Nordic nuclear safety research

NKS-375
ISBN 978-87-7893-460-4

# Ex-Vessel Steam Explosion Analysis with MC3D

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October 2016

## Abstract

A steam explosion is a fast fuel-coolant interaction that might occur if an accident scenario proceeds to late-phase including core degradation and melt relocation. It is of importance in safety research of severe accidents as it could possibly cause loss of safety barriers preventing the release of fission products. The focus is on the type of steam explosion known as ex-vessel steam explosion which can occur if the reactor pressure vessel breaks and molten core material is released into the containment vessel.

A literature review of the steam explosion phenomenon is provided, followed by a description of the MC3D code, used in this report to assess the steam explosion loads in the Nordic BWR geometry and examine the sensitivity of the results for some key input parameters. The effect of an ex-vessel steam explosion is analysed via computational models. The main focus of the analysis is on the dynamic loads on the cavity wall imposed by the explosion.

Simulations were made to analyse the effect of different triggering times on a standard case with central break location. The results showed that as long as the mixture is triggerable the resulting explosion is fairly similar. Different side breaks scenarios were also tested but here the mixture did not trigger.

The sensitivity analysis was done for melt temperature, coolant subcooling, cavity water level and melt drop size. The results show that the parameter with the strongest effect is the drop size, which is largely tied to the physical properties of the melt.

## Key words

Steam Explosions, MC3D, Fuel Coolant Interactions, Severe Accidents

NKS-375
ISBN 978-87-7893-460-4
Electronic report, October 2016
NKS Secretariat
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DK - 4000 Roskilde, Denmark
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e-mail nks@nks.org

**RESEARCH REPORT** VTT-R-04356-16

# Ex-Vessel Steam Explosion Analysis with MC3D


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Confidentiality: Public

| Report's title | |
|---|---|
| Ex-Vessel Steam Explosion Analysis with MC3D | |
| **Customer, contact person, address**<br>SAFIR2018 Research Program | **Order reference**<br>SAFIR 6/2015 |
| **Project name**<br>Comprehensive Analysis of Severe Accidents | **Project number/Short name**<br>108735/CASA |
| **Author(s)**<br>Magnus Strandberg | **Pages**<br>46 |
| **Keywords**<br>Steam explosions, MC3D, FCI, Ex-vessel steam explosions, Severe accidents | **Report identification code**<br>VTT-R-04356-16 |


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| **Confidentiality** | Public |
|---|---|

Espoo, 10.10.2016

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**Distribution (customer and VTT)**

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# 1. Introduction

There are currently four nuclear reactors operating in Finland, two Boiling Water Reactors (BWR) in Olkiluoto and two VVER-440 Pressurized Water Reactors (PWR) in Loviisa, there is also one European Pressure water Reactor (EPR) under construction in Olkiluoto. A Decision-in-Principle has been made for an AES-2006 reactor to be constructed in Hanhikivi. Nuclear safety research plays a major role in ensuring a safe operation of the plants. A part of that research is the analysis of accident scenarios. Accidents can be categorized as design basis accidents or severe accidents. In this thesis the focus is on the latter.

A steam explosion is a fast fuel-coolant interaction that might occur if an accident scenario proceeds to late-phase including core degradation and melt relocation. It is of importance in safety research of severe accidents as it could possibly cause loss of safety barriers preventing the release of fission products. In this thesis the focus is on the type of steam explosion known as ex-vessel steam explosion which can occur if the reactor pressure vessel breaks and molten core material is released into the containment vessel.

To begin with, a brief overview of the steam explosion risks in the currently operating plants in Finland is provided. [1]

For the Loviisa nuclear power plant only in-vessel steam explosions are feasible in the case of a severe accident and core melt down. The Loviisa VVER-440 reactors rely on in-vessel melt retention. Applying this method is possible, since the core has low energy density, there are no penetrations in the vessel lower head and ice condensers provide a passive water source for reactor pit flooding. Loviisa severe accident management plan states that the reactor vessel should be depressurised so the pressure inside the reactor vessel would be low in the case of core relocation into the vessel lower head. This low pressure in the Reactor Pressure Vessel (RPV) affects the void build-up in such a way that a steam explosion becomes less probable.

The Olkiluoto 1 and 2 boiling water reactors do not rely on in-vessel melt retention.It has not been considered as a probable accident management strategy due to the reactor design: the reactor pit is to lager in order for the vessel to be submerged on time. Furthermore, the lower head penetrations make the vessel vulnerable. This means that both ex-vessel and in-vessel steam explosions have to be taken into account. The in-vessel case is similar to the Loviisa power plants, because also in the severe accident management protocols of the Olkiluoto power plants they have a procedure for the reactor vessel depressurisation. In the case of a vessel rupture there will be a risk of an ex-vessel steam explosion, since flooding the cavity is one of the severe accident management protocols. Flooding is required to minimize the possibility of a lower drywell basemat melt-through, as well as minimize the load to the containment caused by Direct Containment Heating (DCH). The containment penetrations are hardened to withstand the thermal and mechanical loads of a vessel ejection to the containment and steam explosions.

Firstly, a literature review of steam explosion phenomenon is provided. Secondly, a description is given for the MC3D code, used in this thesis to assess the steam explosion loads in Nordic BWR geometry and examine the sensitivity of the results to some key input parameters. Thirdly, the effect of an ex-vessel steam explosion is analysed via computational models. The main focus of the analysis is on the dynamic loads on the cavity wall due to the explosion.

# 2. The steam explosion phenomena

## 2.1 Precursors of Steam Explosions

Since a stem explosion might occur as a part of a severe accident there are quite a few precursors that are needed for the accident to proceed to a stage at which a steam explosion is even possible. Firstly the accident needs to progress into a severe accident, meaning that the fuel start melting. This in turn requires simultaneous failure of multiple safety systems and backup systems.

A precursor to a severe accident might for example be a station blackout or a loss of coolant accident (LOCA). In the station backup scenario the power plant is isolated from the energy grid and its backup electricity systems are inoperable for a prolonged time. Whereas, a loss of coolant accident means that the coolant flow to the reactor core is stopped, usually due to a break in one of the main coolant pipes.

This loss of coolant or cooling capability might cause the core to start uncovering if cooling is not restored via backup systems. This is due to the decay heat of the fission products, which is present even if the emergency shutdown, i.e. scram, of the reactor has been initiated at the start of the accident. Decay heat decreases exponentially and it is proportional to the nominal power level of the reactor. Once the core is uncovered the temperature of the fuel rods starts to increase. The core uncovery rate usually decreases after some part of the fuel is revealed and typically there is still some water left in the bottom of the vessel even at a late stage.

When the fuel rods start to heat up, zirconium in the fuel cladding starts to oxidise. This occurs at around 1500K. Oxidation is very exothermic which causes the temperature increase to accelerate. It also causes the remaining metallic zirconium to melt. Then if the outer oxidation layer ruptures the molten Zr can redistribute ant start to oxidise a different location in the fuel assembly further accelerating the process. This heat buildup is also the start of uraniumdioxide ($UO_2$) dissolution into zirconium and liquidation of the mixture. The dissolution of the fuel is govorened both by the zirconium oxygen content as well as the chemical composition of the fuel pellet, i.e. how much of the fission products that are present in the fuel. When the cladding start to rupture, at around 1375 K, gaseous fission products might also be released into the vessel.

As the temperature continues to rise, more $UO_2$ will start to liquefy and also melt, this happened arounds 3120 K. This melt is assumed to flow downwards and if the local temperature is lower resolidify. At a stage where most of the fuel is molten and the fuel rods are ruptured, the accident can be said to be in the late-phase. A collective name given for all the molten material from the core is Corium which is made up of for example: fuel, fuel cladding and structural material. At this stage the corium melt can form a pool, with a solid crust in some regions of the core. If the crust of the pool suddenly fails it can cause a large mass of melt to relocate into the bottom of the Reactor Pressure Vessel (RPV). For example in the Three Mile Island (TMI-2) Accident in 1979, a large mass of molten material relocated into the vessel lower head. This is an event that might cause a steam explosion to occur. To give some perspective of the different timescales involved in accident progression, some general progression times can be found in table 1.

Once the melt has relocated into the vessel lower head it might form a coolable debris bed ending the accident progression. Whether the bed is coolable or not depends on the geometry and the operability of the safety cooling systems. If the melt is not coolable, it might induce such a massive thermal load on the vessel lower head that the RPV breaks. The melt is usually separated to different phases that will stratify based on density. The bottom layer is richer in oxides and the top layer is richer in metals. The highest temperature is usually in the middle of oxide layer. As the heat convection trough the sides of the pool lowers the temperature

*Table 1. General timescales of different accident scenarios, in a high power PWR. From [2].*

| Different scenarios | Beginning of core uncover | Core completely uncovered | Significant start of cladding oxidation | Fuel melting starts significantly | Molten pool relocation |
|---|---|---|---|---|---|
| Small break | 29h | 34h | 37h30min | 42h30min | 48h |
| Medium break | 3h15min | 7h15min | 8h30min | 12h15min | 17h |
| Large break | 8min | 35min | 41min | 1h12min | 2h4min |
| Station Blackout | 2h30min | 3h15min | 3h35min | 4h35min | 8h5min |

at the edges. However the highest heat flux to the vessel wall is usually located next to the metallic layer. Because metals have a higher heat conductivity than the oxides. This increases the thermal load to the vessel wall at this location. this is called focusing effect and can cause the wall to fail at this location. Another weak point, in Boiling Water Reactors (BWR) is the instrumental guide tubes in the bottom of the vessel.

If the cavity contains water the melt ejection from the vessel can cause a steam explosion, these ex-vessel steam explosions are the focus of this thesis. However whether or not there is a steam explosion, there is still the question of cooling the melt and debris after it has been ejected from the vessel. The coolabilty of the debris is dependent on the geometry in which it spreads. Different plant designs utilize different methods to handle the cooling of the debris bed. For example the European Pressure water Reactor (EPR) uses sacrificial material to guide the melt into a core catcher that has been designed to increase melt cooling capabilities.

The a steam explosion might only occur relatively late in the accident scenario. Because of this, depending on the operability of the safety systems, the accident might be brought under control and stopped before a steam explosion is even physically possible. In this thesis when steam explosions are discussed it must be assumed that the accident scenario was not stopped and that the status of the plant is such that a steam explosion might occur.

## 2.2 Steam explosions

A steam explosion is an extreme form of a Fuel Coolant Interaction (FCI), which might occur when molten fuel fragments into water to form an instable liquid-vapour-liquid system. This instable system might collapse locally inducing a propagating shock wave which collapses the rest of the system. This in turn leads to a rapid transfer of thermal energy into mechanical energy in the form of an explosion.

Steam explosions have three distinct stages: premixing, triggering and propagation. In the premixing stage the molten corium is fragmented into the coolant due to thermohydraulic forces[3]. A large portion of the corium forms molten drops suspended in the coolant by vapour film. This instable liquid-vapour-liquid system is locally collapsed by a triggering pulse. If the mixture properties are favourable, the trigger propagates in the mixture collapsing all the melt drops so that the thermal energy of the melt is almost instantly transferred to the coolant causing instantaneous high pressure increase.

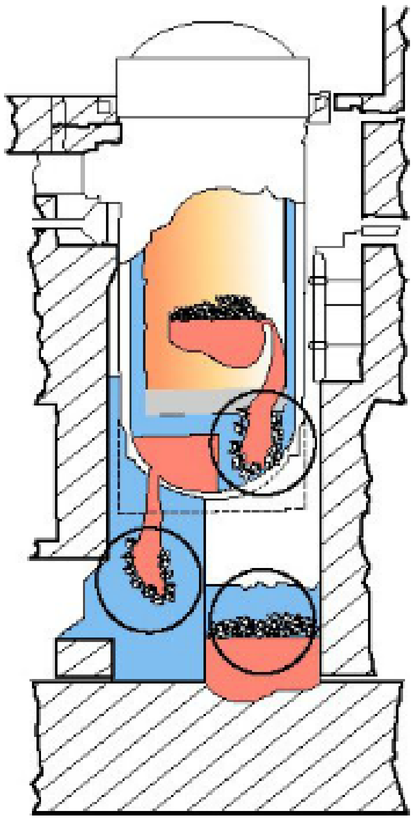


*Figure 1. A schematical figure of the different steam explosion locations in a light water nuclear power plant. The top circle is the in-vessel case, the bottom left is the ex-vessel and the bottom right is the debris bed reflooding.[3]*

Traditionally two distinct cases have been considered, in-vessel and ex-vessel steam explosions. Depending on whether there is an in-vessel or an ex-vessel explosion the effects differ. The in-vessel explosion could occur when the molten core material relocates to the vessel lower head, if the lower head still contains water [4]. The ex-vessel case could occur after vessel lower head failure when the molten corium is ejected from the vessel into a flooded reactor cavity [5]. There is also a different third form of steam explosions that might occur in a light water nuclear power plant when the debris bed is flooded with water to ensure its coolability. In Fig. 1 is illustrated the different locations schematically.

As the melt jet connects with the bottom of the vessel or cavity it will spread out and depending on the coolability solidify. After a while, if no explosion happens, the solidified and molten drops will start to deposit and form a debris bed. Depending on the geometry and the coolability, the debris bed could either solidify or form a molten pool surrounded by crust.

## 2.3 Phases of steam explosions

In this section the three main stages related to steam explosions are explained in greater detail. The time scales of the stages differ: the premixing can be up to a couple of tens of seconds whereas the trigger and propagation stages happen in a couple of milliseconds. It is therefor better to split the analysis into three different parts.

### 2.3.1 Premixing

Premixing is the first stage of a steam explosion. It is called premixing as the actual explosion can also be considered a mixing process. Premixing is the stage when the molten corium jet comes into contact with the coolant. The jet fragments into smaller molten drops due to hydrodynamic forces. These drops produce vapour as the thermal energy is transferred to the water. Due to the major temperature difference, the drop is almost instantly suspended by film boiling. When this steam is mixed with the coolant, a void fraction increases. The void fraction increase in the mixture is called void build-up.

The most important physical phenomenon that affects the premixing is the fragmentation of molten corium into the coolant. As this produce the liquid-vapour-liquid system, i.e molten drops surrounded by the boiling film suspenden in coolant. Fragmentation also indirectly governs the limiting factors, void build up and drop solidification. The fragmentation can either be from the molten corium jet or further fragmentation of large molten corium drops. The jet fragmentation is considered to be the larger source for drops out of the two[6].

Jet fragmentation is an extremely complex problem which does not have a strong theoretical foundation. R. Meignen [6] views it as a “transition to turbulence in a multiphase environment” and he also states that it involves three main mechanisms; a large scale instability, a stripping mechanism of the material at the crest of these large instabilities and then further fragmentation of the stripped material. The process is due to the tangential frictions between the liquids known as a Kelvin-Helmholtz instability. Though it in some part might also be due to Rayleigh-Taylor instability.[6] An example of the complexity of the fragmentation can be seen from Fig. 2.

The Rayleigh-Taylor instability gives a wave length of the instability wave in the boundary between the two liquids. This is illustrated in Fig. 3. The equation governing the Rayleigh-Taylor instability is:

$$\lambda = 2\pi\sqrt{\frac{3\sigma_j}{(\rho_j-\rho_s)g}} \tag{1}$$

Where the subscript j refers to jet and s to the coolant. $\sigma$ and $\rho$ are the surface tension [Nm] and density [kg/m$^3$], respectively and g is the acceleration due to gravity [kgm/s$^2$]. [7]

The melt drops that are fragmented from the jet might be further fragmented in the coolant due to hydrodynamic forces that arise from the velocity differences between the drop and the surrounding gas or coolant. The break-up or fragmentation of the drops have been studied experimentally and the results seem to indicate differences between a drop suspended in gas or in a liquid. The gas case yields more complex fragmentation shapes, including bag like formations, whereas the liquid cases seem to be governed by a shear process yielding simpler formations.[6] In the case of melt drop fragmentation in water, the drops are in any case suspended by a gas film due to the temperature differences. R. Meignen [6] states that even though the drops are suspended in gas the fragmentation could be described the same way as for a liquid case due to the film thickness and high viscosity of the gas, that are results of its high temperature. The coarse fragmentation rate could be simplified into:

$$dD/dt = -C_0\sqrt{\frac{\rho_c}{\rho_d}}\delta v \tag{2}$$

Where $dD/dt$ describes the change of drop diameter over time[m/s] and $\delta v$ is the initial velocity difference between the drop and the medium [m/s]. The subscripts d and c stands for drop and coolant, respectively. $C_0$ is a case specific constant that is determined experimentally. This

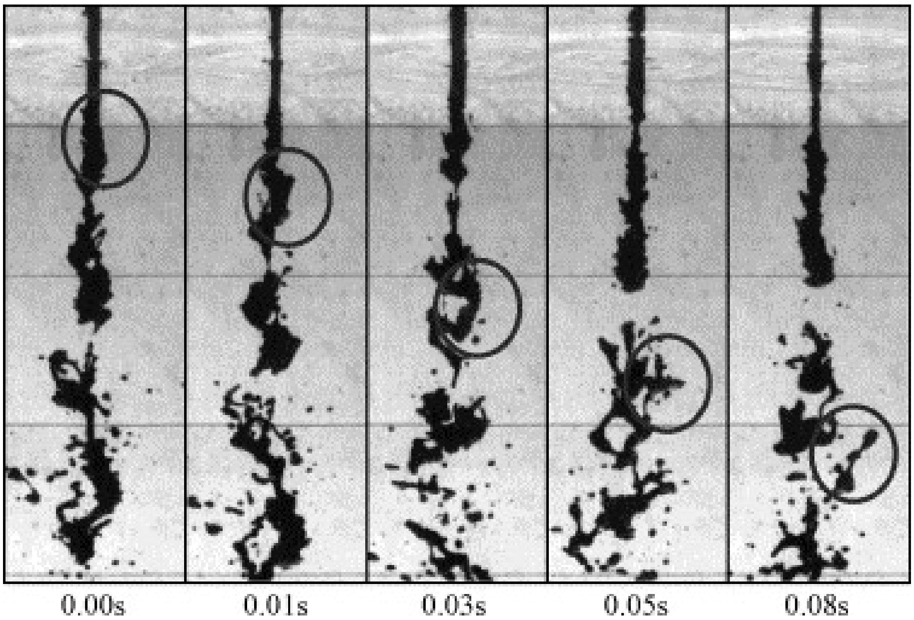



*Figure 2. Fragmentation behavior in one of the experiments form [7]*

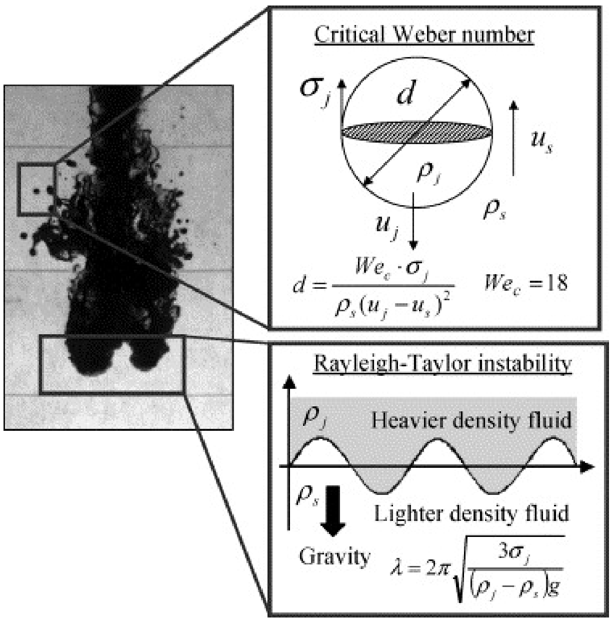



*Figure 3. Fragmentation behavior as described by the Rayleigh-Taylor instability and the critical Weber number compared to a snapshot of a fragmenting jet. [7] In the weber number equation: d is the drop diameter[m], We is the Weber number and u represents the velocity [m/s] of the drop and the surrounding media. In the Reyleigh-Taylor instability equation: g is acceleration due to gravity[m/s$^2$] and λ is the Rayleigh-Taylor wavelength[m].*

relation is said to hold for Weber numbers higher than 350.[6] The Weber number describes fluid flows at the boundary between two different fluids, and is defined in 3, this relation is also shown in Fig. 3.

$$We = \frac{\rho_c (u_d - u_c)^2}{\sigma_d} D \tag{3}$$

It has been experimentally found that the characteristic timescale for the drop fragmentation can be approximated with the following equation, even thought the cases differ in how the fragmentation occurs.

$$T = \sqrt{\frac{\rho_d}{\rho_a}} \frac{D}{\delta v} \tag{4}$$

In this equation subscript a is for the ambient fluid and d fro the drop. D is the initial drop diameter[m].

As the fragmentation, and thus the premixing, is very dependent on initial conditions of the melt as well as of the coolant it is prudent to try to give a description of how the changes in the initial continuous effect to premixing. Therefore the rest of this section is dedicated to the different initial conditions and their effect on the steam explosion progression. All the different parameters and their effect on steam explosion probability and strength are summarised in table 2.

The first parameter affecting the explosion strength is the amount of melt being able to participate in the explosion. If the triggering, and the following explosion, were to happen directly as the melt contacts the water, only a small amount of melt would be able to take part in the explosion. Since only a small part of the melt has fragmented into smaller drops. This in turn results in a weaker explosion compared to a case where more of the melt has had time to fragment. This this is also why certain moments in the premixing are less likely to ignite a steam explosion, as the vapour build-up around the jet can push the coolant back from the jet and make the drops suspended in vapour instead. [3]

The second factor affecting the strength of the explosion is the initial temperature of the melt. Higher temperature means more thermal energy and thus a stronger explosion. Higher initial temperature also makes solidification of the melt drops less likely to occur which in turn also increases the possibility of an explosion to occur. Solidified drops are not able to take part in the explosion the same way as molten drops as they are not able to undergo further rapid fragmentation [3], this is explained in further detail in the propagation subsection 2.3.3. Therefore not only the melt temperature is of interest but also other material properties of the melt such as solidus and liquidus temperature, heat conductivity and heat capacitance. As all these govern the solidification of the melt drops.

The third factor that affects the explosion strength is the density of melt, as it affects the fragmentation rate. A lower density has been shown in experiments to lead to more violent explosions. For example aluminium melt results in stronger explosions than corium melts. This is considered to be because lower density leads to fragmentation into larger drops which when exploded would be able to transfer larger amounts of thermal energy into the coolant. Due to higher volume to area ratio of larger drops heat transfer is less effective, and the system is not able to transfer as much thermal energy in the premixing stage, as would be the case with smaller drops. Thus it can release more energy in the explosion phase, and larger drops are less likely solidified. Larger drops would also lead to a smaller void fraction than many small drops.[3]

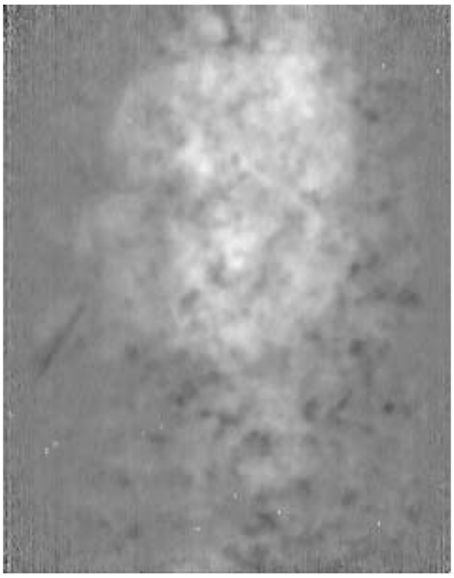


*Figure 4. Void fraction in one of the KROTOS experiments. Lighter areas contain more gas and black dots are melt fragments. From the KS-5 test at 11.9670s [9].*

If the melt is not yet fully oxidized, some oxidation will occur when the melt is fragmented into water, which leads to hydrogen production. The produced hydrogen might in itself constitute an explosion risk, as a hydrogen-air mixture may form a flammable composition that is able to ignite for example in contact with a hot surface. From the steam explosion point of view, the hydrogen gas contributes to a higher void fraction that might make the steam explosion less probable.

Another important factor is also the void fraction of the mixture. Void fraction mainly affects the explosion probability. Mainly due to two reasons. Firstly, a large void fraction causes more drops to be suspended in vapour instead of coolant. Secondly, a large void fraction means a thicker gas film around the drops, which in turn makes the rapid fragmentation discussed in triggering 2.3.2 and propagation 2.3.3 subsections less probable. In simulations[5] it has been shown that steam explosions were most likely to occur in regions with low void build-up. This proves that also ambient pressure is important.

Also coolant temperature affects the premixing. Water with temperatures way below the boiling temperature, i.e. having high subcooling, will result in smaller void build-up as the gas film in the the film boiling will be thinner. This will result in a premix that is more likely to trigger and also due to smaller void fraction might result in a stronger explosion. Since there is more water participating in the fine fragmentation in the propagation stage[5]. However, larger subcooling will also increase melt solidification which leads to a weaker explosion. If the water on the other hand is at saturation temperature, the void build-up will be larger which in turn might result in a weaker explosion.

Ambient pressure also affects the premixing stage, because higher ambient pressure inhibits large void build-up. In Fig. 4 is shown the void build-up during the premixing stage of the KS-5 Krotos experiments. Inhibited void build-up could lead to a stronger explosion if the mixture is successfully triggered. In Fig. 5 experimental data of ambient pressure effects to steam explosions are illustrated [8].

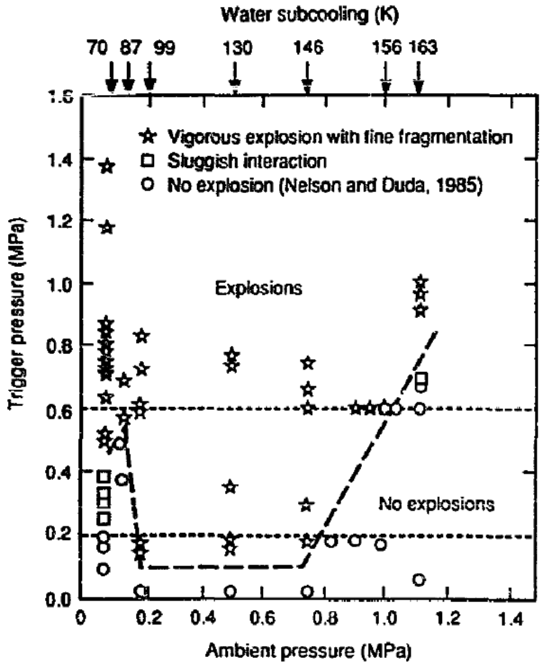



*Figure 5. The experimental data from the effect of ambient pressure to the steam explosion probability. The tests were done with several ambient pressurs and trigger pressures. It is possible to see that higher ambient pressure first made the explosion more likely to appear with a lower trigger pressure but at even higher ambient pressure had an inhibiting effect. [8]*

*Table 2. A quick overlook of the different premixing parameters and their effect on the explosion probability and strength. For the ambient pressure, Fig. 5 shows a more detailed explanation.*

| Property | Explosion probablity | Explosion strength |
|---|---|---|
| Amount of melt ↗ | ↗ | ↗ |
| Melt temperature ↗ | ↗ | ↗ |
| Melt density ↘ | ↗ | ↗ |
| Hydrogen production ↗ | ↘ | ↘ |
| Void fraction ↗ | ↘ | ↘ |
| Ambient pressure (<0.8MPa) ↗ | ↗ | ↗ |
| Ambient pressure (>0.8MPa) ↗ | ↘ | ↗ |
| Coolant temperature ↘ | ↗ | ↗ |

### 2.3.2 Trigger

Triggering is the event where the gas film around one or more melt drops is collapsed so that the coolant comes into direct contact with the melt drop. This causes further rapid fragmentation of the melt drop, which is explained in further detail in the propagation subsection 2.3.3. The fragments are in turn able to rapidly transfer their thermal energy to the coolant causing nearly instantaneous vaporisation and pressure build-up. If the premixing conditions are favorable the pressure wave will propagate through the coolant and furthur collapse the gas-drop assembly. A triggering event does not necessarily lead to a steam explosion. [3]

The actual triggering event is highly random in its nature and therefore it is best from a safety perspective to always assume that the triggering will occur. A spontaneous or internal trigger has its origin inside the melt-coolant system itself. For example if a melt drop contains a cavity it might trap water, causing the drop to fragment further. These fragments might then be propelled into the water breaking the vapour film. If the pressure peak is large enough it will propagate and start a chain reaction.

Spontaneous triggering has often been observed when the melt jet meets the bottom of the vessel or cavity. This is assumed to be because it is easy for water to get trapped inside the melt which would lead to a local pressure increase as well as further fragmentation of the melt. This pressure increase could then act as a triggering event.

Internal triggering might also occur due to sudden large velocity differences between the coolant and the drops, for example when the expelled coolant rushes back towards the jet. In simulations preformed by Leskovar and Ursic [5] this “water rush back” caused the mixture to have high explocivity at this instance.

Spontaneous thermal fragmentation due to small disturbances in the vapour film have been studied as a possible trigger phenomenon [10]. The thermal fragmentation could happen if the boiling film around the drop is not stable and water is able to come into direct contact with the molten drop. Research has shown that such a event could be able to act as a trigger.

An external trigger is a triggering event that has its origin outside the melt drop configuration. For example it might be a pressure wave coming from a rupturing pressure vessel or a shock-wave from something colliding with the vessel wall. External triggers are usually utilized in experiments so that the triggering event can be assured to happen and also so that the timing can be controlled. This is typically done with a a small pressure container that is ruptured to produce a pressure spike in the system. For example the TROI experimental facility in South Korea uses external trigger [11].

Experiments done for example at the KROTOS facility [12] has shown that even though corium melts were not so prone to spontaneously trigger, as aluminum melts, they could almost always be triggered with an external source.

### 2.3.3 Propagation

The propagation stage it is when the shockwave from the triggering event passes through the system and the semi-stable melt drops start to collapse. This causes the molten drops to come in contact with water leading to fast fine fragmentation and rapid transfer of thermal energy to the coolant. This fast energy transfer causes the coolant to vaporise and leads to an almost instant pressure increase. If the properties of the mixture are favourable, the pressure wave will propagate trough the mixture as a chain reaction. This stage of the explosion takes only a few milliseconds.

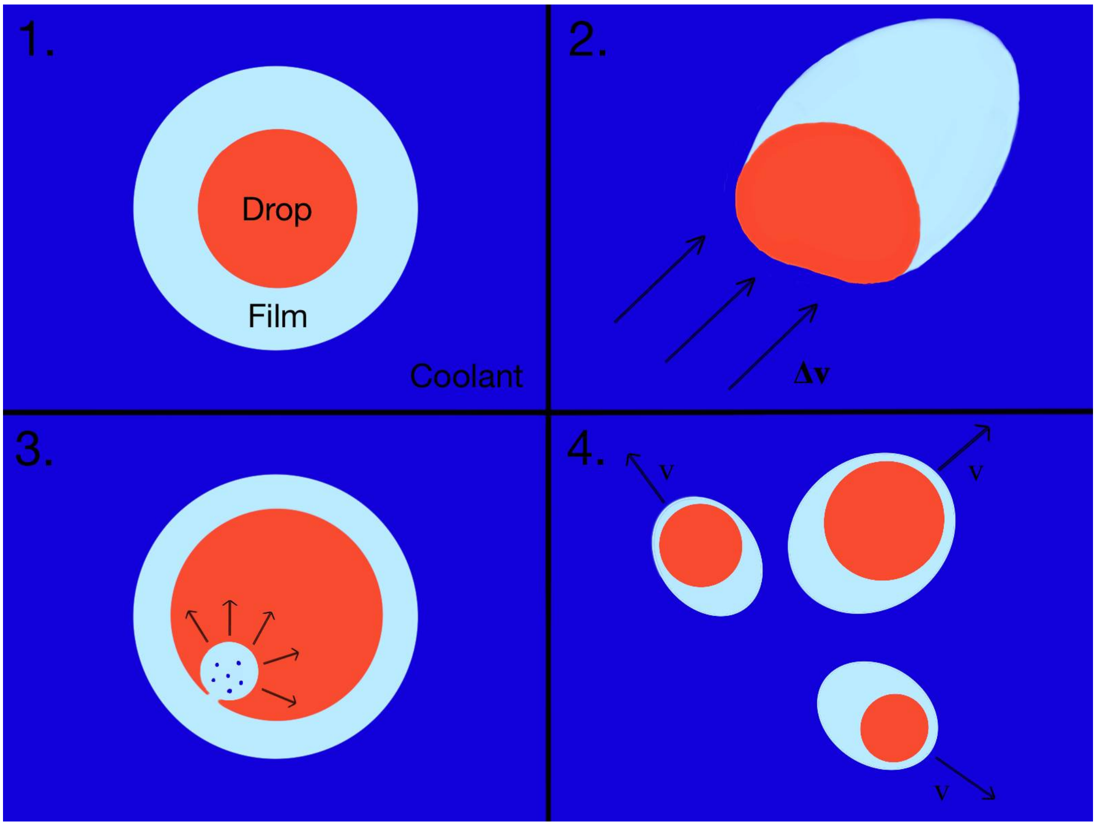



*Figure 6. A simplified graphical representation of the thermal fragmentation via liquid-liquid contact of the coolant and the drop. 1, undisturbed drop with gas film. 2, disturbance causing liquid-liquid contact. 3, entrapment. 4, fragmentation. [13]*

The main factor affecting the explosion strength is the amount of melt available to undergo fine fragmentation and thus transfer its energy to the water. Other factors were explained earlier in this chapter as they impact also the earlier stages of the phenomenon. The fine fragmentation occurs due to a process called thermal fragmentation. When water connects with the small irregularities in the surface of the melt drop, water becomes trapped inside. The rapid heating and vaporisation of the entrapped water causes it to expand and fragment a part of the drop. When this happens at multiple locations of the drop simultaneously and multiple times it eventually fragments the whole drop. One could say that this is the “explosion of the drop”.[3] A simplified graphical representation of this can be seen in Fig. 6.

The propagation speed of the pressure wave varies depending on the premixing conditions, for example void factor, but also on whether there is an actual steam explosion or only a triggering event. If there is no explosion, the propagation speed of the pressure wave is usually in the range of 10 m/s and the pressurisation of the system as a whole is limited and uniform. If there is a steam explosion, the shock-wave may accelerate to supersonic speeds. According to Seghal [3] this can not be caused by thermal fragmentation alone but also hydrodynamic fragmentation due to the different velocity between the coolant and the melt. The melt-coolant mixture outside the shock-wave does not “sense” the explosion before the shock-wave has passed it over, i.e. the part of the mixture not yet passed over is unaffected. The zone, already passed over by the shock-wave is called the expansion zone.

After the propagation phase the thermal energy is converted into mechanical energy and the system expands. This expansion induces pressure loads to the surrounding structures. If the induced pressure increase occurs in a region with water and loose material above it, the pressure might accelerate the water and material so that it forms a slug. If the explosion occurs inside the reactor vessel this slug might rupture the vessel upper head in such a way that part of it is also accelerated. This missile might in turn break the containment leading to early release of fission products and active material to the environment. This accident type is known as $\alpha$-mode failure[14].

Even if no slug is created, the increased pressure might still break the reactor vessel or the surrounding support structure, if the explosion takes place outside the vessel. Though, it is hard to estimate the actual pressure impulse that the structures has to withstand since venting could possibly relieve pressure.

## 2.4 Ex-vessel explosion

Steam explosions might occur outside the reactor vessel if the lower head fails and the melt is ejected into a water filled cavity. If the steam explosion was to happen in the cavity the increased pressure might damage or destroy containment walls. Also equipment needed to provide the necessary debris-bed cooling might be destroyed. Weakened walls do not necessarily collapse directly, but they might fail later as they usually are supporting relatively heavy equipment. This might further complicate the accident management measures.

Depending on the way the reactor vessel broke, the melt ejection speed might vary substantially. The location of the break also determines the amount of melt that is released from the vessel. A central break on the bottom will probably mean that more melt is ejected than if the break is further up on the side. A break higher on the reactor vessel wall is usually caused by focusing effect resulting from metal layer stratification on top of oxide layer. An ejection from the side of the vessel might also cause the explosion to occur closer to the side walls, which in turn would lead to uneven load on the cavity wall. This difference in break location also further increases the complexity of predicting the steam explosion probability and strength, as the molten pool is usually separated in layers. [15] Meaning that a difference in break location could lead to very different types of melt forming the first parts of the jet. The differences in the material compositions of the molten pool layers especially affects the density and temperature of the melt that form the first part of the jet.

Depending on reactor type, the depth of the cavity might also differ. With increased fall distance the melt will be able to accelerate to higher speed before contacting water, which in turn would effect on the way the melt fragments. Another factor effecting the melt ejection speed is whether the reactor vessel depressurisation was successful or not. Different release velocities have been studied by Leskovar and Ursic [5], who concluded based on simulations that a pressurized primary system leads to a stronger explosion. In their analyses another interesting factor occurred with side breaks as the pressurized primary system caused the melt to spray on the cavity walls instead of producing a melt jet.

Differences in reactor pit geometries effect water availability and flooding efficiency of the pit. This naturally has an impact on the steam explosion progression, deeper pool produces more effective fragmentation. Another factor that does not affect the steam explosion probability but strength is the availability of venting in the reactor dry well. A well vented space is more likely to result in a weaker explosion.

In addition to the amount of available water another factor that makes ex-vessel and in-vessel explosions different, is that in the ex-vessel case the water is not always at or close to saturation temperature. Depending on the reactor design and the origin of the water in the flooded cavity, the water can be substantially subcooled in the ex-vessel case. Experiments have been done with subcooling up to 80 degrees [16]. In section 2.3.1 the effects of subcooling were explained in more detail.

The varying water depth and temperature, as well as melt velocity increases uncertainties making accident prediction and analysis more difficult.

# 3. MC3D

## 3.1 MC3D general description

The MC3D (Multi Component 3D)[17; 18] code is developed by IRSN and CEA in France, and is a multidimensional Eulerian code used to simulate multiphase and multi-constituent flows for nuclear safety applications. It is usable for both research and safety usage. MC3D is built as modules, so called applications. These are built around a common core with similar structure to provide a flexible and easily modified code. A module is composed of a set of mass components, momentum and energy mixtures, connected through “physical” laws. Historically 10 different applications have been developed but currently only 3 are active[6]. Of which only 2 are of interest in the simulations of this thesis.

MC3D utilises two different FCI applications that have a common numeric solver. One of the presented applications is for the premixing stage and the other for the explosion stage. The triggering stage is incorporated into the code used for the explosion stage. This splits the simulation into two parts. In the first part the fragmentation of the melt jet, the vapour build-up and the heat transfer is simulated. The second part, that can be started at a time chosen by the user, handles the rapid fragmentation of the melt drops and the heat transfer from the molten drops to the coolant. [19] The code itself is very complex and explaining it in all its details is well outside the scope of this thesis, though in the following chapter the most important parts of the code will be presented.

### 3.1.1 Premixing stage description

Different materials are defined as different components in MC3D. Separate components then form volume mixtures. The volume mixtures form momentum mixtures that in turn make up energy mixtures. Fig. 7 shows a schematic of the different levels and how they relate. For example the different gases and water vapour are components and together these could form a volume mixture. This gas mixture might either form a momentum mixture on its own or if it is interconnected with some other volume mixture these together would form a momentum mixture. The mixtures are them self interacting via different physical phenomena, for example mass transfer between the vapour and the liquid components occur as coolant is either vaporised or condensed. [6]

In the premixing stage of MC3D V3.8 the fuel can be present in two different fields, continuous fuel and drops. A third field, where the drops are sorted by size, is also available for testing but this field is still under development. [6] The first field contains several forms of continuous fuel, for example molten fuel jet and a molten pool. From the continuous field, fuel is fragmented into the drop field. A reverse transaction may also occur. If the volume fraction of drops in a cell is above a set limit, the drops may coalescence into the continuous field. Both of these processes require that the fuel is in liquid form. Solidified fragments are handled by a different field.

The behaviour of continuous fuel field is analysed utilizing a Volume of Fluid-Piecewise Linear Interface Construction(VOF-PLIC). VOF-PLIC is a commonly used method for Computational Fluid Dynamics (CFD). VOF handles multiphase fluids by calculating cell fractions and constructing an interface in cells where the fraction of any fluid is not 1 or 0. PLIC is then used as a method to construct the fraction dependent interface as a line or plane in the cell [20]. In Fig. 8 is shown a graphical representation of th VOF-PLIC technique. The fragmentation of the

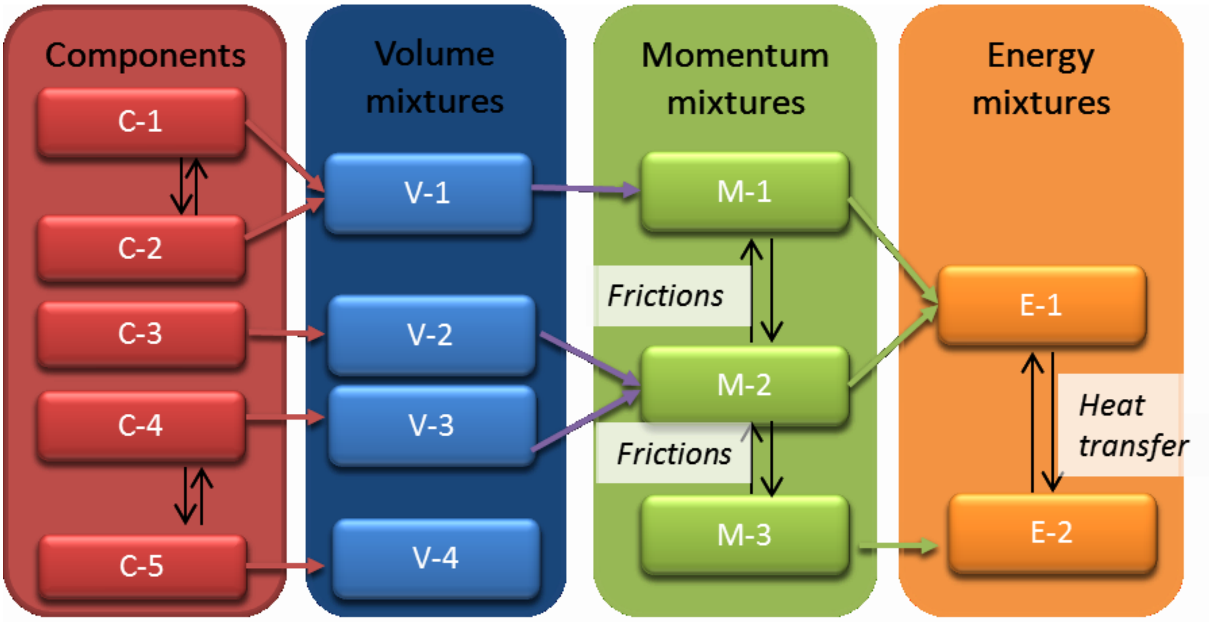



*Figure 7. Schematic description of MC3D structures and their interactions. Different materials are stored as components, which are part of volume mixtures. The volume mixtures form momentum mixtures that in turn make up energy mixtures. [6]*

(a) 1.0 mm

(b) 8.0 mm

*Figure 8. Schematic description of VOF-PLIC technique used to approximate volume interfaces. 8(a) computation without PLIC, 8(b) with PLIC. [13]*

continuous fuel into drops is handled either with a global correlation model or a local fragmentation model. The global correlation model utilises a user specified fragmentation parameter. This means that all fragmented drops are of the same size, and the size is defined via user input. whereas, the local model utilizes the Kelvin-Helmholtz extension model to calculate the drop diameter. The Kelvin-Helmholtz model calculates the fragmentation of the jet from the difference in velocity between the jet and the coolant. The coalescence of drops is handled via a geometrical model.

Regions containing moving drops, including the medium they are suspended in, is called the flow. In Fig.9, the different flow types, i.e. bubbly flow, transition flow and droplet flow are illustrated. The vapour volume fraction in the cell determines the flow type and the limit between the different regions can be specified by the user. In the premixing stage the solid melt fragments are in equilibrium with the water [21].

Melt solidification is a phenomenon that also needs to be taken into account in the simulations. Solidified drops are thought to have a dampening effect on an ex-vessel steam explosion. In

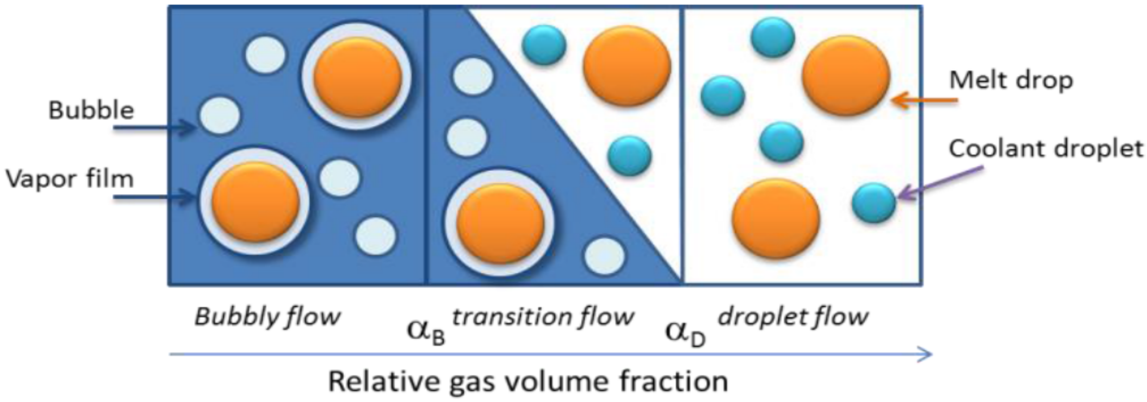



*Figure 9. Different flow regions in MC3D, where $\alpha_B$ and $\alpha_D$ are specified gas volume fraction limits of the different regions. Default values are 0.3 and 0.7. [6]*

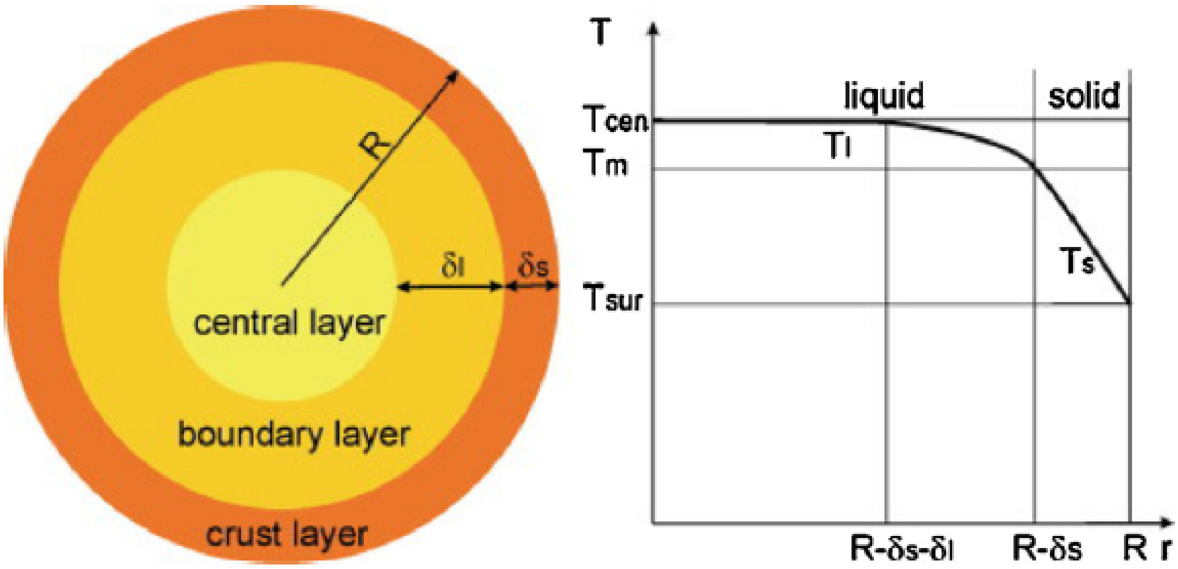



*Figure 10. Temperature behavior of the different regions of the drop.[17]*

Fig 10 the behavior of different temperature regions of the melt drop are shown[17]. In theory, the central part of the drop is in liquidus temperature and in the boundary layer the temperature decreases towards solidus temperature. In the crust the temperature further decreases linearly. The crust thickness increases and eventually the drop can be considered to be completely solidified. Although in MC3D this is simplified mathematically as a threshold model.

### 3.1.2 Explosion stage description

In MC3D external triggering is used by setting the local pressure in a cell or zone of cells to a high, user specified value. The triggering time is also a user specified parameter. The simulation is started at the closest save point before the set triggering time. It is also possible to specify a large zone of cells and let the code choose the optimal triggering location. The choice is based on the amount of hot drops and coolant in the cells, where regions that contain many hot drops as well as water is favored.

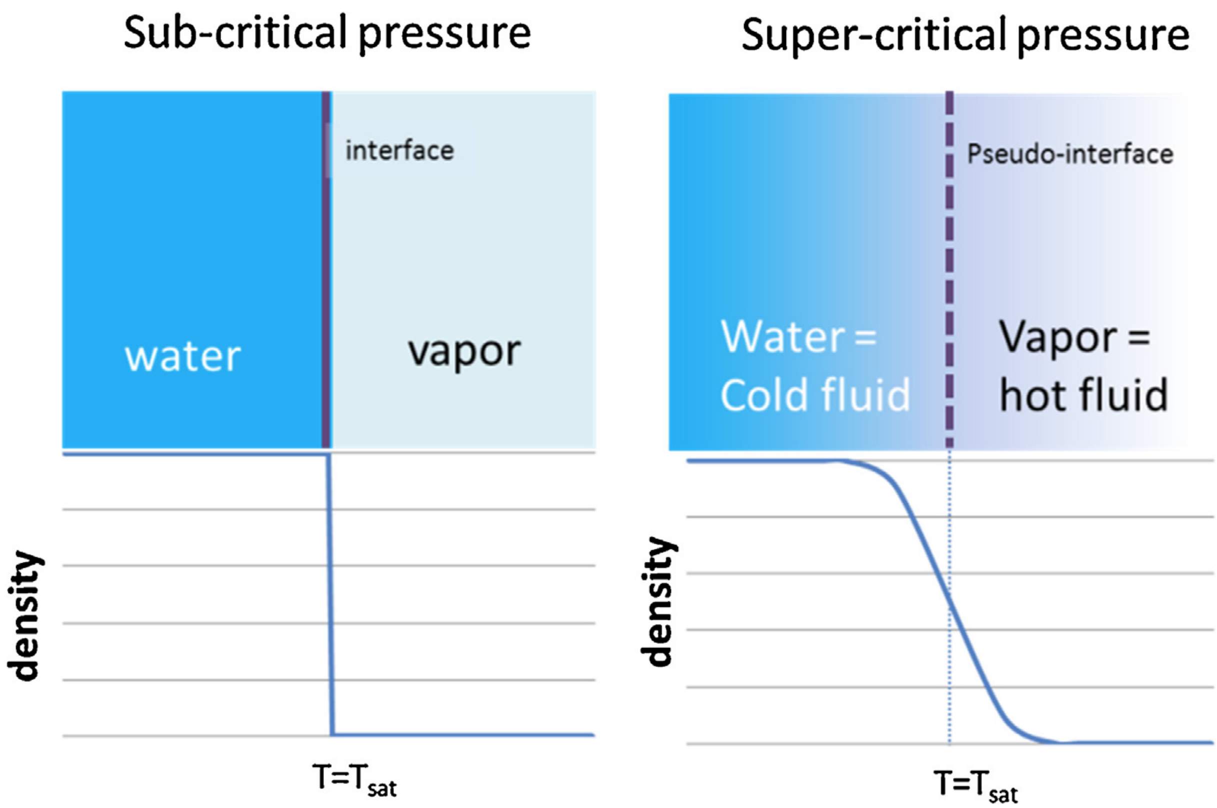



*Figure 11. When the pressure of the system is above the critical pressure the fields for liquid and vapour are modified. They are still kept separate as the pressure might not be super critical in all cells.*

At the explosion stage the component fields are modified from the premixing stage. The jet field is no longer available and all fuel is either in the drop field or in the new fragments field. As the pressure in the explosion stage can reaches such high levels ($> P_{crit}$) that the coolant becomes supercritical, which means a new field is needed. Therefore the liquid and the vapour fields, are now modified so that the liquid field contains the liquid coolant ($P < P_{crit}$) and "cold" supercritical coolant($P > P_{crit}$). The vapour field contains vapour($P < P_{crit}$) and "hot" supercritical coolant($P > P_{crit}$)[18]. The changes in the fields are illustrated in Fig. 11.

MC3D uses a direct vaporization approach, meaning that there is vapor production around the fragments, leading to pressurization. This is achieved via the Epstein-Hauser model for heat transfer correlation.

## 3.2 Code limitations

Most of the MC3D code is run as a single threaded application. This means that the calculation time of the code is quite fixed and can not be easily accelerated, for example by running it in a cluster environment. A very fine mesh would of course produce the most accurate results but is not optimal due to the time calculating such a mesh would require. The increase in time is nearly linear with the increase in mesh size. Therefore the size of the mesh is a compromise between detail and speed.

The use of the constant fragmentation model means that all fragmented drops are of the same size and that all fragmented drops are stable. Whereas, in reality their size would vary, and most large drops would most likely undergo further fragmentation until they end up in a stable region. This simplification compared to reality imposes some restrictions on the simulations.

First it requires that the fragmented drop size be significantly smaller than the diameter of the jet. Secondly that the model does not contain multiple jets.[6]

MC3D should also not be used as a “black box tool”, under any circumstances [22]. The code is quite sensitive to changes in user input. Although most parameters left at their default values, some modifications are almost always necessary in order to simulate different scenarios. These modification have to be done carefully so to not unintentionally making the code produce unrealistic results or crash. Therefore an familiarity with the phenomenon is needed to be able to asses the produced results. However, this complexity is also a advantage as it means that a familiar user can use the code to simulate very specific scenarios as almost all parameters can be changed by user input.

# 4. Simulation models and scenarios

## 4.1 Scenarios

The objective of this thesis is to analyse ex-vessel steam explosions. The research is firstly focused on the effects of different break locations and triggering times on steam explosion loads in Nordic BWR geometry, and secondly on assessing the sensitivity of key input parameters. All the analysed cases are listed in table 3.

Three different break locations are taken into account: central and two varying locations to the side. In Fig. 12 is illustrated the different break locations. The different break locations are studied to evaluate if this causes a notable difference in loads on the cavity walls. The central case is analysed with a 2D model and the side breaks with 3D models. The side breaks could not be simulated with a 2D model as they are not axisymmetric. The visualization of the mesh as well as the other figures presenting the results are done with the VisIt program [23].

The break sizes correspond to the size of control rod guide tube failiure. The size of the instrumentation guide tube is notably smaller. The used constant jet fragmentation model limits the jet to be notably larger than the size of created drops, therefore the size of the break corresponds with the larger control guide tube failure. In addition, it has been assumed, that the melt may solidify already in the instrumentation guide tube blocking the breach. This would also make multiple small jets less unlikely, which is good as the use of the constant fragmentation model prohibits analysing multiple simultaneous break locations.

Cases with the different break locations were first simulated with the premixing part of the code and after analysis of the premixing results the 2D central case explosion stage was simulated. The triggering times were distributed over the whole time period, from when the melt first reaches the water and when it starts to spread on the bottom of the cavity. Triggering times were also toke in to consideration the explosivity of the mixing configuration. Explosivity of the mixture is a result of an internal MC3D function for the premixing stage. It gives information on the probability and strength of the steam explosion in regards to triggering as a function of time. After the analysis of the the 2D case explosion results it was concluded that it was enough to simulate the 3D cases with one triggering time each, chosen at the time of highest explocivity, as the results very very similar as long as the mixture was ignitable.

After analysing the effect of break location, the focus is on sensitivity of different parameters done with the 2D central break model. Each case is then set to trigger at the time when it has the highest explosivity value. This point is also assumed to yield the strongest explosion. The parameters studied in the sensitivity analysis are melt temperature, coolant temperature, water level and drop size. The drop size is an internal parameter of the constant fragmentation model and was chosen to be analyzed as this value has a large effect on premixing. Since it is also

*Table 3*

| Case | Different Premixes | Explosions per premix | Explosions total |
|---|---|---|---|
| Break 1 (central) | 1 | 4 | 4 |
| Break 2 (semi-side) | 1 | 1 | 1 |
| Break 3 (side) | 1 | 1 | 1 |
| Melt temp. | 4 | 1 | 4 |
| Coolant temp. | 4 | 1 | 4 |
| Water level | 4 | 1 | 4 |
| Drop size | 6 | 1 | 6 |
| Total | 21 | - | 24 |

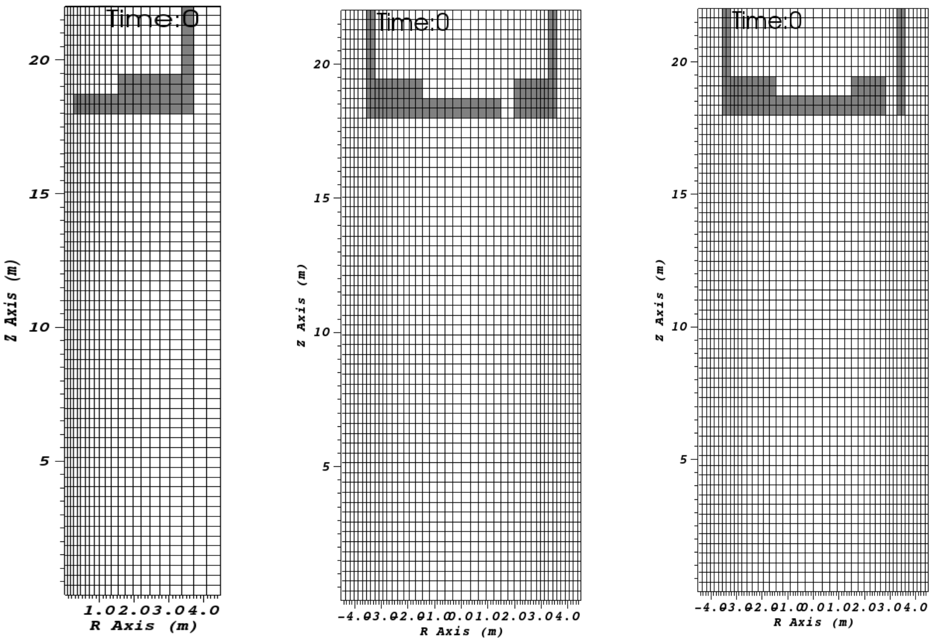
a purely user based value it was deemed interesting to see its effect. In an accident scenario the actual value of the drop size would be largely controlled by the chemical properties of the melt, as discussed in Chapter 2. From a safety perspective it is important to test, if some values causes a significantly stronger explosion. Melt temperature, coolant temperature and water level were chosen for the sensitivity analysis as these values also differ in a accident scenario and they theoretically could have a large effect on the explosion size.

## 4.2 The input

The input geometry is a simplification of the reactor cavity. The cavity is modelled as an empty cylinder having correct dimensions. Equipment support structures are not included in the model. An illustration of the 2D model mesh structure with central break is shown in Fig. 12. The grey zones represent the lower part of the RPV. In the central break case the size of the opening is about 50 cm in diameter. The lower part of the RPV is spherical but due to complexity required in adding spherical objects to MC3D the RPV is modeled as a cylinder, this is considered to have no notable effect on the simulations. Adding a spherical shape would only increase venting witch might slightly lower pressure build-up in the upper parts of the cavity, but as the largest pressure build-ups will be on the lower parts of the cavity this will have no effect on the results. The mesh is defined to have a finer structure in the areas where much melt fragmentation is excepted, so as to get better results. In other regions the mesh is more coarse to speed up the simulation. For the 3D models a similar approach has been used.

Not modelling the internal structure of the cavity is done for two different reasons. The first reason is to speed up the simulation process, as adding the structures would require a very fine mesh compared to the one used. As the simulation time increases almost linearly with the increasing mesh size, this would result in inefficient simulations. The second reason is that the actual status of the equipment in the cavity is very uncertain at this stage of an actual accident. So to get realistic results many different scenarios would need to be analysed. However, the effect of obstacles in the cavity would mainly affect the premixing as it might change the way the melt fragments. Also, if the melt impacts with some larger object, it might serve as an internal trigger similarly to that of the melt jet hitting the cavity bottom. As the simulations are done with the assumption that an triggering event always happens the added effect of an possible internal trigger would not be notable in the simulations. Therefor it was deemed best to do the simulations with an empty cavity.

Realistic values for MC3D input paramters were considered by analysing a LOCA and a station blackout for a Nordic BWR plant with integral code MELCOR [24]. The results for the evolution




(a) 1 (b) 2 (c) 3

*Figure 12. The meshes used in the simulations. Meshes number two and three are 3D models and shown here as 2D slices over the opening.*

*Table 4. Simulation parameters in the standard case*

| Parameter | Value |
|---|---|
| Melt temp | 2900 K |
| Ambient pressure | 246 kPa |
| Ambient overheating | 0 K |
| Coolant subcooling | 50 K |
| Water level | 11.824 m |

of ambient pressure, ambient temperature and coolant temperature in the cavity are shown in figures 13 and 14 The results from both the LOCA and station blackout cases were so similar from a steam explosion perspective that the MC3D input parameters could be made as a single set. Meaning that a steam explosion resulting from a LOCA or a station blackout does not need to be analysed separately. The selected input parameters for a base case are shown in table 4. Also the simulations performed in MELCOR indicated that the time it takes for the melt to eject from the RPV is quite long compared to the time-scale of the premixing, this means that the model was constructed so that there is sufficient melt in the RPV to feed a continuous jet for the duration of the premixing part of the simulation.

According to MELCOR, the melt temperature in the RPV lower plenum is relativly low, in the region of 2200K, this is because the melt is actually assumed to be a mixture of melt and debris[25]. This low melt temperature does not result in steam explosions for the standard case model. It was decided to set the base case melt temperature to 2900 K. Corium consists mostly of uraniumdioxide, and zirconiumdioxide. Liquidus temperature of such a mixture is in-between the liquidus temperatures of the pure materials. The melting temperature of pure $UO_2$ is at around 3120 K [26]. In the simulations the standard MC3D corium material was used, for which liquidus temperature is 2800 K [19].

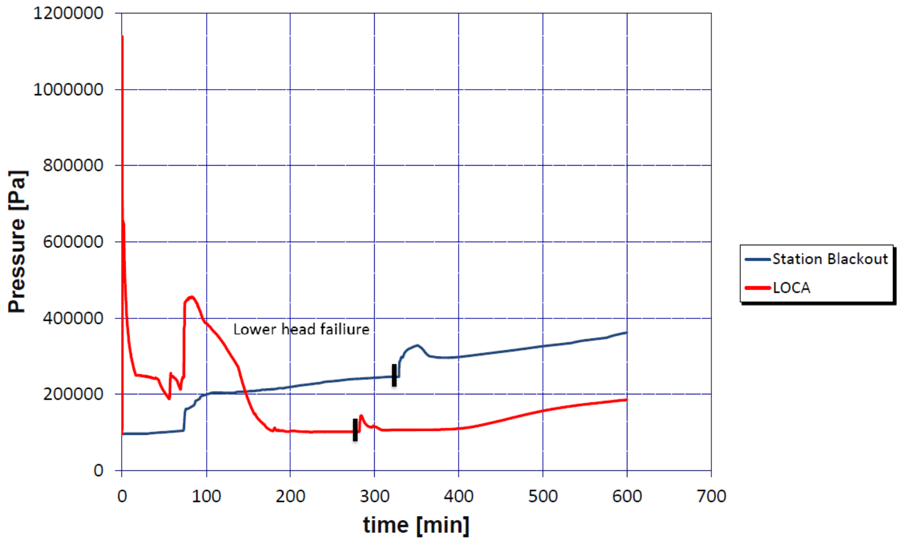



*Figure 13. Pressure in the cavity according to MELCOR results, black lines indicates time of RPV failure.*

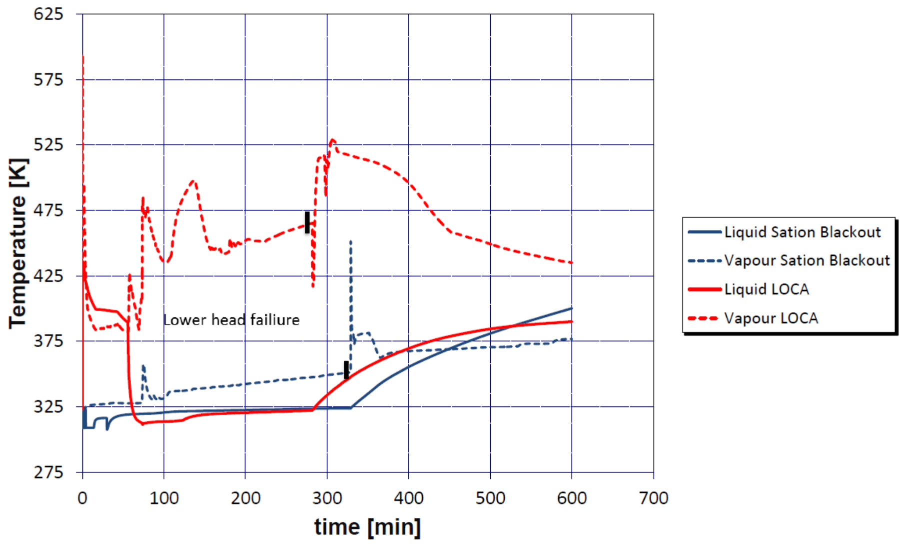



*Figure 14. Temperature in the cavity according to MELCOR results, black lines indicates time of RPV failure.*

# 5. Results

## 5.1 Central break

The first test case that was analysed was the 2D central break case simulated with 4 different triggering times. The case was run with the standard parameters presented in table 4, and the standard 2D mesh shown in figure 12. The premixing part of the simulation is illustrated in Fig. 15, the figure also gives a graphical representation of the void build-up. Here the oscillating nature of gas film of the jet is also noticeable. In figure 16 the explosivity of the mixture is presented.

The four triggering times were chosen based on the explosivity and on the position of the melt jet front. The first triggering time is set to 1.5 s which is just after the jet has impacted with the water. The second triggering time, 2.30 s, is when the jet front is almost at the bottom. The third and fourth are slightly after the jet has impacted the bottom (2.9 s and 3.66 s). The 4 snapshots presented in Fig. 15 are taken at the closest saving time to the triggering times. The slight inconsistency in times are due to the mismatch in saving frequency between the save file and the data output.

The explosion stage of the simulation is analysed via the pressure build-up along the cavity wall and the impulse it induces. In Fig. 17 is shown the maximum dynamic pressure in any of the cells along the cavity wall. The graph contains only three lines as the third triggering time (2.9 sec) did not result in an explosion due to the low explocitivity of the premixture. Since the location of the maximum pressure changes along the wall, the position of the wavefront is not visible in this figure. The wavefront can however be seen in Fig. 18, where is a snapshot of the dynamic pressure of the first triggering time explosion stage. It is clear that the mixture has been triggered close to the top of the water pool, since the radial wave has its centre in the small region with the highest pressure at the top of the pool. The progression of the pressure wave can also be seen in Fig 19, where the pressure evolution of all three successful triggering times are shown at different levels on the wall. The levels are illustrated on the mesh in Fig. 20. There does not seem to be a strong correlation between high explosivity and high dynamic pressure, as both trigger time one and two achieved similar maximum pressure even though their explosivity was quite different. However, there is a strong indication that low explosivity cases are not triggerable. The fourth triggering time is a bit different from the two other cases other as the first pressure spike is lower than the second spike, which is the lowest of the three and also the narrowest. This could indicate that the premixture contains multiple highly triggerable regions and that the explosion reaches its maximum strength after contact with one of these regions.

The highest recorded impulses are plotted in Fig. 21 for the successful triggering times. It should be noted that the location of maximum impulse varies between the different triggering times. For trigger one and two the largest impulse was on the lowest cell at the wall and for trigger four it was on the second lowest cell. The recorded impulses behaved as excepted from the pressure behaviour, trigger one shows a step increase and then saturation as the pressure increase was only a high spike, trigger two on the other had has both a large first rise and a smaller secondary rise from the smaller secondary pressure spike. Whereas, trigger four is a slow rise with a few smaller steps as a result of the smaller pressure spikes observed in the pressure recordings.

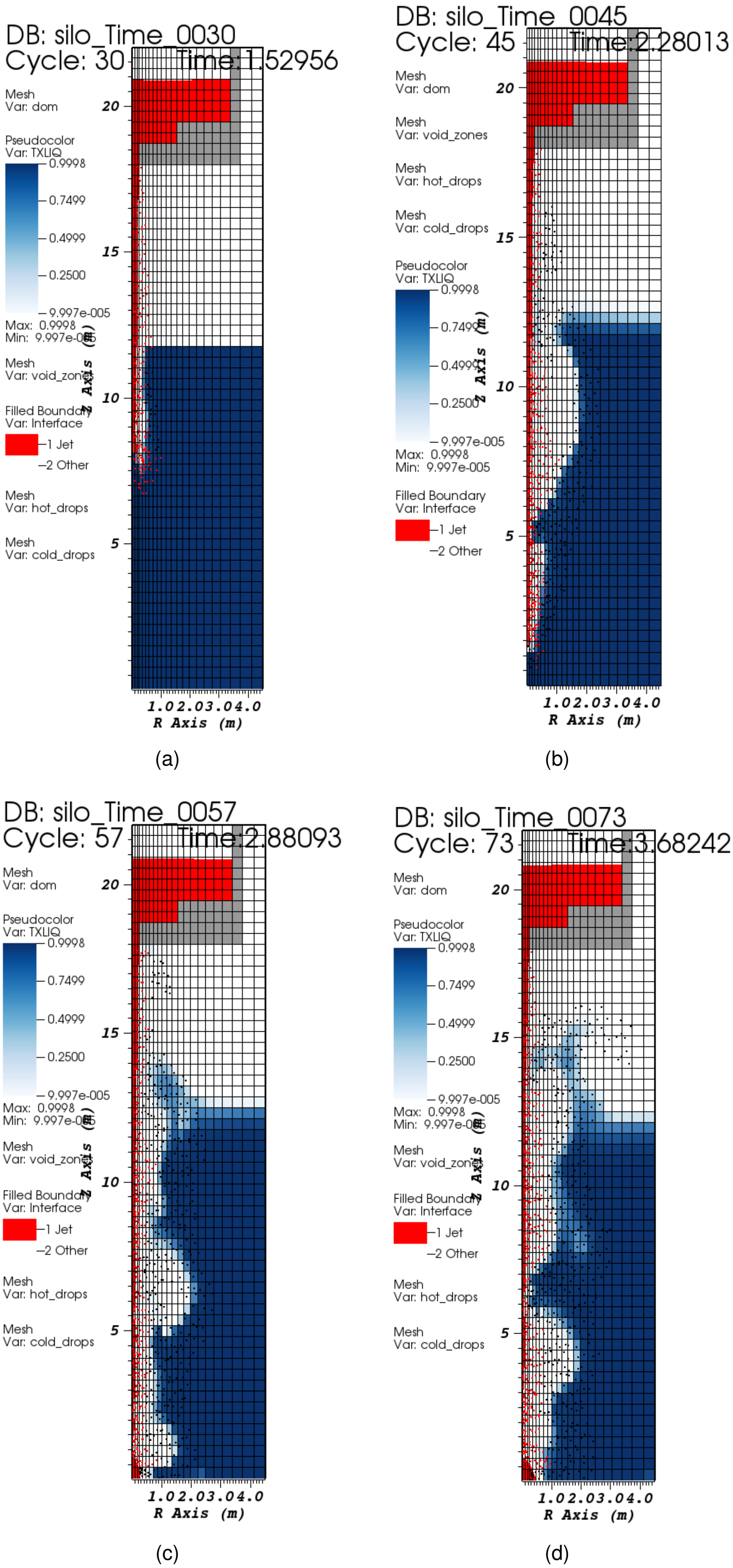



*Figure 15. Snapshots of the premixing condition for the central break, showing the mixture at the four different trigger instances: 15(a) 1.529 s, 15(b) 2.280s, 15(c) 2.880 s and 15(d) 3.682 s. Red dots indicate molten hot drops and black dots solidified cold drops.*

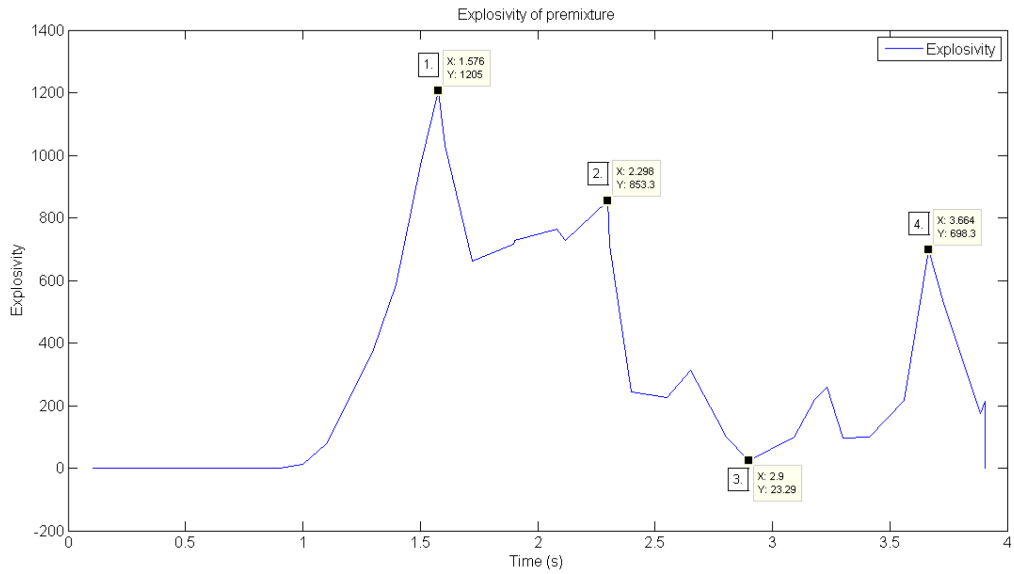



*Figure 16. Explosivity of the central break premixing condition. The four different triggering times are indicated in the graph*

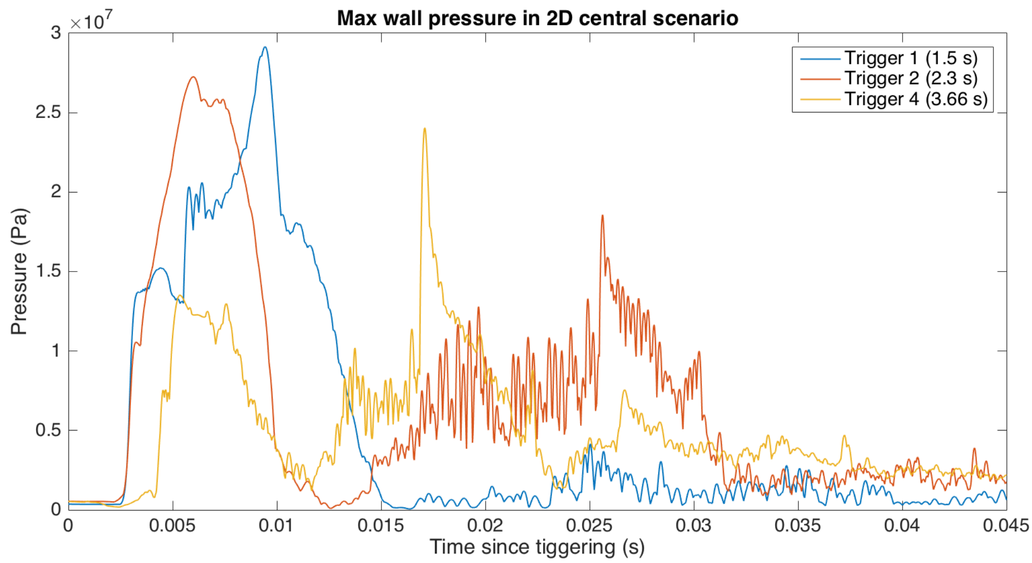



*Figure 17. Maximum dynamic pressure recorded in any cell along the wall in the central break simulations for the different triggering times.*

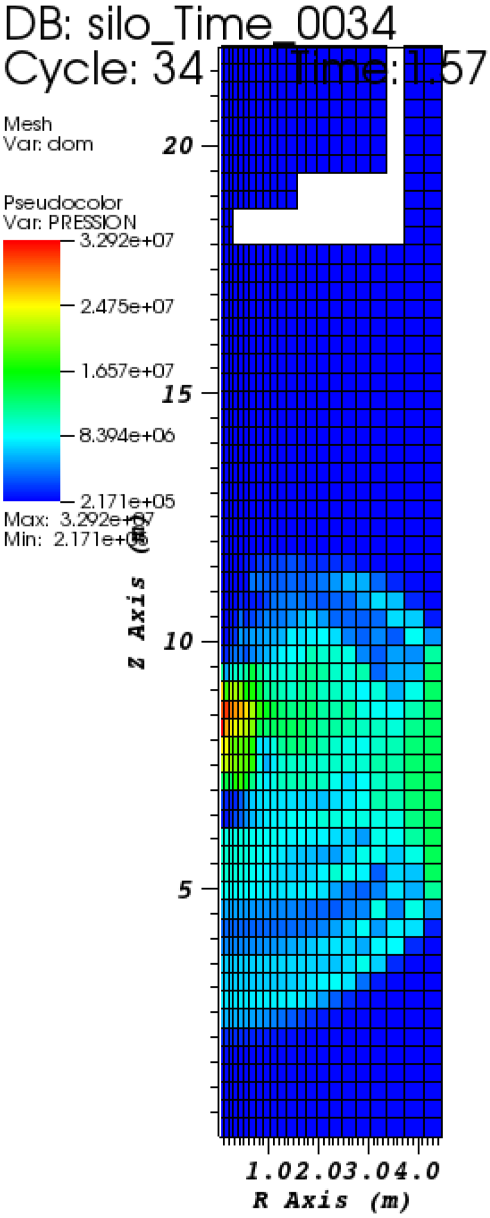
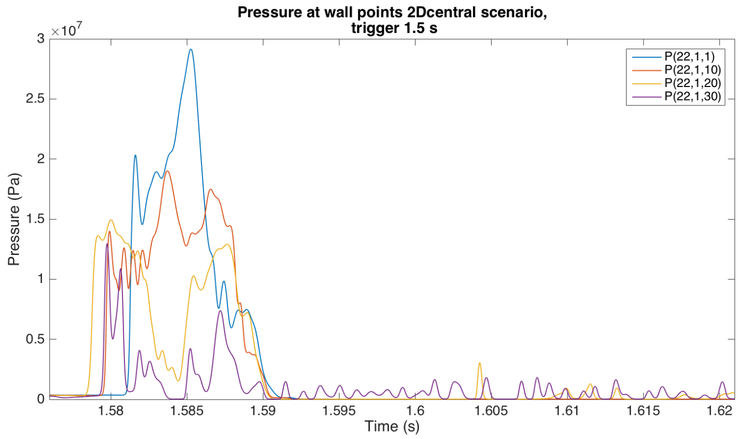
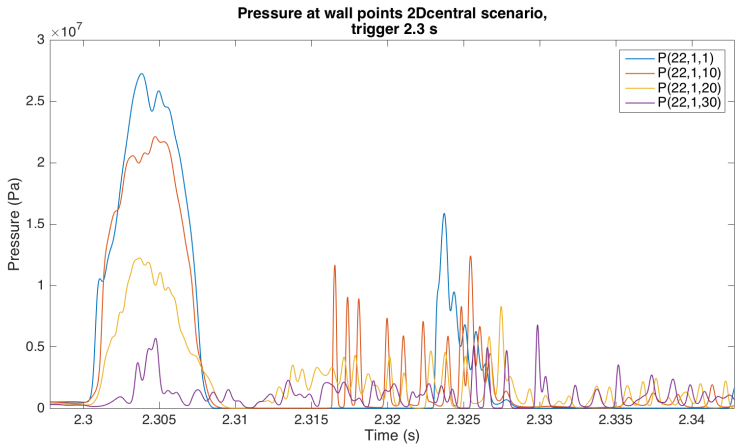



*Figure 18. The dynamic pressure in the mixture for triggering time 1.5 s of the central break simulations.*




(a)

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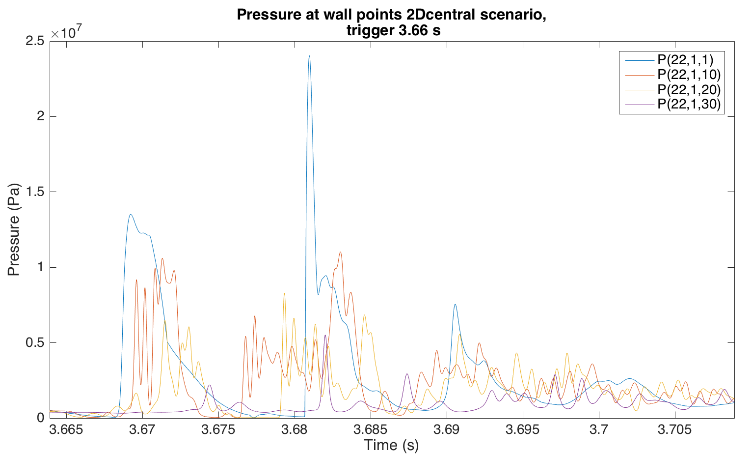



(c)

*Figure 19. Dynamic pressure at four fixed locations for all successive central break trigger times. The location of the pressure wave front can be observed from the delay in pressure increase at the different points, as the pressure wave has not reached the point until pressure increases.*

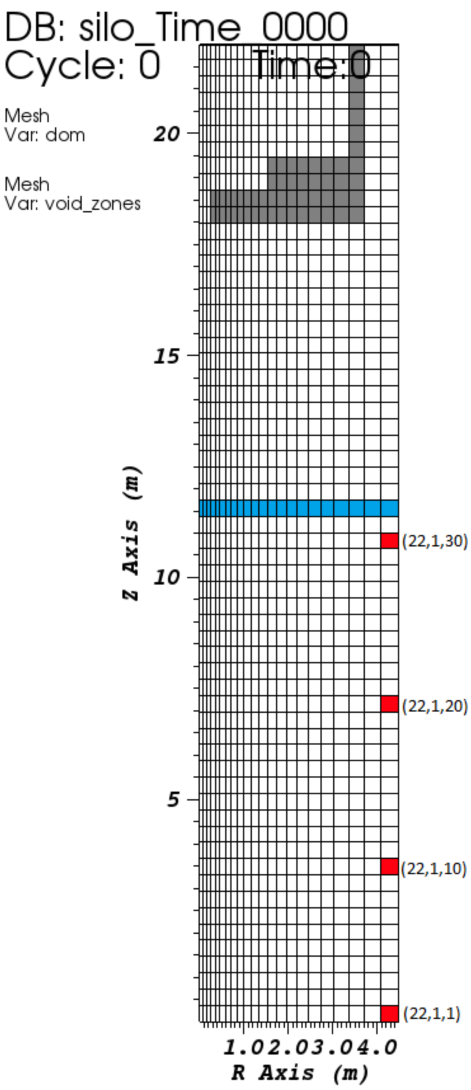



*Figure 20. The four locations, used for illustrating the dynamic pressure wave front evolution, are indicated in red. The blue line shows the water level in the standard case.*

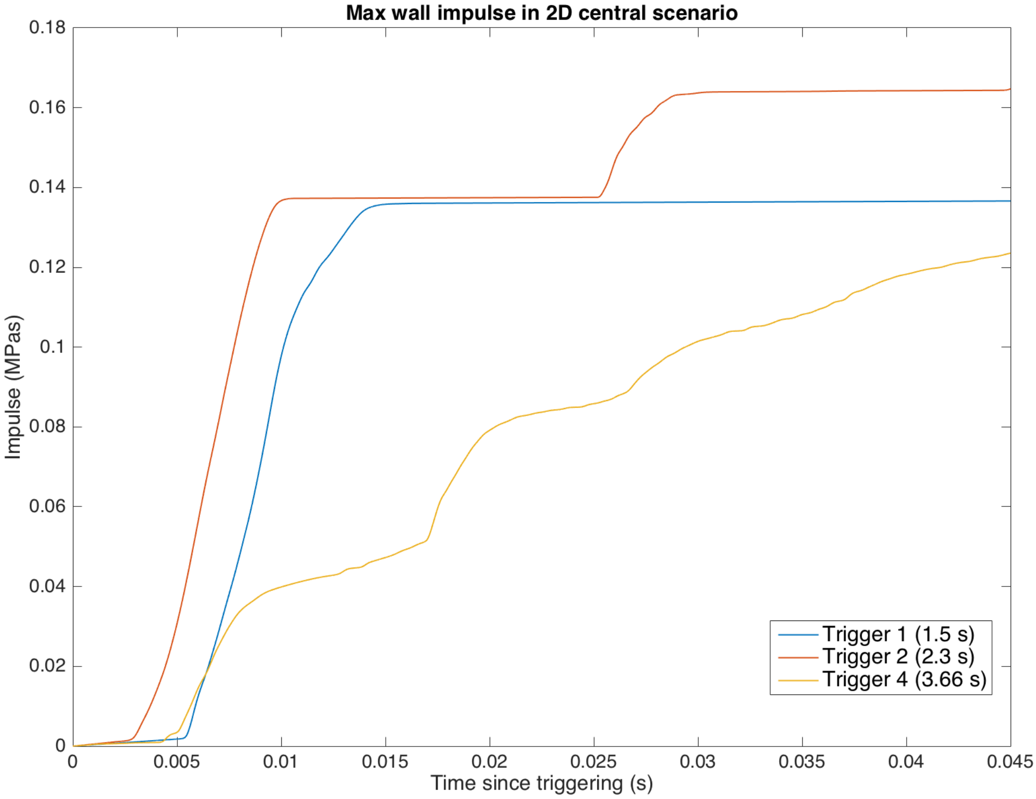



*Figure 21. Impulse plots for the locations along the cavity wall that receive the maximum impulse in the central break simulations.*

## 5.2 Side breaks

The 3D scenarios were run with the standard parameters presented in table 4, and with the break locations presented in Fig. 12. The premixing parts of both cases were run and the results analyzed. In figure 22 the explosivity of the mixtures can be seen, together with that of the central case. Notable is that in the case of the second location the simulation did stop at around 2.5 seconds. The reason for this is unknown, but multiple restart attempts did not let the simulation progress beyond this point. A possible reason could be model imperfections that causes errors which stop the simulation. The triggering time for both mixtures were chosen to be at the moment of highest explosivity, as the results from the central case showed no significant difference in the resulted pressures from mixtures that were properly triggered. The explocitivity for the 3D and 2D models can not be directly compared as explositivity is also dependent on the model. For the location two the highest explosivity was at 2.24 seconds and for location three at 2.226 seconds. Due to the 3D nature the premixture can not be illustrated as clearly as in the 2D case but a snapshot of the premixture from the second side break is shown in 23. The jet is not visible in the figure since the renderer does not support the VOF-PLIC method, which is used to approximate the location of the jet as discussed in section 3.1.1.

The results from the explosion phase of the two side breaks are shown in Fig. 24, with the central cased added for comparison. It is clear from the figure that the triggering did not successfully ignite the mixture in break location two and three even though the explosivity was high in comparison to the 2D central case. Due to this further analysis were done by modelling also a 3D central break case, but also in this case the triggering was unsuccessful even though explosivity was similar to the 2D case. Therefore, the most probable reason for the side break cases not exploding is faults in the models and not that the side break scenarios would be unable to produce steam explosions.

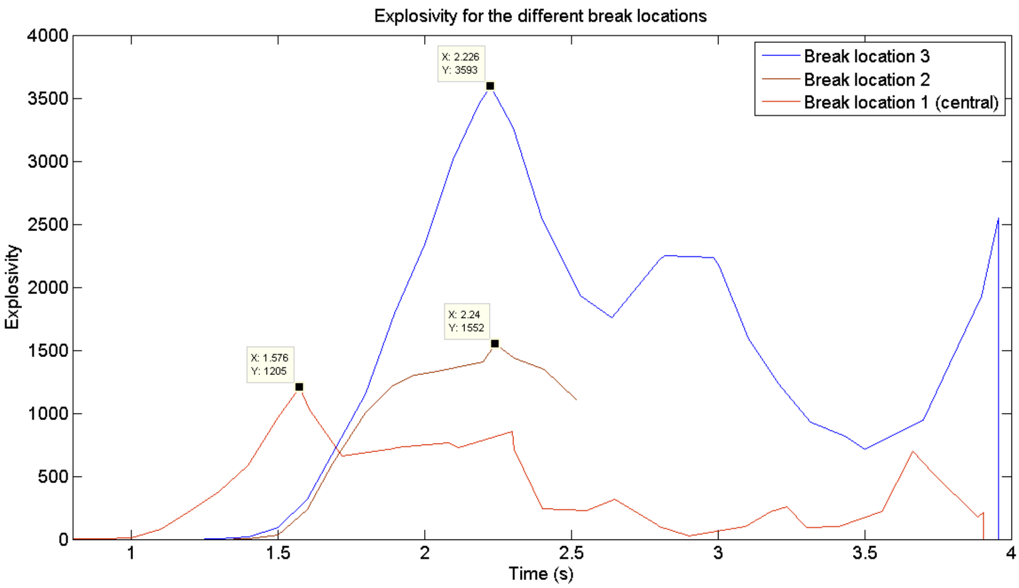



*Figure 22. Explosivities of the premixtures of all the break locations, highest values are marked. For locations two and three these points served as triggering times in the 3D analysis. Central case added for comparison.*

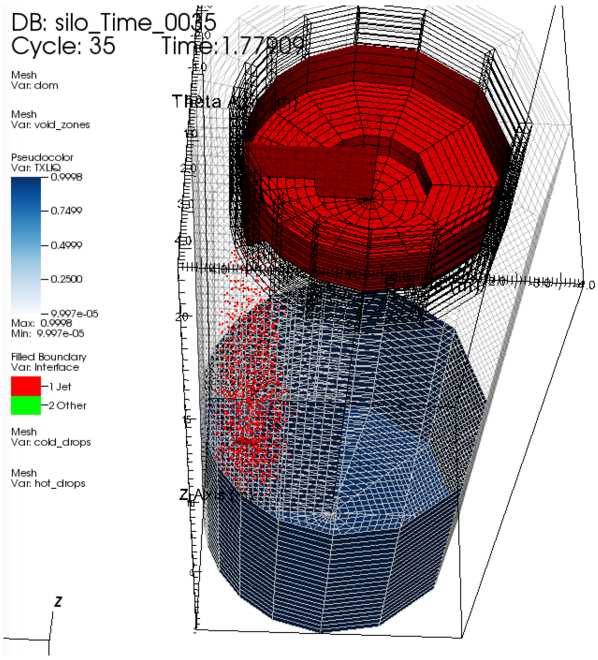



*Figure 23. Snapshots of the premixing mixture for the second side break location. Red dots indicate molten hot drops and the few black dots the cold drops. The rendering has problems showing the jet due to the VOF-PLIC method.*

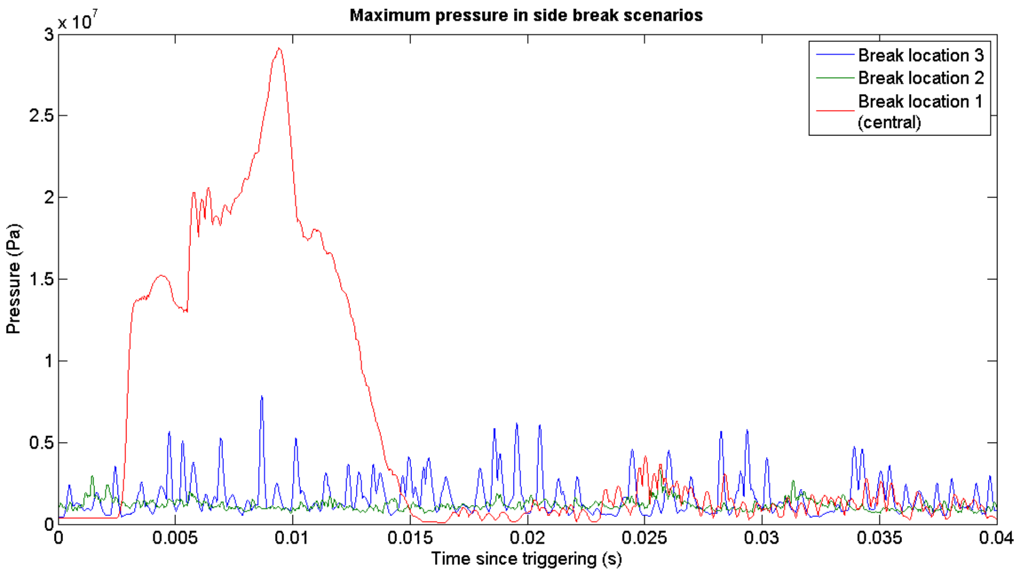



*Figure 24. The maximum wall pressure from the side break scenarios. For both side breaks triggering was unsuccessful.*

## 5.3 Sensitivity analysis

The sensitivity analysis was performed on the parameters: melt temperature, coolant temperature, water level and drop size. Each performed with the different parameter values listed in table 5. The parameters where selected to try to cover as many realistic cases as possible. All mixtures were then simulated and the pressure and impulse along the wall recorded.

### 5.3.1 Melt temperature

Steam explosion cases with five different melt temperatures were simulated and the results analysed. The temperatures were chosen to be between the lower limit of what could be triggered in the model and the liquidous temperature of uranium-dioxide. The explosivities of the premixtures can be seen in Fig. 25. In all cases the explocivity is the highest at around 1.5 s, and all premixses reach roughly the same value. It is interesting that two temperatures, 2950K and 3050K, show a very high secondary peak at 2.3 s. These peaks are not present at any of the other temperatures, not even slightly in the 3000K case, even though that temperature is in between the two. The second peak is also not as high as the first. It would seem that increased temperature above 2900K does not futher increase the probability of ignition of the mixture.

The mixtures were triggered at the point of their highest explocivity, around 1.5 to 1.6. The maximum dynamic pressures on the wall are illustrated in Fig. 26 and the maximum impulses in Fig. 27. The impulses were all recorded in the lowest cell. In the figures the lines for the 3000K case is missing. This is not due to the mixture not triggering but due to the simulations stopping at 0.0014 seconds in. This might be the result from a rounding error due to very high pressure differences between cells. As the results did not match the theoretical predictions that higher melt temperature should lead to stronger explosion, it seemed prudent to discuss the results with the code developers from IRSN. After an email discussion with Stephane Picchi from IRSN [27], it became clear that the results are as could be expected in this scenario as the melt temperatures in all test cases are above the liquidus temperature and the melt does not have enough time to cool down. Therefore, most drops stays in molten form and are able to participate in the explosion.

### 5.3.2 Coolant subcooling

The coolant subcooling level was analysed with four different degrees of subcooling ranging from 0K to 75K, with increments of 25K. The differences in the results are already visible at the premixing stage as the subcooling affects the void build-up. From the explosivities, shown in Fig. 28, it becomes clear that the initial peak in explosivity increases with a higher degree of subcooling as the subcooled water inhibits heavy void build-up. Interesting is also that at a subcooling of 25K the second peak is higher than the first.

*Table 5. Sensitivity analysis parameters*

| Melt temperature | Coolant subcooling | Water level | Drop size |
|---|---|---|---|
| 2900K | 0K | 6m | 1.0mm |
| 2950K | 25K | 8m | 2.5mm |
| 3000K | 50K | 12m | 3.0mm |
| 3050K | 75K | 16m | 4.0mm |
| 3100K | | | 6.0mm |
| | | | 8.0mm |

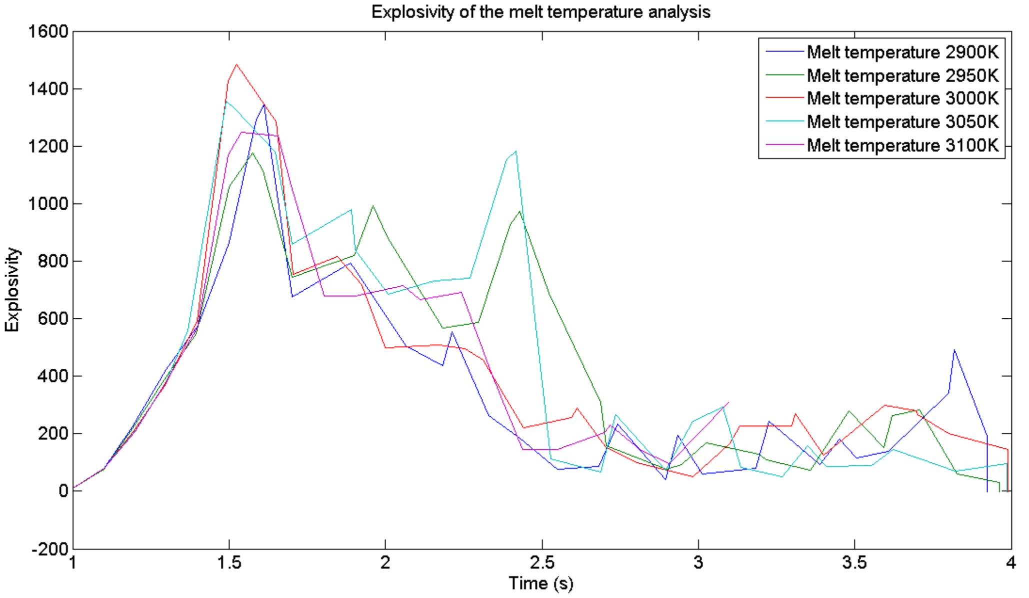



*Figure 25. The explocivities when analysing the effect of melt temperature. The selected trigger times are,in the order from lowest to highest melt temperature: 1.613s, 1.576s, 1.524s, 1.492s and 1.539s.*

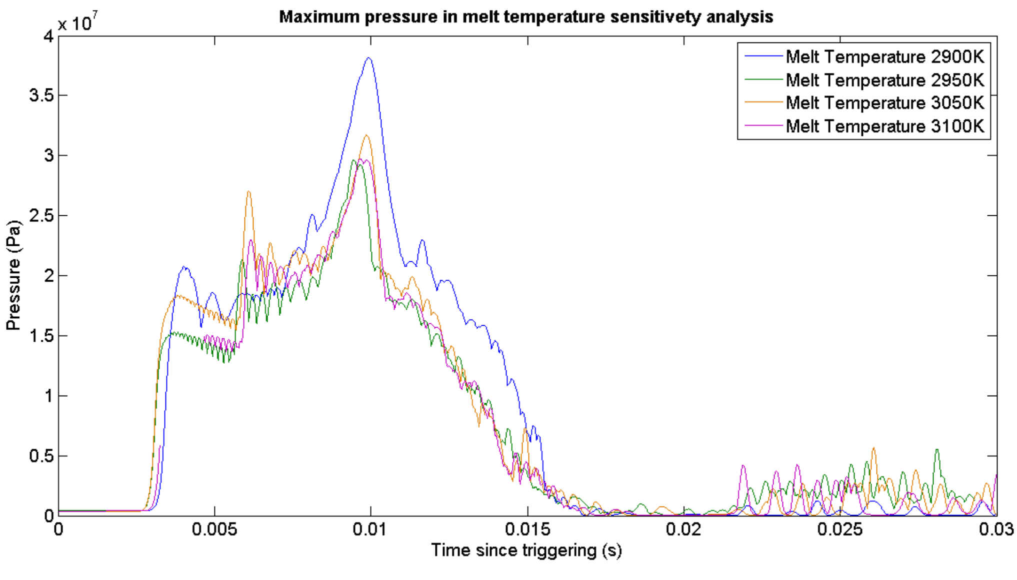



*Figure 26. The maximum dynamic pressures on the wall from the melt temperature analysis.*

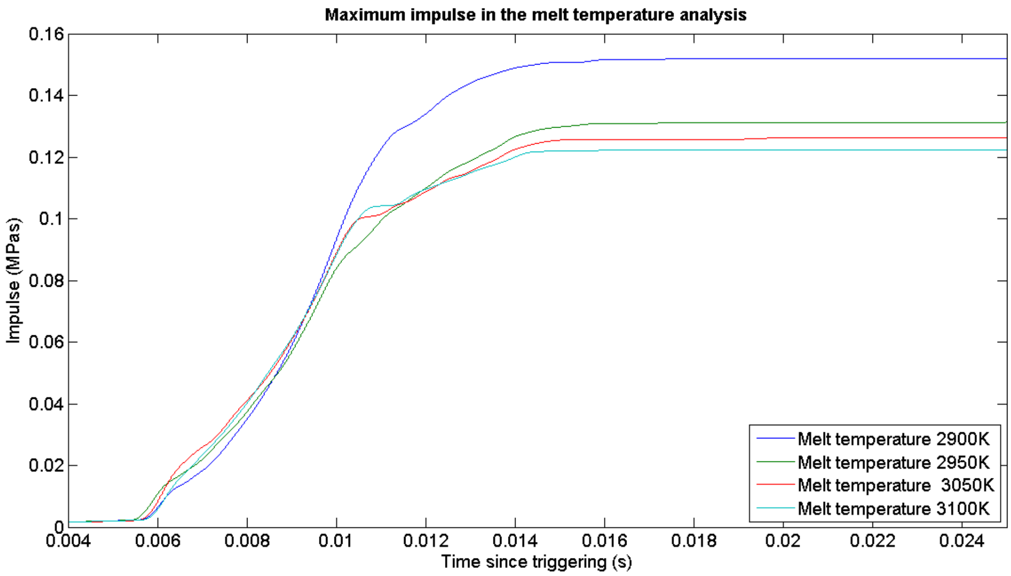



*Figure 27. The maximum impulses from the melt temperature analysis. All impulses were from the lowest cell.*

The mixtures were then triggered at the point of their highest explosivity. The maximum dynamic pressures and impulses are illustrated in Fig 29 and Fig. 30, respectively. A greater subcooling results in a stronger explosion compared to lower subcooling cases, most probably due to the decrease in void build-up. The strong second peak in the 25K case is probably due to a second pressure wave reaching the wall due to ignition of a separate region. This is similar to the fourth trigger in the standard central case, which makes sense as the 25K case was triggered at a later time than the other cases and the melt drops therefore have more time to separate into different regions.

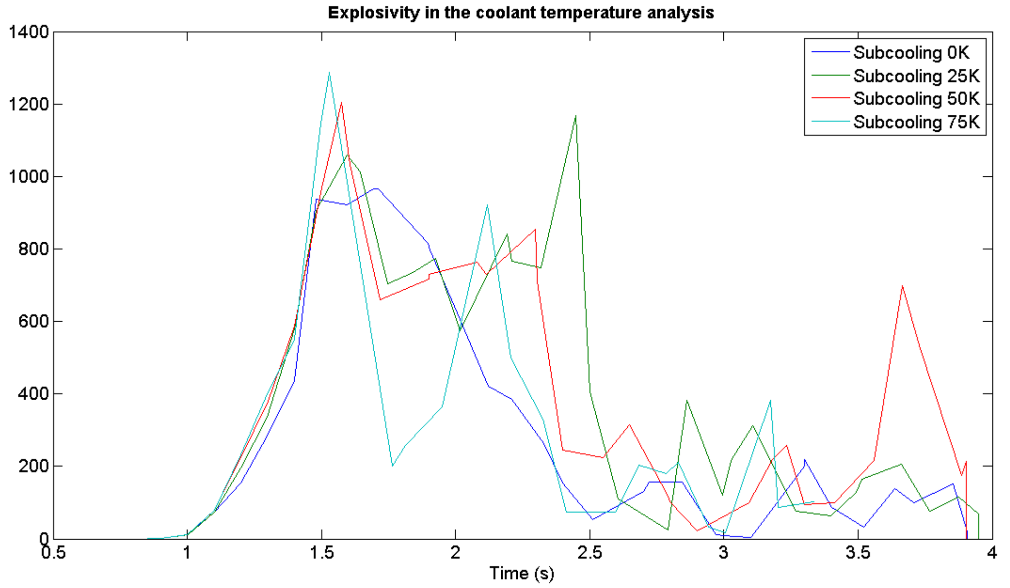



*Figure 28. The explosivities for the coolant subcooling. The selected trigger times in the order from lowest to highest subcooling are: 1.713s 1.597s, 1.576s and 1.530s.*

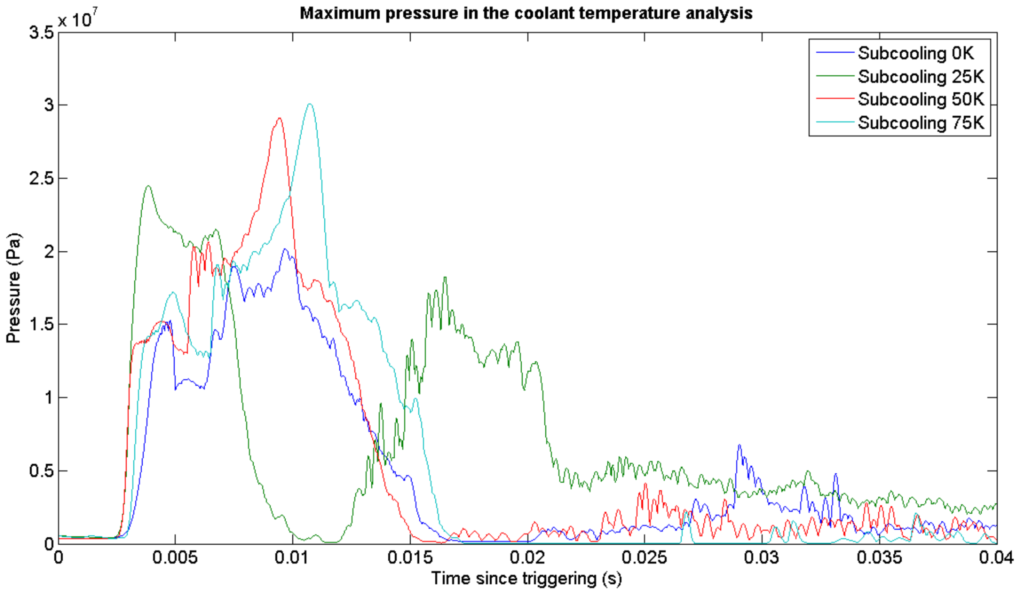



*Figure 29. The maximum dynamic pressures on the wall from the coolant temperature analysis.*

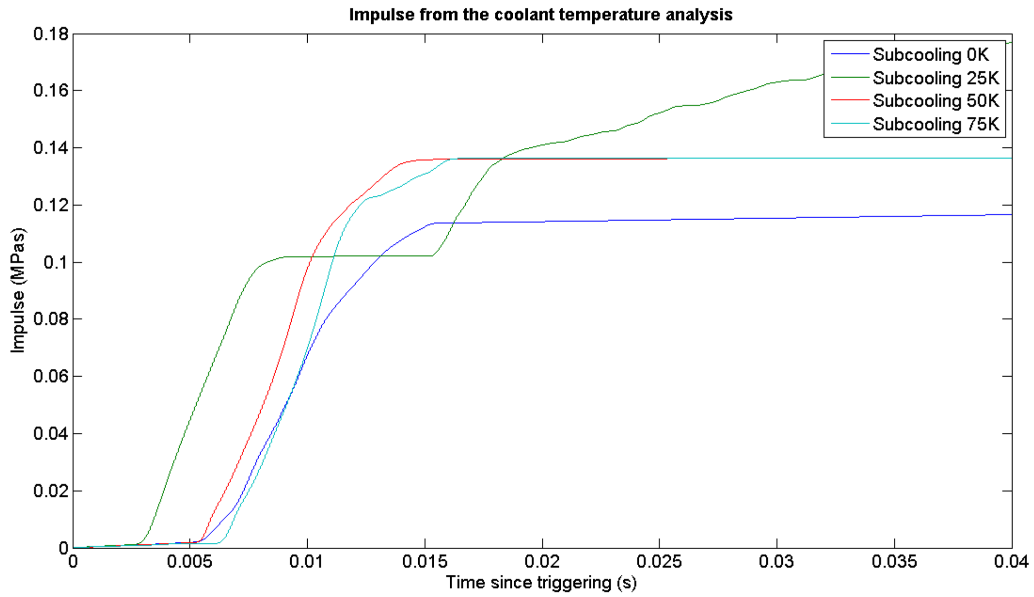



*Figure 30. The maximum impulses from the coolant temperature analysis. All impulses were recorded on the lowest cell.*

### 5.3.3 Water level

The effect of the water level in the cavity on the steam explosion strength was also analysed. The premixing was defined for four different water levels: six, eight, twelve and sixteen meters. The explosivities of the mixtures is shown in Fig.31. It is clear that the highest explosivity occurs, in all cases, just as the melt jet enters the water pool, since the first peak is the highest. In the cases with more water, 12 m and 16 m, it is also obvious that the vapour film around the jet oscillates, as the explocivity increases again when water floods back towards the jet.

The mixtures are then triggered at the point with their highest explosivity. The maximum dynamic pressures and impulses can be seen in Fig 32 and 33, respectively. Based on the results it seems like the 16 meter case causes a notably stronger explosion, but the dynamic pressure is on the same level as recorded in the central standard case, shown in Fig. 17, where the water level was 11.824 m. The other cases exhibit similar explosion strengths with each other. Another interesting fact is that the low water level case, 6m, seem to have a secondary pressure peak of almost the same hight as the first one. Similar phenomenon was also observed when simulation with even lower water level, i.e. multiple similar spikes, however the results from these cases were not included as the results became very unphysical. Probably, as a result of the scenarios being outside of the codes intended use-case.

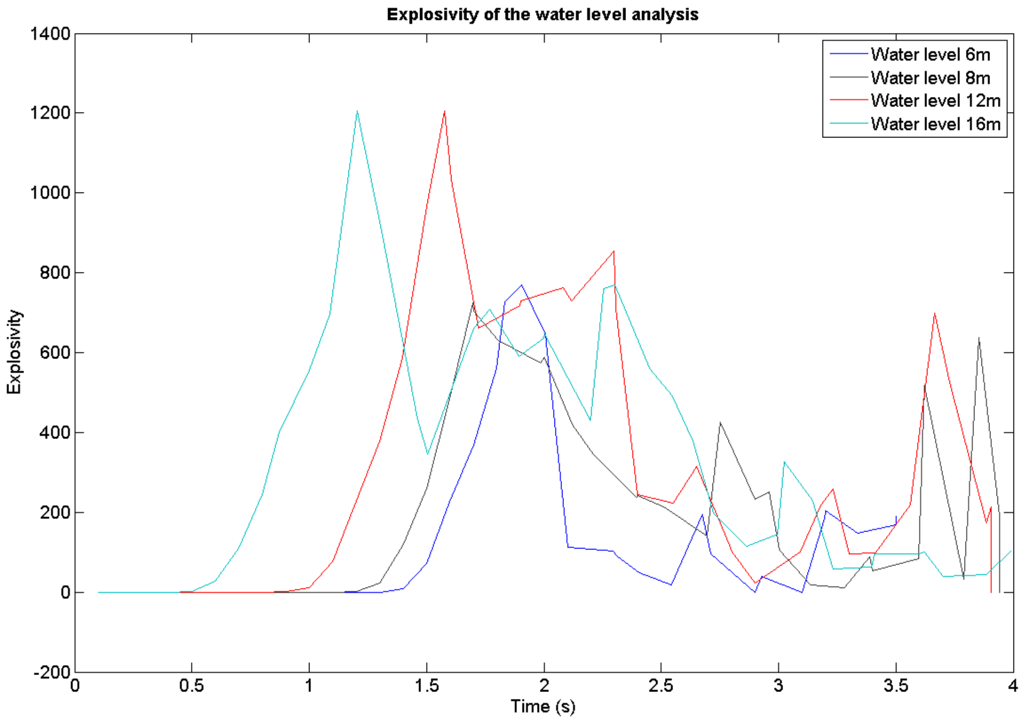



*Figure 31. The explosivities of the water level cases. The selected trigger times in the order from lowest to highest water level are: 1.906s, 1.699s, 1.576s and 1.200s.*

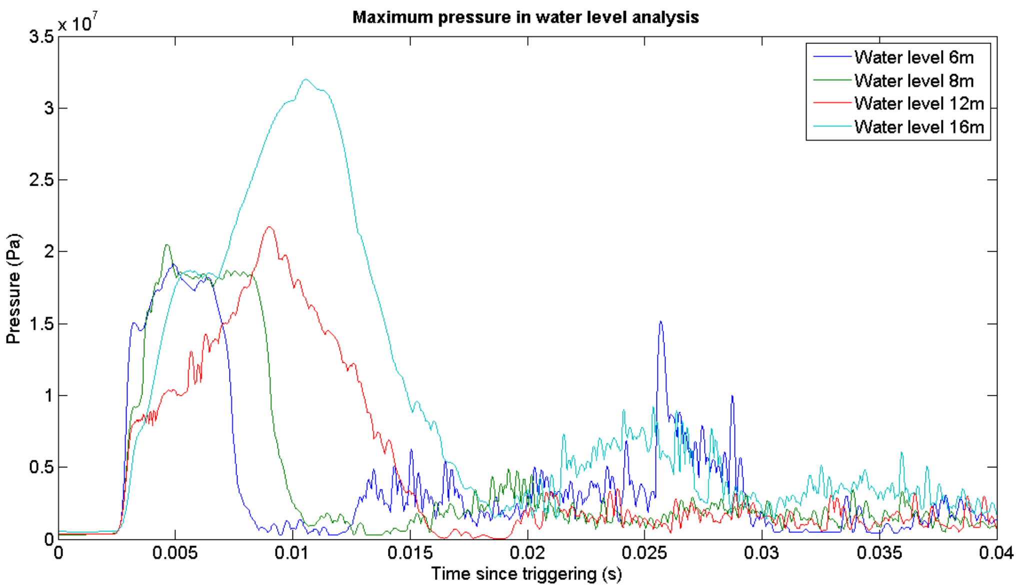



*Figure 32. The maximum dynamic pressures on the wall from the water level analysis.*

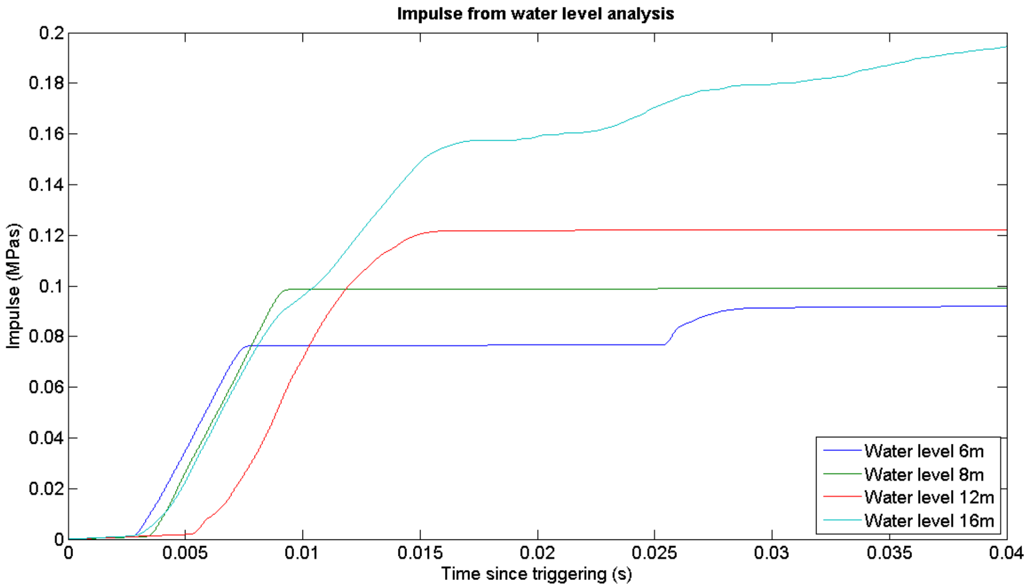



*Figure 33. The maximum impulses from the water level analysis. All impulses were from the lowest cell except for the 16m case where the maximum was recorded in cell number 20, form the bottom. Which is approximately at 7 meters from the bottom.*

### 5.3.4 Drop size

In the drop size sensitivity analysis both the explosion probability and explosion strength aspects are of interest, as a bigger drop size should strongly increase both. This is because larger drops should not solidify as easily and thus they are supposed stay in the molten regime longer, as discussed in section 2.3.1.

In Fig. 34 are the results from the premixing stage in the form of a explosivities. Based on the results it is obvious that the explosivity increases with increasing drop size. To visualize the reason for this behaviour in Fig. 35 is illustrated the premixing stages at the same instant for 1.0 mm and 8.0 mm drop sizes. In the 1.0 mm case it is clear that a major part of the drops solidify as soon as they enter the water causing the mixture to have a very small explosivity, i.e. explosion probability, whereas in the 8.0 mm case almost none of the drops are solidified. The smaller drops also causes a higher heat flux into the water and thus a larger void build-up, this also effects the explosivity but this effect is minor compared to drop solidification.

In Fig. 36 is shown the maximum dynamic pressure in the explosion phases. There is a very clear increase in the explosion strength with increasing drop size. The maximum pressure for example recorded in the 6.0 mm case is 175 per cent of that in the 1.0 mm case. The 8.0 mm case does not result in the highest pressure peak but the broadest and thus it results in the strongest maximum impulse on the wall. The impulses are presented in Fig. 37.

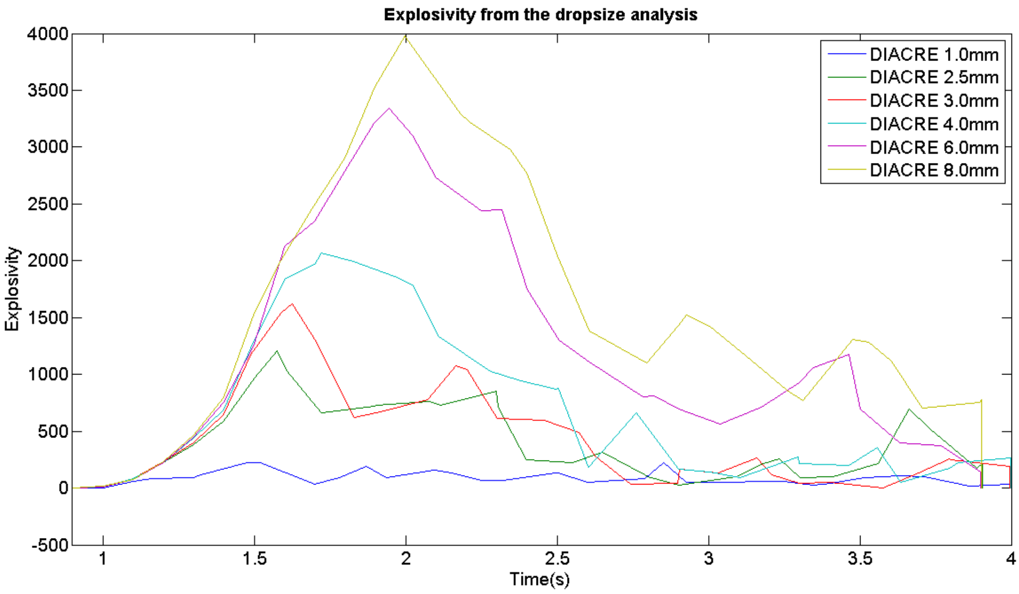
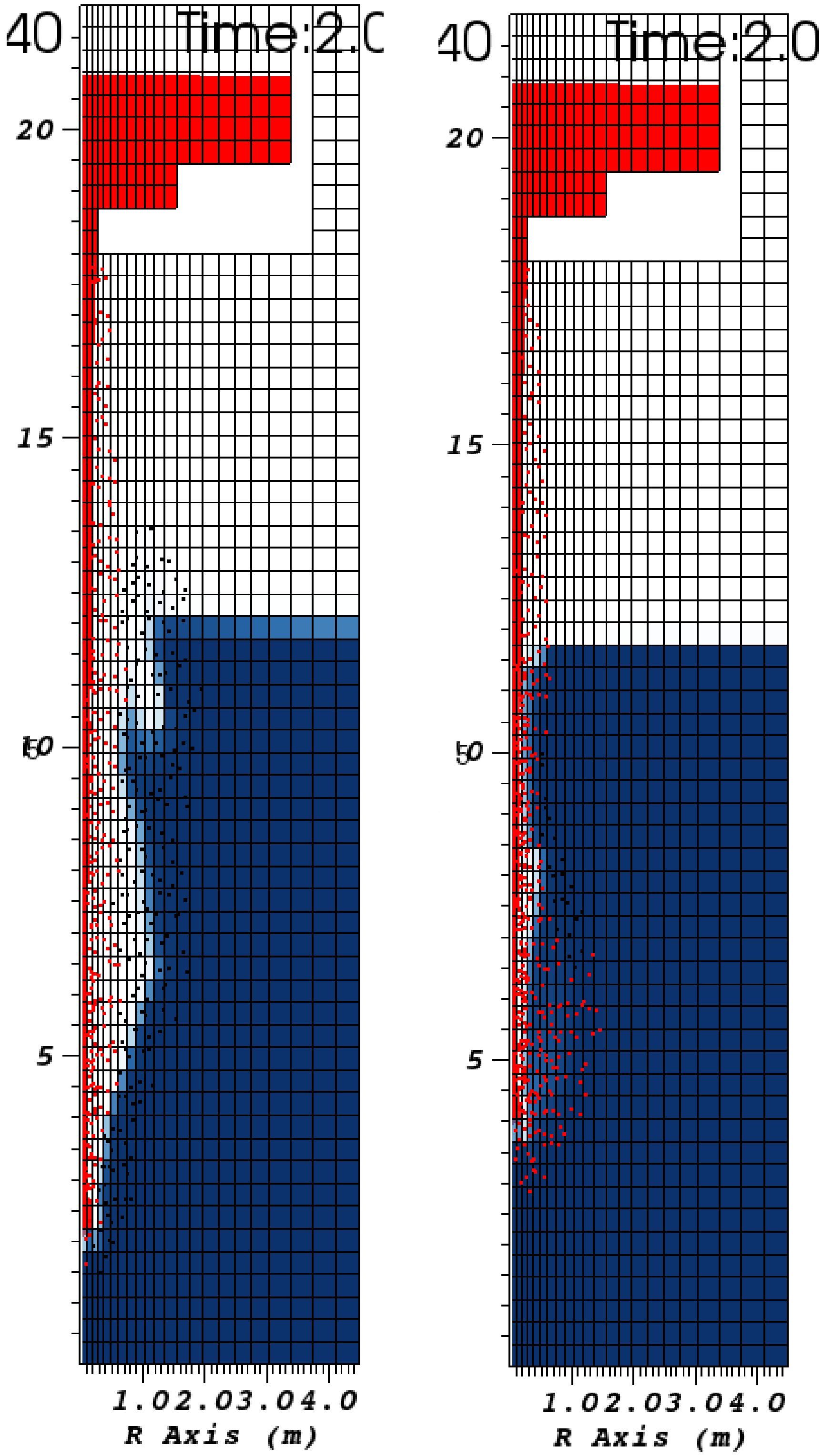



*Figure 34. The explosivities for the drop sizes. The selected trigger times in the order from smallest to largest drop size are: 2.851s, 1.576s, 1.625s, 1.721s, 1.944s and 1.998s.*




(a) (b)

*Figure 35. Snapshots of the premixing with different, 1.0 mm (a) and 8.0 mm (b), drop sizes at 2.02 s.*

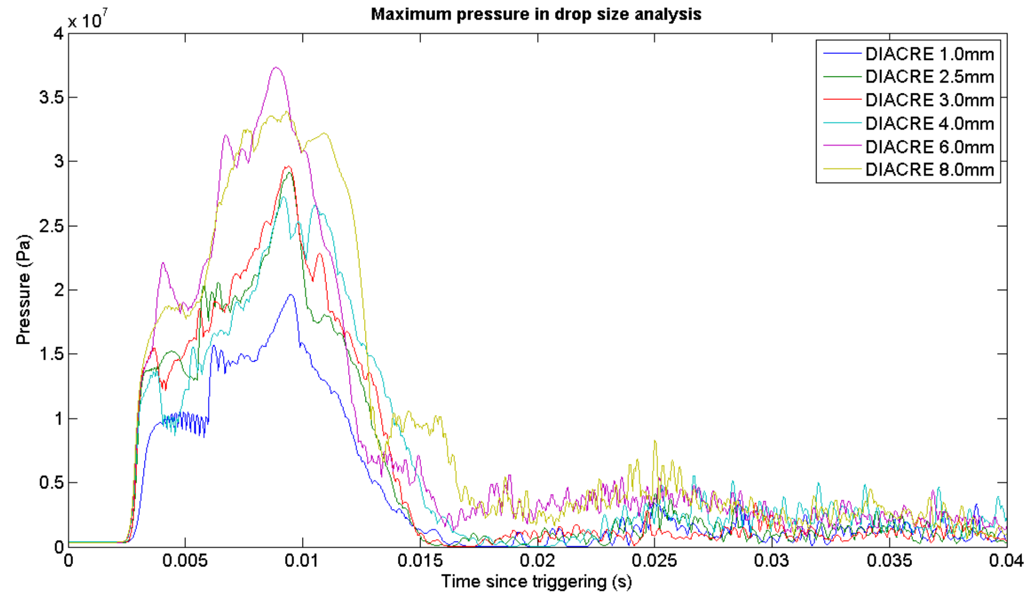



*Figure 36. The maximum dynamic pressures at the wall from the drop size analysis.*

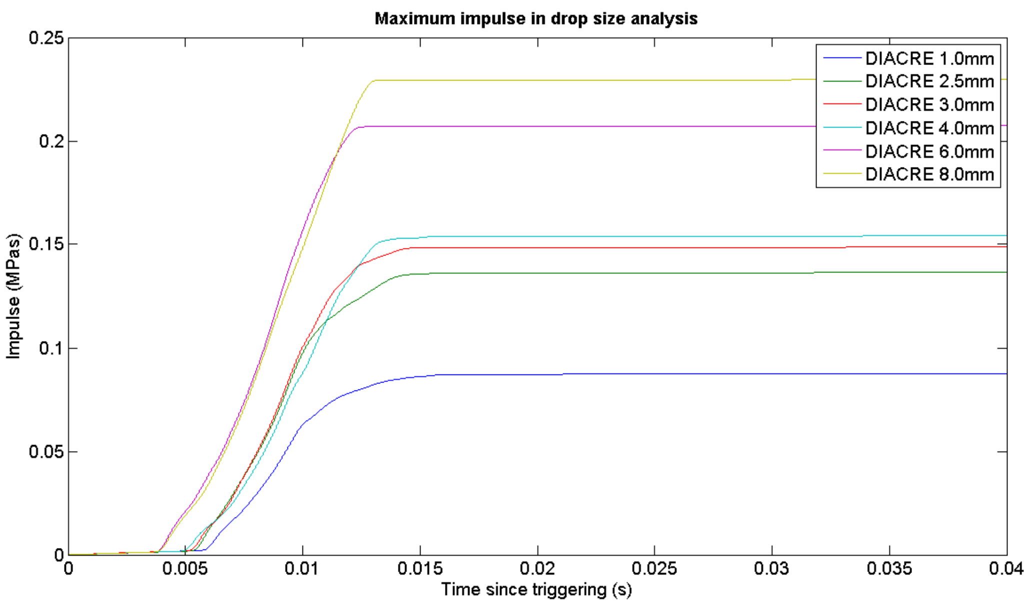



*Figure 37. The maximum impulses from drop size analysis. All impulses were from the lowest cell.*

# 6. Discussion

As seen from the results the dynamic pressure loads on the cavity wall show quite a large variation, around 175 per cent between the minimum and the maximum value in all analysed scenarios. However, in all the test scenarios the maximum recorded impulse had relatively similar values. Also it should be noticed that the received impulses were very similar all over the wall in all cases. So, even though the exact strength of an steam explosion is difficult to predict, it seems to be possible to estimate a case which yields an explosion with maximum strength.

The different side breaks scenarios, even though triggering was unsuccessful, still gives indication on how complex problem steam explosions are and how large the role of mesh geometry has in the simulations.

Based on the sensitivity analysis, the drop size has the largest and mostpredictable impact on both explosion strength and probability. When assuming larger drops, explosion becomes more probable and also stronger.

Another interesting result was that when analysing the melt temperature sensitivity, there was no clear correlation between higher melt temperatures and stronger explosions. This was explained by the fact that the melt in all cases was overheated and that the time span is so short that no solidification takes place. Also, the difference in temperature, thereby the difference in thermal energy between the highest and lowest case, is only about seven per cent. However, it should be noted that the melt temperature does still have a huge significant impact on the outcome as melt temperatures lower than the standard case did not result in steam explosions.

Based on the water level analysis it seems clear that a larger water volume is able to generate a stronger explosion, as there is a larger region with drops in coolant compared to the lower water level cases. The coolant temperature analysis did not offer clear results but it seems likely that a higher subcooling level could cause stronger explosions.

Looking at all the different parameters in the sensitivity analysis it should be possible to construct a case that is likely to cause the most triggerable premixture which at the same time yields the strongest explosion. Such a case would include: (1) a melt temperature well above the melt liquification temperature, (2) a well filled cavity (12 or more meters of water), (3) a subcooling of the coolant to at least 50K, (4) melt fragmentation into large drops.

As previously discussed, the drop size in a accident scenario is quite uncertain as melt composition varies on a case to case basis. In the method used in the simulations, the fragmentation is constant and the drop size is determined by a user specified parameter. In a realistic case the fragmented drops would vary in size. However, the size distribution would be governed by the properties of the melt, mostly density. This, together with the fact that other melt properties affect for example drop solidification temperature and melt temperature, makes it clear that an accurate prediction of the melt properties is crucial for analysing the steam explosion probability and strength.

The strongest explosion would be a product of the melt having a low density as that leads to larger drops. This low density melt would mean a melt phase more rich in metals that is typically stratified on top of the melt pool in RPV lower plenum. Metal phase liquidus temperature is notably lower than that of the oxide phase. This means that with a central break the first parts of the melt should generally be mainly hot oxidic melt with a high density. Whereas, in the case of a side break, due to metal layer focusing effect, the melt arriving to the containment includes more metals. This means that a low density high temperature melt is quite unrealistic.

As the starting parameters and conditions of the melt are so uncertain, a very wide spectrum of melt properties would have been needed to cover all possible scenarios. Therefore it was deemed justifiable to use the constant fragmentation model and the standard corium melt parameters for the standard case simulations, and then use melt temperature and drop size as parameters for the sensitivity analysis to see the effect of changing melt properties. The loss of accuracy with a constant fragmentation and standard parameters should therefore be small compared to the starting uncertainties, and the standard case should represent a solid approximation for an average scenario.

When considering the ex-vessel steam explosion as part of the severe accident scenario as a whole, it is apparent that the most important question becomes: “How does this affect the containment? ”

First and foremost, the dynamic pressure load on the cavity wall needs to be considered, as it might cause direct damages or weaken the cavity wall. Secondly the steam explosion might fragment some of the debris into very small particles and might also distribute these particles in the whole cavity very differently than a scenario with no explosion would. This in turn affects the coolability of the debris bed and causes more long term effect than the immediate explosion.

As the results presented in this thesis shows, predicting the exact strength and likelihood of a steam explosion in a specific case would be quite impossible. However, from the safety perspective this is not as urgent as being able to estimate a realistic upper limit to the strength of the explosion and identify potential weaknesses of the containment to which a steam explosion could pose problems. The result in this thesis is in no means enough to set this limit but it is at least a good starting point.

# 7. Summary and outlook

Steam explosions are an important factor to take into account in nuclear safety and the research has come quite far since it started. The continuous development of both simulation codes and fundamental knowledge about the phenomenon via experimental research, has been profitable as some important milestones have been reached. Most important of these is probably the conclusion that an $\alpha$-mode failure is not a feasible outcome of an in-vessel explosion.

However, there are still open questions and inconclusive data. For example, as discussed in chapter 2, the drop fragmentation process is still not thoroughly comprehended.

The MC3D code is also under constant development, and the code handles 2D situations quite well as the simulations done as part of this thesis states, whereas the 3D cases seem to be a bit less mature.

The results in this thesis have to be analysed with these two aspects in mind as well as with the uncertainties involved in a realistic ex-vessel steam explosion scenario, of which melt jet composition is probably the one of largest impact. This of course makes the phenomenon difficult to simulate and therefore the simulation results presented in this thesis might not always provide such a clear answer as one would like.

However, from a safety perspective it might not be that important to be able to exactly determine the strength of every possible steam explosion case. More important would be to determine an upper limit for the explosion strength, and also which measures could most effectively be utilised to minimize the likelihood of a steam explosion to occur.

The work done as part of this thesis shows that the most important factor with regards to a steam explosion probability and strength is the drop size of the fragmented drops during the premixing stage. This fragmentation process is directly affected by the melt properties, and thus it is clear that being accurately able to determine the physical and chemical properties of the melt as it ejects from the RPV is of utmost importance for determining steam explosion probability and strength.

Future research of the steam explosion phenomena could concentrate on the continued development of the codes, and the physical understanding of the phenomenon. One new interesting approach could be to utilize the new advances in machine learning to construct new ways to handle the drop and jet fragmentation. The problem here is of course that machine learning usually requires a large data set to produce good results. The different processes and phenomena behind the triggering event could also be a good candidate for future research, as the current understanding is quite limited. The steam explosion phenomenon is also strongly connected to the other parts of severe accident research and advances made for example in the field of melt pool formation and RPV failure would help reduce the uncertainties in the starting parameters. Luckily, these are active fields of research and the knowledge of the related phenomena is continuously extended.

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## Bibliographic Data Sheet **NKS-375**

| | |
|---|---|
| Title | Ex-Vessel Steam Explosion Analysis with MC3D |
| Author(s) | Magnus Strandberg |
| Affiliation(s) | VTT Technical Research Centre of Finland Ltd |
| ISBN | 978-87-7893-460-4 |
| Date | October 2016 |
| Project | NKS-R / DECOSE |
| No. of pages | 46 |
| No. of tables | 5 |
| No. of illustrations | 37 |
| No. of references | 27 |

Abstract
max. 2000 characters

A steam explosion is a fast fuel-coolant interaction that might occur if an accident scenario proceeds to late-phase including core degradation and melt relocation. It is of importance in safety research of severe accidents as it could possibly cause loss of safety barriers preventing the release of fission products. The focus is on the type of steam explosion known as ex-vessel steam explosion which can occur if the reactor pressure vessel breaks and molten core material is released into the containment vessel.

A literature review of the steam explosion phenomenon is provided, followed by a description of the MC3D code, used in this report to assess the steam explosion loads in the Nordic BWR geometry and examine the sensitivity of the results for some key input parameters. The effect of an ex-vessel steam explosion is analysed via computational models. The main focus of the analysis is on the dynamic loads on the cavity wall imposed by the explosion.

Simulations were made to analyse the effect of different triggering times on a standard case with central break location. The results showed that as long as the mixture is triggerable the resulting explosion is fairly similar. Different side breaks scenarios were also tested but here the mixture did not trigger.

The sensitivity analysis was done for melt temperature, coolant subcooling, cavity water level and melt drop size. The results show that the parameter with the strongest effect is the drop size, which is largely tied to the physical properties of the melt.

Key words Steam Explosions, MC3D, Fuel Coolant Interactions, Severe Accidents

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