SEISMIC ANALYSIS OF A FULL 3D REACTOR CORE USING MULTI-PHYSICS MODELING METHODOLOGY

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ABSTRACT

A multi-physics analysis of a sodium-cooled fast reactor core subjected to seismic phenomena is presented as an example of both a methodology and a practical engineering toolset. A conceptual design of the TerraPower TWR-300 is modeled in a framework providing interfaces to an arbitrary number of other physics simulations. Neutronics, thermal/hydraulics, and mechanical behaviors are coupled capturing effects including assembly thermal/irradiation distortions, heat transfer, and reactivity changes. The full set of core assemblies are modeled, considering their interactions with each other and with core support structures. The results presented here provide consistent evaluations of reactivity changes, control assembly distortion, and impact forces induced by seismic activity. This self-contained analysis demonstrates a methodology that has general applicability. Other physics such as core assembly inelastic deformation, control rod insertion, core shuffling, or core assembly insertion/withdrawal can be likewise integrated. The software could be used for analysis of other core types (like LWR) though other simulation tools may need to be interfaced with the framework.

1. Introduction

In the United States, a nuclear power plant must safely operate during the operating basis earthquake (OBE) and be able to maintain coolable geometry after safe shutdown earthquake (SSE) events as described in the U.S. Nuclear Regulatory Commission’s regulation 10 CFR Part 50, Appendix S [1]. Knowing the mass and stiffness of the structure in the load path from the soil to a reactor core as well as the load bearing elements within the core, one can estimate the seismic response of the core. This alone is not sufficient to size these components for this requirement. The analysis requires input from, and gives feedback to, many of the coupled physics that influence the design of a reactor core.

For example, the neutronic and mechanical behaviour of the core structure depends on the core temperature profiles and the resulting thermal expansion and interaction of the core components at any given time of reactor operations. As the core components expand and contact each other, the relative position of the fuel affects the neutronics and the interaction between the assemblies affects their mechanical performance. However, the history and state of the core components influences their response too. Specifically, the core components’ irradiation creep and swelling which are a function of dose rate and temperature affect their position, deformation and interaction forces. Thermal creep also results in inelastic deformations over time. These inelastic states can cause nontrivial bowing and dilation of the ducts, which if not managed can result in handling difficulties. To mitigate core management issues, the core assemblies are moved and rotated to other core positions. Thus, in order to know the thermal response of the core at any given time, one must know the reactor operating cycles, shuffling history, and the resulting deformations and forces.

In addition to the mechanical concerns, the other physics are also complex and all are interdependent. In a fast reactor, even a small translation of the fuel within the reactor caused by thermal expansion or mechanical loading changes the reactivity significantly. These also change the heat generation, further affecting the thermal mechanical state of the core.

The seismic requirements for a TWR design are as follows.

To remain operational during and after OBE:

1) Control rods shall not SCRAM during OBE without operator signal.
2) In the case of SCRAMs initiated during OBE by non-earthquake initiators, control rods shall provide negative reactivity as required to prevent component damage.
3) OBE shall not require changes in the plant operating procedures following the earthquakes.
4) Structural damage of core components shall be within acceptable limits.

To maintain the safety functions during and after SSE:

1) Reactivity insertion due to seismic displacements before SCRAM initiation shall be limited to preclude prompt supercriticality.
2) Control rod SCRAM shall provide negative reactivity as required to prevent significant fuel melting and onset of coolant boiling.
3) The core geometry shall remain coolable during and following the earthquake.

For the TWR reactor, the peak value of inserted reactivity during the seismic event will be the focus of this paper, though all of the other requirements are also checked in any given seismic modelling effort.

Many simplifications are used to make the seismic modelling of a reactor manageable, or even possible. Historically, these seismic analyses have been done in two dimensions using a simplified temperature distribution and uncoupled from the other physics models [2]. While this may be acceptable to satisfy regulatory bodies, the goal of this paper is to demonstrate that a reactor design can be better understood with a coupling of reactor physics and inclusion of the full three dimensional effects. The TerraPower TWR-300 will provide the basis for the analysis presented here, but the methodology is generally applicable to other reactor designs such as LWRs.

The TerraPower TWR-300 reactor core, like many of its predecessors, is made up various types of slender core assemblies such as fuel, reflector, shield, and control assemblies. While their internal components differ, they are all contained in a similarly shaped, hexagonal cross-sectioned duct. These ducts are supported at their base where their inlet nozzles fit into a receptacle that is a part of core support structure. Along the length of these assemblies are two load pads which serve to transfer load from one assembly to its neighbors. The assemblies transfer load at the periphery to one or more core former rings that are attached to the core support structure. An example core is shown in Figure 1 with one core former ring at the top of core assembly [3] [4].

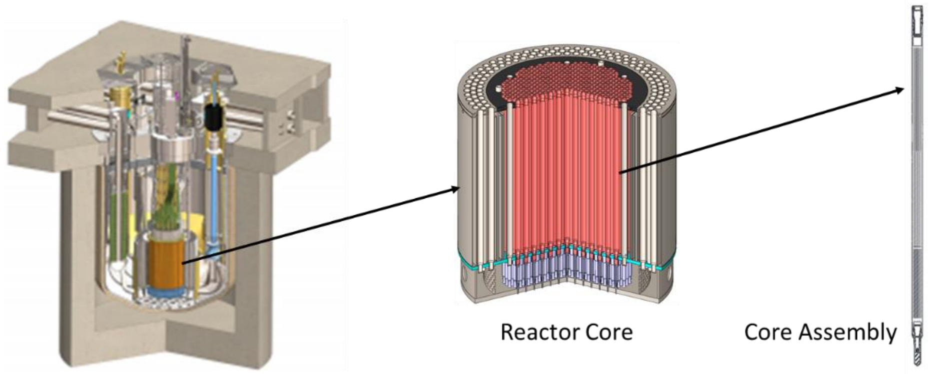

Figure 1: A concept of the TWR reactor, core and assembly duct design

2. Methodology

TerraPower's Advanced Reactor Modeling Interface (ARMI) [5] and the OXBOW suite of software [6] are designed to perform loosely coupled, multi-physics analyses such as core assembly distortion and reactivity insertion due to seismic activity.

Before the seismic event is considered, the state of the reactor must be well defined. The geometric layout of the reactor, including all of the core assemblies are defined within the ARMI software by input data specific to the reactor design. This input data has dimensions and materials sufficiently defined for the neutronics, thermal/hydraulic, and mechanical analyses. The operation of the reactor can then be simulated within the ARMI framework up to the point in time when the seismic event is to occur. This simulation of the reactor operation must include the loosely coupled neutronics and thermal/hydraulics analyses and solved iteratively to a steady state. These are only two of the many interoperable interfaces to the ARMI framework some of which are illustrated in Figure 2 [4].

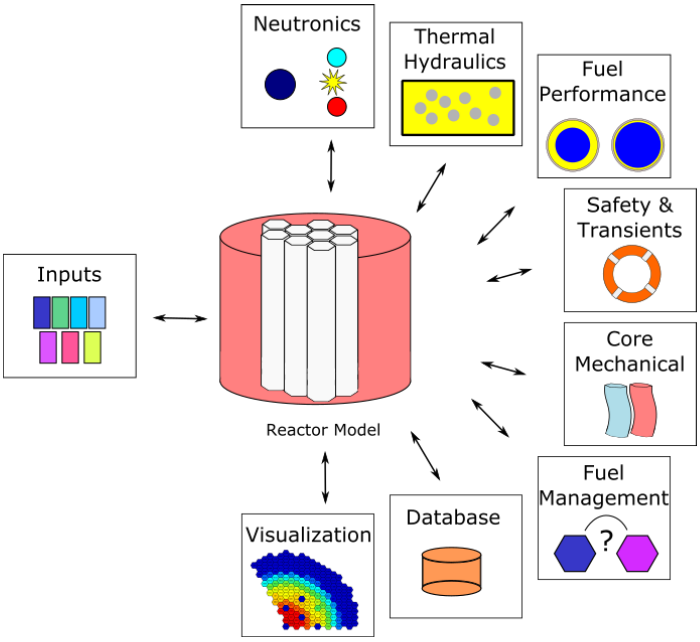

Figure 2: The Advanced Reactor Modeling Interface (ARMI) simulation life cycle

Alternatively, the state of the reactor can be loaded from a database generated by a previous ARMI solution. At TerraPower, the entire life of the reactor is simulated for each core design iteration and saved in a database accessible to the core design engineers for further analyses. This is the approach typically used at TerraPower for mechanical analyses. The history of the irradiation and temperature states seen by the materials is used to approximate the inelastic deformation of the ducts, including dilation and bowing. This history must be tracked with the shuffling and rotation of the core assemblies. For simplicity, the analysis here simulates a seismic event while the reactor is operating at its beginning of life.

Once the state of the reactor is defined, it can be modeled for mechanical analysis and its response to seismic activity can be characterized. The reactor core model is based on the geometry of each core assembly generated by the OXBOW software directly from the ARMI data loaded in memory. This model reflects the thermal state of the reactor and can also include the irradiation damage seen by the material.

The topology of the model and portion of the core included in the mechanical model depends on the objective of the analysis. Single assembly models may be made of beam elements for a modal analysis or of highly refined volumetric elements to determine the impact stiffness of the assemblies at their various load pads. A one-third or -sixth wedge shape core model could be made with symmetric and reflected boundary conditions for 3D-based detailed analysis such as thermal and irradiation bowing, insertion/withdrawal, or shuffling simulations. These assemblies could be modeled with shell elements as well.

On the other hand, the OXBOW/seismic models require non-linear time-history analysis and therefore use beam representations of the core assemblies. The OXBOW/seismic models have the mass of each component defined based on its internal components at any given elevation. The stiffness of the beams is based on the cross section and materials, all of which are defined in and provided by the ARMI model. The temperature distribution from the thermal/hydraulics model solved previously via ARMI is used to determine the material properties of the OXBOW/seismic models, which are provided by a shared materials database. These thermal loads are also used to expand the dimensions of the reactor core support structures that provide boundary conditions of the core. Figure 3 shows a representative temperature distribution in a full core model.

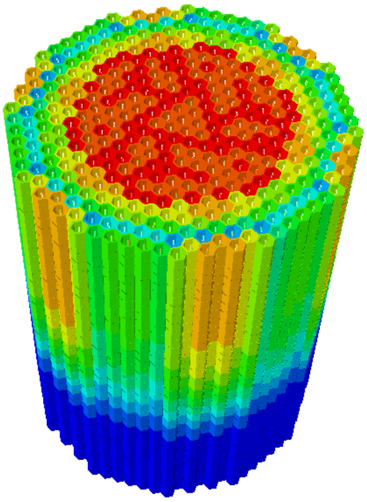

Figure 3: A representative temperature distribution in a full core model.

In addition, the core can be represented as a single row if the row is in-line with the loading and interactions between the core assemblies perpendicular to that row can be neglected. The single row core seismic model can be used to benchmark a single row dynamic test described in IAEA-TECDOC-798 and 829 [2, 7]. If the loading is not aligned with a row of assemblies, or if a more accurate model that accounts for the interaction of the neighboring assembly rows is desired, then a full core model can be used. Figure 4 shows the geometry for a full core seismic analysis model with a cut-away view to illustrate the changes in beam properties with elevation and assembly type.

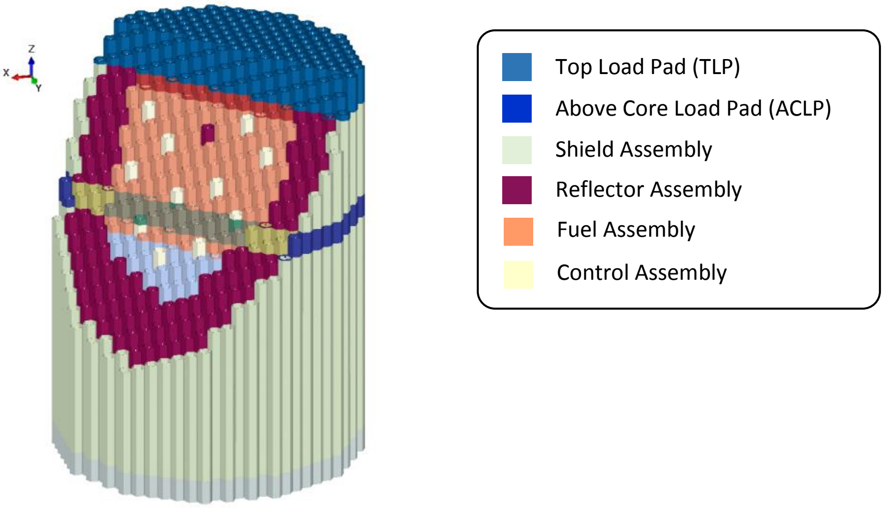

Figure 4: A full core with a cut away view to illustrate the property changes with elevation and assembly.

The interaction between assemblies is of critical importance. The TWR core assembles have load pads at two elevations, top and above core, as shown in Figure 4. These load pads are on each of the faces of these hexagonal ducts, creating a potential for twelve nonlinear contact conditions for each of the assemblies. This is easily the source of the most complexity with thousands of the individual contact conditions throughout a full core model. There are also contact interfaces at the core former ring which serves to provide lateral support for the ducts at the TLP elevation as a component of the core support structure.

The stiffness of the interaction between the assemblies and between the assemblies and the core former ring is determined by the same software framework. A reactor state defined by the ARMI software is used to model individual assemblies with a refined mesh of solid elements. Using a finite element analysis (FEA) model in ABAQUS [8], these individual assemblies are compressed at their load pads, modeling the contact between assemblies in order to obtain a load/deflection relationship. There are many states of possible contact between assemblies. When the core is fully compact, the assemblies tend to be compressed from all six sides. When the assemblies are first coming into contact or are in a loading state that is in flux, a common loading condition is when the duct is compressed on two opposing faces. There can in general be any number of the six faces in contact at a given instant during a dynamic loading event. The two face contact is the most compliant that can be seen in a steady state condition and the six face contact is the stiffest. If the goal of an analysis is to predict the reactivity insertion that is related to the compaction of load pads, the least stiff relationship should be used for the most conservative evaluation. An example of the models used for these stiffness calculations is shown in Figure 5.

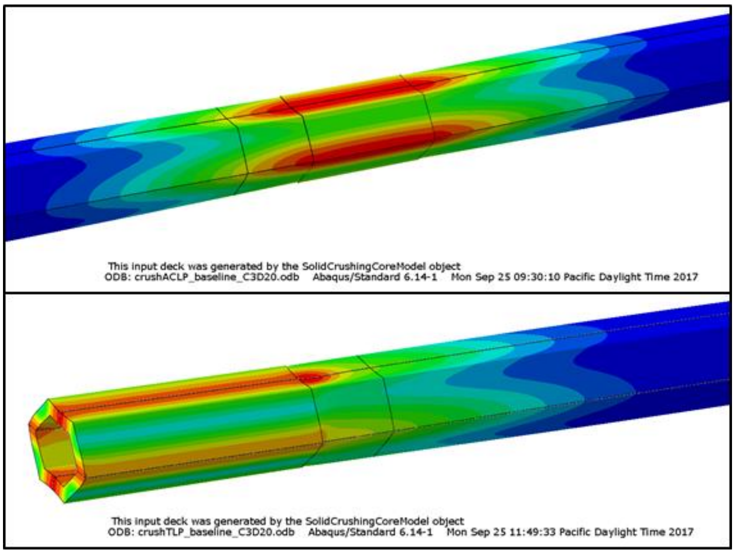

Figure 5: ARMI generated duct models for calculating the load pad contact stiffness (deformation magnitude plotted).

The boundary conditions at the base of the ducts represent the constraints of the inlet nozzle inserted into a receptacle and supported by the grid plate of the core support structure. This condition can be fairly complex due to gaps and frictions between them, but a pinned and a fixed condition bound the possibilities. An accurate representation of this condition is only possible with detailed analysis of the joint and experimentation. A simple solution in the absence of test data is to use pinned conditions with a radial stop determined by the gaps between the nozzle and receptacle.

Each of these models would be quite complex to build by hand in ABAQUS, but automating the process within an existing software representation of the core reduces the effort dramatically. Because mechanical models access the reactor defined by the same software used by the rest of the core design team to design, there is confidence that the model represents the current state of the design.

There are multiple objectives of a seismic model. Arguably, the most important are to ensure that the control rods can be dropped during a SCRAM and that the coolable geometry of the core can be maintained under the Design Basis Earthquake. Therefore, the following items shall be evaluated.

- load pads of the control assembly shall not be permanently deformed to prevent excessive friction forces on the control rods
- load pads of any other core assembly shall maintain its structural integrity to prevent excessive coolant flow blockage
- Fuel pins shall not be damaged to prevent local flow blockage or fuel dispersion into the coolant

There will also be a requirement for the Operating Basis Earthquake (OBE) that the reactor continues to function without needing to SCRAM. This requirement is the one of most interest in this study since it requires the reactivity insertion analysis.

The solutions of the seismic models depend on the time-history loadings at boundary locations obtained from upstream seismic analysis. An explicit dynamic solution representing a specific or equivalent earthquake's excitation of a full core for enough time to ensure that the seismic requirements can be satisfied is a significant effort. This is not the type of analysis that should be run many times in a trade study or parameter sweep. Alternatives may be a single row subjected to the same conditions or a quasi-static implicit solution with a bounding or equivalent loading.

Post processing the seismic models for load pad impact forces or control assembly distortion is similar to any other finite element analysis modeling effort, though the control assembly distortion time-history is to feed into a follow-on detailed analysis to confirm the ability to drop the control rods.

The reactivity insertion check requires continued interaction with ARMI which uses a perturbation-theory module based on virtual densities [9] to calculate radial expansion coefficients efficiently. Because the model was created within the ARMI framework and execution of the solver is controlled by the same, it is simple to read the distortions of the core assemblies back into the ARMI data model and use them for the reactivity insertion as a function of time in "cents."

3. Discussion

The proposed seismic analysis methodology in this study is able to quickly characterize the reactivity insertion, duct impact loads, the distortion of the control assemblies, and dynamic responses in the core support structures due to seismic activity such that it allows design teams to establish design limits in trade studies. These studies can inform the design of the reactor core, its support structure, and any structure that lays in the load path between the ground and the core assemblies.

It may not always be obvious how parameters such as gaps and the stiffness of support structure are correlated to seismic related requirements. For example, if the gap at the core former ring at the top load pads was increased how would it change the crushing loads at the above core load pads? What about the reactivity insertion? These are the type of questions this analysis can answer to inform the design beyond just checking that a margin or requirement has been met. Figure 6 and Figure 7 show the deformation contour plots of a full core model with a section view. These are subjected to the same loading conditions and shown at the same times. The plots use the same contour interval and multiplier to the deformation. It is immediately obvious that the loosely constrained core deforms significantly more than the highly constrained core, as is expected. What is less intuitive is that this more constrained core has more than 50% greater reactivity insertion during this loading, but has a significantly lower peak crushing load at the load pads. Another consideration is the distortion of the control assemblies. While the overall deformation is greater in the loosely constrained core, the highly constrained core has higher curvatures and is more likely to have control rod insertion concerns. This example illustrates the various tradeoffs that this approach can illuminate.

While verifying design requirements for the reactor is the primary function of the simulations within the ARMI and OXBOW frameworks, the qualitative results from the seismic models can also inform design decisions.

The modal shapes of the individual assemblies can guide us towards the shapes these assemblies will deform into during an earthquake, but the reality will be quite different once these assemblies interact. For example, Figure 8 shows the deformed shapes of the assemblies in a single row from the unloaded condition through the first major reversal of input load. This figure only shows a few moments of time, but illustrates the variety in the shapes we expect to see. The configuration and constraints simulated by the model shown in Figure 8 correspond to the model shown in Figure 6.

The behavior of the whole of the assemblies can also be quite interesting in the way the compaction can occur locally within a core and that group of assemblies behave as a single entity for a period of time. This is an aspect of the core response that can be missed in overly simplified models.

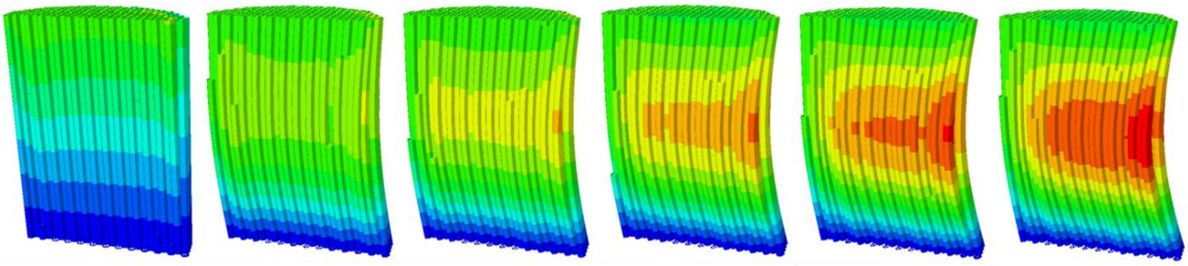

Figure 6: Assemblies in a full core illustrating lateral compaction due to acceleration for a loosely constrained core

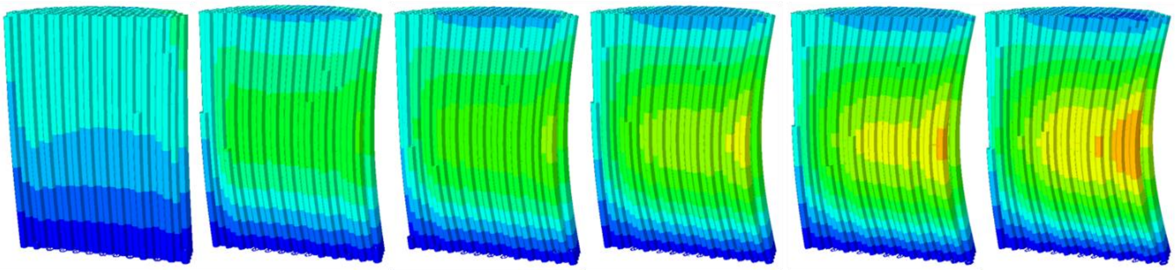

Figure 7: Assemblies in a full core illustrating lateral compaction due to acceleration for a highly constrained core

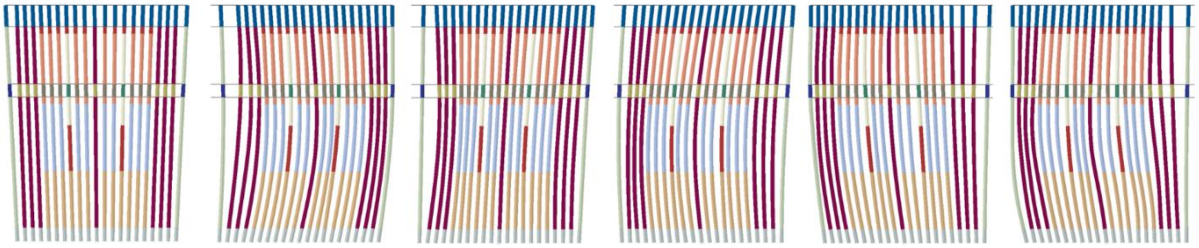

Figure 8: Deformed assemblies in a single row during the first major load reversal in input

4. Conclusions

This paper focused on the reactivity insertion during seismic events using a multi-physics modeling framework that couples neutronics and thermal/hydraulic to calculate a mechanical response. The mechanical response is fed back to neutronics simulations. This is one example of implementing a methodology and toolset for reactor core design that affects the design and analysis of core components. There are many other phenomena that can be modeled within this framework. The core assembly crushing stiffness estimation was discussed briefly, as its results were used as an input to the seismic analysis. The control rod insertion check is an example of an analysis that would follow the seismic analysis using the distorted shapes of the control assemblies as inputs. Cyclical loading of components is needed to understand the seismic event's contribution to low cycle fatigue.

The inelastic deformation of core assembly due to thermal/irradiation creep and irradiation dilation is the most mature of the analyses performed using OXBOW. This analysis is coupled with the ARMI reactor state and takes into account the shuffling and rotation of the assemblies as well. These results can be used for core assembly insertion and withdraw force checks and as an initial state for the seismic analysis.

Following this methodology results in a family of core mechanical models that derive from one common input source defined by the core design team. The reactor state has been determined from other physics simulations based on those same design inputs ensuring consistency of data throughout the design and analysis cycle.

There is a general applicability to this methodology and tool set. All reactors with beam-like core assemblies will exhibit a similar behavior and could conceivably be modeled with the methodology and toolset described here though some interfaces to additional simulation software may be required to use the ARMI framework itself.

The ARMI framework currently interfaces fast reactor physics packages for the evaluation of the temperature profiles as well as the neutronics impact of the distortions induced by the seismic activity (using perturbation theory), therefore some changes would be needed to apply the framework to LWR analysis. Possible changes to the interfaces could include the support of different core simulator, lattice physics and thermal-hydraulics codes in addition to small changes related to the seismic lateral displacements and its formulation under perturbation theory. Given that the required Cartesian geometry is supported by the ARMI framework and that its modular design philosophy would allow for simple implementation of interfaces to LWR-specific physics packages, these changes would be somewhat limited in scope. The overall methodology discussed in this paper, as reflected in the multi-physics analysis sequence performed by the framework, is however applicable to LWR analysis.

5. About TerraPower

To best catalyze and assist human enterprise, reactors with enhanced safety, reduced costs, minimal ties to weaponry, and reduced waste are called for. The TerraPower Traveling Wave Reactor (TWR) is designed specifically to answer this call. Building on the world’s past experiences, it features the key benefits of the breeder reactor while eliminating the key hurdle: the need for a reprocessing facility. The TerraPower effort involves supply chain, manufacturing/fabrication, and experimental development work in the US and around the world as well as modern engineering design and modeling.

6. References

[1] U.S. Nuclear Regulatory Commission, "10 CFR Part 50 - Domestic Licensing of Production and Utilization Facitlities," 2007.

[2] IAEA, "IAEA-TECDOC-798, Intercomparison of liquid metal fast reactor seismic analysis codes, Volume 1," in *Proceedings of a Research Coordination Meeting*, Vienna, 1993.

[3] P. Hejzlar, "Traveling Wave Reactor: A Once-Through SFR for Sustainable Globally Scalable Energy Solution and Overview of Development Status," in *MIT CANES-LCEC Special Symposium*, Cambridge, MA, 2016.

[4] J. Cheatham, "TerraPower Nuclear Energy Endeavors," in *Georgia Tech ANS Chapter Meeting*, 2017.

[5] N. W. Touran, J. Gilleland, G. T. Malmgren, C. Whitmer and W. H. Gates, "Reactors, Computational Tools for the Integrated Design of Advanced Nuclear," *Engineering,* vol. 3, no. 4, pp. 518-526, 2017.

[6] J. B. Meng and F. Deleo, "Considerations from the Benchmark Comparison of OXBOW against IWGFR Mechanical Analysis Codes," in *International Congress on Advances in Nuclear Power Plants*, 2018.

[7] IAEA, "IAEA-TECDOC-829, Intercomparison of liquid metal fast reactor seismic analysis codes, Volume 2," in *Proceedings of a Research Coordination Meeting*, Vienna, 1993.

[8] Dassault Systèmes, *Abaqus United FEA, Version 6.14.1,* 2014.

[9] M. Reed, K. Smith and B. Forget, ""Virtual density" and traditional boundary perturbation theories: Analytic equivalence and numeric comparisons," *Annals of Nuclear Energy,* vol. 112, pp. 531-548, 2018.