Design of a Freeze Plug Grate

by

André Makkinje

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Thesis committee:	Dr. ir. M. Rohde,	TU Delft, supervisor
	Prof. dr. ir. J. L. Kloosterman,	TU Delft

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TU Delft
Delft University of Technology

Abstract

The safety of nuclear power plants is a controversial subject. The most recent large-scale accident happened in 2011 at the Fukushima Daiichi nuclear power plant in Japan. That incident has shown that an active cooling system may not be the safest available option. The molten salt reactor is being developed as part of the next generation IV reactors and uses a passive safety system. The passive safety system consists of several freeze plugs that block the pipe leading to the emergency underground draining tanks. When the fuel overheats or the power falls out because of a station blackout, the freeze plugs will melt, unblocks the pipe and causes the fuel to be drained towards the underground tanks. This whole process has to be finished within 8 minutes to prevent damage to the reactor vessel[6].

The focus of this thesis lies on finding a design that complies with the safety standard. COMSOL was used to simulate the melting process. The melting time represents the time it takes for the freeze plug to melt at the edges and presumably fall through. MATLAB was used to analytically solve the draining time and process the combined total time for the possible configurations. Assumptions have been made about the minimum ratio of height and radius of the freeze plug, the necessary surface area, the properties of the solid salt and the resistance coefficient of the design. The recommended design fits within a pipe with a radius of $0.1m$ and consists of twelve identical freeze plugs that have a radius of $20mm$ and an internal wall thickness of $4mm$. It takes $344s$ to melt the plugs and drain the reactor, which is faster than the safety standard. There are faster configurations but those would require a bigger pipe radius. Even though assumptions had to be made, the results show that the current idea of using multiple freeze plugs is feasible.

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Nomenclature

Symbol	**Description**	**Units**
δ	melted length	m
λ	thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
λ_{liquid}	thermal conductivity of molten salt	$\mathrm{W\,m^{-1}\,K^{-1}}$
λ_{solid}	thermal conductivity of solid salt	$\mathrm{W\,m^{-1}\,K^{-1}}$
ρ_{solid}	density of solid salt	$\mathrm{kg\,m^{-3}}$
a	thermal diffusivity	$\mathrm{m^2\,s^{-1}}$
A_a	crossectional area at point a	$\mathrm{m^2}$
A_b	crossectional area at point b	$\mathrm{m^2}$
D	diameter of freeze plug	m
d_k	diameter of freeze plug k	m
f	Fanning friction factor	-
g	gravitation constant on earth, 9.81	$\mathrm{m\,s^{-2}}$
h	height of freeze plug	m
$h(t)$	height of liquid level in reactor vessel	m
H_{tank}	height of the reactor vessel	m
K_{tot}	total K value	-
L_f	latent heat of fusion	$\mathrm{J\,kg^{-1}}$
n_k	number of freeze plug k	-
P	distance between adjacent freeze plugs	m
P_a	pressure at point a	Pa
P_b	pressure at point b	Pa
r	radius of freeze plug	m
r_k	radius of freeze plug k	m
r_{pipe}	radius of the drainage pipe	m
R_{tank}	radius of the reactor vessel	m
r_w	radius of internal wall	m
T	temperature	K
t	time	s
T_0	initial temperature	K

T_{melt}	melting temperature	K
t_{melt}	melting time	s
v_a	velocity at point a	$\mathrm{m\,s^{-1}}$
v_b	velocity at point b	$\mathrm{m\,s^{-1}}$
z_a	height at point a	m
z_b	height at point b	m

1 Introduction

The safety of nuclear power plants is a controversial subject. Large accidents as Chernobyl and Fukushima makes people question the safety of nuclear energy. The IAEA (International Atomic Energy Agency) has defined a scale to communicate the safety-related information and consequences of nuclear disasters. The scale goes from level 1(anomalies) to level 7 (Major accidents) where each level is ten times more severe than the previous level. Since 1957 there have been only two instances that have been graded with a level 7 (Chernobyl in 1986 and Fukushima in 2011) [20]. The Fukushima accident is important for this research.

One of the factors that caused the Fukushima accident is the failure of their active cooling system. To increase the safety of new nuclear reactors, it is important to change the dependency from an active cooling system to a passive safety system. This change can be achieved by using freeze plugs.

Therefore this thesis will look at a design that enables a passive safety system for the molten salt reactor which is part of the next generation of nuclear reactors.

1.1. Molten Salt Reactor

Newer generations of nuclear power plants keep on being developed. One of the goals is to improve the safety and reliability of nuclear power plants. Generation IV reactors are being developed and are expected to be deployed between 2020 and 2030 [4]. The generation IV reactors consist of six possible ideas, one of which is the molten salt reactor which is the main focus of this thesis.

One of the properties of the molten salt reactor is that it is possible that its coolant and nuclear fuel are both made from the same mixture of molten salt. Therefore a solid moderator is not required. Pumps circulate the molten salt throughout the reactor. Figure 1.1 shows a schematic drawing of the molten salt reactor.

There are several safety benefits of a molten salt reactor including:

- Can operate under atmospheric pressure. Thus it will not carry the same risks as the pressured water reactors
- The boiling point of the salt mixture lies around $1670K$ which is higher than the typical operating temperature of $973K$.
- Passive safety system through the use of freeze plugs and drainage tanks

This is by no means an exhaustive list, however for this thesis only the last item is of importance, the possibility of a passive safety system. A passive system circumvents the problems of an active system. Fukushima is a good example that showcases one of the problems of an active cooling sytem.

1.2. Fukushima

What happened at the Fukushima Daiichi nuclear power plant is that it was first hit by an earthquake and then a tsunami. The earthquake caused the reactor to shutdown automatically [5], however this does not stop the production of the decay heat. Their heat removal system ran on a power supply, which could be supplemented with their backup generators. Their backup generators were also protected with a wall against tsunamis, however that protection was insufficient. The tsunami disrupted the power supply and destroyed

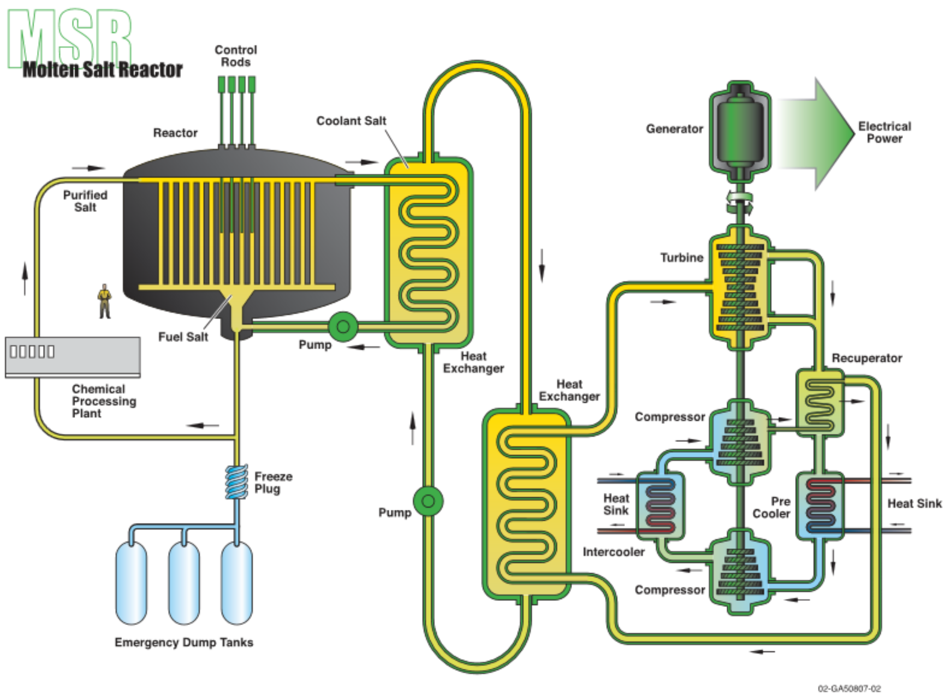


Figure 1.1: A schematic drawing of the Molten Salt Reactor.[1]

the backup generators, therefore their active cooling system lacked the energy to be put to use. The end result was a partial nuclear meltdown.

1.3. Passive Safety System

The molten salt reactor has the possibility of using a passive safety system. In the case of an emergency, the freeze plug will melt and the molten salt mixture will be drained to an underground storage tank. What makes this sytem a passive system is because the freeze plug does not need an external energy source to melt, the decay heat of the molten salt is sufficient. The emergency storage tanks are placed underground, underneath the reactor vessel, as can be seen from figure 1.1. Therefore the molten salt can flow downwards with the help of gravity instead of a pump. This system actually needs an external energy source to keep the frozen plug cooled, to prevent it from melting during operational conditions. This shifts the focus of using an external energy source to shut down the reactor to a focus of using an external energy source to keep the reactor running.

1.4. Previous Research

The idea of the freeze plug is not new. It has been a part of the design for the Molten Salt Reactor Experiment design of A. Weinberg in 1965 [9]. Swaroop has looked at a simplified 1D analytical model of the freeze plug. In that model he used the properties of ice and water as a replacement for solidified and molten $LiF-ThF_4$ and reported a melting time of more than 10 minutes for a freeze plug with a length of $100mm$, however he expects that a freeze plug made from solidifed $LiF-ThF_4$ would melt faster because of its higher thermal conductivity and lower latent heat of fusion[17].

Koks has looked at a different design of the single freeze plug. Her design is shown in figure 1.2. She reported that it would take 165 for the freeze plug to drop. The top part would take $115s$ to melt $5mm$ from the top, then the molten salt would flow past the plug and the Hastelloy-N ring would heat up and melt the freeze plug from the side. It would then take another $50s$ to melt $2mm$ from the side of the freeze plug and let the freeze plug drop [13]. She also reported it would take more than 8 minutes to melt a $50mm$ freeze plug.

The research done by Swaroop and Koks, show that the freeze plug needs to become smaller or the heat transfer has to be improved. However decreasing the size of the freeze plug would lead to a smaller diameter and thus a longer draining time. van den Bergh showed that t_{drain} scales with $\frac{1}{r^2}$ [18].

A new design was mentioned in a research done by van Tuyll, which incorporated multiple freeze plugs.

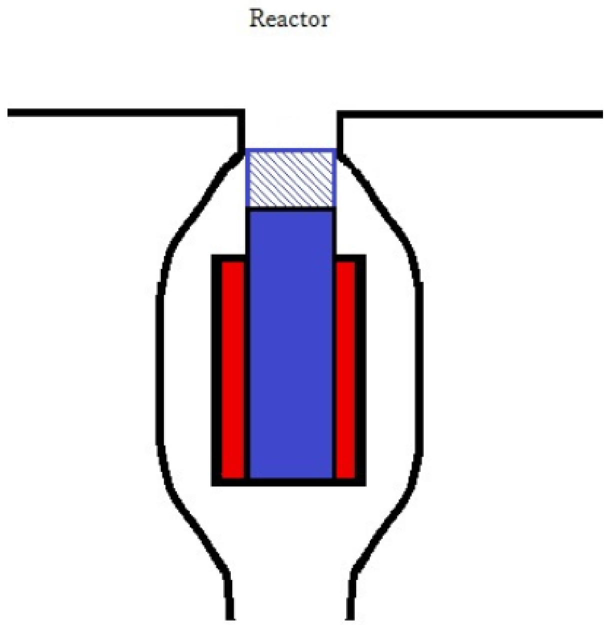


Figure 1.2: A schematic drawing of the design researched by I. Koks[13]. The blue part represents the Freeze Plug. The red part is a Hastelloy-N ring. The striped blue part is represents the freeze plug that needs to melt to allow the molten salt to flow past the freeze plug and to allow for convective heat transfer.

This decreases the size of the freeze plug which speeds up the melting time, while maintaining or increasing the crossectional area that is necessary to minimize the draining time. Also, because the design has a layer of Hastelloy-N between the freeze plugs, it allows for heat transfer to the sides. This should mean that it is possible that the freeze plug drops before it has fully melted. The focus of her research was on the influence an additional layer of copper would have on the melting time and not on the specifications of the new design. So it is unknown how many freeze plugs are necessary, what the optimal radius and height of the freeze plug should be or what the optimal thickness of Hastelloy-N should be between freeze plugs.

1.5. Goal, Hypothesis and Thesis outline

The goal is to find the fastest configuration of the new design. Fastest is defined as the smallest total time taken to melt the freeze plugs and drain the tank. The total time has to be less than 8 minutes to be safe [6].

This new design also uses heat transfer to the sides of the freeze plug as was done in the research done by Koks. In her design it would take more than 8 minutes to melt a freeze plug of $50mm$, however in this design the heat transfer to the side does not rely on the freeze plug to melt, therefore I expect a height of $50mm$ to be possible. A bigger freeze plug will have a larger radius which should decrease the draining time significantly. For this research I assume the radius to be the same as the height.

van den Bergh showed that the effect of the pipe radius on the draining time is minimal after a radius of $0.1m$. The draining time is dependent on the crossectional area of the pipe. Because this design uses a freeze plug with a smaller diameter and thus a smaller crossectional area, it would have to be compensated by increasing the number of freeze plugs. Four pipes with a radius of $0.05m$ would have the same crossectional area as a single pipe of $0.1m$. However more pipes would lead to more friction, so I believe a minimum of five freeze plugs to be necessary.

The thesis will start with an explanation of the necessary theory to melt the freeze plug and to drain the tank. This will be followed by the models that will be used to simulate the melting and draining behaviour. Afterwards the results will be presented followed by a conclusion and recommendations for future research.

2

Theory

2.1. Design of the plug

This report will be focused on the design (shown in 2.1) using multiple, smaller freeze plugs.Two versions will be tested.

- Version 1: All freeze plugs are identical
- Version 2: There are a minimum of 2 freeze plugs with a different radius and height

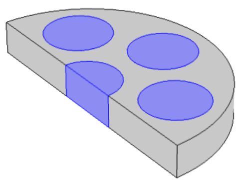


Figure 2.1: Half of the design made in COMSOL using identical freeze plugs. The blue circles are the freeze plugs. The gray area is the Hastelloy N.

2.1.1. Ratio between height and radius

Figure 2.2 shows a schematic drawing of the side view of the design. It also shows the forces acting upon the freeze plug. Under normal operating conditions, the freeze plug has to stay solid and remain in place.

A $\frac{height}{radius} = 1$ (will be referred to as $\frac{h}{r}$ for the rest of the report) will be assumed during the experiments unless stated otherwise. The importance of this ratio will be explained in this section.

The dependency of the forces in figure 2.2 on the dimensions of the freeze plug will be listed below:

- F_p is the force caused by the pressure of the molten salt that lies on top of the freeze plug. The following equation holds:

$$F_p = \rho_{liquid} g H A_{top,plug}$$
$$A_{top,plug} = \pi r^2$$

  So this force scales with the surface area of the top of the freeze plug. All the remaining terms can be considered constant.

- F_z is the force of gravity that acts upon the freeze plug. The equation

$$F_z = \rho_{solid} g V$$
$$V = \pi r^2 h$$

  So this force scales with the volume of the freeze plug. All the remaining terms can be considered constant.

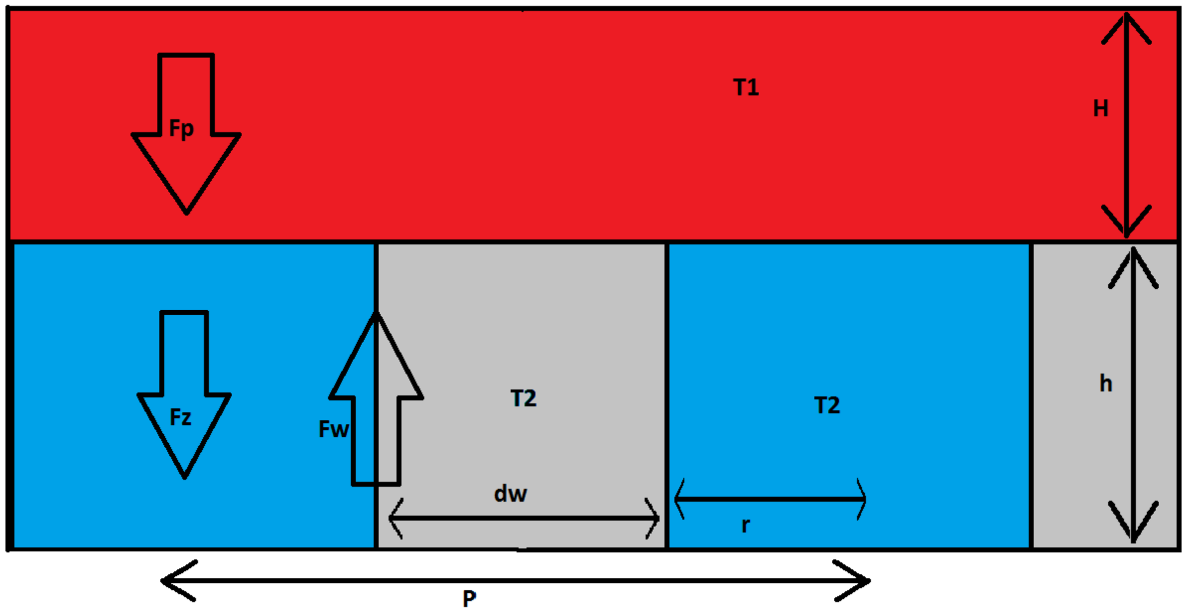


Figure 2.2: Schematic Drawing of the forces acting on the freeze plug. Red represents the molten salt, blue represents the freeze plug, and gray represents the Hastelloy-N. F_p is the force of the pressure of the molten salt that presses on the freeze plug. F_z is the force of gravity acting upon the freeze plug. F_w is the force of friction between the freeze plug and the Hastelloy-N. H is the height of the molten salt, h the height of the freeze plug. r is the radius of the freeze plug and d_w the diameter of the Hastelloy-N. T_1 the temperature of the molten salt and T_2 the temperature of the freeze plug and the Hastelloy-N. P is the distance between two adjacent freeze plugs.

- F_w is the force of friction between the freeze plug and the Hastelloy-N. The equation is unknown but will probably be of the form

$$F_w = \mu A_{curved,plug}$$
$$A_{curved,plug} = 2\pi r h$$

  Where μ is a constant friction coefficient. It is assumed that this force scales with the curved surface area of the freeze plug.

- The bottom area of the freeze plug has no contribution to any of these forces. So whenever surface area of the freeze plug is mentioned, it will only refer to the curved area and the top.

- the relation between $A_{curved,plug}$ and A_{top} using the relation $h = \frac{h}{r} r$

$$A_{top} = \pi r^2$$
$$A_{curved,plug} = 2\pi r h = 2\pi r^2 \frac{h}{r}$$
$$A_{curved,plug} = 2A_{top} \frac{h}{r}$$

The freeze plug will stay in place if:

$$F_w \geqslant F_p + Fz \approx F_p \tag{2.1}$$

The last approximation is made because $F_p >> F_z$. F_w and F_p can be simplified because the majority of the terms are constant.

$$F_w = \mu A_{curved,plug} = C_1 A_{curved,plug} = C_1 2 A_{top} \frac{h}{r} \tag{2.2}$$
$$F_p = \rho_{liquid} g H A_{top,plug} = C_2 A_{top} \tag{2.3}$$

Substituting equation 2.2 and 2.3 into equation 2.1 and rewriting to $\frac{h}{r}$ will give you the following:

$$\frac{h}{r} \geqslant \frac{1}{2} \frac{C_2}{C_1} \tag{2.4}$$

As long as that holds, the freeze plug should remain in place, however it is unknown what the exact form is of the equation for F_w and as a result what the minimum value should be for $\frac{h}{r}$.

The importance of this ratio is that there is a minimum value for which the freeze plug will not collapse under the pressure for normal operating conditions. There is also a minimum value for which it will remain in place. Both minimum values are unknown.

In figure 2.3 you can see the surface area (only the curved area and the top of the freeze plug) being plotted against $\frac{h}{r}$. From this plot, you can see that the surface area is smallest for $\frac{h}{r} = 1$. As a result F_w and F_p are both small.

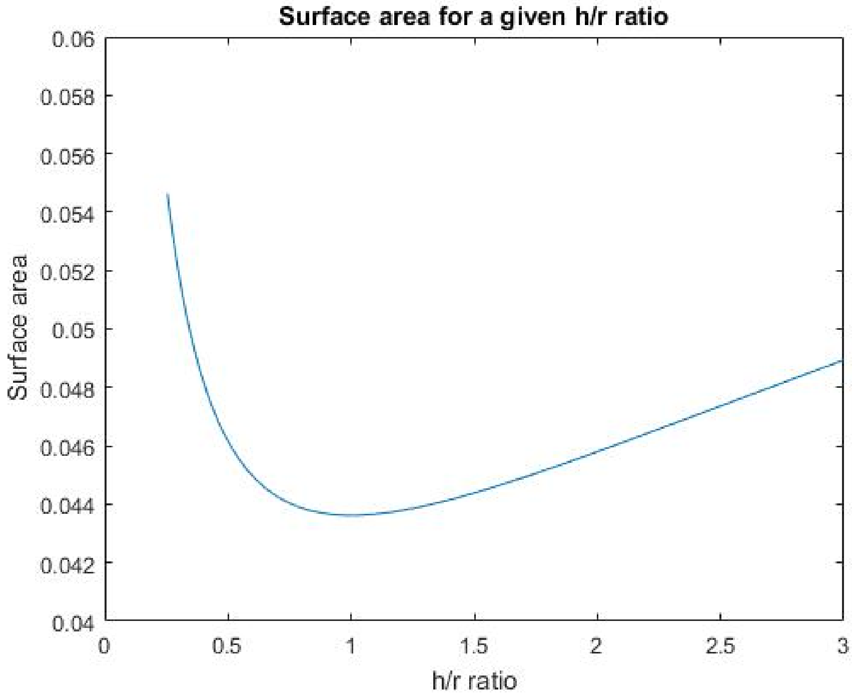


Figure 2.3: Here you can see the normalized surface area being plotted against the $\frac{h}{r}$. When $\frac{h}{r} = 1$ the surface area is at its lowest.

2.1.2. Wall thickness

The wall will be made of Hastelloy-N because of its compatibility [15] and its minimum thickness r_w for each freeze plug can be found with

$$r_w = \frac{d_w}{2} \tag{2.5}$$

$$r_w = r\left(\frac{P}{D} - 1\right) \tag{2.6}$$

where r is the radius of the freeze plug, $\frac{P}{D}$ is a ratio of the distance P between the centers of two adjacent freeze plugs,d_w is the distance between the edges of two adjacent freeze plugs and D the diameter of the freeze plug. Figure 2.2 shows those distances as well.

Past research used a wall thickness of $8.5mm$ [2]. However this was for a core region with a diameter up to $3.7m$. This is significantly larger than the diameter of the freeze plugs of this design. So a smaller wall thickness should be possible [14].

The corrosion rate of Hastelloy-N in a salt mixture of $LiF - ThF_4$ is approximately $0.02mm/year$ with a minimum found value of $0.01mm/year$ and a maximum found value of $0.025mm/year$ [7]. The smallest radius that will be tested in this project is $r = 10mm$ and the smallest value for the $\frac{P}{D}$ is 1.1. Thus the smallest wall thickness in this research is $1mm$ which should last a bit less than 40 years in the worst case scenario, which is in line with most lifetimes of nuclear energy plants. Because of these reasons, the minimum wall thickness will be ignored.

2.1.3. Packing Theory

Besides altering the dimensions of the freeze plug and its wall, it is also important to know how many freeze plugs fit within a given pipe radius. Packing theory will be used to determine the amount of freeze plugs that fit. Figure 2.4 shows six examples. There are a lot of optimally proven or trivially optimal configurations,

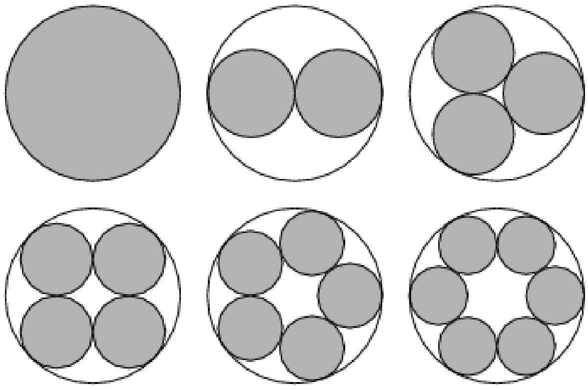


Figure 2.4: six examples of circle packing.[3]

however there is no known formula. Because there is no known formula, the experiment uses only the first twenty cases of this theory.

A different approach will be used if more then twenty freeze plugs are necessary. In that case it will be dependent on the equation 2.7. Where n is the number of freeze plugs and m is the amount of rings. An example is shown in figure 2.5.

$$n = 3m(m-1) + 1 \tag{2.7}$$

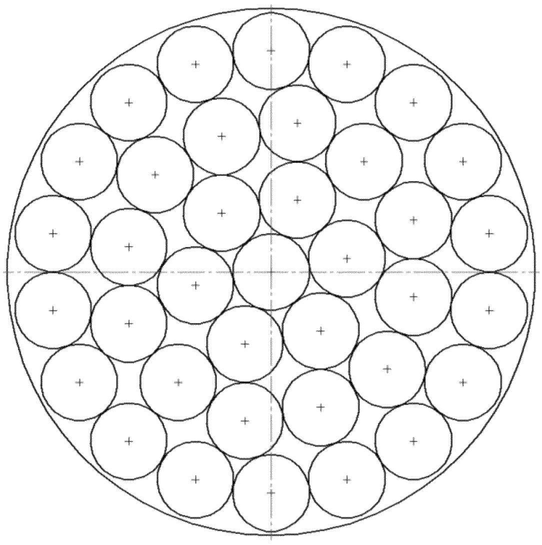


Figure 2.5: Example where $n = 37$ and $m = 4$ [12]

2.2. Heat Transfer

2.2.1. Conduction

There will be heat transfer, in the form of conduction, in the contact area between the freeze plug and the wall made out of Hastelloy-N. The formula that expresses the conduction is

$$\phi_q'' = -\lambda \nabla T \tag{2.8}$$

This equation shows that the heat transfers from the warm surface towards the cold. Figure 2.6 shows how the heat, from the molten salt on top, would penetrate into the design. At any distance P the heat should reach the bottom of the freeze plug, however the larger the distance P, the faster. Figure 2.6 is a rough example that shows why a larger P would lead to the heat reaching the bottom of the freeze plug faster. In the figure you can see that the arrows stop at the midpoint of the freeze plug. As P increases, the heat will penetrate more into the Hastelloy-N before it gets diverted towards the freeze plug. There is a P_{max} for which the heat will penetrate deep enough to reach the bottom of the freeze plug. This means that for $P > P_{max}$ the arrows would hit the bottom of the plate and it would just end up heating the Hastelloy-N. So the melting time would not decrease any further by increasing P.

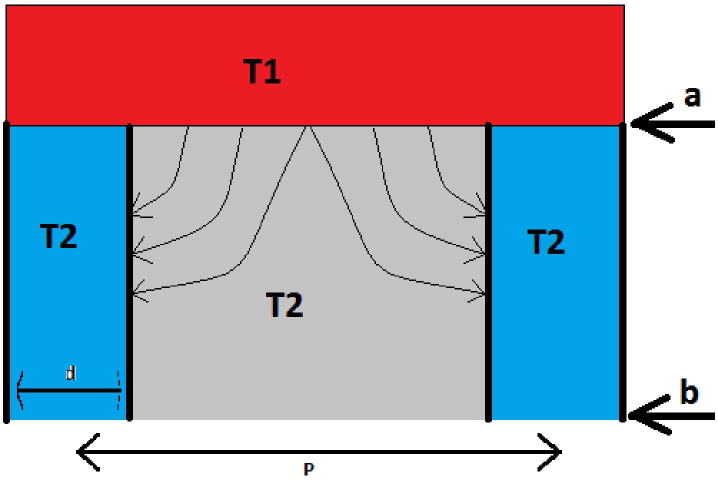


Figure 2.6: The sideview of the design. The blue area represents the freeze plugs, the gray area the wall of Hastelloy N between them. d is the diameter of the freeze plug. P is the distance between the center of two adjacent freeze plugs. The arrows represent the heat flow from the top that has a temperature T_1 towards the freeze plug at temperature T_2 with $T_1 > T_2$

2.2.2. Phase Change Solid-Liquid

The melting process of the freeze plug can be split into two different processes. A one-dimensional melting of a cylinder and a radial melting process. This section will illustrate the one-dimensional melting process. Equation 2.9 shows the energy balance at the contact area $h = a$ between the molten salt and the frozen salt.[17]

$$\lambda_{liquid} \frac{\partial T(x,t)}{\partial x}\bigg|_{h=a} + L_f \rho_{solid} \frac{\partial h}{\partial t} = \lambda_{solid} \frac{\partial T(x,t)}{\partial x}\bigg|_{h=a} \tag{2.9}$$

This equation can be solved for h, so it becomes possible to calculate the melting front after $t > 0$. Although the phase change is important, it is outside the scope of this project. The focus of this project lies on making the freeze plug drop as fast as possible and thus only the edges (shown as the thick black lines in figure 2.6) of the plug have to melt, and not the whole freeze plug.

2.2.3. Penetration Theory

Penetration theory is used when the situation is non-stationary and the heat has not reached a certain depth. For a plate, the penetration theory is valid if equation 2.10 holds.

$$\sqrt{\pi a t} \leqslant 0.6 D \tag{2.10}$$

When the theory holds, we can make use of the following equation

$$t_{pen} = \frac{h^2}{\pi a} \tag{2.11}$$

Where h is the length of the freeze plug and a the thermal diffusivity of the Hastelloy-N. h is the height or depth the heat has to reach. Penetration theory can only be used if the other side remains at the same temperature. So in figure 2.6 the heat comes in through line a. As the heat penetrates into the material, it gets diverted to the freeze plugs as is shown by the bent arrows. As mentioned before, for a P_{max} it will hit the bottom of the freeze plug, on line b, the fastest, however at this value, the heat did not reach all of the Hastelloy-N at line b. Therefore the penetration theory can be used to calculate the melting time, however this is only a valid approximation if $P \approx P_{max}$. If $P << P_{max}$ then the melting time, would be much larger. The melting time t_{melt} should converge to t_{pen} if $P \rightarrow P_{max}$.

2.3. Draining of the Tank

The tank needs to be drained in less than 8 minutes [6] The draining of the tank can be calculated using a steady-state one-dimensional mechanical balance.

$$\phi_m \left(\frac{1}{2} v_a^2 - \frac{1}{2} v_b^2 + g\left(z_a - z_b\right) + \frac{P_a - P_b}{\rho} \right) + \phi_w - \phi_m e_{fr} \tag{2.12}$$

Indice a and b refer to the top of the tank and bottom of the pipe respectively, as can be seen in figure 2.7. Equation 2.12 can be simplified to:

$$\phi_m \left(-\frac{1}{2} v_b^2 + g\left(z_a - z_b\right) \right) - \phi_m e_{fr} \tag{2.13}$$

There is no work done on the system so $\phi_w = 0$. The reactor operates under atmospheric conditions [16], and the pressure in the underground tanks should also be equal to that. Thus there is no pressure difference between points a and b. Lastly $r_{tank} >> r_{pipe}$. Thus $v_a^2 - v_b^2 \approx -v_b^2$.

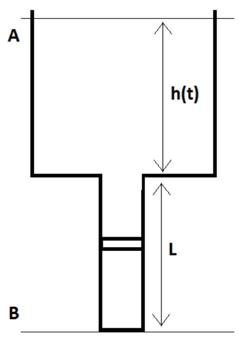


Figure 2.7: A schematic drawing of the tank and pipe. The small banded area within the lower pipe represents the freeze plugs.

The energy lost by friction is:

$$e_{fr} = \frac{1}{2} v_b^2 \left(4f \left(\frac{n_1 h_1}{d_1} + \cdots + \frac{n_k h_k}{d_k} \right) + 4f \frac{L-h}{D_{pipe}} + K_{tot} \right) \tag{2.14}$$

with f representing the fanning friction factor and n_k stands for the number of freeze plugs with diameter d_k and height h_k where the subscript k is used to differentiate between freeze plugs with different diameters and heights.h will be the largest value of h_k. K_{tot} stands for the total K-value used to calculate the friction loss in the pipes. L is the length of the pipe as can be seen in figure 2.7

By substituting equation 2.14 into equation 2.13 and substituing $z_a - z_b = h(t) + L$ and with further simplfcation:

$$-\frac{1}{2} v_b^2 + g\left(h(t) + L\right) = \frac{1}{2} v_b^2 \left(4f \left(\frac{n_1 h_1}{d_1} + \cdots + \frac{n_k h_k}{d_k} \right) + 4f \frac{L-h}{D_{pipe}} + K_{tot} \right) \tag{2.15}$$

$$v_b = \sqrt{\left(\frac{2(g(h(t)+L))}{1+4f\left(\frac{n_1h_1}{d_1}+\cdots+\frac{n_kh_k}{d_k}\right)+4f\frac{L-h}{D_{pipe}}+K_{tot}}\right)} \tag{2.16}$$

$h(t)$ can be solved using the conservation of mass

$$\frac{d}{dt}\pi\rho R_{tank}h(t) = \rho(v_aA_a - v_bA_b) \tag{2.17}$$

with $A_b = \pi(n_1r_1^2+\cdots+n_kr_k^2)$ and r_k the radius of the different freeze plugs.

$$\frac{dh(t)}{dt} = -\frac{(n_1r_1^2+\cdots+n_kr_k^2)}{R_{tank}^2}\sqrt{\left(\frac{2g}{1+4f\left(\frac{n_1h_1}{d_1}+\cdots+\frac{n_kh_k}{d_k}\right)+4f\frac{L-h}{D_{pipe}}+K_{tot}}\right)}\sqrt{h(t)+L} = -k\sqrt{h(t)+L} \tag{2.18}$$

Solving the differential equation 2.18 gives

$$h(t) = \frac{1}{4}\left(k^2t^2 - 2C_1kt + C_1^2 - 4L\right) \tag{2.19}$$

And by using the boundary condition of $h(0) = H_{tank}$ gives us $C_1 = \sqrt{H_{tank}+L}$ we can rewrite the function to find the draining time t_d

$$t_d = \frac{R_{tank}^2}{(n_1r_1^2+\cdots+n_kr_k^2)}\sqrt{\left(\frac{2\left(1+4f\left(\frac{n_1h_1}{d_1}+\cdots+\frac{n_kh_k}{d_k}\right)+4f\frac{L-h}{D_{pipe}}+K_{tot}\right)}{g}\right)}\left(\sqrt{H_{tank}+L}-\sqrt{L}\right) \tag{2.20}$$

2.3.1. Value of K_{tot}

The new design resembles a grate because of the multiple freeze plugs that are being used. There are no standard K-values for a grate, however because of the dimensions, it resembles a gate-valve that is partially opened. There are four known K-values for a gate-valve, they are for when the gate-valve is fully opened, 75% open, 50% open and 25% open [11]. Then using an exponential fit using those four data points, a function can be extrapolated for the K-value of a gate for any % of openness.

Then K_{tot} can be approximated by taking the ratio of the total area of the crosssections of the freeze plug and the crosssection of the pipe. This value will determine how 'open' the gate is and thus what the appropriate value is for K_{tot}.

3

Numerical Methods

The melting process of the freeze plug is modelled in COMSOL. Several models have been used because not all designs are possible within the same modelling environment of COMSOL.

3.1. Applicable to all COMSOL models

The following section will describe all the used materials, boundary conditions and variables that are applicable for all the models described below. It will be explicitly mentioned if it does not apply to all models.

3.1.1. Materials

The freeze plug and the molten salt consist of the salt $LiF-ThF_4$. In table 3.1 the properties of the molten salt can be found, however the properties of the salt in solid state are unknown. Therefore in this experiment, the salt has been substituted by the salt LiCL. Its properties are registered in the COMSOL database. The melting temperature of LiCL (610 °C) is close to the melting temperature of $LiF-ThF_4$(570 °C). It is assumed that its other properties are therefore a close approximation however that has not been tested.

Table 3.1: Properties of molten salt $LiF-ThF_4$, temperature T is in K. The value of C_p for 700 °C is extrapolated, since the highest temperature of the validity range is below 700 °C.[10]

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

The remaining geometry will be made out of Hastelloy-N. This consists of the walls and the material between adjacent freeze plugs. The choice for Hastelloy-N has been made because of its compatibility with molten salt reactors. [15] It was also selected as a structural material candidate for any internal wall that is in contact with the fuel salt. [8]

3.1.2. Boundary Conditions

The COMSOL module 'heat transfer in solids' has been used. The following initial and boundary conditions have been applied:

- Initial value: T_0 of 500 °C. Well below the melting temperature of the salt LiCL. This is applied everyhwere but the top as shown in figure 3.1.
- Temperature: T of 700 °C. The initial temperature of the molten salt that is applied on top of the design.

- Thermal Insulation: In figures 3.1 and 3.3 to 3.5 these are the faces you cannot see. In figure 3.2 it would be the edge on the far right.
- Heat transfer with phase change: This is only applied to the freeze plug. With T_{melt} set at 570 °C, being the melting temperature of $LiF - ThF_4$.
- (3D models only) Symmetry: Used on the internal faces of the design. In figure 3.1 those faces are numbered from 1-6. In figures 3.3 to 3.5 the same faces would be numbered.

These conditions have been taken from previous research[13]

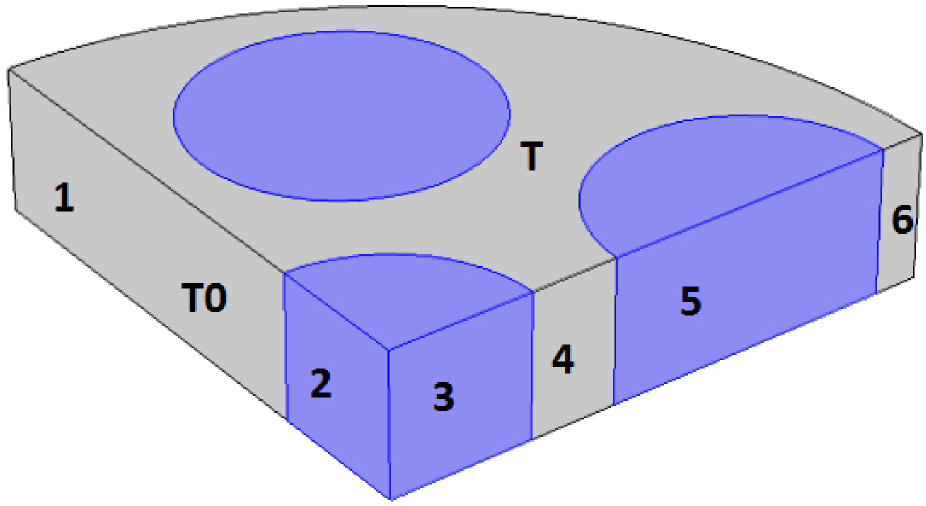


Figure 3.1: Example showing where the boundary conditions should be applied. Blue represents the freeze plug and gray represents the Hastelloy-N

3.1.3. Variables

The variables that were subject to change in all models were the following:

- The radius of the freeze plug. Different ranges have been tested, but the minimum value was $10mm$ and the maximum value $100mm$.
- The height of the freeze plug. The height has been linked to the radius as described in secion 2.1.1, however in one modelling session they have been varied independently to look at a possible relation between t_{melt} and the plug height h.
- The $\frac{P}{D}$ ratio. It has been explained in section 2.2.1 that a larger value of P would lead to a faster melting time. Instead of altering P, the choice has been made to alter this ratio to better compare freeze plugs with different radii. Different ranges have been used, but the minimum value was 1.1 and maximum was 3.0.

3.2. COMSOL

3.2.1. Model 1: 2D Axi Symmetry

This is done using the 2D Axi Symmetry module of COMSOL. This type of modelling consists of using a vertical crosssection of the design and revolving that 2D-design around an axis to create a 3D model. Because of this type of modelling, it is only possible to test a single freeze plug with this design.

This model (see figure 3.2) was mainly used to find appropiate values for the radius and the $\frac{P}{D}$ to use in the 3D model. This was done because this model would require less time to finish the computations. This model should resemble a 3D version, however in the 3D model the value of P will depend on the angle since a freeze plug is not completely surrounded by freeze plugs. The value of the 2D model should not be completely the same as that of the 3D model, however it should be a good approximation because they are quite similar.

The tested range for the radius ranged from $10mm$ to $100mm$ in steps of $10mm$. For the $\frac{P}{D}$ the range was from 1.1 to 3.0 in steps of 0.1. t ranged from 1 to 1200 in steps of 1. Because this model is only used to find appropiate values for the 3D models, these ranges will not necessarily be repeated for the other models.

3.2.2. Model 2: 3D Freeze Plug with 1/4 Symmetry

Figure 3.3 shows the 3D variant of the previous model. It has been cut up into 4 pieces to reduce computation time. The effective range of values used for the variables in this model depend on the results of the 2D model. A minor difference with the 2D model is that this model uses a hexagonal shape around the round freeze plug. This is based on a previous research [19]. A hexagonal shape is a close approximation to a circle to allow the usage of thermal insulation on the edges. The usage of edges is allowed because the heat flux at those edges should be equal to zero because it is an equal distance between the edge and the two nearest freeze plugs.

The tested range for the radius ranged from $20mm$ to $50mm$ in steps of $10mm$. For the $\frac{P}{D}$ the range was from 1.2 to 2.0 in steps of 0.1. t went from 1 to 300 in steps of 1.

There is also a data set where the height and the radius were independently varied. The tested ranges for radius was from $10mm$ to $80mm$ and for height from $10mm$ to $70mm$. Both used steps of $10mm$. The $\frac{P}{D}$ had a range from 1.2 to 2.2 in steps of 0.5. t went from 1 to 800 in steps of 1.

3.2.3. Model 3a: 7 Identical Freeze Plugs with 1/4 Symmetry

Figure 3.4 uses the same freeze plug from model 2, with the minor difference of using 7 freeze plugs. This results in one freeze plug in the center and six around it. This model was used to confirm if the t_{melt} found for a single freeze plug is the same when the freeze plug is surrounded by multiple freeze plugs. If t_{melt} is the same or the difference is insignificant, then it will not be necessary to make models that consist of n freeze plugs.

The tested ranges of variables were the same as Model 2.

3.2.4. Model 3b: 6 Identical Freeze Plugs with a larger centered Freeze Plug with 1/4 Symmetry

Figure 3.5 has the same setup as model 3a. The only difference is that the outer six freeze plugs are smaller than the single freeze plug in the center. The difference in size is dependent on a ratio that varies between known values. This ratio is an additional variable that is used during calculations. Because the outer freeze plugs are smaller, the shape of the whole design becomes more like an inverted cone with a flat top instead of a thick disk.

The tested ranges for the radius was from $20mm$ to $50mm$ in steps of $10mm$. For the ratio between freeze plugs was 0.30.50.70.9. The $\frac{P}{D}$ varied from 1.2 to 1.6 in steps of 0.1. t went from 1 to 300 in steps of 1.

3.3. Matlab

Matlab has been used to calculate t_{drain} and t_{total}.The script can be found in appendix A. The variables were:

- Radius freeze plug
- $\frac{P}{D}$
- Radius of the pipe
- Number of freeze plugs
- Ratio between freeze plugs
- Height of the freeze plug

The pseudocode for the matlab script looks like this

- Initializing all the constants for the tank, pipe, model
- Importing the information from COMSOL
- Extrapolate a function for the K-value of a gate
- Calculate t_{melt} using imported COMSOL data

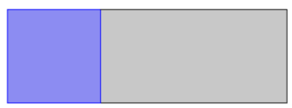


Figure 3.2: 2D Axisymmetry Model

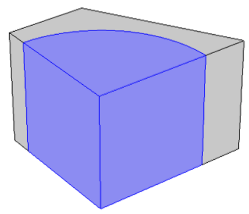


Figure 3.3: 3D Single Plug Model

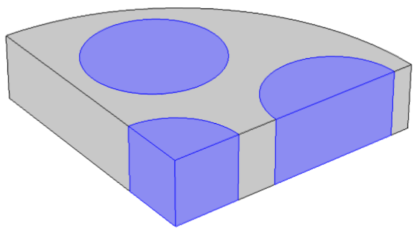


Figure 3.4: 3D Seven Plugs Model

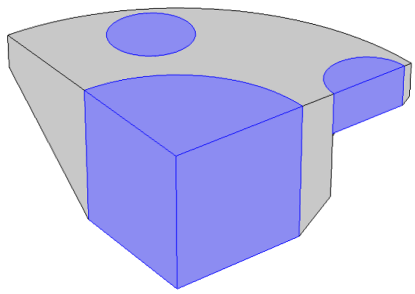


Figure 3.5: 3D Seven Plugs Model with 2 different freeze plugs

The four different geometries that were used in the different models. The blue area represents the freeze plugs, the gray area represents the Hastelloy-N

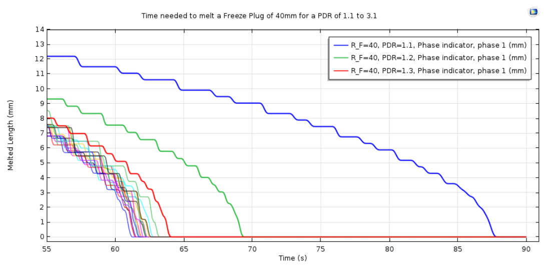
- Input Circle packing cases
- start for-loop for pipe radius
- Calculate number of freeze plugs that fit based on radius of pipe and freeze plug and $\frac{P}{D}$.
- Calculate K_{tot} using extrapolated function for K-value of a gate valve
- Calculate t_{drain}
- Calculate t_{total} and remember fastest configuration
- end loop over pipe radius

4

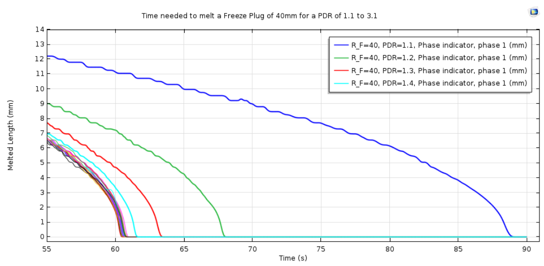
Results

4.1. Mesh Refinement

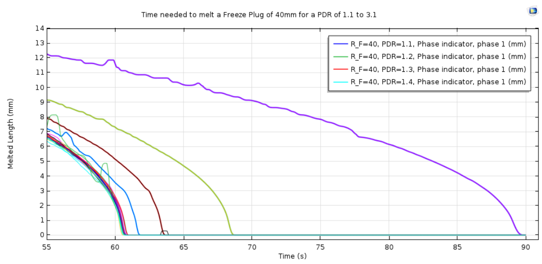
In figure 4.1 you will find the results of the mesh refinement that has been applied by decreasing the maximum mesh size possible. As the amount of elements increase, the graph becomes smoother and for lower values of $\frac{P}{D} ratio$ it becomes more accurate. However t_{melt} seems to converge to the same point regardless of how refined the mesh is. Looking at those graphs it would seem a mesh of around 760 elements, which is approximately the predefined states of 'normal'/'coarse' in COMSOL should give the neccessary accuracy with a reasonable computation time. The choice for this element size is because the increase in accuracy is $\approx 2-3s$ while the computation time increased significantly.



420 Mesh Elements



760 Mesh Elements



1500 Mesh Elements

Figure 4.1: These graphs show the differences in t_{melt} for the same freeze plug but with a different amount of mesh elements. The rest of the graphs can be found in appendix C.2

4.2. Melting Time

Model 1 was used over the ranges of $10mm$ to $100mm$ for the radius and $1.1 to 3.0$ for the $\frac{P}{D}$ to find a suitable range of values to test the models 2-3b for. A suitable range is defined as a melting time that is less than 480 seconds for the combination of radius and $\frac{P}{D}$. A suitable range was from $20mm$ to $50mm$ with $\frac{P}{D}$ from 1.2 to 2.0. This range was selected because the melting time was much smaller than 480 seconds, the choice for not selecting $10mm$ is because the crossectional area would be so small that it would not become a valid option because of the impact on the draining time.

At first this seemed to be a valid range to test model 2 for, however near the end of the project a mistake in the used formula's was found. After the mistake was corrected, it seemed a more suitable range for the radius would be $20mm$ or less and a $\frac{P}{D}$ smaller than 1.3. There are no results for this range for models 2-3b. There will be results shown for this range using model 1 however the results will be less accurate compared to the results that would have been found using model 2.

During the tests for the $\frac{P}{D}$(will be referred to as PDR in some plots) it was found that the decrease in t_{melt} by increasing the $\frac{P}{D}$ drops significantly after a $\frac{P}{D}$ of approximately 1.2 – 1.4 which can be seen in figure 4.2. All these plots were done with the same height of $h = 30mm$. As the $\frac{P}{D}$ increases, t_{melt} seems to converge to $t = 63s$ regardless of the radius of the freeze plug. This is in line with the expected theory explained in section 2.2.3.

4.2.1. Height independent of Radius

A computation has been run using model 2, where the value of the height was not dependent on the value of the radius and the predefined $\frac{h}{r}$. The radius ranged from $10mm$ to $80mm$ in $10mm$ increments. The height ranged from $10mm$ to $70mm$ in $10mm$ increments. The $\frac{P}{D}$ only used the values: 1.2, 1.7, 2.2.

Figure 4.3 show the amount of time it takes to melt the edges of a freeze plug of variable height plotted against the radius with a fixed $\frac{P}{D}$. In those figures, every line represents a fixed height. For low values of $\frac{P}{D}$, the melting time decreases as the radius increases. For high values of $\frac{P}{D}$, the melting time is almost constant.

In this model P is defined as $P = \frac{P}{D} \cdot 2r$. So an increase in either the radius or the $\frac{P}{D}$ results in an increase of P. Figure 4.3 show that an increase in the radius or an increase in $\frac{P}{D}$ (both lead to an increase in P) leads to a faster t_{melt}, however it also shows that t_{melt} converges to a constant value. In section 2.2.3 it was expected that as $P \to P_{max}$ would result in $t_{melt} \to t_{pen}$. Graph C in figure 4.3 shows an almost constant t_{melt}. The results seem to be in line with the theory, because as P increases, t_{melt} seems to converge to a constant value. In the next section, the t_{melt} will be compared to the t_{pen}.

4.2.2. Comparison between experimental t_{melt} and Penetration Theory

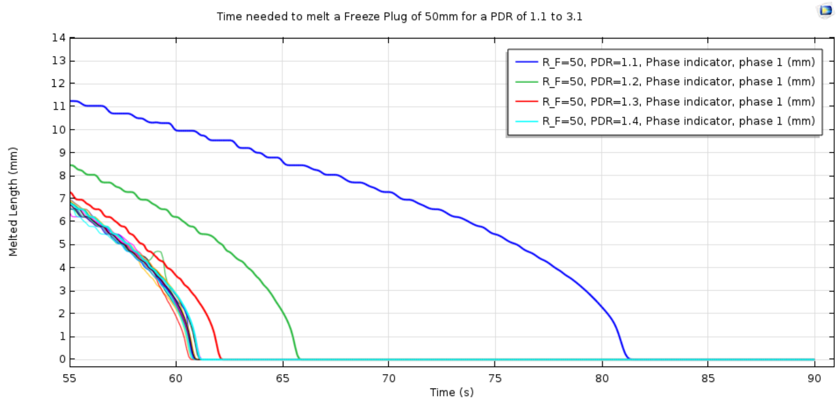
The dataset of the previous section has also been used to plot the dependence of t_{melt} on the height of the freeze plug and how it compares to t_{pen} that would have been gotten out of equation 2.11. A selection of the results are shown in figure 4.4

The graphs from figure 4.4 show that as you increase the radius, the plotted t_{melt} converges to the plotted t_{pen}. This is in line with the findings from the previous section and the theory explained in section 2.2.3. What is odd is that the graph also show that for some combinations of height with a $\frac{P}{D}$ of 1.7 and\or 2.2 the $t_{melt} < t_{pen}$. This is not as expected, because the expectation was that t_{pen} would have been the fastest possible time. The most likely explanation is that the accuracy of the results found using COMSOL are the reason why t_{melt} is occasionally smaller than t_{pen}. It was stated in section 4.1 that the chosen mesh is not the most accurate.

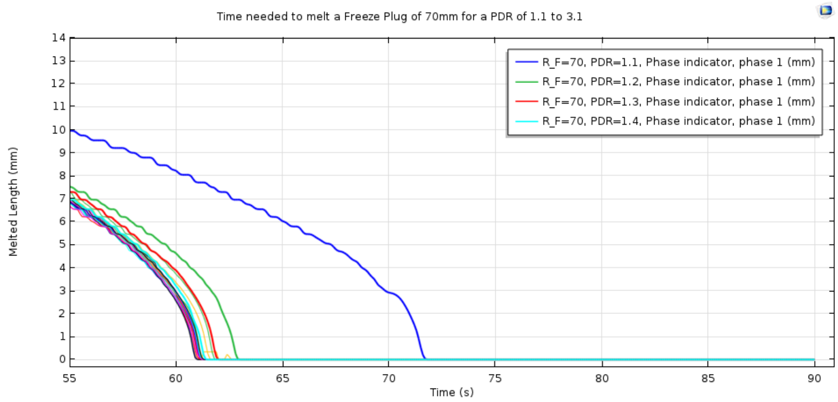
4.2.3. Comparison between single plug and multiple plugs

The melting times of model 2 has been compared to the melting times of model 3a. The comparison can be found in figure 4.5. What is to be noted is that although the legend shows three lines, the graphs only show two. This is because there was no difference between the t_{melt} of the center plug and the outer plug. The maximum absolute difference was $\Delta t = 3s$ and the maximum relative difference was $\Delta t = 4.7\%$. That is a high percentage, however this mainly happened for the freeze plugs with a low t_{melt} since the absolute differences were spread relatively random throughout the sizes of the freeze plugs. Because the absolute differences in t_{melt} are quite low shows that it is possible to use that melting time for any kind of design that uses multiple freeze plugs.

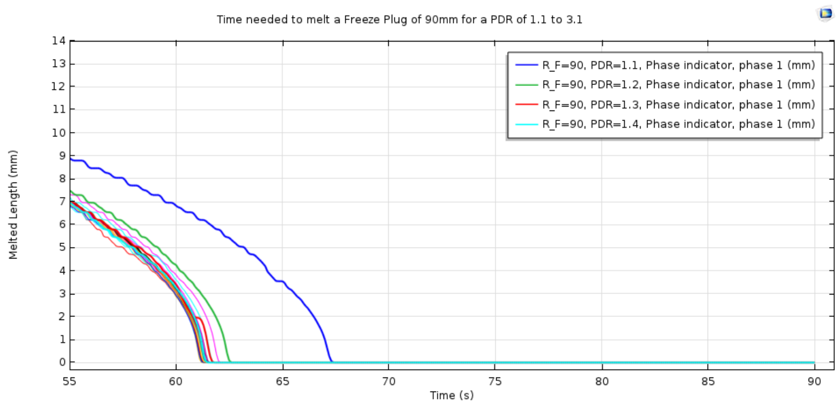
The reason why Δt is small is most likely because of the method that defines the melting time. The melting time is defined as the time it takes for the freeze plug to completely melt around the edges and fall. This means that the edge with the slowest melting time determines t_{melt}. The only difference between edges of the same freeze plug is the distance between the edge and the closest freeze plug. The edge with the smallest distance will have the highest melting time and determines t_{melt}. The $\frac{P}{D}$ is defined as a straight line between the centers of two adjacent freeze plugs and is by definition the shortest possible distance. As a result, t_{melt} of a freeze plug should not depend on the amount of freeze plugs that surround it.



Radius of 50mm

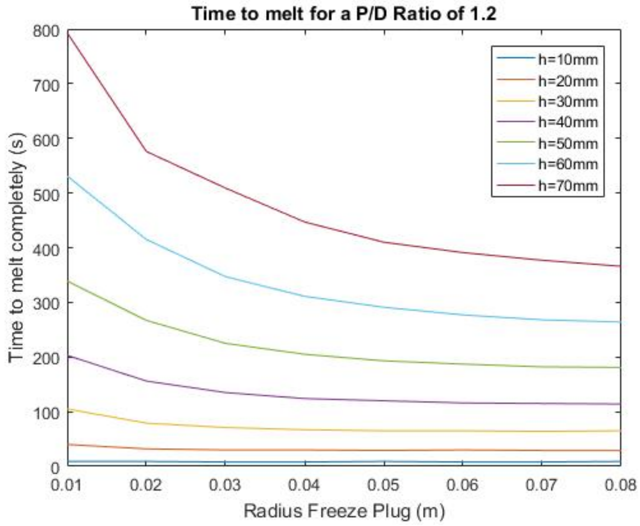


Radius of 70mm

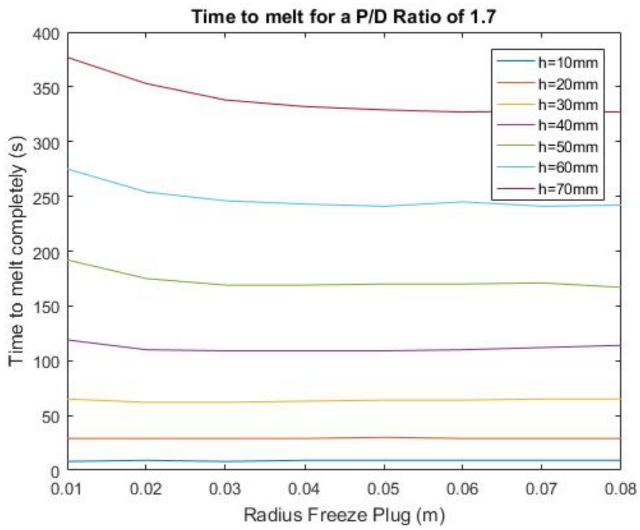


Radius of 90mm

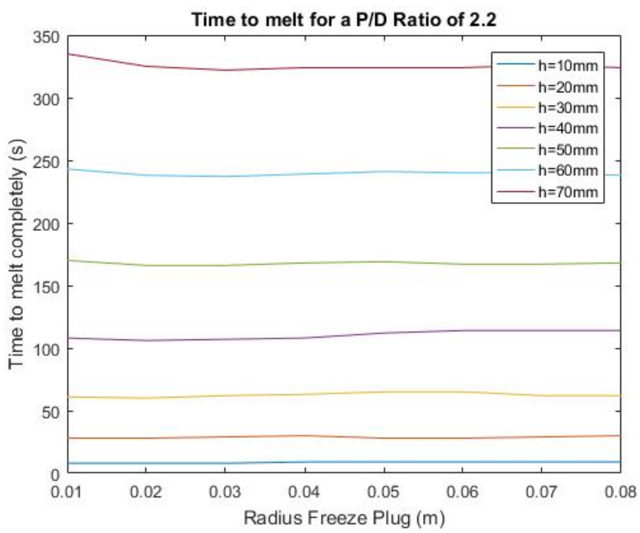
Figure 4.2: These graphs show the t_{melt} for a freeze plug with a height of $30mm$ and varying radius. The rest of the graphs can be found in appendix C.1



A: $\frac{P}{D} ratio = 1.2$

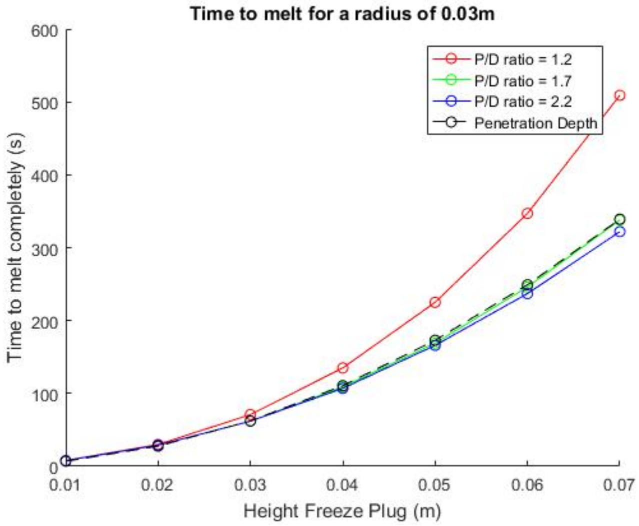


B: $\frac{P}{D} ratio = 1.7$

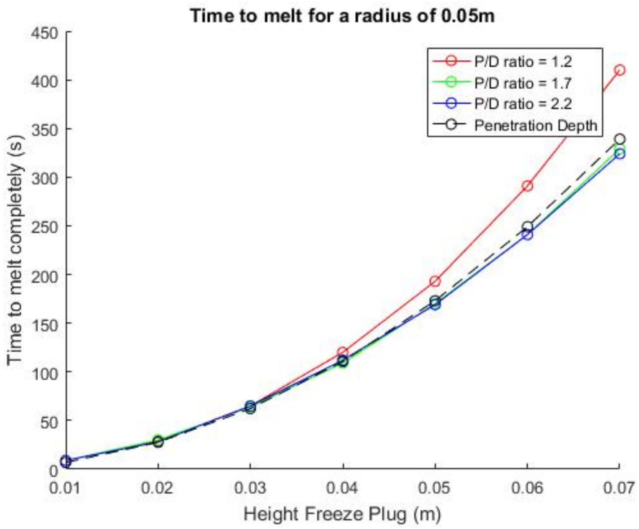


C: $\frac{P}{D} ratio = 2.2$

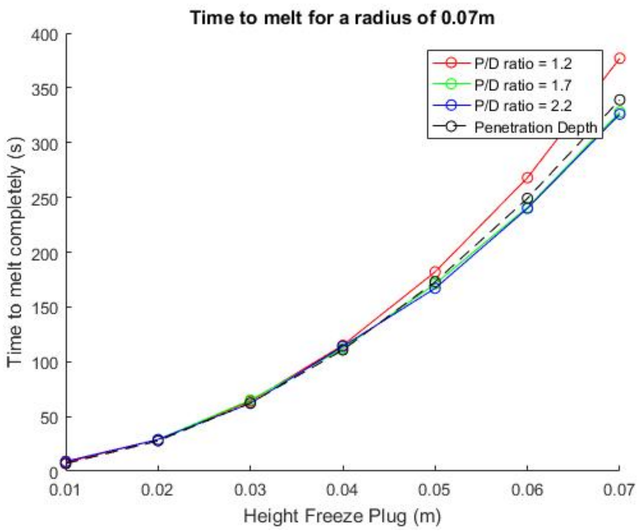
Figure 4.3: Comparison of t_{melt} at their respective $\frac{P}{D} ratios$.



Radius of 30mm

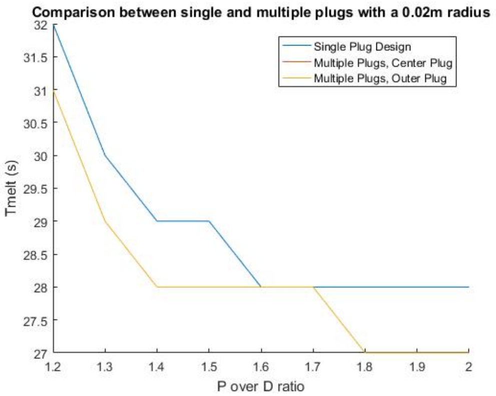


Radius of 50mm

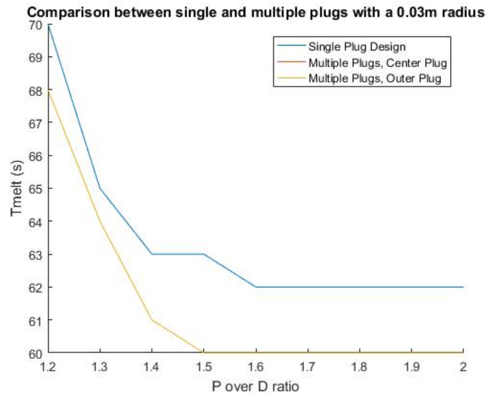


Radius of 70mm

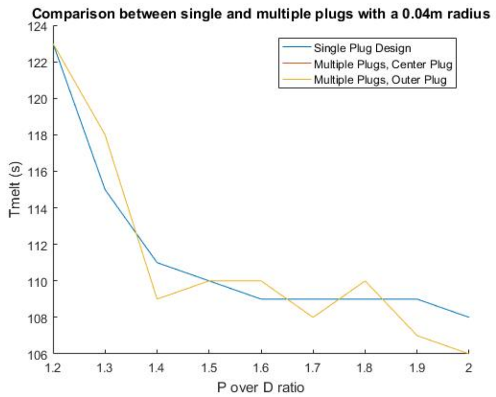
Figure 4.4: These three graphs show the dependence of t_{melt} on the height and how it would compare to the time it would take according to equation 2.11. The rest of the graphs can be found in appendix C.3



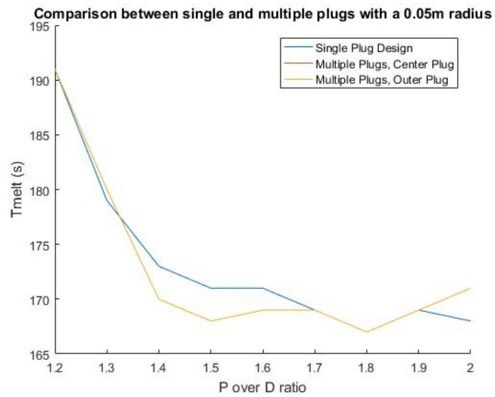
Radius of $20mm$



Radius of $30mm$



Radius of $40mm$



Radius of $50mm$

Figure 4.5: These four graphs show the comparison between the melting time of a single plug and of multiple plugs at different radii.

4.3. Drainage Time and Total Time

Models 3a and 3b were used for this section. Equation 2.20 was used to calculate the drainage time in Matlab. The used script can be found in appendix A.1 to A.3. A section is added to show the results of Model 1 because of the corrected formula's as explained in section 4.2.

4.3.1. Model 3a

This is the model that made use of identical freeze plugs. The melting time is found with COMSOL. As is shown in the previous section, the melting time found with this model are valid for any number of used freeze plugs.

The draining time is found with Matlab using equation 2.20. The amount of freeze plugs used was limited by the radius of the pipe, the radius of the freeze plug and $\frac{P}{D}$. The number of freeze plugs will be determined by using those three values in combination with the packing theory explained in section 2.1.3.

The total time is found by adding the melting time and the draining time. The final solution of this script is a table that shows the fastest configuration for a given pipe radius. The possible configurations are limited to the combination of variables mentioned in section 3.2.3. Figure 4.6 shows the fastest total time for a given pipe radius.

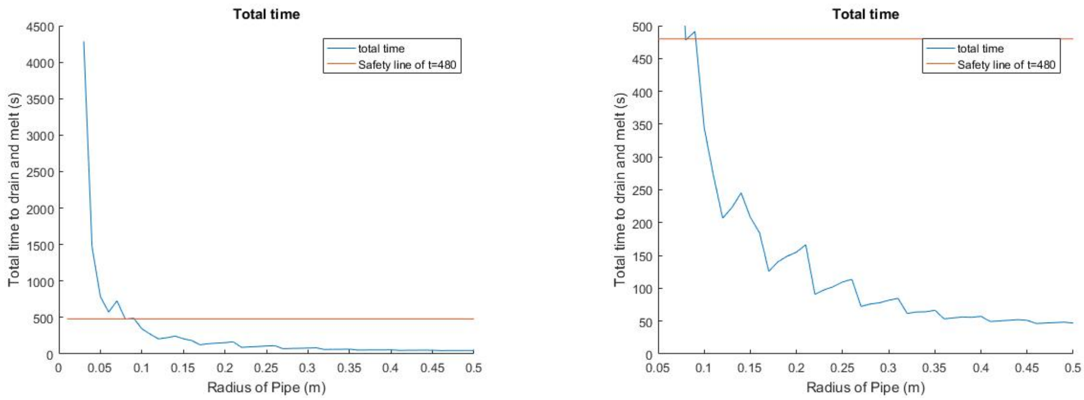


Figure 4.6: The blue line represents the fastest configuration of model 3a for a given radius of the pipe. The red line represents the safety standard of 480s. The graph on the right is a zoomed in version of the graph on the left.

Table 4.1 shows a selection of configurations that have a $t_{total} < 480s$ starting from the smallest pipe radius. There is an exception on row 2, apparently an increase in the number of plugs actually lead to an increase in the total time. This can be explained by looking at equation 2.20. An increase in n may lead to a larger total crossectional area, which decreases t_{drain}. It also increases the friction, which increases t_{drain}. Thus in this particular case, the friction was the more dominant factor. The complete table can be found in appendix B.1.

Table 4.1: Selection of configurations.

Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.08	478.16	0.02	1.2	8
0.09	491.31	0.02	1.2	9
0.1	344.6	0.02	1.2	12
0.11	271.84	0.02	1.2	15
0.12	206.78	0.02	1.2	19
0.13	222.91	0.02	1.2	20
0.14	245.35	0.03	1.2	10
0.15	208.08	0.03	1.2	12
0.16	184.6	0.03	1.2	14
0.17	125.88	0.02	1.2	37
0.18	140.42	0.02	1.2	37

4.3.2. Model 3b

This is the model that uses a maximum of seven freeze plugs of which the center freeze plug is bigger than the remaining 6 freeze plugs that surround it. The result can be seen in figure 4.7. It shows that there is a faster configuration for the same radius of the pipe. The details of the faster configurations can be found in table 4.2.

The outer freeze plugs are smaller than the center freeze plug. As a result, they will melt faster and start draining the molten salt earlier. So by the time all the plugs have molten, the volume of molten salt that has to be drained is less. This could lead to faster configurations, however there was only one faster and safe configuration within the limited dataset.

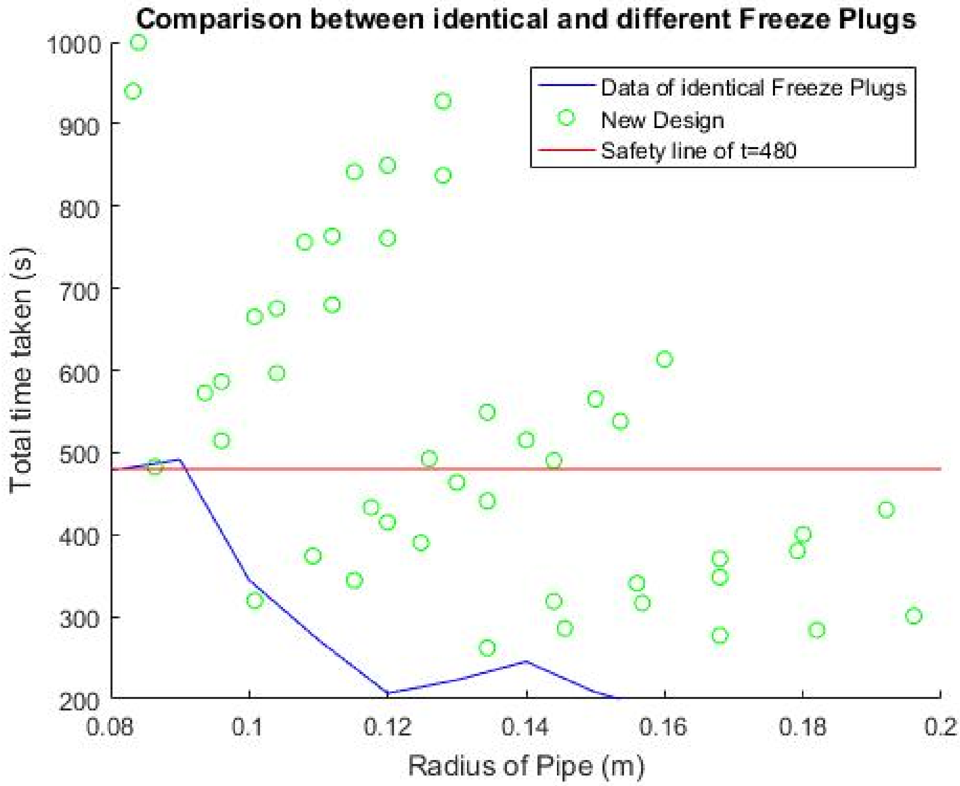


Figure 4.7: The green dots shows the results of model 3b.The blue line represents the data of model 3a. The red line represents the safety standard of 480s.

Table 4.2: Details of the faster configurations. R. stands for the radius

Radius_Pipe	Total_Time	Radius_Inner_Freeze_Plug	Radius_Outer_Freeze_Plug	P_D_Ratio	Time_Saved
0.1008	323.98	0.03	0.027	1.2	22.97

4.3.3. Model 1

This is the results of using the melting times from model 1 instead of model 3a. The reason why this dataset is being used is mentioned in section 4.2. This dataset will be using the same Matlab script as was used for the dataset of model 3a. The purpose of this section is to illustrate the total time for values of radius and $\frac{P}{D}$ that were not tested with model 3a. The melting times of model 1 are a good approximation of the melting times of model 3a, however the inaccuracy is higher. Only t_{melt} has a higher inaccuracy, t_{drain} will have the same accuracy as model 3a because it uses the same Matlab script. A table with selected values is shown in table 4.3. The rest of the table can be found in appendix B.2.

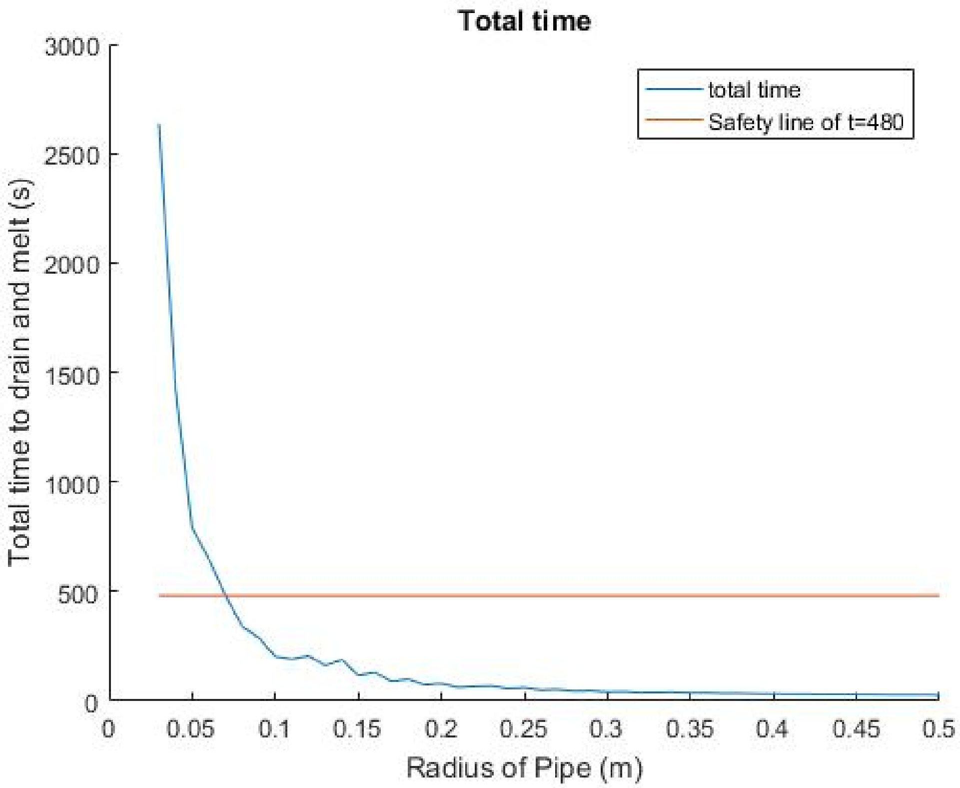


Figure 4.8: The total time for a given pipe radius, using the melting time from model 1

Table 4.3: Selection of configurations.

Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.08	340.59	0.01	1.1	37
0.09	288.69	0.02	1.1	12
0.1	201.82	0.01	1.1	61
0.11	190.12	0.02	1.1	19
0.12	205.43	0.02	1.1	20
0.13	162.04	0.01	1.1	91
0.14	187.64	0.01	1.2	91
0.15	116.35	0.01	1.1	127
0.16	129.66	0.01	1.2	127
0.17	89.83	0.01	1.1	169
0.18	99.78	0.01	1.1	169

5 Conclusions and Recommendations

The goal was to find the fastest configuration of the new design. Where fastest was defined as the smallest total time taken to melt the freeze plugs and drain the tank. The total time had to be less than 8 minutes.

To achieve that goal, the optimal amount of freeze plugs, radius and height of the freeze plug and the thickness of Hastelloy-N had to be found.

The optimal configuration has not been found. Mistakes were made in the formula, which were discovered late in the research. This led to the testing of a different range of values for the radius and the $\frac{P}{D}$ for model 2, 3a and 3b. To compensate for this, results have been shown using model 1, which have a slightly higher inaccuracy.

Although the configurations presented in this research may not be the most optimal, they do comply with the safety standard by having a t_{total} that is smaller than $480s$. This shows that the idea of using multiple freeze plugs can work.

Only the configuration that fit a pipe radius of $0.1m$ will be discussed here because both model 3a and model 1 will have faster times by increasing the pipe radius from this point onwards. The configuration of model 3b will not be discussed, although it was faster for a smaller pipe radius. The configurations of model 3a might be $\approx 1mm$ larger, it decreases the time by $\approx 60s$. Also only one configuration was faster, the rest were all slower.

The fastest configuration of model 3a has a total time of $\approx 344s$. It uses 12 freeze plugs with a radius of $20mm$ and a $\frac{P}{D} = 1.2$. The fastest configuration of model 1 has a total time of $\approx 201s$. It uses 61 freeze plugs with a radius of $10mm$ and a $\frac{P}{D} = 1.1$.

My hypothesis about the radius is wrong. I expected the optimal radius to be $50mm$. Since I set the $\frac{h}{r} = 1$, the radius is equal to the height. I assumed $50mm$ to be the optimal radius because a larger crossectional area would lead to a faster draining time. Because the height depends on the radius, it is difficult to determine why my hypothesis was wrong. It is unclear whether the influence of the height on the melting time is more important than expected, or because the influence of the radius on the draining time is less important than expected.

My hypothesis about the number of freeze plugs is wrong too. I expected around five freeze plugs. That expectation was based on having at least the same crossectional area as a pipe with a radius of $0.1m$ using freeze plugs with a radius of $50mm$. However the total crossectional areas of the two models is smaller than that.

In the end, the most optimal configuration has not been found. However the remaining configurations do comply with the safety standard. Although assumptions had to be made during the research, the results show that it is possible the new design can comply with the safety regulations. It has also been shown that configurations that use different freeze plugs could be faster than a design that uses identical freeze plugs.

5.1. Recommendations

Although the results show that the design is possible, there are still some doubts. During this research, several assumptions had to be made to get to a sensible result. These assumptions should be tested.

- The minimum $\frac{h}{r}$ to prevent the freeze plug from collapsing and falling.
  In this research, the freeze plug was modeled with the minimum possible surface area. This resulted

in a height which equals the radius, however the essential height could be smaller or larger for a given radius. Since t_{melt} seems to depend at least quadratically on the height, it would prove valuable to minimize this property. At the same time, it is essential that the freeze plug remains in place during normal operating conditions. Further research is necessary to determine what the requirements are to keep the freeze plug in place.

- The properties of the solid salt.
  A substitute salt has been used for the calculations and computations. However it is unknown whether this is a valid substitution. The actual properties of the solid salt have to be determined. It will either prove that LiCl is a valid substitution or it makes subsequent research possible with a higher accuracy.

- The maximum radius of the pipe.
  In the models used in this research, the maximum of the pipe has been set at $0.5m$ to satisfy the condition of $A_{pipe} >> A_{tank}$ which was neccessary for equation 2.20. The chosen radius of the pipe was to make it easier to compare the models, however that is not the fastest option.It is unknown what the maximum radius of the pipe could and should be. There could be a limit based on the melting behaviour of the salt or perhaps a practical limit based on the design of the reactor.

- Using an additional layer of a material with a higher thermal conductivity.
  This research has not made use of an earlier research using an additional layer of a material that has a higher thermal conductivity than Hastelloy-N. In a previous research it has been investigated for a single material on only one freeze plug. It is unknown what the effect of an additional layer could have on the melting, draining or total time. It is also unknown how it would affect the variables as the height and radius of the freeze plug, the $\frac{h}{r}$ and the necessary radius of the pipe to comply with safety standards.

- Increasing the surface area for conductive heat transfer
  More surface area to tranfer heat from the molten salt to the freeze plug could decrease the time to melt even further.

- A higher amount of different sized freeze plugs
  The design used in this project showed it could be faster for a given radius compared to the design using identical freeze plugs. But it has only been tested for seven freeze plugs and with only two different sizes. This gives a small range of possible combinations.

Bibliography

[1] A technology roadmap for generation iv nuclear energy systems. Technical report, U.S. Nuclear Energy Research Advisory Committee and Generation IV International Forum, 2002.

[2] L.G. Alexander, D.A. Carrison, H.G. MacPherson, and J.T. Roberts. Nuclear characteristics of spherical, homogeneous, two-region, molten-fluoride-salt reactors. Technical report, Oak Ridge National Laboratory, September 1959.

[3] Wolfram Alpha. Circle packing, January 2017. URL `http://mathworld.wolfram.com/CirclePacking.html`. Online; accessed 7 February 2017.

[4] World Nuclear Association. Generation iv nuclear reactors, July 2016. URL `http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx`. Online; accessed 26 January 2017.

[5] World Nuclear Association. Fukushima accident, January 2017. URL `http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx`. Online; accessed 26 January 2017.

[6] M. Brovchenko, D. Heuer, E. Merle-Lucotte, M. Allibert, V. Ghetta, A. Laureau, and P. Rubiolo. Design-related studies for the preliminary safety assessment of the molten salt fast reactor. *Nuclear Science and Engineering*, 175:329–339, November 2013.

[7] P. Calderoni and C. Cabet. *Nuclear Corrosion Science and Engineering*, chapter 23. Series in Energy. Woodhead Publishing, 2012.

[8] EVOL. Final report - evol project. report, CNRS, JRC-ITU, TUD, HZDR, KIT, POLITO, AD, EVM, BME, UOXF-DJ, INOPRO, PSUD, 2013.

[9] R. Hargraves and R. Moir. Liquid fluoride thorium reactors. *American Scientist*, 98, 2010.

[10] V. Ignatiev, O. Feynberg, A. Merzlyakov, A. Surenkov, A. Zagnitko, V. Afonichkin, A. Bovet, V. Khokhlov, V. Subbotin, R. Fazilov, M. Gordeev, A. Panov, and A. Toropov. Progress in development of MOSART concept with Th support. 2012.

[11] L.P.B.M. Janssen and M.M.C.G. Warmoeskerken. *Transport Phenomena Data Companion*. VSSD, third edition, 2006.

[12] T.J. Keenan and J. Bianchi. Method for maximizing packing density with cylindrical objects in cylindrical cavities, Augustus 2010.

[13] I. Koks. A new design for the safety plug in a molten salt fast reactor. Bachelor's thesis, TU Delft, July 2016.

[14] D. Leblanc. Molten salt reactors: A new beginning for an old idea. *Nuclear Engineering and Design*, 240: 1644–1656, December 2009.

[15] H. E. McCoy, W. H. Cook, R.E. Gehlback, J.R. Weir Jr., C.R. Kennedy, C.E. Sessions, R.L. Beatty, A.P. Litman, and J.W.Koger. Materials for molten-salt reactors. *Journal of Nuclear Applications*, May 1969.

[16] J. Serp, M. Allibert, O. Benes, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J.L. Kloosterman, L. Luzzi, E. Merle-Lucotte, J. Uhlír, R. Yoshioka, and D. Zhimin. The molten salt reactor (msr) in generation iv: Overview and perspectives. *Progress in Nuclear Energy*, 77:308–319, 2014.

[17] P. Swaroop. Design of a freeze plug for the molten salt reactor (msr). Master's thesis, TU Delft, September 2015.

[18] O. van den Bergh. Passive emergency drainage of the molten salt fast reactor. Bachelor's thesis, TU Delft, July 2016.

[19] F. van Tuyll. A new design for the safety plug in a molten salt fast reactor. Bachelor's thesis, TU Delft, December 2016.

[20] Wikipedia. Nuclear and radiation accidents and incidents, 2017. URL https://en.wikipedia.org/wiki/Nuclear_and_radiation_accidents_and_incidents#Nuclear_power_plant_accidents. Online; accessed 26 January 2017.

A
Matlab Scripts

A.1. Calculating the $t_{melt}, t_{drain} and\, t_{total}$ for identical freeze plugs

```
%% Berekening t_total
clear variables; close all; clc;

%% Constanten Reactor
H_T= 2.84;  %Height of tank
R_T= 1.42;  %Radius of tank
rho=4080;   %Property Salt
mu=1.01e-2; %Property Salt
g=9.81;     %Gravity
dt=1;       %Time Step
f=0.0034;   %Franning Friction Factor
Kinlet = 0.5;%Friction at an Inlet
Ktot = Kinlet;
L=3.5;      %Length of pipe

% Determining Kgate formula
a_ratio = [1 0.75 0.5 0.25];
Kw = [0.2 0.9 4.5 24];
p = fit(a_ratio',Kw','exp1');
q = coeffvalues(p);


%% Data+Variabelen !!These must be changed manually to fit the data!!
COMSOL = readtable('Tabel R_F(20,10,50)mm PDR(1.2,0.1,2.0) t=(1,1,300) quarter.csv');
Data=COMSOL(:,2:end);
Data= table2array(Data);
PDR = 1.2:0.1:2.0;            %P over D ratio
r_FP = 1e-3*(20:10:50);     %Ratio Freeze Plug
R_B = 0.11%:0.01:0.50;         %Radius of pipe
ts = 1;                     %Time step used in your data

%% Berekening tmelt voor verschillende PDR en r_FP
[sel, z] = min( Data~=0, [], 1 );
z = z*ts; %time needed to fully melt the freeze plug in seconds
tmz = zeros(size(Data,2)/length(PDR),length(PDR));
for i = 1:size(Data,2)/length(PDR)
tmz(i,1:length(PDR))=z(1+length(PDR)*(i-1):length(PDR)*i);
end

%% Circle & Hexagon Packing possibilities

```

```
%Circle Packing
mc(1)= 1;
mc(2)= 2;
mc(3)= 1+2/3*sqrt(3);
mc(4)= 1+sqrt(2);
mc(5)= 1+sqrt(2*(1+1/sqrt(5)));
mc(6)= 3;
mc(7)= 3;
mc(8)= 1+csc(pi/7);
mc(9)= 1+sqrt(2*(2+sqrt(2)));
mc(10)=3.813;
mc(11)=1+1/(sin(pi/9));
mc(12)=4.029;
mc(13)=2+sqrt(5);
mc(14)=4.328;
mc(15)=1+sqrt(6+2/sqrt(5)+4*sqrt(1+2/sqrt(5)));
mc(16)=4.615;
mc(17)=4.792;
mc(18)=1+sqrt(2)+sqrt(6);
mc(19)=1+sqrt(2)+sqrt(6);
mc(20)=5.122;

nc = zeros(length(r_FP),length(PDR));

%Hexagon Packing
mh = zeros(length(r_FP),length(PDR));
nh = zeros(length(r_FP),length(PDR));

n = ones(length(r_FP),length(PDR));
%% Berekening tdrain voor verschillende PDR en r_FP en R_B
Final_Solution = zeros(length(R_B),5);
td = inf(size(tmz));
C = zeros(size(tmz));
for i = 1:length(R_B)
for j = 1:length(r_FP)
for k=1:length(PDR)

% Finalizing mh in the while loop
while ((2*(mh(j,k)+1)-1)*PDR(k)*r_FP(j))<=R_B(i)
mh(j,k)=mh(j,k)+1;
end

% Finalizing nh
if mh(j,k) == 0
nh(j,k)=0;
else
nh(j,k)= 3*mh(j,k)*(mh(j,k)-1)+1;
end

% Finalizing nc in the for-if loop
for l =1:length(mc)
if PDR(k)*r_FP(j)*mc(l)<=R_B(i)
nc(j,k)=l;
end
end

% Finalizing n amount of freeze plugs
n(j,k) = max(nh(j,k),nc(j,k));


% Decide on which K-value you want to use
```

```
% K for a gate valve
A2 = n(j,k)*r_FP(j).^2;
A1 = R_B(i)^2;
ar = A2/A1;
Kgate = q(1)*exp(q(2)*ar);

% K for an open entrance
Kin = n(j,k)*Kinlet;

% Choose K-value: Ktot = either gate or in
Ktot = Kgate;

%Calculating t_drain
C(j,k) = n(j,k).*(r_FP(j)/R_T).^2.*sqrt((2.*g./(1+n(j,k).*4.*f.*L./(2*r_FP(j))+Ktot)));
td(j,k) = 1./C(j,k).*2.*(sqrt(H_T+L)-(sqrt(L)));

end
end
%Calculating t_total
ttotal = td+tmz;

%Find minimum value with the corresponding row and column
tmin = min(ttotal(:));
[row, col] = find(ttotal == tmin,1,'first');

%Putting everything in the final solution
Final_Solution(i,1) = R_B(i);
Final_Solution(i,2) = tmin;
Final_Solution(i,3) = r_FP(row);
Final_Solution(i,4) = PDR(col);
Final_Solution(i,5) = n(row,col);
end
Final_Solution(:,2)=round(Final_Solution(:,2),2)
%% Plotting
hold on
plot(Final_Solution(:,1),Final_Solution(:,2))
plot([Final_Solution(1,1) Final_Solution(end,1)],[480 480])
title('Time taken for a given radius of the pipe')
xlabel('Radius of Pipe (m)')
ylabel('Total time to drain and melt (s)')
legend('total time', 'Safety line of t=480')
%axis([0.05 .5 0 500])
%% CSV Table for export
headers = {'Radius_Pipe', 'Total_Time', 'Radius_Freeze_Plug', 'P_over_D_Ratio','
    Amount_of_Freeze_Plugs'};
FS_table=array2table(Final_Solution,'VariableNames',headers);
writetable(FS_table,'FS_3abest.csv')
%
% tmz_table = array2table(tmz);
% writetable(tmz_table,'TMZ_3.csv')
```

A.2. Calculating the $t_{melt}, t_{drain} and t_{total}$ for different freeze plugs

```
%% Berekening t_total voor 7x met 2 FP
clear variables; close all; clc;

%% Constanten Reactor
H_T= 2.84;  %Height of tank
R_T= 1.42;  %Radius of tank
rho=4080;   %Property Salt
```

```
mu=1.01e-2; %Property Salt
g=9.81;     %Gravity
dt=1;       %Time Step
f1=0.0034;   %Franning Friction Factor
Kinlet = 0.5;%Friction at an Inlet
Ktot = Kinlet;
L=3.5;      %Length of pipe

% Determining Kgate formula
a_ratio = [1 0.75 0.5 0.25];
Kw = [0.2 0.9 4.5 24];
p = fit(a_ratio',Kw','exp1');
q = coeffvalues(p);

%% Data+Variabelen !!These must be changed manually to fit the data!!
Data_0 = readtable('Tabel Inner FP R_F(20,10,50)mm R(0.3,0.2,0.9) PDR(1.2,0.1,1.6) t(0,1,300).
    csv');
temp_half = (size(Data_0,2)-1)/2;
Data_1 = Data_0(:,1:temp_half+1);
Data_2 = Data_0(:,[1 size(Data_0,2)-temp_half+1:size(Data_0,2)]);

% Data_1 = readtable('Tabel Inner FP R_F(20,10,50)mm R(0.3,0.3,0.9) PDR(1.2,0.1,1.6) t
    (0,1,300).csv');
% Data_2 = readtable('Tabel Outer FP R_F(20,10,50)mm R(0.3,0.3,0.9) PDR(1.2,0.1,1.6) t
    (0,1,300).csv');

FP_inner=Data_1(:,2:end);
FP_outer=Data_2(:,2:end);


FP_inner= table2array(FP_inner);
FP_outer= table2array(FP_outer);

r_FP_inner = 1e-3*(20:10:50);     %Radius Freeze Plug
ratio_FP=0.3:0.2:0.9;        %Ratio between Freeze Plugs
PDR = 1.2:0.1:1.6;           %P over D ratio
ts = 1;                      %Time step used in your data
n = 7;                       % # of Freeze Plugs

ratio_temp = repelem(ratio_FP,length(r_FP_inner),length(PDR));
r_FP_temp = repelem(r_FP_inner',1,length(PDR)*length(ratio_FP));
r_FP_outer= ratio_temp.*r_FP_temp;
r_FP_inner_2=repelem(r_FP_inner',1,length(PDR)*length(ratio_FP));

% R_B Berekenen
R_B = r_FP_inner_2+2*r_FP_outer;
PDR_temp = repelem(PDR,length(r_FP_inner),1);
PDR_2 = repmat(PDR_temp,1,length(ratio_FP));
R_B = R_B.*PDR_2;
%% Berekening tmelt voor verschillende PDR en r_FP
[~, z_inner] = min( FP_inner~=0, [], 1 );
[~, z_outer] = min( FP_outer~=0, [], 1 );

z_inner = z_inner*ts; %time needed to fully melt the freeze plug in seconds
z_outer = z_outer*ts; %time needed to fully melt the freeze plug in seconds

tmz_inner = zeros(length(r_FP_inner),length(PDR)*length(ratio_FP));
tmz_outer = zeros(length(r_FP_inner),length(PDR)*length(ratio_FP));

for i = 1:length(r_FP_inner)
tmz_inner(i,1:length(PDR)*length(ratio_FP))=z_inner(1+length(PDR)*length(ratio_FP)*(i-1):
```

```
    length(PDR)*length(ratio_FP)*i);
tmz_outer(i,1:length(PDR)*length(ratio_FP))=z_outer(1+length(PDR)*length(ratio_FP)*(i-1):
    length(PDR)*length(ratio_FP)*i);
end
tmz_diff = tmz_inner-tmz_outer;
%% Berekening tdrain
% Eerste fase waarin alleen de 6 outer plugs gesmolten zijn

% Using Kgate
A2 = (n-1).*r_FP_outer.^2;
A1 = R_B.^2;
ar = A2./A1;
Ktot = q(1)*exp(q(2)*ar)/(n-1);

C_1 = (n-1)*r_FP_outer.^2/R_T^2.*sqrt((2*g./(1+(n-1)*4*f1*L./(2.*r_FP_outer)+(n-1)*Ktot)));
h_t = 0.25*(C_1.^2.*tmz_diff-2*sqrt(H_T+L)*C_1.*tmz_diff+(2*sqrt(H_T+L))^2-4*L);

%2de fase waarin alle FP zijn gesmolten

% Using Kgate
A2 = (n-1).*r_FP_outer.^2+r_FP_inner_2.^2;
A1 = R_B.^2;
ar = A2./A1;
Ktot = q(1)*exp(q(2)*ar)/n;

C_2= ((n-1)*r_FP_outer.^2+r_FP_inner_2.^2)/R_T^2.*sqrt((2*g./(1+4*f1*L*((n-1)./(2.*r_FP_outer)
    +1./(2.*r_FP_inner_2))+(n)*Ktot)));
td = 1./C_2.*2.*(sqrt(h_t+L)-(sqrt(L)));

ttotal = tmz_inner+td;



%% Putting everything into a single matrix
Final_Solution = zeros(size(FP_inner,2),5);
Final_Solution(:,1)=reshape(R_B',size(FP_inner,2),1);
Final_Solution(:,2)=reshape(ttotal',size(FP_inner,2),1);
Final_Solution(:,3)=reshape(r_FP_inner_2',size(FP_inner,2),1);

%Final_Solution(:,5)=reshape(ratio_temp',size(FP_inner,2),1);
Final_Solution(:,5)=reshape(PDR_2',size(FP_inner,2),1);
Final_Solution(:,4)=Final_Solution(:,3).*Final_Solution(:,5);
FS = sortrows(Final_Solution);

%% Vergelijken met de standaard versie

Data = readtable('FS_2hgate.csv');
Data = table2array(Data);

hold on
a = 0.08;
b = 0.2;
axis( [a b 200 1000])
plot(Data(:,1),Data(:,2),'b');
plot(FS(:,1),FS(:,2),'-go')
plot([FS(1,1) FS(end,1)], [480 480],'r')
title('Comparison between identical and different Freeze Plugs')
xlabel('Radius of Pipe (m)')
ylabel('Total time taken (s)')
legend('Data of identical Freeze Plugs', 'New Design', 'Safety line of t=480')

```

```
c = find(Data(:,1) == a);
d = find(Data(:,1) == b);

e = find(FS(:,1) >= a,1);
f = find(FS(:,1) >= b,1);

q = 6;

p1 = polyfit(Data(c:d,1),Data(c:d,2),q);
f1= 0;
f2 = 0;
for i = 1:length(p1)
f1 = f1+p1(i)*Data(c:d,1).^(length(p1)-i);
f2 = f2+p1(i)*FS(e:f,1).^(length(p1)-i);
end

%plot(Data(c:d,1),f1)
%plot(FS(e:f,1),f2)


FS_diff = f2 - FS(e:f,2);
row1 = find(FS_diff > 0);
row2 = row1+e-1;
FS_verbetering = zeros(length(row2),size(FS,2)+1);
for i = 1:length(row2)
FS_verbetering(i,1:(end-1)) = FS(row2(i),:);
FS_verbetering(i,end)=FS_diff(row1(i));
end
FS_verbetering(:,2)=round(FS_verbetering(:,2),2);
FS_verbetering(:,6)=round(FS_verbetering(:,6),2);
FS_verbetering

headers = {'Radius_Pipe', 'Total_Time', 'Radius_Inner_Freeze_Plug', 'Radius_Outer_Freeze_Plug'
    ,'P_D_Ratio','Time_Saved'};
FS_table=array2table(FS_verbetering(1,:),'VariableNames',headers);
%writetable(FS_table,'FS_3bbest.csv')

FS_Temp = table2array(FS_table);
FS_Table2 = array2table(FS_Temp.');
FS_Table2.Properties.RowNames = FS_table.Properties.VariableNames;
writetable(FS_Table2,'FS_verbetering2.csv')
```

A.3. Calculating the t_{melt} for different radii and height

```
%% Berekening t_melt
clear variables; close all; clc;
%% Data+Variabelen !!These must be changed manually to fit the data!!
COMSOL = readtable('Tabel R_F(10,10,80)mm H(10,10,80) PDR(1.2,0.5,2.2) t(0,1,800).csv');
Data=COMSOL(:,2:end);
Data= table2array(Data);
PDR = 1.2:0.5:2.2;          %P over D ratio
r_FP = 1e-3*(10:10:80);     %Ratio Freeze Plug
h_FP = 1e-3*(10:10:80);
R_B = 0.01:0.01:0.91;        %Radius of pipe
ts = 1;                    %Time step used in your data

%% Calculating tmz
[~, z] = min( Data~=0, [], 1 );
z=z*ts;
tmz = reshape(z,length(h_FP)*length(PDR),length(r_FP));
tmz = tmz';
```

```
tmz(tmz==1)=inf;

%% Sorting tmz in blocks of PDR with rows as radius
tmz_pdr = zeros(size(tmz));
for i = 1:length(PDR)
for j = 1:length(h_FP)
tmz_pdr(:,1+length(h_FP)*(i-1):i*length(h_FP))=tmz(:,i:length(PDR):length(h_FP)*length(PDR));
end
end

%% Sorting tmz in blocks of PDR with rows as height
tmz_pdr_h = zeros(size(tmz));
for i = 1:length(PDR)
for j = 1:length(h_FP)
tmz_pdr_h(:,1+length(h_FP)*(i-1):i*length(h_FP))=tmz_pdr(:,1+length(h_FP)*(i-1):i*length(h_FP)
    )';
end
end

%% Plotting tmz sorted in pdr-blocks with rows as radius
plot(r_FP,tmz_pdr(:,17:23))
xlabel('Radius Freeze Plug (m)')
ylabel('Time to melt completely (s)')
title('Time to melt for a P/D Ratio of 2.2')
legend('h=10mm','h=20mm','h=30mm','h=40mm','h=50mm','h=60mm','h=70mm')

%% Plotting tmz sorted in pdr-blocks with rows as height
hold on
r = 8;
plot(h_FP(1:7),tmz_pdr(r,1:7),'ro-')
plot(h_FP(1:7),tmz_pdr(r,9:15),'go-')
plot(h_FP(1:7),tmz_pdr(r,17:23),'bo-')
a = 4.6e-6;
f = h_FP.^2./(pi.*a);
plot(h_FP(1:7),f(1:7),'ko--')
legend('P/D ratio = 1.2','P/D ratio = 1.7','P/D ratio = 2.2','Penetration Depth')
title(['Time to melt for a radius of ' num2str(r_FP(r)) 'm'])
xlabel('Height Freeze Plug (m)')
ylabel('Time to melt completely (s)')
```

B

Tables

B.1. Table of the Final Solutions using model 3a

Table B.1: Fastest total time possible for a given Radius of Pipe

Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.03	4284.72	0.02	1.4	1
0.04	1465.38	0.03	1.3	1
0.05	787.17	0.04	1.2	1
0.06	573.37	0.05	1.2	1
0.07	729.01	0.05	1.4	1
0.08	478.16	0.02	1.2	8
0.09	491.31	0.02	1.2	9
0.1	344.6	0.02	1.2	12
0.11	271.84	0.02	1.2	15
0.12	206.78	0.02	1.2	19
0.13	222.91	0.02	1.2	20
0.14	245.35	0.03	1.2	10
0.15	208.08	0.03	1.2	12
0.16	184.6	0.03	1.2	14
0.17	125.88	0.02	1.2	37
0.18	140.42	0.02	1.2	37
0.19	148.99	0.03	1.2	20
0.2	155.04	0.03	1.3	20
0.21	166.4	0.03	1.3	20
0.22	90.76	0.02	1.2	61
0.23	97.57	0.02	1.2	61
0.24	102.61	0.02	1.3	61
0.25	109.75	0.02	1.3	61
0.26	113.67	0.03	1.2	37
0.27	72.46	0.02	1.2	91
0.28	76.16	0.02	1.2	91
0.29	77.97	0.02	1.3	91
0.3	81.83	0.02	1.3	91
0.31	84.73	0.02	1.4	91
0.32	61.75	0.02	1.2	127
0.33	63.95	0.02	1.2	127
0.34	64.22	0.02	1.3	127
0.35	66.53	0.02	1.3	127
0.36	53.58	0.02	1.2	169
0.37	54.94	0.02	1.2	169

Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.38	56.35	0.02	1.2	169
0.39	55.8	0.02	1.3	169
0.4	57.28	0.02	1.3	169
0.41	49.42	0.02	1.2	217
0.42	50.34	0.02	1.2	217
0.43	51.29	0.02	1.2	217
0.44	52.26	0.02	1.2	217
0.45	51.26	0.02	1.3	217
0.46	46.44	0.02	1.2	271
0.47	47.09	0.02	1.2	271
0.48	47.75	0.02	1.2	271
0.49	48.43	0.02	1.2	271
0.5	47.13	0.02	1.3	271

B.2. Table of the Final Solutions using model 1

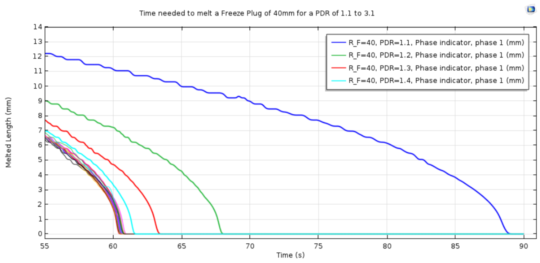
Table B.2: Fastest total time possible for a given Radius of Pipe

Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.03	2633.53	0.01	1.1	5
0.04	1422.19	0.01	1.1	9
0.05	788.3	0.01	1.1	15
0.06	648.39	0.01	1.1	20
0.07	480.85	0.02	1.1	7
0.08	340.59	0.01	1.1	37
0.09	288.69	0.02	1.1	12
0.1	201.82	0.01	1.1	61
0.11	190.12	0.02	1.1	19
0.12	205.43	0.02	1.1	20
0.13	162.04	0.01	1.1	91
0.14	187.64	0.01	1.2	91
0.15	116.35	0.01	1.1	127
0.16	129.66	0.01	1.2	127
0.17	89.83	0.01	1.1	169
0.18	99.78	0.01	1.1	169
0.19	73.12	0.01	1.1	217
0.2	79.5	0.01	1.1	217
0.21	61.91	0.01	1.1	271
0.22	66.17	0.01	1.1	271
0.23	67.98	0.01	1.2	271
0.24	56.95	0.01	1.1	331
0.25	60.28	0.01	1.1	331
0.26	50.3	0.01	1.1	397
0.27	52.67	0.01	1.1	397
0.28	45.32	0.01	1.1	469
0.29	47.05	0.01	1.1	469
0.3	41.5	0.01	1.1	547
0.31	42.78	0.01	1.1	547
0.32	38.48	0.01	1.1	631
0.33	39.45	0.01	1.1	631
0.34	40.52	0.01	1.1	631
0.35	36.79	0.01	1.1	721
0.36	37.61	0.01	1.1	721
0.37	34.62	0.01	1.1	817
0.38	35.27	0.01	1.1	817

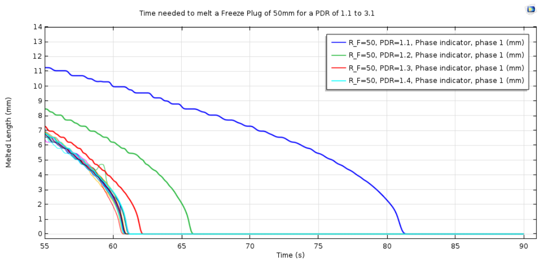
Radius_Pipe	Total_Time	Radius_Freeze_Plug	P_over_D_Ratio	Amount_of_Freeze_Plugs
0.39	32.83	0.01	1.1	919
0.4	33.33	0.01	1.1	919
0.41	31.32	0.01	1.1	1027
0.42	31.72	0.01	1.1	1027
0.43	30.03	0.01	1.1	1141
0.44	30.36	0.01	1.1	1141
0.45	30.16	0.01	1.2	1027
0.46	29.19	0.01	1.1	1261
0.47	28.52	0.01	1.2	1141
0.48	28.18	0.01	1.1	1387
0.49	28.42	0.01	1.1	1387
0.5	27.29	0.01	1.1	1519

C Graphs

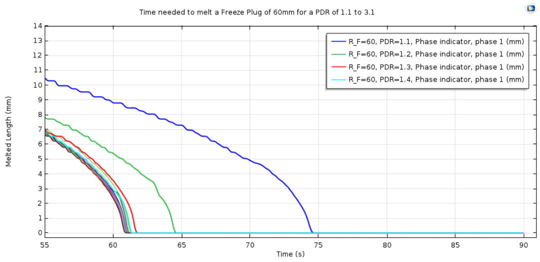
C.1. t_{melt} for $h = 30mm$ and varying radii



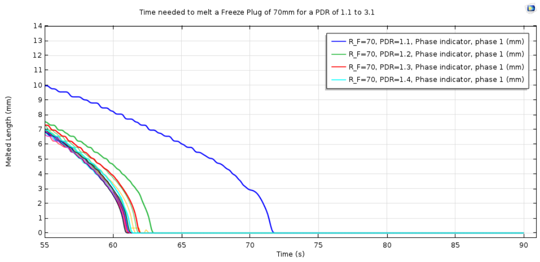
Radius of 40mm



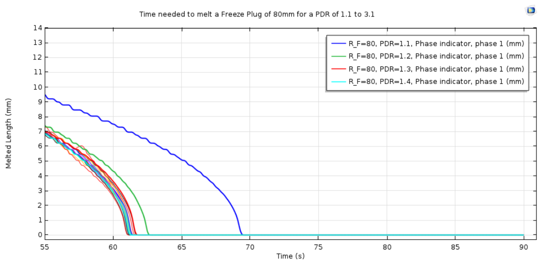
Radius of 50mm



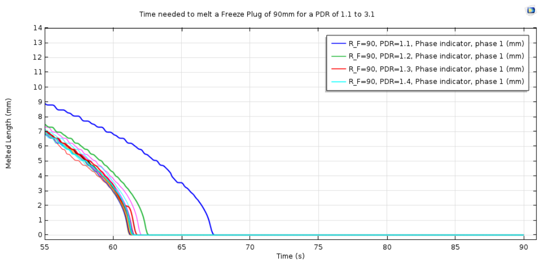
Radius of 60mm



Radius of 70mm



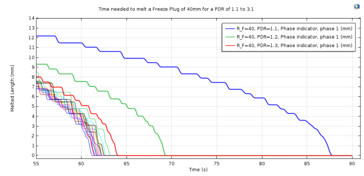
Radius of 80mm



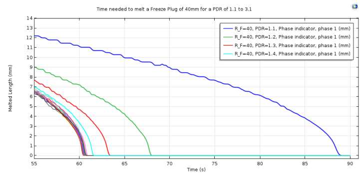
Radius of 90mm

Figure C.1: All graphs showing t_{melt} at $30mm$ of height and different radii

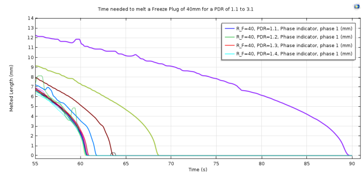
C.2. Mesh Refinement



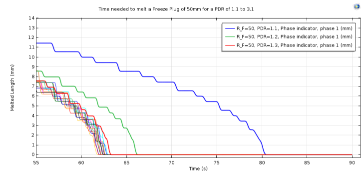
Radius of 40mm, Mesh of 420 Elements



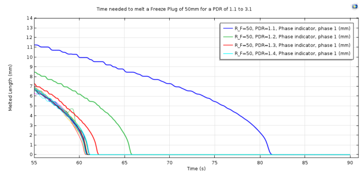
Radius of 40mm, Mesh of 760 Elements



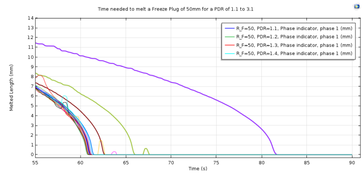
Radius of 40mm, Mesh of 1500 Elements



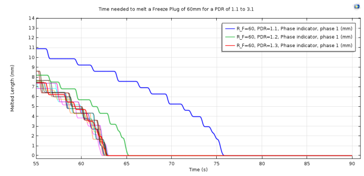
Radius of 50mm, Mesh of 420 Elements



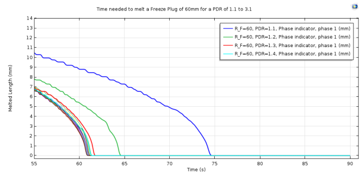
Radius of 50mm, Mesh of 760 Elements



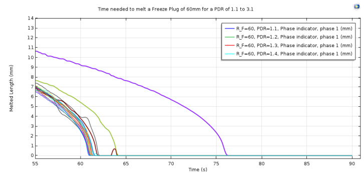
Radius of 50mm, Mesh of 1500 Elements



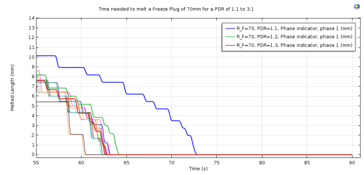
Radius of 60mm, Mesh of 420 Elements



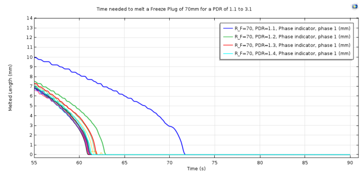
Radius of 60mm, Mesh of 760 Elements



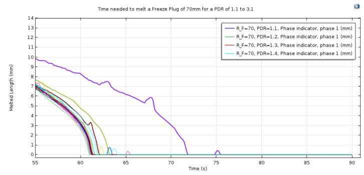
Radius of 60mm, Mesh of 1500 Elements



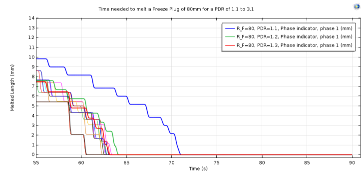
Radius of 70mm, Mesh of 420 Elements



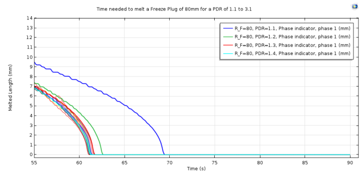
Radius of 70mm, Mesh of 760 Elements



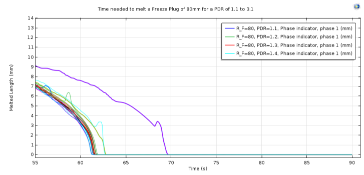
Radius of 70mm, Mesh of 1500 Elements



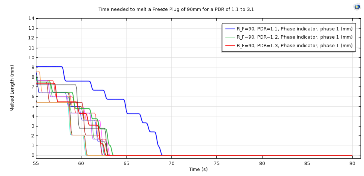
Radius of 80mm, Mesh of 420 Elements



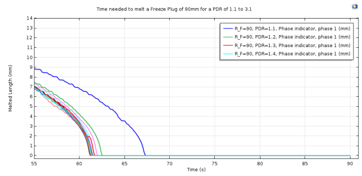
Radius of 80mm, Mesh of 760 Elements



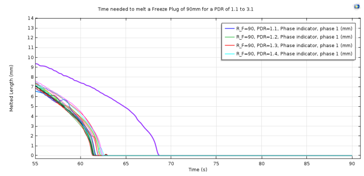
Radius of 80mm, Mesh of 1500 Elements



Radius of 90mm, Mesh of 420 Elements



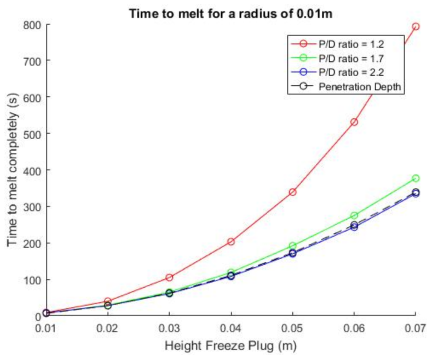
Radius of 90mm, Mesh of 760 Elements



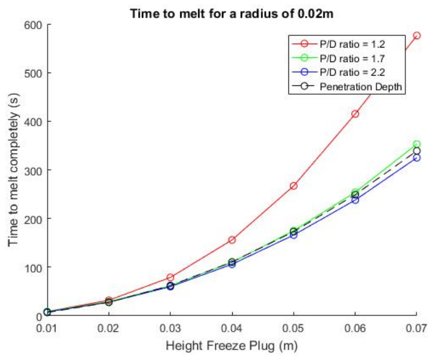
Radius of 90mm, Mesh of 1500 Elements

Figure C.2: All graphs showing mesh refinement for the different radii

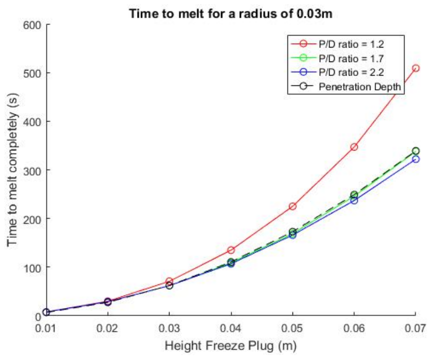
C.3. Comparison t_{melt} and penetration theory



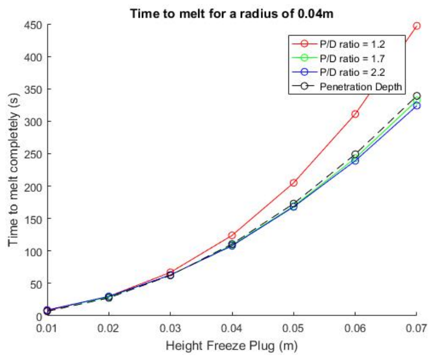
Radius of 10mm



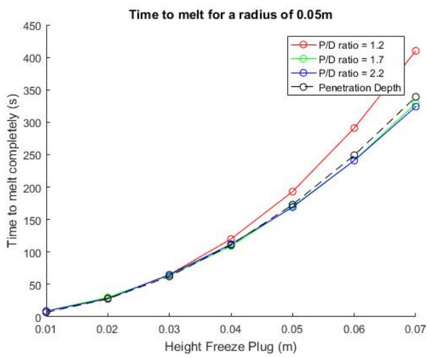
Radius of 20mm



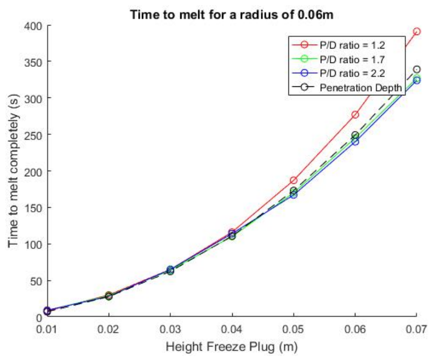
Radius of 30mm



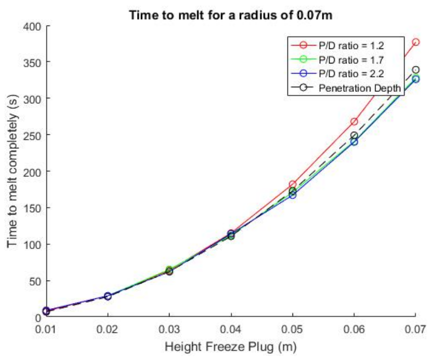
Radius of 40mm



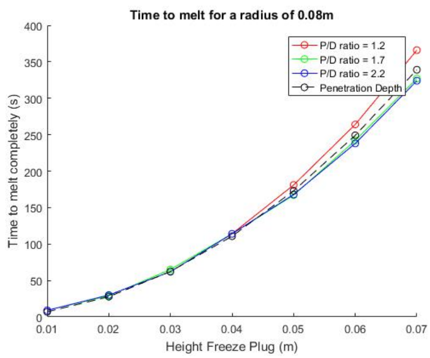
Radius of 50mm



Radius of 60mm



Radius of 70mm



Radius of 80mm

Figure C.3: All graphs showing the comparison of t_{melt} and the penetration depth.