Developing a Molten Salt Reactor Safeguards Model

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INTRODUCTION

Molten Salt Reactor (MSR) designs can represent a significant departure from a typical light water reactor. Though the designs vary, liquid-fueled designs with the potential for on-site salt reprocessing will have unique safeguards requirements. Safeguards requirements of light water reactors is based on item accounting and containment and surveillance since the fuel assemblies are discrete entities. On the other hand, liquid-fueled MSRs may have materials accountancy requirements similar to bulk processing facilities. In this work, a safeguards model of a MSR was developed in order to better understand safeguards needs and develop initial materials accountancy system designs.

BACKGROUND

Recently, there have been a number of new companies developing MSRs for commercial deployment. Several variations of MSR designs exist, but they generally fall into three categories.

The first category are MSRs with liquid fueled cores and full on-site processing of the salt. These designs stem from the work on the Molten Salt Reactor Experiment at Oak Ridge National Laboratory in the 1960's [1]. Molten salt is used as both the fuel and coolant, and salt processing is required to replenish actinides and remove fission products and gases. Typical designs can include a fuel salt and blanket salt for a breed and burn system, and can have a design life of up to 60 years. The Liquid-Fluoride Thorium Reactor (LFTR) design from Flibe Energy appears to be the most mature current concept in this category [2]. These designs will have the most significant safeguards challenges since the actinide content may need to be determined through measurement. The processing loops are similar to reprocessing plants, and in particular pyroprocessing salts.

The second category of MSRs are liquid fueled drop-in cores. These are designed as self-contained designs where the reactor module is replaced every 7-8 years or so. An example design is the Integral Molten Salt Reactor by Terrestrial Energy [3]. The salt is not processed on-site, but the entire core would be removed and processed at a centralized processing facility. Part of the driver for these designs is the design life of reactor materials. Materials accountancy measurements of the molten salt will still be required, but there may be advantages to self-contained cores.

The third category of MSRs are solid fueled cores with molten salt as the coolant. These designs are using TRISO fuel either in fixed assemblies or pebble bed designs. The Small Fluoride Salt-Cooled High Temperature Reactor, developed by Oak Ridge National Laboratory is an example of this type of design [4]. Fixed assemblies would have similar safeguards requirements as light water reactors (mainly based on item accounting and containment and surveillance). Pebble bed designs may have an added complication in keeping track of pebbles, but generally the requirement of large numbers of pebbles to get enough material for a significant quantity probably makes theft unrealistic.

This work is specifically focused on modeling liquid-fueled designs with on-site processing since they pose the greatest safeguards challenges. Future work may examine the liquid-fueled drop-in core designs based on lessons learned from this work.

MODELING APPROACH

The safeguards model was built using Matlab Simulink, and pulls on past work developing the Separation and Safeguards Performance Model (SSPM). The SSPM has been used for safeguards analysis and design of both aqueous and electrochemical reprocessing plants, so it was designed to evaluate accountancy systems for bulk handling facilities [5]. The architecture of the SSPM was used to build the salt processing loop for the MSR model; however, the model was linked with ORIGEN in order to approximate depletion in the core and decay in decay tanks. The work in this first year has only focused on modeling the elemental flows and inventories—future work will need to add in various safeguards elements.

The MSR design and flowsheet that was used for this model was based on the Liquid-Fluoride Thorium Reactor (LFTR) [2]. This design was a collaboration between the Electric Power Research Institute and Southern Company and pulls heavily on the MSRE work. The reactor is liquid-fueled, graphite moderated, and utilizes a thorium fuel cycle. U-233 is burned in the fuel salt, and a separate blanket salt is used to breed U-233 from thorium.

Reference 2 was used in part because it was the only one available which contained enough information about the salt processing loops to model. This reference included the processing steps and flow rates, which were directly used to build the Simulink model. The specific details will not be described here.

SIMULINK MODEL

The preliminary MSR safeguards model is shown in Figure 1. The blocks in this figure represent the major unit operations. The most detail is included in the reactor subsystem, shown in red. The rest of the blocks are various tanks and columns used for the salt processing.

The reactor design uses both a fuel salt and blanket salt. The fuel salt flow to the heat exchangers is not modeled for simplicity and since the flow rate is so large compared to the chemical processing loop. However, it is taken into account in the reactor model and to determine the correct off-gas production.

The top half of Figure 1 is the fuel salt processing loop. A small stream of the fuel salt goes to the drain tank where the material is held up for about 30 days to allow short-lived fission products to decay. Then the fuel goes through the remaining processing steps. The subsequent steps remove fission products and then re-fuel the salt with UF_6 from the blanket loop. Then the fuel salt is returned to the reactor.

The bottom half of Figure 1 is the blanket salt processing loop. The blanket salt is first processed in an extraction column to remove the bred protactinium and replace lost thorium. The protactinium needs to decay in the Decay Tank for about 100 days so that most of the protactinium decays to U-233. That material is then transferred into the fuel salt for re-fueling.

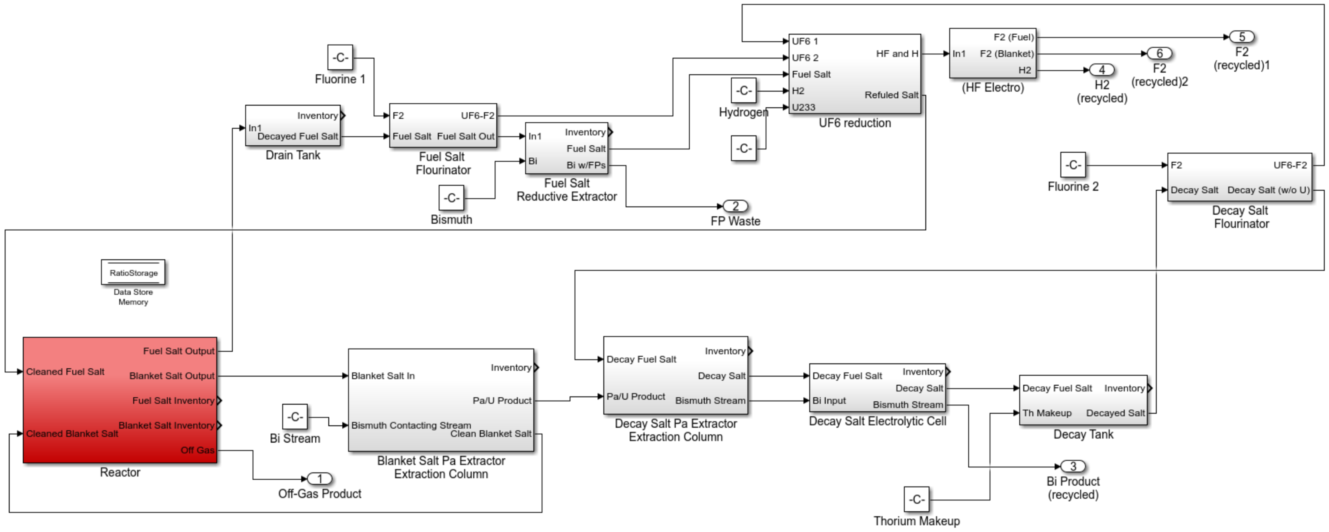

Figure 1: Molten Salt Reactor Safeguards Model

Reactor Subsystem

The reactor subsystem consists of the fuel salt and blanket salt inventory terms. These inventory terms are periodically updated by calling the ORIGEN depletion code. Simulink constantly updates the blanket and fuel salt inventory terms as recycled salt is added from the various chemical processing systems. Every 20 simulation hours ORIGEN is called to update the salt terms. The Simulink calculation is paused as the inventory terms are formatted and written to an ORIGEN file.

Currently, the salt inventories are depleted separately. The salt depletion is calculated by ORIGEN using a library derived from the flux spectra and one-group cross-section library of a Westinghouse 17x17 pressurized water reactor assembly. This flux shape is not representative of the conditions inside a molten salt reactor, however, reactor physics tools for molten salt reactors are still in heavy development. In the future, the depletion model will be updated to be more representative of molten salt reactor conditions. The power applied to the fuel and blanket salt are tuned to provide a specified breeding ratio.

Once ORIGEN has depleted the blanket and fuel salt, Matlab reads the ORIGEN output, formats the data, and updates the Simulink model. Transport delays are used in Simulink to ensure that the simulation time is then synchronized with the time elapsed during the depletion. After the inventory has been updated, the Simulink calculation continues to run until the next ORIGEN update.

Salt Processing Loops

The salt processing loops consist of tanks and extraction columns. The drain tank and decay tank require unique programming since they take into account decay of the actinides and/or fission products. This is further complicated by the assumption that the tanks are designed without mixing, so the salt that leaves the tank must be representative of what went in 30 days or 100 days before (depending on the tank). This is modeled by segmenting the tank into ten regions and performing an ORIGEN decay calculation on each segment for the proper amount of time. The segmenting is required in order to make sure the total quantities in the tanks are realistic.

The extraction columns use bismuth to extract quantities of interest. The unit operation models in Simulink use gain blocks to determine the fraction of each element that goes into each output.

Finally, the loops also contain chemical reactors that use hydrogen and fluorine gas for various steps. The model does not track specific chemicals, so the important aspect is just to keep track of the total elemental quantities in each stream.

CURRENT STATUS AND PATH FORWARD

The current status of the model is that it runs and is generating useful results. The model has been balanced so that the actinide levels reach a steady-state level. The fission products build up considerably, which is expected in the beginning life of a reactor. One challenge is that the external calls to ORIGEN lead to significant modeling times on the order of several hours to model one year of operation. Steady-state conditions in a MSR that occur after several years may take 24 hours of run time. Modeling results need to be reviewed in more detail but will be presented in the future.

Safeguards measurements have not been added to the model yet. Fortunately, this work can leverage recent work on safeguards and process monitoring for pyroprocessing, so many of the same measurement technologies can be used. The models for these measurements as well as the material balance calculations exist in other SSPM models.

It is hoped that this work can be linked with on-going work at Oak Ridge National Laboratory to provide more realistic depletion calculations. This may involve updating cross-section libraries or directly linking to the ChemTriton depletion and transport code [6].

CONCLUSION

A preliminary MSR safeguards model has been generated in the Matlab Simulink platform. The model is designed for liquid-fueled designs with on-site salt processing. The work in this past year focused on building the base of the model and correctly modeling flow rates, depletion, and decay. Future work will need to verify those calculations and add in the safeguards aspects to the model.

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