Framatome's advanced core distortion simulation capabilities

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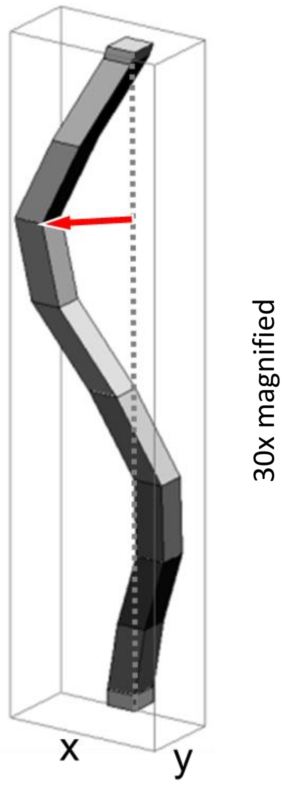
Introduction

- Lateral distortion (bow) of fuel assemblies (FAs) is a known phenomenon in PWR.
- Consequences of increased FA bow
  - Adversely affects fuel handling core loading and unloading
  - Leads to high handling forces and potential delays during outages
  - May impair core performance and increase rod cluster control assembly (RCCA) drop times
- Nuclear safety and plant operability require prevention of excessive FA bow.
- Framatome’s response to observed FA bow:
  - Comprehensive investigations to understand and predict the phenomenon
  - Development and implementation of countermeasures
  - Mitigation of operational issues
- An overview on the existing FA bow analysis tools, the status of the tool development for VVER-1000 and the next steps will be presented.

Main drivers of FA bow

- FA bow in PWR is the result of a complex interaction between mechanical, hydraulic, and irradiation effects.
- FAs as slender structures with a predominantly compressive loading are sensitive to FA bow.
- During operation, FAs develop a creep deformation triggered by the temperature, fast neutron flux, and hydraulic forces.
- FA bow measurements reveal the
  - Evolution of typical bow patterns (e.g. radial, unidirectional) and shapes
  - Dependence of the bow pattern on FA design and shuffling strategy
  - Some repeatability of bow directions and amplitudes at individual core positions

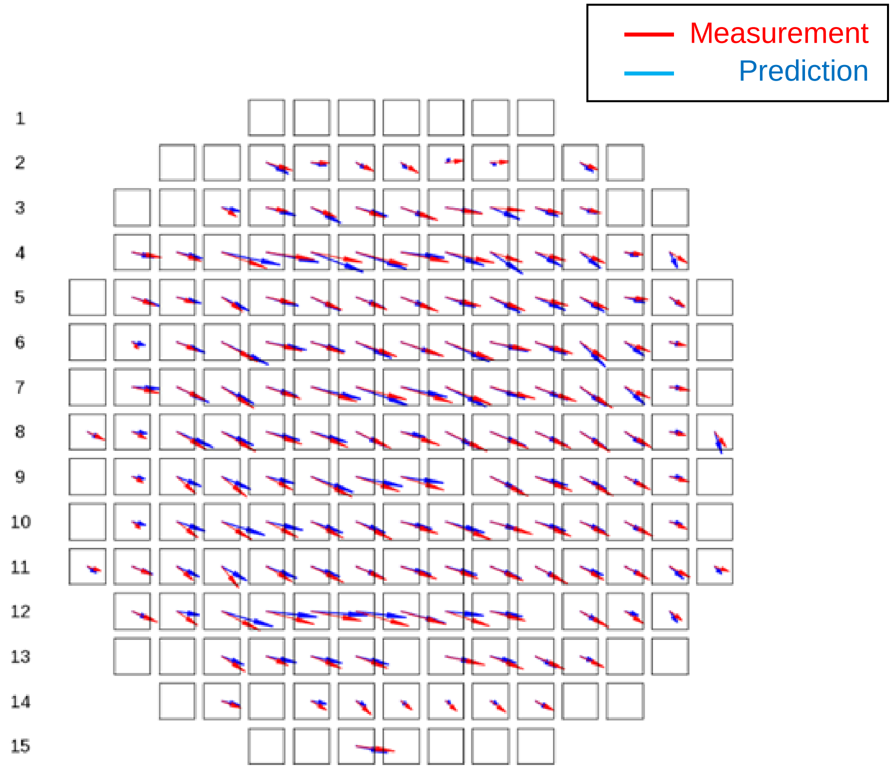


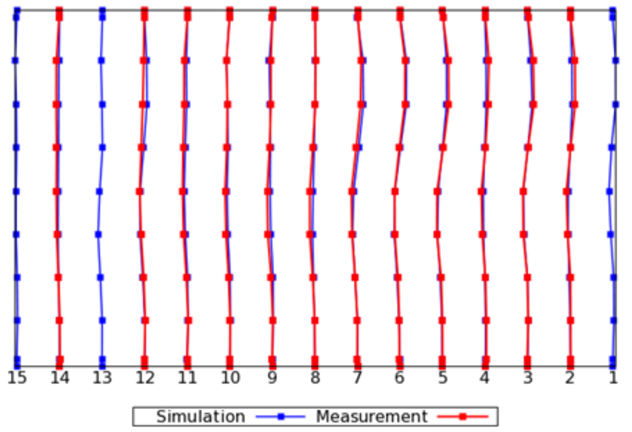
Fluid Structure Interaction (FSI) plays a key role for the formation of FA bow patterns in PWR cores

FA bow prediction tools

- Coupled modeling approach:
  - Integrates mechanical, thermal-hydraulic, and irradiation-induced effects
- Versatile application:
  - Cycle-specific predictions for operational planning and mitigation
  - Generic studies to develop and assess countermeasures
  - Direct evaluation of design modifications
- Validation and performance:
  - Extensive validation with bow measurement data
  - Very good agreement between predicted and measured bow amplitudes, patterns and shapes
  - Successfully used in Europe and the US

Full core bow deformation can be reliably predicted

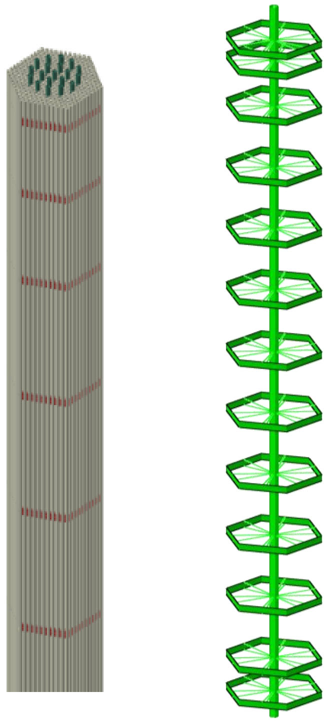




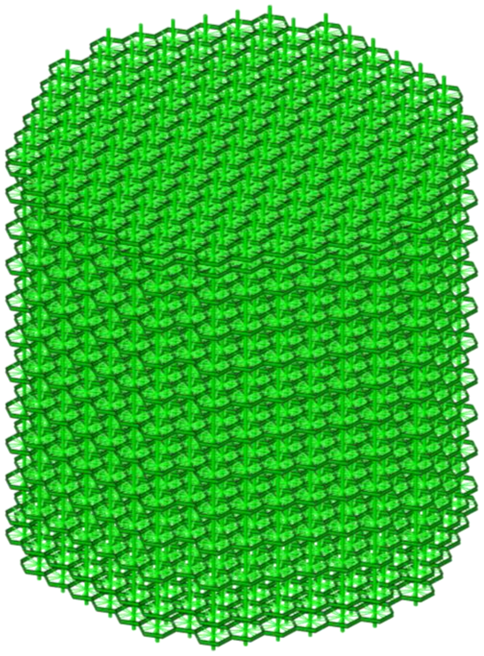
Bow prediction approach for VVER-1000

- The validated bow prediction approach can be adapted to VVER-1000.
- The multiscale and multiphysics bow prediction model consists of a
  - mechanical model (detailed → simplified → core)
  - hydraulic model (detailed CFD→ porous CFD → core)

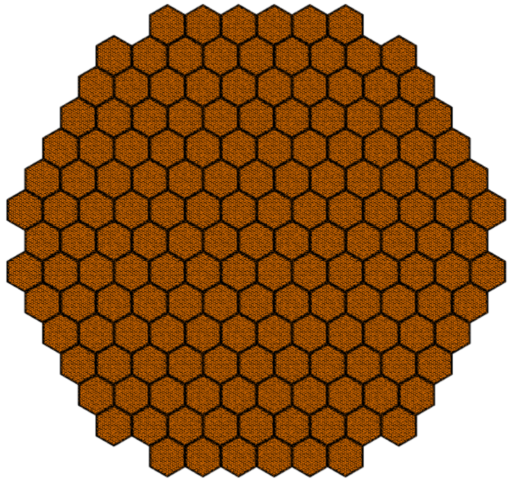
detailed/simplified mech. FA model



mech. core model



hydraulic core model

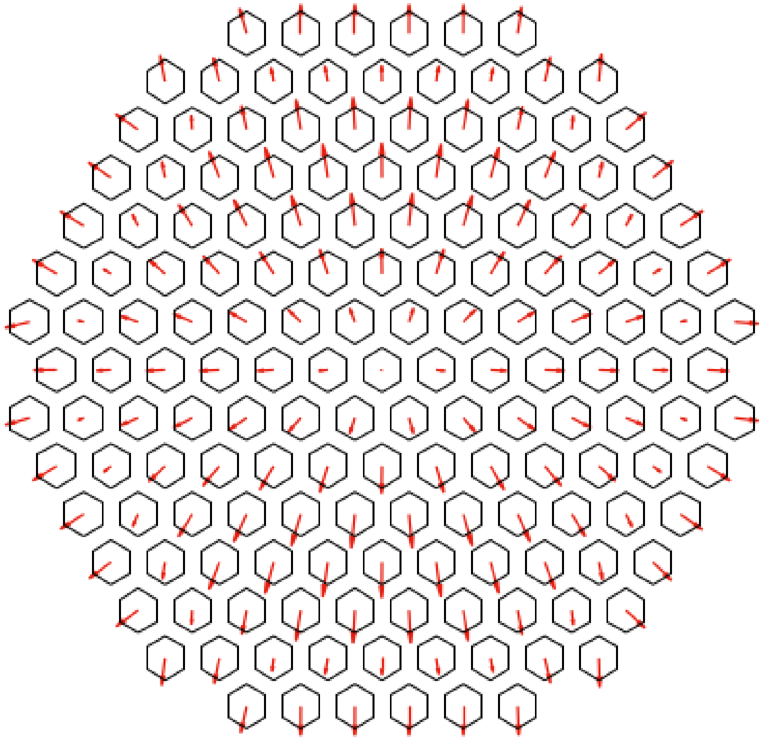


Adapted tool enables direct investigation of design changes and operational scenarios for VVER-1000

Bow prediction model for VVER 1000

- Finite element mechanical model:
  - Developed to simulate FA deformation and bowing.
- Hydraulic core modeling:
  - CFD-based approach captures coolant flow and associated forces.
- Preliminary results:
  - First generic simulation results for VVER-1000 available.
- Validation:
  - Model validation possible via measured FA bow data from VVER-1000 cores.

Calculated bow pattern

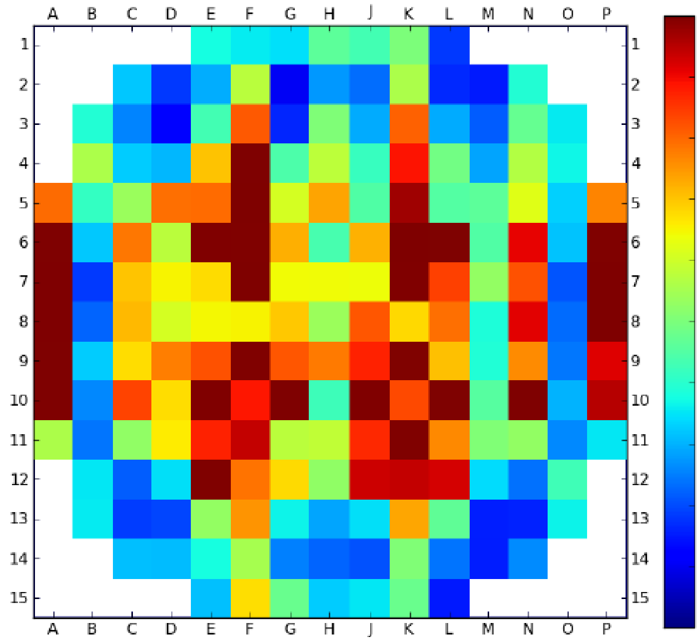


Full core bow prediction tool exists for VVER-1000

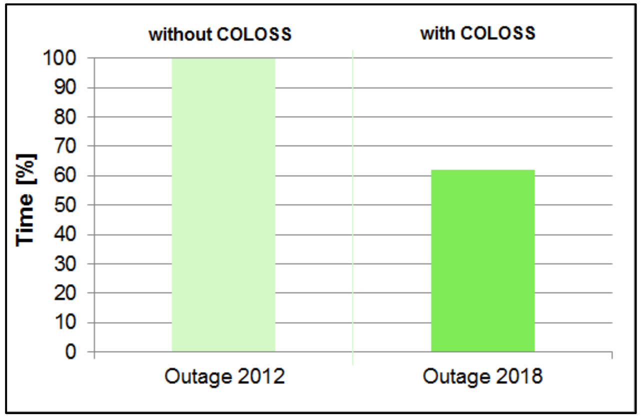
COLOSS tool

- Functionality:
  - Evaluates FA interaction forces using predicted, interpolated, or measured FA deformations.
- Application scope:
  - Analysis of single handling steps, partial and complete core loading sequences, and in-core shuffling.
  - Supports various reactor types and FA designs.
  - Easily extendable to additional PWR designs and plant types, including VVER-1000.
- Decision support:
  - Provides a robust basis for assessing and optimizing loading/unloading sequences.
  - Enables identification and mitigation of potential handling challenges.

Friction forces unloading



Reduction core loading time

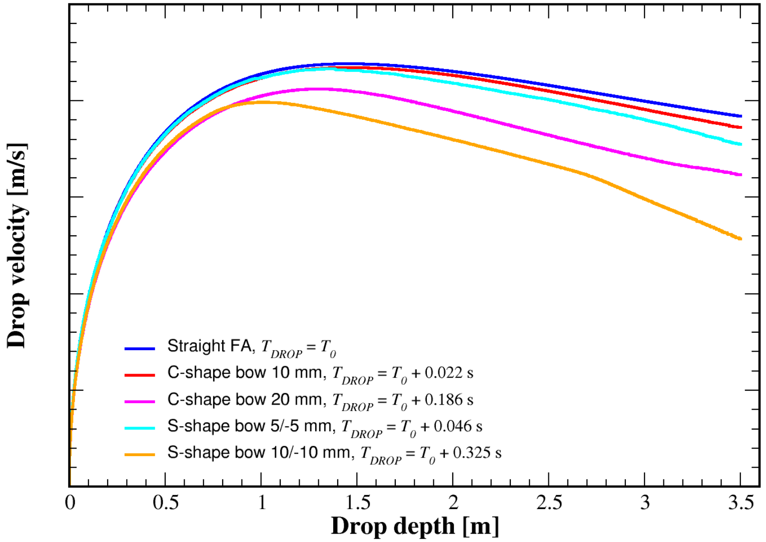


The COLOSS tool helps to minimize the time and reduce risks of handling operations

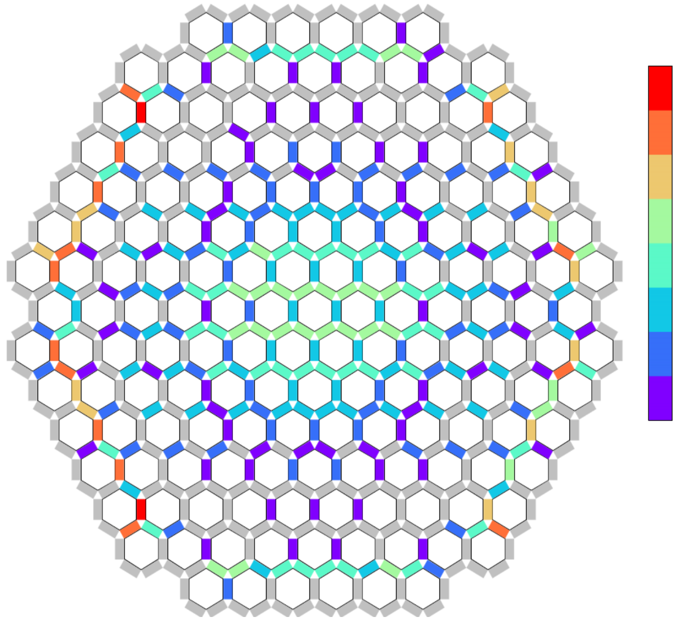
Other analysis tools

- RCCA drop time:
  - Justification required for bowed FAs and distorted grids
  - Dedicated calculation tool developed by Framatome
  - Tool accounts for geometric deviations to ensure safety margins
- To support neutronic calculations:
  - Water gap data for the actual operating state can be provided.
  - Enables calculations of power distribution considering FA distortion.

Drop time dependency on bow



Exemplary water gap distribution



Conclusions

- Framatome possesses a high level of expertise in understanding and mitigating FA distortion issues.
- Advanced, validated tools have been developed for FA bow prediction and for supporting core loading and unloading operations.
- These tools are adaptable and can be extended to VVER-1000 reactors.
- First results for VVER-1000 applications are already available.
- Framatome is ready to provide comprehensive engineering services to support customers in managing FA distortion issues.

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Thank you

The CFD hydraulic model

- The hydraulic model is based on:
  - A porous core representation
  - An explicit modelling of the lower plenum and the upper plenum (optional)
- The core inlet and outlet boundary conditions are directly coupled to the hydraulic model of lower plenum and upper plenum.
- The global properties of the porous medium for the hydraulic core model are fitted with detailed assembly models (local hydraulic model).
- Models account for the exact geometry of distorted fuel assemblies.