

# Study of cooling requirements in the fertile blanket and the freeze-plugs of the MSFR

by

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# Abstract

Nuclear energy has endured a questionable reputation for decades. The main criticisms it received have been related to reactor safety and the production of nuclear waste. While all safety is relative and nuclear waste is inherent to nuclear power production the Molten Salt Reactor (MSR) has the means to take away a lot of concern.

MSRs cannot experience meltdown scenarios, and have passive built in safety mechanisms that will activate in the event of excess temperatures. This safety is assured by freeze plugs, which this thesis has examined. At the same time, MSRs do not only produce less waste, but also less long-lived waste. These features could lead to nuclear energy being reconsidered as a viable alternative in the battle against climate change.

The Molten Salt Fast Reactor is a generation IV nuclear fission reactor with breeding capabilities. It is the subject of the SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor) project, which this research is part of. This thesis aims at investigating how large the heat production in the blanket and plug regions of the MSFR is in order to quantify their cooling requirements. Nuclear simulations were done in order to find out how large the neutron flux was in the regions under assessment. The acquired data was subsequently used to simulate the composition of the blanket and plug, using MATLAB.

Results show that the heat production in the blanket can be approximately 46 MW for a refresh rate of 40 L/day, of which 36.3 MW is due to fission events, and 8.03 MW due to radiative capture events. These figures are somewhat different than the earlier described in the SAMOFAR project, namely 7 MW for fission and 24 MW for capture.

The heat production in the plug is strongly correlated with the depth at which the plug is placed. Simulation shows that it can vary between 13.8 kW per m<sup>3</sup> at a depth of 3 cm, to negligibly small at a depth of 30 cm. This heat production is several orders of magnitude smaller than what earlier research has suggested for cooling due to the flow of molten salt over the plug, so additional cooling to account for the nuclear reactions within the plugs is not necessary.



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# Introduction

This research project focuses on the Molten Salt Fast Reactor (MSFR), which is a variant on the Molten Salt Reactor (MSR) concept. This is one of the six types of nuclear reactors proposed by the Generation IV International Forum, which aims to map out the developmental options for nuclear energy in the 21<sup>st</sup> century [9]. The MSR is of particular interest because it possesses several characteristics that make it an interesting option for nuclear energy production.

Nuclear energy has endured a questionable reputation for decades. The main criticisms its received have been related to reactor safety and the production of nuclear waste. While all safety is relative and nuclear waste is inherent to nuclear power production the MSR has the means to take away a lot of concern.

MSRs cannot experience meltdown scenarios, and have passive built in safety mechanisms that will activate in the event of excess temperatures. This safety is assured by freeze plugs, which this thesis has examined. At the same time, MSRs do not only produce less waste, but also less long-lived waste. These features could lead to nuclear energy being reconsidered as a viable alternative in the battle against climate change.

## 1.1. Characteristics of the MSR

As its name suggests, the operational medium of the MSR is molten fluoride salts. These salts are solvents for fluorinated actinides (thorium, uranium, plutonium etc.). What this means is that the molten salt concept allows for a liquid nuclear reactor fuel, compared to conventional reactors which operate using a solid fuel in pellets. The advantages of operating a liquid core are numerous, among which is online reprocessing, allowing for the removal of fission products during operations. Common choices for the fluoride salts are LiF-BeF<sub>2</sub> (FLiBe) or LiF-NaF-KF (FLiNaK) due to their limited impact on the neutron economy and low melting point.

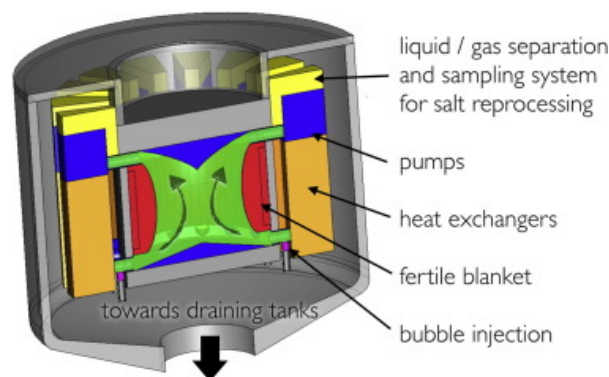


Figure 1.1: A vertical cross section of an MSFR [1]

The design of the MSR is given in Figure 1.1. Nuclear reactions take place primarily in the core region indicated in green. As nuclear fission takes place, the liquid fuel starts to heat and is subsequently guided towards the heat exchangers by use of a pump. This causes the reactor to exhibit a continuous flow during

operation, in which energy is generated in the centre of the core and extracted at its outer bounds. The other indicated regions are the bubbling system, a mechanism used to extract fission products from the core by using helium bubbles to carry the fission precipitates out of the core at the liquid/gas separation unit; the fertile blanket, a region at the boundaries of the core designed to capture the neutrons generated in order to produce new, fissile fuel from the fertile material contained within it (Th-232/U-238).

If operated properly, this reactor does not require any significant downtime as it can be refueled and refreshed during regular operations.

### 1.1.1. MSFR properties

This project has examined the specific situation of the MSFR reference model, as defined by the SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor) project [10]. The SAMOFAR project is an initiative by several European institutes seeking to prove the safety features of the MSFR and create a design to guide development of the MSFR.

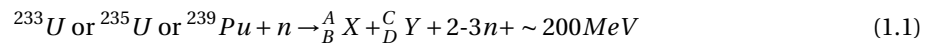
The 'Fast' in MSFR relates to its fast (or high energy) neutron spectrum. This is in contrast with most reactors, which run on a thermal (or low energy) spectrum. The neutron spectrum refers to the 'temperature' of the neutrons, or more accurately, their kinetic energy. When neutrons have a higher energy, their velocity will be larger (scaling with the square root of their kinetic energy) which has a significant impact on the type and rate of interactions it will encounter in a nuclear reactor.

The MSFR can be classified as a fast-breeder, meaning it is a nuclear reactor with a fast spectrum that can be used to breed fissile material. Breeding is a process in which the amount of fissile fuel generated will be larger than the amount initially used. They make use of fertile material, expose it to neutron flux and extract the newly bred fissile material.

The breeding process is a great concept because it does not require a large amount of enriched uranium but instead runs on fertile isotopes like thorium 232 and uranium 238 which are incredibly more common in nature than the only natural fissile element on earth, uranium 235. There is around 3 times as much thorium as uranium in the earth's crust, and only 0.72% of natural uranium is uranium 235, thus there is more than 400 times as much thorium as there is uranium 235 [11]. What this means is access to a more plentiful source of nuclear fuel without the need for enrichment facilities.

### 1.1.2. Nuclear reactions

Energy generated in a nuclear reactor is the product of the fission reactions happening when a neutron is captured and splits the fissile isotope in two smaller isotopes, releasing energy and extra neutrons. This process is described in equation 1.1.



Because this reaction generates more neutrons than it consumes during fission, the remaining neutrons can be used to breed more fuel. The breeding reactions for Th-232 are given in equations 1.2.



Th-232 absorbs a neutron, becoming unstable, and subsequently decays twice into the fissile isotope U-233. Seeing as the cost of fission is one neutron, and the cost of breeding is another neutron, the total cost per reaction is two neutrons. Luckily, a fission of U-233 in the fast spectrum can yield an average of around 2.5 neutrons [12]. From this yield one still has to subtract inevitable losses due to capture in non-fissile or fertile materials, as well as leakage, but will still result in a bit more than 2 neutrons available per reaction; enough to sustain a chain.

### 1.1.3. Safety features

The MSR possesses multiple active and passive safety features that make it a safer alternative to traditional nuclear reactors. First of all, the biggest concern with current reactors is the potential of a meltdown scenario, in which the control over the reactor is lost, cooling stops and the reactor's solid core will melt. This scenario does not exist in MSRs seeing as the core is already liquid and thus cannot melt. If the core temperature

does significantly increase, its reaction rate will decay due to a negative feedback coefficient meaning the reactivity of the core decreases as temperature increases. Even though excessive core temperature does not pose an immediate threat to the operation, it will cause structural damage to the reactor vessel at extremely high temperatures. For this reason, it is desirable that the core is fully drained before it reaches 1200 °C [13].

In the event that control over the reactor is lost, a safety mechanism called the freeze plug will activate (Figure 1.2). The freeze plug is a mass of solidified salt, similar to the salt in the liquid core. It stays manually cooled during operations, and in a drainage event the cooling stops and the plug will melt. Along with it, the liquid core will drain out of the main vessel into a drain tank at the bottom of the structure, where it will gradually lose the decay heat from the fission products it contains.

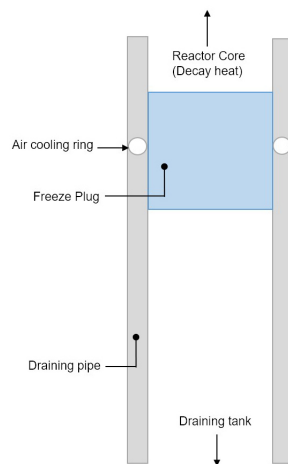


Figure 1.2: A schematic visualization of the freeze plug [2]

## 1.2. Research goals

The breeding process is the first major subject of this project. I have looked at how the breeding of new fuel in the fertile blanket of the reactor will effect the heat production within in (due to the decay of the fertile material) and thus how much cooling is required to compensate for this phenomenon. So, the first research question is:

*What is the magnitude of heat production in the fertile blanket due to nuclear reactions?*

The freeze plug is the second major subject of this project. In similar fashion I have examined the heat production within the freeze plug in order to quantify how much additional cooling power is required to keep the plug solidified. The second research question is:

*What is the magnitude of heat production in the freeze plug due to nuclear reactions?*

## 1.3. Thesis outline

The dimensions and properties of the MSFR are discussed in chapter 2, leading to a better understanding of how to interpret the research goals. Chapter 3 explains how nuclear reactions within the MSFR take place, and in what manner this is simulated. Chapter 4 processes the information from the simulations and presents the results along with their implications. Chapter 5 will draw conclusions and look at possible further research into this subject.



# 2

## Reactor specifications

As mentioned in chapter 1, this thesis looks at the SAMOFAR reference model. The design specifications of the reference model that have been established have been used in calculations and simulations in this project.

### 2.1. The core geometry

The MSFR core vessel consists of 16 identical regions, whose dimensions of which are given in Figure 2.1. The incline at the top and bottom of the vessel are due to the conical neutronic reflectors, currently not shown.

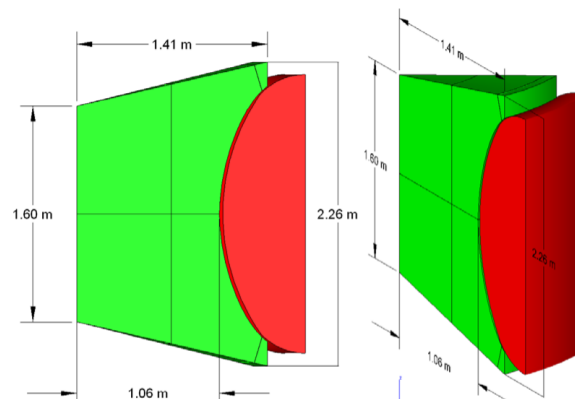


Figure 2.1: Dimensions of the active core. The green region corresponds to the fuel salt and the red region to the fertile blanket [3]

Each of these sectors is in turn connected to a pump at the top which leads to a heat-exchanger and then flows the cooled salt back to the bottom of the sector. This is the primary loop of the reactor. The core region is initially filled with a mixture of 75% LiF, 20% ThF<sub>4</sub> and 2.5% <sup>233</sup>UF<sub>4</sub> in order to get the fission chain started [14]. During nominal operations there is a continuous inflow of fissile material and an outflow of fission products. The properties of the liquid core are given in Table 2.1.

Volume of core fuel salt [m <sup>3</sup> ]	9
Initial composition	77.5% LiF, 20% ThF <sub>4</sub> and 2.5% <sup>233</sup> UF <sub>4</sub>
Density of salt at operating temp. of 650 °C [kg · m <sup>-3</sup> ]	4224
Power during steady state operations [MW <sub>th</sub> ]	3000

Table 2.1: The parameters of the liquid core

## 2.2. The fertile blanket

The fertile blanket is continuously refuelled and refreshed in order to maximize the amount of fertile material, and minimize the amount of fissile material. Its initial composition is largely similar to that of the core, but without any fissile material: 77.5% LiF and 22.5% ThF<sub>4</sub>. During reactor operations, the fertile blanket is exposed to the neutron flux of the core, causing several reactions to take place. These reactions include, but are not limited to

- the breeding of fissile fuel by means of neutron capture in thorium;
- fission of fissile isotopes that prematurely fission in the blanket;
- neutrons being captured in non-fertile actinides causing unwanted transmutations;
- neutrons being captured in non-actinides.

The goal of the blanket is to introduce new fertile material, have it absorb a neutron, let it decay twice and remove it from the blanket. This process is far from instantaneous, as shown in the decay chain in Figure 2.2.

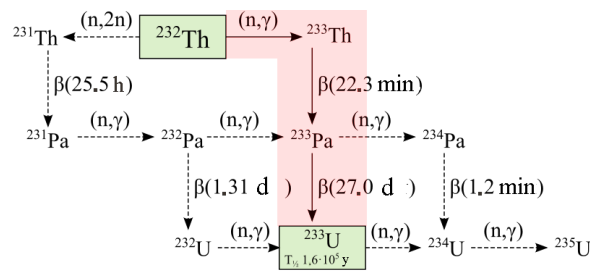


Figure 2.2: Possible ways to reach a fissile isotope from Th-232 [4]

After Th-232 absorbs a neutron, which is the most common type of reaction, Th-233 will subsequently decay twice into Pa-233 and U-233. The first decay takes approximately half an hour, and the second approximately 39 days.<sup>1</sup> Because of protactinium's relatively long decay time this will result in a build-up of protactinium in the blanket. This build-up can be problematic, as long term exposure to the neutron flux of the core can result in an extra neutron being captured, another beta decay occurring causing U-234 to be created. In order to make this isotope fissile, it needs to capture an additional neutron. This means it effectively cost two extra neutrons to produce a fissile isotope compared to Pa-233 decaying regularly. The extra neutron cost is bad for the neutron economy of the reactor, as it means less neutrons are available for other reactions.

Not only does the breeding process cause fissile isotopes, it also generates heat. This heat production is the result of both the radiative capture of neutrons as well as the beta decay energies.

Volume of blanket [m <sup>3</sup> ]	6-7
Initial composition	77.5% LiF and 22.5% ThF
Density of salt at operating temp. of 650 [kg · m <sup>-3</sup> ]°C	4224

Table 2.2: The parameters of the fertile blanket

In order to find out how much heat is being produced in the blanket, we need to know the composition of the blanket over time. This requires knowledge of the initial composition, the magnitude of neutron flux in the blanket region and the amount of in- and outflow of isotopes in the blanket.

The first piece of information is known, based on Table 2.2. One can calculate the mass of the blanket inventory using the density, and subsequently compute the amount of fertile <sup>232</sup>Th atoms present at  $t = 0$ . The second part, the neutron flux, will be discussed in Chapter 3. Lastly, the in- and outflow rate are fixed at 40L/day based on the specifications of the SAMOFAR project [1].

<sup>1</sup> Mean lifetime of unstable isotope:  $\langle t \rangle = \frac{t_{1/2}}{\ln 2}$

## 2.3. The freeze plug

A freeze plug is placed in each of the 16 regions of the reactor. The positioning of the plug has to be at the lowest point of the sector, to ensure that all the molten salt flows out of the core region in case of emergency. The properties of the freeze plug have been examined are reported in Table 2.3.

Diameter [cm]	20
Height [cm]	20
Composition	77.5% LiF, 20% ThF <sup>4</sup> and 2.5% <sup>233</sup> UF <sub>4</sub>
Temperature of salt in frozen state [K]	836 [15]
Density of salt in frozen state [kg·m <sup>-3</sup> ]	4296

Table 2.3: The parameters of the fertile blanket

Several previous studies were performed on the thermodynamic behaviour of the freeze plug. Shafer looked at influence of different designs on the melting time of the freeze plug [15], while Kamp did research on the cooling requirements of the freezeplug with respect to the heat transfer due to the flow of molten salt [5].

## 2.4. Previous research

The cooling requirements for the freeze plug were found to be 1.8 MW m<sup>-3</sup> [5]. However, this quantity was applicable to a slightly different freeze plug design, an example of which is given in figure 2.3.

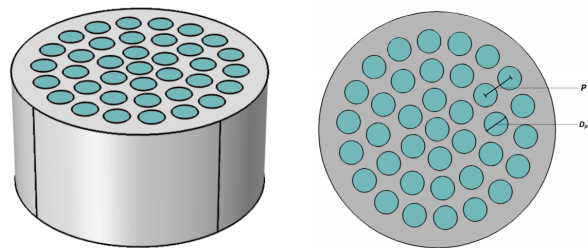


Figure 2.3: A grated freeze plug design [5][6]

Nonetheless it does indicate the order of magnitude that one might typically encounter when attempting to cool a freeze plug. It is a low estimate as well, as having a single large plug requires more cooling power due to the surface to volume ratio being smaller.

Earlier research in the SAMOFAR project has assigned a figure to the heat production within the blanket. What it found was a 7 MW production due to U-233 fission and 24 MW due to the radiative capture of Th-232 [1].





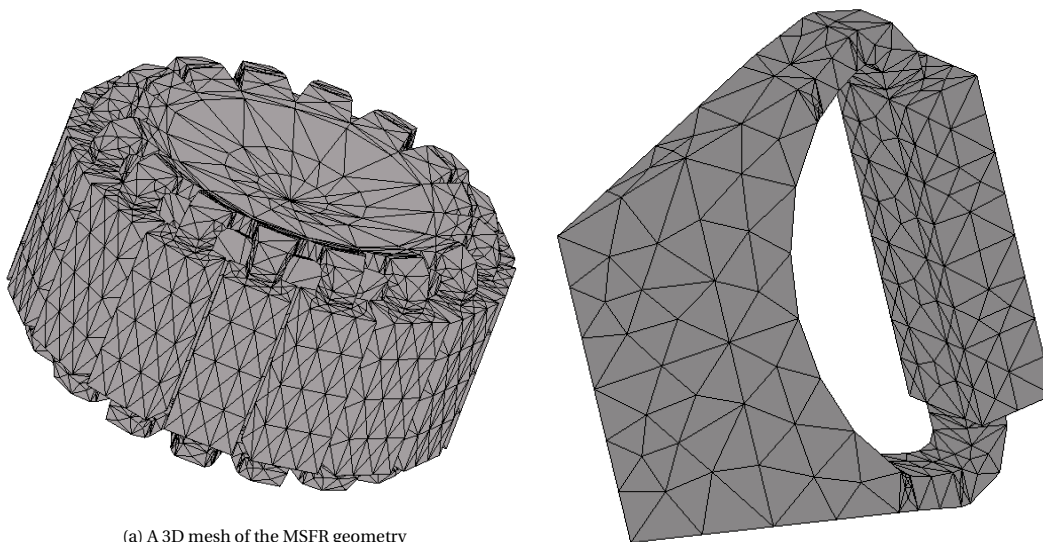
## Simulation Methods and Nuclear Physics

This chapter examines the physics behind the reactions that take place within the reactor, as well as what their implications for heat production are. Then, it explains how this knowledge can be used to perform simulations to quantify this behaviour.

To be able to calculate the amount of reactions that take place in each region of interest, it is required to perform radiation transport simulations. This is done using the in-house FORTRAN code of TU Delft's RPNM department: Phantom-SN. This code will calculate the fission and capture rates occurring in the reactor.

### 3.1. Mesh

The most important input to the simulation is the geometry of the reactor. This input is in the form of a three-dimensional mesh of the geometry. A 3D model of the MSFR was available to be used for the simulations at the beginning of this project (figure 3.1a) [7]. However, this geometry did not yet include the regions of interest for this project: the blanket and the freeze plug. It was also lacking the conical neutron reflectors at the top and bottom of the central core.



(a) A 3D mesh of the MSFR geometry

(b) A 3D mesh of a single sector

Figure 3.1: Meshes of the geometry [7]

I edited the mesh using Gmsh, a 3D finite element grid generator with CAD capabilities [16]. This program allowed me to isolate one of the 16 sectors (figure 3.1b) so I could adjust the geometry to include the blanket and freeze plug. Due to computational reasons, it was more convenient to simulate only a portion of the

reactor, and multiply the results by the fraction to receive the results of the full reactor. The symmetry of the reactor would allow this if reflective boundary conditions are applied.

After adjusting the mesh it was fit for simulation. The reason for this mesh being a quarter of the full loop will be explained in section 3.2. The new mesh is shown in Figure 3.2. For the chosen mesh coarseness it has around 22000 to 24000 tetrahedra, depending on the depth of the plug.

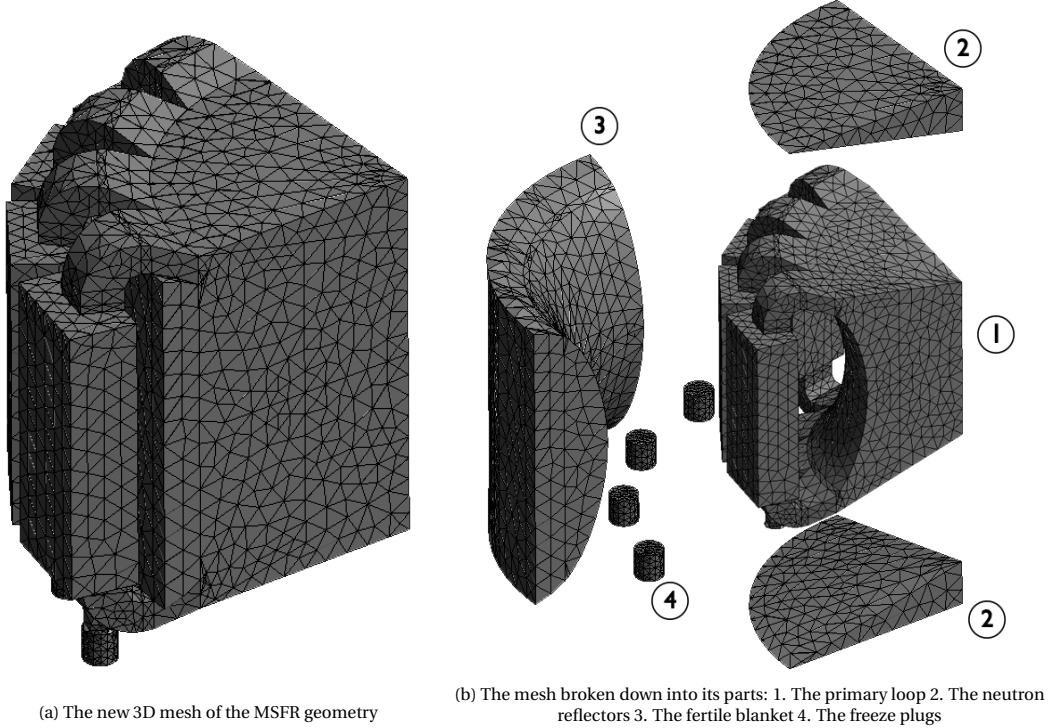


Figure 3.2: Meshes of the new geometry

What is worth noting on the new design is that the volume of the fertile blanket is slightly higher than initially specified. Since I followed the design specifications of the SAMOFAR reference model, the volume of the fertile blanket region is set at  $8.3 \text{ m}^3$ , more than the  $6\text{-}7 \text{ m}^3$  called for in Table 2.2.

### 3.2. Nuclear simulations

To understand how to properly use Phantom-SN, one has to know what problem it tries solves and how it does this. The behaviour of neutrons within a nuclear reactor is described by the neutron transport equation:

$$\frac{\partial n}{\partial t} + v \hat{\Omega} \cdot \nabla n + v \Sigma_t n(\vec{r}, E, \hat{\Omega}, t) = \int_{4\pi} \int_0^\infty dE' v' \Sigma(E' \rightarrow E, \hat{\Omega}' \rightarrow \hat{\Omega}) n(\vec{r}, E', \hat{\Omega}', t) + s(\vec{r}, E, \hat{\Omega}, t) \quad (3.1)$$

With angular neutron density  $n$ , neutron velocity  $v$ , solid angle  $\hat{\Omega}$ , total macroscopic cross section  $\Sigma_t$  and source term  $s$ . The problem is that the variables in these equations have angular dependence, and these angles are continuous.

The SN (actually  $S_N$ ) in Phantom-SN refers to the discrete ordinates method. This method discretizes the angles in the equation so one is left with a system of equations that can be solved. What this means in practice is that there is a finite set of angles at which the neutrons can reflect at certain interfaces. The implication of which is that when defining the boundaries of the volume for which you want to solve the transport equation, these boundaries must be placed at specific angles defined by the set of ordinates one uses. For the choice of ordinates in this simulation, the smallest angle that could accommodate this was  $90^\circ$ . This corresponds to a quarter of the full reactor; so 4 sectors. This was also the reason why it was absolutely necessary to add the neutron reflectors, instead of simply applying reflective boundary conditions at the top and bottom. If this was not done, the upper and lower surface of the reactor core would make an angle with the  $z$ -plane that could not accommodate the discrete ordinates.

Phantom-SN allows for what is known as detectors, which can measure a specific nuclear quantity. In this case, the quantities of interest were the total neutron flux through both the blanket and the freeze plugs (shown in Figure 3.2b number 3 and 4 respectively), as well as the fission rate in the plug and the capture rate in the blanket.

These outputs are given in the form of response integrals. The result for the neutron flux looks as follows:

$$\sum_{\langle E \rangle} \int_V \phi(E, \vec{r}) d\vec{r}^3 \quad (3.2)$$

The sum of all energies  $E$  is due to the fact that the code runs on discretized energy groups, so in order to receive the total output one must sum over all these energy groups. The flux is integrated over volume to account for the entire region within the bounds of the specific volume. To know the average flux within the region one can simply divide by the volume of the region:

$$\phi_{eff} = \frac{\sum_{\langle E \rangle} \int_V \phi(E, \vec{r}) d\vec{r}^3}{V} \quad (3.3)$$

The capture and fission rate integrals are handled differently. What they do is integrate the product of the neutron flux and a macroscopic cross section. Dividing this integral by the flux integral gives:

$$\Sigma_{i,A} = \frac{\sum_{\langle E \rangle} \int_V \Sigma_{i,A}(E) \phi(E, \vec{r}) d\vec{r}^3}{\sum_{\langle E \rangle} \int_V \phi(E, \vec{r}) d\vec{r}^3} \quad (3.4)$$

Equation 3.4 gives the macroscopic cross section with index  $i$  being either fission or capture in this case and  $A$  referring to the isotope for which it is applicable to. This can be converted into a microscopic cross section:

$$\sigma_{i,A} = \frac{\Sigma_{i,A}}{N_A} \quad (3.5)$$

in which  $N_A$  [ $\frac{\#}{cm^3}$ ] is the atomic density of isotope  $A$ . This is a known quantity, since it can be calculated based on the initial composition of the blanket and the plugs (Tables 2.2, 2.3).

### 3.3. MATLAB simulations

#### 3.3.1. Blanket

Using MATLAB, I simulated the isotopic composition of the blanket over a given period of time to see when and if an equilibrium sets in. I used a source term that is equal to the initial amount of Th-232 over a set period of days. Section 2.2 called for an amount of 40L of Th-232 per day, but I looked at different periods to see how this effects the composition. There also needs to be a removal term to extract the bred fissile products, as well as all other isotopes that are being created in the blanket. The total removal term is equal in magnitude to the source term, but for each specific isotope is proportional to its concentration within the blanket. Of course, it would be extremely counter-productive to remove and discard isotopes that are on their way to becoming a fissile isotope. For this reason, the *useful isotopes* will be recirculated into the blanket. I accomplished this by simply not removing them, and subtract the amount that would be removed from the magnitude of the source of incoming thorium.

The amounts of different isotopes present obey the following equations:

$$\begin{aligned}
\frac{dTh^{232}}{dt} &= -\phi\sigma_c^{Th^{232}} Th^{232} + S - S\left(\frac{Th^{233}}{Th_0} + \frac{Pa^{233}}{Th_0} + \frac{Pa^{234}}{Th_0} + \frac{U^{234}}{Th_0}\right) \\
\frac{dTh^{233}}{dt} &= \phi\sigma_c^{Th^{232}} Th^{232} - \lambda_{Th^{233}} Th^{233} \\
\frac{dPa^{233}}{dt} &= \lambda_{Th^{233}} Th^{233} - \lambda_{Pa^{233}} Pa^{233} - \phi\sigma_c^{Pa^{233}} Pa^{233} \\
\frac{dU^{233}}{dt} &= \lambda_{Pa^{233}} Pa^{233} - \phi\sigma_f^{U^{233}} U^{233} - S\frac{U^{233}}{Th_0} \\
\frac{dPa^{234}}{dt} &= \phi\sigma_c^{Pa^{233}} Pa^{233} - \lambda_{Pa^{234}} Pa^{234} \\
\frac{dU^{234}}{dt} &= \lambda_{Pa^{234}} Pa^{234} - \phi\sigma_c^{U^{234}} U^{234} \\
\frac{dU^{235}}{dt} &= \phi\sigma_c^{U^{234}} U^{234} - \phi\sigma_f^{U^{235}} U^{235} - S\frac{U^{235}}{Th_0} \\
\frac{dFP}{dt} &= \phi\sigma_f^{U^{235}} U^{235} + \phi\sigma_f^{U^{233}} U^{233} - S\frac{FP}{Th_0}
\end{aligned} \tag{3.6}$$

Where  $\phi$  refers to the time and spatial averaged neutron flux in the blanket,  $\sigma_c$  and  $\sigma_f$  are the microscopic cross sections for capture and fission for their respective isotopes, FP stands for fission products (the result of the fission of U-233 and U-235 in the blanket) and  $Th_0$  is the amount of Th-232 isotopes present at  $t=0$ .<sup>1</sup>

After solving the system of differential equations, the presence of each isotope is given as a function of time. With this information, one can calculate the amount of capture and fission events.

Fission energy U233	198
Fission energy U235	200.7
Radiative capture energy	~7
$\beta$ decay Th-233	1.24
$\beta$ decay Pa-233	0.57
$\beta$ decay Pa-234	2.19

Table 3.1: The energy releases in the blanket [MeV][8]

Combining this information with the relevant energetic properties (Table 3.1) yields the heat production within the blanket due to nuclear reactions. The equations that determine the heat production look similar to the differential equations 3.6:

$$\begin{aligned}
P_{decay} &= \lambda_{Th^{233}} Th^{233} E_{\beta}^{Th^{233}} + \lambda_{Pa^{233}} Pa^{233} E_{\beta}^{Pa^{233}} + \lambda_{Pa^{234}} Pa^{234} E_{\beta}^{Pa^{234}}; \\
P_{fis} &= \phi\sigma_f^{U^{235}} U^{235} E_{fis}^{U^{235}} + \phi\sigma_f^{U^{233}} U^{233} E_{fis}^{U^{233}}; \\
P_{cap} &= \phi\sigma_c^{Th^{232}} Th^{232} E_{cap}^{Th^{232}} + \phi\sigma_c^{Pa^{233}} Pa^{233} E_{cap}^{Pa^{233}} + \phi\sigma_c^{U^{234}} U^{234} E_{cap}^{U^{234}}; \\
P_{tot} &= P_{decay} + P_{fis} + P_{cap}
\end{aligned} \tag{3.7}$$

### 3.3.2. Freeze plug

The simulations for the freeze plug proceed in an almost identical fashion as the blanket. The difference lies in the fact that because the freeze plug is a closed off volume with a finite amount of fissile and fertile isotopes the breeding and fission process occurs only once through. This is accomplished in the simulation by excluding the source term present in the equation 3.6, as well as adjusting the relevant conditions to that of the the freeze plug.

<sup>1</sup>  $Th_0$  is actually not the proper term to divide the source term by. One should actually divide by the sum of all isotopes present in the blanket, but in this situation this sum is constant and equal to  $Th_0$ . Thus, this notation is chosen for convenience and clarity.

$$\begin{aligned}
\frac{dTh^{232}}{dt} &= -\phi\sigma_c^{Th^{232}} Th^{232} \\
\frac{dTh^{233}}{dt} &= \phi\sigma_c^{Th^{232}} Th^{232} - \lambda_{Th^{233}} Th^{233} \\
\frac{dPa^{233}}{dt} &= \lambda_{Th^{233}} Th^{233} - \lambda_{Pa^{233}} Pa^{233} - \phi\sigma_c^{Pa^{233}} Pa^{233} \\
\frac{dU^{233}}{dt} &= \lambda_{Pa^{233}} Pa^{233} - \phi\sigma_f^{U^{233}} U^{233} \\
\frac{dPa^{234}}{dt} &= \phi\sigma_c^{Pa^{233}} Pa^{233} - \lambda_{Pa^{234}} Pa^{234} \\
\frac{dU^{234}}{dt} &= \lambda_{Pa^{234}} Pa^{234} - \phi\sigma_c^{U^{234}} U^{234} \\
\frac{dU^{235}}{dt} &= \phi\sigma_c^{U^{234}} U^{234} - \phi\sigma_f^{U^{235}} U^{235} \\
\frac{dFP}{dt} &= \phi\sigma_f^{U^{235}} U^{235} + \phi\sigma_f^{U^{233}} U^{233}
\end{aligned} \tag{3.8}$$

This means that at a certain point in time the heat production will decrease and steadily converge to zero. What needs to be determined is how large the heat production at its peak is (using Equation 3.7), and if that production merits an increase in cooling power.



# 4

## Results and discussion

This chapter examines the data acquired from the nuclear simulations, and processes these data to calculate heat production in the different regions. This leads to the results of the simulations which will be discussed.

### 4.1. Nuclear data

Along with the response integrals discussed in Section 3.2 Phantom-SN also calculates the neutron flux in the reactor within the mesh.

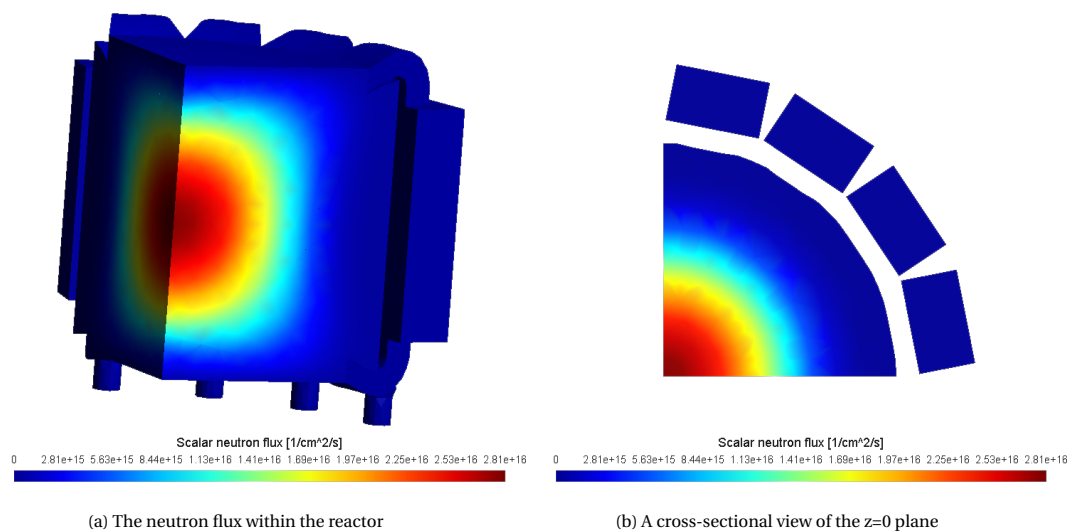


Figure 4.1: Visualisation of flux for one energy group within the geometry.

Figure 4.1 gives an intuitive visualisation of what one can expect the distribution of neutron flux to look like in various locations. The  $k_{eff}^1$  was calculated to be 0.982, which is only around 183 pcm off criticality.

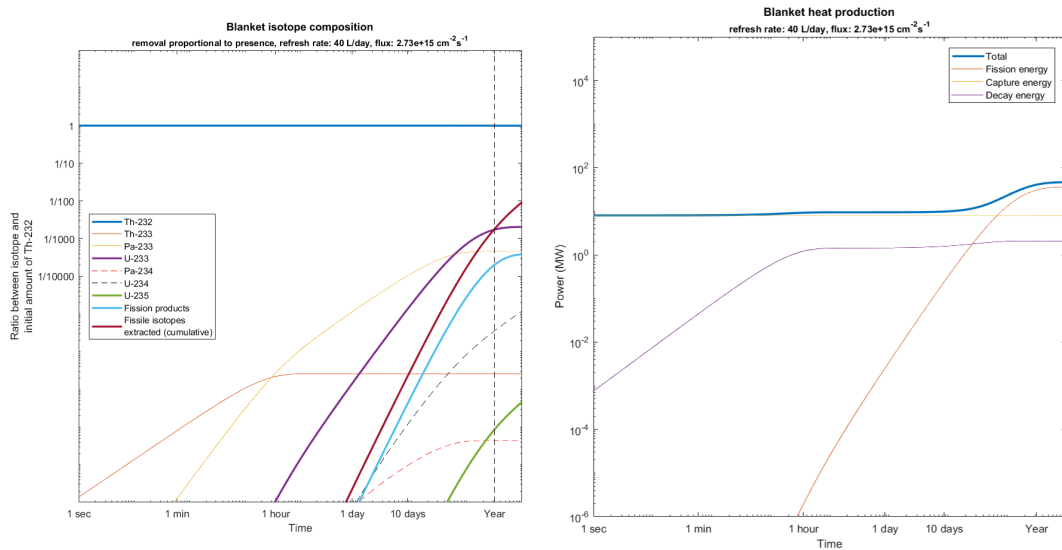
Regarding the cross sections that would be calculated using equation 3.5, only the U-233 fission cross section value calculated was used. This value was 3.89 barn. The Th-232 capture cross section was calculated to be 0.92 barn, which was not a representative value based on reference values [17] [18]. The value that was actually used, as well as the values for the other isotopes are mentioned in appendix A.1.

<sup>1</sup> $k_{eff}$  is the effective multiplication factor, it indicates reactor criticality. Smaller than one is subcritical, larger than one is supercritical and equal to one critical (which is desirable).

## 4.2. MATLAB simulations

### 4.2.1. Fertile blanket

The MATLAB simulation was ran using the data acquired from Phantom-SN. The system of equations 3.6 was solved. The results for the blanket with a refresh rate of 40L/day are shown in Figure 4.2.

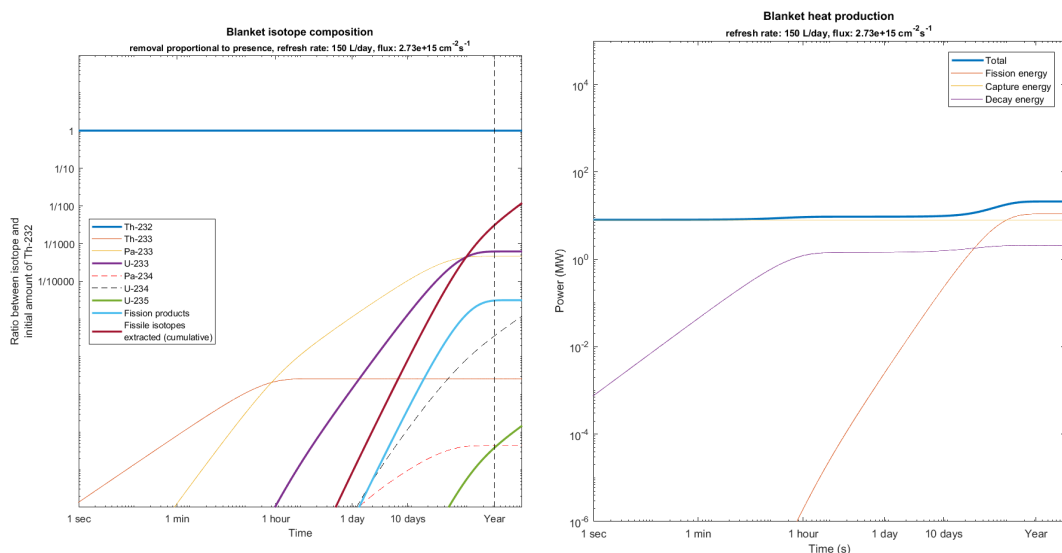


(a) The composition of the blanket over a period of 2 years.

(b) The heat production corresponding to the data of Figure 4.2a.

Figure 4.2: Plots showing the evolution of the blanket over time. (Refresh rate: 40 L/day)

Figure 4.2a shows how the isotopic composition of the blanket changes over time. The graphs show that an equilibrium tends to set in after around a year (vertical dashed line). Note that the red line describes the cumulative amount of fissile isotopes extracted from the blanket, not a quantity present in the blanket. It merely indicates what breeding yield one can expect with this set-up. The increase in fissile isotopes can also be clearly seen in Figure 4.2b, where the heat production is initially dominated by radiative capture, but, once enough fissile material is present, it is primarily dependent on the fission rate. The amount of heat production after reaching equilibrium is 8.03 MW due to radiative capture, and 36.3 MW due to fission.



(a) The composition of the blanket over a period of 2 years.

(b) The heat production corresponding to the data of Figure 4.3a.

Figure 4.3: Plots showing the evolution of the blanket over time. (Refresh rate: 150 L/day)



It is also interesting to look at the effects of different refresh rates. Figure 4.3 shows the composition and heat production of the blanket for a refresh rate of 150 L/day, which corresponds to the blanket being refreshed in around 55 days. There are some notable differences with the results seen in Figure 4.2. Due to the higher refresh rate, the amount of fissile material in the blanket is lower because it is extracted faster. The consequence is that there will be less blanket fission events, which is reflected in the heat production in 4.3b. The amount of heat production after reaching equilibrium is 8.05 MW due to radiative capture, and 11.0 MW due to fission. The heat production due to radiative capture has barely changed, while the fission heat is significantly smaller.

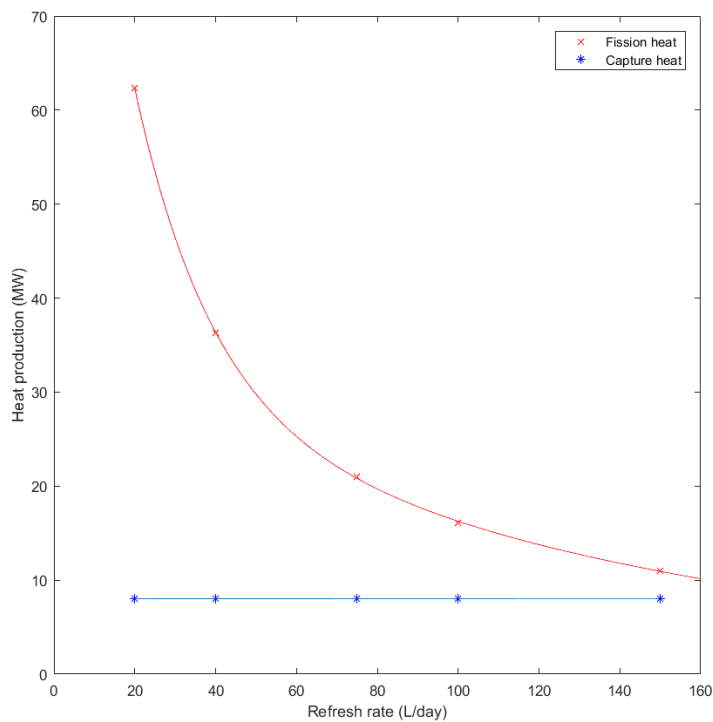


Figure 4.4: Heat production in the blanket for various refresh rates.

Figure 4.4 shows the relation between refresh rate and heat production. As discussed in the previous paragraph, there is barely any increase in release due to radiative capture at higher refresh rates, but it is clear that the fission rate is highly dependent on the refresh rate of the blanket.

### 4.2.2. Freeze plug

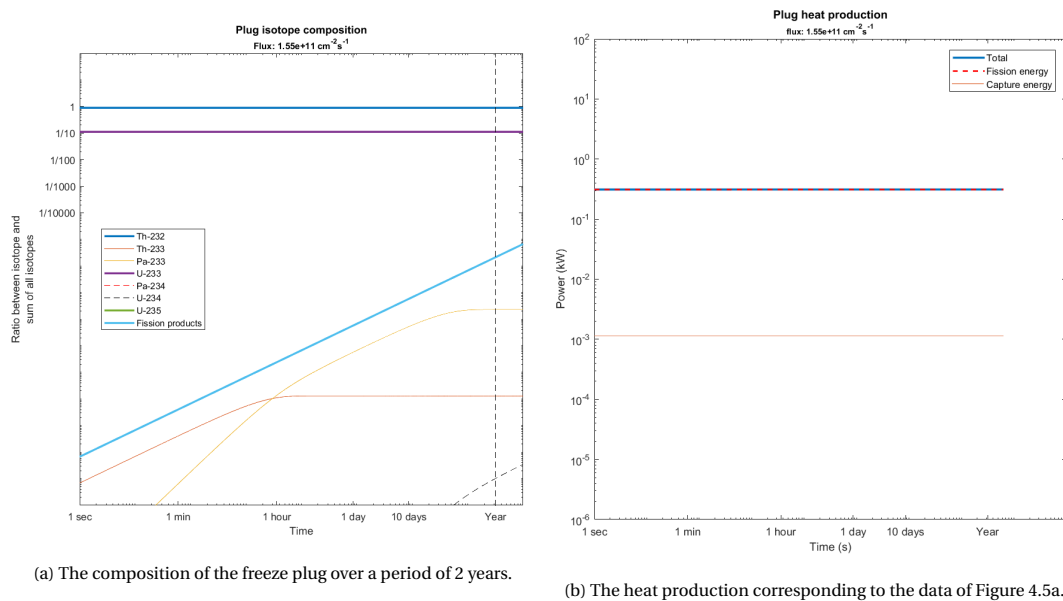


Figure 4.5: Plots showing the evolution of the plug over time. (heat production 4 plugs) (plug depth 3 cm)

Figure 4.5 shows the activity in the plug region. There are a number of interesting difference with the blanket to note here. Firstly, we can see that the heat production is constant in time and dominated by fission energy. The reason it is constant in time is that because the flux within the plug is so small that barely burns up any uranium at all. This is reflected in Figure 4.5a where we see the amount of Th-232 and U-233 to be close to unchanged after 2 years. There is evidence of activity however, shown in both the build up of fission products as well as the breeding of thorium, evident by the build up of Th-233 and Pa-233. The heat production for four freeze plugs with a plug depth of 3 cm has a value of 0.312 kW, or a volumetric heat production of 13.80 kW per m<sup>3</sup>.

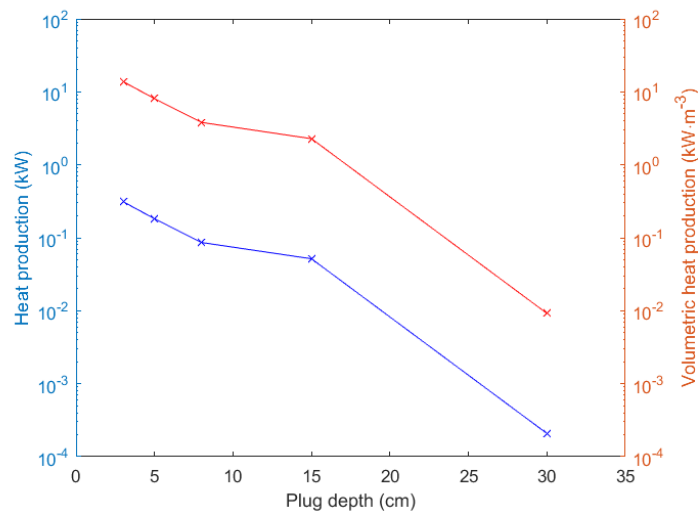


Figure 4.6: The (volumetric) heat production within the plug at various depths.

Increasing the depth of the plug means it is further away from the higher flux regions. The result of varying the plug depth is shown in Figure 4.6. One can clearly see that the heat production within the plugs drops three orders of magnitude when lowering it to a depth of 30 cm. The corresponding heat production at that depth is only 0.2 W, which is negligible by any standard.

### 4.3. Discussion

The presented results clearly indicate the effects of varying the used parameters. In the fertile blanket there is sufficient evidence to show that heat production due to fission is largely dependent on the refresh rate. Radiative capture release was relatively constant for varying refresh rates. The 40 L/day results showed the amount of heat production after reaching equilibrium is 8.05 MW due to radiative capture, and 11.0 MW due to fission. These results can be placed in perspective by looking at the results from previous research. The SAMOFAR project had spoken of a 7 MW production due to U-233 fission and 24 MW due to the radiative capture of Th-232. The results from this thesis do not perfectly correspond to those from the SAMOFAR report, but are within an order of magnitude. The reason for these differences can be numerous, but hard to determine without knowing the different methodologies. Reasons for the difference could be:

- This research used a larger blanket volume ( $8.3 \text{ m}^3$ ) than SAMOFAR specifications ( $6\text{-}7 \text{ m}^3$ ).
- The interpretation and implementation of the refresh rate could be different.
- Most likely a different set of cross sections was used to calculate reaction rates.

In the freeze plug it has been shown that heat production is close to constant due to the low neutron flux (compared to that in the blanket). The (volumetric) heat production within the plug showed strong correlation with the depth at which it is placed. At its highest point, the volumetric heat production was  $13.80 \text{ kW per m}^3$ .

To place this in context, we can look at the cooling requirement which was determined in previous research. This was set at  $1.8 \text{ MW m}^{-3}$  by Kamp [5]. What can be concluded here is that heat production due to nuclear reactions in the plug do not contribute significantly enough to justify additional cooling power.



# 5

## Conclusions and recommendations

### 5.1. The research questions

The questions this thesis aimed to answer were:

*What is the magnitude of heat production in the fertile blanket due to nuclear reactions?*  
and

*What is the magnitude of heat production in the freeze plug due to nuclear reactions?*

The first question will be answered first:

- For a fertile blanket with a volume of  $8.3 \text{ m}^3$  and an initial composition of 77.5% LiF and 22.5% ThF<sub>4</sub> with a refresh rate of 40 L/day the heat production within the blanket is 8.03 MW due to radiative capture and 36.3 MW due to fission.
- The heat production for the blanket with a refresh rate of 150 L/day is 8.05 MW due to radiative capture, and 11.0 MW due to fission.
- Fission heat production exponentially decreases with refresh rate.

The SAMOFAR project had spoken of a 7 MW production due to U-233 fission and 24 MW due to the radiative capture of Th-232. The results from this thesis do not perfectly correspond to those from the SAMOFAR report, but are within an order of magnitude.

The second question:

- For four freeze plugs with a diameter and height of 20 cm, and an initial composition of 77.5% LiF, 20% ThF<sub>4</sub> and 2.5% <sup>233</sup>UF at a depth of 3 cm it was found that the heat production (almost entirely due to fission) was 0.312 kW, or volumetrically 13.80 kW per m<sup>3</sup>.
- When lowering the plug depth to 30 cm the heat production becomes negligibly small.

Previous research by Kamp [5] set the plug cooling requirement at  $1.8 \text{ MW m}^{-3}$ . What can be concluded here is that heat production due to nuclear reactions in the plug do not contribute significantly enough to justify additional cooling power.

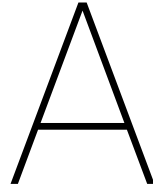
### 5.2. Recommendations for future research

What this thesis has done is give an insight into the orders of magnitude for heat production that can be expected for typical conditions of an MSFR reference model. These results are subject to change when a more realistic model design is present. For example, the dimensions of the fertile blanket should be adjusted to properly incorporate the structural materials of the reactor (and the cooling equipment that this thesis aimed to acquaint the requirements of), which would lower the effective volume of the blanket and thus the heat production.

This research looked at the SAMOFAR reference model configuration. It could be useful to investigate how heat production changes when scaling the reactor up or down. How does the cooling requirement for the blanket depend on different magnitudes of neutron flux? This research only examined a specific situation with one value of  $\phi$ .

Different breeding materials could also be considered. There is a large amount of nuclear waste that is full of fertile U-238 which could be reprocessed into blanket salt material. What adjustments to the blanket would have to be to accommodate other types of breeding material?

Further research on the cooling requirements of freeze plug with regards to the nuclear reactions that take place within it do not seem necessary as the results from this research show the heat production to be negligibly small compared to the already established cooling requirements.



# Appendix

## A.1. Cross sections

The cross sections used in the simulations in this research were estimated using the cross section plotter of the Korea Atomic Energy Research Institute webtool, with data from the JEFF 3.1 [17] and ENDF-VII [18] cross section libraries.

Th-232 $\sigma_c$	0.05
Pa-233 $\sigma_c$	0.1
U-234 $\sigma_c$	0.1
U-235 $\sigma_f$	1.0

Table A.1: Cross sections used in simulation [barn]

## A.2. Matlab Code

```
1 %% Blanket composition script
2 clc
3 clear all
4 close all
5
6 prompt = {'Simulate how much time? [years]:', 'What is the blanket neutron flux?:', ...
7          'What is the blanket capture integral response?:', 'What is the plug neutron flux?:', ...
8          'What is the plug fission integral response?:', 'Removal rate [L/day]:'};
9 inptitle = 'Input';
10 dims = [1 35];
11 definput = {'5', '5.67E+21', '3.32E+19', '3.50E+15', '9.804E+12', '40'};
12 answer = inputdlg(prompt, inptitle, dims, definput);
13
14 %Constants
15
16 %decay constants (log(2)/T_1/2)
17 lambth233=5.2920e-04;
18 lambp233=2.9740e-07;
19 lambu233=1.38e-13;
20 lambp234=2.8737e-05;
21
22
23 %Initial composition
```

```

24 V=8.3024; %Volume of blanket (integrated by gmsh)
25 Top=700+273; %Operating temperature in K
26 rho=4983-0.822*Top; %Density of fluid [kg/m3] at operating temp of 650C
27
28 %mol% of initial salt and molecular weights blanket
29 percTh=22.5; %percentage ThF4 in fuel
30 percLiF=77.5; %percentage LiF in fuel
31 MThF4=308; %g/mol
32 MLiF=26; %g/mol
33 Mtot=(MLiF*percLiF+MThF4*percTh)/100; %Total molecular weight g/mol
34 rhomol=rho/(Mtot*1e-3); %mol/m3
35 Avo=6.022e23; %Avogadros constant
36 Th0=V*rhomol*percTh/100*Avo; %Initial amount of Th atoms in blanket at time 0
37
38 %mol% of initial salt and molecular weights plug
39 percThp=20; %percentage ThF4 in plug
40 percLiFp=77.5; %percentage LiF in plug
41 percUFp=2.5; %percentage UF4 in plug
42 MUF4=309; %g/mol
43 Mtotp=(MLiF*percLiFp+MThF4*percThp+MUF4*percUFp)/100; %Total molecular weight g/mol
44 rhop=4276;
45 rhomolp=rhop/(Mtotp*1e-3); %mol/m3
46 vol4plugs=0.0226; %integrated volume of 4 plugs (gmsh) [m3]
47 Th0p=vol4plugs*rhomolp*percThp/100*Avo; %Initial amount of Th atoms in plugs at time 0
48 U0=vol4plugs*rhomolp*percUFp/100*Avo; %Initial amount of U233 atoms in plugs at time 0
49
50
51 %Nuclear properties blanket
52 CU=U0/vol4plugs*1e-6; %concentration U0 in plug #/cm^3
53
54 mu233fis=str2num(answer{5})/str2num(answer{4});
55 u233fis=mu233fis/CU;
56
57 b=1e-24; %barn in cm2
58 th232cap=5e-2*b;
59 pa233cap=1e-1*b; %capture cross section of Pa233 [cm2]
60 u234cap=1e-1*b; %capture cross section of U233 [cm2]
61 u235fis=b; %fission cross section of U235 [cm2]
62
63 flux=str2num(answer{2})/(V/4*1e6); %neutron flux in blanket [1/cm2/s]
64 fluxp=str2num(answer{4})/(vol4plugs*1e6); %neutron flux in plugs [1/cm2/s]
65
66 rate=str2num(answer{6}); %removal rate in L/day
67 day=3600*24; %day in seconds
68 S=Th0/(day*(V*1000/rate)); %source term: initial amount is inserted/removed over s
69 %%
70 %Differential equations
71
72 cons=[Th0 0 0 0 0 0 0 0 0];
73
74
75 f1 = @(t,x)[-flux*th232cap*x(1)+S*(1-x(2))/Th0-x(3)/Th0-x(5)/Th0)...
76 -1*x(1)*S/(x(1)+x(2)+x(3)+x(4)+x(5)+x(6)+x(7)+x(8));...
77 flux*th232cap*x(1)-lambth233*x(2);...
78 -lambp233*x(3)+lambth233*x(2)-flux*pa233cap*x(3);...
79 +lambp233*x(3)-flux*u233fis*x(4)-1*x(4)*S/(x(1)+x(2)+x(3)+x(4)+x(5)+x(6)+x(7)+x(8));

```



```

80     +flux*pa233cap*x(3)-lambp234*x(5);...
81     +lambp234*x(5)-flux*u234cap*x(6);...
82     +flux*u234cap*x(6)-flux*u235fis*x(7)-1*x(7)*S/(x(1)+x(2)+x(3)+x(4)+x(5)+x(6)+x(7)+x(8));...
83     flux*u235fis*x(7)+flux*u233fis*x(4)-1*x(8)*S/(x(1)+x(2)+x(3)+x(4)+x(5)+x(6)+x(7)+x(8));...
84     (x(4)+x(7))*S/(x(1)+x(2)+x(3)+x(4)+x(5)+x(6)+x(7)+x(8))];
85
86 [T,Y]=ode45(f1,[0 str2num(answer{1})*3600*24*365],cons);
87
88 Th232=Y(:,1);
89 Th233=Y(:,2);
90 Pa233=Y(:,3);
91 U233 =Y(:,4);
92 Pa234=Y(:,5);
93 U234 =Y(:,6);
94 U235 =Y(:,7);
95 Other=Y(:,8);
96 Yield=Y(:,9);
97
98
99 consp=[Th0p 0 0 U0 0 0 0 0];
100
101
102 f2 = @(t,x)[-fluxp*th232cap*x(1);...
103     fluxp*th232cap*x(1)-lambth233*x(2);...
104     -lambp233*x(3)+lambth233*x(2)-fluxp*pa233cap*x(3);...
105     +lambp233*x(3)-fluxp*u233fis*x(4);...
106     +fluxp*pa233cap*x(3)-lambp234*x(5);...
107     +lambp234*x(5)-fluxp*u234cap*x(6);...
108     +fluxp*u234cap*x(6)-fluxp*u235fis*x(7);...
109     fluxp*u235fis*x(7)+fluxp*u233fis*x(4)];
110
111 [Tp,Yp]=ode45(f2,[0 str2num(answer{1})*3600*24*365],consp);
112
113 Th232p=Yp(:,1);
114 Th233p=Yp(:,2);
115 Pa233p=Yp(:,3);
116 U233p =Yp(:,4);
117 Pa234p=Yp(:,5);
118 U234p =Yp(:,6);
119 U235p =Yp(:,7);
120 Otherp=Yp(:,8);
121
122 %% plotting
123 figure('units','normalized','outerposition',[0 0 1 1])
124 loglog(T,Th232/Th0,'LineWidth',2)
125
126 hold on
127 loglog(T,Th233/Th0)
128 loglog(T,Pa233/Th0)
129 loglog(T,U233/Th0,'LineWidth',2)
130 loglog(T,Pa234/Th0,'--r')
131 loglog(T,U234/Th0,'--k')
132 loglog(T,U235/Th0,'LineWidth',2)
133 loglog(T,Other/Th0,'LineWidth',2)
134 loglog(T,Yield/Th0,'LineWidth',2)
135 line([365*day 365*day],[1e-10 100],'Color','k','LineStyle','--');

```

```

136
137
138 title ({{ 'Blanket isotope composition' };[ '\fontsize{9}removal proportional to presence, refresh r
139         answer{6} ' L/day, flux: ' num2str(flux, '%10.2e\n') ' cm-2s-1' ]})
140
141
142 hold off
143 ylabel ({{ 'Ratio between isotope and'; 'initial amount of Th-232' })
144 xlabel ( 'Time' )
145 legend ( 'Th-232', 'Th-233', 'Pa-233', 'U-233', 'Pa-234', 'U-234', 'U-235', 'Fission products', ...
146         [ 'Fissile isotopes' newline 'extracted (cumulative)'], 'Location', 'best' )
147 ylim ([10-10 102])
148 xlim ([100 108])
149
150 names = { '1 sec'; '1 min'; '1 hour'; '1 day'; '10 days'; 'Year' };
151 set (gca, 'xtick', [1,60,3600,1*3600*24,10*3600*24,365*3600*24], 'xticklabel', names)
152 ynames = { '1/10000'; '1/1000'; '1/100'; '1/10'; '1' };
153 set (gca, 'ytick', [1e-4,1e-3,1e-2,1e-1,1], 'yticklabel', ynames)
154
155 %% Decay heat production
156 %
157 %Decay energies
158 mth233=233.0415818;           %mass of Th233 in amu
159 mpa233=233.0402473;           %mass of Pa233 in amu
160 mu233 =233.0396352;           %mass of U233 in amu
161 mpa234=234.043308;           %mass of Pa234 in amu
162 mu234 =234.0409521;           %mass of U234 in amu
163
164 deltam1=mth233-mpa233;         %mass difference decay 1
165 deltam2=mpa233-mu233;         %mass difference decay 2
166 deltam3=mpa234-mu234;         %mass difference decay 3
167
168 amu=1.660539040e-27;          %1 amu in kg
169 c=299792458;                  %speed of light
170
171 E1=deltam1*amu*c^2;            %decay energy Th233->Pa233
172 E2=deltam2*amu*c^2;            %decay energy Pa233->U233
173 E3=deltam3*amu*c^2;            %decay energy Pa234->U234
174 E4=198e6*1.6e-19;             %fission energy U233
175 E5=200.7e6*1.6e-19;           %fission energy U235
176
177 Ecap=7e6*1.6e-19;             %radiative capture energy (around 7MeV)
178
179 %Power generated
180
181 Power1 = (lambth233*Th233*E1+lambp233*Pa233*E2+lambp234*Pa234*E3 + ...
182           (flux*u235fis*U235*E5+flux*u233fis*U233*E4) + ...
183           (th232cap*flux*Th232+pa233cap*flux*Pa233+u234cap*flux*U234)*Ecap) / (1e6);
184 Power1b= (flux*u235fis*U235*E5+flux*u233fis*U233*E4) / (1e6);
185 Power1a= (th232cap*flux*Th232+pa233cap*flux*Pa233+u234cap*flux*U234)*Ecap / (1e6);
186 Power1c= (lambth233*Th233*E1+lambp233*Pa233*E2+lambp234*Pa234*E3) / (1e6);
187 figure ( 'units', 'normalized', 'outerposition', [0 0 1 1])
188
189
190 loglog (T, Power1, 'LineWidth', 2)
191 hold on

```

```

192 loglog (T, Power1b)
193 loglog (T, Power1a)
194 loglog (T, Power1c)
195 legend('Total', 'Fission energy', 'Capture energy', 'Decay energy')
196
197 ylim([10^-6 10^5])
198 xlim([10^0 10^8])
199 ylabel('Power (MW)')
200 xlabel('Time')
201 title(['Blanket heat production']; ['\fontsize{9}refresh rate: ' answer{6}...
202       ' L/day, flux: ' num2str(flux, '%10.2e\n') ' cm^{-2}s^{-1}' ])
203
204 names = {'1 sec'; '1 min'; '1 hour'; '1 day'; '10 days'; 'Year'};
205 set(gca, 'xtick', [1, 60, 3600, 1*3600*24, 10*3600*24, 365*3600*24], 'xticklabel', names)
206 hold off
207
208 disp(['Blanket capture power = ' num2str(Power1a(length(T))) ' MW'])
209 disp(['Blanket fission power = ' num2str(Power1b(length(T))) ' MW'])
210
211 %% Freeze plug power
212 %%Repeat same calculations as for blanket, but without source term
213
214 %%Composition plot
215
216 figure('units', 'normalized', 'outerposition', [0 0 1 1])
217 loglog (Tp, Th232p / (Th0p+U0), 'LineWidth', 2)
218 hold on
219 loglog (Tp, Th233p / (Th0p+U0))
220 loglog (Tp, Pa233p / (Th0p+U0))
221 loglog (Tp, U233p / (Th0p+U0), 'LineWidth', 2)
222 loglog (Tp, Pa234p / (Th0p+U0), '--r')
223 loglog (Tp, U234p / (Th0p+U0), '--k')
224 loglog (Tp, U235p / (Th0p+U0), 'LineWidth', 2)
225 loglog (Tp, Otherp / (Th0p+U0), 'LineWidth', 2)
226 line([365*day 365*day], [1e-20 100], 'Color', 'k', 'LineStyle', '--');
227 title(['Plug isotope composition']; ['\fontsize{9}Flux: ' ...
228       num2str(fluxp, '%10.2e\n') ' cm^{-2}s^{-1}' ])
229
230
231 hold off
232 ylabel(['Ratio between isotope and'; 'sum of all isotopes'])
233 xlabel('Time')
234 legend('Th-232', 'Th-233', 'Pa-233', 'U-233', 'Pa-234', 'U-234', 'U-235', ...
235       'Fission products', 'Location', 'best')
236 ylim([10^-15 10^2])
237 xlim([10^0 10^8])
238
239 names = {'1 sec'; '1 min'; '1 hour'; '1 day'; '10 days'; 'Year'};
240 set(gca, 'xtick', [1, 60, 3600, 1*3600*24, 10*3600*24, 365*3600*24], 'xticklabel', names)
241 ynames = {'1/10000'; '1/1000'; '1/100'; '1/10'; '1'};
242 set(gca, 'ytick', [1e-4, 1e-3, 1e-2, 1e-1, 1], 'yticklabel', ynames)
243
244
245 %%Power generated
246
247 Power2 = (lambth233*Th233p*E1+lambp233*Pa233p*E2+lambp234*Pa234p*E3 + ...

```

```

248         (fluxp*u235fis*U235p*E5+fluxp*u233fis*U233p*E4) + ...
249         (th232cap*fluxp*Th232p+pa233cap*fluxp*Pa233p+u234cap*fluxp*U234p)*Ecap)/(1e3);
250 Power2b= (fluxp*u235fis*U235p*E5+fluxp*u233fis*U233p*E4)/(1e3);
251 Power2a= (th232cap*fluxp*Th232p+pa233cap*fluxp*Pa233p+u234cap*fluxp*U234p)*Ecap/(1e3);
252 figure('units','normalized','outerposition',[0 0 1 1])
253
254
255 loglog(Tp,Power2,'LineWidth',2)
256 hold on
257 loglog(Tp,Power2b,'r--','LineWidth',1.5)
258 loglog(Tp,Power2a)
259 legend('Total','Fission energy','Capture energy')
260
261 ylim([10^-6 10^2])
262 xlim([10^0 10^9])
263 ylabel('Power (kW)')
264 xlabel('Time')
265 title('Plug heat production')
266 title({'Plug heat production';[\fontsize{9}Flux: ' num2str(fluxp,'%10.2e\n') ' cm^{-2}s^{-1}']})
267
268 names = {'1 sec';'1 min';'1 hour'; '1 day'; '10 days'; 'Year'};
269 set(gca,'xtick',[1,60,3600,1*3600*24,10*3600*24,365*3600*24],'xticklabel',names)
270 hold off
271
272 disp(['Plug power = ' num2str(Power2(length(Tp))) ' kW'])
273 disp(['Volumetric plug power = ' num2str(Power2(length(Tp))/vol4plugs) ' kW/m3'])

```

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