# A new design for the safety plug in a Molten Salt Fast Reactor

by

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# Abstract

It is commonly believed that nuclear energy is more dangerous and more wasteful than other sources of energy. Extensive research is therefore expended on generation IV Reactors with the aim of improving their safety and decreasing the waste produced. One type of generation IV Reactors is the Molten Salt Fast Reactor, which has a safety system that includes a freeze plug at the bottom of the tank, keeping the fuel from flowing away through exit pipes. In the event of a power outage, however, or when the tank should overheat, the fuel must leave the tank in less than 8 minutes through these pipes.

This report studies a new design for the freeze plug. In this design, multiple small pipes with individual freeze plugs are used instead of one large pipe. The new plug will have a wall made of 8.5 mm of hastelloy N coated with a thin copper sheet of 2.5 mm. The total time the reactor needs to fully drain all of its content is the sum of the time needed for the plug to melt and the time the fuel takes to leave the tank. The melting time depends among other things on the radius of the plug; a larger radius leads to a slower melting process. Varying the radius from 0.01 m to 0.1 m, the melting time varies from 40 to 46 seconds. The drainage time depends on the radius and length of the pipe but also on the number of pipes that are used. The total length of the pipe is set at a constant of 3.5 m and the number of pipes is fixed per radius based on an equal volume flow rate of 0.2315 $m^3\,s^{-1}$ for all radii. Due to a constant volume flow rate the drainage time is also constant and remains 78 seconds. With the addition of the range of melting times, the total emergency drainage time will thus vary from 118 to 124 seconds for different radii of the plug. This is well below the maximum time allowed, leading to the conclusion that this new design for the freeze plug could be viable.

This study is done using COMSOL Multiphysics and Matlab.

*Frederique van Tuyll*
*Delft, November 2016*

# Contents

# List of Figures

# List of Tables

# Nomenclature

| Symbol | Description | Units |
|---|---|---|
| $\lambda$ | thermal conductivity | $\mathrm{W\,m^{-1}\,K^{-1}}$ |
| $\mu$ | dynamic viscosity | $\mathrm{Pa\,s}$ |
| $\nu$ | kinematic viscosity | $\mathrm{m^2\,s^{-1}}$ |
| $\rho$ | density | $\mathrm{kg\,m^{-3}}$ |
| $a$ | thermal diffusivity | $\mathrm{m^2\,s^{-1}}$ |
| $A_i$ | area at point i | $\mathrm{m^2}$ |
| $C_p$ | specific heat | $\mathrm{J\,kg^{-1}\,K^{-1}}$ |
| $D$ | characteristic length or hydraulic diameter | m |
| $e_{diss}$ | energy dissipation | $\mathrm{J\,kg^{-1}}$ |
| $f$ | fanning friction factor | - |
| $g$ | gravitation constant on earth, 9.81 | $\mathrm{m\,s^{-2}}$ |
| $h$ | convective heat transfer coefficient | $\mathrm{W\,m^{-2}\,K^{-1}}$ |
| $h_f$ | convective heat transfer coefficient of the fluid in the reactor | $\mathrm{W\,m^{-2}\,K^{-1}}$ |
| $h_m$ | convective heat transfer coefficient of the metal hastelloy N | $\mathrm{W\,m^{-2}\,K^{-1}}$ |
| $h_t$ | height of liquid level in reactor vessel | m |
| $H_{tank}$ | height of the reactor vessel | m |
| $K_{tot}$ | resistance coefficient | - |
| $L$ | pipe length of drainage system | m |
| $L_{fus}$ | latent heat of fusion | $\mathrm{J\,kg^{-1}}$ |
| $P_i$ | pressure at point i | Pa |
| $r$ | radius of the pipe | m |
| $R_{plug}$ | radius of the molten salt in the plug | m |
| $R_{tank}$ | radius of the reactor vessel | m |
| $T$ | temperature | K |
| $t$ | time | s |
| $T_s$ | temperature of solid | K |
| $T_\infty$ | temperature of the surroundings | K |
| $t_{drain}$ | drainage time | s |
| $t_{melt}$ | melting time | s |

| | | |
|---|---|---|
| $t_{tot}$ | melting time plus the drainage time | s |
| $v$ | velocity | $m\,s^{-1}$ |
| $v_i$ | velocity at point i | $m\,s^{-1}$ |
| $X$ | thickness of the extra material attached to the hastelloy N in the plug wall | m |
| $x$ | location in cartesian coordinates | m |
| $z_i$ | height at point i | m |
| $\phi_m$ | mass flow | $kg\,s^{-1}$ |
| $\phi_{V,1}$ | volume flow rate for one pipe | $m^3\,s^{-1}$ |
| $\phi_{V,m}$ | volume flow rate for multiple pipes | $m^3\,s^{-1}$ |
| $\phi_v$ | volume flow rate | $m^3\,s^{-1}$ |

# 1 Introduction

In the last 50 years three significant accidents have happened in nuclear reactors. While the accidents at Chernobyl (1986) and the Three Mile Island (1979) grew more distant , a new disaster occurred at Fukushima(2011). Due to this event and the fact that nuclear waste is still harmful for humans and other creatures for thousands of years, people tend to have little trust in nuclear energy. Therefore extensive research needs to be done to improve the safety of reactors and decrease the produced waste. An example of an organisation that does this kind of research is GIF (Generation IV International Forum)[4]. GIF is an international collective which find nuclear energy vital for the future. The focus of GIF lies in the generation IV Reactors, which they believe score highest in safety and sustainability. These reactors include 6 different technologies:

- The Gas-cooled Fast Reactor (GFR)
- The Lead-cooled Fast Reactor (LFR)
- The Molten Salt Reactor (MSR)
- The Sodium-cooled Fast Reactor (SFR)
- The Supercritical-Water-cooled Reactor (SCWR)
- The Very-High-Temperature Reactor (VHTR)

At the TU Delft or specifically the Reactor Institute Delft (RID) research is done on the Molten Salt Reactor. This project called SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor) is done together with ten other universities and research laboratories. Its goal is to prove the innovative safety concepts of the MSR. But in order for the MSR to be successfully used, the design has to be optimized. In this project a small part of the design of the reactor called the safety plug will be studied.

## 1.1. Molten Salt Fast Reactor

### 1.1.1. Design of the MSFR

The Molten Salt Fast Reactor (MSFR) is a type of reactor in which the fuel, which consists of thorium fluoride, lithium fluoride and a heavy nucleus like uranium, is dissolved in the molten salt[1]. This fuel is not only the place where the nuclear reactions occur but it also works as the coolant. The Molten Salt Fast Reactor has a total fuel salt volume of 18 $m^3$ which is distributed half in the core and half in the external fuel circuit. The design of the reactor, which is shown in figure 1.1, contains a single compact cylinder in which the nuclear reactions occur. The fuel can move up to the top without any moderator but when going down it is lead by heat exchangers and 16 sets of pumps located around the core of the reactor. Flowing past the heat exchangers gives the salt the chance to release a part of its heat, which is then used to generate electricity. At the end of the heat exchangers, bubbles are injected into the salt to clean the fuel and then the salt will move up again. The total cycle is done in 3 to 4 seconds.

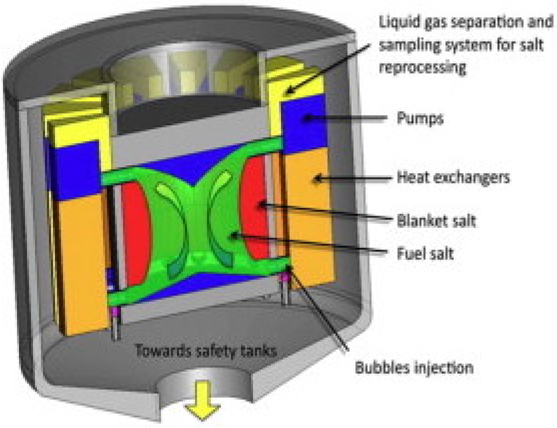
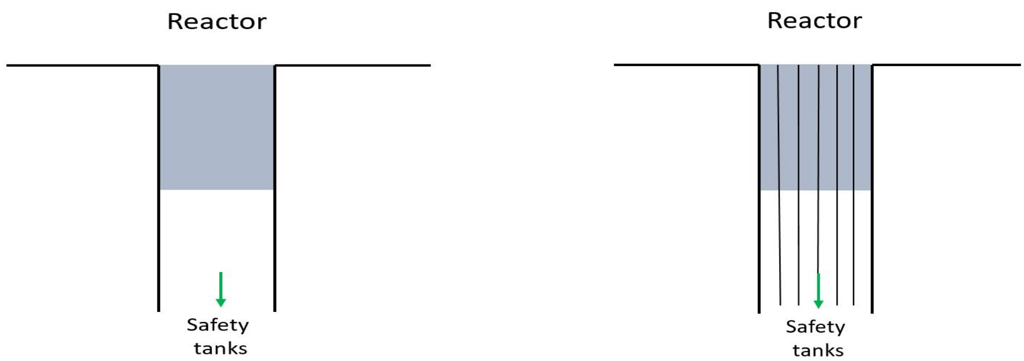



**Figure 1.1:** Design of the Molten Salt Fast Reactor[1]

In this figure the drainage system is not included. The place in the figure where it says *towards safety tanks* is where the drainage system is placed in the reactor. It consists of a pipe leading to multiple underground tanks. At the top of the pipe a safety plug is installed to make sure the fuel will only leave the reactor tank when it is needed. The workings of this plug are explained in the next section.

### 1.1.2. Safety plug

The MSFR can work at temperatures up to 750 °C but when the temperature in the core exceeds this temperature, the reactor must be shut down and the entire fuel must be drained to sub-critical, passively cooled tanks. In case of an accident in which the fuel is not actively cooled anymore, the fuel must leave the tank through exit pipes. At the top of such a pipe a safety plug is installed. This freeze plug is made up of solidified salt which is actively cooled surrounded by metal. The design of such a safety plug with attached exit pipe is shown in figure 1.2a. This design has been previously studied by Koks[5], Swaroop and others. In this report a new design for this plug will be studied. The difference between them is that in the new design multiple pipes will be used instead of only one. This is done in order to decrease the melting time of the plug. The new design is shown in figure 1.2b. Note that both figures are not on scale.




**(a)** Previous design **(b)** New design

**Figure 1.2:** Vertical cross sections of the previous and the new design of the freeze plug. In grey the frozen salt is displayed.

In both figures the grey area is the frozen salt. The fuel in the tank can only leave the reactor when all the salt has melted. The advantage of the new design is that heat will be transferred at multiple places due to an increased touching surface between the frozen salt and the surrounding metal. Therefore the melting process will go faster.

When a power outage occurs the heat exchangers will stop working. Therefore the fuel is no longer actively cooled which leads to a rise in temperature. Cracks can begin to form in the walls of the MSFR causing the leakage of fuel and radioactive material. But the absence of electricity and the rise in temperature will also cause the salt in the freeze plug to melt. The melting of the salt and the following drainage of the reactor must happen within 8 minutes after the power outage[6]. This is based upon a mean operating temperature of 700 °C and a maximum temperature of 1200°C. The necessity of an excellent safety measure when electricity is shut down is easiest to understand by explaining what occurred at Fukushima.

## 1.2. Fukushima disaster

In 2011 an earthquake with a magnitude of 9 on the Richter scale occurred near the coast of Japan. Around 160 km from the epicentre of this earthquake lies Fukushima, a nuclear power plant consisting of 6 Boiling Water Reactors. All operating units within Fukushima have as a safety precaution that when an earthquake occurs, they will be shut down[7]. This is possible because during an earthquake the ground acceleration will increase which can be measured. When all units were shut down, the Boiling Water Reactors were connected to backup generators to drive emergency cooling systems for releasing the decay heat in the vessel. These backup generators were placed in the basements of the nuclear power turbines. Though the turbines were protected for tsunami waves by a seawall, the wave that hit Fukushima 50 minutes after the earthquake exceeded that wall by 5 metres. The wave flooded the basements thereby disabling the backup generators and stopping the cooling process. In all reactors the temperature of the nuclear fission product rose which eventually lead to some of the reactors to explode.

From the disaster in Fukushima a lot can be learned and furthermore improved. As the accident clearly shows a better safety system should be implemented in reactors. An example of an improvement in the safety system is the safety plug. The best solution would be a plug that does not depend on electricity. In this case when all the electricity will fall out and the reactor will not be actively cooled anymore, the fuel will leave the tank and flow to safety tanks. This type of plug is part of the Molten Salt Fast Reactor.

## 1.3. Goals and outline

The goal of this research is to examine a new possible design for the safety plug. The main question that will be answered is whether the frozen water in the plug will melt faster for this design as opposed to the previous one. This will be studied using multiphysics software COMSOL but also MATLAB is used to make certain calculations. In the next chapter the theory behind the workings of the safety plug will be discussed. In chapter 3 the design of the plug will be further elaborated on and the way it is modelled in COMSOL will be explained. The results are shown in chapter 4 and conclusions will be drawn and discussed in chapter 5. In this final chapter possible further research and new designs are discussed as well.

# 2

# Theory

## 2.1. New design of the plug

In this report a new design of the safety plug will be studied. The difference between this plug and the previous one is the amount of pipes that is used. As was seen in figure 1.2 the previous design of the plug shows one hole in which the salt is frozen whereas in the new design multiple pipes are placed. When looking at the plug from a bird's eye view, it will look like figure 2.1. The small pipes in this figure represent the different holes of the plug in which the frozen salt is placed. These pipes are then surrounded by a metal.

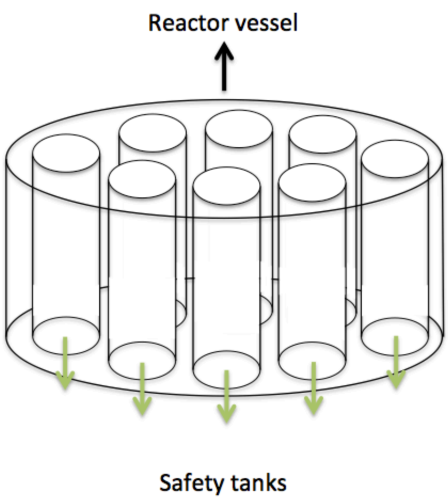



**Figure 2.1:** New design of the plug from a bird's eye view. The small pipes represent the different holes containing frozen salt of the plug, these are surrounded by a metal. The green arrows show the direction in which the fuel will flow whereas the black arrow shows the place of the reactor vessel.

Each hole has to be surrounded with the metal hastelloy N. This material is used in Molten Salt Reactors because it has a low corrosion rate[8]. The thickness of the hastelloy N part in this study is taken to be 8.5 mm to ensure the plug will hold for several years[9].

### 2.1.1. Design of a single pipe

In figure 2.2 and 2.3 the geometry of a single hole with surrounding metal walls is shown.

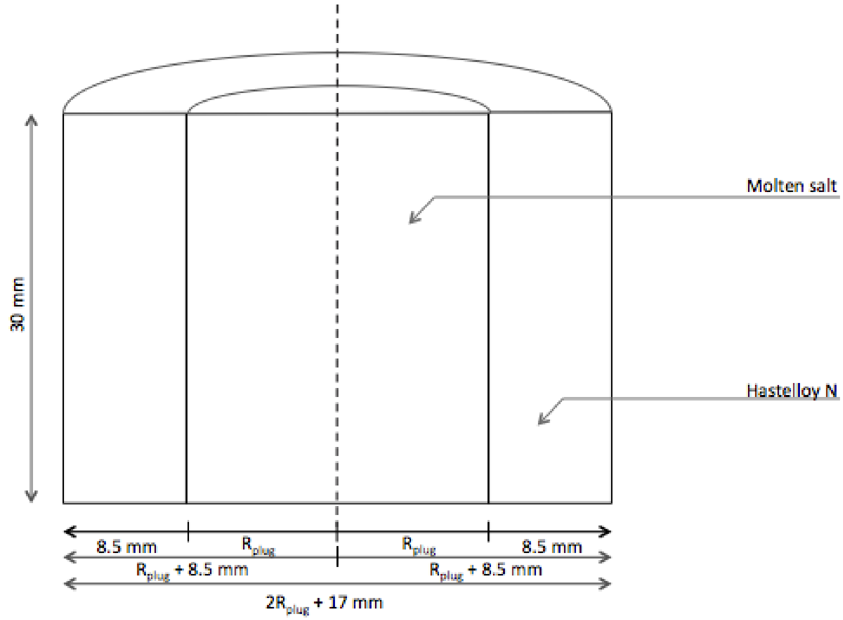



**Figure 2.2:** Cross-section of one hole of the plug with only molten salt and hastelloy N

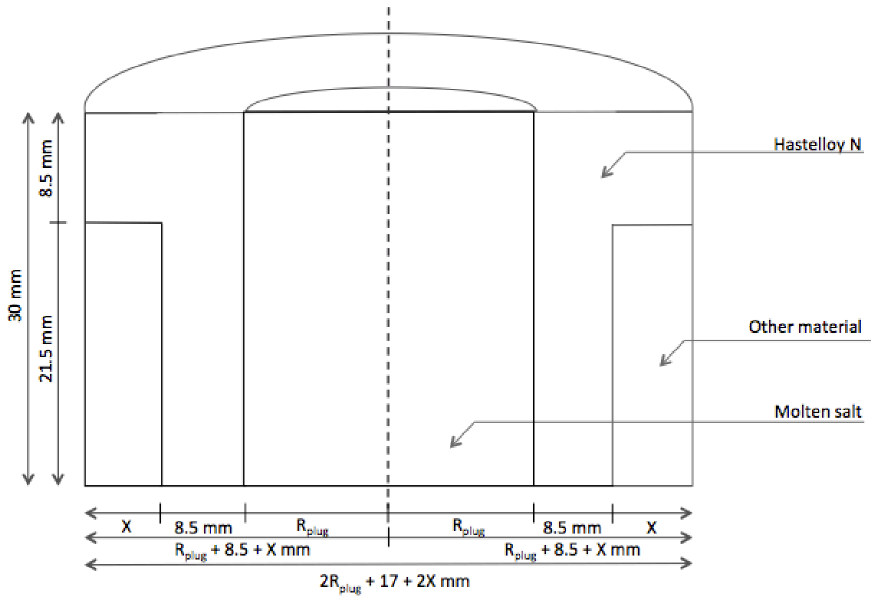



**Figure 2.3:** Cross-section of one hole with molten salt, hastelloy N and the other material

The first model consists of a narrow pipe made of hastelloy N as can be seen in figure 2.2. The second model is seen in figure 2.3 and has a thin wall of thickness $X$ of another heat conducting material attached to the hastelloy N. In both models the places where the metal comes in contact with the molten salt, a thin wall of 8.5 mm of hastelloy N is placed. The thickness of the unknown material is gradually changed in order to find an optimum at which the heat will be transferred fastest. The choice of this material depends on what material will conduct heat fastest. This choice will be made depending on the thermal conductivity and the specific heat of the material, how these affect the heat transfer will both be explained in chapter 2.3. Hastelloy N has $\lambda = 23.6$ and $C_p = 578$[3]. The extra metal that will be attached must have a larger thermal conductivity and a smaller specific heat.

The height of the plug is 30 mm which is only a small part of the total exit pipe. This height is chosen because the cross sectional area of the frozen salt is relatively small and can therefore withstand a large force. But also because the total plug in this design is filled with multiple metal walls which can carry more weight together than the one wall in the previous design. However it is not confirmed if this height is enough to really work in the reactor. It is possible that it could be less, making the melting time even smaller. To find an optimal height for the plug further research should be done. In both models the radius of the molten salt part is denoted as $R_{plug}$. This is because this radius has not been established and will be varied to find the relation between the melting time and the radius of the molten salt.

### 2.1.2. Advantages of the new design

The main advantage of this new design over the previous one is that the salt will melt much faster. This is the case due to the increased touching area between the frozen salt and the metal walls. But this is not the only advantage; the height of the frozen salt can be less in this new design because the cross sectional area of each pipe is smaller. The gravitational force of the fuel in the reactor vessel finds more resistance due to friction because of the increased touching area between the salt and metal. By decreasing the height of the frozen salt not only less salt will be needed, but also less salt needs to be molten before the plug will fall through the pipe.

## 2.2. Heat transfer

Energy can be transferred in multiple ways, an example is through transfer of heat. This transfer follows the two laws of thermodynamics. The first law states that the total energy is conserved, therefore to change the energy in a system energy must cross its boundaries. The second law states that energy will not flow spontaneously from a colder body to a warmer one. Moreover will this flow be in the direction in which it increases the total entropy of the system. Heat transfer can be divided into three subdivisions:

1. Conduction
2. Convection
3. Radiation

In this plug heat will be transferred through conduction and convection only. Therefore only those two will be discussed. Heat transfer with phase change also takes place. That is why a phase change will also be explained later on in this chapter.

### 2.2.1. Conduction

Conduction is the transfer of heat at the scale of one molecule[10]. Each molecule in a substance has its own energy, mass and momentum. When one molecule collides with another, the one with the higher energy will give a net of its momentum and energy to the other molecule. When there is a temperature gradient, flux of internal energy will occur in the direction of the lower temperature regions. Hence heat will be transferred without mass transfer. The most important equation used with conduction is the law of Fourier[11] shown in equation 2.1. In this equation $\phi''_{q,x}$ is the heat transfer on location x per unit area and $\lambda$ is the thermal conductivity.

$$\phi''_{q,x} = -\lambda\frac{\partial T}{\partial x} = -\lambda(T|_{x_2} - T|_{x_1}) \tag{2.1}$$

This equation shows that a gradient in temperature in the x direction will lead to a heat flux in the x direction as well. Moreover it says that heat will flow from a high temperature region to a low temperature region. This can be seen by looking at the case when the temperature at $x_2$ is higher than at $x_1$. The flux will then be negative due to the minus sign and will therefore be in the negative x direction. Leading to a flux from a higher temperature region to a lower one.

In this research conduction takes place in the metal that surrounds the molten salt as was seen in the beginning of this chapter. When an accident like a power outage happens, the metal surrounding the frozen salt will no longer be actively cooled. The temperature of the fuel inside the reactor vessel will rise and release its heat to the metal. This heat will then spread through conduction letting the temperature of the metal rise.

### 2.2.2. Convection

For convection thermal energy is transferred with the motion of the fluid. Molecules in the fluid move together and take energy and thus heat with them. This type of heat transfer can be further specified using the cause of the flow as our starting point. When the flow is caused by external forces such as a pump or a fan, it is called *forced convection*. But when there are no external forces, the motion happens due to density differences in the fluid caused by temperature gradients. This type of heat transfer is called *free* or *natural convection*. No matter the type of convection, the equation used to determine the heat flux $\phi''$ is known as the Newton's law of cooling for convection and is shown in equation 2.2.

$$\phi''_q = h(T_s - T_\infty) \tag{2.2}$$

This equation states that the heat flux depends on the difference in temperature of a surface ($T_s$) and the temperature of its surroundings ($T_\infty$). The parameter $h$ is called the *convection heat transfer coefficient* and depends on the conditions in the boundary layer.

In this research convection takes place at the interface of the hastelloy N and the reactor vessel. Because the fluid in the reactor is moving due to pumps, heat is here transferred because of forced convection. Because both the hastelloy N and the reactor fluid have their own heat transfer coefficient, a combined coefficient needs to be used. In figure 2.4 the way heat is transferred is shown.

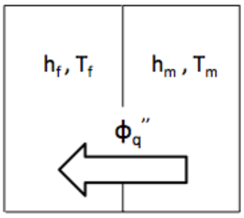



**Figure 2.4:** The way heat is transferred between two objects, one at temperature $T_m$ with heat transfer coefficient $h_m$ and the other at temperature $T_f$ with heat transfer coefficient $h_f$.

To calculate the heat flux, the overall heat transfer coefficient is needed. This is calculated using equation 2.3.

$$U = (\frac{1}{h_m} + \frac{1}{h_f})^{-1} \tag{2.3}$$

In this equation $h_m$ and $h_f$ are the heat transfer coefficients of the metal hastelloy-N and the reactor fluid respectively. When $h_m$ is much larger than $h_f$, $U$ in equation 2.3 will become almost equal to $h_f$. In this case the temperature of the surroundings can be set equal to the temperature of the wall meaning $T_\infty = T_w$.

### 2.2.3. Phase change

Heat transfer with phase change is more commonly known as for example freezing, condensation and vaporization. When a material changes phase, the properties often change as well. An example of this is the density decrease when liquid becomes gas. In this project the molten salt changes from solid to liquid, better known as melting. When this happens energy is added to the system. But instead of a rise in temperature, the material's molecular structure is changed. The step by step transition from solid to liquid is as follows:

1. Heat is applied to a solid material

2. The particles in the solid absorb the heat energy
3. The heat energy is converted by the particles into kinetic energy
4. The kinetic energy increases and thereby the particles vibration increases as well
5. When melting point is reached, the particles have enough energy to overcome the forces that keep the particles together
6. The particles move away from each other and their initial position
7. Liquid has formed

The heat energy that is absorbed by the particles to overcome the forces that keep the particles together when there is no temperature change is called the latent heat. This latent heat, also known as the enthalpy of fusion, is a specific property of a material and shows the change in enthalpy when a substance changes from solid to liquid.

In this project the frozen salt in the holes of the plug will change phase from solid to liquid. Heat will be applied to the frozen salt from the top, due to a rise in temperature of the fuel, and from the sides, due to a rise in temperature of the metal. At a certain moment the sides of the frozen salt will melt and cause the friction force between the salt and the hastelloy N to decrease. When the gravitational force of the weight of the salt exceeds this friction force, the frozen salt will fall down the pipes and the reactor fuel is able to flow through these pipes out of the vessel.

## 2.3. Effects of the design on the heat transfer

Heat transfer differs if another material or another geometry is used. It is influenced by for example thermal conductivity, specific heat and the density of a material. The geometry of the system also has an effect on the heat transfer. How this effects the transfer of heat will be explained in the following section.

### 2.3.1. Thermal conductivity

The rate at which heat is transferred depends solely on the thermal conductivity. This value is a specific property of a material and tells the capability to conduct heat. A material with a higher thermal conductivity will therefore conduct heat faster than a material with a lower conductivity. This is easily seen when looking at equation 2.2. The thermal conductivity depends on the temperature and density of the material. In this project heat will be transferred with conduction in the metal part of the plug. The metal that is used in the plug will have a specific thermal conductivity. When other metals are used, this will lead to a different rate at which the heat will be transferred. Therefore the metal that is used in the plug will be varied in this project.

### 2.3.2. Specific heat

The specific heat can be defined as the amount of energy that is needed to raise the temperature of 1 kilogram of a material with 1 K. Specific heat is therefore also a property of a material. It has no influence on the rate at which heat is transferred but it has influence on the rate at which the temperature changes. Less energy is needed to change the temperature of a material with a lower specific heat. As for the thermal conductivity the specific heat will be determined by the metal that is chosen to surround the frozen plug and the metal will be chosen based on the materials specific heat.

### 2.3.3. Geometry

The transfer of heat between two objects depends on the amount of area between the objects that touch. A larger touching area means more heat transfer. However when one or both objects contain large volumes that don't touch, heat will transfer through this volume without effecting the other object. Imagine for example an oven with a thick stone wall, inside the oven the temperature can be up to

200 °C but outside of the oven you might not feel anything of it. This is because of the large amount of stone the heat must go through before it reaches the outside. In this report the thickness of the metal part surrounding the plug will be varied. By doing this the volume through which the heat must go before it reaches the salt is therefore different in each case. Not only the thickness of the metal but also the radius of the plug will be changed. If the radius of the pipe is small, multiple pipes will be used. Therefore the total area between the frozen salt and the metal is larger.

## 2.4. Draining of the tank

When an accident happens, the reactor must be emptied of all its content in under 8 minutes as was discussed in chapter 1.1.2. Within this time the plug has to be melted and all the fluid has to have left the reactor. The fluid will exit the tank through a pipe which is closed with the freeze plug. In the original design only one pipe is used whereas in the design that will be studied in this report multiple smaller plugs and accompanying pipes are used. Using more plugs will reduce the time the plug needs to be fully melted. This is because the area between the metal and the frozen salt is larger and therefore the plug will be heated at more places at once. The frozen salt will then fall through the pipe faster. However the time the fluid takes to leave the reactor, called the drainage time, shouldn't be more in this new design. The total outgoing flux of both designs must therefore be equal. In order to achieve this a certain amount of pipes has to be found.

### 2.4.1. Drainage time with one pipe

The drainage time for one pipe[12] can be calculated using the one dimensional steady state mechanical-energy balance [11].

$$\phi_m(\frac{1}{2}v_1^2 + \frac{P_1}{\rho} + gz_1 - \frac{1}{2}v_2^2 - \frac{P_2}{\rho} - gz_2) - \phi_m e_{diss} = 0 \tag{2.4}$$

In this equation $\phi_m, g$ and $p$ are respectively the mass flow through the pipe, the gravitational acceleration and the density, which are all constant in this situation. $P, v$ and $z$ are the pressure, the velocity and the height respectively at point $i$. The points that are taken into account are, as shown in figure 2.5, firstly at the top of the fluid in the reactor and secondly at the bottom of the exit pipe. $P_1$ is equal to $P_2$, both are at atmospheric pressure since that is the pressure the reactor works under. Because the radius of the reactor tank is much larger than the radius of the pipe, the velocity at point 1 can be neglected as it is very small compared to $v_2$. The height ($z$) is divided into two parts $h_t(t)$, the height of the fluid in the tank and $L$, the length of the exit pipe. The energy that is dissipated due to friction in the exit pipe is denoted as $e_{diss}$ and can be calculated using equation 2.5.

$$e_{diss} = \frac{1}{2}v^2(4f\frac{L}{D} + K_{tot}) \tag{2.5}$$

Here the velocity $v$ is equal to $v_2$ used in equation 2.4 as the diameter, denoted as $D$, of the pipe does not change. The fanning friction factor is noted as $f$ and $K_{tot}$ is the resistance coefficient. Combining equation 2.4 and 2.5 leads to the following equation.

$$g(h_t(t) + L) - \frac{1}{2}v^2 - \frac{1}{2}v^2(4f\frac{L}{D} + K_{tot}) = 0 \tag{2.6}$$

From equation 2.6 we can find the velocity at the exit of the pipes.

$$v = \sqrt{\frac{2g(h_t(t) + L)}{1 + 4f\frac{L}{D} + K_{tot}}} \tag{2.7}$$

The only unknown in this equation is the time dependent height of the fluid in the tank $h(t)$. This is easily found using the law of conservation of mass which is shown in equation 2.8.

$$\frac{\partial M}{\partial t} = \rho\pi R_{tank}^2\frac{\partial h_t}{\partial t} = \rho(A_1v_1 - A_2v_2) \tag{2.8}$$

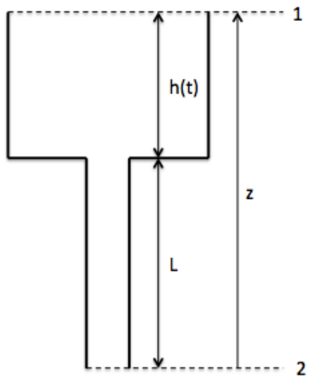



**Figure 2.5:** Geometry of the reactor tank and the drainage pipe.

In which $R_{tank}$ stands for the radius of the tank and $A_1$ and $A_2$ for the surface area of the tank and the pipe respectively. Using equation 2.7 for $v_2$ and the fact that $v_1$ is zero, a function for $\frac{\partial h}{\partial t}$ can be found.

$$\frac{\partial h_t}{\partial t} = -\frac{r^2}{R^2}\sqrt{\frac{2g}{1+4f\frac{L}{D}+K_{tot}}}\sqrt{h_t(t)+L} = -k\sqrt{h_t(t)+L} \tag{2.9}$$

Here $r$ is the radius of the pipe and $k$ is defined to simplify the equation since it is constant. This is a first order differential equation which can be solved with the help of boundary conditions. For this problem the boundary condition that is used is $h(0) = H_0$, $H_0$ stands for the height of the fluid in the tank before the plug has melted and the drainage has started. Applying this boundary condition to equation 2.9 will lead to equation 2.10.

$$h_t(t) = \frac{k^2}{4}t^2 - kt\sqrt{H_0+L} + H_0 \tag{2.10}$$

A function for the drainage time can be found when equation 2.9 is integrated from $t = 0$ to $t = t_{drain}$ and $h = H$ to $h = 0$. This will give the following expression.

$$t_{drain} = \frac{R_{tank}^2}{r^2}\sqrt{\frac{2\left(1+4f\frac{L}{D}+K_{tot}\right)}{g}}\left(\sqrt{H+L}-\sqrt{L}\right) \tag{2.11}$$

### 2.4.2. Volume flow rate

When the new design and the old design of the plug must have an equal drainage time, the volume of fluid that comes out of the pipe per second has to be equal for both designs. This volume flow rate can be defined by:

$$\phi_V = Av \tag{2.12}$$

In which $v$ is the volume flow rate and $A$ the cross-sectional area of the pipe. The radius of the pipe in the new design is smaller than the radius in the old design leading to a different value for $A$. Moreover the velocity in both systems is different. To still achieve an equal volume flow rate at the exit of the pipes, multiple pipes are placed in the new system. The amount that has to be placed can be calculated using equation 2.13.

$$amount\,of\,pipes = \frac{\phi_{V,1}}{\phi_{V,m}} \tag{2.13}$$

In this equation $\phi_{V,1}$ stands for the volume flow rate for one pipe and $\phi_{V,m}$ for multiple pipes.

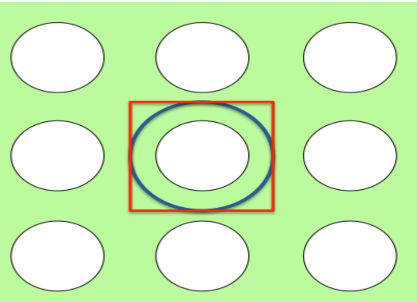
# 3

# Numerical methods

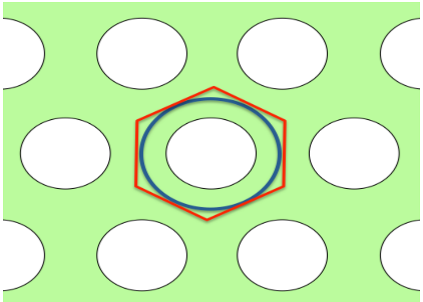
This project is done using two different programs: COMSOL Multiphysics and MATLAB. COMSOL is a simulation environment where real life problems can be modelled as closely as possible. The geometry of the problem can easily be made within COMSOL and after building the model, properties of the materials and specific physics can be added to certain domains or boundaries. To simulate the problem a choice can be made from a wide range of possible physic studies, a few examples of this are acoustics, fluid flow and heat transfer. In this research the only used model is heat transfer and specifically heat transfer in solids. COMSOL can also make a difference between stationary and time-dependent studies. The time it takes for the plug to be melted with different geometries is investigated using COMSOL whereas the time for the tank to be drained of all its content is calculated using MATLAB.

## 3.1. Geometry

The reactor has a geometry as is shown in figure 2.5. The plug will be placed at the entrance of the exit pipe. When looking at the safety plug from above it will look similar to a shower drain as can be seen in figure 3.1 in which each black circle corresponds with one plug. Instead of only one hole as was used in the previous design, a lot of small holes together form the new plug. Modelling this in COMSOL, only one small hole is investigated. For simplicity a 2D axisymmetric space dimension is used. The boundary of one hole in this dimension will take the form of a circle, shown in figure 3.1 in blue, while in reality the boundaries will not have this form. When the holes lie as in figure 3.1a the real boundaries will take the form of a square, shown in red. However when the holes are placed close-packed together, see figure 3.1b, the real boundaries will have the form of a hexagon, shown in red, which is more similar to the circle boundaries modelled in COMSOL.



**(a)** Geometry of the plug when the holes lie lined up horizontally and vertically



**(b)** Geometry of the plug when the holes lie closepacked together

**Figure 3.1:** Different geometries of the plug. The black circles represent the holes of the plug containing the frozen salt. These holes are surrounded by the metal shown in green. In blue the boundary used in COMSOL and in red the real boundary when that geometry is used.

### 3.1.1. Materials

The composition of the molten salt is not the same in every MSR and of these different types of salt not all properties are known for all conditions. However the properties of LiF-$ThF_4$ (78 − 22 mol %) for specific temperature ranges have been investigated by Ignatiev et al. [2]. The results of this investigation are shown in table 3.1. Because the melting temperature of the molten salt is 570 °C, the properties found by Ignatiev et al. can only be used for the liquid salt and not for the solid salt. For the solid salt the properties of lithium chloride (LiCl) are used[3]. This salt is chosen because it has a melting temperature close to the melting temperature of LiF-$ThF_4$, 610 °C for LiCl as opposed to 570 °C for the molten salt. However it is not known if this is a reliable estimation or even if these are remotely similar because nothing is yet known about the properties of the solid salt. The necessary properties of LiCl are all available in the database of COMSOL.

**Table 3.1:** Properties of molten salt LiF-$ThF_4$, where in all formulae temperature $T$ is in K. The value of $C_p$ for 700°C is extrapolated, as it is outside of the range that is investigated by Ignatiev et al[2].

| | Model | Value at 700 °C | Validity range (°C) |
|---|---|---|---|
| $\rho$ (g cm$^{-3}$) | $4.094 - 8.82 \cdot 10^{-4}(T - 1008)$ | 4.1249 | [620 − 850] |
| $\nu$ (m$^2$ s$^{-1}$) | $5.54 \cdot 10^{-8} \cdot \exp(3689/T)$ | $2.46 \cdot 10^{-6}$ | [625 − 846] |
| $\mu$ (Pa s) | $\rho$ (g cm$^{-3}$) $\cdot 5.54 \cdot 10^{-5} \cdot \exp(3689/T)$ | $10.1 \cdot 10^{-3}$ | [625 − 846] |
| $\lambda$ (W m$^{-1}$ K$^{-1}$) | $0.928 + 8.397 \cdot 10^{-5} \cdot T$ | 1.0097 | [618 − 747] |
| $C_p$ (J g$^{-1}$ K$^{-1}$) | $-1.111 + 0.00278 \cdot T$ | 1594 | [594 − 634] |

### 3.1.2. Optimal thickness of the extra material

To find the optimal thickness of the extra material attached to the hastelloy N a new study is added. This extra study is called the *parametric sweep*. Here multiple thicknesses of the extra material can be studied at once. The sweep is done from $x = 1.5mm$ to $x = 3.5mm$ with a step of $0.1mm$.

## 3.2. Physics

The physics interface applied to this model is heat transfer in solids. This interface has some sub-functions:

- Heat transfer in solids
- Initial values
- Temperature
- Thermal insulation
- Heat transfer with phase change

Heat transfer in solids is applied to the metal part of the model, first only hastelloy N but in the second model in the extra material as well.

### 3.2.1. Initial and boundary conditions

The initial temperature of the whole model is set at 773 K. This temperature is well below the melting temperature of the molten salt in order to make sure that everything is frozen and the melting time is not underestimated.

When an accident happens in the reactor the temperature will rise at the top of the plug. Therefore this new higher temperature will be applied at the top boundary of the plug. Because an initial value is set at the entire model, this new temperature can not just be set at the top because this will produce unphysical values in the numerical computation. A step-function (figure 3.2) can help to avoid these undershoots of the temperature. Starting at the initial temperature of 773 K and ending at 973 K, the step function will make the temperature transition smoother.

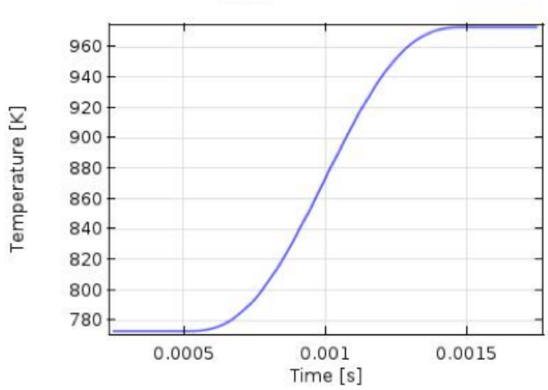



**Figure 3.2:** Step function modelled in COMSOL to smooth the time dependent temperature change which is applied at the top of the plug. The x-axis displays time and the y-axis the factor to which it ramps $T(0)$.

The other outer boundaries, meaning the sides and the bottom of the plug, are set to be thermally insulated. This means that at these places the transfer of heat is minimized. When looking at the sides of one plug the amount of heat flowing in equals the amount flowing out due to symmetry. This is the reason why thermal insulation can be used here.

The salt will at first be frozen but when the temperature rises, this will start to melt. Therefore the module heat transfer with phase change is applied to the salt part. The properties of the salt that need to be known are: heat capacity, density, thermal conductivity, specific heat ratio, melting temperature, melting temperature range and latent heat of fusion. These properties have to be known of both the frozen and the molten salt in order to get a working phase change. The melting temperature of the salt is set at 570 °C. The chosen melting temperature range is taken from the project done by Koks [5] and is 0.5 K.

## 3.3. Estimation of the time the plug may drop

At the interface between the hastelloy N and the salt a line is drawn as is shown in figure 3.3 with a red line. This line will be studied in order to find out at which time the plug has melted. When the bottom of this line shows change, meaning a changing phase, the plug will fall through the pipe due to its weight. The time at which this happens will be called the melting time.

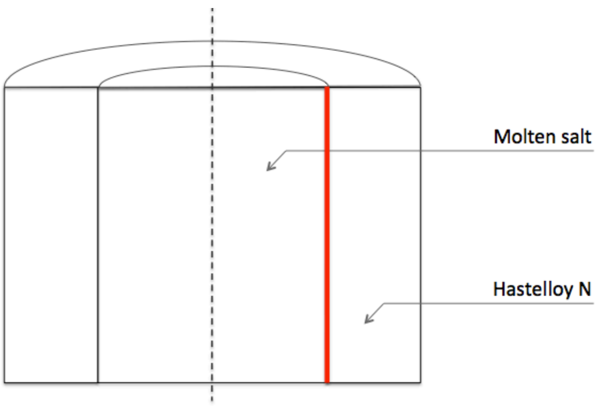



**Figure 3.3:** In red the line at which the phase change of the model is studied. When the bottom of this line shows change, the plug will most likely fall through the pipe.

This study is done within a certain time range. This range is chosen to be from 0 until 50 seconds with time steps of 0.01 seconds. This time step is chosen in order to find the time at which the frozen salt has melted at the studied line accurately. First a time range from 0 to 480 was studied with time step of 20 seconds. The max of 480 seconds was chosen because that is the total permitted time the tank has to be completely empty. The choice for 0 to 50 seconds follows from this study because at 50 seconds the studied line had fully melted. However a smaller step can be used in order to make it even more accurate. For this project it is only of importance whether the time the plug needs to melt is less than the total permitted time and less than the time the previous plug needed to melt. Therefore a time step of 0.01 is enough for this study.

## 3.4. Meshing

The meshing is of importance in order to get an accurate result. Of interest is the way the frozen salt melts at the line which is shown in figure 3.3. Therefore the highest level of accuracy is required near the interface between the hastelloy N and the frozen salt. At the other places in the plug the density of the mesh is less because these places will not be studied. The final used mesh is shown in figure 3.4.

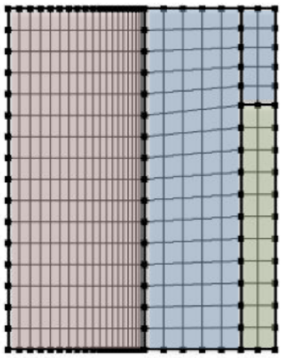


**Figure 3.4:** Mesh put on the geometry as is seen in figure 2.3. In pink the frozen salt is shown, in blue the metal hastelloy N and in green copper. The total number of elements that are placed is 432.

In this figure the pink, green and blue area denote respectively the frozen salt, the copper and the hastelloy N as is seen in figure 2.3. A total of 432 elements are used which is divided in 22 elements for the copper, 90 elements for the hastelloy N and the remaining 320 elements for the frozen salt. More elements could be placed in this mesh to make the model more accurate. However this would take even more time to compute and this mesh already shows the influence of this design on the melting time with respect to the previous design.

## 3.5. Drainage time and amount of pipes

The drainage time is calculated using equation 2.11. The results are produced using MATLAB, in which the drainage time is calculated for different values of pipe radius and length. The following parameters, shown in table 3.2 are constants and are taken from the project of van den Bergh [12].

**Table 3.2:** Constants applied in calculating the drainage time

| $R_{tank}$[m] | $H_{tank}$ [m] | $\rho$ [kg/m$^3$] | $f$ | $K_{tot}$ |
|---|---|---|---|---|
| 1.42 | 2.84 | 4125 | 0.0034 | 0.5 |

The radius and the length of the pipe are varied from respectively $0.01m$ to $0.1m$ and from $0.5m$ to $8m$. The MATLAB scripts are shown in the appendices.

# 4
# Results

In this chapter the results of the computations done with COMSOL and Matlab as discussed in chapter 3 are shown. These results are split into two parts, the melting time and the drainage time and at the end the total time will be discussed.

## 4.1. Melting time

The time it takes for the plug to be melted is calculated in a less reliable way than the way the drainage time is calculated. This is because there is no analytical way to calculate this, all the results are taken from COMSOL and are read from the graphs made by COMSOL. The reason this is less reliable is because here it can not be checked if the calculations that are made are realistic or correspond to the reality. It is not very accurate as many of the results are read from graphs made in COMSOL. When the scale of such a graph is changed, the visual perception of the data may change as well.

The variables that are taken into account are the choice of material, the thickness of this material and last but not least the radius of the pipe.

### 4.1.1. Choice of the metal used in the plug

The material that is attached to the hastelloy N in figure 2.3 is chosen on grounds of the properties of the material. In order to get an short melting time, the rate at which heat is transferred must be large. Because hastelloy N does not have a large thermal conductivity nor a small specific heat, the rate of heat transfer is not optimal. When looking at the properties of different other materials, the one that seems best for this purpose is copper. To compare it with hastelloy N, some of its properties are denoted in table 4.1 at a temperature of 700 °C.

**Table 4.1:** Properties of copper compared to hastelloy N[3]

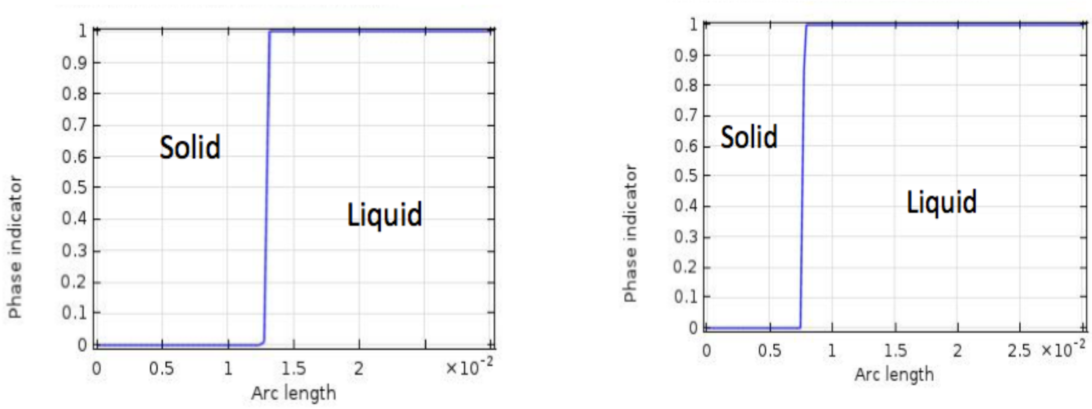
| | $\lambda$ (W m$^{-1}$ K$^{-1}$) | $C_p$ (J g$^{-1}$ K$^{-1}$) | $a$ (m$^2$ s$^{-1}$) | Melting point (°C) |
|---|---|---|---|---|
| Copper | 357 | 0.385 | $1.16 \cdot 10^{-4}$ | 1083.2-1083.6 |
| Hastelloy N | 23.6 | 0.578 | $4.6 \cdot 10^{-6}$ | 1300-1400 |

In this table $a$ is the thermal diffusivity of a material. It measures the rate at which heat is transferred and can be calculated using equation 4.1.

$$a = \frac{\lambda}{C_p \rho} \tag{4.1}$$

It is seen clearly from table 4.1 that copper will transfer heat much faster than hastelloy N as it has a larger thermal conductivity and that the temperature change will go faster as well due to a smaller heat capacitance. Both melting points are high enough in order to make sure that they will not melt during the process.

Both models displayed in chapter 3.1.1 are made with COMSOL. For the second model (figure 2.3) the material that is attached to the hastelloy N has now been chosen to be copper. For an equal radius of the frozen salt, set at 10 mm which was randomly chosen, and an equal thickness of the hastelloy N, set at 8.5 mm because that is the minimal thickness of the hastelloy N as was discussed previously, the models are compared. The copper thickness is set at $x = 2mm$, this value is randomly here chosen merely to find if the extra metal part will have a positive effect on the melting time. The melting depth at 40 seconds is read from graphs off both models. These graphs, shown in figure 4.1, show the change in phase from solid to liquid at the line at the interface which was mentioned before in section 3.3. In these figures a "1" means the material is in liquid phase and a "0" means it is still solid. The horizontal axis shows the length of the line in meters, 0 being at the bottom and $3 \cdot 10^{-2}$ the top of the plug.




**(a)** Only hastelloy N

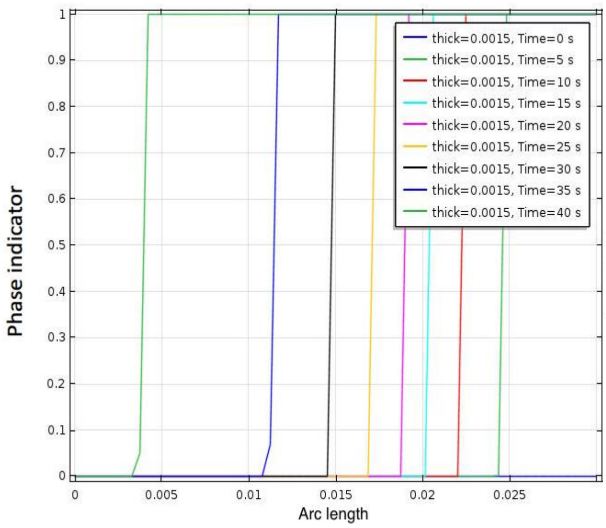
**(b)** Copper and hastelloy N

**Figure 4.1:** Graphs showing the phase change at 40 seconds at the interface between the salt and the hastelloy N for a pipe with only hastelloy N and a pipe with hastelloy N and copper. With arc length the length of the line at the interface is meant, 0 being at the bottom of the line and $3 \cdot 10^{-2}$ the top of the plug.

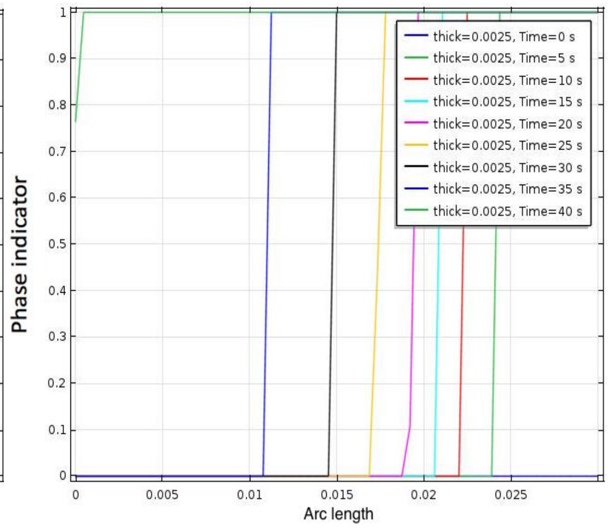
From figure 4.1 it can clearly be concluded that adding the copper to the construction will improve the heat transfer.

### 4.1.2. Thickness of the material

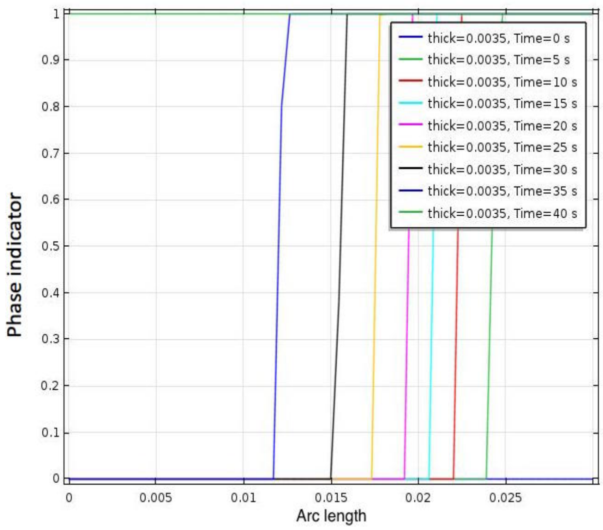
The thickness of the copper attached to the hastelloy N is varied from $1.5mm$ to $4mm$ with steps of $0.5mm$. This is determined by studying the phase change at the line at the interface between hastelloy N and the frozen salt. For each thickness a graph like the graphs in figure 4.1 is made. This is done using the parametric sweep study as was explained in chapter 3. This study gives the phase change for each different thickness. In figure 4.2 the graphs for a thickness of 1.5, 2.5 and $3.5mm$ are shown. When comparing the different thicknesses per time, the one with the faster heat transfer is the one which has a line more to the left. From these graphs it can then be concluded that a thickness of $2.5mm$ will lead to the fastest heat transfer and melting process.




**(a)** Copper thickness 1.5 mm




**(b)** Copper thickness 2.5 mm




**(c)** Copper thickness 3.5 mm

**Figure 4.2:** Graphs showing the phase change at the interface between hastelloy N and the salt for different thicknesses of the copper. The vertical axis shows whether the phase is liquid or solid; a "1" meaning liquid and a "0" meaning solid. The horizontal axis shows the length of the studied line. The phase is measured with three different thicknesses for the copper and at 9 different times.

### 4.1.3. Diameter of a single hole in the plug

The radius of the hole in the plug also has an influence on the melting time. This is because the area of the frozen salt that is in contact with the hastelloy N changes size with a changing radius of hole of the plug containing the frozen salt. Making the radius larger will increase the interface and will lead to a larger area where heat can be exchanged.

The phase change along the height of the plug is again studied. In figure 4.3 the length of the pipe which has yet to melt is shown versus the radius of the pipe. This is calculated at four different times, $t = 15$ seconds, $t = 20$ seconds, $t = 25$ seconds and $t = 30$ seconds.

Because the data in this graph is read from COMSOL, it is not very accurate. This is why the graph shows a lot of bumps.

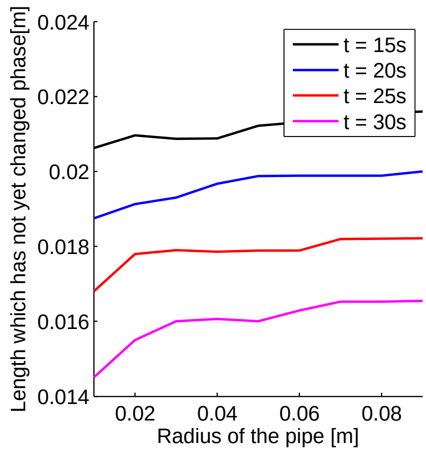



**Figure 4.3:** The length of the plug that still has to melt versus the radius of the hole in the plug which contains the frozen salt at $t = 15s$, $t = 20s$, $t = 25s$ and $t = 30s$. The total height of the plug is $0.03m$.

The time at which the bottom of the line has changed phase and as such the time at which the plug will fall through the pipe is shown per radius in figure 4.4.

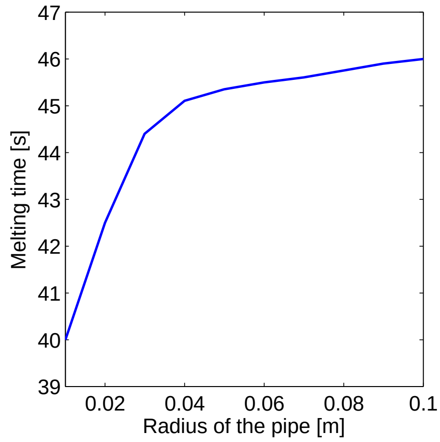



**Figure 4.4:** Time [s] the frozen salt in the plug needs to be completely molten per radius [m] of the pipe.

As can be seen from this figure the melting time varies between 40 seconds for a radius of $0.01m$ to 46 seconds for a radius of $0.1m$.

## 4.2. Drainage time

As said before the drainage time can be analysed more accurately than the melting time. The variables that affect the drainage time are the length and diameter of the pipe. Varying these will have an effect on the volume flow rate and therefore on the number of pipes needed.

### 4.2.1. Pipe length

The length of the pipe has an influence on the drainage time as was seen in chapter 2.4. The length will have an effect on the velocity of the fluid, this can be seen in equation 2.7. Here it is clearly shown that the length of the pipe has a positive and a negative effect on the final value of the velocity. The negative effect comes from the resistance the fluid will undergo through the pipe and the positive effect from the total potential energy that will be converted into kinetic energy. To find the dependence of the drainage time on the pipe length, the length is varied from 0.5 m to 8 m. At the same time the radius of the pipe is varied from 0.01 m to 0.05 m. The results are shown in figure 4.5.

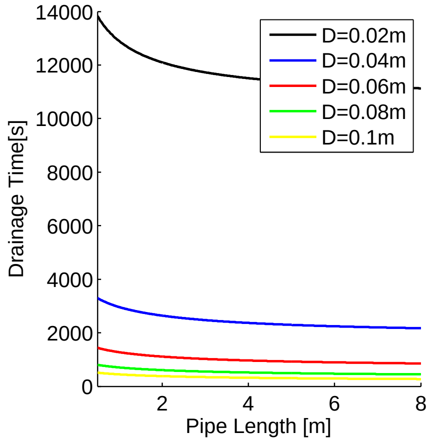


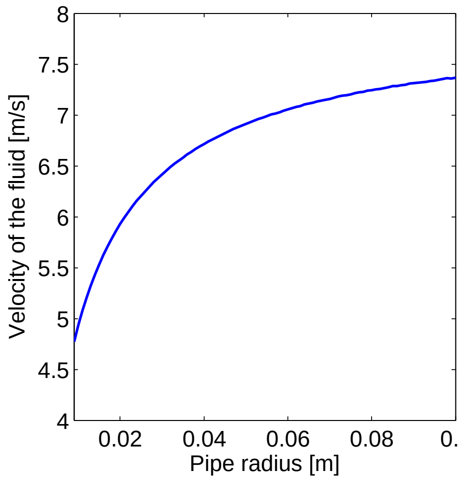

**Figure 4.5:** Drainage time[s] plotted against the length of the pipe [m] per diameter D of the pipe.

In this figure for each diameter of the hole in the plug a graph is made varying the length of the pipe and therewith calculating the drainage time per pipe length. The highest line corresponds to the smallest radius while the lowest line corresponds to the largest used radius. While calculating this the thickness of the metal and the amount of fuel that has to leave the tank is held constant. Also in every calculation only one plug and accompanying pipe is taken into account.

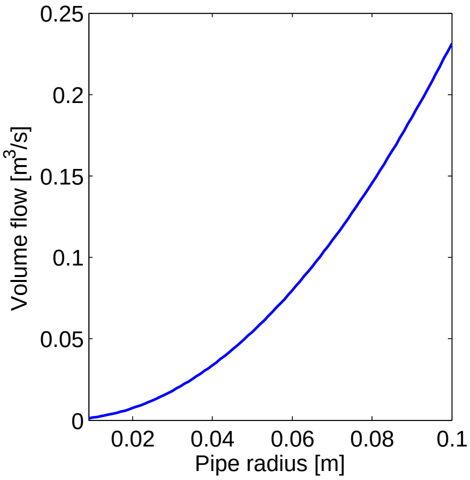
In the study done by van der Bergh [12] it was found that when the diameter is held constant, the drainage time does not vary a lot after it has reached 3.5 m. From this figure it can now be seen that this counts for all different diameters. Moreover it can be seen that varying the pipe length has a much smaller effect on the drainage time than varying the diameter. From here on the pipe length is therefore set at 3.5m for all calculations.

### 4.2.2. Diameter of a single hole in the plug

The diameter of the holes in the plug are also varied but this time at a constant pipe length. The diameter of the hole in the plug has an effect on the velocity of the fluid as well. The way the diameter effects the velocity was discussed in chapter 2 and can be seen in equation 2.7. Moreover it is is shown in figure 4.6a. Here the mean velocity of the fluid is calculated per radius of the pipe.




**(a)** Mean velocity [m s$^{-1}$] of the fluid flowing through the pipe.




**(b)** Volume flow [m$^3$ s$^{-1}$]of the fluid flowing through the pipe.

**Figure 4.6:** The length of the pipe is constant at $3.5m$ and the radius is varied from $0.01m$ to $0.1m$. Only one pipe is taken into account.

The importance of the velocity of the fluid can be explained using equation 2.12. As can be seen in this equation the velocity of the fluid has a direct effect on the volume flow and therefore on the drainage time. An increasing radius leads to an increase in volume flow as is expected because both the area $A$ and the velocity $v$ in equation 2.12 get larger with a larger radius.

In figure 4.6a it is seen that a smaller radius leads to the fluid moving slower through the pipes. This is not what is expected when looking at the continuity equation. The continuity equation for this case is shown in equation 4.2.

$$\Phi_{m,0} = m\phi_{m,1} + \phi_{m,2} + \phi_{m,3} + ... + \phi_{m,n} \tag{4.2}$$

In this equation $\Phi_{m,0}$ denotes the mass flow when one pipe is used whereas $\phi_{m,i}$ is the mass flow of the $i^{th}$ pipe with a total of $n$ pipes. When the mass flow is written in terms of velocity, area and density the equation can be rewritten.

$$v_0 A_0 \rho = v_1 A_1 \rho + v_2 A_2 \rho + v_3 A_3 \rho + ... + v_n A_n \rho \tag{4.3}$$

Because the density is equal at every point, the equation will be reduced to the following:

$$v_0 A_0 = v_1 A_1 + v_2 A_2 + v_3 A_3 + ... + v_n A_n \tag{4.4}$$

From equation 4.4 it can be concluded that a decrease in radius should lead to an increase in velocity because the left side of the equation does not change. However in this case it was found that the velocity rises with an increased radius. This probably follows from the fact that by using multiple pipes, the fluid will encounter more friction as the area between the fluid and the walls is increased.

The decreasing velocity is not the only negative effect on the drainage time. As was seen in equation 2.11 the drainage time depends on the radius of the pipe with $r^{-2}$. This leads to the following graph.

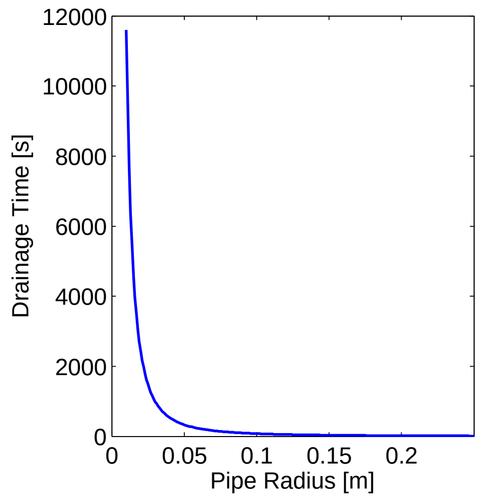



**Figure 4.7:** Drainage time [s] for different radii of the pipe. The length of the pipe is constant at $3.5m$ and the radius is varied from $0.01m$ to $0.25m$. Only one pipe is taken into account.

From this graph (figure 4.7) it is seen that the effect of the radius of the exit pipe is large for radii smaller than approximately $0.05m$. An equal outgoing volume flow for all different radii will cause an equal drainage time per radius. To achieve an equal drainage time and volume flow the number of holes placed in the plug will differ per radius. For radii smaller than approximately $0.05m$ the number of holes will have to be much larger than for radii bigger than $0.05$. The exact number of pipes that have to be placed per radius will be discussed in the next section.

### 4.2.3. Number of pipes

The number of pipes or the number of holes inside the plug that will be placed in the reactor is arbitrary. It can be chosen on grounds of multiple different parameters. In this report the number of pipes will be chosen by comparing the new design and the previous design on two different grounds.

- Equal volume flow rate [$\phi_v$]
- Equal total area [$A$]

### Number of pipes based on an equal volume flow rate [$\phi_v$]

First the number of pipes is chosen depending on an equal volume flow rate. The value for the volume flow rate that is chosen is the volume flow rate of the previous design which is $0.2315 \text{m}^3\,\text{s}^{-1}$. The volume flow rate depends on the radius as was discussed in chapter 2.4.2. For all different radii this flow rate must be equal, therefore the number of pipes placed in the plug is different per radius. In figure 4.7 it was seen that small radii have a large effect on the total drainage time. Therefore more pipes are needed for these radii in order to get an equal volume flow rate.

The volume flow rate depends on the area of the pipe perpendicular to the direction of motion and the velocity of the fluid, see equation 2.12. For small radii of the pipe not only the velocity is much smaller but also, with a much bigger effect, will the area be smaller.

In figure 4.8 the number of pipes per radius are plotted against each other.

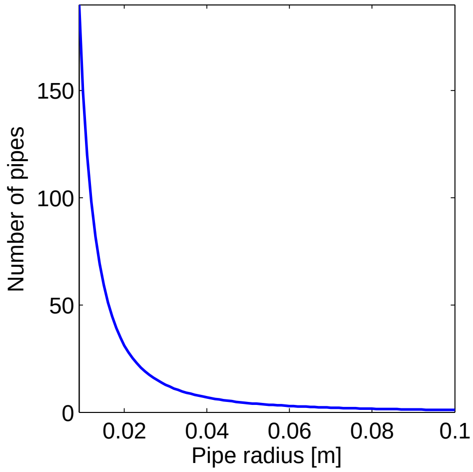



**Figure 4.8:** The number of pipes needed to obtain an equal volume flow rate per radius of the exit pipe. The value for the volume flow rate that is chosen is the volume flow rate of the previous design which is $0.2315 \text{m}^3\,\text{s}^{-1}$.

For several radii the number of pipes rounded up is also shown in table 4.2 for more clearance.

**Table 4.2:** Number of pipes needed for certain radii of the pipe when a set value of the volume flow rate ($\phi_v = 0.2315 \text{m}^3\,\text{s}^{-1}$) is chosen.

| Radius of pipe [m] | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of pipes | 150 | 32 | 13 | 7 | 5 | 3 | 3 | 2 | 2 | 1 |

### Number of pipes for an equal total area

When not the volume flow rate but the area of the pipes or the holes in the plug must be equal for both designs, it is evident that the volume flow rate will not be equal. If for instance the old plug is chosen as an initial starting area, the number of pipes that fit in this circle are shown in table 4.3 for certain radii.

**Table 4.3:** Number of pipes needed for certain radii when contained in a circle with radius 0.1 m.

| Radius of pipe [m] | 0.010 | 0.015 | 0.020 | 0.025 | 0.030 | 0.035 | 0.040 | 0.045 | 0.050 |
|---|---|---|---|---|---|---|---|---|---|
| Number of pipes | 16 | 9 | 7 | 5 | 4 | 3 | 1 | 1 | 1 |

In this table the radius of the pipe, or the hole in the plug, is shown. To find how many of these holes fit in a larger circle, the walls around the frozen salt must be taken into account as well. This can be seen in figure 4.9. In this figure the radius of a single hole and the radius of a hole with the metal is shown. It is evident that when calculating the number of pipes that can be placed, the thickness of the walls must be considered as well.

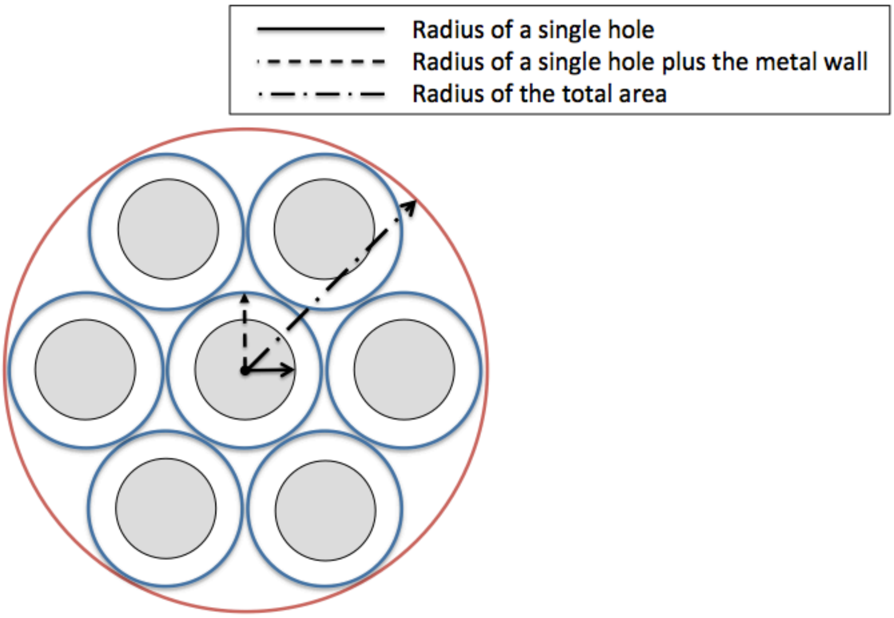



**Figure 4.9:** The total area the plug takes in is shown in red. This plug contains multiple holes with frozen salt shown in grey with a metal wall shown in blue. When calculating the number of holes that fit inside the plug, the thickness of the metal walls surrounding the frozen salt must be taken into account as well.

When a wall of 8.5 mm of hastelloy N and a wall of 2.5 mm of copper is chosen, a total of 11 mm must be added to each radius. Therefore already when the hole gets a larger radius than 39 mm only 1 pipe will fit in the 100 mm wide radius of the initial hole.

However the reactor vessel has a radius of 1.42 m. When this is the radius that is chosen as an initial reference radius, a lot more pipes can be added to the system. By choosing this, the total bottom of the tank will be filled with pipes. The number of pipes that fit per radius are shown in table 4.4. Whether this is realistic hasn't been confirmed and should be further investigated. It could be that by having this many pipes the plug will not be able to hold the weight of the fuel in the reactor.

**Table 4.4:** Number of pipes needed for certain radii when the whole bottom of the reactor tank is filled with pipes.

| Radius of pipe [m] | 0.010 | 0.015 | 0.020 | 0.025 | 0.030 | 0.035 | 0.040 | 0.045 | 0.050 |
|---|---|---|---|---|---|---|---|---|---|
| Number of pipes | 3574 | 2329 | 1634 | 1211 | 932 | 739 | 601 | 498 | 418 |

The number of pipes that will be placed will be chosen on grounds of the volume flow rate instead of the total area. This is done because when the area as in the 10 cm initial plug hole is taken into account the only profitable radii will be those that are near the old initial radius and for this old radius the melting time is not profitable. Moreover will these radii still have a smaller volume flow rate and therefore a larger drainage time.

## 4.3. Total time

The total time the tank needs to be completely empty after an accident happens is calculated using equation 4.5.

$$t_{tot} = t_{drain} + t_{melt} \tag{4.5}$$

The total time is influenced by some variables. These variables are:

- The choice of metal
- Pipe length
- Number of pipes
- Pipe radius

These variables have been discussed and conclusions have been made about them. These conclusions are firstly that the material used in this setup is hastelloy N with a strip of 2.5 mm of copper attached to it. Moreover that the length of the pipe is set at 3.5 m and lastly that the number of pipes is chosen to be compatible with an equal volume flow rate for all radii. The only variable that is left is the radius of the hole in the plug. Because a set volume flow rate is chosen, which is $\phi_v = 0.2315\text{m}^3\,\text{s}^{-1}$, $t_{drain}$ won't change. This is because for each different radius the total volume that has to leave the tank is equal and due to the equal volume flow rate the time the fuel takes to leave the reactor is the same for all different radii as well. Therefore equation 4.5 can be rewritten to equation 4.6.

$$t_{tot} = 78s + t_{melt} \tag{4.6}$$

The drainage time is set at this value because that is the time it took the old design investigated by van den Bergh[12] to completely empty. Because the volume flow rate is equal for both models, the drainage time is equal and can be set at 78 seconds.

The melting time depends on the radius as is shown in figure 4.4 and as discussed in chapter 4.1.3. When the drainage time is added to the melting time, a new graph is formed. This is shown in figure 4.10.

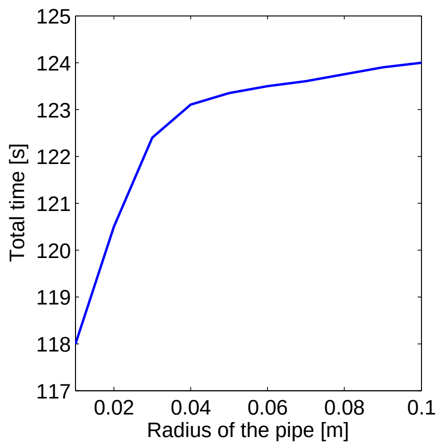



**Figure 4.10:** Total time the tank needs from the moment an accident happens until the tank is empty measured against the radius of the hole in the plug. The pipe length is constant being $3.5m$ and the number of holes depends on an equal volume flow rate($\phi_v$) for each radius of the hole.

In this figure it can be seen that the total time will vary between 118 seconds until 124 seconds while varying the radius. This is less than the total permitted time of 8 minutes and therefore this design could be a possible new design for the safety plug.

# 5
# Conclusion

This thesis studies a new design for a safety plug. Whether this plug is an improvement over the previous design is dependant on the total time the fuel takes to leave the tank in the event of an accident. The time lapse can be split into two different parts: the time the plug needs to melt and drop down, and the time the tank needs to be drained of all its content. The dimensions of the new design have been studied and varied. In the design ultimately retained for the plug the frozen salt is surrounded by a thin wall of $8.5mm$ of hastelloy N which in its turn will be surrounded by a coat of $2.5mm$ of copper. The total length of the pipe is set at $3.5m$ and the number of pipes that will be placed will depend on the volume flow rate and therefore on the radius of the frozen salt. The volume flow rate of both the new and the previous designs will be kept equal at $0.2315 \mathrm{m^3\,s^{-1}}$ and as a consequence once a certain radius for the frozen salt is chosen, the number of necessary pipes can easily be calculated. Because of this equal volume flow rate the draining time for the new design is identical to that of the previous design, i.e. $78$ seconds. The melting time however differs per radius of the frozen salt and ranges from $40$ seconds for a radius of $1cm$ to $46$ seconds for a radius of $10cm$. This leads to a total time varying from $118$ seconds until $124$ seconds. This is well below the maximum permitted time lapse. This new design could therefore be incorporated in reactors in the future.

## 5.1. Recommendations

It can be deduced that this new design could be a profitable design for the safety plug as the total time is within the period of 8 minutes. Some things however need to be further investigated that were not done in this report.

- The height of the plug

  It should be investigated what an optimal height would be to shorten the melting time but plug must also be able to withstand the pressure of the full content of the tank.

- Mesh

  For a more reliable result, more elements should be used in the mesh. This way the result is more accurate because smaller steps are taken per calculation.

- Starting temperature

  In the model made in COMSOL the top of the plug is set at a certain temperature. In reality the temperature of the fluid in the tank will increase gradually after an accident happens. Therefore the temperature that is used in the model is not realistic. It is possible that the plug will start melting before the initial temperature used in this project is reached.

- Total length of the pipe

  In this report the length of the pipe has been set at a constant which has been chosen by studying a graph. This value van be optimized by further research to find a more accurate relation between the radius of the frozen salt and the length of the pipe.

- Properties of the molten salt

  The properties of the molten salt have not been investigated. An assumption has been made that their properties are similar to the properties of lithium chloride. Whether this is true can not be said before further research has been done on the molten salt.

- Hastelloy N

  The choice that hastelloy N is used as the material that surrounds the frozen salt was based on previous studies[8][9]. However hastelloy N has a low thermal conductivity and a high specific heat which is not optimal for heat transfer. If another material could be used with a higher thermal conductivity and a lower specific heat the melting time would decrease.

- Thickness of hastelloy N

  The hastelloy N part that is included in the plug is set at 8.5 mm. However if it were possible that this thickness could be less, the melting time would drop. The melting time would drop due to the fact that the volume through which heat energy must go before reaching the frozen salt decreases. Whether this is possible should be investigated.

- Thickness of the copper

  The thickness of the copper is calculated in COMSOL using steps of $0.5mm$. This can be done more precise with smaller steps. This could be useful because in this case the amount of copper that will be used is more precise and an even faster melting time can be obtained.

- Geometry of the plug

  In this model the frozen salt floats in the middle of the pipe. This is not possible in reality. A construction should be made to make sure the frozen salt will stay in place.

- Freezing of the frozen salt

  The way the frozen salt will freeze has not been taken into account in this project. Instead the assumption is made that the plug will be completely flat at the top. The form the salt takes when it freezes should be further investigated to find a better estimation of the melting time.

- Melting time

  At a certain moment the edges of the frozen salt have melted enough in order for the salt to fall through the plug. The exact moment, the moment the gravitational force of the weight of the salt exceeds the friction force between the salt and the hastelloy N, has not been determined and should be studied.

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# A

# Appendix

## A.1. Variation of pipe length per diameter in comparison to the drainage time

```
clc
clear all
close all

%% Different colours added to each graph
C = {'k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y','k','b','r','g','y'}

%% Variables
K=0.5;
g=9.81;
f=0.0034;
r=1.42;
R=[0.01:0.001:0.1];
H=2.84;
L=[0.5:0.01:8];
D=2*R;

%% Drainage time per radius and per length of pipe
for i=1:length(R);
    for j=1:length(L);
        t_eff(i,j)=(r./R(i)).^2.*sqrt(2*(L(j).*4*f./D(i) + K + 1)./(g)).*(sqrt(H+L(j))-sqrt(L(j)));
    end
end

%% Plot of drainage time
hold on
for i=1:length(R)
    plot(L,t_eff(i,:),'color',C{i})
end

xlabel('Pipe Length [m]')
ylabel('Drainage Time[s]')
title('Variation of pipe length per diameter')
```

## A.2. Variation of pipe radius with a constant pipe length in comparison to the drainage time

```
clc
clear all
close all

%% All variables
K=0.5;
g=9.81;
f=0.0034;
r=1.42;
R=[0.01:0.001:0.25];
D=2*R;
H=2.84;
L=3.5;

%% Drainage time
t_eff=(r./R).^2.*sqrt(2*(L*4*f./D + K + 1)/(g)).*(sqrt(H+L)-sqrt(L));

%% Plot
figure(1)
plot(R,t_eff)
xlabel('Pipe Radius [m]')
ylabel('Drainage Time [s]')
title('Variation of pipe radius for constant pipe length(3.5 m)')
legend('No obstruction')
```

## A.3. Mean velocity and amount of pipes per radius of the pipe

```
clc
clear all
close all

%% Variables
H=2.84;
R=1.42;
rho=4080;
mu=1.01*10^-2;
g=9.81;
dt=1;
f= 0.0034;
Ktot= 0.5;
L=3.5;

ts=0:dt:100000;
rb=0.009:0.001:0.1;
Db=2*rb;
k_b=zeros(length(rb));
hb=zeros(length(rb),length(ts));
vb=zeros(length(rb),length(ts));
vb_m=zeros(1,length(rb));

%% Calculating the mean velocity per radius
for i=1:length(rb);
    k_b(i)=sqrt(2*g./(1+4*f*(L./Db(i))+Ktot)).*(rb(i)./R).^2;
    for j=1:length(ts);
        hb(i,j)=0.25.*k_b(i).^2.*ts(j).^2-sqrt(H+L).*k_b(i).*ts(j)+H;
        vb(i,j)=sqrt(2*g.*(hb(i,j)+L)./(1+4*f*L./Db(i)+Ktot));
    end
```

```
    first(i,:) = find(hb(i,:)<0,1); %% Only include velocities where the tank is
    not yet empty
    vb_f=vb(i,:);
    vb_f=vb_f(1:first(i));
    vb_m(i)=mean(vb_f);
end

%% Plot for mean velocity
figure(2)
set(gca,'fontsize',14)
plot(rb,vb_m);
axis([0.009 0.1 4 8])
xlabel('Pipe radius [m]')
ylabel('Velocity of the fluid [m/s]')
title('Fluid velocity per radius of the pipe')

%% Calculating the amount of pipes per radius
for i=1:length(rb);
    As(i)=pi.*rb(i)^2;
    phi_o=Al*vl_m;
    phi_m(i)=As(i)*vb_m(i);
    p(i)=phi_o/phi_m(i);
end

%% Plot for the amount of pipes
set(gca,'fontsize',14)
hold on
plot(rb,p)
axis([0.009 0.1 0 190])
xlabel('Pipe radius [m]')
ylabel('Amount of pipes')
title('Variation of pipe radius effect on amount of pipes)')
```

## A.4. Melting time and total time per radius of the pipe

```
%% steps of 0.01 m
clear all
close all
C = {'k','b','r','m'};
x1=[0.01:0.01:0.09];
y(1,:)=[0.02062 0.02096 0.02087 0.02088 0.02122 0.02131 0.02155 0.02156 0.0216];
y(2,:)=[0.01875 0.01913 0.0193 0.01967 0.01988 0.01989 0.01989 0.01989 0.020 ];
y(3,:)=[0.0168 0.0178 0.0179 0.01786 0.01789 0.01789 0.0182 0.01821 0.01822 ];
y(4,:)=[0.014505 0.0155 0.016 0.01606 0.016 0.01629 0.01653 0.01653 0.01655 ];

hold on
for i=1:4;
    plot(x1,y(i,:),'color',C{i});
end
set(gca,'fontsize',14)
legend('time = 15', 'time = 20', 'time = 25', 'time = 30')
xlabel('Radius of the pipe [m]');
ylabel('Length of pipe which has not yet changed phase [m]');
title('Length of interface line that is still solid per radius of the pipe');

%% Melting time
clear all
close all

x1=[0.01:0.01:0.1];
t=[40 42.5 44.4 45.1 45.35 45.5 45.6 45.75 45.9 46];
```

```
plot(x1,t);
set(gca,'fontsize',14)
axis([0.01 0.1 39 47])
xlabel('Radius of the pipe [m]');
ylabel('Melting time [s]')
title('Melting time in seconds versus the radius of the pipe');

%% Total time

clear all
close all

x1=[0.01:0.01:0.1];
t=[40 42.5 44.4 45.1 45.35 45.5 45.6 45.75 45.9 46];
t1=t+78;
plot(x1,t1);
set(gca,'fontsize',14)
axis([0.01 0.1 117 125])
xlabel('Radius of the pipe [m]');
ylabel('Total time [s]')
title('Total time in seconds versus the radius of the pipe');
```

## A.5. Better quality for the figures

Because for each figure the same script is used, this will only be shown for one as an example.

```

width = 4;      % Width in inches
height = 4;     % Height in inches
alw = 0.75;     % AxesLineWidth
fsz = 13;       % Fontsize
lw = 1.5;       % LineWidth
msz = 8;        % MarkerSize


% Normal plot
plot(x1,t1);
set(gca,'fontsize',14)
axis([0.01 0.1 117 125])
xlabel('Radius of the pipe [m]');
ylabel('Total time [s]')

% Better quality but the same plot
pos = get(gcf, 'Position');
set(gcf, 'Position', [pos(1) pos(2) width*100, height*100]); %<- Set size
set(gca, 'FontSize', fsz, 'LineWidth', alw); %<- Set properties
plot(x1,t1,'LineWidth',lw,'MarkerSize',msz); %<- Specify plot properites
axis([0.01 0.1 117 125])
xlabel('Radius of the pipe [m]');
ylabel('Total time [s]')

%
% Here we preserve the size of the image when we save it.
set(gcf,'InvertHardcopy','on');
set(gcf,'PaperUnits', 'inches');
papersize = get(gcf, 'PaperSize');
left = (papersize(1)- width)/2;
bottom = (papersize(2)- height)/2;
myfiguresize = [left, bottom, width, height];
set(gcf,'PaperPosition', myfiguresize);

% Save the file as PNG
```

```
print('tott','-dpng','-r300');

print('tott','-depsc2','-r300');
if ispc % Use Windows ghostscript call
  system('gswin64c -o -q -sDEVICE=png256 -dEPSCrop -r300 -ototott_eps.png tott.eps');
else % Use Unix/OSX ghostscript call
  system('gs -o -q -sDEVICE=png256 -dEPSCrop -r300 -ototott.png tott.eps');
end
```