



# SFR CORE RESTRAINT SYSTEM DESIGN USING THE OXBOW SUITE OF ANALYSIS TOOLS

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## ABSTRACT

Numerous competing design criteria drive the mechanical design of a sodium fast reactor (SFR) core in support of a safe, predictable, and economic design. The core restraint system (CRS) comprises all assemblies in the core and their interfacing support structures. The structural response of the core restraint system to various load states over the reactor lifecycle has wide-reaching performance and economic impacts including effects on core power, core assembly response to seismic excitation, control rod insertion time, and refueling outage durations. To solve this complex and interrelated set of core mechanical design problems, TerraPower, LLC has developed a suite of mechanical analysis tools, OXBOW, which enables rapid design cycles involving multiple modeling fidelities to support core mechanical performance and assembly lifecycle management of high residence fuel systems.

This paper explores the use of the OXBOW suite of core mechanical analysis tools in the design cycle of SFR core restraint. The ability of OXBOW to combine various levels of modeling fidelity with other multiphysics codes in the ARMI<sup>®</sup> software ecosystem enables fast core design iterations and sensitivity studies, which greatly reduces the analysis burden of an analyst. For a given core design, the core restraint system mechanical and reactivity response can be quickly evaluated. Results are passed between the various OXBOW analysis implementations to evaluate detailed assembly deformations resulting from inelastic material behaviors and predict handling loads on refueling equipment. The impacts of core shuffling operations on radial feedback, assembly deformations, and assembly handling loads are analyzed. Statistical methods are also applied to quantify uncertainties impacting these figures of merit. The OXBOW suite of core mechanical analysis tools is combined with the ARMI<sup>®</sup> software ecosystem to quickly map design space, assess core design viability, and support the core management strategy for an SFR.

## INTRODUCTION

Fast reactor cores are highly sensitive to fuel motion which is primarily a result of core assembly bowing. This can occur quasi-statically during different states of reactor operation or dynamically during a seismic event. Core assembly deformations influence the neutron balance within the core (primarily through neutron leakage), which leads to changes in reactivity. This radial reactivity feedback can be significant in SFRs and play a considerable role in the core power coefficient.

A primary function of the core restraint system is to control the position and alignment of core assemblies to control reactivity changes resulting from assembly deformations and displacements in an SFR core. Changes in thermal, irradiation, and mechanical loads at various states of reactor operation induce core-wide assembly movements causing reactivity changes which affect core power. The core restraint

system should also ensure that assemblies can be withdrawn or inserted into the core which can be challenged by excessive accumulation of inelastic deformations. This damage accumulation is mitigated by shuffling (relocating and reorienting) assemblies into different core positions during refueling operations. Additionally, the core restraint system maintains alignment between core assemblies and interfacing systems above the core such as refueling equipment or the control rod drive line.

Nonlinear material effects are an important consideration in the design of the core restraint system and the core management program. Assemblies subjected to high temperature, fluence, and bending loads, will undergo inelastic strains over their residence times, including contributions from thermal creep, irradiation creep, and void swelling. Between each cycle of reactor operation, core assemblies are shuffled, a subset of assemblies is discharged, and an equivalent number of fresh assemblies are introduced into the core lattice. A well-designed core restraint system will account for residual inelastic assembly deformations and ensure deformed assemblies can be removed from the core without overly challenging the fuel handling equipment. Each generation of core configurations should also be capable of providing well-behaved radial reactivity feedback characteristics.

## OXBOW OVERVIEW

Analysis of a complex system such as an SFR core restraint system necessitates the development and application of advanced computational tools. TerraPower, LLC. has developed the OXBOW suite of core mechanical analysis tools in support of coupled multiphysics analyses with integration to the Advanced Reactor Modeling Interface (ARMI<sup>®</sup>) software ecosystem as illustrated in Figure 1. While other historical CRS analysis codes such as NUBOW3D, from Argonne National Laboratory (1978), are available, OXBOW combines CRS analysis with a range of additional finite element modeling capabilities of varying fidelities. The OXBOW suite is built on top of a framework that describes the data associated with the finite element model, provides that data to commercial finite element solvers and seamlessly parses the results of those solvers. Utilizing ARMI<sup>®</sup> reactor state information, OXBOW generates models of varying fidelity for different core mechanical analyses as described in Baylor, et al (2018). The software design of OXBOW enables analysis results to be passed between its various analysis implementations independent of their fidelity, described in James, et al (2024). The mechanical results generated by OXBOW are additionally used by other physics models for applications such as reactivity insertion and safety analysis.

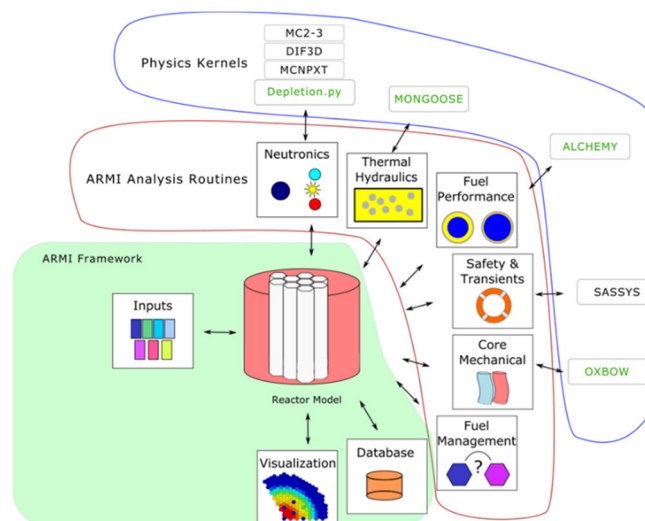


Figure 1. ARMI<sup>®</sup> Analysis Framework and Multiphysics Interfaces. See <https://terrapower.github.io/armi/> for more details.

## CORE RESTRAINT SYSTEM ANALYSIS

The International Atomic Energy Agency's (IAEA) International Working Group on Fast Reactors (IWGFR), now the Technical Working Group on Fast Reactors (TWG-FR), facilitated a series of benchmark problems, IAEA (1990), for reactor core mechanical analysis codes from various countries. The benchmarks have varying complexity including single assembly, free-flowing core restraint, and limited free bow core restraint cases.

IWGFR benchmark problem 5 (IWGFR 5) is selected for the analysis case study below as it defines a limited free bow core restraint system with nonlinear material behaviors (creep and swelling). The benchmark geometry, boundary conditions, and loading condition details can be found in the problem definition of IAEA (1990). Overall, it defines a limited free bow core restraint system with a single ring of bowing assemblies (38-61) as shown in Figure 2a. A spatially varying dose distribution is defined for this ring of assemblies which induces material creep and swelling behavior. Assembly 44 is highlighted as the subject of more detailed examination in later sections. The OXBOW Core Restraint System modeling implementation (OXBOW.CRS) is used to examine the core-wide assembly response to the dose distribution. An OXBOW.CRS model for IWGFR 5 is shown in Figure 2b. While 1/12 symmetry is sufficient for modeling this benchmark, a 1/3 core symmetry model is presented for consistency with models in subsequent sections. The study below extends the IWGFR 5 benchmark to incorporate several additional components. This includes a generic set of reactivity coefficients associated with the displacement profile of each assembly, arbitrary load pad heights, frictional contact behavior, and internal assembly pressure profiles contributing to duct dilation.

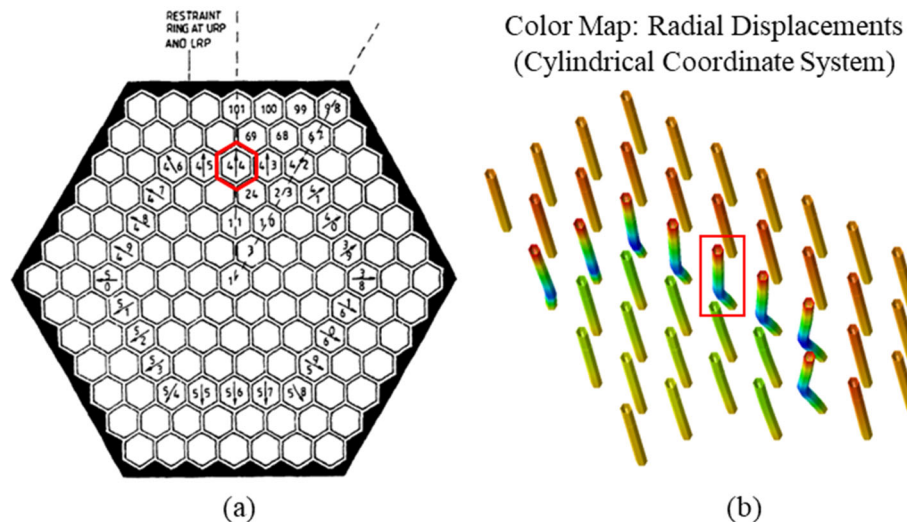


Figure 2. (a) IWGFR 5 illustration from IAEA (1990) and (b) OXBOW model rendered with 5x deformation and 20% beam section scaling.

To examine detailed assembly deformations including cross sectional changes (dilation) which are typically not captured by core-wide beam models, the OXBOW Core Assembly Distortion Analysis implementation (OXBOW.CADA) is used. A detailed single assembly model is meshed with solid elements and a hydrostatic pressure load is applied along the interior surfaces of the duct of Assembly 44. Assembly contact loads are applied on the appropriate load pad surfaces based on the assembly contact force history from OXBOW.CRS. Under these combined loads, OXBOW.CADA predicts the bowing and dilation deformations of Assembly 44 based on the IWGFR 5 creep and swelling model (Figure 3a).

The detailed state of assembly deformation from OXBOW.CADA can be utilized by other OXBOW implementations for further analysis. In the case below, a withdrawal analysis of Assembly 44 is performed utilizing the OXBOW Withdrawal and Insertion implementation (OXBOW.WI). In this mixed-element model (Figure 3b), an assembly is selected for withdrawal or insertion into the core. The deformed assembly of interest and its neighbors are meshed with solid elements in order to model contact interactions resulting from residual bowing and dilation due to creep and swelling deformations. As the assembly is withdrawn from the core, reaction forces are examined to predict handling loads on refueling equipment. A representative withdrawal force curve for the OXBOW.WI model of Assembly 44 is shown in Figure 4. Three force peaks are observed. The first peak is the force required to dislodge the assembly which is in contact with its neighbors at both the above core load pad (ACLP) and top load pad (TLP) elevations. The second load peak occurs when the ACLP of Assembly 44 passes through the TLP elevation of its neighbors. Finally, a third peak occurs when the dilated portion of Assembly 44 is withdrawn through the TLP elevation of the neighboring assemblies. In this example using the IWGFR 5 benchmark, the withdrawal loads are not significantly higher than the assembly weight. However, as part of the design cycle for core restraint, if predicted assembly handling loads exceed structural limits of assembly handling equipment or critical assembly structures, the design team can examine alternative core shuffling schemes or propose changes to the system.

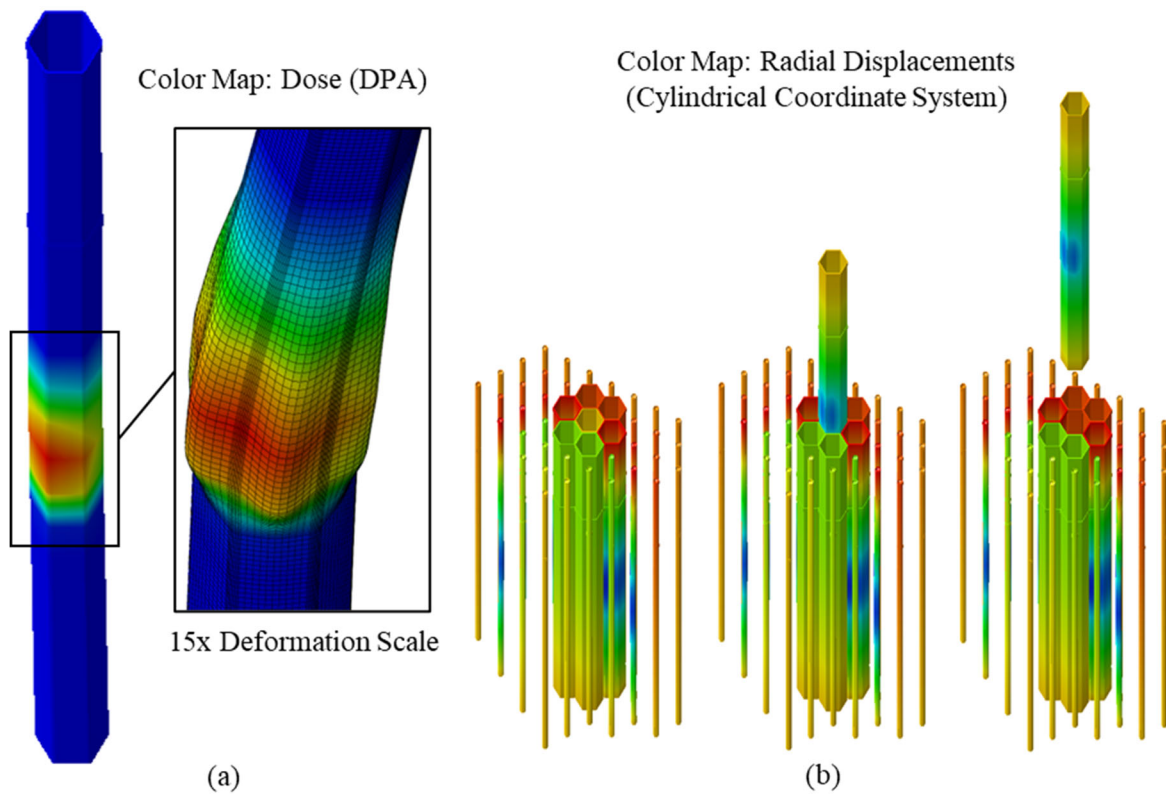


Figure 3. (a) OXBOW.CADA model of Assembly 44 and (b) OXBOW.WI Assembly 44 withdrawal model with 20% beam section scaling.

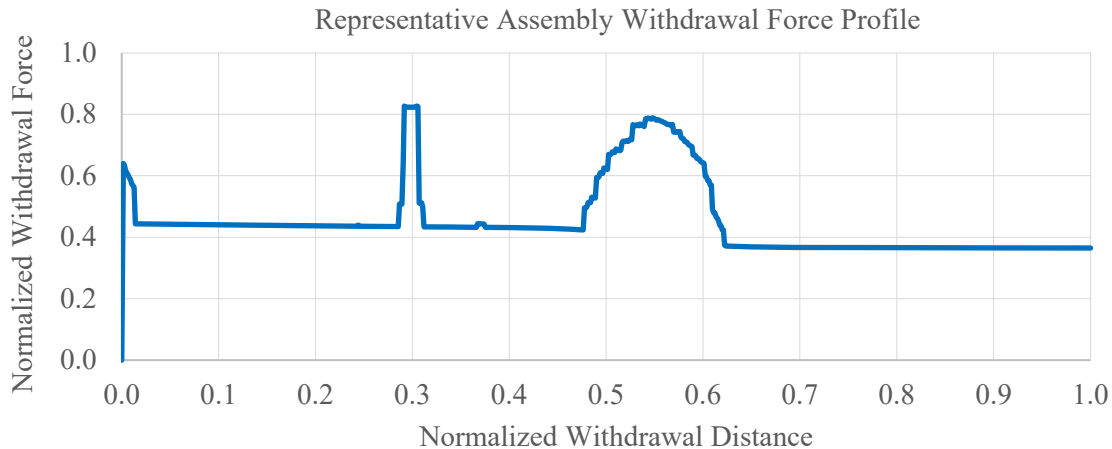


Figure 4. Representative withdrawal force profile for IWGFR 5 Assembly 44.

## CORE SHUFFLING

As discussed in previous sections, assemblies in an SFR core can be shuffled to improve the neutron economy of the core and extend the life of individual assemblies. As part of this core management process, high residence assemblies are discharged from the core and fresh assemblies are introduced. Shuffling operations allow for more uniform distributions of fuel burnup in the core which can extend assembly residence time. Additionally, judicious core management is used to manage inelastic deformations (e.g., creep and swelling) that accumulate in the duct of core assemblies. Reductions in these assembly residual deformations reduce the likelihood of challenging force limits on fuel handling equipment and can extend the achievable residence time of core assemblies. For example, if an assembly resides in a core position that accumulates significant inelastic bowing deformations, this assembly can be rotated 180° to balance out the strain distribution over subsequent cycles, resulting in a straighter assembly for withdrawal from the core. Shuffling operations will also alter core radial feedback behavior which is an additional consideration for analysts. Assemblies can be shuffled into configurations where neighboring assemblies can bow synergistically and promote favorable radial feedback behavior. Conversely, poor assembly shuffling management can lead to detrimental radial feedback performance or excessive accumulation of assembly distortions.

OXBOW.CRS implements user-specified shuffling cascades by instantiating fresh assemblies to be shuffled between cycles of operation. An example shuffling scheme is shown in Figure 5. In conjunction with OXBOW.CADA and OXBOW.WI, this enables analysts to examine the impact of proposed shuffling schemes on radial reactivity feedback, detailed assembly deformations, and assembly handling loads. Analysts utilize the various OXBOW implementations and collaborate with other physics disciplines (neutronics, fuel performance, thermal hydraulics, etc.) in order to develop proposed shuffling and assembly management schemes for each refueling outage. These core management strategies become inputs to fuel handling time history modeling software to examine refueling outage times and potential impacts to plant capacity factor. Additionally, this software examines assembly storage capacity and enforces appropriate load leveling for core assembly discharges based on the available storage positions.

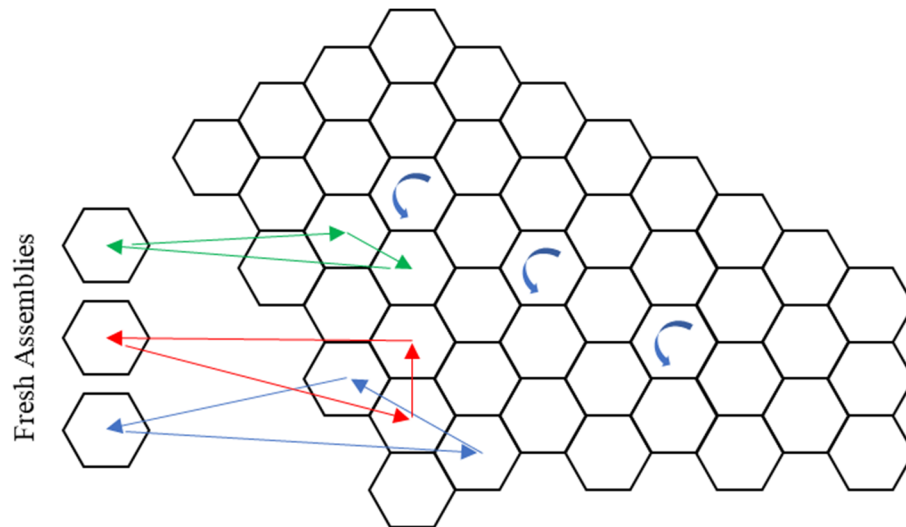


Figure 5. Example shuffle and rotation scheme which can be modeled using OXBOW.CRS.

## UNCERTAINTY QUANTIFICATION

Numerous sources of uncertainty can impact the functional performance of an SFR core restraint system. For example, changes to the core assembly nozzle or receptacle can alter the rotational stiffness of assemblies. Uncertainty in this boundary condition will affect core assembly displacement response and subsequently the accumulation of stress-dependent inelastic material deformations (e.g. creep). Temperature distributions on duct structures can also be challenging to accurately predict as it is difficult to characterize the interstitial flow occurring between assemblies or even within assemblies that have very low flow rates. This uncertainty has a direct effect on core bowing deformations and radial reactivity feedback response. Material models for inelastic material behavior also have associated uncertainties and some, such as creep data, can have significant scatter. Additionally, void swelling performance can be heavily dependent on the material microstructure which is affected by the component fabrication processes. Fabrication uncertainty including tolerancing of core assemblies, load pads, and interfacing core support structures will also affect the performance of the core restraint system. Using OXBOW software tools, analysts can apply statistical methods and quantify the effects of various uncertainties on analysis figures of merit.

In the case study below, statistical methods are applied to IWGFR 5 using OXBOW to examine fabrication uncertainty on a radial reactivity figure of merit. Specifically, the effect of assembly straightness is examined. A straightness deviation is applied to each assembly in the core model as a bending deformation based on a normal distribution and oriented in random directions as shown in Figure 6a. This was applied to 1000 OXBOW.CRS models for this study. Using a generic set of reactivity coefficients associated with the displacement profile of each assembly, an initial altered reactivity state is calculated for each case relative to a perfectly straight core assembly condition.

The application of statistical methods to examine reactivity effects of assembly straightness variability expands an analyst's capability to perform uncertainty quantification. As can be seen in Figure 6b, the scatter associated with different distributions straightness variability can be quantified. Furthermore, as manufacturing data becomes available through the course of fabrication studies, analysts can apply the representative distributions of as-fabricated critical dimensions rather than a simple normal distribution which further improves uncertainty quantification. Similar studies can be applied to the other previously described sources of uncertainty to examine their effects on analysis figures of merit.

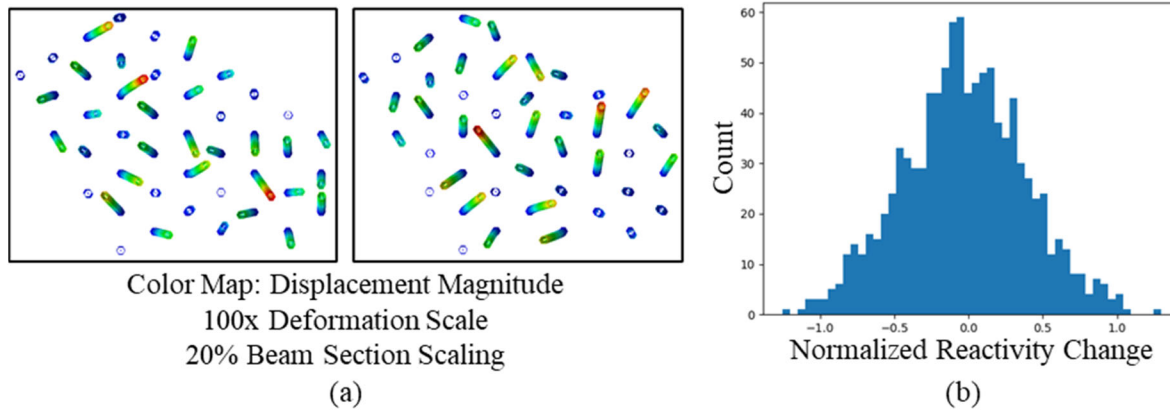


Figure 6. Uncertainty quantification of assembly straightness variability on radial reactivity.

## CONCLUSION

This paper explores the use of the OXBOW suite of core mechanical analysis tools in the design cycle of SFR core restraint. For a given core design, the core restraint system mechanical and reactivity response can be quickly evaluated. Results are passed between the various OXBOW analysis implementations to evaluate detailed assembly deformations resulting from inelastic material behaviors and predict handling loads on refueling equipment. The impacts of core shuffling operations on radial feedback, assembly deformations, and assembly handling loads are analyzed. Statistical methods are also applied to quantify uncertainties impacting these figures of merit. The OXBOW suite of core mechanical analysis tools is combined with the ARMI<sup>®</sup> software ecosystem to quickly map design space, assess core design viability, and support the core management strategy for an SFR.

## ACKNOWLEDGEMENTS

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