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Idaho National Laboratory

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Multiphysics-Coupled Seismic Safety Analysis of Molten-Salt Reactors

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INTRODUCTION

Pool-type molten-salt reactors (MSRs) are a promising advanced nuclear reactor concept relying on passive physical behavior to provide increased safety characteristics. The high heat capacity and high boiling point of the unpressurized liquid salt contains the nuclear fuel and, as it passes through the vessel, achieves criticality and produces nuclear power. The salt then carries away the heat produced along with the delayed neutron precursors towards heat exchangers and primary pumps before entering the core. This forms a highly coupled multiphysics problem between neutronics and fluid flow, which makes modeling these reactors challenging. The safety-licensing case heavily relies on modeling and simulation to prove their safety, and significant effort has been expanded by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program to develop the appropriate simulation tools.

As a part of the required safety-licensing studies, MSRs will need a thorough behavior analysis during earthquake-based transients. Earthquakes are a transient condition commonly experienced at many sites and are safely survived by dozens of reactors every year. Nonetheless, significant design conservatisms were introduced as limited predictive modeling and simulation are available. The first-of-a-kind capability developed by this research will allow engineers to analyze ranges of design-basis and beyond-design-basis accident scenarios to assess the integrity of the reactor vessel, fuel salt, and support systems, possibly allowing for limiting the costly conservatisms in the MSR design.

This project uses MASTODON (Multi-hazard Analysis of STOchastic time-DOmaiN phenomena) [1], Griffin [2] and Pronghorn [3] in the NEAMS ecosystem to model the coupled multiphysics problem posed by an earthquake in an MSR. The project investigates a number of coupling schemes, from uncoupled simulations to tightly two-way coupled simulations. The appropriate level of coupling for these simulations will then be determined based on the accuracy in the quantities of interest (QoI) and computational effort involved in each scheme. The QoIs chosen for this paper include the mass flow rate across the heat exchanger (for Pronghorn simulations), power output of the reactor (for Griffin simulations), and the maximum Von Mises stress (for MASTODON simulations). This summary paper reports on the current progress of this project.

Codes and Features Used

MOOSE (Multiphysics Object-Oriented Simulation Environment) [4] is an open-source finite-element and finite-volume framework on which this research is based. The MOOSE-based or wrapped applications encompass a large number of physics, from fracture mechanics to reactor physics to porous flow and more. Three applications were coupled for this analysis: MASTODON for seismic analysis, Pronghorn for thermal hydraulics, and Griffin for neutronics. These were coupled using the MultiApp system. This coupling is described in the next section.

MASTODON is a seismic analysis and risk assessment code with capabilities that include structural mechanics, thermomechanics, acoustics and acoustics-based fluid-structure interaction, contact mechanics, uncertainty quantifications, and probabilistic risk assessments. Some capabilities of MASTODON include earthquake fault rupture, source-to-site wave propagation, and nonlinear soil-structure analysis. The acoustic fluid-structure interaction capabilities [5] are leveraged in this research in a multiphysics coupling with Griffin and Pronghorn.

Griffin is a multifidelity reactor physics solver developed by the NEAMS program. It uses a finite-element discretization of the multigroup neutron diffusion (low-fidelity) and transport (medium-fidelity) equations. This research uses the continuous finite-element diffusion solver.

Pronghorn is a coarse-mesh thermal hydraulic solver developed by the NEAMS program. It makes use of the finite-volume MOOSE capabilities to discretize the Navier Stokes equations using a cell-centered scheme. Pronghorn supports a variety of incompressible (INS), weakly compressible (WCNS), and fully compressible Navier Stokes formulations. It currently uses a single-matrix direct solver approach, though segregated schemes are under development. Pronghorn solves both the fluid flow and delayed precursor advection problems. A formulation of coarse mesh $k-\epsilon$ turbulence is under development in Pronghorn, but this paper is limited to a basic 0D mixing-length turbulence model.

The fluid simulation uses a weakly compressible formulation with an approximate analytical relation for considering the effect of bubbles in an MSR. The density as a function of pressure and temperature is:

$$\text{density(Pressure P, Temperature T)}\ [kg/m^3] = 4284(1 - \text{bubble fraction}\frac{10^5}{P}\frac{T}{1000})$$

MULTIPHYSICS APPROACH TO SEISMIC ANALYSIS OF MOLTEN-SALT REACTORS

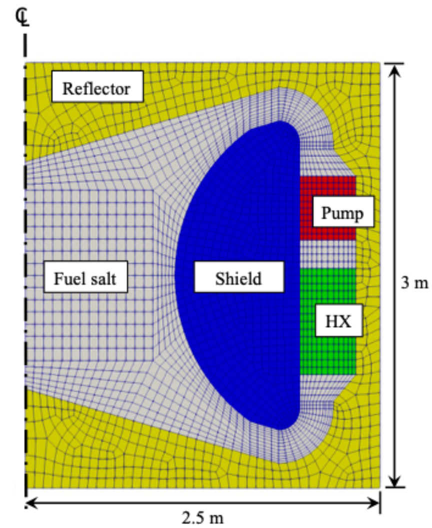
We selected SAMOFAR's Molten Salt Fast Reactor (MSFR) model as a test case for this analysis. A 2D axisymmetric (R-Z) slice of the system is simulated and subjected to an axial earthquake (vertical direction). Because of such symmetry, horizontal earthquakes cannot be modeled in the system, as a horizontal movement in the symmetric system would be a radial movement in 3D, which is not realistic. For this study, vertical earthquake shaking is assumed to be adequate to understand the coupling behavior. The MSFR mesh used for Griffin and Pronghorn simulations is presented in Figure 1a. The figure shows that the MSFR model comprises the fuel salt, heat exchanger, and a pump in the core and a shield and reflector outside the core. However, this mesh does not include any structural supports or the reactor vessel, both of which are needed for a seismic simulation.

For a more realistic seismic simulation, we developed a modified mesh for MASTODON that explicitly includes a stainless-steel reactor vessel (1-inch thick) and structural supports but still preserves the core mesh, including the fuel salt, pump, and heat exchanger. For the seismic simulations, we assumed that the reactor has three structural supports: the structural slab at its mid-height, from where the reactor vessel is suspended from, the upper cylindrical skirt, and the lower cylindrical skirt. The model assumes that supports are rigid and modeled in the simulation by prescribing the earthquake excitation at the support nodes. Figure 1b illustrates the 2D axisymmetric mesh used in MASTODON, including the nodes for the slab and skirt supports.

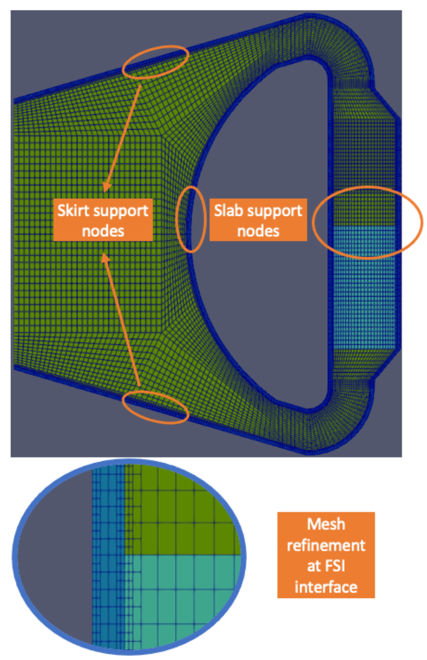
The physics at play are neutronics, fluid flow, precursor advection, acoustic wave propagation, acoustic fluid-structure interaction, and structural dynamics. The coupling interactions we considered are: the fluid flow modifies the precursor concentration that affects the power distribution; the heat generation distribution affects the fluid flow through buoyancy effects; the fluid density, its temperature, and the core thermal expansion impact the neutronics of the core; the density field, a product of coupled neutronics (through power) and fluid flow, affects the acoustics calculation; the acoustics calculation generates a pressure wave, which in turn affects density, which affects the fluid flow; and the acoustics calculation deforms the vessel, which may affect both neutronics and fluid flow (not modeled at this stage of the study). Griffin, Pronghorn, and MASTODON are coupled in the scheme shown in Figure 2 using the MultiApp system in MOOSE. MultiApps in MOOSE are individual physics applications (e.g., Griffin, Pronghorn, or MASTODON) that are coupled using field and scalar quantity transfers. A data transfer between the applications is automatically carried out as requested by the analyst, making multiphysics simulations very convenient. When two-way coupling between two applications is needed, a Picard or quasi-Newton iteration scheme may be employed to achieve convergence.

INVESTIGATING COUPLING USING 2D ANALYSIS

We simulated the scenario as follows: an earthquake occurs at the plant, causing the pump to trip and the pump force to drop by 50% over 2 seconds. The earthquake input is modeled as a simple sinusoid ramped to its full amplitude in 0.5 sec and ramped down to a zero amplitude from 4 to 4.5 sec. The earthquake shaking therefore continues for 2.5 more seconds after the pump trip while the flow in the reactor core slows



(a) Mesh used in Griffin and Pronghorn



(b) Mesh used in MASTODON

Fig. 1: 2D axisymmetric meshes used in this study.

down to a new steady state. We investigated the coupling between different physics while simulating this scenario with increasing levels of complexity:

- First, benchmark simulations are performed without any coupling between seismic shaking and neutronics or thermal hydraulics. Results from the seismic simulations in MASTODON include maximum Von Mises stress in the reactor vessel as a function of time. Results from the coupled thermal hydraulics and neutronics simulations (Pronghorn + Griffin) include mass flow rate across the heat exchanger and the power output with time.

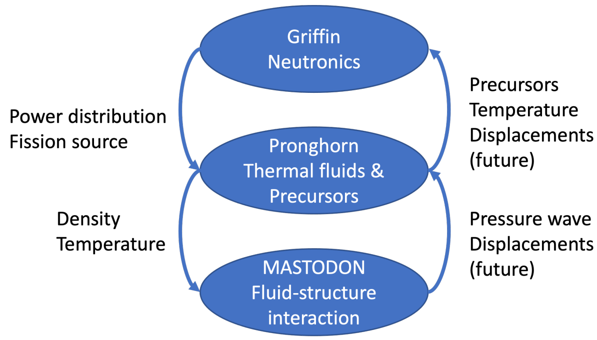


Fig. 2: Coupling scheme for the earthquake transient simulations.

- Second, one-way coupling is performed where the body forces from earthquake-induced pressures are input into coupled neutronics and thermal hydraulics simulations and their effect is observed. The QoIs from the coupled neutronics and thermal hydraulics simulations are compared with the benchmark simulations without seismic shaking.
- Third, two-way coupling is performed where pressure gradients from MASTODON are input into the coupled neutronics and thermal hydraulics simulations as body forces and the fuel density field is input into MASTODON at each time step. All QoIs are then compared with the benchmark solutions. Results for a full coupling are not included in this summary and will be included in future publications.

Three different compressibility formulations are considered for the thermal hydraulics simulations: incompressible Navier Stokes, weakly-compressible Navier Stokes, and weakly-compressible Navier Stokes accounting for the effect of bubbles to also investigate the effect of the formulation.

Benchmark Simulations Without Seismic Coupling

Figure 3 presents the mass flow rate calculated from thermal hydraulics (indicated as NS) and coupled thermal hydraulics and neutronics.

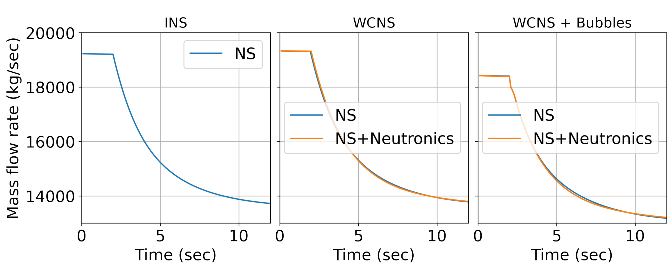


Fig. 3: Results without seismic coupling: mass flow rate across the heat exchanger.

From the figure, note that the pump coast down starts at 2 seconds when the mass flow rate starts decreasing towards a new steady state. The results show that the benchmark mass flow rate for all the formulations with or without neutronics coupling is almost the same.

Figure 4 presents the maximum Von Mises stress in the reactor vessel as a function of time calculated using MASTODON without coupling from thermal hydraulics (i.e., assuming a constant density field for the fuel). These results are presented for three different shaking frequencies (in Hz) and two different shaking amplitudes (in units of gravity, g). The figure shows that the amplitude of the Von Mises stress is larger for the 9Hz input, indicating that the dynamic properties of the reactor vessel play a role, and that the peak stresses for even the 1.0 g shaking is much smaller than the yield stress of steel (around 0.2 GPa) and therefore the 1-in. thickness chosen for the reactor vessel is adequate for this study.

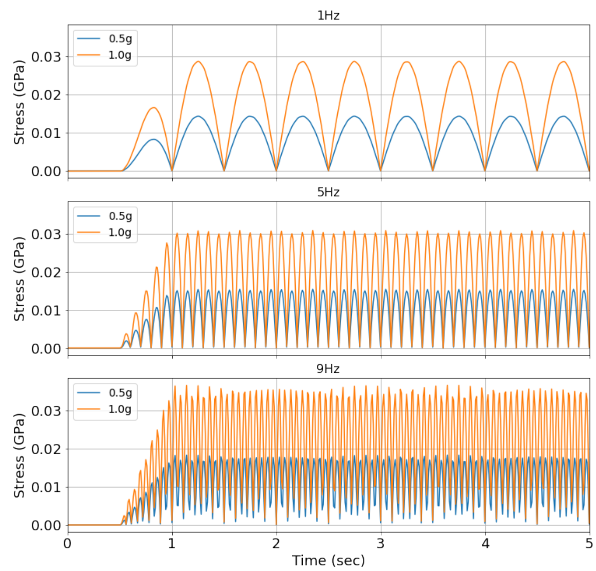


Fig. 4: Maximum Von Mises stress in the reactor vessel calculated without coupling with neutronics or thermal hydraulics.

One-Way Coupling Simulations

Prior to performing the one-way coupling simulations from MASTODON to Griffin+Pronghorn, sensitivity studies investigate the effect that analysis time step and frequency of shaking have on the results. Figure 5 presents the mass flow rate calculated from a one-way coupling simulation where the pressure gradients from MASTODON are input into the thermal hydraulics simulation in Pronghorn during each time step. The results show perturbations in the mass flow rate when the earthquake occurs. The figure shows results from a 1 and 5-Hz shaking frequency for time steps of 0.01, 0.05, and 0.1 sec. While the 1-Hz results are unchanged for different time steps, the 5-Hz results are quite different. Notice that, with a time step of 0.1 sec, the perturbations in the mass flow rate are almost negligible; although, considerable perturbations are visible for the other time steps. This is clearly an erroneous result caused by an insufficient time step for a 5-Hz frequency. This result therefore shows that, in order to capture the seismic transient in the thermal hydraulics simulations, an adequately small time step must be used that can adequately resolve all frequencies in the seismic input.

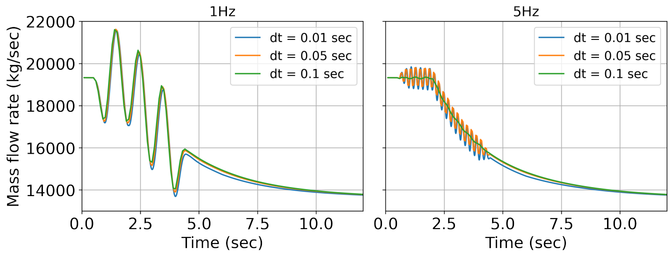


Fig. 5: One-way coupled: sensitivity of dt on the mass flow rate.

Figure 6 shows similar results as the previous figure but for different NS formulations (incompressible Navier Stokes [INS] and weakly-compressible Navier Stokes [WCNS] with and without bubbles), frequencies (1, 5, and 9Hz), and amplitudes (0.5 and 1.0 g). A time step of 0.1 seconds was used for these simulations. The figure shows reasonable results for the 1-Hz shaking but not for the larger frequencies. The 5-Hz results shows almost no perturbations, and the 9-Hz results with bubbles (and 1.0 g amplitude) show that the perturbations are not cyclic. These results are an artifact of an inadequate time step, showing the importance of choosing an appropriate time step in these simulations.

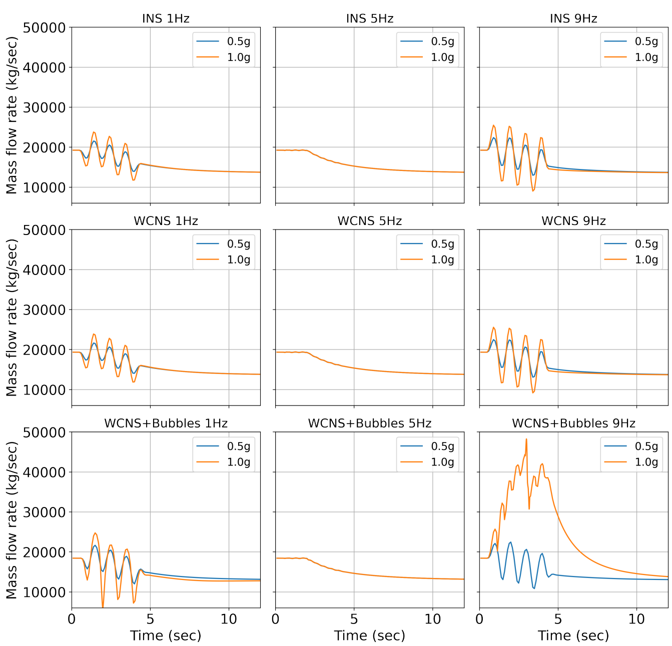


Fig. 6: One-way coupled: sensitivity of shaking amplitude and frequency on the mass flow rate.

SUMMARY AND FUTURE WORK

We summarized the progress in the capability of MASTODON and the NEAMS-developed tools, Griffin and Pronghorn, towards modeling earthquakes in an MSR. The results show that the tools can be coupled, that the coupling has a small effect on the flow rate during the earthquake, and that the steady state reached after the earthquake is the same as the one reached without earthquake shaking. More realistic earthquake shaking and tighter coupling will be investigated in the future.

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