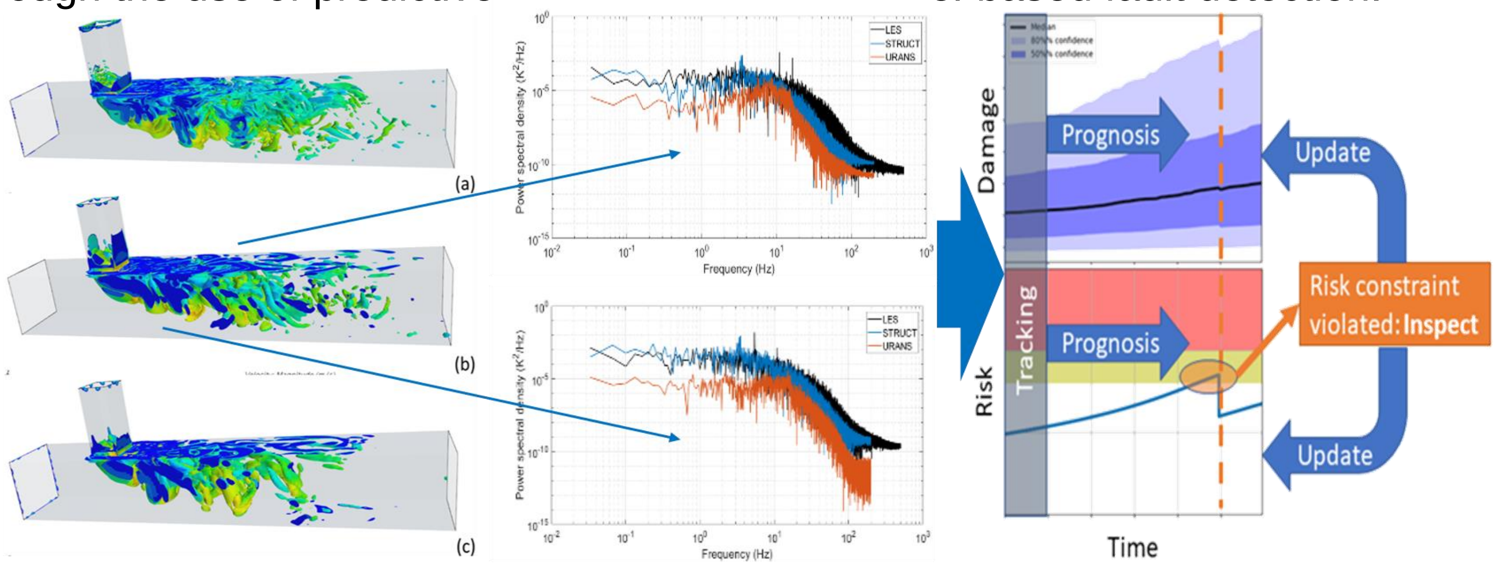


High Fidelity Digital Twins for performance driven maintenance

ARPA-E recognition of importance of Digital Twins

- ARPA-E's program, Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) will develop digital twin technology for advanced nuclear reactors, using artificial intelligence and advanced modeling controls to create tools that introduce greater flexibility in nuclear reactor systems, increased autonomy in operations, and faster design iteration.

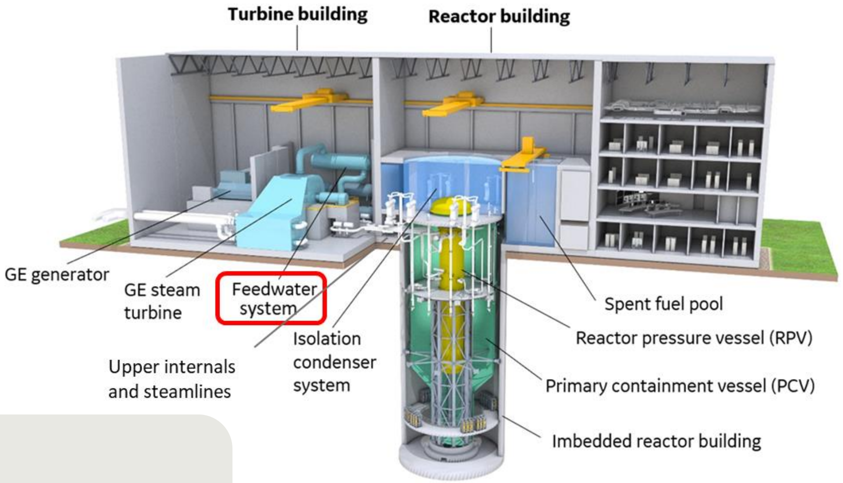
- The GEMINA program will work to transform O&M systems in advanced reactors through the use of predictive maintenance and model-based fault detection.



http://news.mit.edu/2020/making-nuclear-energy-cost-competitive-0527

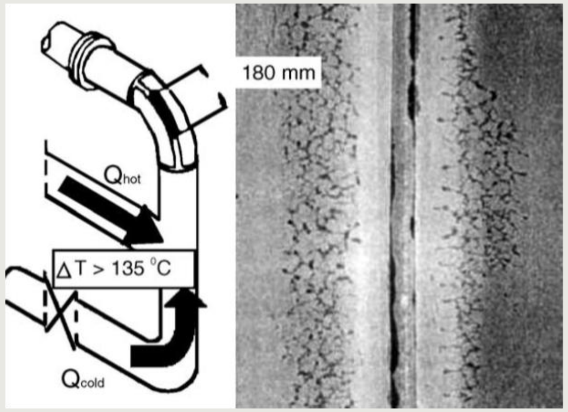
Thermal striping driven fatigue prediction

- Thermal striping fatigue has largest applicability to all AR concepts, beyond BWRX-300 – **FIRST OBJECTIVE**



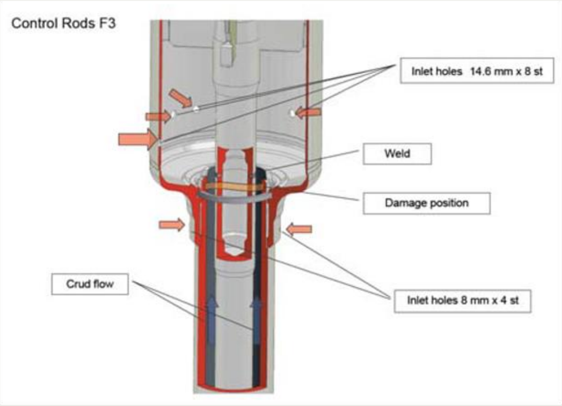
A few notorious examples

Civaux (PWR)



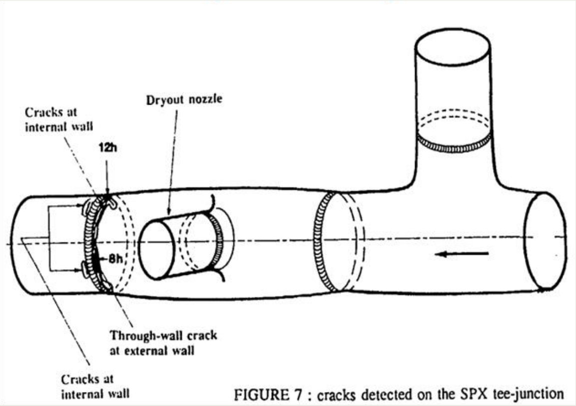
Civaux, EDF, crack in an elbow weld [K.-J. Metzner, U. Wilke /Nuclear Eng. and Design 235 (2005) 473–484 481]

Swedish BWRs CR Stems



Fatigue Inside Control Rod Guide Tubes [Eric Lillberg, ICONE21-16632]

Superfenix (LMFBR)

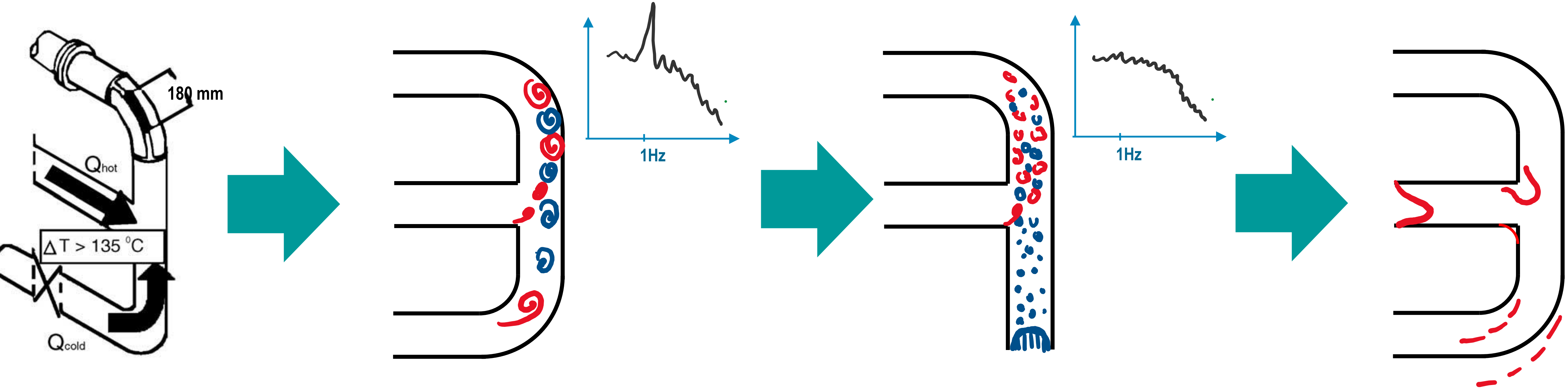


Auxiliary pipe in secondary circuit [O. Gelineau, M. Sperandio/IAEA-IWGFR/90 (1994)]

NSE
Nuclear Science and Engineering

The challenge in a (hand drawn) nutshell

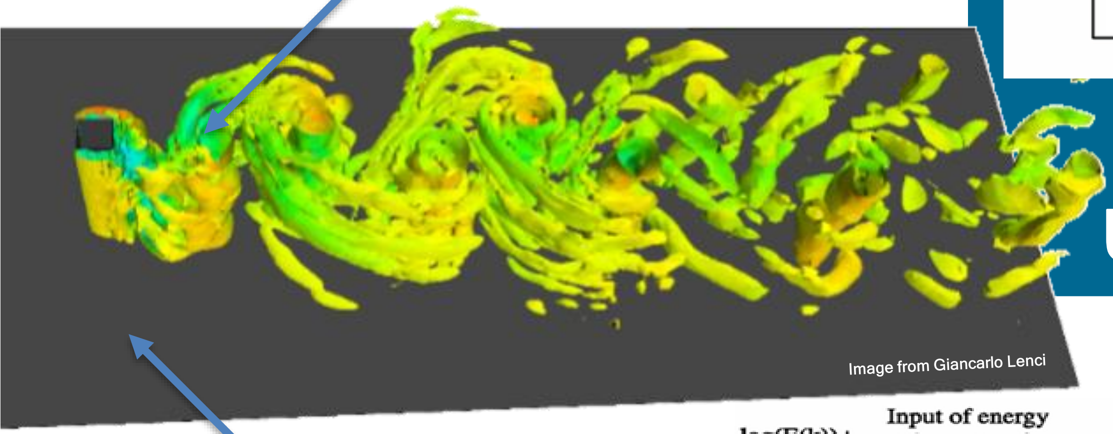
We can leverage the Civaux failure for discussion

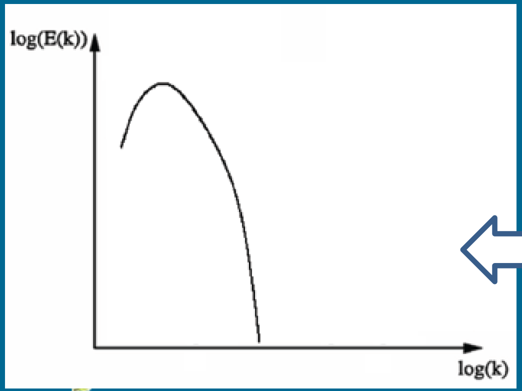


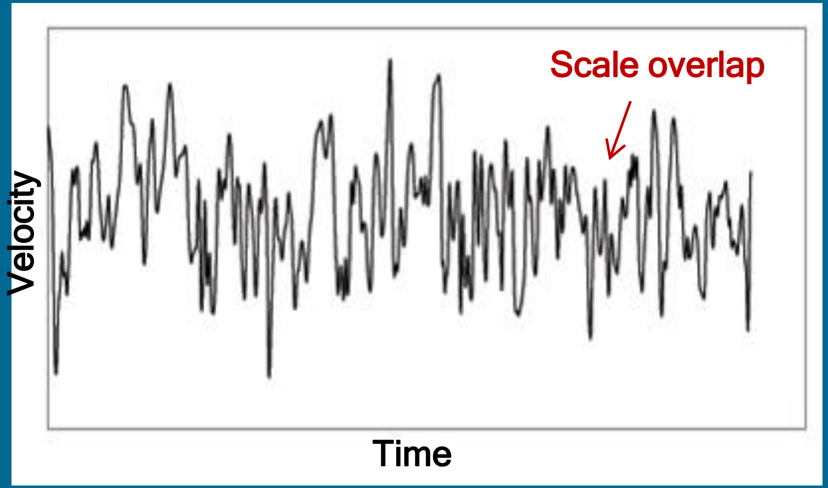
- The turbulent structures generated at the 90° elbow interact at the T and lead to low frequency (1-3 Hz) large temperature oscillation that lead to accelerated fatigue failure
- The same T connection without the elbow does not suffer of these oscillations (but small flow / geometry variations could lead to the opposite results)
- **Phenomenon is driven by formation and interaction of large turbulent structures and is strongly non-linear, not prone to “lumping” and generalization**

The STRUCT idea *(Lenci and Baglietto, 2016)*

In regions with separation, jets, swirls, and strong mixing, flow deviates from equilibrium

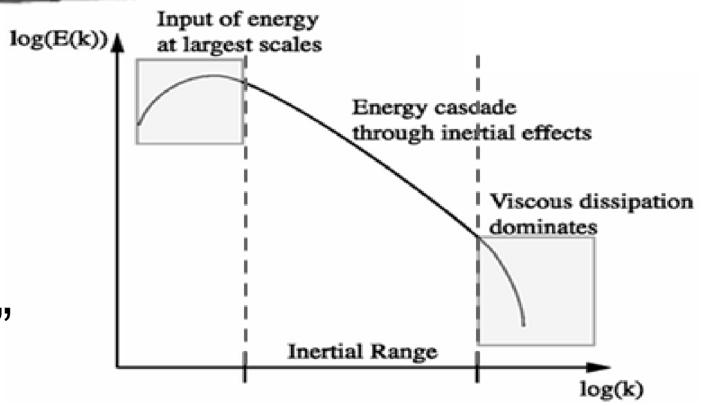




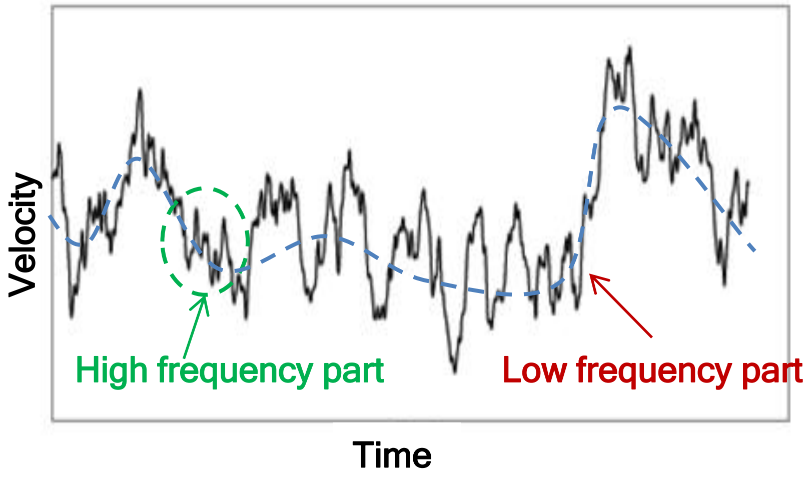


URANS is not applicable to scale overlap

(U)RANS models are based on the assumption of an "equilibrium spectrum"



http://ffden-2.phys.uaf.edu/647fall2013_web.dir/j_stroh/tec.html

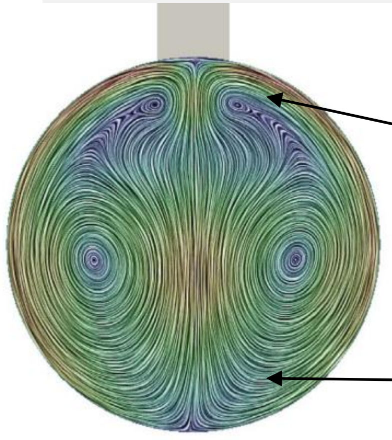


Application on feedwater system recap

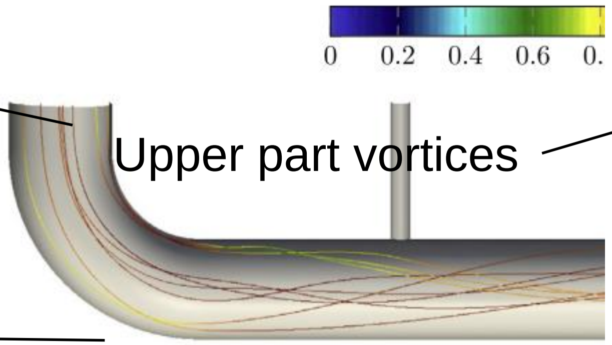
Manchester LES

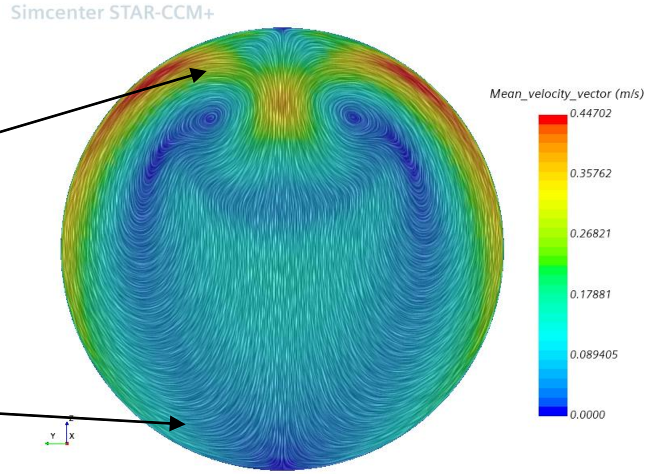
STRUCT

Velocity Vector



(a) $7D_b$ upstream





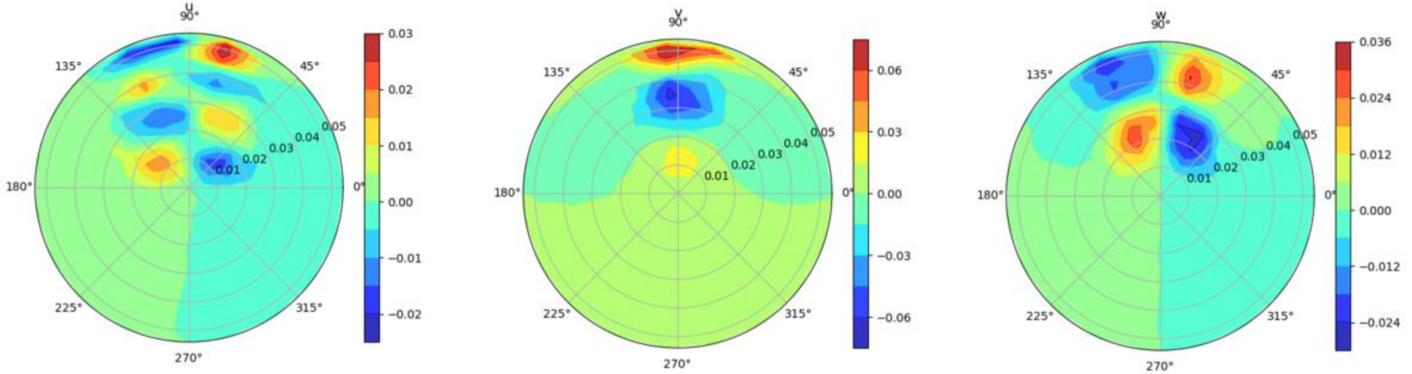
Upper part vortices

Lower part vortices

A method for flow feature extraction

POD Mode 1

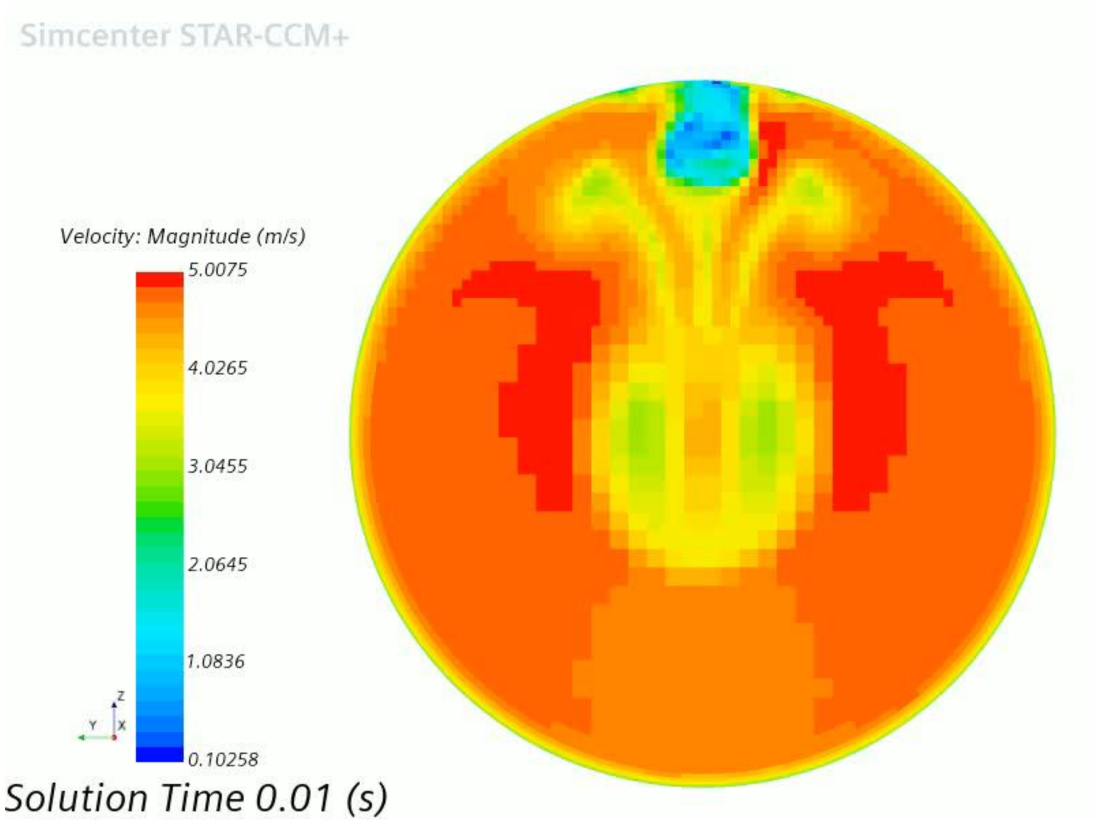
(a) $7D_b$ upstream



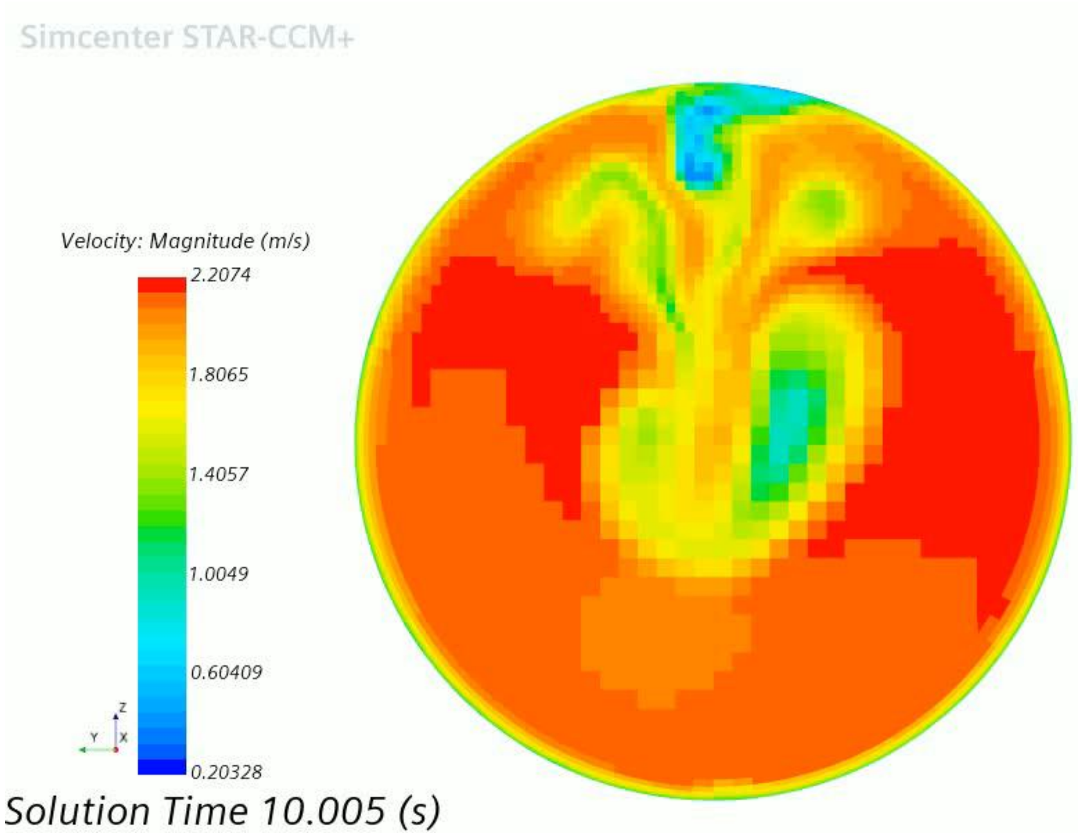
– The STRUCT model accurately captures the swirl switching features

Swirl-Switching example
Fluid (~3.5 inch downstream)

100%

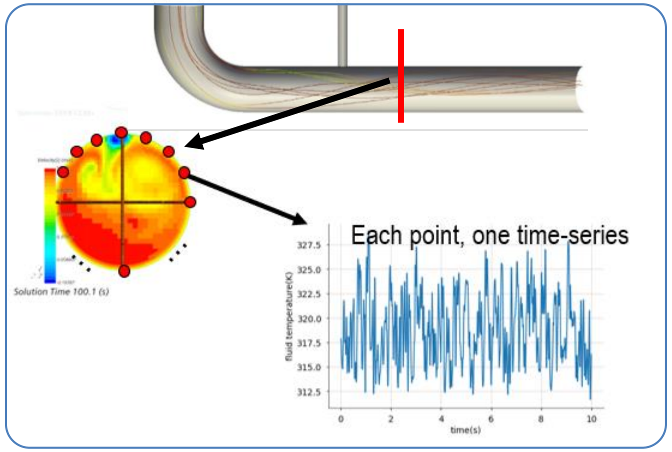


50%



High-fidelity simulation based DT generation

Inputs → Model → Temperature & Stress →



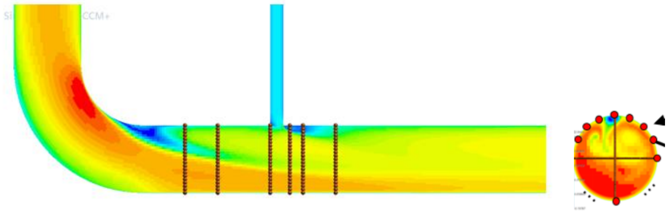
→ Damage or Fatigue lifetime

The model outputs will look like this:

$$\begin{array}{r c c c c c}
 & \text{Labels (BC)} & \text{Point 1's stress time-series} & \text{Point 2's stress time-series} & & \text{Point n's stress time-series} \\
1^{st}\text{ operation conditions} \rightarrow & \dot{m}_{C1}\ \dot{m}_{H1}\ T_{C1}\ T_{H1} & S_{1,p1}(t_1)\ldots S_{1,p1}(t_n) & S_{1,p2}(t_1)\ldots S_{1,p2}(t_n) & & S_{1,pn}(t_1)\ldots S_{1,pn}(t_n) \\
2^{nd}\text{ operation conditions} \rightarrow & \dot{m}_{C2}\ \dot{m}_{H2}\ T_{C2}\ T_{H2} & S_{2,p1}(t_1)\ldots S_{2,p1}(t_n) & S_{2,p2}(t_1)\ldots S_{2,p2}(t_n) & \cdots & S_{2,pn}(t_1)\ldots S_{2,pn}(t_n) \\
\vdots & \vdots\quad\vdots\quad\vdots\quad\vdots & \vdots & \vdots & & \vdots
\end{array}$$

- **The high-fidelity data provide a uniquely rich database for DT generation**
- **Capability of including sensitivity to many parameter variations**

Digital Twin Prototype
Feedwater subsystem



Analysis of number of cycles to damage initiation (N_i) using simulated data at each power level:

1. *Selection of power level (user input)*
2. *Running Rainflow Counting on the available simulated stress histories*
3. *Calculating N_i values*
4. *Modeling N_i across all angles and positions in the data for each cycle using Gaussian Process models*

Uncertainty Quantification in Crack Initiation

Power Level

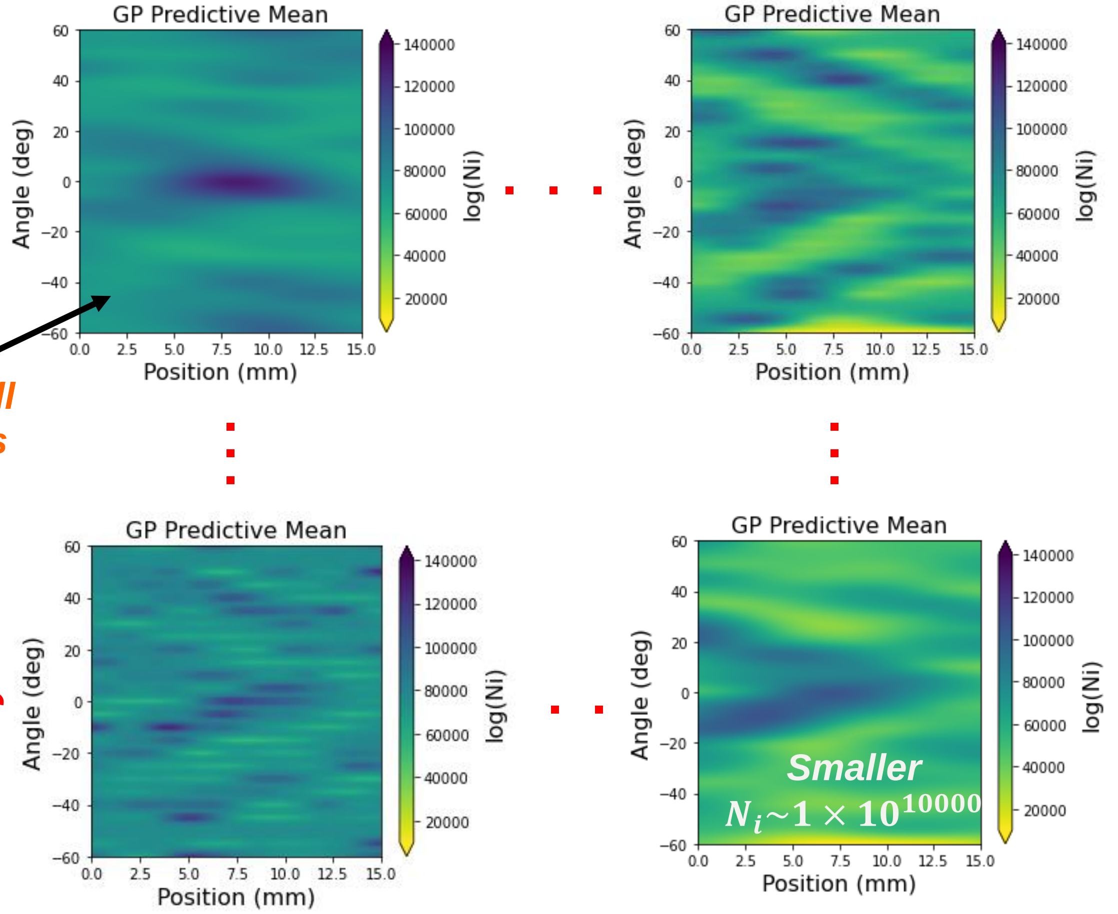
Cycles

20%

100%

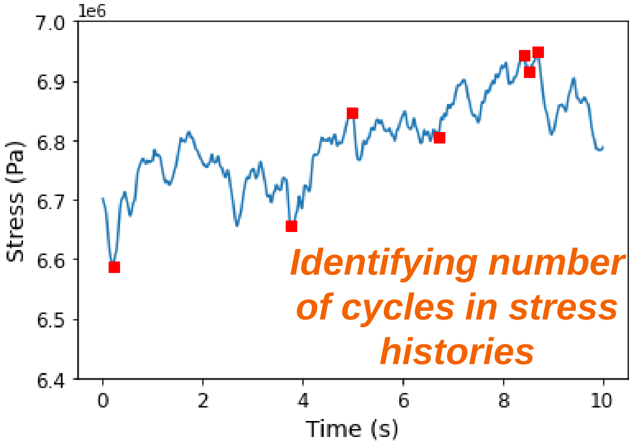
1st Cycle

nth Cycle

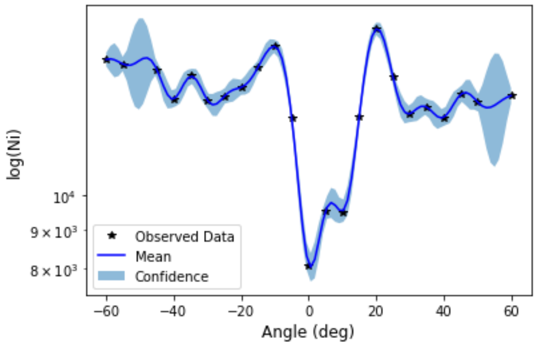


Crack initiation Predictions across all positions and angles

Rainflow Counting Algorithm

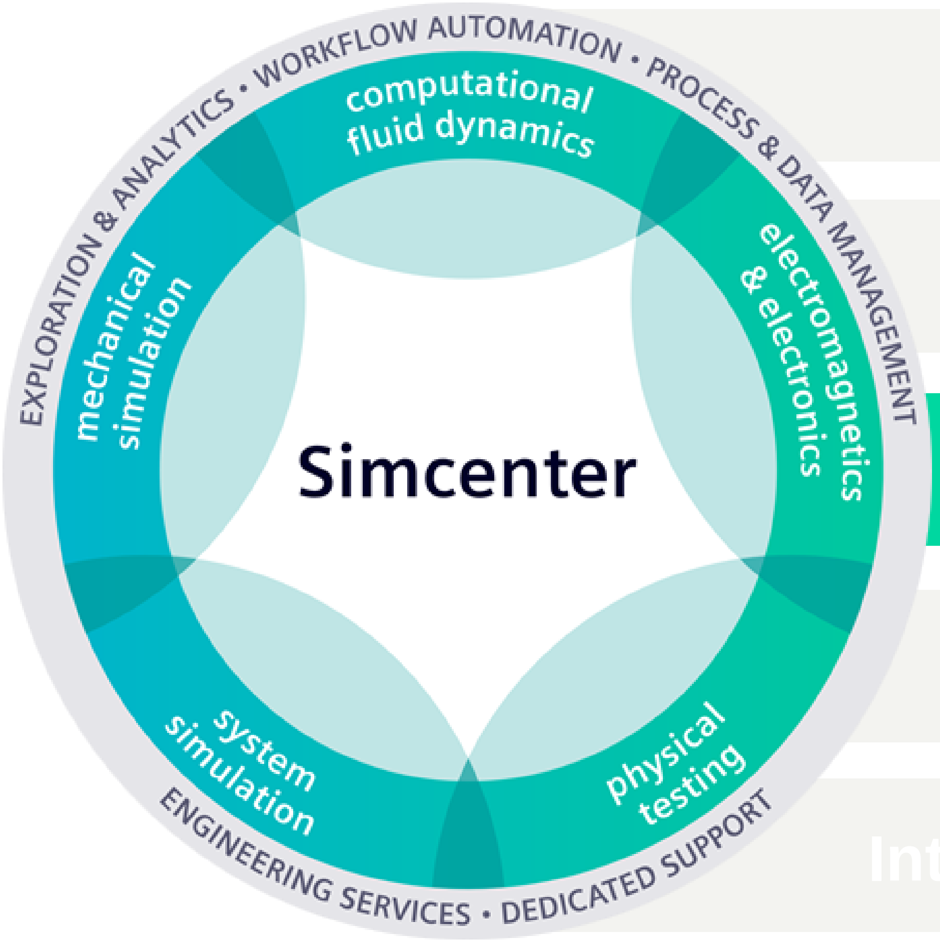


Uncertainty Quantification in crack initiation



Simcenter Portfolio

Engineer innovation for nuclear energy performance



Fuel Performance

Plant Performance

Advanced Reactors

Back-end

Integration, Verification & Certification

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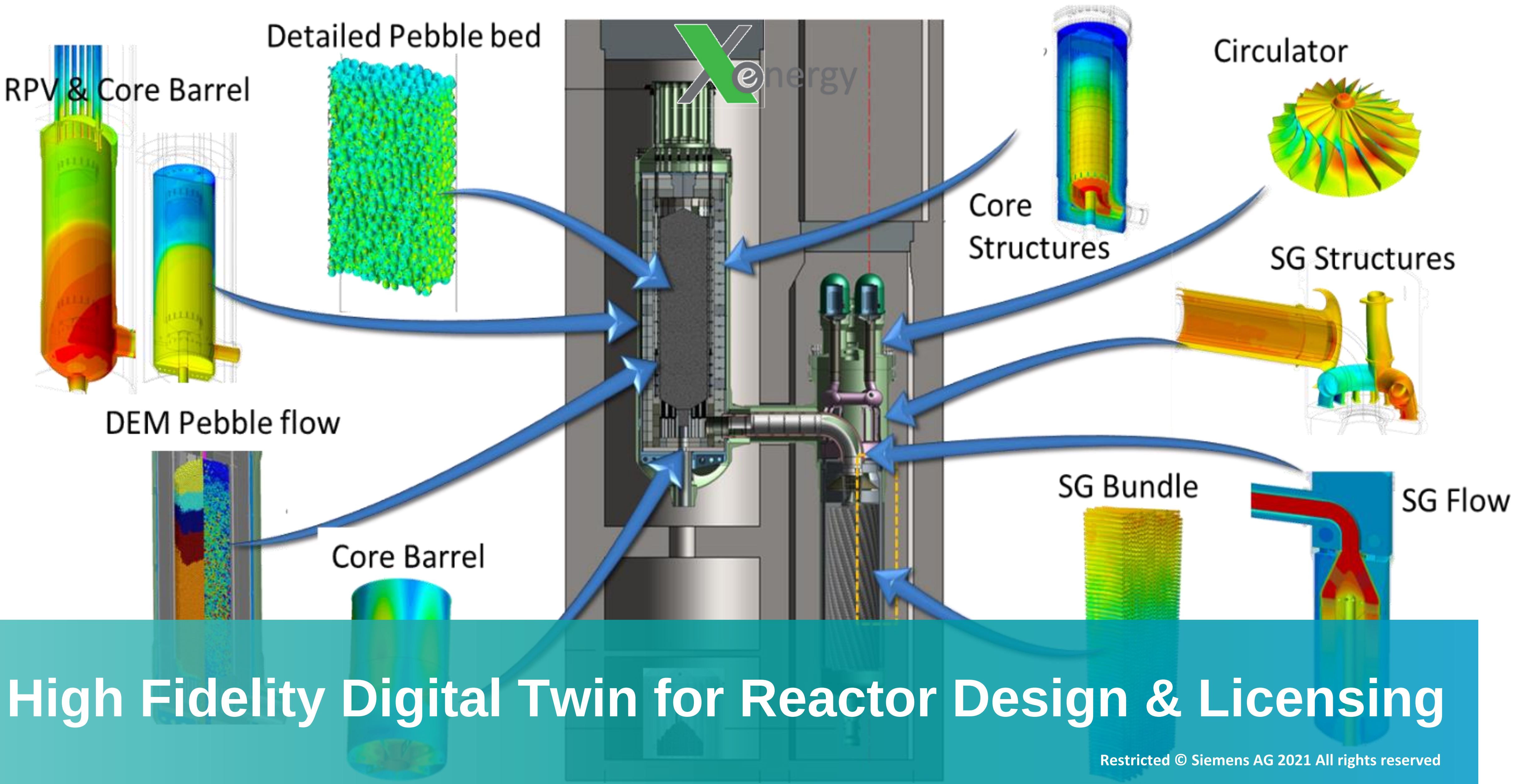

High Fidelity Digital Twin for Reactor Design & Licensing

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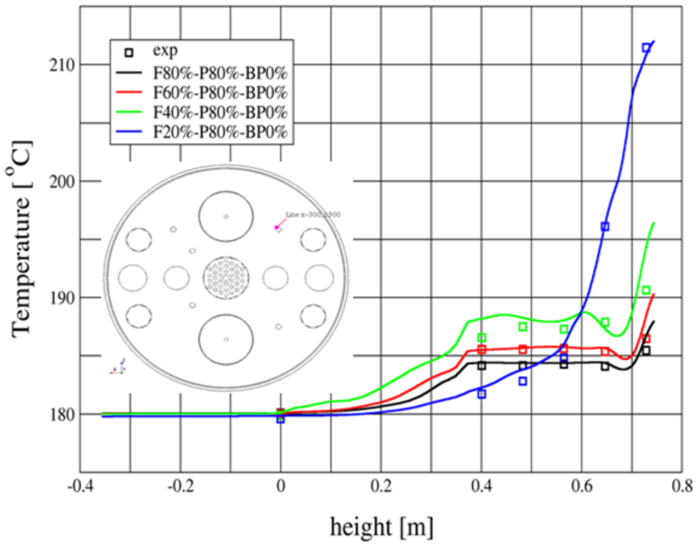
Methods Validation

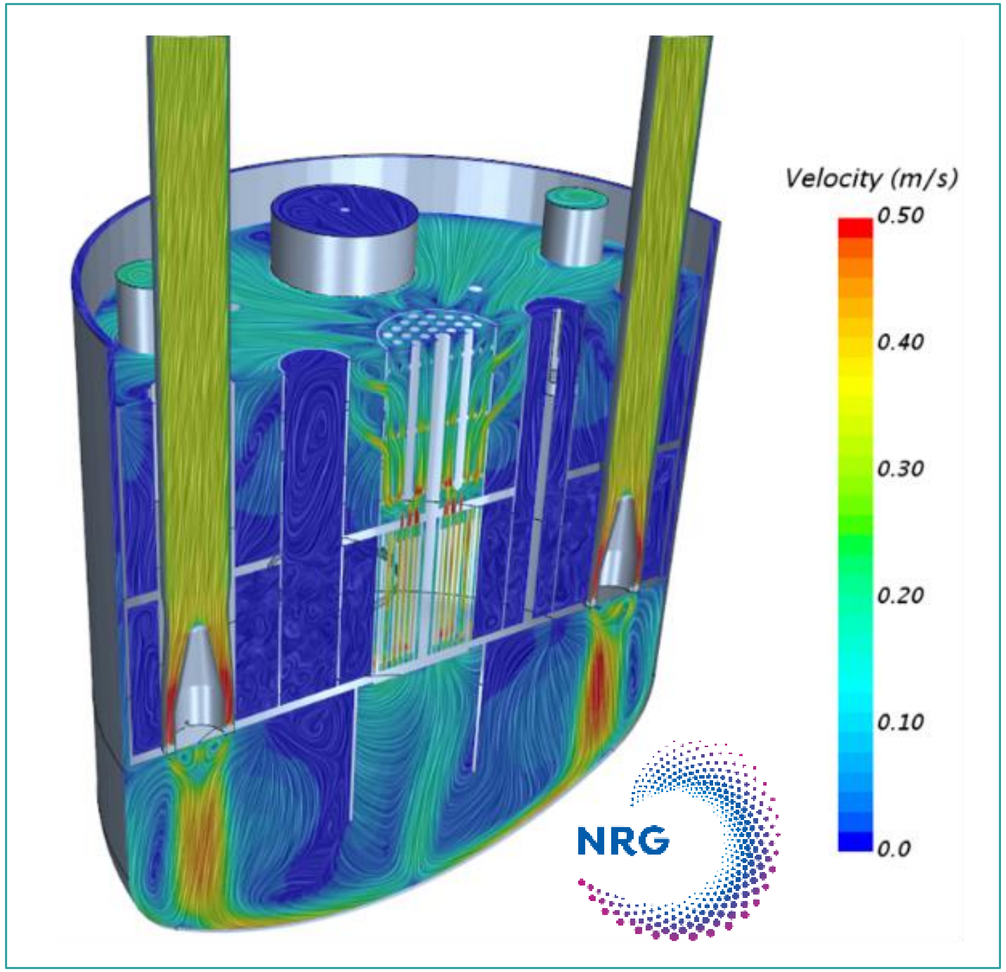
Primary System Virtual Model
Example: wire wrapped metal cooled fuel

Simcenter STAR-CCM+ model of ESCAPE experiment

- No tuning required
- Thermocouple data compare well with predictions
- Stratification at low flow rate well simulated.



Visser et al. (2020) NE&D



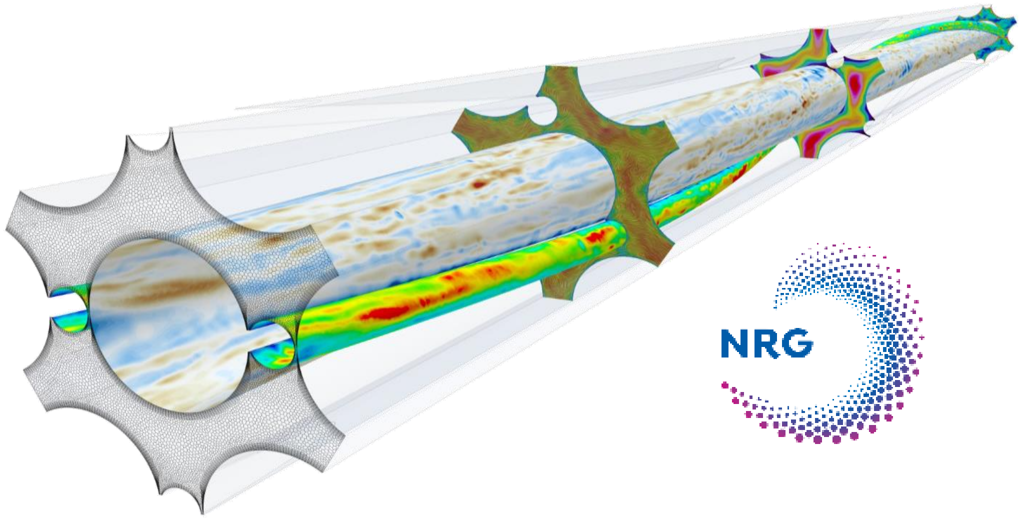
Wire Wrapped Fuel Validation at NRG
Example: wire wrapped metal cooled fuel

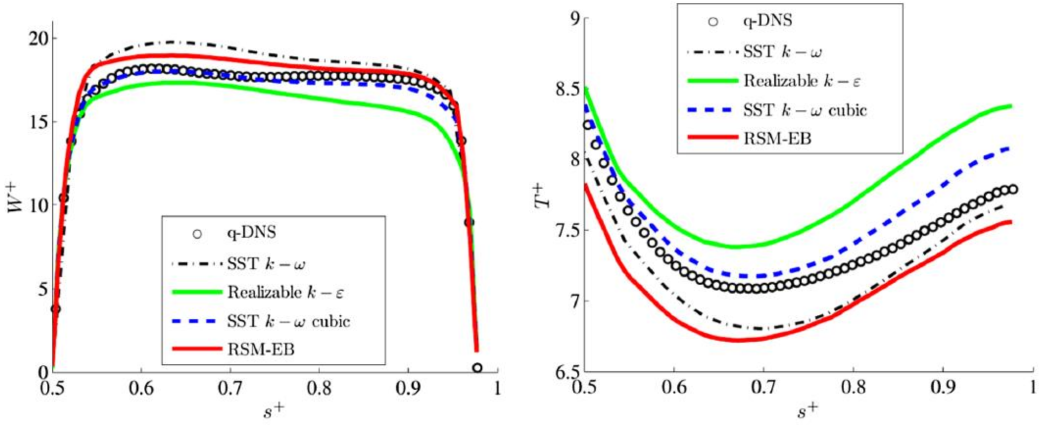
Quasi-DNS as reference for RANS model validation in Simcenter STAR-CCM+

- DNS quality spatial and temporal resolution
- RANS assessment
  - linear models (SST k-ω and real. k-ε)
  - non-linear SST k-ω cubic
  - RSM-EB

References

- A. Shams, F. Roelofs, E. Baglietto, E.M.J. Komen, High fidelity numerical simulations of an infinite wire-wrapped fuel assembly, Nuclear Engineering and Design, Volume 335, 2018, Pages 441-459.
- Shams A., Mikuž B., Roelofs F. Numerical prediction of flow and heat transfer in a loosely spaced bare rod bundle. International Journal of Heat and Fluid Flow, Volume 73, 2018





Dovizio et al. (2019 and 2020) NE&D

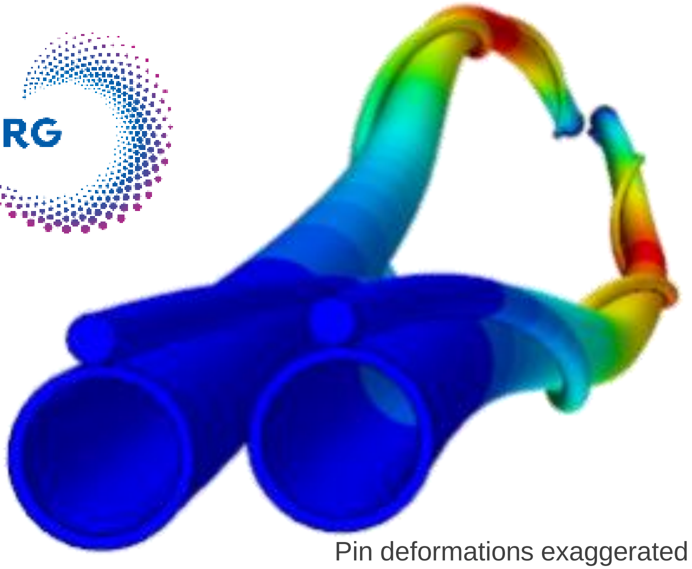
Wire Wrapped Fluid Structure Interaction (FSI)

Example: wire wrapped metal cooled fuel

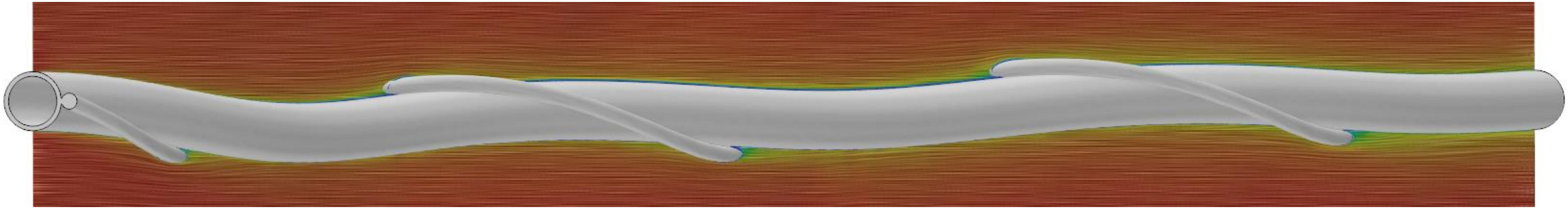
Fully coupled FSI with complex wire-wrap geometry

- Efficient process with flexible meshing and built-in FSI
- Validation based on experiments without wires
- Analyze influence of wire
- Study effects of working fluid (water vs liquid metal)

NRG



Pin deformations exaggerated



Modeling Advancement

DOE Consortium for Advanced Reactors M&S

- Four challenge problems focusing on Sodium, lead, salt and high temperature gas reactors
- **Industrial Partrners TerraPower, Westinghouse, KAIROS Power, General Atomics**

Lab Center Leadership
NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

University Consortium Leadership
Director, Integration & Management: Elia Merzari

Advisory Board
Chair: Bajorek

CP 1 - Flexible modeling for heat transfer
Lead: Bolotnov
- 1.1 - Merzari (PSU)
- 1.2 - Dinh/Bolotnov (NCSU)
- 1.3 - Baglietto (MIT)
- 1.4 - Merzari (PSU)
  Hu/Zou (ANL)

CP 2 - Thermal striping of internals
Lead: Baglietto
- 2.1 - Manera (UM)
- 2.2 - Merzari (PSU)
- 2.3 - Baglietto (MIT)
  Strasser (LU)

CP 3 - Mixing in large enclosures
Lead: Manera
- 3.1 - Manera (UM)
- 3.2 - Hassan/Manera
- 3.3 - Baglietto (MIT)
- 3.4 - Merzari/Bolotnov
- 3.5 - Dinh/Bolotnov (NCSU)
  Martineau/Schuhert (INL)
  Hu/Zou (ANL)

CP 4 - Multiscale core modeling coupled to fuel performance
Lead: Hassan
- 4.1 - Hassan (TAMU)
- 4.2 - Hassan (TAMU)
- 4.3 - Merzari (PSU)
- 4.4 - Merzari (PSU)
  Martineau/Schuhert (INL)

- Large Eddy Simulation/Direct Numerical Simulation
- Hybrid Turbulence Modeling
- Reynolds Averaged Navier-Stokes
- Porous media/Subchannel/Coarse CFD Lumped parameter approaches
- Experimental Methods

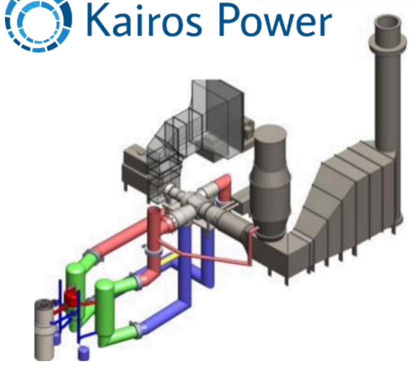
Industrial Partners

Martin (TerraPower)
Choi (General Atomics)
Dzodzo (Westinghouse)
Jackson (Kairos Power)

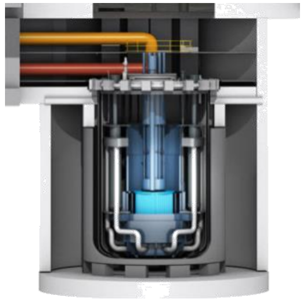
Support all tasks and ensure relevance/value to industry

PennState MIT MICHIGAN ATM

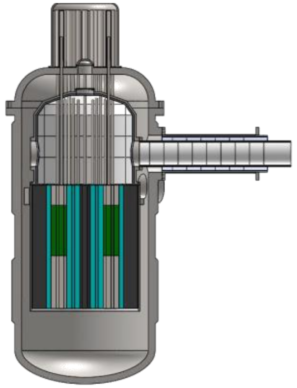
Kairos Power



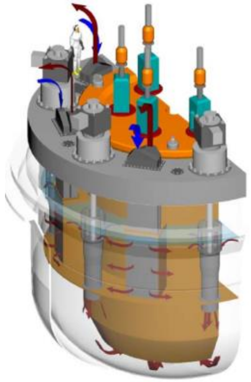
TerraPower
A nuclear innovation company



GENERAL ATOMICS



Westinghouse



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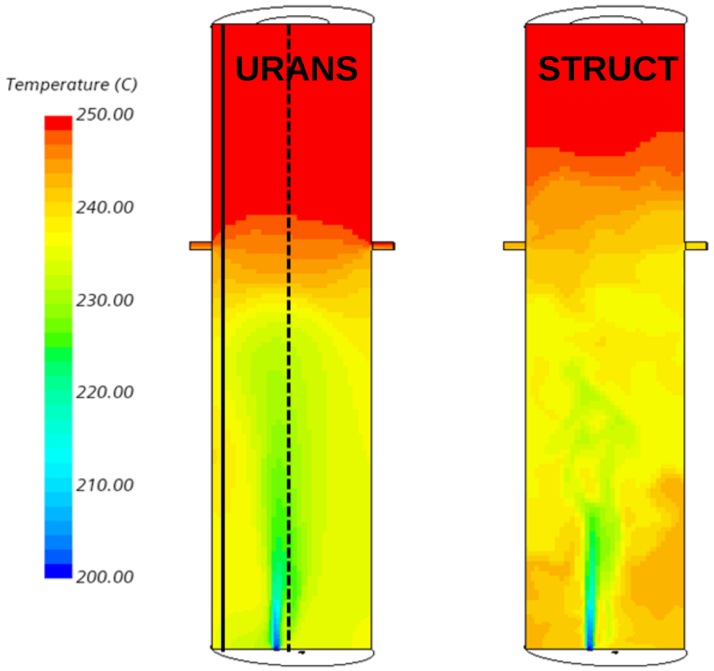
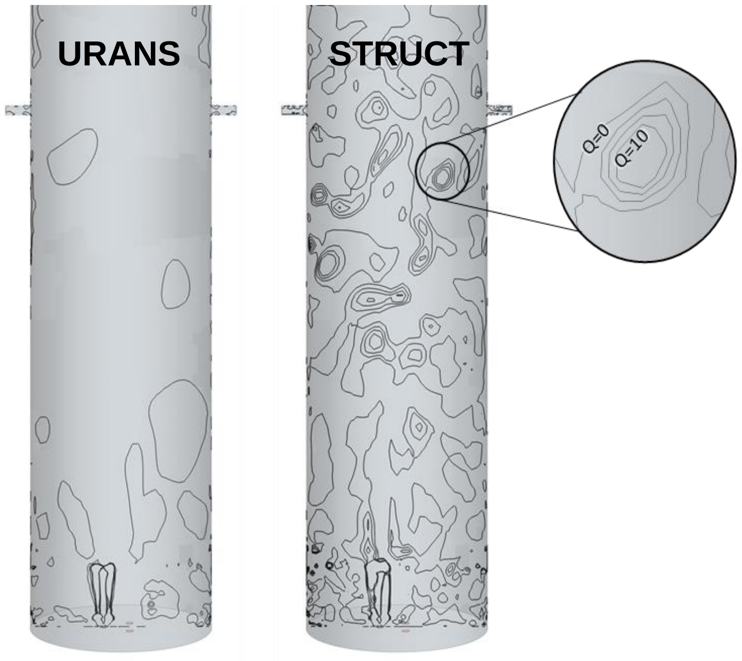
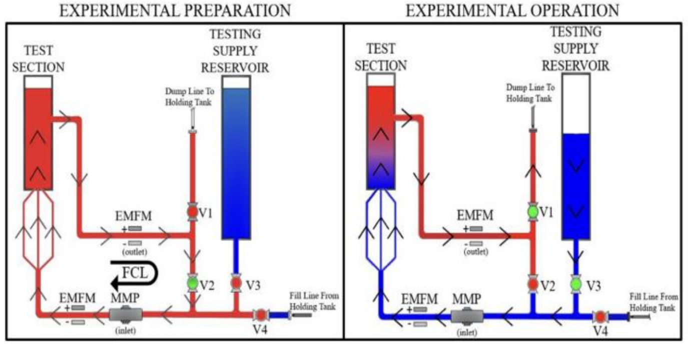
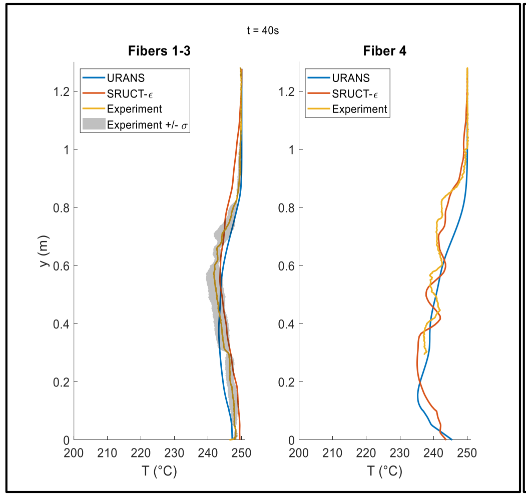
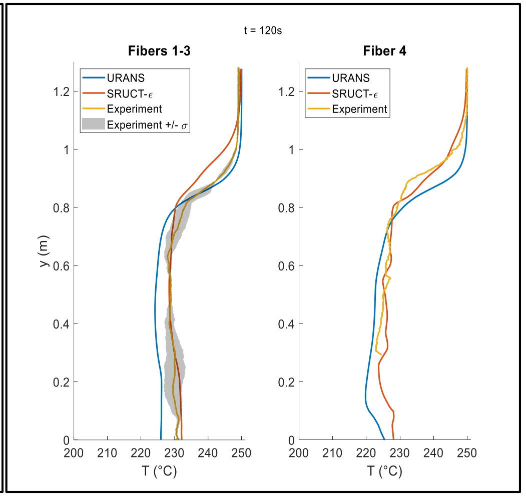
Example: Thermal Stratification / mixing in Sodium Pools

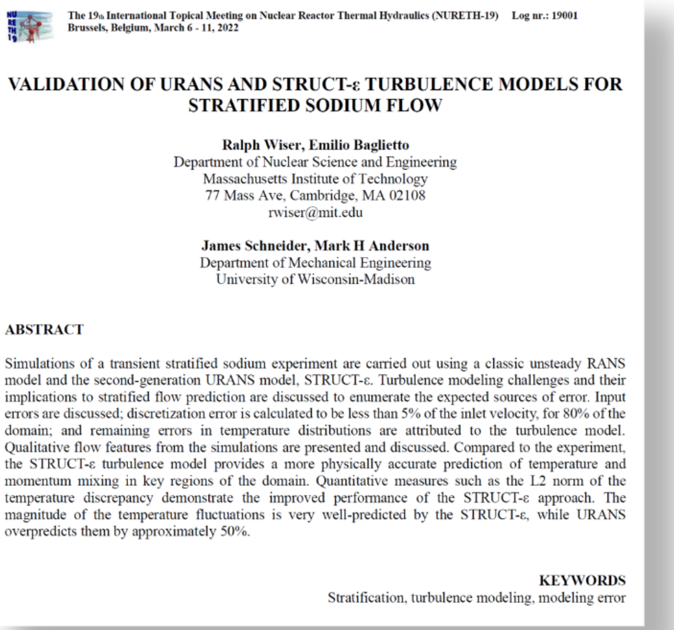












The 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) Log nr.: 19001
Brussels, Belgium, March 6 - 11, 2022

VALIDATION OF URANS AND STRUCT-ε TURBULENCE MODELS FOR STRATIFIED SODIUM FLOW

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Department of Mechanical Engineering
University of Wisconsin-Madison

ABSTRACT

Simulations of a transient stratified sodium experiment are carried out using a classic unsteady RANS model and the second-generation URANS model, STRUCT-ε. Turbulence modeling challenges and their implications to stratified flow prediction are discussed to enumerate the expected sources of error. Input errors are discussed; discretization error is calculated to be less than 5% of the inlet velocity, for 80% of the domain; and remaining errors in temperature distributions are attributed to the turbulence model. Qualitative flow features from the simulations are presented and discussed. Compared to the experiment, the STRUCT-ε turbulence model provides a more physically accurate prediction of temperature and momentum mixing in key regions of the domain. Quantitative measures such as the L2 norm of the temperature discrepancy demonstrate the improved performance of the STRUCT-ε approach. The magnitude of the temperature fluctuations is very well-predicted by the STRUCT-ε, while URANS overpredicts them by approximately 50%.

KEYWORDS
Stratification, turbulence modeling, modeling error

U.S. DEPARTMENT OF ENERGY

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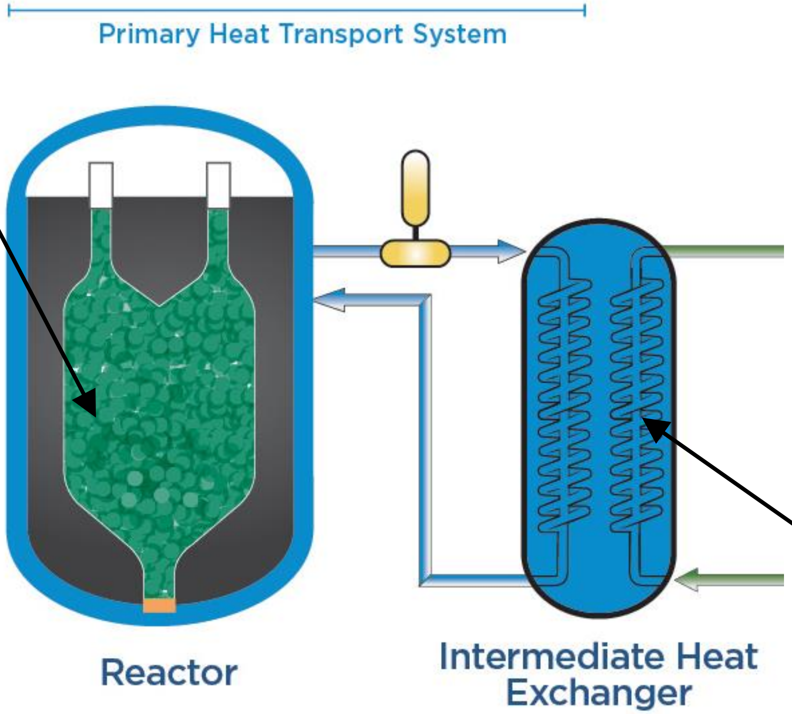
Modeling (nuclear/solar) molten salts

Carolyn Coyle, 2020 - Advancing Radiative Heat Transfer Modeling in High-Temperature Liquid-Salts. MIT PhD Thesis

Thermal radiation property measurements

FTIR spectroscopy experimental apparatus

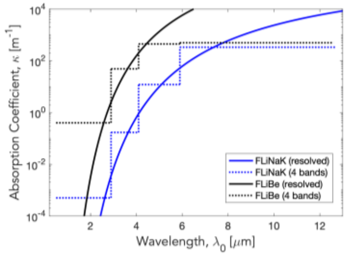
Determination of RHT effects and modeling best practices



Kairos Power FHR Design

Participating media RHT modeling methodology

CFD-DOM spectral banding methodology

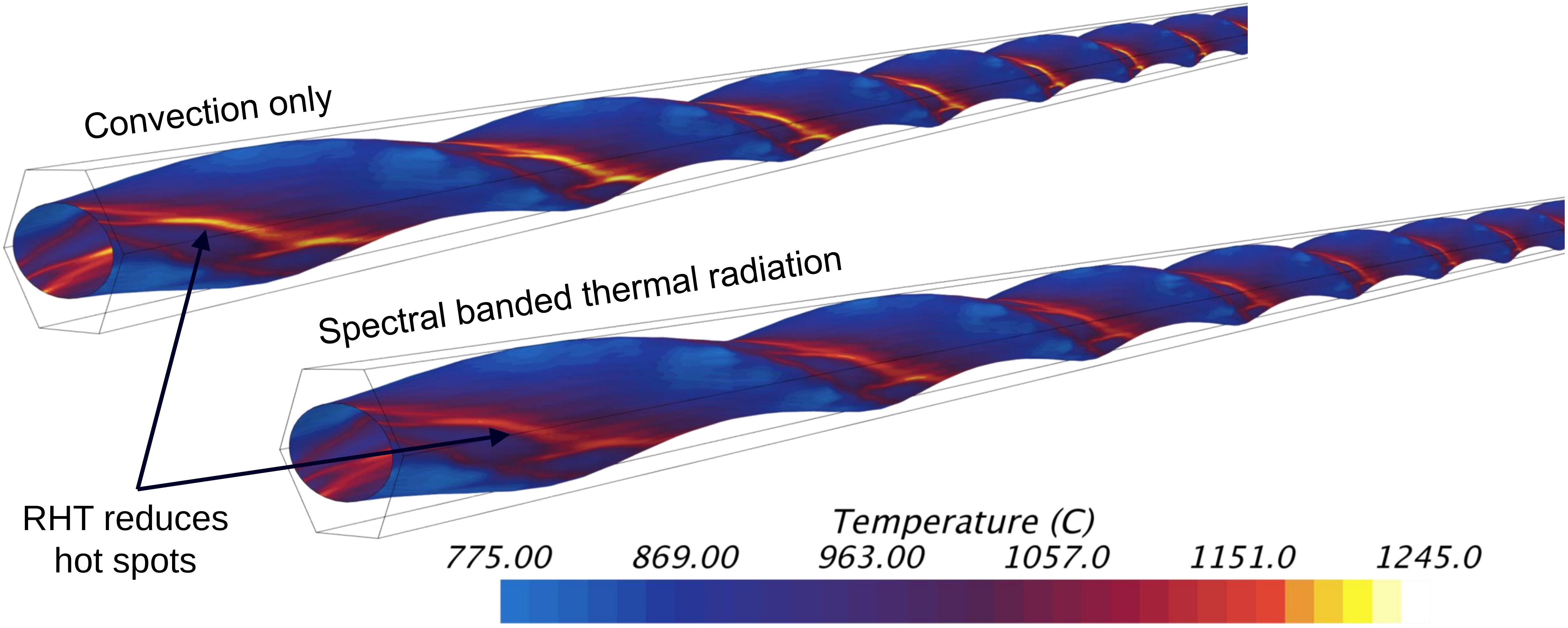


Computational analysis

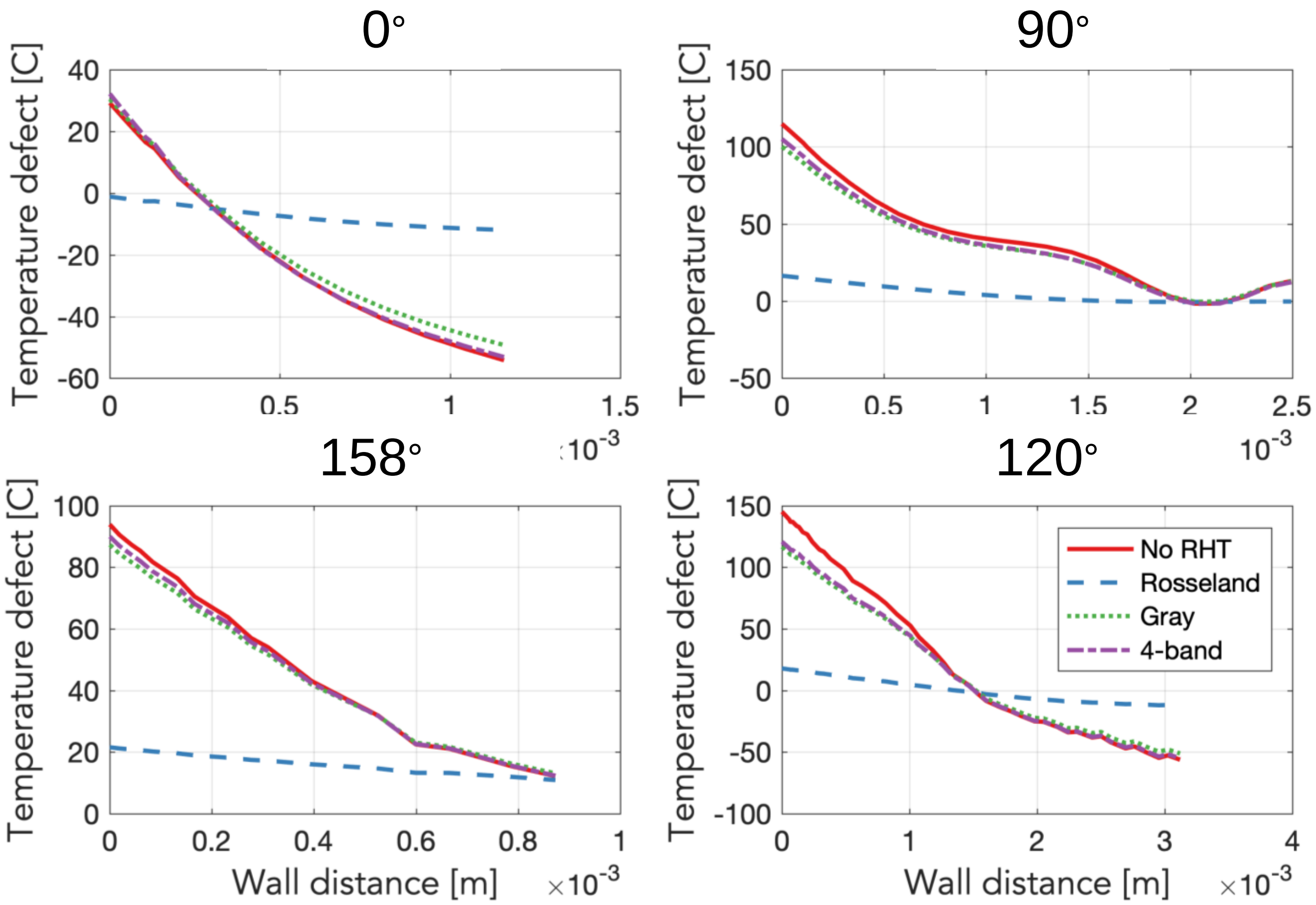
Twisted elliptical tube heat exchanger

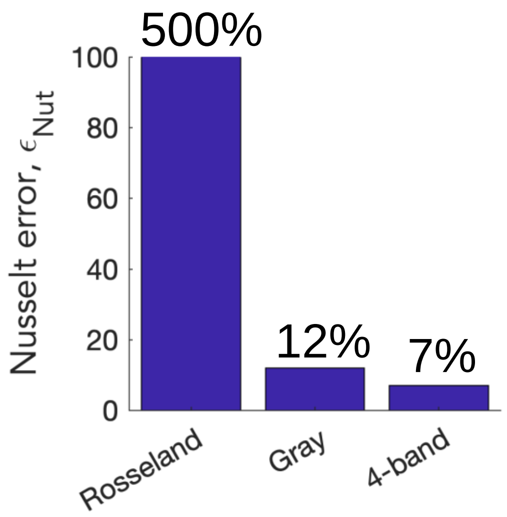
*KP-FHR figure from Kairos Power

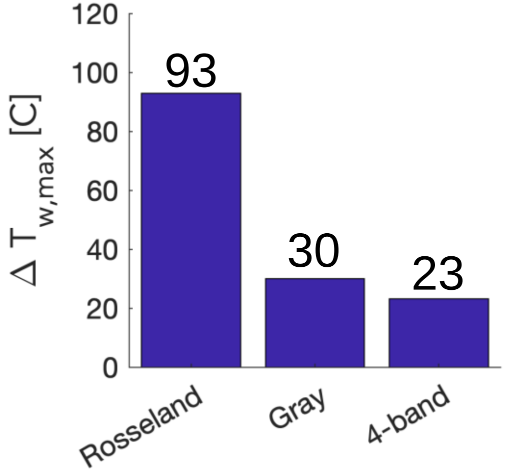
Maximum wall temperature may have large effects on material corrosion during normal operation

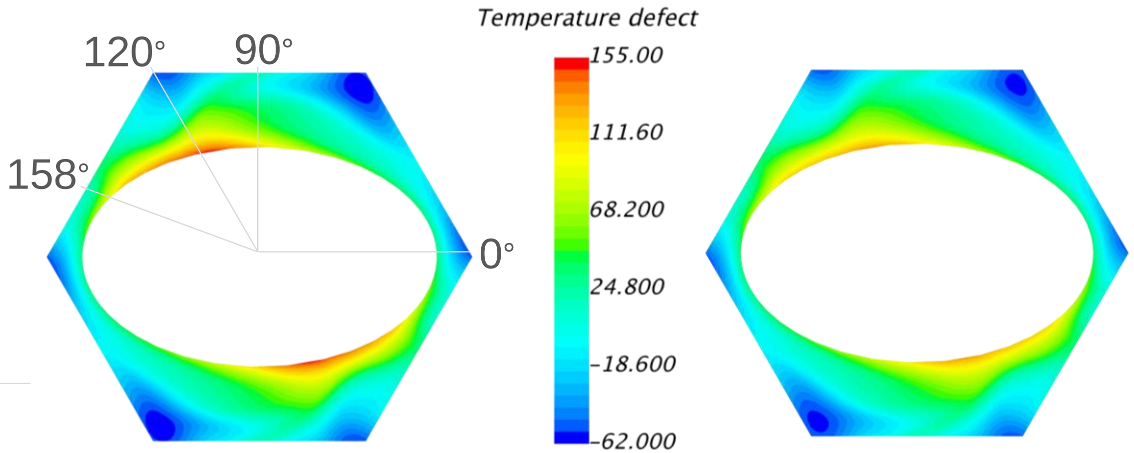


FLiNaK, Re = 500, q'' = 0.12 MW/m²









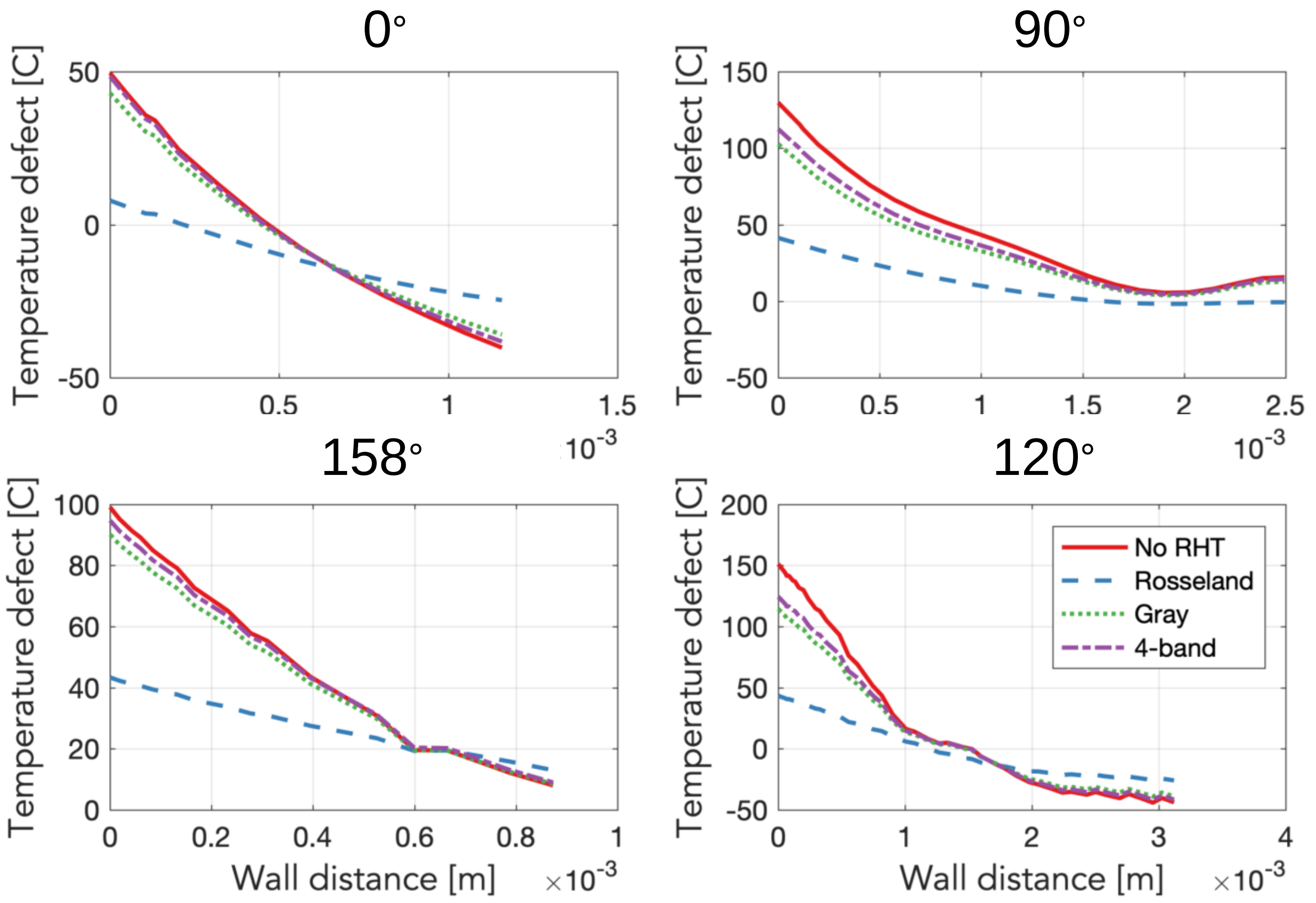
No radiation

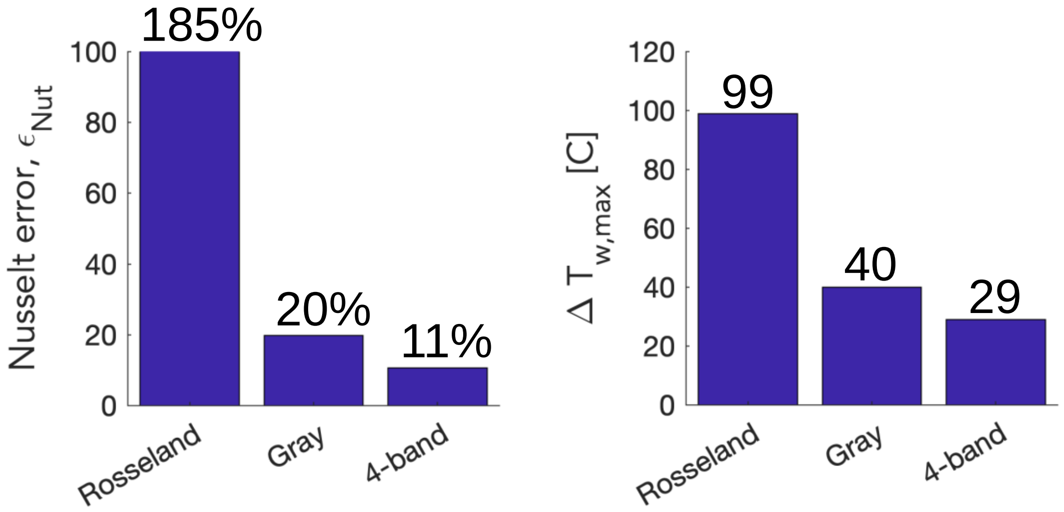
4-band RHT

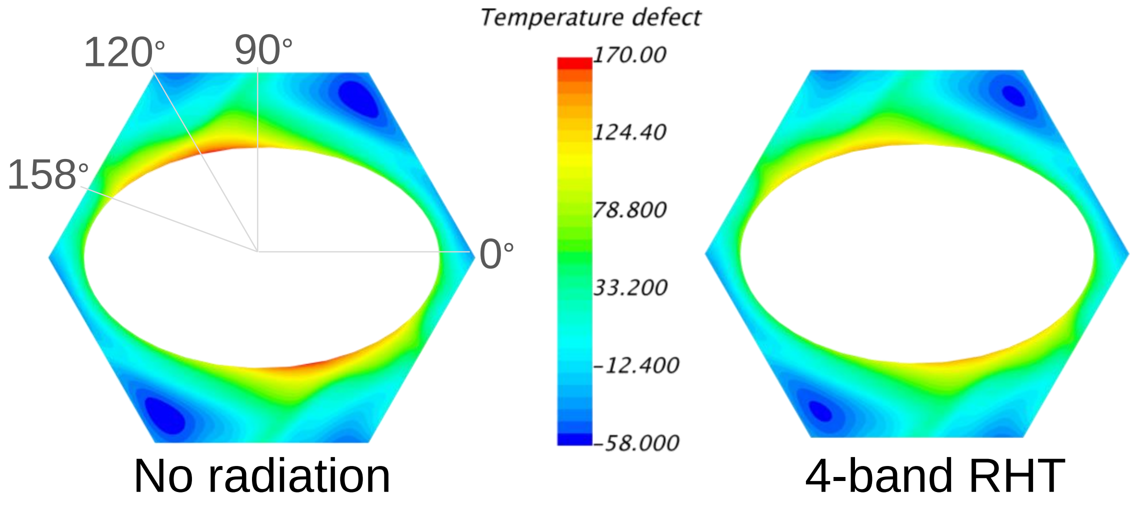
Low κ: Scale of RHT effects are reduced, but still present

Carolyn Coyle, 2020 - Advancing Radiative Heat Transfer Modeling in High-Temperature Liquid-Salts. MIT PhD Thesis

FLiBe, Re = 247, q” = 0.15 MW/m²







High q”: Effects of RHT increases with heat flux

FUTURE ENERGY CAMPUS

ArtEZ MIT

Landscape urbanism of the Energy Campus