Development and parameter study of the containment analysis program EBBE

Master of Science Thesis

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Göteborg, Sweden 2014

Master's Thesis
CTH-NT-287 ISSN:1653-4662

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Abstract

To be able to study the temperature in the wetwell for different types of pipe ruptures in order to be able to draw power limitation diagrams to determine the highest allowed thermal power during operation with non-zero power, a new model of the containment simulation program Ebbe has been developed. Ebbe is a containment simulation program focusing on simulating the temperature in the liquid part of the wetwell. Ebbe has then been compared to other simulation program results such as the old Ebbe code from 1989, and other containment simulating programs to verify that the results are reasonable. This has been done as a master thesis for OKG, to improve the code used in Ebbe that could only before handle guillotine breaks, because guillotine breaks was seen as the worst case scenario. To enable Ebbe to also simulate minor ruptures Ebbe has been rewritten from its very core, where the most important new implementations are a reactor vessel with pressure calculations. The new version of Ebbe has also switch programming language from Fortran 77 used in old Ebbe to Matlab to simplify future maintenance of the code. The old Ebbe code has also been revised in order to locate approximations and assumptions, those approximations and assumptions have been studied if possible by study the end results when the approximation or assumption is removed. The objective for the master thesis was to show that the new Ebbe had results in proximity to other containment simulating programs including old Ebbe, and also had acceptable behaviours of certain parameters such as the pressure. Future development of the new Ebbe code is required to include logic from more cases and also the different plants.

Contents

Nomenclature

ANS American Nuclear Society

ATWS Anticipated transient without scram

*B*1 The upper part of the codensation pool

*B*2 The in-between B1 and B3 part of the condensation pool

*B*3 The lower part of the condensation pool

BWR Boiling water reactors, usually a light water reactor

CRF Code of Federal Regulations

DBA Design basis accident

EBBE Containment analysis program. Abbreviation of EffektBegransningsBErakningar

LW Light water

*MB*1 The mass contained in B1

*MB*2 The mass contained in B2

*MB*3 The mass contained in B3

MNDW The mass contained in the lower drywell

MR The mass of water reactor vessel

MRS The mass of steam in the reactor vessel

NDW Lower drywell

NRC Nuclear Regulatory Commission

OKG Oskarshamns KraftGrupp AB

PS Pressure suppression

R The water part of the reactor vessel

RHR Condensation pool cooling system. Abbreviation of Residual Heat Removal

RS The steam part of the reactor vessel

$SCRAM$ Is an shutdown of a nuclear reactor

$SHELL$ The shell of the reactor vessel

$THAV$ Temperature of the sea

TR The temperature of volume R

TRS The temperature of volume RS

Chapter 1

Introduction

The containment simulation program Ebbe is used at Oskarshamn power plant to produce power limitation diagrams to determine the highest allowed thermal power during operation with non-zero power. The reason for the limitation in thermal power is to avoid a too high temperature in the codensation pool resulting in harming components, maintain pump suction and be able to maintain enough condensation. The maximum allowed power in regards of the power limitation diagram made from containment analysis depends on the starting temperature in the codensation pool, the temperature of the sea, and the cooling capacity of cooling systems. It is from these three parameters power limitation diagrams are drawn.
By introducing a new model for the containment where also the reactor vessel is simulated and systems depending on the water levels inside the reactor vessel, reactor vessel pressure and time, a more realistic behaviour of the program have been developed that can take into account rupture cases that the old version of Ebbe could not. It is important to notice that Ebbe does not analysis transients of reactivity or the core in general but is a program simulating the end temperature in the wetwell so that the pump capacity is maintained, and therefore the core temperature is not considered of interest for the analysis even though it is calculated. The old Ebbe have been reviewed to look at the different approximations and assumptions effect on the end result of the maximum temperature in the wetwell.

1.1 Nuclear power

During different scenarios to uphold the requirements set for a safe and effective operation. To be able to predict those behaviours simulation program such as Ebbe has been designed to handle specific part of the nuclear power plant during specific cases, Ebbe is specialized in containment analysis during ruptures for the wetwell and its main purpose is to determine the temperature in the condensation pool. Ebbes power limitation diagrams are used to operate a BWR nuclear power plant at OKG. The LW-reactor is the most common commercial reactor type and is cooled and moderated by light water and uses enriched uranium as fuel. Since the introduction of nuclear power plants the necessity to predict the behaviours of those plants during operation and initial events to avoid unwanted sequences.
As a carbon-free alternative to many energy sources today nuclear power a green alternative in respect to global warming, because of the small amount of uranium needed to produce

the energy it is also a long-term solution. Nuclear and hydropower accounts for a majority of power produced in Sweden today.

1.2 Thesis Background

The design of the code for Ebbe and the study of the old Ebbe code is a master thesis from Viktor Lindqvist at OKG with the aim to be able to simulate pipe ruptures ranging from small breaks up to guillotine breaks and to find the approximations and assumptions in the old Ebbe code. Before Ebbe was developed other containment analysis programs was used for its purpose. The reason why Ebbe was developed was because an older containment analysis program used did not calculate the decay heat accurately enough. The other containment analysis program decay heat was calculated lower than in reality, meaning that the simulations from that program were not conservative enough.
The design of Ebbe made the simulation of small ruptures very difficult if possible. And since minor ruptures are of interest and the design of Ebbe was not made for those, a reconstruction of the code was necessary to make it more flexible, user-friendly and have a more generalized code to be able to handle all the different cases and ruptures. Also the translation of the old Ebbe code from Fortran 77 to Matlab and the review of approximations, assumptions and parameters, resulted in deeper understanding of the design of Ebbe.

1.3 Purpose

The purpose with the master thesis was to construct a new Ebbe code that would give results in the same proximity as the past codes used and also be able to:

- Handle more design basis accident, DBA, example breaks/ruptures of different size at different places during different scenarios and times,
- Easier to maintain and use, for example by switching from Fortran 77 to Matlab
- Have the flexibility to be able to be developed for future needs
- The physics and system logic simulation should be closer to reality than before

Another goal of the master thesis was to review the old Ebbe and find room for improvement. For me personally the purpose of the master thesis was to obtain greater insight in how a safety analysis at a nuclear power plant works in reality, the satisfaction to contribute to society in a way that will hopefully be used.

1.4 Scope

The new Ebbe is a containment analysis code for temperature calculations of the wetwell, and by so has not as it purposes to fully simulate the sequence at a microscopic level or transients such as ATWS. Ebbe is built up by blocks containing properties such as mass, enthalpy, pressure and temperature. That can be transported between the blocks. The new Ebbe can simulate times during the sequence with time steps of fractions of seconds but a simulated event continues usually up to 12 hours. With the desire to have simulation that takes less then one day in real life, led to simplifications in heat exchange between the reactor fuel/shell/coolant. Other reasons for other simplifications were also due to constraints of the master thesis time length. Simplifications concerned mainly the viscosity and the logic for the various facilities and initial events.

1.5 Confidential data

Because of the commercial and safety related nature of the master thesis some data is confidential such as:

- New and old version of Ebbe source code
- Input data
- Scales of some graphs
- The programs and codes used to compare the results
- Some of the references

1.6 Containment of the reactor

Ebbe is a containment analysis program for Oskarshamns nuclear power plats after a SCRAM. The reactor vessel is situated in the upper part of the drywell. The wetwell, containing the condensation pool and a volume of gas, is situated below the drywell. An example of a typical containment can be seen in figure 1.1 [1]. Also shown in the figure is a guillotine break of a steam pipe. As can be seen in the figure the steam is transported down to the wetwell into the condensation pool to be transmuted to water. This happens according to the pressure suppression principle, PS, to keep the pressure at low levels inside the containment. This is also necessary in order to handle the decay heat since the cooling systems, RHR, are heat exchanging between the condensation pool and the sea.

1.7 Wetwell

The wetwell contains in reality of a volume of steam and other gases and a volume of water, the liquid part will be referred to as the condensation pool containing only water in the simulation. The condensation pool is simulated by two blocks that interacts with each other and one block that is passive, this distribution of the condensation pool is a result of indications from other plants that the condensation pool can be layered in different temperatures. But the modified old Ebbe and new Ebbe is also able to simulate a homogeneous condensation pool. To preserve conservatism the third block that are below sieves, sieves that takes in water to the pumps for core cooling system and the RHR of the condensation pool, is set to passive. The natural flow of water between the different blocks of the condensation pool is set to a constant and the forced flow comes from the cooling system pumps are redirected to mix the water in the condensation pool instead of cooling.
The condensation pool temperature is also used as the main result of the simulation and

Ebbes purpose is to simulate the temperature in the condensation pool inorder to keep it below certain limits. The temperature in the condensation pool has to be low enough in order to:

- be able to maintain enough condensation
- not harm the components of the wetwell
- maintain the suction of the pumps.

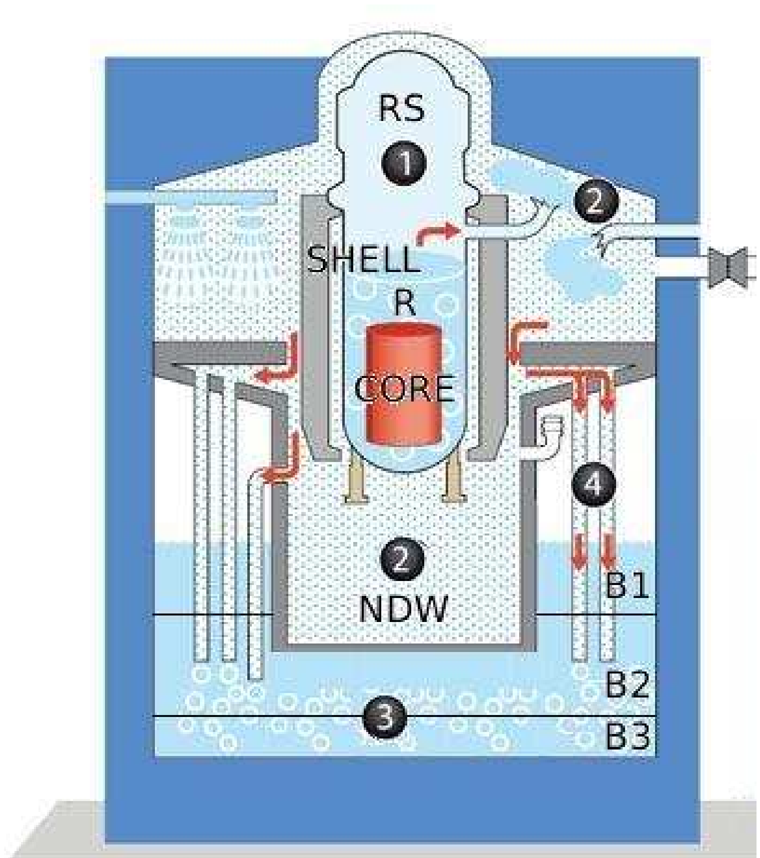

Figure 1.1: *The figure shows the reactor containment, where 1 is the reactor vessel with core, 2 is the drywell showing a guillotine break, 3 is the condensation pool is and 4 is where steam is transported by vent tubes down to the condensation pool.*[1]

1.8 Core cooling system and RHR

Core cooling system is built up by two systems, one high pressure and one low pressure system, the high pressure system works during higher pressure but has lower flow capacity than the low pressure system. These systems to cool the reactor vessel are turned on if possible after a break/rupture occurs and takes coolant from the condensation pool.

The other cooling system, RHR, takes it water from the condensation pool and cools it down by heat exchangers that exchange heat with seawater, before returning either to the condensation pool or to the drywell, both is sprinkled down. These two different cooling systems will be referred to as core cooling system that goes from the condensation pool to the core and RHR that goes from the condensation pool to the sea.

1.9 Method

The methodology is the same for new and old version Ebbe and is constructed upon blocks with properties such as mass, enthalpy, temperature and also pressure in new version Ebbe. These blocks are mainly interacting with each other by flow of mass and enthalpy. Other properties such as pressure require knowledge about more than one blocks volumes and the block volume can be dynamic. This because some blocks are made of entirely of water and others of steams that interact with each other and exist in the same volume limit. A good example of this is the reactor vessel that contains a water volume, R, and a steam volume, RS, these together with the knowledge about the volume limit for the reactor vessel makes it possible to obtain the pressure inside the reactor vessel.
Maximum temperature is taken from the condensation pool after simulation sequence is done and is compared to the results from the old version Ebbe (Fortran 77 code) and other containment analysis programs. This is done to verify the code used in new version Ebbe, and if the code is suitable for future development.

Also in consideration of the behaviour of some parameters during the sequence, such as pressure or the overshoot of temperature in the condensation pool after the drywell is overflowing depending on how many pumps have been redirected to sprinkle the drywell after a rupture/break. The sprinkling of the drywell is made possible by redirecting the cooling systems loop from the condensation pool to condensation pool to go from condensation pool to drywell and can be used after an event such as a rupture.This can result in a smaller overshoot in temperature of the condensation pool after the drywell is filled up and can affect the condensation pool end temperature.
For further, information on the method of Ebbe see [3].

1.10 Chapter dispotions

A short dispotions list of what can be expected in the different chapter sections:

Second Chapter

A short theory of the old version of Ebbe and new version of Ebbe. Both sections are required to be read to understand the new version of Ebbe theory, and contains:

- Theory of the old version of Ebbes code and some new utilities of the version of Ebbes code utilities in the common areas.
- New version of Ebbes theory regarding new components and changes from the old version of Ebbes theory.

Third Chapter

Describtion of an event in old version of Ebbe and investigation of some approximations and equations. The sections contains investigation and explaination of the approximations and equations investigated.

Fourth Chapter
Investigation of behaviour of an event in new version of Ebbe and a comparison with chapter three and validation of the investigated event. The sections contains:

- The comparison of the event of regarding the temperature in the codensation pool between new and old version of Ebbe in behaviour.
- Valdiation of the code and subsections regarding some behaviours in the new version Ebbe.

Fifth Chapter
Sums up the chapters and talks about the results and future work. The section contains:

- Thoughts about the validation process
- Some generall explaination of what Ebbe is and its limitation
- A brief sum up about the Ebbe results in general terms.
- Future improvements of Ebbe that can be done in a near future.

Chapter 2

Theory

The theory is roughly the same behind the calculations of old and new version of Ebbe beside the fact that new version of Ebbe has added some theory for the simulation of the reactor vessel and ruptures that are not guillotine breaks. Therefor the theory is divided into two chapters where the theory of old version of Ebbe is used in new version of Ebbe if nothing else is stated. Also new features and extended options are refeered to in old version of Ebbe theory that concerns new version of Ebbe.

2.1 Theory of old version of Ebbe

In the old version of Ebbe theory there is decay heat, vaporization, mass/enthalpy transfer and guillotine break approximation.

2.2 Decay heat

The decay heat from the core is simulated from equations from ANS, American Nuclear Society, 71 with an additional 20% on the thermal effect from the nuclear power plant and is implemented by adding two sigma on the decay heat (two sigma corresponds to a multiplication on the decay heat of 1.07) to maintain the conservatism in the decay heat calculations. The option exists in the new Ebbe user interface to add an additional thermal effect above the already added effect. Those additions on the thermal effect and decay heat are applied during the entire simulation sequence and not only during the first thousand seconds of simulation as the NRC, Nuclear Regulatory Commission, prescribes in 10 CRF, Code of Federal Regulations, 50. NRC 10 CRF 50 prescribes 20% raise the first thousand seconds and then a 10% raise of the thermal effect. The decay heat is calculated accordingly to ANS 71, equation 2.2.1, and approximates the decay heat to only depend on two nuclei U-239 and Np-239. The precalculations needs shutdown times, reactor effect history, and cross section for a fission event, these precalculations calculates the conversation factor K, K represents the number of U-239 atoms produced per fission events with regards to the reactor composition at the time for the shutdown, and is needed to be able to calculate equation 2.2.1 [2]. Those precalculations will not be shown. Note lambda is decay constants for U-239 and Np-239 and that $E_{U_{239}}$ and $E_{Np_{239}}$ are the average recoverable energy from decay of U-239 and Np-239 seen in equation 2.2.1.

$$\begin{aligned} F_{U_{239}}(t,T) &= E_{U_{239}}K(1-e^{-\lambda_1 T})e^{-\lambda_1 t} \\ F_{Np_{239}}(t,T) &= E_{Np_{239}}K(\frac{\lambda_1}{\lambda_1-\lambda_2}(1-e^{-\lambda_2 T})e^{-\lambda_2 t}-(\frac{\lambda_2}{\lambda_1-\lambda_2}(1-e^{-\lambda_1 T})e^{-\lambda_1 T}) \end{aligned} \tag{2.2.1}$$

2.3 Vaporization

Vaporization occurs when a excess of energy exist at boiling temperatures for the reactor water under current pressure after the total energy is calculated during one time step. If the there is an excess the surplus of energy will be divided with the phase transition cost under the current pressure subtracted by the feed water enthalpy that are the water that takes the vaporized waters place in the reactor vessel, to obtain the amount of steam produced during one time step. In old Ebbe the equation 2.3.1 is used that shows that phase transition cost which means a pressure of 70 bar and that the temperature is set to boiling temperature during the phase where there occurs boiling. The logic for the release valves down to the condensation pool is so that all produced steam is transported down to the condensation pool before rupture and break after all steam produced are sent down to drywell.

$$\begin{aligned} M_{steam} &= \frac{DecayHeat - CoolingSystem}{PhaseCost - feedwaterenthalpy} \\ E_{steamOut} &= M_{steam}PhaseCost \end{aligned} \tag{2.3.1}$$

2.4 Mass/enthalpy flowcharts

Mass/enthalpy transfer occur in old Ebbe between NDW, B1 and B2 accordingly to figure 2.1 for enthalpy flow and for mass flow. And can be compared to the more complicated case of new Ebbe where the mass is transported between MNDW, MR, MRS, MB1 and MB2 according to figure 2.3 and the enthalpy is transported between NDW, R, RS, CORE, SHELL, B1 and B2 according to figure 2.2.

2.5 What happens inside each specific block in old version Ebbe

A short description on the events that occur in the different blocks during time steps as can be seen in figure 2.1: Note that core cooling systems and other logics in-between the blocks will not be described.

- B1) Temperature calculations after subtracting energy from outflows to B2 and adding energy from R, NDW, B2 after adding mass from MNDW and MR and subtracting mass to MB2.
- B2) Temperature calculations after subtracting energy from outflows to NDW and adding energy from B1. No mass calculation, mass is assumed to be constant.
- NDW) Temperature calculations after subtracting energy from outflows to B1 and adding energy from B2 after adding mass from MB2 and subtracting mass to MB1.

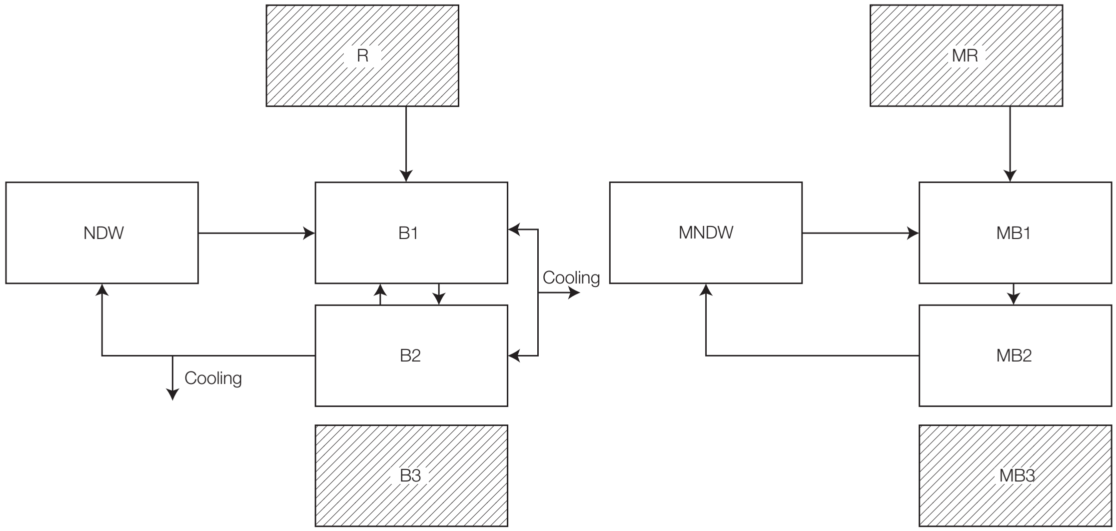

Figure 2.1: *Flowchart for the enthalpy- and mass flow in old Ebbe*

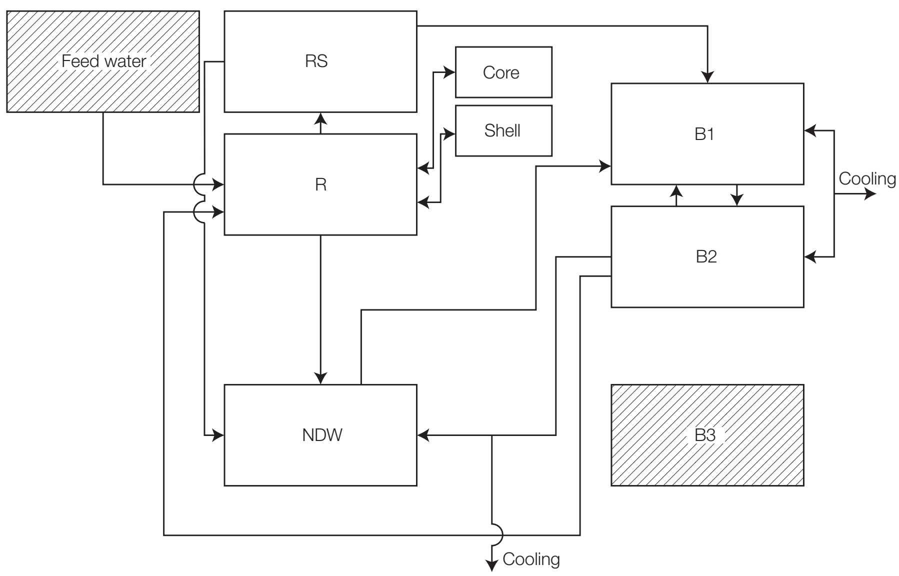

Figure 2.2: *Flowchart for enthalpy flow in new Ebbe*

Please note that R is not a block and I only added MR, and R here so the description would make sense.

2.6 What happens inside each specific block in new version Ebbe

A short description on the events that occur in the different blocks during time steps as can be seen in figure 2.2 and 2.3, and also some pressure calculation.

- B1) Temperature calculations after subtracting energy from outflows to B2 and adding energy from RS or R, NDW, B2 after adding mass from MNDW and MRS or MR and

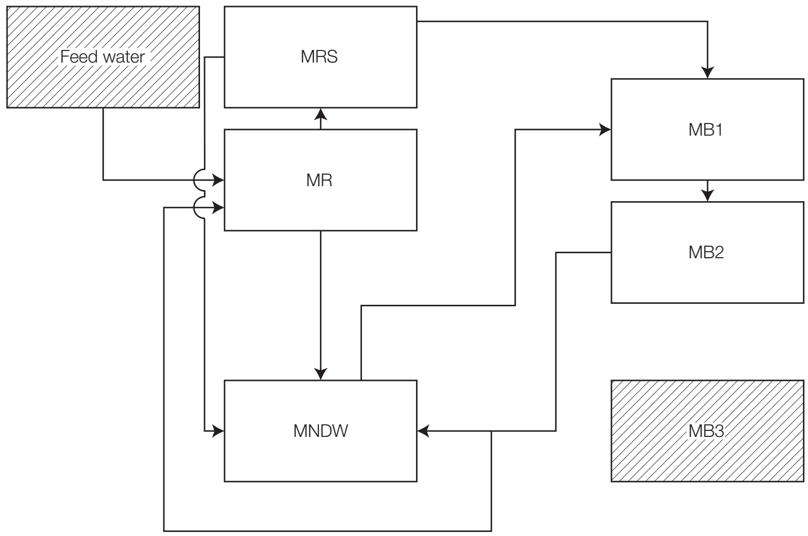

Figure 2.3: *Flowchart for mass flow in new Ebbe*

subtracting mass to MB2.

- B2) Temperature calculations after subtracting energy from outflows to NDW and R and adding energy from B1.
- Pressure in wetwell) There is no pressure calculations done in the wetwell and the pressure is set to 1 Bar.
- NDW)Temperature calculations after subtracting energy from outflows to B1 and adding energy from B2, R and RS after adding mass from MB2, MR and MRS and subtracting mass to MB1.
- Pressure in drywell) There is no pressure calculations done in the drywell and the pressure is set to 1 Bar.
- R) Temperature calculations after subtracting energy to RS, CORE and SHELL and energy added from B1, FEEDWATER, CORE and SHELL after adding mass from MB2 and FEEDWATER and subtracting mass to MNDW and MRS or MB1.
- RS) Temperature calculations for steam and not liquid after adding energy from R and subtracting energy to B1 and NDW after adding mass from MR and subtracting mass to MNDW and MB1.
- Pressure in reactor vessel) There are several pressure calculations every time step to ensure right pressure done at times as before outflows of mass from MRS, after outflows from MRS and flashing in MR.
- Core) Temperature calculations after adding energy from DECAY HEAT and R and subtracting energy to R. No mass calculations.
- shell) Temperature calculations after adding energy from R and subtracting energy to R. No mass calculations.

2.7 Temperature calculations including RHR calculations

Temperature calculations are performed in old version Ebbe with only liquids and only under constant pressure, 1 bar, and even if temperatures occur in the drywell above 100 degrees Celsius, events like that will be simulated by extrapolating data from tables. This is an approximation to be able to keep the energy inside the block and avoid steam temperature calculations. And since the temperature in normal conditions should be below 100 degrees Celsius before the drywell overflows to the condensation pool and that when the temperature in the drywell becomes relevant.
The temperatures in the blocks are used in many ways such as triggering ruptures, the cooling effect from the cooling system and vaporization. The temperature is also the deciding factor if a simulation needs to lower its reactor thermal effect under the current conditions to not get temperatures above the limits in the condensation pool during these conditions. And in the end it is the simulations that do not break those limitations that will make a list providing the power limitation diagrams.
The cooling system heat exchanger, which is placed outside the containment, is an important component to maintain balance between the decay heat and the temperature in the condensation pool, because it is the only effect in the simulated system that actually removes enthalpy from the system as a whole. The cooling system takes water from the condensation pool at the sieves, B2, and with help of a temperature difference between B2 and the seawater, the effect from the cooling system is calculated from equation 2.7.1, where N is the number of cooling system chains, β is the cooling effect from one cooling system chain and T_{const} is the difference the heat exchanger requires to work.

$$CoolingSystem = max(T_{B2} - T_{THAV} - T_{const}, 0)N\beta \tag{2.7.1}$$

2.8 Guillotine break approximation

Guillotine break approximation is used when a very large rupture occurs that would leak so much steam/liquid that the pressure would drop very fast from the initial value to 1 bar and most of the reactor vessels energy contained would also be dumped into the drywell or the condensation pool. According to approximation transfer of energy and mass is done in one time step. This approximation in some extent is used in new version Ebbe when it comes to relief valves for steam is about to open for event such as the reactor vessel is about get filled to the brim. The logic states that the relief valves should first be open if the reactor vessel reaches a certain pressure or is filled to the brim but to avoid pressure spikes those vents are open some seconds before this occurs. Guillotine break approximation between old and new version Ebbe is also different in the sense that old version Ebbe takes away water from the condensation pool to fill up the imaginary reactor vessel meanwhile when new version Ebbe only transport mass/enthalpy from RS to B1, meaning steam from reactor vessel to the condensation pool.

2.9 Theory of new version of Ebbe

The new version Ebbes theory includes as stated above old version Ebbe theory with some changes regarding vaporization due to new blocks added, also rupture flow and valve openings are introduced. To be able to describe vaporization in new Ebbe properly, the core, reactor shell and the reactor blocks, R that contains only water and RS that contains only steam is described.

2.10 Core and reactor shell

The core and the reactor shell are modelled by using the same equations beside the fact that the core has an energy source. This energy source is the decay heat that are added to the cores total energy every time step. Both the core and the reactor shell has an initial temperature and energy that are calculated in fps (full power(reactor) seconds), from the initial temperature to 286 degrees Celsius and from 286 degrees Celsius to 100 degrees Celsius accordingly to tables. These have been extrapolated down to 0 degrees Celsius. Energy transfer depends on the temperature difference between core and coolant or shell and coolant.

2.11 The reactor vessel

In the reactor vessel there are two volumes, volumes R and RS: Reactor vessel volume R that contains only water and starts at normal level. The volume R volume depends on the amount of water inside and its density, the volume is kept from dropping below the normal level by regulation of the feed water as long as there is a water reserve for the feed water. In the event that the reactor vessel is filled up by the core cooling systems the volume R will expand at the expense of RS. Level calculations conducted in R is done by dividing the reactor vessel into 4 parts, as can be seen in figure 2.4:

- First part, V1, is above the normal level.
- Second part, V2, is below normal level down to the core top.
- Third part, V3, is between the core top and the core bottom.
- Fourth part, V4, is below the core bottom.

These four different parts has different volume coefficients to symbolize the different geometric structure inside the reactor vessel that occupies space. Level calculations are used in the logic of such as valves ,pressure calculations, and rupture flow to determine when to open/close valves, how large the pressure is and how large the flow out from the reactor vessel is.

Reactor vessel volume RS contains only steam and it is RS mass and temperature, MRS and TRS, that decides the pressure by the ideal gas law, and since the volume RS is dynamic the volume R is also needed to do these calculations. The pressure difference from the drywell is what determines the amount of steam flow out from a rupture or opening of valves, the amount of liquid flow out from a rupture or valve depends on the initial size of the rupture or valve and some conditions regarding level calculations, both liquid and steam can be going out from the same rupture or valve at the same time step. All steam generated in volume R by vaporization is transferred, both enthalpy and mass, into RS.

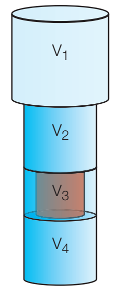

Figure 2.4: *The reactor vessel is divided into four parts with different volume coefficients to enable the level calculations depending on the amount of water inside R. Note that the core exists in region nr 3, and makes that V3 is the smallest volume coefficient.*

2.12 Vaporization

The difference between vaporization in old and new version Ebbe is profound because the decay heat does not directly go into vaporization calculations but goes through the core. The interaction between core/shell/RHR/feeding water/core cooling systems makes the production of steam difficult to overview in the same manner as before. But basically it is the temperature in R, TR that if it exceeds above the boiling temperature under the current pressure will result in vaporization. In order to avoid oscillations in pressure because of the interaction between pressure, boiling temperature and the flashing that occurs when pressure drops the vaporization is controlled by iteration. The result is that the water flashes only enough to make it into a steady state with the water at boiling temperatures at the new pressure.

2.13 Rupture/Valve flow

The flow through rupture and valves are both simulated in the same way, apart from the opening of all relief valves that are approximated with a guillotine break. The pressure difference between the blocks determine the volume velocity of steam of the rupture unless the level calculations result in that water is above the level of the rupture with enough volume this time step to flow out only water. Water flow rate is dependent only on the initial size of the rupture or valve. The flow rate calculation for steam flow will stop when the pressure difference reaches zero. Equation 2.13.1, where Frac is the percentage of liquid or steam covering the vent or rupture, and P is in Bar, Break Flow is a volume. Note that equation for outflow of liquid is divided with a constant to represent the difference in viscosity between water and steam, a small remark is that viscosity simulated more realistically should be barely pressure dependent but temperature dependent.

$$
\begin{aligned}
Frac_{outsteam}\frac{BreakFlow_{ini}\sqrt{P_{reactor}-P_{outsidereactor}}}{\sqrt{P_{reactor_{ini}}-P_{outsidereactor_{ini}}}} &= BreakFlow_{steam} \\
Frac_{outliquid}\frac{BreakFlow_{ini}}{10} &= BreakFlow_{liquid} \qquad (2.13.1)
\end{aligned}
$$

Chapter 3

Old version of Ebbe

The simulation in old version Ebbe, Fortran 77, can be divided into four phases:

- The first phase is the preheating of the condensation pool until rupture occurs, triggering event of a rupture is when the temperature in the condensation pool is stabilized below the given temperature.
- The second phase happens instantaneously by a guillotine break approximation that transfer most part of the energy contained in the reactor vessel down into the condensation pool and drywell. Also enough water is taken from the condensation pool to fill up the reactor vessel.
- The third phase is when the drywell is starting to get filled up and meanwhile the temperature in the condensation pool will drop, because of RHR, this phase last until the drywell is filled.
- The fourth phase begins when the drywell is filled to the brim and overflows over to the condensation pool. This leads to an overshoot in temperature in the condensation pool, it is when this overshoot is declining that the highest value of the temperature is set in the Fortran 77 Ebbe code.

Unfortunately there is no graphic interface from the Fortran 77 code beside output written in list form but since the code have been transferred into Matlab, there is virtually no difference between the simulations in the Matlab code and Fortran 77 code, the graphic representation of the above mention phases can be seen from the Matlab simulations in figure 3.2.

3.1 Purpose of looking at the old version Ebbes approximations

The purpose of looking at the approximations of the old version of Ebbes was to obtain an easy comparison tool towards the development of new Ebbe and also to get an overview over the old version code. It was also an insurance that in case new version Ebbe would not meet the criterias,that improvements to the containment analysis tools had been done. Making it easier to developed and work with in the future. As an example the graphic option alone gives a better overview and understanding of the simulation than only list form.

3.2 Investigation of approximations

Within the limits of what old Ebbe can do investigation of the approximation has been focused around three equations/approximations because these three was more or less influential on the end temperature in the condensation pool.

- Decay heat calculations, which are set as averages of an time intervall with a fixed length .
- Investigate why there is no shifting in time when the guillotine break approximation occurs since the reactor vessel is filled up and this should take some time to do, this shift in time will have some impact on decay heat calculations.
- Introducing a natural flow by adding a constant to the transfer of masses/enthalpy inbetween the blocks inside the condensation pool, B1 and B2, for the entire simulation.

The difference between calculating the decay heat every time step and by having an average over a time intervall with a constant of time in between can be seen in figure 3.1. The impact of calculating the decay heat every time step compared to an averaged decay heat in a time interval of 180 seconds was that the maximum temperature in the condensation pool was 0.39 degrees Celsius lower.

The introduction of a time shift was made because the time that it takes to the fill up the reactor vessel after a rupture/break is not taken into consideration in the old version of Ebbe. This time shift is set to 30 min because of how the variables in the old version Ebbe code was described and used. This time shift will take place at the second phase where the guillotine break approximation occur and had an impact on the simulation tested with 0.71 degrees Celsius smaller in the condensation pool. A comparison of the impact of time shift and calculating a new decay heat every time step showed that the dominating effect was the time shift when both were implemented in the same code. However these effects are not additative.

The introduction of a natural flow by a constant had been done before but implemented in such a way in the code that it only affected the code in the first phase and not beyond the second phase. Here the natural flow is implemented to affect all phases. The comparison of having a natural flow constant or not can be seen in figure 3.2 and the effect on the end result during simulations conducted was at a most 2.45 degrees Celsius lower than the case with no natural flow constant. Not using a natural flow implies a more conservative case but probably more unrealistic.

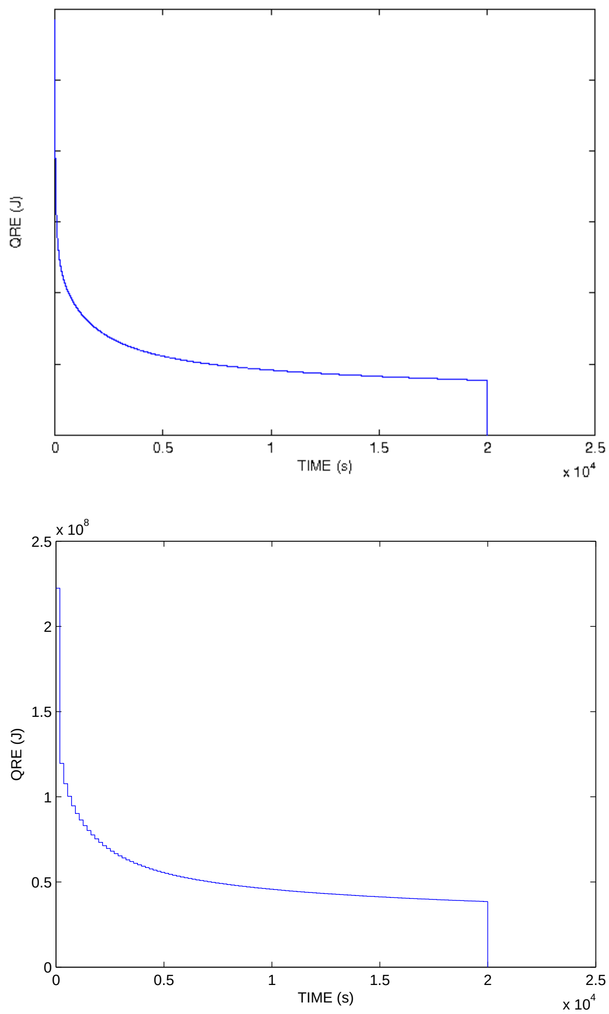

Figure 3.1: *Comparison between calculating the decay heat at every time step or taking an average decay heat in a time interval of 180 seconds can be seen in the figure above. The averaged decay heat generates a larger area meaning more thermal energy over time, than the decay heat curve with a decay heat calculated every time step.*

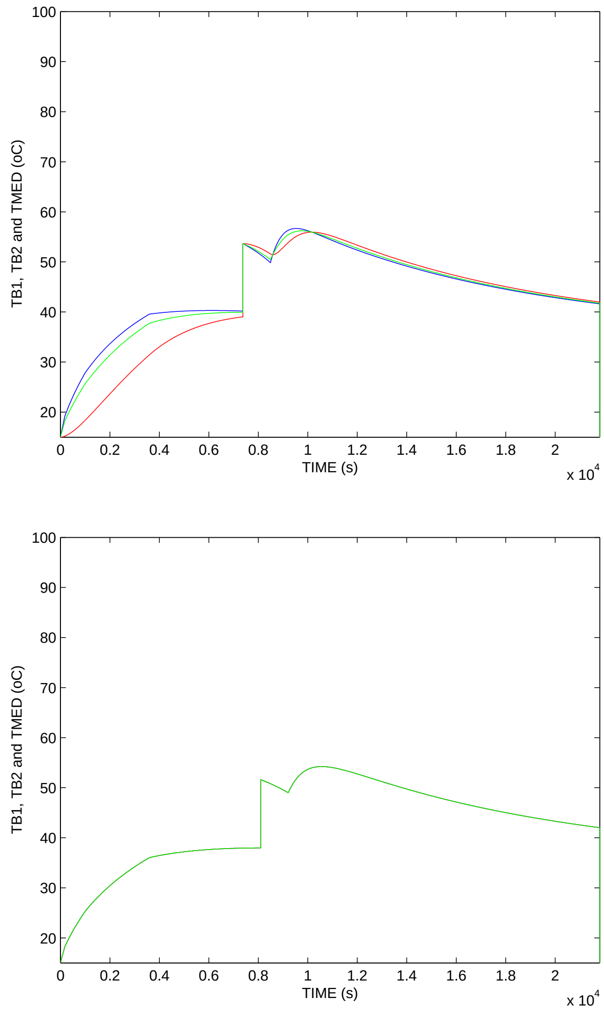

Figure 3.2: *Comparing the effect on the end result of having a very high natural flow constant or not having a natural flow constant at all. Blue is B1, Red is B2 and green is the average of B1 and B2.*

Chapter 4

New version of Ebbe

Within the frames of the master thesis a new code for Ebbe has been developed, with the important property to be able to simulate minor and major ruptures with results within the boundaries of other containment analysis programs such as old Ebbe. The simulation made in new Ebbe can be divided into six phases, see figure 4.1. These six phases can contain minor phases and events:

- The first phase is the preheating of the condensation pool until the temperature reaches a given temperature. This is done because it is a worse scenario for the simulation if the break occurs earlier because of the decay heat as well as how the RHR works for the condensation pool.
- In the second phase a top rupture occurs and relief valves are closed, and thus very little energy is transferred down to the condensation pool, and mainly goes by the rupture to the drywell.
- In the third phase the water valves has opened and let steam/liquid go down to the condensation pool once again from the reactor vessel, these openings is reactor level dependent.
- In the fourth phase the guillotine break approximation for new Ebbe is used to dump the remaining steam in the reactor vessel down into the condensation pool from the steam valves, still all water leaking out from the reactor vessel goes to the drywell.
- In the fifth phase the drywell is getting filled up.
- In the sixth phase the drywell is filled to the brim and flows over to the drywell will make the temperature rise in the condensation pool until balance between reactor vessel water/ dry well water / condensation pool water temperatures are set and is mainly a balance between the cooling system in the condensation pool and the decay heat in the core.

4.1 Differences between old and new version Ebbe regarding simulation events

The main difference between old version Ebbe and new version Ebbe regarding simulation events are after the rupture, but there is also some minor differences before rupture. For ex-

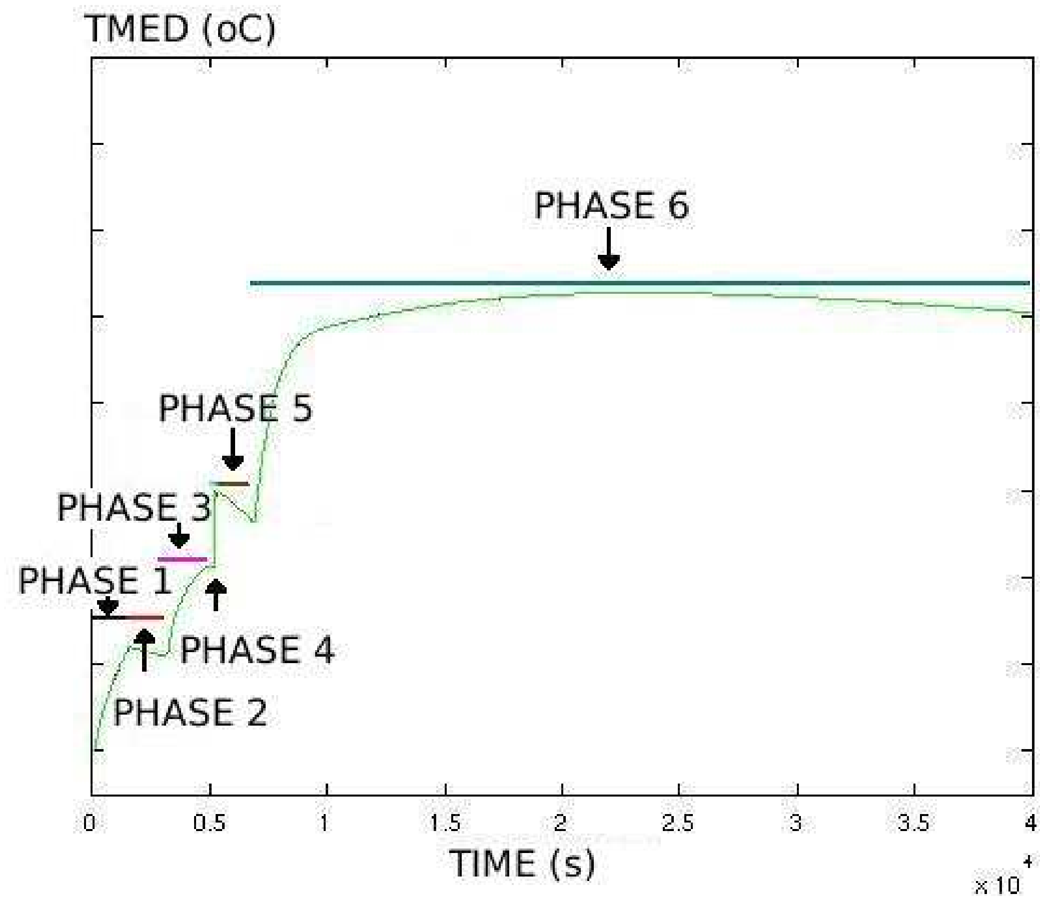

Figure 4.1: *The different phases of a simulation with a top rupture in new Ebbe. Phase 1 before rupture, phase 2 after rupture no valves opened, phase 3 some valves opens, phase 4 all valves opened, phase 5 is when the drywell is about to get filled and phase 6 when the drywell is filled.*

ample old version of Ebbe waits until the temperature is stabilized in the condensation pool before rupture occurs. New version of Ebbe trigger a rupture event if the temperature in the condensation pool reaches a specific temperature. After the rupture old version Ebbe goes straight to phase 4. In the old version of Ebbe, phases 2 and 4 are the same, and phase 3 does not exist. With the possibility to simulate the reactor vessel in the new version of Ebbe the phases between rupture and drywell filling up are no longer coarsely approximated, and it enables the simulation of a wider variety of events, for example minor ruptures. Depending on the amount of energy transported from the drywell and reactor vessel, the temperature in the condensation pool can overshoot. Whereas this overshoot in temperature usually happens in the old version of Ebbe, due to the energy being added to the condensation pool is constant and without time dependence (it is approximated to occur during one time step), this seldom occurs in the new version of Ebbe meanwhile in the old version of Ebbe the overshoot in temperature in the condensation pool usually happens because the energy added in the case of a break is constant and have no time dependence.

4.2 Validation of the new version Ebbe code

To be able to see if the code developed was realistic and behaved in a manner that was satisfying, graphs of about 25 parameters, from the around 100 that existed, was used and observed during simulations. Graphs comparable to other analysis tool programs were compared, and noncomparable parameters were studied for expected behaviour. Some of the more interesting parameters are the newly implemented parameters such as pressure, reactor vessel water temperature during the simulation, but also mass preservation in the system as whole and the drywell filling up process during different events. The mass preservation graph should be and was a straight line if all system were included (the feed water reserve and such) and was just another trial for the code if it actually worked or leaked mass somewhere.

4.3 Simulation of the reactor vessel pressure

New version Ebbe simulates the pressure during the sequence for the reactor vessel which can be seen in figure 4.2, where different events and analysis conditions affect the behaviour differently such as how many core cooling systems are used or how many valves are opened and ruptures sizes. Here can also be noted that things that make the sequence from initial pressure to 1 bar, when the reactor vessel is filled, is mainly the core cooling system for low pressure since the capacity is quite large, ruptures if they are considerably large, or the opening of valves. The behaviour of the pressure can be seen in figure 4.2 looks realistic and was expected and can be divided into 5 phases. Phase 1 is when the pressure are at initial value before rupture with stabilization around 70 bars from relief valves opening and closing. Phase 2 is when rupture has occurred and core cooling system for high pressure is activated. Phase 3 is when core cooling system for low pressure is turned on. Phase 4 is when all steam valves open, which is equivalent to a guillotine approximation. Phase 5 is when the reactor vessel is filled.

4.4 Simulation of the reactor vessel water temperature

The simulation of the reactor vessel water temperature can be seen in figure 4.3, where it can be clearly seen that the temperature is lowered when the pressure inside the reactor vessel drops and when the drywell is filled up gets a overshoot that stabilizes after a while when the decay heat and cooling system at the condensation pool are in balance, also the behaviour of this graph is as expected.

4.5 Simulation of the filling of the drywell

The impact of when the drywell is filled and overflows to the condensation pool on the temperature in the condensation pool is substantial, and is affected by how many core cooling systems there are and how large the rupture is, and can be observed with two different cases:

- Low rupture flow and few core cooling systems
- Large rupture and many core cooling systems

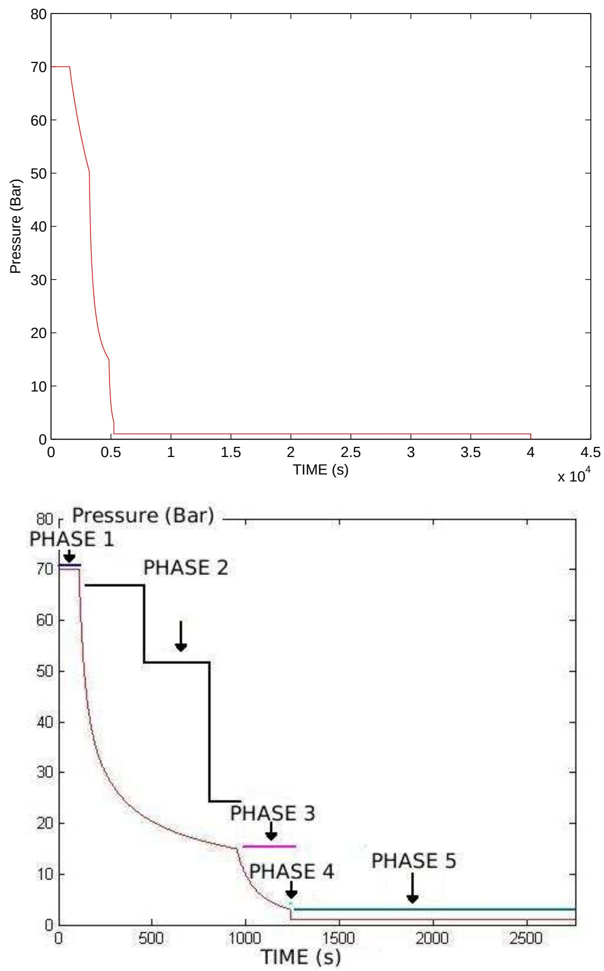

Figure 4.2: *These two figures shows the pressure behaviour during different simulations, the lower graph shows a simulation with many core cooling systems and a large rupture and the upper graph shows a simulation with few core cooling systems and a minor rupture. Phase 1 shows the pressure at 70 bars before rupture with stabilization around 70 bars from steam valves opening and closing. Phase 2 is when rupture has occurred and core cooling systems for high pressure is working. Phase 3 is when core cooling systems for low pressure is turned on. Phase 4 is when the guillotine approximation meaning opening of all relief valves. Phase 5 is when the reactor vessel is filled.*

see figure 4.4 for simulations with top ruptures with the two cases mentioned above. Note that the hump at first in the figure depends on the rupture flow when liquid not yet have reached the rupture level, therefore there is steam in the drywell during that phase.

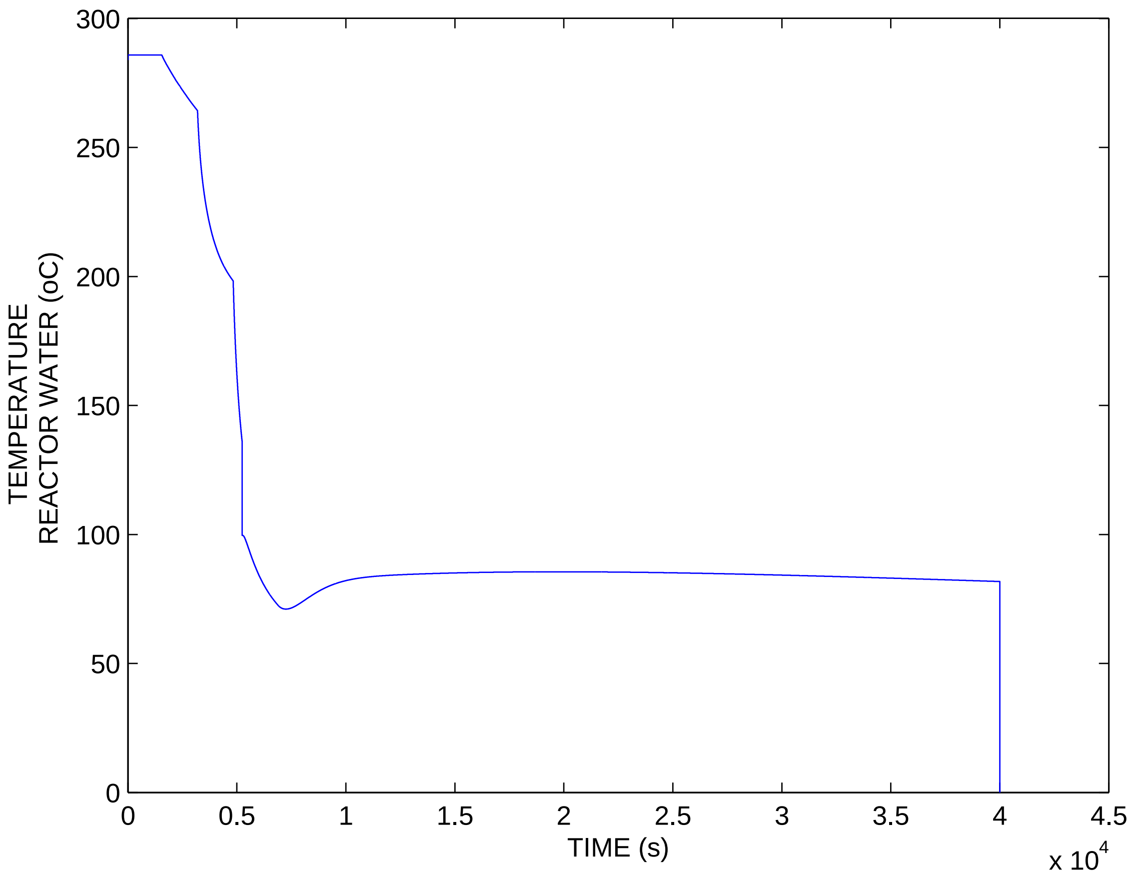

Figure 4.3: *The temperature behaviour of the reactor vessel water, in volume R parameter TR, that follows at start the boiling temperature for the pressure but then continues below it until it stabilizes with the drywell and the condensation pool. This graph data is related to the upper picture in figure 4.2*

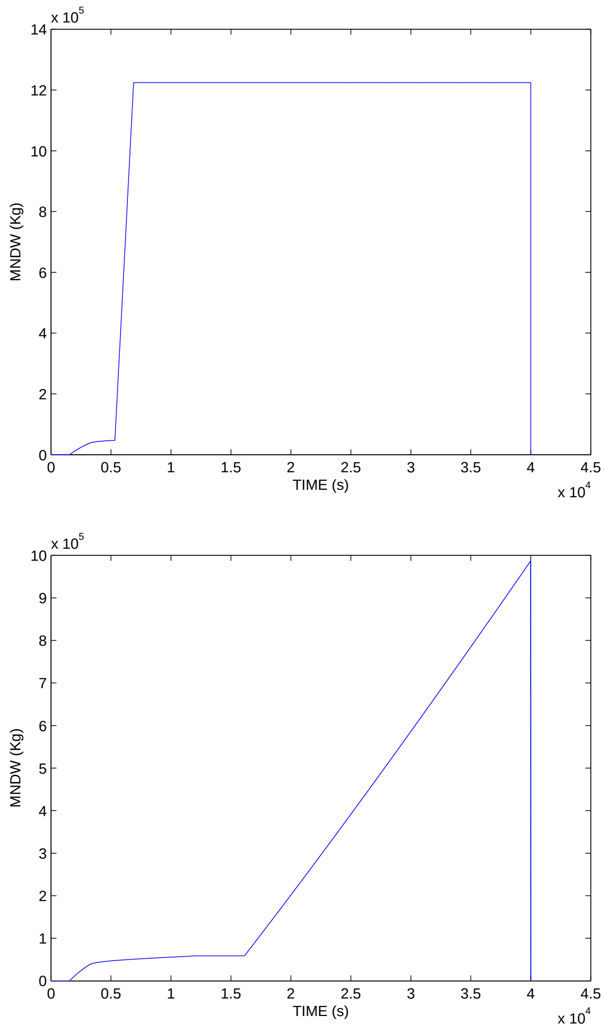

Figure 4.4: *Here are two figures comparing the filling behaviour of the drywell during different conditions. Such as low rupture flow with few core cooling systems, the lower graph, versus large rupture flow and many core cooling systems, the upper graph. Both are top ruptures and the first hump in the graph are when steam are flowing down to the drywell before water have reached the rupture.*

Chapter 5

Discussion and conclusions

A new code has been developed parallell with the review and update of the old code. The reason for the development of new version Ebbe was to enable future implementations of cases, events and sequences which was not easily implemented in the old fortran version. This was done by implementing new blocks like the reactor vessel and by comparing the results simulated with old Ebbe and other containment simulation programs. The results was compared with the other containment simulating programs by looking at the result of the end temperature in the condensation pool and if it was in a reasonable proximity of the other programs results. The test where conducted by simulating a variety of scenarios of top rupture with different sizes and compared those simulations to similar cases from old Ebbe and other containment simulating programs. There was also some parameter studies regarding the behaviour of pressure inside the reactor vessel from volume changes of RS and R and also the rupture flow/valve flows.

5.1 Insights from the old version of Ebbe, and other simulation programs

The simulation results from the old version of Ebbe and other simulation programs was used as benchmarks for the results from new version Ebbe. Among those simulation program used there was some not primarily used for containment analysis but for meltdown scenarios, and it is only old version Ebbe code that I as the developer of new version Ebbe had access to. It is also from old version Ebbe most simulations have been conducted to be able to study the differences between the codes, old version Ebbe and new version Ebbe. So the cradle for new version Ebbe is the comparison from old version Ebbe that is a guillotine break approximation code with quick transfer of energy down to the condensation pool/drywell, even if focus of the new version Ebbe code have been on simulating minor ruptures the guideline from old version Ebbe simulation regarding validation of results has undeniably directed the code towards simulation of larger rupture scenarios. This also means that the error in simulations were minor ruptures are involved are harder to identify then those concerning major ruptures. And it has been experiences during simulation that the logic that should avoid the effect of spikes in pressure when the reactor vessel is almost filled are more sensitive against small ruptures and few core cooling systems. That new version Ebbe results are in the proximity of the other containment analysis programs can be because the initial values for some parameters have been taken or inspired by the simulations of those programs and therefore the end result should be fairly equal if realistic logic are present. So by using the initial values of other programs the verification process was faster and smoother since the results where easier to investigate and verify, otherwise it is guesses if it was the parameters or the logic in the code that made the differences or an error in either code.

5.2 New Ebbes limitations

Limitations in the new version of Ebbe has been tried to be avoided and generalised solutions has been preferred and implemented where it was found possible. But the new version of Ebbe was written to simulate the end temperature for the condensation pool without taking regards to systems that exist in reality but have not been classified as safety systems, i.e. system concerning the operation of the plant, if not those system have a negative impact on the end temperature in the condensation pool. Parameters such as core temperature and shell temperature purpose is not to be necessary accurate but have a realistic behaviour and was designed to as simple as possible but still be able to simulate the main features of the process. By adding new parameters and their behaviours into the simulations opens up the possibility to study other parameters behaviours where those parameters are necessary and look at the difference between those cases and the cases where the new parameters are not present regarding the end temperature in the condensation pool. So even if new version Ebbe has less limitations than old version Ebbe it is still a program with purpose to calculate the end temperature in the condensation pool and nothing else.

5.3 Conclusions

The conclusion of the master thesis shows that it is possible to model containment analysis with the help of a very basic program and still keep a complex logic when it comes to system inside the process with the help of a few blocks that interacts with each other and still get results very similar to other more complex containment analysis codes. Parameters such as pressure and water temperature in the reactor vessel follows the expected behaviour pattern. With simplifications on heat transfer from the reactor core/shell to the reactor water, and even other approximations such as latent heat, pressure calculations and vaporizations have new version Ebbe reached the results from given initial values that was very satisfying.

5.4 Future work/development for new Ebbe

New Ebbes weakness is that the new version of Ebbe have not been tested for other ruptures than top ruptures because of lack of time, but it looks promising since the code is more flexible than any other Ebbe code has been before it. Things that I believe could be improved in the code is the following:

- The difference between outflow from water and steam from valves/ruptures, should be investigated. This approximations impact on the end results should be quantified.

- The logic for all plants and cases should be implemented in future versions of the code.

- The drywell and the wetwell should not be simulated entirely by water volumes. But also a gas volume in addition to the water volumes to improve calculations of the rupture flow.
- The exchange of energy from the core to the reactor vessel water should be improved. The heat exchange should be dependent on the temperature on the core itself.
- Latent heat inside the core/shell from 100 to 0 degrees Celsius is an approximation extrapolated from the latent heat from 286 to 100 degrees Celsius. This is perhaps necessary to be investigated further.
- Give more possibilities for heat exchange between drywell and wetwell during the phase when the drywell is filling up.
- Similar to the dividing of the wetwell, the reactor volume R could be divided into smaller blocks, since it is indicated from the initial values that the temperature in the reactor volume R is not at boiling temperatures from start and by that the approximation of a temperature homogeneous reactor vessel volume R is not entirely correct. Because boiling occurs at initial stage but in new version Ebbe there is a slight delay before boiling occurs.

All these changes should give an impact on the end result, the question is how large it would be and in what way. Because it is worth noticing that many of the approximation above could perhaps be fixed but some of them are perhaps conservative and would give a better result on the end temperature in the condensation pool, that are not always desirable.

Acknowledgements

I would like to give a special thanks to my supervisors at OKG Viktor Lindqvist and Georg Lagerström for all the help and to have given me the chance to work in such an interesting field as new Ebbe became. It has also given me a more profound insight in how safety analysis can be conducted at a nuclear power plant and have increased my understanding for Fortran 77. I also want to thank my family that have supported me the entire way, and special thanks to my nephews Alma and Hugo.

I want to thank examiner Anders Nordlund for all the conversations regarding the master thesis structure also by giving me the chance to work with this master thesis during a time frame that are unusual for master thesis do be conducted on.

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