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Simple Flexible Molten Salt Reactor

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Simple Flexible Molten Salt Reactor (SF-MSR) Full Report

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1 Introduction:

Molten salt reactors (MSRs) with liquid fuel have several features which make them useful as next generation reactors. Some of these features include increased safety due to lower operating pressures, improved grid incorporation via solar salt thermal storage, and the potential of adding spent fuel actinides in the fuel. Because of the useful features of the MSR design, analyzing the different aspects of a MSR is of particular interest. A MSR design which is both simple and flexible would allow for analysis of different important aspects of MSRs.

This project is meant to propose a way to design and implement a Simple Flexible Molten Salt Reactor (SF-MSR). It includes possible core designs, neutronics, a dynamic model, safeguards, and an economic model that takes into account other power production methods such as solar energy. Due to SF-MSRs not being used commercially, there are no current binding regulations and standards. Currently, there is only a draft regulation, ANS 20.2. In order to demonstrate the viability of SF-MSRs, this project will use a prospective design similar to one from ThorCon as a model for developing neutronics, a dynamic model, safeguards, and a cost model.

2 Approach:

The work for this project was divided into four parts: neutronics, dynamic model, economic model, and safeguards. Luke Seifert is responsible for the neutronics, Jackson Breakell (Team lead) is responsible for the dynamic model, Alexander Boettinger is responsible for the economic model, and Patrick Wooden is responsible for the safeguards.

2.1 Neutronics Model:

The neutronics model was developed by taking data from the ThorCon Executive Summary [1] and using code structure from previous work by Dr. Chvala [3], along with a combination of Serpent and Python codes, to develop a deck builder to provide multiple similar models based on the same design [2]. The model uses a default fuel salt of NaF-BeF_2-ThF_4-UF_4 (76/12/9.5/2.5) with a uranium enrichment of 25%, though the Advanced Reactor Information System (ARIS) source which deals with the ThorCon reactor shows 19.7% enrichment [6]. The model input variations include temperature variation of the fuel salt and graphite, density variation of the fuel salt, and burnup of the fuel salt. Incorporation of these variations allow for various desired outputs to be retrieved including fuel temperature feedback, fuel void feedback, graphite temperature feedback, multiplication factor, precursor decay constants, and delayed neutron fractions. These values can be determined at various combinations of input values to be used in the dynamic model. The scheduling for how this work was accomplished can be seen in Table 2.1.1.

It can be seen in the table that the reprocessing and fuel cycles milestone was not completed. This is because it was found that the branch functionality in Serpent which allowed the computing time to be reduced significantly is incompatible with the reprocessing flows. This means that a large amount of restructuring is necessary in order to account for this, as well as a large amount of time to rerun the code. Unfortunately, the amount of time necessary to complete this milestone is too much, and it was incomplete. The fuel cycles portion was not complete because the reprocessing was given priority over it, since the feedback coefficients over burnup needed reprocessing to resemble reality.

Table 2.1.1: Neutronics Model Schedule		
Milestone	Due Date and Status	Description
Model Geometry	2020-02-01 Completed	Model geometry is functional and complete.
Useful Outputs	2020-03-01 Completed	Model outputs multiplication constant, precursor decay constants, and delayed neutron fractions.
Feedback Outputs	2020-04-01 Completed	Model outputs provide feedback coefficients.
Reprocessing and Alternate Fuel Cycles	2020-04-20 Incomplete	Model incorporates offgas, refueling, and fuel types for the initial and refueling fuel salt.

The model is designed with future updates in mind, as the current reprocessing feature is designed to have the added fuel be unique from the starting fuel. The makeup fuel in the reprocessing function is planned to be NaF-BeF_2-UF_4 (76/12/12) by default, but can be customized by the user [6]. The exact enrichment of the makeup fuel is not known yet, since the ARIS source displays it as 19.7%, the same as the startup fuel.

2.2 Dynamic Model:

The dynamic model was adapted from previous work by graduate students to fit the parameters of the Thorcon power plant design [7]. This required significant changes to be made to the model, requiring a lengthy period of rebuilding and debugging of the model. Using MATLAB/Simulink software, the parameters and system itself were edited to allow testing the effects of reactivity and load-following transients on system temperature and stability. Specifically studied are the temperatures of the coolant loops and neutronic power during a random load-following power transient and hard reactivity ramp insertions. The model contains: PKE's for the core that were modified to account for the use of liquid fuel, (including precursor drift), heat transfer for the core, primary heat exchanger, secondary heat exchanger, and limited steam generator.

Table 2.2.1: Dynamic Model Schedule		
Milestone	Due Date	Description
Edit primary coolant loop	2020-01-28 Completed 2020-01-21	Reconfiguring Core and PHX systems in Simulink and parameters in MATLAB
Edit secondary coolant loop	2020-02-18 Completed 2020-02-14	Reconfiguring SHX and SG systems in Simulink and parameters in MATLAB
Rebuild/Debugging	2020-04-8 Completed 2020-04-8	Certify model accuracy and functionality through generation of sample results after thorough rebuild and debug task
Generate final results	2020-04-16 Completed 2020-04-16	Create plots that observe the systems reaction to certain specified transients

2.3 Economic Model:

The goal of the economic model is to determine the commercial viability of a SF-MSR, especially with increasing grid contributions from renewables such as solar energy. A few basic assumptions were made in developing the model. These include that the SF-MSR costs are comparable to those proposed by ThorCon in their Executive Summary [1], prices for repeating costs remain constant throughout the lifetime of the SF-MSR, and inflation is ignored. All parts of the model were developed in Python. The model works in three parts. First, a lifetime cost profile that is scalable with grid demand is made using ThorCon price estimates. This is done to show how various items affect the total MSR costs, the effects of large initial loans, and to serve as a basis for calculating the supply curve. Second, the effects on ramp rates and thermal storage need from increasing solar contributions is modelled. This is modelled because solar energy production follows a sine function and, at large levels, can significantly change the shape of the daily demand curve. Finally, a supply curve is developed to show how grid demand and various solar contributions affect power pricing. The work breakdown is shown in Table 2.3.1.

Table 2.3.1: Economic Model Schedule

Milestone	Due Date	Description
Complete Scalable Cost Model/ Lifetime Costs Model	2020-02-21 Completed 2020-02-21	Finish Python script that calculates lifetime costs of a Thorcon reactor while taking into account thermal storage needs and the periodic nature of some costs.
Complete Ramp Rate and Excess Energy vs Solar Contribution Model	2020-02-21 Completed 2020-02-21	Modify Dr. Chvala's plant sizing code to create ramp rate vs solar contribution curves at various grid sizes.
Complete Price vs Solar Contribution Model	2020-04-03 Completed 2020-02-21	Finish code that calculates changes in power prices based on different levels of solar contribution.
Create Report on Describing Entire Model	2020-04-08 Completed 2020-04-06	Create a report detailing all the developed code, add sample results, and recommend future work that can improve the model.

2.4 Safeguards:

The goal of developing safeguards for this type of facility is to formulate ways to operate a facility with a MSR in such a way to satisfy the IAEA's Non-Proliferation Treaty (NPT) and Additional Protocol (AP). By implementing these standards directly into the design of the facility, this allows for the MSR to much more easily reach an international market. This means that this reactor design could be built in facilities that are not already in registered weapon states. In order for these places to build such a facility, they must satisfy both the NPT and AP, so by implementing these safeguards by design allows such states to gain the ability to build a facility more easily. The significant quantity analysis, however, was not able to be completed on time, as there was not enough time to calculate the different significant quantities that were needed to expand upon in the paper.

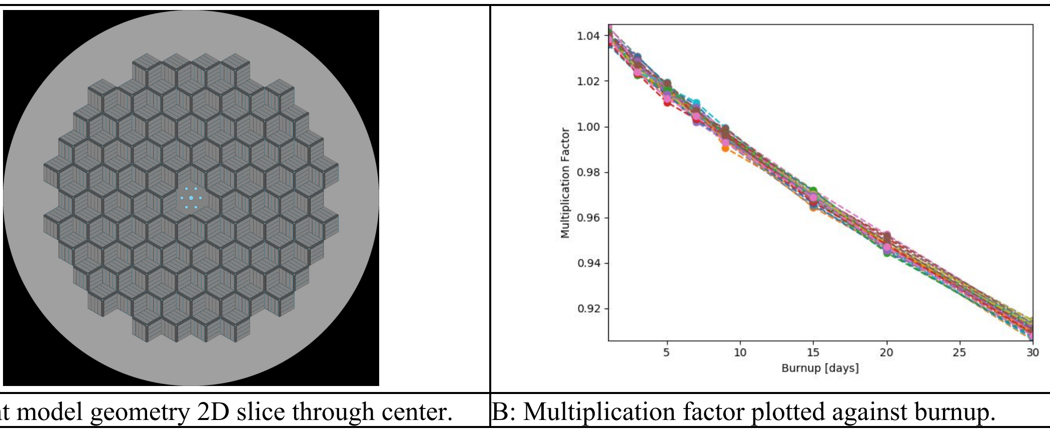
Table 2.4.1: Safeguards Schedule

Milestone	Due Date	Description
Complete First Draft of Plan for Safeguards	2020-02-21 Completed 2020-02-21	Develop the basic flow of nuclear material through a MSR facility enough to formulate a basic plan for implementing safeguards

Create Draft of Paper Documenting Safeguards Plan	2020-02-28 Completed 2020-03-06	Formulate a paper that breaks down each element of designing the safeguards, with leading sections defining safeguards and their importance
Design Method(s) to Effectively Communicate Safeguards	2020-04-03 Completed 2020-04-01	Develop images to show the general idea of the safeguards in order to easily communicate the premise of the plan
Update the Paper to Implement Images & Significant Quantities	2020-04-20 Incomplete	Introduce the developed methods into the paper to better communicate the safeguards plan; include an analysis of significant quantities, if possible

3.1 Neutronics Results:

The results of the neutronics model are the Serpent model and the data from the particular cases analyzed. The Serpent model is shown in Figure 3.1.1a. It can be adapted to use different fuel salts, temperatures, densities, moderating materials, control rod diameters, safety rod diameters, and more. It is also designed to be easily customized by the lattice-based design, as any log in the model can be replaced by a different one. It is planned to be easily customizable in the reprocessing as well, where the user can select one of several different makeup salts to be incorporated in the reprocessing function.



A: Serpent model geometry 2D slice through center.

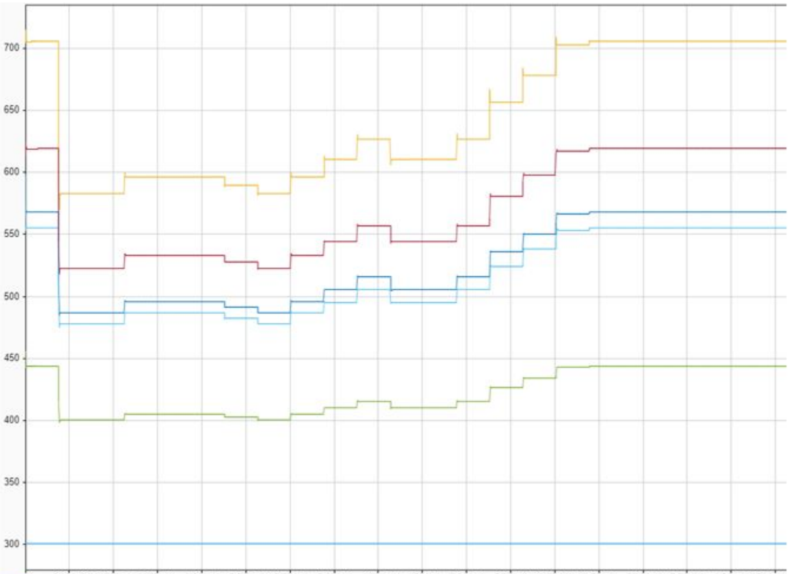
B: Multiplication factor plotted against burnup.

Figure 3.1.1.

The point of interest for the dynamic model is at a fuel salt temperature of 907.15 K, so the data from that point was collected. Gifs were created which would display the different data points at temperatures near the temperature of interest at various burnup values. An example plot showing all frames of a gif is shown in Figure 3.1.1b. This is a plot of the multiplication factor plotted against time without reprocessing. Each color represents a different state of the system with a unique combination of fuel temperature, fuel density, and graphite temperature. In this case, there are three variations for each, meaning there are 27 unique variations displayed. The different points are at fuel and graphite temperatures of 902.15 K, 907.15 K, and 912.15 K, and densities at the fuel salt densities which correspond to the associated fuel salt temperatures.

3.2 Dynamic Model Results:

One primary result that was desired from the development of the dynamic model is the system behavior regarding a load-following transient. For these results, the loop temperatures were recorded over a simulation time of an entire 24 hour day in response to a custom load following program that was developed using data from German commercial nuclear power plants [5]. The corresponding thermal power output in megawatts was calculated using these temperatures in Equation 1, $Q_{dot} = m_{dot} * c_p * \Delta T$, in an excel spreadsheet. This equation was also useful in the rebuild/debug phase of the dynamic model development to guarantee the proper power output and heat transfer functionality. This run features PKE and feedback values from the neutronics model at 1 day of burnup. Figure 3.2.1 shows loop temperature in Celsius and time in seconds (24 hours total).



🟨	Primary salt outlet temperature
🟦	Primary salt inlet temperature
🟥	Secondary salt outlet temperature
🟩	Secondary salt inlet temperature
🟦	Tertiary salt outlet temperature
🟦	Tertiary salt inlet temperature

Figure 3.2.1
System loop temperatures (Celsius) as a function of time (seconds)

24-hour weekday load approximated using https://www.oecd-nea.org/nea-news/2011/29-2/nea-news-29-2-load-following-e.pdf

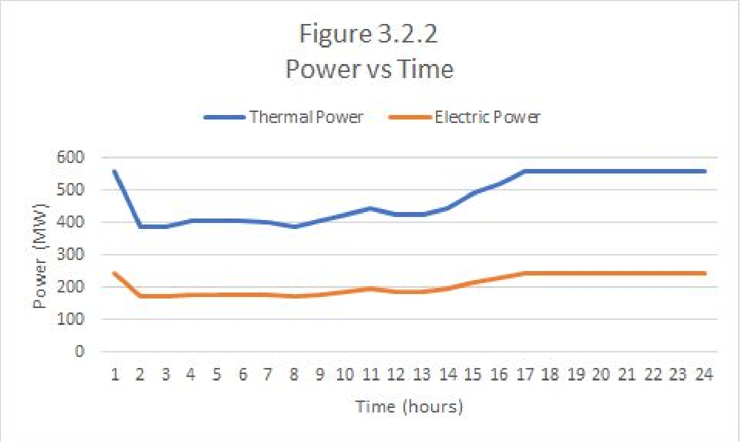
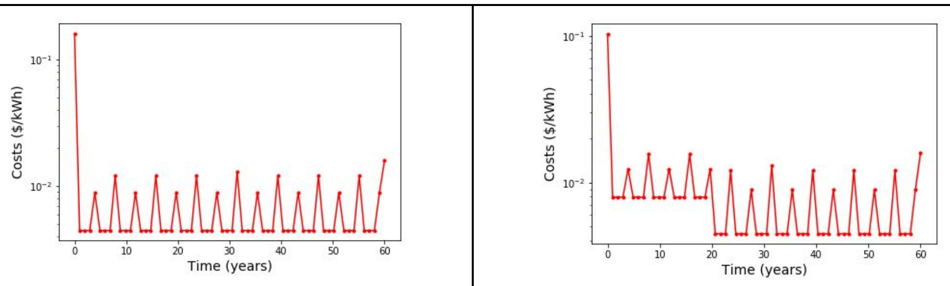


Figure 3.2.2
Power vs Time

Results from Figure 3.2.1 show the change in system loop temperatures are rapid and stepwise. This is due to the insertion of negative reactivity into the system to achieve lower power levels that are needed throughout the day. In reality, these steps would resemble ramps and would occur more slowly as control rods or feedwater is adjusted by grid demand or operator control. Figure 3.2.2 was calculated using the loop temperature values and Equation 1 to show the reactor thermal power output in megawatts during the full day. Also included in Figure 3.2.2 is the electric power provided in megawatts using Thorcon's projected thermal efficiency of 44% [1]. Additionally, the fuel and graphite temperature feedbacks that used in the model were produced from the neutronics model mentioned earlier. These results indicate a fast and stable response to the commercial reactor load-following transient and loop temperatures that are acceptable and within design criteria.

3.3 Economic Model Results:

As shown from Table 2.3.1, all milestones were completed on schedule. Two sample lifetime cost profiles for a 1000 MWe plant are shown in Figure 3.3.1. Figure 3.3.1a shows the lifetime cost profile of a MSR with costs similar to those found in the ThorCon Executive Summary. The peaks in the graph are due to can replacements every four years, primary salt (fuel salt) replacement every eight years, and secondary and thermal storage salt replacement every 32 years. Figure 3.3.1b represents the same MSR but with a large initial loan. The elevation of costs during the first 20 years is due to loan payments. Both cost profiles show that the vast majority of costs are the initial costs of building the facility. Financing the facility with a loan can significantly ease the initial cost burden while not significantly reducing the total cost profile as shown in Figure 3.3.1b.

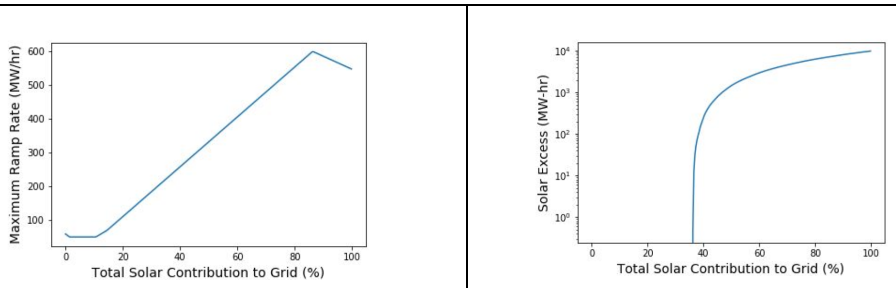


A: Default ThorCon parameters, no loan.

B: Lifetime Cost Profile: Default ThorCon parameters, 20 year, $500 million loan at 2%.

Figure 3.3.1: Scalable Lifetime Cost Model.

The ramp rate and excess power production as functions of solar contribution for a 1000 MWe grid are shown in Figure 3.3.2. From Figure 3.3.2a, it is apparent that small levels of solar contribution can decrease maximum ramp rates. However, at levels above 10.3% total contribution, the ramp rates drastically increase. In regards to excess energy production, there is none up until the solar is 36.2% of the peak power demand. Any increases in solar contributions will lead to drastic increases in excess energy production.



A: Maximum ramp rate.

B: Storage needs for excess solar energy.

Figure 3.3.2: Effects of Increasing Solar Contribution.

Figure Figure 3.3.3 shows some sample supply curves for power production with total solar contributions of 0%, 10%, and 20%. At low grid demands, the costs of power production are very similar. At higher demands, power production becomes cheaper, especially at smaller solar contributions.

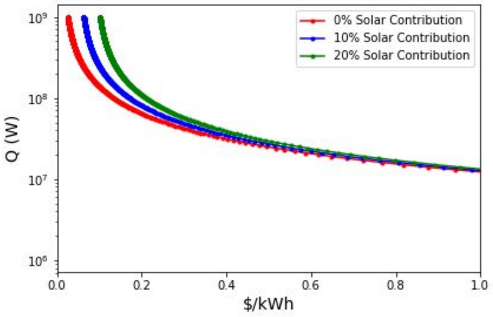


Figure 3.3.3: Supply vs Price Curve.

3.4 Safeguards Results:

The results formed for safeguards would be the plan formulated to implement them in a MSR facility similar to the one the reactor being designed would exist in.

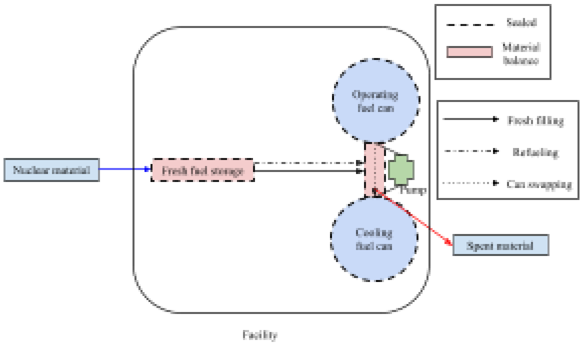


Figure 3.4.1: Nuclear Material Flow & Balance Model

This model is designed to show both the nuclear material flow through the facility and the general layout for material balance in regards to safeguards. Since we are not renovating existing reactors, a particular advantage we can utilize is safeguards by design [4]. The model includes the main points of interest, such as the material balance areas and the fuel cans. The most effective way to implement safeguards for such a facility were to setup material balance in both the area where fresh fuel would be introduced and stored in the facility, and also in an area that could pump both the operating and cooling cans, as it makes up almost all of the material flow outside of the material entering or exiting the facility. This is also where the spent material is pumped out of the cooling can and packaged to be sent out.

4.0 Conclusions and Future Work:

At the beginning of cycle, with a uranium enrichment of 25%, and at the defined temperature, the feedback coefficients are negative and the multiplication constant is approximately 1.01. These are good parameters to have, but to get more accurate data further into the burnup cycle, reprocessing will need to be incorporated. The dynamic model results show a stable, easily controllable reactor that has very predictable heat transfer properties that would be excellent for use as a commercial power plant. The average price per kWh from a SF-MSR can be made to be around $0.10 and large loans can be used to significantly reduce the initial financial burden without significantly increasing average price. Increasing grid solar contributions can drastically increase ramp rates and thermal storage needs. This will result in increased costs due to increased wear on machinery and thermal storage needs. Economies of scale have a significant impact on reducing the costs of SF-MSR power production. Utilizing liquid fuel can make for difficult material accountability, but this can be minimized by applying safeguards by design. Historically, safeguards can be difficult to implement due to the fact they were typically retroactively implemented on facilities that were already running before they were required. However, by incorporating these requirements for safeguards directly into how the layout of the facility is designed, this will make the process of satisfying the Non-Proliferation Treaty and Additional Protocol for the IAEA much simpler.

Future work for the neutronics model includes alternate fuel cycles and reprocessing. For the dynamic model, fully incorporating the steam turbine and generator in the model would provide useful data about plant thermodynamics. Additionally, incorporating burnup dependent feedback and PKE constants in the parameters would allow dynamic analysis over the entire fuel cycle. Future economic model work includes updated turbine and generator costs, periodic machinery replacement and maintenance costs, effects of inflation, and a more robust calculation of costs associated with solar power production. Currently, the turbine and generator costs are represented by placeholder values, some machinery is not replaced, inflation is not included, and solar costs are represented by production and land costs. Future work for the safeguards portion of this project would be to do a significant quantity analysis of the fuel that would be used in the MSR, or the quantity of the fuel that is considered significant for timely detection for various fuel cycles with different uranium and plutonium fractions.

5.0 References:

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