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DEVELOPING A MOLTEN SALT REACTOR SAFEGUARDS MODEL

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Abstract

Molten Salt Reactor (MSR) designs can be significantly different from a typical light water reactor. Current designs include solid fuelled cores with molten salt coolants, liquid fuelled drop-in core designs, and liquid-fuelled designs with on-site salt reprocessing. The liquid-fuelled designs in particular have unique materials accountancy challenges. Safeguards requirements for light water reactors are based on item accounting and containment and surveillance since the fuel assemblies are discrete entities. MSRs may have materials accountancy requirements similar to bulk processing facilities. In this work, a material tracking and safeguards model of a MSR was developed in order to better understand safeguards needs and develop initial materials accountancy system designs. The model is built using Matlab Simulink and is linked to the SCALE code to calculate depletion and decay at various points in the reactor salt loop as needed. This paper presents the modelling philosophy and technical challenges. Initial results will be presented, but more detailed analysis will be required before safeguards approaches can be considered.

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I. INTRODUCTION

Recently, there have been a number of new vendors developing Molten Salt Reactors (MSRs) for commercial deployment. Of all the advanced reactors types, MSR designs vary the most since they can include liquid-fuelled molten salt cooled designs with solid fuel. As such there are various safeguards challenges depending on the design. The purpose of this work is to develop a modelling capability to evaluate materials accountancy approaches for MSRs.

II. BACKGROUND

Several variations of MSR designs exist, but they generally fall into three categories: liquid-fuelled designs with full on-site salt processing, drop-in liquid-fuelled core designs with limited on-site salt processing, and solid fuelled designs that use a molten salt coolant.

The first category are MSRs with liquid-fuelled cores and full on-site processing of the salt. These designs stem from the work on the Molten Salt Reactor Experiment (MSRE) 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 sampling and destructive analysis. The processing loops are similar to reprocessing plants, and in particular pyroprocessing salts.

The second category of MSRs are liquid-fuelled 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. One advantage of this design is to reduce the risk of neutron damage to 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-fuelled 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 obtaining large numbers of pebbles to get enough material for a significant quantity makes theft unrealistic.

This work is initially focused on modelling liquid-fuelled designs with on-site processing since they pose the greatest safeguards challenges. Future work will examine liquid-fuelled drop-in core designs based on lessons learned from this work.

III. MODELLING APPROACH

The MSR 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, and is 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 calculations.

A key challenge of this work has been to correctly model the changing isotopic and elemental inventories as a function of time. Linking with ORIGEN provided a starting point upon which to build the rest of the model, but future work will integrate with more mature modelling efforts at Oak Ridge National Laboratory [6]. The work to date has focused on modelling the elemental and isotopic flows and inventories, but future work will add in various safeguards elements.

The MSR design and flowsheet that was used for the 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-fuelled, 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 modelled (for simplicity) and because the flow rate is so large compared to the chemical processing loop. However, it is taken into account in the reactor model and in determining 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. The fuel salt is then 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-fuelling.

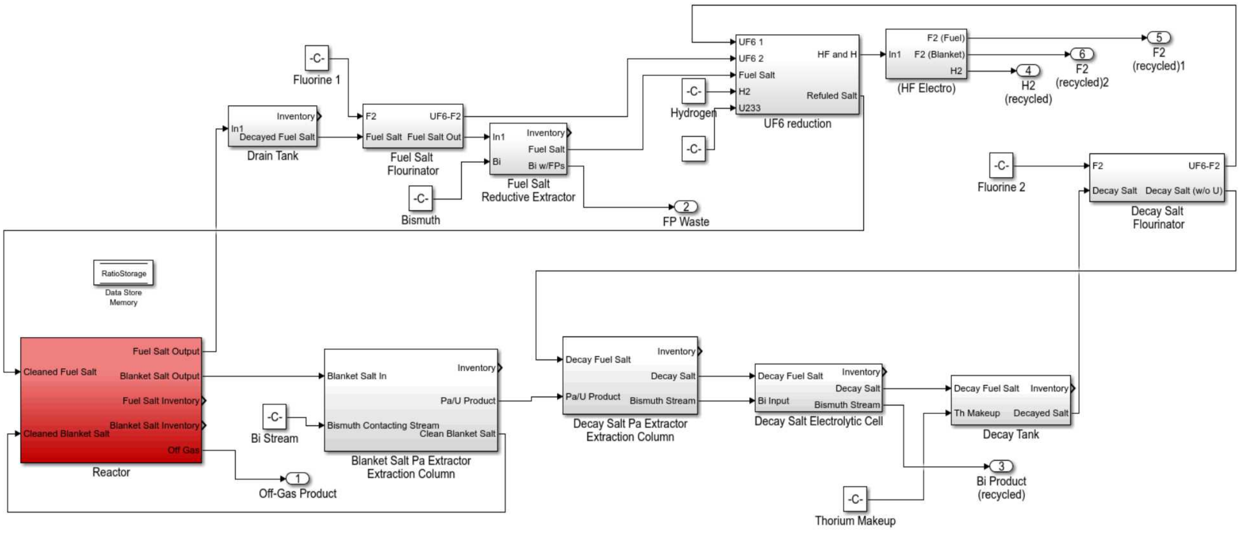

Figure 1. Molten Salt Reactor Safeguards Model

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. These are described more in the following section.

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.

Starting with the blanket salt output, in the Blanket Salt Pa Extraction Column, the blanket salt is contacted with a metallic Bi stream that contains Th. The extraction essentially removes any Pa and U from the blanket salt and replaces it with Th. The Pa and U are then in the metallic state in the Bi stream. The cleaned and re-fuelled blanket salt is returned to the reactor.

The Decay Salt Pa Extraction Column and the Decay Salt Electrolytic Cell extract the Pa and U back into the decay salt and keep any Th in the metallic Bi stream. The decay salt with Pa and U then goes to the decay tank.

The decay tank provides enough time for most of the Pa to decay to U, and the U is then transferred to the fuel salt loop in the Decay Salt Fluorinator. The decay tank is also where fresh Th is added to the blanket—it ultimately gets transferred to the Bi stream which re-fuels the blanket in the Blanket Salt Pa Extraction Column.

Moving up to the fuel salt loop, the Drain Tank is used to allow time for short-lived species to decay. The slightly-cooled fuel salt goes to the Fuel Salt Fluorinator which temporarily removes U.

The fuel salt is then contacted with metallic Bi in the Fuel Salt Reductive Extractor to remove fission products as a waste.

The cleaned fuel salt, the temporarily removed U, and the U-233 from the blanket salt are combined in the UF6 Reduction vessel and then returned to the reactor.

The loops also contain chemical reactors that use hydrogen and fluorine gas for various steps. The model does not track specific chemicals, instead it tracks the total elemental quantities in each stream.

Drain and Decay Tanks

The drain tank contains fuel salt that needs to decay before further processing. The fuel salt decays to reduce the short-lived (and high thermal output) fission product concentration. The material residence time in the drain tank is approximately 30 days.

The decay tank contains blanket salt and allows time for the Pa-233 to decay to U-233 which is later used as fuel. The material residence time in the decay tank is approximately 100 days, which provides enough time for four half-lives.

Both decay tanks are modelled 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.

Modelling 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. The changing input fuel is approximated by modelling the tank in 10 “slices” as seen in Figure 3. Initially, the decay tank is assumed to contain 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 1/10th of the tank volume or one “slice”.

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.

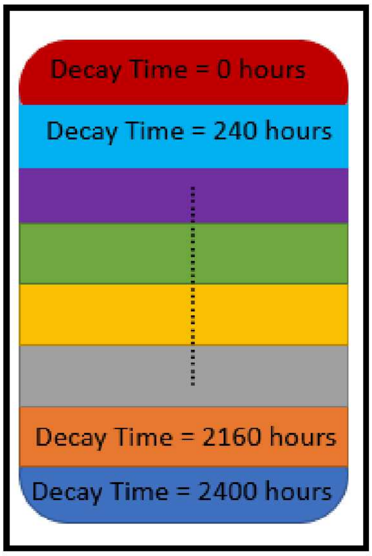

Fig 3. Decay tank inventory

To summarize, the reactor subsystem and drain and decay tank subsystems are the more complex areas of the model. The calls to ORIGEN to calculate the depletion or decay calculations require the most computational time. The separations of elements in the salt processing loops is relatively straight-forward in comparison. The following sections describes the current status of the model and some preliminary results.

IV. CURRENT MODEL STATUS

Currently the model is generating useful results. The model has been balanced so that the actinide levels reach steady-state. Figure 4 shows the modelling results for the protactinium content in the blanket salt as a function of time. It takes on the order of ten days or so for the content to stabilize after start-up of the reactor.

The fission products build up considerably in the fuel salt, which is expected since only a small slip stream of the fuel salt is processed. Figure 5 shows the build-up of cesium in the fuel salt—even after 4000 hours the reactor is not in a steady-state condition. The acceptable build-up levels of fission products will be determined based on the effect on core neutronics and heat load. In future design work, the volume of the salt processing loop can be changed to accommodate design requirements.

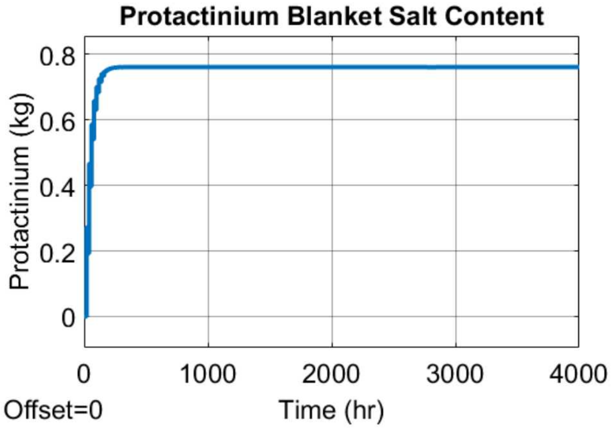

Fig 4. Protactinium Content in the Blanket

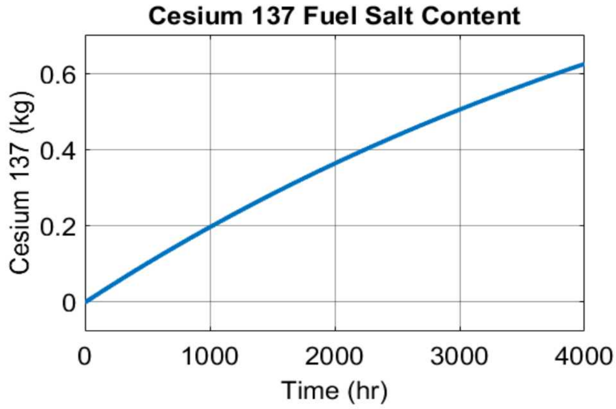

Fig 5. Cesium Content in the Fuel Salt

The xenon content in the fuel salt was also examined since it is important to minimize this poison. Since the xenon is removed in the main fuel salt heat transfer loop, considerably more is removed as a function of time, and it reaches a steady-state condition sooner. Figure 6 shows the xenon content as a function of time—by about 3000 hours, the xenon is near a steady-state condition.

One challenge with the modelling is that the external calls to ORIGEN lead to significant computational times. Several hours are required to model one year of operation. Steady-state conditions in a MSR that occur after several years may take 24 hours of run time.

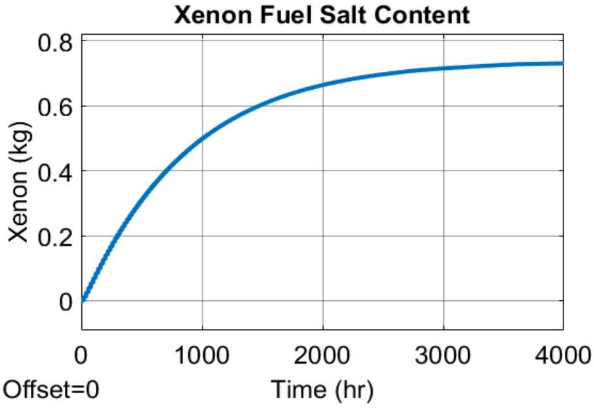

Fig 6. Xenon Content in the Fuel Salt

In the next year, safeguards measurements will be added to the model. Fortunately, past work on safeguards and process monitoring measurements for pyroprocessing can be leveraged since pyroprocessing facilities also work with molten salts. Particular attention will be focused on materials accountancy requirements, which may be undefined for a liquid-fuelled reactor. 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].

V. CONCLUSION

A preliminary MSR safeguards model has been generated in the Matlab Simulink platform. The model is designed for liquid-fuelled designs with on-site salt processing. The work in this past year focused on building the base of the model and correctly modelling flow rates, depletion, and decay. Future work will either use more robust code results from Oak Ridge National Laboratory or verify the existing calculations. The ultimate purpose of this work is to model the safeguards systems, so future work will add in safeguards and process monitoring measurements and propose preliminary safeguards system designs.

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Nomenclature

LFTR	Liquid Fluoride Thorium Reactor
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
ORIGEN	Oak Ridge Isotopic Generation
SCALE	Standardized Computer Analysis for Licensing Evaluations
SSPM	Separation and Safeguards Performance Model
TRISO	Tri-Isotropic

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