UPDATES FROM THE INVOLUTE WORKING GROUP

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ABSTRACT

The High Flux Isotope Reactor, High Flux Reactor, and Research Neutron Source Heinz Maier-Leibnitz reactors represent a particular class of research and test reactors that provide some of the most intense and continuous neutron fluxes for science, industry, and medical applications. These high-performance reactors have achieved compact cores by operating with highly enriched uranium (HEU) fuel (^{235}U/U ≥ 20 wt %) and using fuel plates curved as an involute. Because of the proliferation risks, the international community aims to reduce or eliminate, when possible, the use of HEU fuel in civilian facilities by converting them to a low-enriched uranium (LEU) fuel (^{235}U/U < 20 wt %). Converting these reactors without significantly compromising their performance or safety is a challenging endeavour that can tremendously benefit from advanced computational tools and thus eliminate unnecessary conservatism to ensure sufficient thermal margins. Therefore, models are being developed via modern computational fluid dynamics and computational structural mechanics software to evaluate the steady-state safety margins of various LEU designs instead of relying on more traditional, conservative methods. To gain the confidence and acceptance of high-fidelity modelling by nuclear regulators, Argonne National Laboratory and the involute reactors have formed an informal scientific group: the Involute Working Group (IWG). The IWG facilitates interorganizational collaboration on experimental benchmarking, code-to-code comparisons, and verification and validation. This paper describes some of the recent IWG efforts in validating software against the existing experimental data, as well as code-to-code comparisons of different software that the IWG members use.

1. Introduction

Three research reactors have fuel plates curved as a circle involute (i.e., a spiral generated around a circle):

- the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR) located in Oak Ridge, Tennessee, USA [1],

- the Laue-Langevin Institute (ILL) High Flux Reactor (RHF) located in Grenoble, France [2], and
- the Technical University of Munich (TUM) Research Neutron Source Heinz Maier-Leibnitz (FRM II) located in Garching, Germany [3].

These reactors can produce a particularly intense and continuous flux of thermal neutrons (i.e., ~1.0 × 10^{15} n/cm^2/s) to fulfil critical scientific (e.g., neutron scattering experiment) and industrial missions (e.g., isotope production).

All three reactors currently use highly enriched uranium (HEU) ($^{235}U/U \geq 20$ wt %) as fuel, and all three are actively engaged in activities to convert to low-enriched uranium (LEU) ($^{235}U/U < 20$ wt %) fuel.

These reactors have expressed interest in using advanced computational methods and tools to perform some of their safety conversion calculations. These tools represent a significant departure from traditional methods and require thorough qualification (i.e., software quality assurance) before the conversion analyses can be submitted to a regulator. In the context of this paper, *qualification* means recognizing that the software can provide results that are trustworthy and usable for a nuclear safety case.

Thermal-hydraulic experts from Argonne National Laboratory (ANL) and the involute reactors formed an informal group—the Involute Working Group (IWG)—to help each other in this endeavour. IWG aims to support the qualification of advanced computational methods that support conversion to LEU fuel. Activities include benchmarking, code-to-code comparison, verification and validation, technical support, and the issuance of lessons learned and other relevant publications.

This paper aims to provide an overview of ongoing IWG activities. Section 2 presents technical information on the involute-plate reactors. Section 3 provides further details on the IWG and its scope. Finally, Section 4 provides an overview of the ongoing activities.

2. Involute-Plate Reactors

The fuel elements of involute-plate reactors have an annular shape, as shown in Figure 1, which provides a top view of the HFIR, RHF, and FRM II fuel elements. HFIR has two elements, whereas RHF and FRM II each have only one. Fuel elements must be replaced at every new cycle (i.e., once-through core). Figure 2 provides a more detailed view of the HFIR plates and channels. The fuel plates curved as a circle involute are attached (i.e., welded) to two concentric tubes, commonly called *side plates*.

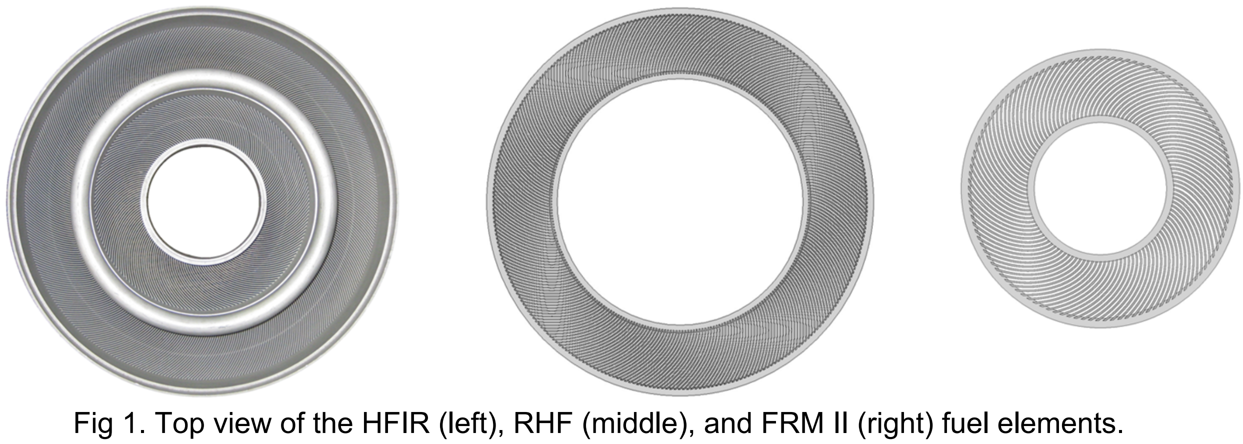

Fig 1. Top view of the HFIR (left), RHF (middle), and FRM II (right) fuel elements. (Source: Bojanowski et al. [4].)

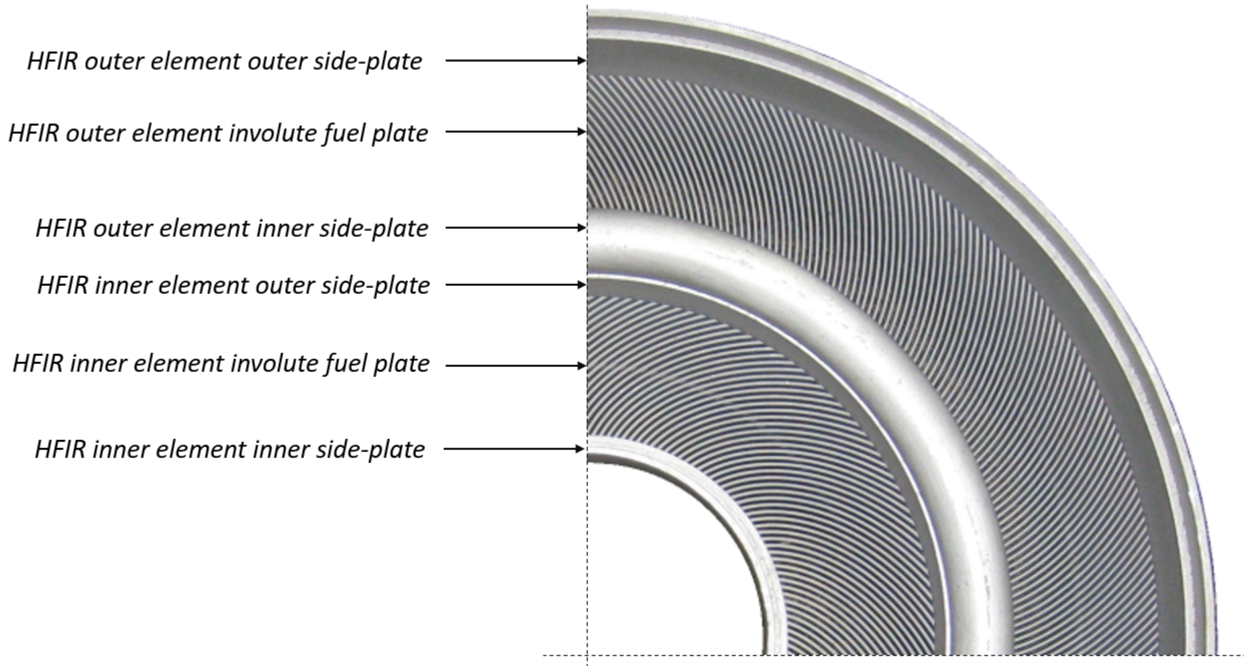

Fig 2. Detailed top view of one-fourth of the HFIR fuel element.
(Source: Bojanowski et al. [4].)

The space between two adjacent fuel plates forms a coolant channel in which the coolant passes at a very high speed (~15 m/s) to remove the heat generated in the fuel plate by nuclear reactions. The fuel plates are very thin (1.27–1.36 mm, depending on the reactor) and have a sandwich-like structure. The fuel is made of HEU mixed with Al. The so-called "meat" is cladded with Al alloy foils on each side. RHF uses heavy water as the coolant, whereas FRM II and HFIR use light water. The coolant flows from top to bottom for all three reactors. More information on these reactors and elements is provided in Table I.

Table 1: Current HEU involute-plate reactor characteristics. (Source: Bojanowski et al. [4].)

Parameters	HFIR	RHF	FRM II
HEU fuel type	U_3O_8/Al	UAlx/Al	U_3Si_2/Al
Number of elements	2	1	1
Cooling fluid	Light water	Heavy water	Light water
Total nuclear power (MW)	85	57.8	20
Number of plates	540 (=171 + 369)	280	113
Plate thickness (mm)	1.27	1.27	1.36
Plate length (cm)	60.96	90.30	72.00
Channel width along involute arc length between side plates (cm)	8.548 and 7.679	7.594	6.940
Channel thickness (mm)	1.27	1.80	2.20
Cladding thickness (mm)	0.254	0.380	0.380
Meat thickness (mm)	Varies along width, Max: 0.693	0.51	0.60
Meat width along involute arc length (cm)	7.798 and 7.087	6.734	6.240
Width inner unfuelled region (from outer radius of inner side plate to inner fuel radius) (cm)	0.234 and 0.218	0.314	0.259
Width outer unfuelled region (from outer fuel radius to inner radius of outer side plate) (cm)	0.516 and 0.374	0.547	0.441
Average coolant velocity (m/s)	15.5	17	15.9
Nominal inlet and outlet bulk temperature (°C)	49 and 69	30 and 50	38 and 53
Nominal inlet and outlet pressure (Bar)	33.3 and 25.72	14 and 4	8.8 and 2.3
Reynolds number	~100,000	~100,000	~100,000
Peak heat flux (W/cm^2)	<400	<400	382.3[1]

The involute shape enables:

- the thickness of a coolant channel to be constant from the inner to the outer edge of the element;
- all channels to be identical within one element, although some local deviations are introduced during the manufacturing process; and
- all fuel plates to experience very similar irradiations conditions, although some possible local azimuthal variations are induced by the presence of safety or experimental components located in the vicinity of the fuel elements.

These features are particularly interesting for steady-state thermal-hydraulic analyses because only one or a few channels must be modelled to characterize the entire element. Additionally, the constant channel thickness could enable modelling the involute-shaped channel as a simple rectangular channel heated on both sides, as depicted in Figure 3. Historically, steady-state thermal-hydraulic analyses have often been performed after a modelling approach in which the coolant channel is divided into several independent sub-channels, and there is no energy exchange between sub-channels. In this simplified representation, heat comes from the direction normal to the plate, as illustrated in Figure 3. Lateral and axial heat conduction, heat-induced mass flow redistribution, or the effect of the unfuelled regions are often ignored, translating into a relatively conservative physical

[1] FRM II was evaluated using a 3D heat conduction model. A 1D model was used for RHF and HFIR.

representation of the heat transfer in the coolant channels. This, in turn, results in a conservative estimation of the safety margins.

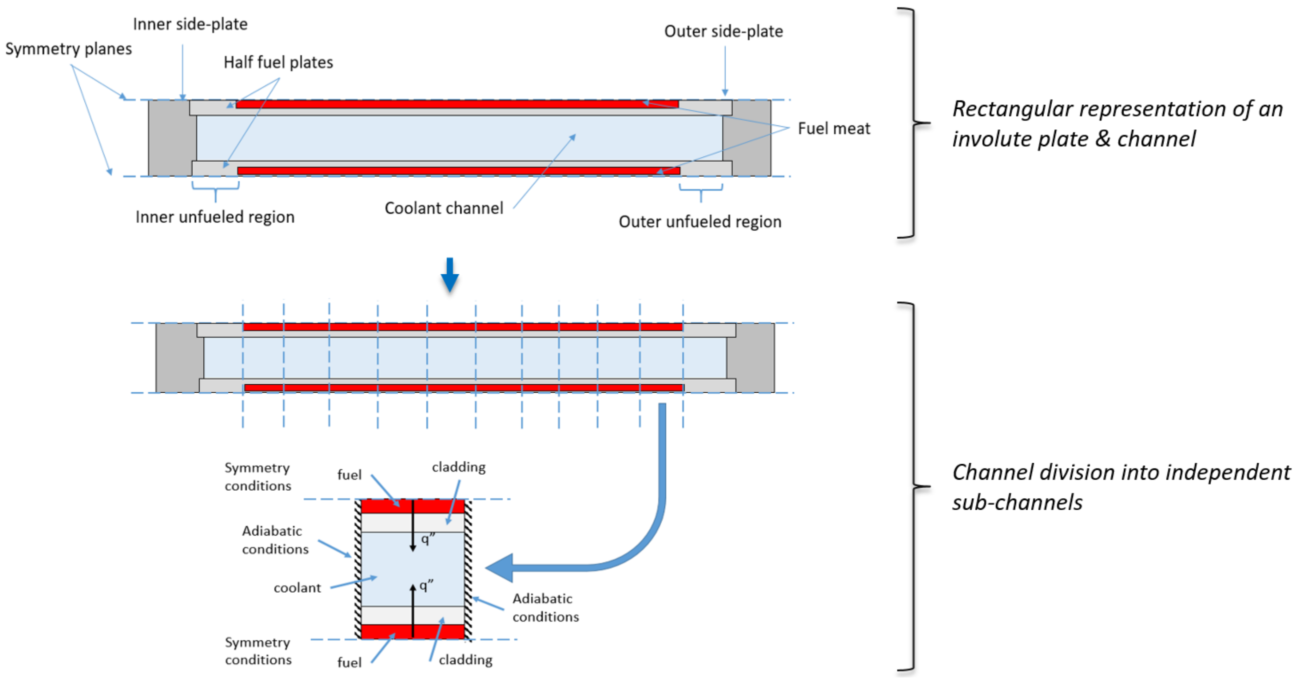

Fig 3. Simplified geometric representation and modelling of an involute plate and channel. (Source: Bojanowski et al. [4].)

The fuel elements of these reactors are located at the centre of a large, pressurized vessel that contains a reflector—heavy water for RHF and FRM II, Be for HFIR—and experimental and safety devices. The cylindrical volume located at the centre of the annular fuel elements is often called the *central cavity*. FRM II and RHF use this space for the control elements, which move vertically to control the reactivity during the cycle. HFIR uses this central cavity for isotope production. HFIR reactivity control is assured by an inner and outer shroud located between the outer edge of the outer element and the Be reflector.

Because of these geometric characteristics, fast neutrons born from fission are thermalized in the reflector and central cavity. Because the fuel plates are oriented “edge on,” thermalized neutrons coming back to the fuel elements tend to be captured more frequently on the edges of the fuel where more fissions—and, therefore, more heat—are generated.

This leads to a nonuniform distribution of power within the plates in which the power tends to spike at the edges. Because of this nonuniformity in power, the involute-plate reactors require additional design features to reduce power peaking locally and satisfy their safety margin requirements. For instance, RHF has borated regions above and below the fuel, FRM II fuel has a lower density near the outer edge, and HFIR fuel thickness is reduced near the inner and outer edges.

Although these complex design features are necessary for satisfying the reactor’s safety requirements, they induce substantial fabrication costs. For features involving mass reduction (e.g., reduced thickness or density), complex design features may also lead to a performance penalty.

3. Involute Working Group

In the framework of its nonproliferation policies, the international community aims to eliminate the use of HEU fuel in civilian facilities, such as research reactors. Many organizations worldwide are developing high-density LEU fuel to replace their currently used HEU fuel. All three involute reactors are actively engaged in conversion to LEU efforts.

Since the inception of the conversion program, ANL has played a crucial role in helping reactors with their conversion effort by sharing expertise, performing independent analyses, and developing software dedicated to the analyses of research and test reactors. ANL is actively collaborating with all three involute-plate reactors.

Conversion to LEU implies changing the fuel and, therefore, changing the material properties, which influence the thermal-hydraulic and thermal-mechanical behaviour of the fuel elements. It often also implies making geometric modifications (e.g., plate length, fuelled length, channel thickness) that affect the elements' thermal-hydraulic and thermal-mechanical performance.

While performing conversion-related analyses, involute-plate reactors encountered several issues with existing tools and methods, including the following:

- a lack of flexibility in legacy codes to model the changes, and
- LEU fuels were denser than HEU and power peaking was typically aggravated, increasing the cladding/coolant interface heat flux; increasing local bulk, wall, and fuel temperature; and, in effect, reducing the calculated safety margins.

To overcome these limitations, the organizations operating the involute reactors have expressed interest in using advanced computational codes (e.g., computational fluid dynamics [CFD] and multiphysics) to perform their conversion safety calculations.

These simulation tools can model virtually any kind of geometry and can model more complex physical phenomena than the legacy codes currently used for involute-plate reactor analysis. The ability to model complex physical phenomena can eliminate some unnecessary conservatism inherently present with legacy methods and provide a better estimate of the margins. Because of the importance of modelling the relevant geometric details and the need for the efficient coupling of multiple physics, modern finite element and/or volume commercial packages—such as COMSOL [7], STAR-CCM+ [8], or ANSYS CFX [9]—are particularly attractive for involute-plate reactors.

Although involute-plate reactors have expressed interest in using these tools to perform their conversion analyses, they generally represent a significant departure from traditional methods. Therefore, a thorough qualification is required before submitting output results to a regulator.

ANL and the involute reactors formed an informal group, IWG, to help each other in this endeavour. One primary objective of IWG is to support the qualification of advanced computational methods, such as CFD, that facilitate the conversion to LEU fuel. IWG is formatted as a voluntary open forum in which thermal-hydraulic and multiphysics experts can exchange ideas and execute activities of mutual interest performed in the spirit of collaboration that can benefit all.

IWG is simply a forum and has not been designed to prepare and submit on a reactor's behalf the necessary documentation that could be expected by a given regulator.

4. Overview of Ongoing Activities

This section describes some examples of past and ongoing activities performed within IWG that feed into the various qualification steps described in the previous section.

4.1 Turbulence Models and Heat Transfer: The Gambill and Bundy Experiment

The Gambill and Bundy experiment [10], which was performed in the 1960s, aimed to verify the suitability of various heat transfer and flow instability correlations for the thermal-hydraulic analysis of HFIR. This experiment is crucial because the conclusions drawn from these studies are still applied today in the HFIR safety basis.

The experiment comprised a simple rectangular test section representative of the HFIR geometry (Figure 4) in which the passing fluid was heated on both sides. Wall temperature was measured and used to estimate the heat transfer coefficient. Sufficient information is available in the literature to create a CFD model for this experiment.

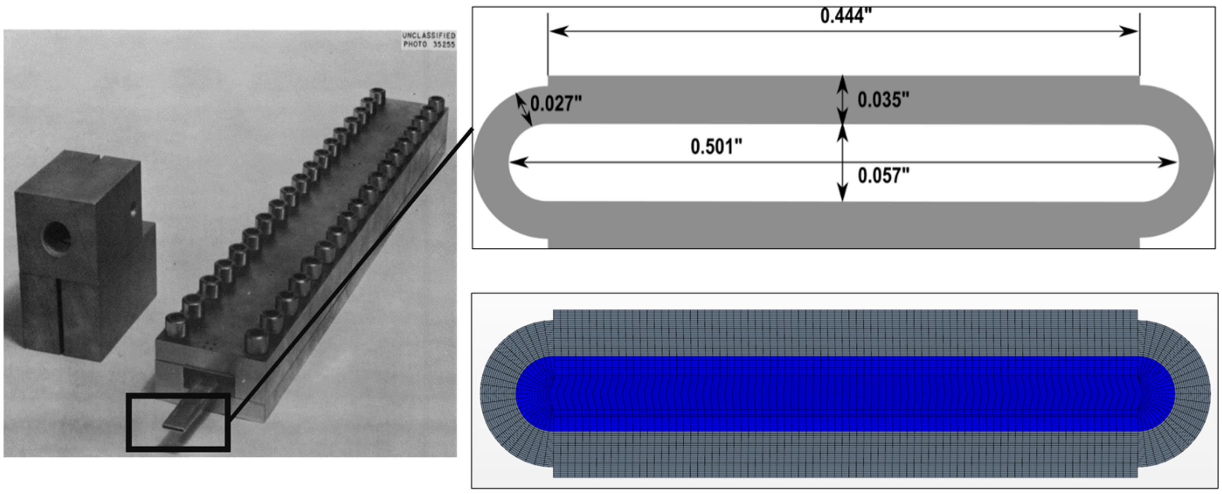

Fig 4. (Left) View of a test section used in the Gambill and Bundy experiment [12]; (top right) schematic representation of the channel [4]; (bottom right) view of a CFD model [4] with mesh of the test section used in the benchmark analysis.

IWG members performed a code-to-code benchmark analysis of this experiment [11] to assess the appropriateness of the standard turbulence models provided with the ANSYS-CFX, STAR-CCM+, and COMSOL software. For illustration, some results obtained with STAR-CCM+ are presented in Figure 5. These analyses show that, for this experiment, using CFD and standard RANS turbulence models was appropriate because they produce results that are in excellent agreement with the experimental ones. This helps justify using these tools and models, which is a critical step in the qualification process.

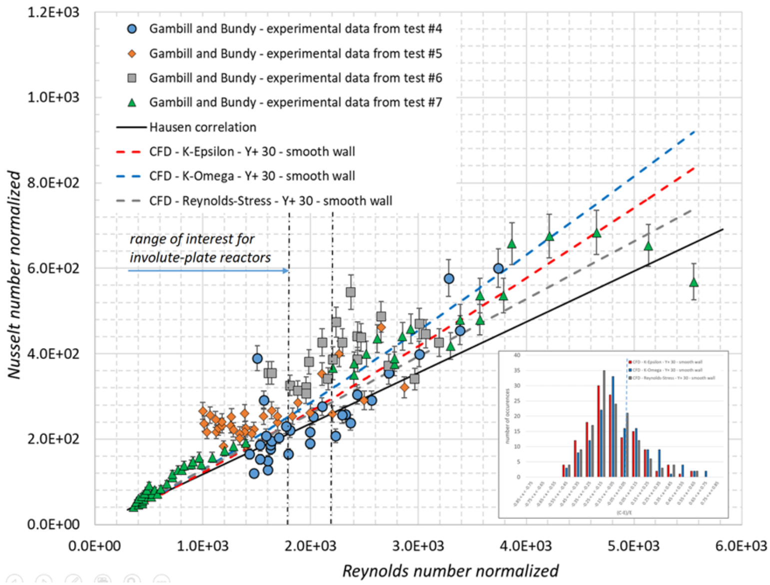

Fig 5. Comparison of experimental and CFD-calculated Nusselt number using the Gambill and Bundy benchmark. Both Reynolds and Nusselt were normalized following the Gambill and Bundy procedure; consult Cheverton and Kelley [12] for more details. (Source: Bojanowski et al. [4].)

4.1. Deflection-Induced Channel Contraction: The Cheverton and Kelley Experiment

During normal operation, plate deformation (e.g., deflection) induced by pressure and/or temperature load is unavoidable and essential to characterize because it creates slight, local perturbations in the flow conditions that ultimately affect heat transfer and, therefore, the margins to boiling. The Cheverton and Kelley experiment, which was performed in the 1960s, aimed at understanding these phenomena by applying uniform temperature and/or differential pressure load on plates representative of the HFIR geometry [13] (Figure 6).

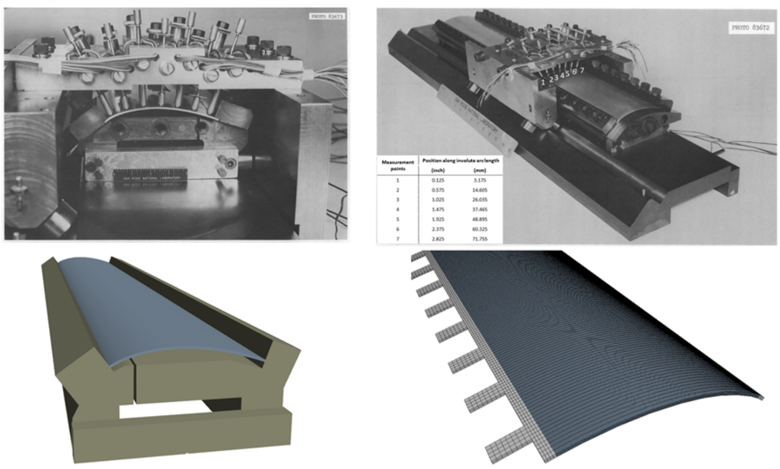

Fig 6. (Top) View of the Cheverton and Kelley experimental setup; (bottom left) CAD model of the experimental setup; (bottom right) detailed view of the involute plate mesh model. (Source: Sitek et al. [14].)

As in the Gambill and Bundy experiment, IWG members performed a code-to-code benchmark analysis of the Cheverton and Kelley experiment [13, 14] to assess the appropriateness of the ANSYS-CFX, STAR-CCM+, and COMSOL software. Some results obtained with COMSOL and STAR-CCM+ are presented in Figure 7. These tools reproduced experimental results relatively well, increasing confidence in their use.

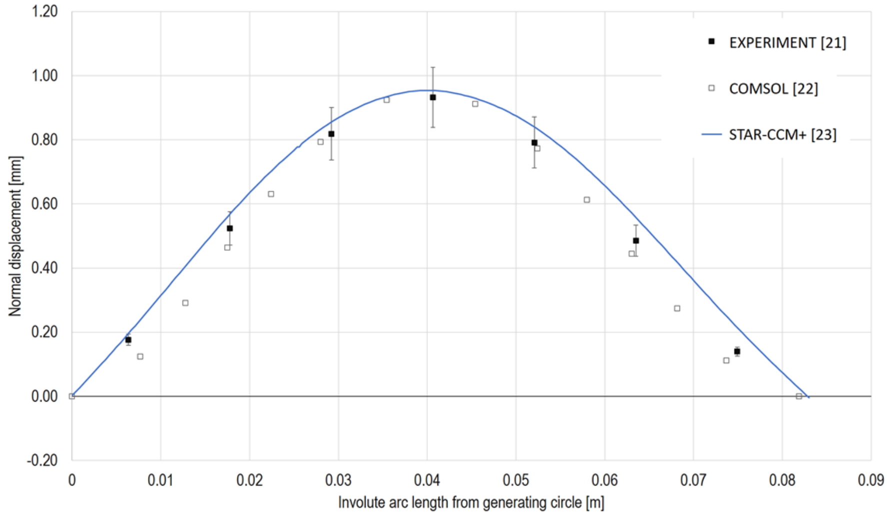

Fig 7. Comparison of experimental and COMSOL and STAR-CCM+ calculated deflection of an involute plate induced by a temperature load. (Source: Sitek et al. [14].)

5. Conclusions

IWG is leading activities to support the qualification of advanced numerical methods and software and their use for safety applications to convert involute-plate reactors to LEU fuel.

IWG is an open forum that gathers thermal-hydraulic experts from ANL, ORNL, ILL, and TUM. Following existing best practice guidelines, the IWG performs benchmarking, code-to-code comparisons, sensitivity analyses, and Phenomena Identification and Ranking Technique analyses. The IWG mandate is not to qualify tools on behalf of a given reactor operator but to prepare reference analysis and documentation that reactors could use to support their individual needs.

This paper provides examples of activities aiming to demonstrate the appropriateness of CFD and computational structural mechanics software. Future work will identify new validation cases, design “CFD-grade” experiments, perform uncertainty quantification, issue lessons learned, and recommend safety applications.

6. Acknowledgments

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