

Development of Continuous Processes for a Molten Salt Reactor Safeguards Model

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INTRODUCTION

Current nuclear safeguards regimes for light water reactors are based on containment and surveillance combined with item accounting. This approach is not well suited for liquid-fueled Molten Salt Reactors (MSRs) which do not have discrete fuel elements. It is possible that the materials accountancy requirements for MSRs will be similar to bulk processing facilities. This work describes the development of a MSR process model in order to develop a safeguards accountancy system.

BACKGROUND

MSRs are defined as a class of generation IV nuclear reactors that have a molten salt mixture as a primary loop coolant or as the fuel itself. The reactors have favorable properties for increased thermodynamic efficiencies and increased safety. There are many different designs, the majority of which can be placed into three different categories.

The first type of design are reactors with solid fuel with molten salt coolants. Typically, these designs consist of a Tristructural-isotropic (TRISO) fuel in an assembly [1] or a pebble bed configuration [2]. Fixed assemblies will have a similar safeguards requirement to conventional light water reactors. However, pebble bed reactors would require a more complicated safeguards system due to the large quantity of pebbles present in the reactor that must be accounted for.

The second type of design is a liquid-fueled core with on-site processing of the fuel, and if applicable, blanket salts. Many of these designs were inspired from the Molten Salt Reactor Experiment (MSRE) [3] conducted in the 1960's by Oak Ridge National Laboratory (ORNL). One option is the use of a single molten salt mixture as both coolant and fuel for the reactor. Designs typically include a breeding and burning region, which is determined by the ratio of fuel salt to moderator. Some designs incorporate separate molten salt mixtures for the fuel and blanket materials [4]. In this variation the active region of the reactor contains a fuel salt surrounded by a blanket salt. Processing of the fuel salts are performed on-site and may have similar safeguards requirements to pyroprocessing facilities.

The final design are liquid fueled drop-in cores. These are self-contained designs with no processing of the salts. Instead, the entire core is replaced every 7-8 years. This design is similar to the Integral Molten Salt Reactor

developed by Terrestrial energy[5]. A self-contained design where cores are processed at a centralized facility may be more attractive economically than designs with on-site processing.

This work focuses on the class of designs that will likely require the most work to develop a safeguards regime, liquid-fueled reactors.

MODELING APPROACH

The MSR safeguards model was created in the Matlab Simulink environment pulling on past experience developing the Separation and Safeguards Performance Model (SSPM) [6]. The Simulink environment is explicitly designed to model dynamic systems and is well suited for this application. The Simulink model was then linked to ORIGEN [7] to approximate the depletion in the core and decay in the decay tanks.

The model was based on the Liquid-Fluoride Thorium Reactor (LFTR). The reactor was studied by the Electric Power Research institute who produced a report detailing many of the system parameters [8]. The reactor is liquid-fueled, graphite moderated, and utilizes a thorium fuel cycle. U-233 undergoes fission in the fuel salt to produce power whereas Th-232 under goes a capture reaction in the separate breeder salt to produce Pa-233 and eventually U-233.

Reference [8] was used to model the salt processing loop and guide the depletion calculation parameters. This reference was the only one with sufficient detail to build a model at the time of this work. It includes processing steps and flow rates which were directly used to build the model.

SIMULINK MODEL

The current MSR safeguards modeled in MATLAB Simulink and consists of several subsystems. Many of the unit operations, excluding the reactor and decay tanks, are quite simple consisting of simple gains and delays to simulate separation operations. The model is divided into separate fuel and blanket salt processing loops.

A small stream of fuel salt is continuously removed from the reactor for processing, however the mass of material in the chemical processing system can be large. This stream is initially held in a drain tank where the material stays for about 30 days to allow the decay of short-lived fission products. The fuel then goes through several other steps to remove other fission products, which would

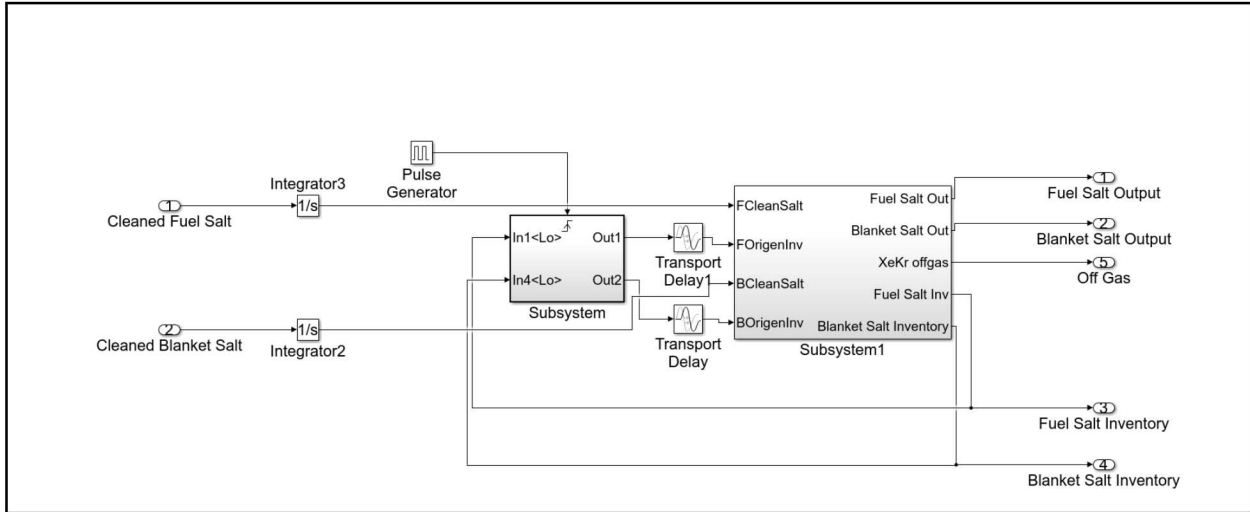


Figure 1: Reactor subsystem layout in Simulink

otherwise poison the fission reaction in the core, and a step to refuel the salt with UF₆ from the blanket loop. Once the fuel salt has been processed it is returned to the reactor.

The blanket salt stream, which has a much larger mass flow rate than the fuel salt stream, has a more simple processing stage because it involves a single extraction step. The blanket salt travels through an extraction column to remove protactinium and replace lost thorium before it returns to the reactor. The removed protactinium is held in a decay tank for about 100 days so that it will decay to uranium. The decayed stream is then used to refuel the fuel salt. The decay tanks and reactor subsystems are more complex than other unit operations, and as such, are outlined in the following sections.

Reactor Subsystem

Unlike a conventional light water reactor, the fuel in a molten salt reactor is not constantly depleted and undergoes chemical reprocessing. The fuel flows through the primary loop only spending a fraction of the circulation time in the active core region. This results in the need for frequent computational updates to the fuel and blanket isotopic terms to simulate this behavior. The reactor subsystem is responsible for updating the blanket and fuel salts in this model.

Unlike other MSR designs, this reference design features a separate fuel and

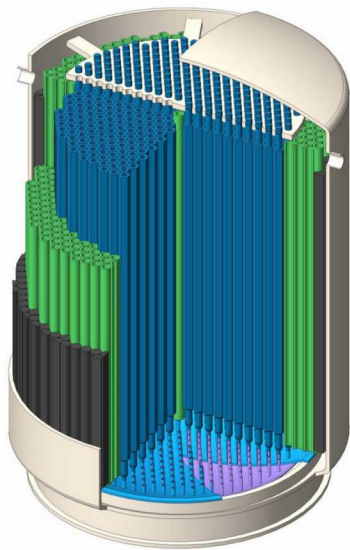


Figure 2: Flibe LFTR core design

blanket salt that do not come into direct contact. In the core, the blanket salt surrounds the fuel salt as seen in Figure 2.

Currently, these inventory terms are updated by calling the ORIGEN depletion code. The blanket and fuel salt isotopics from Simulink that have been updated by the simulated chemical processing operations are written to separate ORIGEN input files and depleted individually, as shown in Figure 1. The specific power of each material is tuned to produce the correct uranium feed and consumption rates. It is important to note that this is not an accurate calculation of a MSR reactor core.

ORIGEN is a code that solves a transition matrix for specified problem parameters. The transition matrix consists of a series of ordinary differential equations, provided in Eq 1, that describe nuclide generation, depletion, and decay.

Equation 1

$$\frac{dN_i}{dt} = \sum (l_{ij} + f_{ij} \sigma_j \Phi) N_j(t) - (\lambda_i + \sigma_i \Phi) N_i(t) + S_i(t)$$

Solving this equation requires knowledge of the angle and energy integrated time-dependent neutron flux as well as spectrum-averaged removal cross sections for a particular nuclide. For our application we use neutron fluxes and collapsed cross sections derived from the neutron transport solution of a 17x17 Westinghouse pressurized water reactor assembly. However, the materials present in a lattice physics calculation to determine the flux and cross sections for that assembly are not representative of a two-fluid molten salt reactor.

Additionally, the neutron flux that originates from the fission of U-233 in the fuel salt will stream to the blanket salt to produce Pa-233. The methodology used in the model

does not consider the neutronic coupling between the fuel and blanket salts.

The errors in approximating both the neutron flux and cross sections will affect the actinide production which will implicitly impact the safeguards results generated by this model. Accurate results will likely require a 2D transport model coupled with material depletion. At this time key parameters to perform this calculation are not available publicly. Specifically, reactor core geometry and material properties must be known.

Decay Tank

The drain tank contains either fuel or blanket salt that needs to decay before further processing. The fuel salt decays to reduce the short-lived fission product concentration whereas the blanket salt decays to allow Pa-233 to decay to U-233 which is later used as fuel. Both decay tanks are modeled exactly the same except for the length of time the material is in the tank. For illustrative purposes the blanket salt decay tank will be described. The blanket salt resides in the decay tank for about 100 days to allow the majority of the protactinium to decay.

Modeling the decay tank is challenging due to the constant change of the blanket material. As stated previously the blanket salt is depleted every 20 hours, which means that the composition of the blanket salt entering the decay tank is changing every 20 hours. We approximate the changing input fuel to the decay tank by modeling the tank in 10 “slices” as seen in Figure 3. We assume that initially, the decay tank contains 10 slices of clean salt. The flow rate into the tank and the tank volume are given in the reference so it is possible to determine the length of time required to accumulate $1/10^{\text{th}}$ of the tank volume or one “slice”.

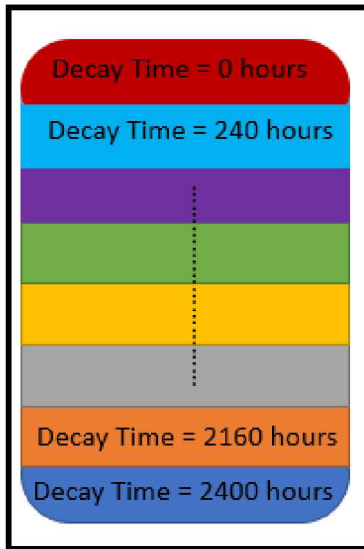


Fig 3. Decay tank inventory

Once enough time has elapsed to accumulate one slice that material is written to an ORIGEN file for decay. The

output of the ORIGEN file describes the decay of the given material in 10 evenly spaced intervals from the initial time $t=0$ to the final decay time $t=100$ days. This data is stored in a persistent Matlab array. This process repeats every time enough material enters the decay tank to create a slice. Every time a slice is created the inventory and decay tank output is updated.

Decay Tank Inventory and Output Calculation

As mentioned previously, the decay tank data is stored as a persistent array. It is useful to visualize the stored data as seen in Figure 4. The colors represent the different material slices each of which has time dependent isotopics.

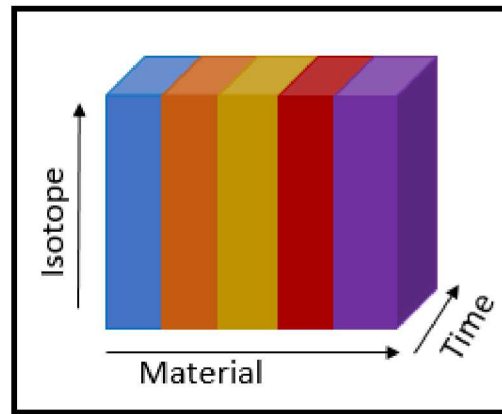


Fig 4. Persistent array used for decay tank inventory and output calculations

Once enough material comes in to generate a slice ORIGEN is called to generate time dependent decay isotopics as seen in Figure 5.

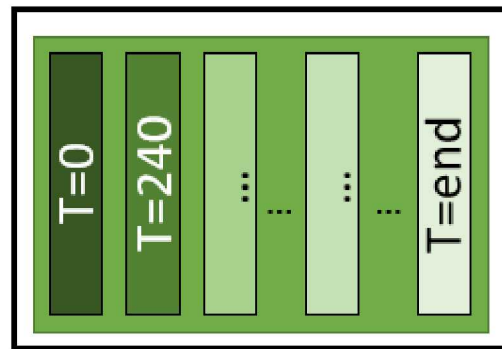


Fig 5. Material slice that is stored in persistent array for decay tank calculations

This data is then stored in the persistent array for further use. Each slice then removes down in the array to accommodate the new slice. The bottom slice is then removed from the persistent array as it has decayed for the full duration. The inventory is then calculated as a sum of the diagonal of this persistent array as shown in Figure 6.

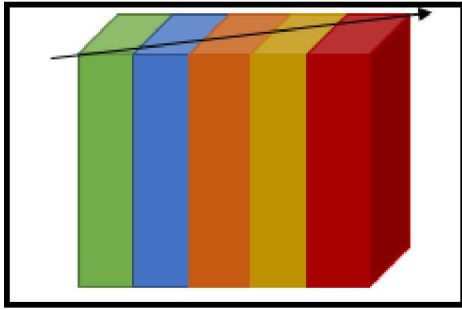


Fig 6. Inventory is calculated by summing the diagonal of the persistent array.

The inventory is calculated as follows:

$$\text{inventory} = m_{1,t-9} + m_{2,t-8} + \dots + m_{10,t}$$

Where m is the material slice m_j at a given time t . In short, the inventory at any given time is the diagonal of the persistent array. The isotopics of the material at the bottom of the tank at the maximum decay time are added to the slice above it at decay time $t-1$ and so on. The decay tank output is simply calculated as the last material slice decayed for the maximum amount of time.

FUTURE WORK

The current model accurately simulates the chemical processing and refueling of the molten salts in a Liquid – Fluoride Thorium Reactor. The model has been updated with calculations to more accurately reflect the mixed inventory of the various decay and drain tanks. However, there are still significant challenges. The frequent calls to ORIGEN are not only computationally expensive, but the results are not representative of conditions inside a LFTR core. In the future we hope to collaborate with ORNL to implement more effective reactor physics tools such as the ChemTRITON code [9].

Additionally, safeguards measurements have not been added to the model. Recent work on safeguards regimes for pyrochemical processing plants that leverage process monitoring data and machine learning algorithms is also applicable to MSR systems.

CONCLUSION

In this paper we have outlined updates to the MSR safeguards platform. The work in the past few months has focused on improving approximations of continuous processes such as the decay and drain tanks as well as the reactor subsystem. The model will continue to be developed to provide a versatile platform to design for next generation molten salt reactors.

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