POLCA-T – evaluation of a parallel steam separator model

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ABSTRACT

POLCA-T is a coupled system for transient thermal hydraulic and 3D neutron-kinetic of a BWR developed by Westinghouse. The parallel channel reactor core, reactor pressure vessel, recirculation pumps, feed water and steam systems can be modeled to desired detail. The purpose of this Master Thesis project is to study the impact of a parallel steam separator model in POLCA-T on transient and stability analysis.
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<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AOO</td>
<td>Anticipated Operational Occurrence</td>
</tr>
<tr>
<td>APRM</td>
<td>Average Power Range Monitor</td>
</tr>
<tr>
<td>BOC</td>
<td>Beginning Of Cycle</td>
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<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>BWR/2</td>
<td>Boiling Water Reactor type 2 (General Electric design)</td>
</tr>
<tr>
<td>BWR/6</td>
<td>Boiling Water Reactor type 6 (General Electric design)</td>
</tr>
<tr>
<td>BWR-1</td>
<td>Plant used in study</td>
</tr>
<tr>
<td>BWR-2</td>
<td>Plant used in study</td>
</tr>
<tr>
<td>CPR</td>
<td>Critical power ratio</td>
</tr>
<tr>
<td>ECCS</td>
<td>Emergency Core Cooling System</td>
</tr>
<tr>
<td>EFPH</td>
<td>Equivalent Full Power Hour</td>
</tr>
<tr>
<td>LRNBP</td>
<td>Load Rejection No By Pass event</td>
</tr>
<tr>
<td>LOAFW</td>
<td>Loss Of All Feed Water flow</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss Of Coolant Accident</td>
</tr>
<tr>
<td>RIP</td>
<td>Reactor Internal Pumps</td>
</tr>
<tr>
<td>RPV</td>
<td>Reactor pressure vessel</td>
</tr>
<tr>
<td>SCRAM</td>
<td>Security Control Rod Axe Man</td>
</tr>
<tr>
<td>SRV</td>
<td>Safety Relief Valve</td>
</tr>
<tr>
<td>TCV</td>
<td>Turbine Control Valve</td>
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1 INTRODUCTION

1.1 BACKGROUND

Simulations using computers is a commonly used tool of nuclear engineers. As the hardware through out the years has been improved so has the codes utilized for simulations been improved. As new codes are developed more advanced models can be constructed, thereby generating a better simulation tool.

The BWR could be modelled in three dimensions in POLCA-T; this is however usually only done for the core.

The purpose of this Master Thesis project is to investigate the impact of a more detailed modelling of the steam separators, applied to transient and stability analysis.

1.2 OBJECTIVE

There are reasons to believe that the steam separators being modeled in a more advanced setting would generate improvements in results. The behavior of the steam separators are depending on the general state of the reactor. The majority of the steam in the reactor is generated in the centre of the core from a radial perspective whereas mostly water leaves the core at the peripheral of the core. In the upper plenum a mixing of the steam and the water liquid takes place; to what extent is not known due to lack of experiments. The standpipes are all identical in construction and are tuned to the average steam and water mixture of the core. If a large radial difference in the mixture of steam and liquid resides and is not made homogenous in the upper plenum the total behavior of the steam separators is shifted to function poorer.

Core stability is evaluated at high power and low flow state points, and sometimes heterogeneous power distributions might require a more detailed modeling of the steam separators.

The currently used model has only one node in the radial direction for each axial level. The steam and the liquid in each level is thus the mass average of the total radial plane. The steam has a considerably larger volume than the liquid. At the radial periphery of the core the mass of steam is very low so the volume taken up by the steam is low. In the middle the amount of steam is high and thus almost all the volume is taken up by steam. As the steam amount increases the volume taken up by steam increases rapidly for small amounts of steam whereas for larger amounts the difference is very small since the steam has already occupied almost the entire volume. Taking the average of mass of the steam in the radial plane will generate a situation where the volume is to a high degree full of steam. The total volume of the steam thus increases if the radial plane is taken as an average. When the void increases the density of the coolant decreases; so although the two phase water level is the same the amount of coolant is less in the currently used model. This difference in coolant can be made apparent for transients when the water level is decreasing; as the liquid is made into steam the amount of liquid in the RPV will display a difference in that the two phase water level should drop with different velocities.

The overall goal of this work is to investigate if a more detailed model approach of the steam separators will be a more accurate way of describing the power plants dynamic behavior. Stability cases and low level transients will be utilized to see how large the impact of the
model will be. Different model approaches are tested to see how the model should be generated.

1.3 BWR AND THE NEED FOR STEAM SEPARATORS

BWR (Boiling water reactor) is a generic name for a specific type of nuclear reactors. The BWR is the reactor type that has the most in common with a non nuclear power plant (coal, biomass); water is turned into steam and is passed through a turbine in order to generate electricity. In comparison to non nuclear power plants the cycle is what is denoted “once through”, that means that the water only passes the heating elements in the nuclear reactor once. This generates a situation where the steam being generated in the core of the reactor is mixed with large amounts of water.

The steam turbines are not able to handle the amount of water coming from the core and since the water content left in the steam going to the turbines acts corrosive on the blades of the turbine low amounts of water in the steam is preferable. Two components in the nuclear power plant are designed to separate the steam from the water. The first separation is done in the steam separators, which removes the majority of the water; further separation is done in the steam driers.

In figure 1 the internals of a reactor pressure vessel is demonstrated. The water enters the vessel through the feed water channel (8). The water travels down through the downcomer (4) and is pumped by the RIP (reactor internal pumps, 10) to the lower plenum (9). The water enters the fuel bundles (3) and exits in the upper plenum before going into the standpipes and the steam separator (2). After then steam separators the steam goes through the steam driers (1) and exits through the steam pipes (7). The control-rods are located in the core (3) or in the lower plenum (9), and are driven by the control rod drive mechanism (6), and kept in place by the control-rod guide tube (5).

1.4 STEAM SEPARATORS

As the steam and the water leaves the core it enters the upper plenum inside of the moderation tank. The flow leaves the moderation tank through the standpipes; dividing the mass flow in parallel channels. At the end of the standpipes the steam separators are located.
The steam separator consists of a vertical pipe, where water and steam in a mix enters in the bottom end of the pipe. The flow moves upwards in the steam separator due to the pressure difference between the bottom and the top of the RPV. The mix of water and steam encounters in the bottom of the tube a rotation rotor. This rotation rotor has no external power source but rotates from the flow of the mixture. As the mixture passes the rotation blade the centrifugal inertia forces the water to the sides of the tube, whereas the steam is located in the middle. Further up in the steam separator a cone is placed that collects the steam. The water being pressed against the walls of the pipe misses the cone and is pressed out of the steam separator through small holes in the side of the tube as visible in figure 2.

Exiting the steam separator is thus steam at the top, and water at the sides. The steam is further separated from the water in the steam drier, whereas the water separated in the steam separator is returned to the core through the downcomer.

1.5 THEORY BEHIND THERMAL HYDRAULIC PARAMETERS

There are several parameters utilized in this text specific to nuclear power technology and thus potentially unknown for the reader; these are described in this section.

Mass flow: Mass flow is the defined as the flow of mass per second; in units $m/s$.

Mass flux: Mass flux is the cross sectional area independent mass flow; in units $kg/sm^2$.

Dryout: Dryout occurs when there is no water in liquid form against a fuel rod. This can occur in BWRs when the power rises too high in comparison to the flow of the coolant. In the section of the rod where dryout has occurred only steam is pressed against the sides of the fuel rod, and since steam transmits heat more poorly then water the temperature of the fuel rod is increased. This is not allowed to occur during normal operations of a BWR.

Carry under: The mass quote of the amount of steam to the total amount of mass in the water coming from the steam separators and the steam driers. The definition is stated below with $CU$ as the carry under, $G_S$ as the mass flow of steam and $G_{TOT}$ as the total amount of the mass flow. [1]

$$CU = \frac{G_S}{G_{TOT}}$$

Carry over: The mass quote of the amount of water to the total amount of mass flow. The equation for this is stated below, with $CO$ being the carry-over, $G_L$ being the mass flow of the liquid phase and $G_{TOT}$ the total mass flow. [1]

$$CO = \frac{G_L}{G_{TOT}}$$
CPR (critical power ratio): The power quota of the power which the hottest fuel rod in the core is determined to have dryout and the actual power of the fuel rod. The definition is written below where $q_{CRIT}$ is the critical power of the fuel rod, and $q_A$ is the actual power of the rod.

$$CPR = \frac{q_{CRIT}}{q_A}$$

Pressure drop over the steam separators: Quite self explanatory, it is defined as the pressure difference between the inlet of the steam separator and the outlet. The definition is written below where $\Delta_{SEP}$ is the pressure drop over the steam separator, $P_{high}$ is the pressure above the steam separator, and $P_{low}$ is the pressure below the steam separator.

$$\Delta_{SEP} = P_{high} - P_{low}$$

Void: The area quota of the cross section taken up by steam in comparison with the total flow area. The void definition is stated below, where $\alpha$ is the void fraction, known simply as void in this work, $A_G$ is the cross sectional area of the gas phase water, and $A_{TOT}$ is the total cross sectional area of the section.

$$\alpha = \frac{A_G}{A_{TOT}}$$

Quality: The quality is defined as the mass quote of the vapour against the total flow. The definition is visible below where $\chi$ is the quality, $m_{vapor}$ is the mass of the vapour and $m_{total}$ is the total amount of the coolant.

$$\chi = \frac{m_{vapor}}{m_{total}}$$

The connection between the void and the quality are demonstrated in the figure 3; where the void versus quality is plotted for 70 bars. A small difference in quality for low levels of quality generates large differences in void, whereas for large qualities the difference in void for a certain quality change is low. This is due to the large expansion of the liquid phase water during phase transition.

![Void as an effect of quality](image)

Reactivity: The reactivity of the reactor is a measure of how the reactor power is changing. The number $k$ signifies the average number of neutrons that one fission event manages to generate new fission events with. K equal to one thus is a steady chain reaction where the same amount of chain fissions take place over time; whereas k over one generates an increase in fission events and k under one a decrease in fission events. The reactivity $\rho$ is given by:
\[
\rho = \frac{(k - 1)}{k}
\]

The slip is the quote of the difference of the velocity of the gas phase and the liquid phase in a two phase mix. Given by the expression:

\[
S = \frac{u_c}{u_L}
\]

Where \( S \) is the slip, \( u_c \) is the velocity of the gas and \( u_L \) is the velocity of the liquid.

The Carry under and the Carry over defined in this work is the parameters utilized in the code, the commonly accepted definition is not the same; but for numerical reasons this definitions is more desirable. The normal convention is that the carry under is the quote of the steam over the liquid, whereas the carry over is the quote of the liquid over the steam. The parameter used in the code has a quote that is between zero and one for flows in one direction, whereas the conventional quote can reach large values for flows in one direction.

1.6 THEORY BEHIND STABILITY PARAMETERS

The main parameter utilized in stability analysis is the decay ratio. The decay ratio is defined as the ratio between two consecutive maxima in response to a disturbance. [2] A decay ratio over one is thus describing an unstable system whereas a decay ratio under one is describing a stable system.

The decay ratio is calculated in this study by utilizing both the maximum values and the minimum values. In order to utilize both a line is drawn in the middle of the oscillation as seen in figure 4. The distance from the line to the maximum or minimum value is then used in the calculation of the decay ratio.

The logarithms of the distances are plotted in figure 5. The behaviour of the logarithms of the distances versus time is linear. The decay ratio is calculated by using linear regression on the logarithmic curve. The deviation from the calculated line to the actual value is given by the standard deviation. The extraction of the decay ratio utilized in this study is taken from reference 3.

Used in the stability analysis are the period of the oscillation and the reciprocal period. These are of less significance in determining the core stability than the decay ratio but are utilized for describing the behaviour of the oscillation.
Void coefficient is the coefficient of how much the reactivity in the core is altered when the void in the core is changed. In a BWR a decrease in coolant density reduces the moderation of the plant and thus reduces the amount of neutrons that generates fission; thereby reducing the power output of the core. This is a positive safety feature since an increase in power reduced the reactivity and thus reduces the power. The definition is written below.

\[ k_{\text{Void}} = \frac{\partial \rho}{\partial \alpha} \]

Where \( k_{\text{Void}} \) is the Doppler coefficient. Besides the void coefficient there is another feedback effect; the Doppler effect. The effect of the Doppler Effect is smaller than that of the void coefficient, it is though faster. The void effect takes effect as the void is increased in the core, this has a delay of seconds before the heat generates is transferred into the water and generates steam. The Doppler Effect is directly affected by the temperature in the fuel and is thus faster. The Doppler Effect reduces the reactivity of the fuel as the temperature of the fuel is increased. This is due to that as the temperature of the fuel is increased the speed of the atoms is increased, that generates a broader spectrum of speeds for when the neutrons and fissile atoms are colliding. The peak of probability of fission is though at a narrow gap that the faster moving fissile atoms have a larger probability of missing. The definition is given below.

\[ k_{\text{Doppler}} = \frac{\partial \rho}{\partial T} \]

Where \( k_{\text{Doppler}} \) is the Doppler coefficient and \( T \) is temperature of the fuel.

1.7 STEAM SEPARATOR PARAMETERS

The steam separator performance is depending on the mass flow and the void going into the steam separator at the inlet. Due to classification of other materials this explanation will have to suffice.
1.8 POLCA-T

POLCA-T is a Fortran based code, designed to be able to simulate the coupled thermal hydraulics and neutron kinetics in a BWR. The code is a best-estimate code developed by Westinghouse for the three dimensional analysis of reactor dynamics. Many old codes, such as BISON, and RELAP are only one dimensional, whereas the new generation of codes are three dimensional such as POLCA-T and TRACE.

1.9 PLANTS

Two BWR:s have been utilized for this work. Using two plants generates more diversity in the investigation and thus renders the result more reliable. The BWRs in this study will be referred to as BWR-1 and BWR-2.

2 PREREQUISITES

2.1 CODES

The codes utilized where POLCA-T version 1.11.1. Generation of the input files was done using an aiding tool named PLINE, where version 1.0.0-T1 was used. Post processing was done using SUPERB, PLOTMON and DECAY.

3 MODEL CONSTRUCTION

The two reactor models are used for investigating the impact of the steam separators model. In this section, the different approaches are described.

Different model alterations were generated in order to see if they had an effect on the simulation of specific events. The simulations were compared to a reference case for each simulated event to be able to detect differences.

3.1 INCREASE OF AXIAL NODES

3.1.1 Objective

The objective of this simulation alteration was to detect whether a change in the amount of axial nodes in the reference case for the steam separator parts would impose a difference in the behaviour of the model.

3.1.2 Method

The amount of nodes in the steam separator was doubled for each of the different systems of the steam separator. The altered axial nodes were generated by splitting each existing node in half and thus generate the double amount of axial nodes in the same boundaries as previously.
3.2 DIVIDE OF STEAM SEPARATORS

3.2.1 Objective

By dividing the steam separators, previously modelled thru one node in radial direction, into several parallel nodes in radial direction it can be decided if that has an impact on the behaviour of the model.

3.2.2 Method

The standpipes where divided into three different regions representing three radial rings. These rings combined where given a total cross section area equal the previous cross section area of the single node. The contact area of the tubes was made proportional to the amount of standpipes represented by the quote of the cross section area that the amount of standpipes would represent. The length of the pipes where made so that they where connected to the three highest nodes of the upper plenum.

The standpipes where then connected to three separate steam separators designed in the same method as described above. The length of these sections in axial length where kept constant. The outlet from the three steam separator regions where connected to a combined bulk steam flow and bulk water depending on phase of the fluid.

This model is more physical correct in that there is not only one steam separator but layers of steam separators. However there are many physical assumptions that may be wrong, since there is only one nod in the radial direction of the upper plenum there will be a perfect mix in the upper plenum, meaning that there will be the same void content and mass flow. The mass flow into the radial rings should be slightly different simply due to that the standpipes are longer in some regions increasing the pressure drop due to friction generating a different mass flow.

3.3 THREE RADIAL RINGS FOR BWR-1

3.3.1 Objective

The idea of the model of three radial rings connected from the fuel channels up to the exit from the steam separators is to attempt to more physically correct describe the flow in the core by allowing for a difference in void and mass flow in the upper plenum.

3.3.2 Method

The upper plenum was divided into three radial rings. The divide of the rings was made according to the lid of the moderation tank where the lid was divided in equal heights. The divide in height generated a circle and two rings with a cross section area the size of the corresponding zones generated given that the lid would be two dimensional. This is demonstrated in figure 7.
Each zone where modelled as a separate section of the upper plenum. For every axial level in the upper plenum there were thus three different nodes in radial direction. On the bottom of the upper plenum each of the radial ring nodes where connected to the fuel channels that fall within each ring. Through the core several cross section connections where connected between the radial rings. These cross connection where included to allow for some pressure and mass homogenization in the radial rings of the upper plenum.

In the core there are nozzles at the inlet of the fuel channels to allow for water to pass into the fuel channel. These nozzles are the same size in the middle of the core to allow for the maximum amount of water to come into the fuel channels. In the edges of the core less steam is formed which generates a smaller pressure drop in those channels, which would generate a large flow of liquid water where less coolant is required for heat transport. The fuel channels in edges of the core thus have a reduced inlet size into the fuel channels, these inlets with lower fuel channels where both for the BWR-1 and the BWR-2 model placed in the outer ring of the radial rings. At the top of each radial ring the upper plenum was connected to three individual stand pipe sections; connected to three separate steam separator sections. The fluid cells are demonstrated in figure 6.

This model is more physically correct then the separate steam separator model in that a difference in void and mass flow is allowed in the upper plenum in the radial direction. The homogenization of the flow is in the upper plenum is however a rough simplification of what occurs. The flow coming up from the fuel channels mixes in the upper plenum and signifying this with a discrete number of cross section flows on radial levels is unlikely to be accurate.

3.4 THREE RADIAL RINGS FOR BWR-2

The radial rings of the BWR-2 model was not generated in the same way as in the BWR-1 model. To more direct alter the model to have three radial steam separators two of the radial stand pipe regions where connected to the previous highest node in the upper plenum which had been divided in two parts of equal area, one being a circle and one being an annulus. The standpipes of these two inner rings where equal in length. The outer stand pipe rings was connected to the upper plenum next highest node and thus had a longer axial length. This generated a situation where the majority of area was in the outer ring.

The model construction of the three radial rings for the BWR-2 model was not done in the same thorough way as for the BWR-1 but required no alterations in the reference model to allow for a separate upper plenum and steam separators.
3.5 FIVE RADIAL RINGS FOR BWR-1

3.5.1 Objective

The objective of the model with five radial rings is to determine if there are any discrepancies with the reference case, but also if there are any discrepancies with the model with the three rings; this to determine if the amount of rings are important to the behaviour.

3.5.2 Method

The method of determining the ring sizes where done in the same way as stated in the model with three rings for BWR-1; this time though the height of the moderation tank lid was divided in five equal parts.

The modelling was done in the same way as in the three ring model in order to be able to compare the two different models; with the self evident difference in that the this model had five radial rings.

The orifices of the inlet of the fuel channels where placed in the outer radial ring.

3.6 UPPER PLENUM WITHOUT RADIAL CROSS FLOWS FOR BWR-1

3.6.1 Objective

It was theorised that the even distribution of mass flow and void due to allowing for cross flows would remove the effect of dividing the steams separators. A simple way of enlarging the difference in the steam separators to the maximum extent would be to simply remove the cross sections. The removal of all radial cross flows in the upper plenum would allow for no radial mass transfer in the upper plenum; the void and mass flow going into every ring at the exit of the fuel channels would be the void and mass flow going into the steam separators. Given that the void and the mass flow is to a large extent dependant on the radius this will probably generate large differences in the rings concerning void and mass flow.

3.6.2 Method

The BWR-1 model utilizing five rings was reconstructed to have no radial cross flows in the upper plenum by simply removing the horizontal fluid paths.

3.7 DIFFICULTIES IN MODELLING

During the modelling several issues arose of difficulties modelling and unphysical behaviours of the models. The most profound of these issues are considered.

3.7.1 Difficulties using cross flows

In the model with three rings for BWR-1 the cross flows between the radial rings where given a cross section area of an arbitrary picked number with reasonable size. This worked in the sense that the model provided values within limits identical to the values of the reference case. The same method was utilized for the radial cross section areas of the five ring model. This however made the model behave in an unphysical way generating a large pressure difference between the radial rings in each axial level of the upper plenum. This pressure difference arose
in some transients and gave that large mass flows began circulating in the upper plenum. These large cross flows were unphysical and rendered numerical issues of the simulation.

This issue was resolved when the area of the cross flows was assorted to be the actual cross sections between the rings. Given that this is more physically correct, the argument can be raised that this was simply an error of modelling with arbitrary cross section sizes; however it raises the issue of that the code is sensitive to the cross section area where any fluid cell node is connected to more than two other fluid cells.

### 3.7.2 Issues using MAPSEP

In the model with five radial rings a negative cross flow in the two outer rings where discovered from the exit of the core; this giving the illusion of that the mass flow in the outer edges of the core are experiencing backflow. This was proven however not to be correct; what transpired was that the bypass channels were used as a connection section between the different radial rings in the first node from the bottom in the upper plenum. The connections where made so that the bypass through the core where a single channel as in the reference case. However when the code sections connecting the different fuel channels to different rings where initiated all rings where connected to the bypass channels, whereas the top axial bypass node where connected to all five respectively three bottom upper plenum ring nodes. This allowed for mass flow between the rings to be exchanged thru the bypass channel.

This was proved to have no impact on the model since cross sections between the radial rings where already connected, this simply supplied one more radial cross sectional ring. However it needs to be noted if the MAPSEP code section is to be utilized again.

### 4 REACTOR STATE

#### 4.1 STATE POINTS OF BWR-1

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<td>74.5%</td>
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<tr>
<td>43%</td>
<td>25%</td>
</tr>
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<td>53%</td>
<td>25%</td>
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</table>

Table 1

A range of state points where constructed for the reactor in order to test the different models constructed for BWR-1, these are visible in table 1. The effect percentage is the percentage of the full effect of the BWR-1, in the same way as the flow is the percentage of the full flow of the BWR-1. The burn up utilized in the BWR-1 model was 14800 EFPH (Equivalent Full Power Hour), which corresponds to the end of the cycle. No control rods are inserted into the core for the transient analysis. For the stability analysis control rods where inserted for some operating points; these are explicitly mentioned.

#### 4.2 STATE POINTS OF BWR-2

For BWR-2 two different cycle burn-ups in the cycle where utilized. The first cycle burnup was at BOC (beginning of cycle); at 0 EFPH. In that model several control rods had to be inserted to lower the reactivity. The control distribution in the core is visible in figure 8. The numbers represents the percent of the rod withdrawn from the core.

The second cycle burn-up was further into the cycle at 6000 EFPH; near the end of the fuel cycle. The control rod pattern that cycle burn-up requires more withdrawn control rods as is visible in figure 9.
The state points tested for the different cycle burn-ups are visible in table 2. The power and the flow in the table are percentages of the full power and the full flow of BWR-2.

<table>
<thead>
<tr>
<th>Burnup [EFPH]</th>
<th>Effect</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>91.3%</td>
<td>29.22%</td>
</tr>
<tr>
<td>0</td>
<td>91.3%</td>
<td>26.62%</td>
</tr>
<tr>
<td>0</td>
<td>96.6%</td>
<td>28.87%</td>
</tr>
<tr>
<td>6000</td>
<td>91.3%</td>
<td>29.22%</td>
</tr>
<tr>
<td>6000</td>
<td>91.3%</td>
<td>26.62%</td>
</tr>
</tbody>
</table>

Table 2

4.3 POWER DISTRIBUTION ALTERATION OF THE BWR-1

To investigate the need for a more detailed steam separator modelling, the radial power distribution where skewed by changing the control rod pattern for some state points. The purpose was to design radial power distributions with extreme high power regions. The figures referenced in this section are placed in appendix 1. For reference the core without control rods is presented in figure 1.

Three different control rod patterns where utilized:

- Dividing the core in two halves by placing the control rods in a vertical row in the middle of the core. The control rod groups used can be seen in figure 2. The effects of the rod formation can be seen in figure 3.

- Placing the inserted control rods in a circle centred at the centre of the core. The radius is short in comparison with the radius of the core creating a low power distribution in the middle of the core. The set up of the control rods can be seen in figure 4, and the effect of the distribution of control rods can be seen in figure 5.

- Placing the inserted control rods in a ring around the centre of the core with a large radius generating a situation where the power distribution is low at the edge of the core. The control rods settings can be seen in figure 6 and the effects of the settings can be seen in figure 7.
The circular patterns are designed to place a majority of the power in one of the radial rings thereby increasing the difference in void and mass flux in the rings into the stand pipes.

5 SIMULATED EVENTS

5.1 TRANSIENTS FOR BWR-1

5.1.1 LRNBP

The description of the LRNBP transient is extracted from reference 10. During electrical grid disturbances the electrical load on the generators is decreased. To prevent the turbine from being damaged due to high velocities of the rotor blades the steam flow to the turbine is stopped by closing the TCV;s (Turbine Control Valve). During normal operating procedures the bypass valves would open; dumping the steam from the steam lines directly into the condenser. In this event however all bypass valves malfunction and thus remain closed. The pressure increases since more steam is generated in the core and there is no exit for the steam flow. The pressure increase in the RPV collapses the void in the core, less void leads to better moderation which increases the power output of the core.

The closure of the TCV;s triggers a SCRAM of the reactor automatically. A SCRAM is that all control rods are moved into the reactor as fast as possible in order to stop the nuclear chain reaction. The closure of the TCV;s are however rapid in their closure in comparison to the time a SCRAM takes.

The closure of the TCV;s also triggers RPT (Reactor internal Pump Trip). When a RPT is initialized four of the ten reactor internal pumps are tripped, meaning that they are no longer supplied by electrical power and thus are stopped quickly. The other pumps are submitted to runback, meaning that the pumps speed is decreased rapid linearly down to a full stop of the pump.

After the TCV:s have triggered the pressure is building up rapidly in the RPV, this is counteracted by the SRV:s (Safety Relief Valves) opening automatically due to the pressure increase. The steam leaves the system through the SRV:s and the pressure is reduced. As the pressure is reduced the SRV:s close again automatically as the pressure goes beneath a specific point. The need for simulating the event is terminated when the control rods are fully inserted into the core.

5.1.2 LOAFW

LOAFW is a transient where the feed water pumps stops supplying the RPV with feed water, the facts utilized in this section are extracted from reference 10. This can be due to several reasons: pump failures, loss of electrical power, operator error, or that the pumps are tripped automatically due to the water level in the RPV is measured to be too high.

The loss of feed water into the core generates an unbalance of mass flow between the inlet of the RPV and the outlet. The power is still high in the core generating steam that leaves for the turbines however since no new water is supplied though the feed water channel the water level in the RPV starts to drop. When the water level reaches the low level L3 set point the reactor automatically SCRAM:s, and RPT is initiated; both to reduce the effect of the reactor.

The simulation has no further importance after the control rods are inserted.
5.2 STABILITY ANALYSIS FOR BWR-1

Stability analysis is conducted to determine the dynamic behavior of a nuclear power plant, to verify the core stability within the power/flow throughout the cycle. A common stability simulation is to perform a reactivity disturbance by control rods or dome pressure and analyze the response to that disturbance (decreasing or diverging oscillation in core power).

The used reactivity disturbance, in this work, offsets the power by inserting four control rods into the core 0.9 meters in 0.1 second followed by removing the same control rods completely from the core in 0.1 seconds. The control rods where fully withdrawn from the core prior to the impulse.

The rods are placed symmetrically in the core and are displayed in figure 10.

5.3 STABILITY ANALYSIS FOR BWR-2

For the BWR-2 model the control rod disturbance has a similar construct as the control disturbance of the BWR-1. Four control rods are utilized as is visible in figure 11. These control rods where withdrawn from the core 0.9 meters linearly between 3.0 seconds and 3.2 seconds. After the rods are fully withdrawn they are immediately inserted within 0.2 seconds.

6 RESULTS

The parameters displayed in the results are different depending on whether it is a transient or a stability case. The reference model referred to in this section is the base model that in each case later have been altered to have three or five separate steam separator rings. The result plots are placed in appendixes that are referred to in each section. The state points are named with the percentage of the power as the first number followed by a “p” for power, the flow is the percentage of flow following the “p”. The flow is followed by an “f” meaning flow. The percentages are given in absolute values; meaning that 10 percent power is simply written as 10p.

Several parameters are demonstrated in this section. CPR is taken as the CPR of the fuel rod that has the lowest CPR. The pressure drop is taken from the upper node in the bypass channel in the core and the pressure in the bulk water on top of the moderation tank lid. The carry over is taken from the exit of the steam separator liquid section. APRM (average power range monitor) is a monitor determining the power output of the reactor via measurement of the
neutron flux from the reactor. CPR placement is the axial point on the control rod that the minimum CPR is found. The water level is the water level that is measured by the control system of the reactor. When the difference is plotted this signifies simply that the second value has been subtracted from the first value.

6.1 MODEL APPROACHES

This section contains the tested simulation approaches. For testing the models generated the LRNBP transient was utilized at the 102p90f state point for BWR-1.

6.1.1 Increase of axial nodes

The figures referred to in this section are located in appendix 2. The reference model in this section is the BWR-1 base deck model utilized with the LRNBP transient.

6.1.1.1 Results

The overall behaviour of the CPR (figure 1) is the same in both cases. Demonstrated is the difference of the CPR (figure 2) between the cases; clarifying that there is negligible differences in the CPR.

The behaviour of the pressure drop over the steam separators (figure 3) demonstrates minute discrepancy which is further confirmed in the difference between the pressures drops (figure 4) for the difference cases.

The carry under (figure 5) demonstrates differences for the steady state. The difference is significant in size although it has a low impact on the transient behaviour as a whole; since the integral parameters of the CPR and the mass flow (figure 7) has low discrepancies. The carry under difference (figure 6) increases as the total carry under increases.

The mass flow in the upper plenum highest node (figure 7,8) displays that the difference in mass flow is around 1% of the total mass flow at the maximum. The heat generated in the core (figure 9,10) has low differences ensuring in combination with the similar mass flow through the core that the void content will be similar in both the models.

6.1.1.2 Conclusion

The conclusion is that there is no need to further increase of the node amount axially since only minor discrepancies could be found between the reference case and the model with more axial nodes. The carry over displayed quite large difference which is peculiar since the mass flow into the standpipes have low differences in both mass flow and void; the difference in carry under amounts to up to 20% of the reference value whereas the heat and mass flow difference amounts to around 0.5% and 0.5 % respectively. The large carry under difference demonstrates that the parameter has a sensitive nature.

This model where minute changes had been done from the reference model demonstrates an important fact; the carry under cannot be utilized as a parameters that singularly cannot decide if there is a difference between two models.
6.1.2 Divide of steam separators

For the separate steam separator model the upper plenum is one node in radial direction. The reference case is the BWR-1 base deck model. The alternate model has three ring sections in radial direction for the steam separators and the standpipes. The standpipes are connected as described in section 2.3.2. The figures for this section are located in appendix 3.

6.1.2.1 Results

The APRM (figure 1) has no visible divergence between the two models. The difference (figure 2) confirms this behaviour; the difference is minute except for during the largest oscillations when a small difference is visible.

The CPR (figure 3) behaves generally in the same way for the reference and the altered model. The differences (figure 4), although larger then for the axial model are small in value.

The pressure drop over the steam separators (figure 5) displays oscillatory differences (figure 6) the amplitude of the difference however does not reach high values in comparison to the total pressure drop and the oscillations are fluctuating around the zero.

The carry under (figure 7) follows the same general behavior. Relatively large differences (figure 8) are though visible for the carry under for when the absolute value increases.

6.1.2.2 Conclusion

The conclusion is that this way of modelling generates small discrepancies from the reference case rendering this model approach not necessary. The differences in carry under are though of notable size; this is interesting since the void and mass flow is homogenous in the upper plenum. The only difference in input to the steam separators is a slightly shifted mass flow as an effect of the difference in stand pipe height. This further demonstrates the sensitivity of the carry under.

6.1.3 Divide of upper plenum for BWR-1

The idea of the divide of the upper plenum is to have a more correct physical behaviour of the flow into the steam separators. In this section the simulation of the divided upper plenum with cross flows is analyzed for steady state.

The fuel channel are all contributing with a upwards directed mass flow; however the mass flow at the end of the fuel channels have different void and mass flow. The void in the centre of the core is higher than in the periphery whereas the mass flux at the edge of the core is higher. This is due to that the pressure difference over the core is the same regardless of the fuel channel and the generation of void imposes a larger pressure drop in the inner radial channels. Some of the outer radial channels have a smaller fuel channel inlet nozzle to reduce flow, and still the mass flux is higher at the radial periphery.
Demonstrated in figure 13 is the cross flows between the radial rings in the upper plenum. The arrows going down into the core is the flow in the bypass channel. The bypass flow is consisting of liquid phase coolant moving towards the middle of the core. The first radial cross flow distributes the mass in the middle of the core, since there is more mass there, out to the peripheral rings; this first cross flow has the highest mass flow. The second mass flow oscillates the mass back to the centre of the core however with lower mass flow. The third cross flow level distributes the mass flow into the middle radial ring. The mass then continues to the end of the upper plenum and out into the standpipes.

The mass flow at the inlet and the outlet of the upper plenum have approximately the same size, the void however changes to a larger extent. At the exit of the upper plenum the void is near to being homogenous.

The mass flow in the model with five rings follows the same behaviour as the model with three rings as visible in figure 14. The bypass flow moves liquid into the middle of the upper plenum, the first cross flows transports mass out from the centre with a high mass flow. The second cross and third radial cross flow oscillates the mass flow with decreasing amplitude of the mass. The distribution of the void at the outlet of the upper plenum is behaving in the same way as for the three ring model, being to large degree homogeneous.

6.1.3.1 Conclusion

The construction of the upper plenum with a number of radial cross flows generates a quite homogenous mixture of void and mass flux into the steam separators. This homogenous behaviour of the void and the mass flux will generate a quite similar behaviour of the three rings and the five rings model with regards to the reference model.

A thermal hydraulic fact of the BWR-1 plant that enhances the probability of a more homogenous void and mass flux at the exit of the upper plenum is the fact that the ECCS has a sprinkler system located at the exit of the core; this will generate rotational flows in the coolant exiting the fuel channels.

6.1.4 Divide of upper plenum for BWR-2

To study the behaviour of the BWR-2 three ring model the steady state behaviour in the upper plenum was analyzed.

The state point utilized was the 91.3p29.22f, which is a high power low flow state point. The low flow gives that the difference in void is lower since less liquid water passes the core at the outer regions. The bypass was connected to the outer ring and is included in the inlet flux. Homogenization occurs to some extent for the mass flux and the void where the void and the mass flux in the inner ring decreases and both variables increase in the outer ring. The middle
ring has a decrease in liquid mass flux generating an increase in void, contrary to the homogenization.

6.1.4.1 Conclusion

The divide of the upper plenum cannot be described as directly contributing to the homogenization of the void and the mass flow. The exit mass flow from the fuel channels is quite homogenous in mass and void from the beginning, rendering a situation where the radial pressure difference driving the homogenization is not present in this model.

6.1.5 Upper plenum without radial cross flows for BWR-1

A trial model was created without radial cross flows in the upper plenum. This model does not allow for radial mass exchange in the upper plenum. The figures of this section are located in appendix 4. The reference refers to the BWR-1 base deck model, the five rings model refers to the alteration of the BWR-1 base deck model to have cross flow in the upper plenum whereas the model without cross flows refers to the five ring model without radial cross flows.

6.1.5.1 Results

The used transient was LRNBP at 102p90f; which for the other models have been simulated for ten seconds. During this transient the simulation could not be run for more then 2.3 seconds due to numerical issues in the code. The numerical issue is due to that the model behaviour becomes too extreme and the numerical calculations can no longer converge.

The ARPM (figure 1) displays large differences between the models without cross flows in comparison to the reference model and the model with five rings. The lower APRM is reflected in the higher CPR (figure 2); the less effect of the core the higher the safety margin.

The pressure drop over the steam separator (figure 3) has a large difference for the model without cross flows in that the pressure drop is higher. The carry under (figure 4) has large differences between all models; the model without cross flows though demonstrates the largest difference from the reference model.

The reasons for the large discrepancies of the model without cross flows can be found in the large differences of mass flow (figure 5, 6) and void (figure 7, 8) into the steam separator. The mass flow is similar in size in the three inner radial rings of the model without cross flows; whereas it is considerably higher in the fourth and the fifth ring from the centre. This behaviour of the mass flow has larger discrepancies to the mass flow of the five rings model. The difference of the mass flow from the area weighted mass flow demonstrates larger differences since the outer rings are the smallest in cross sectional area.

The large difference in mass flow is connected to the large difference in void in the last cell of the upper plenum in comparison to the five rings model. A smaller steam generation but the same pressure drop over the core generates a higher mass flow through the outer radial channels. The void is considerably larger for the inner rings in the model without cross flows.

The increase in pressure drop over the steam separators is due to the increase of mass flow in the outer regions and the decrease in the inner regions as discussed in section 1.1.5. The carry under displays differences for the same reason.
6.1.5.2 Steady state water mass comparison

For steady state of the two state points used in the analysis of the transients the amount of water in the upper plenum and steam separators of the model without cross flows and the reference model was calculated.

The difference of the values is significant; about 10% more coolant for the alternated model. During a transient where the water level is dropping the amount of water in the system would demonstrate a clear difference between the reference and the without cross flows model. The difference will probably increase as the amount of radial rings increases since that generates a more divided upper plenum and steam separators.

The calculation was conducted on the operating points of 102p90f and 64p42f. In the objectives it was theorized that a low power level state point would generate a large difference; this will only be theoretically true if the void distribution becomes more extreme in the core. For this low effect power point the difference in void is smaller than for the full effect state point; this is probably due to the low mass flow of the low power state point.

6.1.5.3 Conclusion

This way of simulation the core demonstrates large differences from the reference case and the model with the radial cross flows in the upper plenum. The differences are due to the large void and mass flow differences into the steam separators. This way of modeling is at the other end of the extreme way of modeling from the presently used model; where the presently used model utilizes a perfect mixture this way allows no mixing. This way of simulating is probably faulty since radial flows can exist in the upper plenum.

The numerical errors that occurred when the model was utilized rendered simulating longer transients difficult. For that reason the model approach was abandoned.

This model with the extreme quality divide in the upper plenum and the steam separators demonstrated the theorized issue of the difference in amount of coolant in the system despite the same two phase water level. The difference in water amount was significant and the inclusion of more radial rings and state points generating large quality differences from the core is theorized to further increase the difference of the total mass in the upper plenum and the standpipes.

6.1.6 Conclusion

The increase of the axial nodes simulation was not a different simulation approach from the previously used but a parameter study of the importance of the nodal amount. For the utilized node amount the increase posed no differences if neglecting the carry under.

The divide of the steam separators allows for a small difference in the behavior of the steam separators and since the upper plenum is not divided the objective of the transient behavior cannot be tested. This model approach was utilized as a stepping stone for the following model approaches.

The model with radial cross flows demonstrated a high degree of being able to homogenize the void and the mass flux in the upper plenum for steady state. This reduces the likeliness of the model demonstrating a difference from the reference case.
The model without cross flows demonstrated large differences in behavior from the reference case. A difference in the amount of coolant could be calculated from the steady state that if the transient could be run for longer periods of time would have demonstrated the theorized difference in the velocity of the level decline. The distribution of the void and the mass flow rendered the situation of the using the model without cross flows impossible to simulate for more than a few seconds.

For further study the model with radial cross flows will be utilized.

6.2 TRANSIENTS

For LRNBP and the LOAFW transients the reference is the BWR-1 base deck model which has been altered to have three and five rings respectively.

6.2.1 LRNBP

6.2.1.1 102p90f

The figures referred to in this section are located in appendix 5.

The model simulates the LRNBP case where the APRM (figure 1) reflects the pressure increase by a steep rise following the TCV;s closure and the dump valves failure. The SRV;s are opened due to the pressure increase and the reactivity is thus lowered. SCRAM and the pump trip combined with the decreasing pressure further decreases the reactivity. Due to the heat transfer delay the minimum CPR(figure 3,4) is reached 1.2 seconds after the reactivity peak is reached. The APRM drops after the pump runback and the SCRAM begins to take effect.

The pressure wave generated upon closing of the TCV;s bounces around in the system making the parameters oscillate, as can be seen in the mass flow (figure 12-17) . The oscillations in the mass flow into the steam separators generate oscillations in the pressure drop over the steam separators (figure 8) since the pressure drop over the steam separators are mass flow dependant and pressure dependant. Oscillations are visible in the level (figure 22) and the void (figure 18-21) but to a smaller extent. The level and the void will oscillate due to the compressibility of the steam for pressure oscillations.

The event was terminated when the transient had passed the critical time. The APRM eventually reached the decay level and the CPR was increasing as the temperature of the fuel rods where decreasing. There is no danger of the plant being damaged after the initial events given that the ECCS is still operational. The water level keeps on dropping as the event is terminated. This will be handled by the ECCS after a specific limit is reached.

The APRM displays a similar behaviour for all three models in general behaviour, however differences can be seen that amounts to 0.02 for certain peak values.

The CPR has the same overall behaviour and demonstrates a low difference for the minimum value (Figure 5). The CPR placement (figure 6,7) is located at the end of the rod except for just prior to minimum CPR being achieved and at the end of the transient when the CPR is high. There is no difference in behaviour between the models of the CPR location. Visible in table 3 is the min CPR achieved for each case, as is visible the differences are minute.
The pressure drop over the steam separators has low differences between the models. The carry under demonstrates differences of up to one percent.

The mass flow in the upper plenum for the alternated models and the references (figure 12, 15) demonstrates that the total mass flow is the same in the three ring model and the five ring model as in the reference model. There are differences amongst the mass flow in each of the rings for the five ring model and the three ring model (figure 13, 16); however some of the differences are since the rings have difference areas. An area weighted mass flow (figure 14, 17) demonstrates that there still are differences even if area has been taken into account; the differences amounts to less then 5 percent of the total flow. The mass flow is the highest in the outer ring and decreases as the radius decreases, this due to the lower void (figure 18, 19) in the outer regions.

The void in the upper plenum highest node for three and five rings (figure 18, 19) demonstrates the same behaviour in that the void in the inner ring is the highest and that the void decreases as the radius increases. This behaviour is logical since more steam is generated in middle of the core from a radial perspective.

The water level difference (figure 22) displays minor differences of up to 6 centimetres. The expected difference of the water level (figure 23) is not present in the results, this due to the similar behaviour of the void in the upper plenum. The void is nearly on the same level in the second node of the upper plenum (figure 20, 21); after only one radial cross section. The difference in void from the expected difference in quality is effectively neutralized by the cross flows.

That the decreased water level generates a larger void difference to the steam separators is physically correct since the inner radial standpipes are shorter than the outer and the decreased water level will place the standpipes in the radial middle in steam instead of under the two phase water level. The water level difference will shift the response time of the transient by about 0.25 seconds since the L3 water level for the emergency SCRAM is reached later.

6.2.1.2 64.5p42f

The figures for this section are located in appendix 6. In this section there are no differences plotted; this is due to that the time step of the models are not of the same magnitude. When POLCA-T encounters rapid changes in the thermo-hydraulics the time step is reduced to safe keep the stability of the numerical calculation. This positive feature in the code generates a difficult situation in difference calculations. A regression can be done in order to get an analytical expression for the curves and then the difference could be calculated; however for these small differences that would pose the issue of the error in regression being if not larger but on the same magnitude as the actual difference of the curves.

The behaviour of the transient as a whole is the same for both the 102p90f and the 64.5p42f with some differences due to the lower effect. The APRM (figure 1) is of course lower for the lower state point as well as the mass flow (figure 7, 10). The decrease of the water level (figure 17) is less rapid in this state point since less heat is generated by the core.
For the APRM there are no visible differences of the models. The same lack of difference can be seen for the overall behaviour of the CPR (figure 2); however for the minimum enhancement of the CPR (figure 3) a difference in behaviour is visible. This difference is displayed in the table 4 below.

<table>
<thead>
<tr>
<th>Reference</th>
<th>3 radial</th>
<th>5 radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,4797</td>
<td>1,4842</td>
<td>1,4821</td>
</tr>
</tbody>
</table>

Table 4

The CPR placement (figure 4) remains at the end of the core during the entire transient for all three models. The pressure drop over the steam separators (figure 5) has the same general behaviour although deviations are visible in the last half of the transient. The same behaviour is true for the carry under.

The mass flow in the highest node of the upper plenum (figure 7, 10) demonstrates that the total mass is the same combined in all the rings for the three rings and five rings model as the reference case. The mass flow (figure 8, 11) is the highest in the inner ring of both the five rings and the three rings model. Weighted for the area (figure 9, 12) however the outer ring has more mass flow. The differences in mass flow of the radial rings increases as the void (figure 13, 14) increases.

As the water level (figure 17) drops below the inlet of the inner stand pipes the difference in void becomes greater. In the steady state the higher void is visible for the inner ring for both the three rings model and the five rings model in accordance with more steam being generated in the middle of the core. The difference in water level is lower for this lower drift point.

The expected difference in water level decrease is not visible for this lower drift point. This is again due to the similarities in void in the upper plenum visible for the second node of the upper plenum (figure 15, 16).

6.2.1.3 Conclusion

The divide into three rings and five rings for this transient has proven to have a low impact on the integral parameters- CPR and APRM. The ARP and the CPR are denoted integral parameters since they are the combined effect of the other parameters. The pressure drop over the steam separators demonstrates significant differences at the end of the simulation this due to significant differences in mass flow and void during the same time period. The difference seems to be that the oscillations are shifted in period and thus deviations occur. The critical part of the simulation is passed without differences.

The expected slower decrease in water level is not present in the results due to the radial cross flows that effectively distribute the quality and thereby generates an evenly distributed void.

The implementation of the three rings and five rings model for LRNBP using the state points tested created small differences between the models.
6.2.2 LOAFW

6.2.2.1 102p90f

The figures for this section are located in appendix 7. The APRM (figure 1) is on a steady level during steady state and after the feed water is shut of the same level is withheld up to five seconds into the transient. After five seconds the mass flow (figure 11, 14) through the core starts to be reduced which in combination with the decreased subcooling of the inlet water to the core, increases the void in the core. The increase in void reduces the reactivity and the APRM drops.

The water level (figure 21) keeps on dropping since there is still steam being generated but no feed water being supplied. As the water level reaches the L3 boundary SCRAM is initiated together with RPT that swiftly reduces the APRM. Minimum CPR is reached as the RPT and the SCRAM take effect; the residual heat of the fuel rods encounters the low mass flow of the main circulation. The minimum CPR is though quite high and not far from the steady state point. The difference in value is not large as seen in the table 5 below.

<table>
<thead>
<tr>
<th>Reference</th>
<th>3 radial</th>
<th>5 radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,4841</td>
<td>1,4859</td>
<td>1,4862</td>
</tr>
</tbody>
</table>

Table 5

The APRM behaves in similar ways for each model however a visible difference occurs when the step drop in reactivity is initiated. There seems to be a delay for the alternated models of a period of 0.4 seconds. This delay generates a large difference in the APRM (figure 2) and is due to the fact that the water level (figure 21) in the three rings model and the five rings model is higher then in the reference case when the L3 level is reached for the reference case, thus the L3 level is reached longer into the transient for the alternated models.

The lag in the behaviour of the alternated models is visible in the CPR when the minimum CPR is reached (figure 4). The difference of the CPR (figure 5) becomes large when the timing of the events is lagged. The CPR location (figure 6) is the same for all three models; at the top of the fuel rod.

The pressure drop over the steam separators(figure 7, 8) experiences the same behaviour as the other parameters with a large divergence at the SCRAM position. This is true also for the carry under (figure 9, 10). The carry under has an increasing difference as the absolute value increases.

The mass flows in the highest node of the upper plenum (figure 12, 15) displays that the inner ring has the highest mass flow and the mass flow drops as the radius increases. Weighted for the area (figure 13, 16) the outer ring has the highest mass flow for both the three ring and the five ring model; this due to as noted earlier that the void (figure 17,18) is lower in the outer region.

The void does not display as large differences as in the LRNBP transient although the water level (figure 21) is dropping. This gives reasons to believe the visible shift in void due to the inner standpipes placed above the two phase water surface is to neat; results seems to not support the theory without deviations.
The water level although responsible for the lag in the transient behaviour does not
differentiate by more than one centimetre at the time of the SCRAM. The expected difference
in water level decrease not seen in these results either due to the same reasons as the in the
LRNBP transient, the void is evenly distributed (figure 19, 20).

6.2.2.2 64.5p42f

The figures referred to in this section are located in appendix 8. The general behaviour of the
transient is the same as in the higher state point. The APRM (figure 1) displays a lower relative
decrease in reactivity than in the higher drift point. The water level drops further in the low
energy state point due to the collapse of the void in the core since the effect is lower. The total
amount of water in the RPV is of course dropping more rapidly in the full effect case since
more steam is generated. The generated steam however increases the two phase water level,
which does not occur to the same extent in the low effect case.

The difference in the behaviour in the transient for the different models is the same as in the
previous state point; the SCRAM is not initialized at the same time, visible in the APRM
difference (figure 2). For this state point the difference in time is lower, due to that there is less
water level difference (figure 24). The lag in time propagates to a list of parameters; CPR
(figure 3, 4) in that the minimum CPR occurs during different times, the pressure drop
difference (figure 7, 8) and the carry under (figure 9, 10).

<table>
<thead>
<tr>
<th></th>
<th>3 radial</th>
<th>5 radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,5726</td>
<td>1,5743</td>
<td>1,5732</td>
</tr>
</tbody>
</table>

Table 6

The CPR, in table 6, remains at the same minimum value although the time of the event is
shifted.

A peculiar behaviour is visible in the carry under that reaches above 2000%. Given the
definition of the carry under values above 100% seems not reasonable; this is true given that
the direction of the steam and the total mass are in the same direction. The peak of the carry
under occurs when the total mass flow in the upper plenum is negative. A positive value of the
steam flow and a total mass flow that approaches zero generates a peak in the carry under seen
as the large positive peak. As the steam flow has become negative and the total mass flow goes
from negative to positive the negative carry under peak is generated.

The water level (figure 23) drops as noted earlier more in this state point generating that the
narrow range monitor becomes out of range. This monitor has been utilized for the level
measurements in the analysis of the other transients. To be able to measure the water level the
wide range monitor (figure 25, 26) was utilized. The narrow range monitor functions through
the pressure difference between two axial points in RPV, if the water level drops below the
level of the lower monitor the water level is out of range for the level monitor.

The expected difference in the water level is not visible for this transient either and for the
same reasons as for the previous transients, the void is evenly distributed.

6.2.2.3 Conclusion

Differences of significant size occur for the pressure drop over the steams separators and the
APRM for both state points. The differences are an effect of the lag of 0.4 and 0.1 seconds for
the different state points for the initiation of the SCRAM. Although the differences are large between the parameters comparing in a specific moment due to the rapid change of the parameters does not mean that the difference of the models is significant; the models behave in the same way with a small time lag.

The difference in water level decrease is not seen in the results, this due to the same reasons as in the LRNBP; the effective evening out of the quality of the upper plenum.

6.3 STABILITY ANALYSIS FOR BWR-1

For the stability analysis several state points of the reactor were tested; these are demonstrated independently in the following section.

The models in this section where all exposed to the same disturbance; a control rod disturbance. As the control rods are inserted the APRM rapidly decreases and as the control rods are withdrawn again an oscillation of the APRM begins. The oscillation of the APRM is due to the different feedback parameters in the core; the void coefficient and the Doppler coefficient.

The physical behavior of the oscillation is that when the control rods are inserted the power of the core decreases since more neutrons are absorbed. As the control rods are withdrawn the power increases yet again; the rise of power is limited by the void coefficient and the Doppler coefficient and the power begins to decrease. As the power decreases the void coefficient has less effect and the power yet again rises; these events are repeated for every oscillation.

The oscillating APRM will propagate to other parameters such as void, mass flow, pressure, and so forth. The APRM affects the other parameters by oscillating the production of steam, which in terms oscillates the pressure and the mass flow, which in turns oscillates the APRM.

Some of the state points in the results have amplitude of the APRM that will decrease over time as the transient progresses, these state points are stable. A stable state point is stable in the meaning the feedback of the system will decrease disturbances until steady state is reached yet again. Some of the state points have an APRM that have increasing amplitude, these state points are unstable. An unstable state point is when the feedback of the core cannot bring the core back to steady state; the oscillations are not decreased and might even be diverging.

6.3.1 64.5p42f

The results of the state point are located in appendix 9. The APRM (figure 1) displays a minute difference in amplitude of small magnitudes. This difference in APRM (figure 2) generates a low oscillation in the pressure drop over the steam separators (figure 3, 4). Peak oscillations are visible in the pressure drop difference, the reason for these are unknown. The carry under (figure 5, 6) fluctuates with the oscillations of the APRM, however a clear difference can be seen in that the carry under is lower as the amount of rings are increasing.

The decay ratio, the period and the standard deviation are visible in table 7.
The deviations of the decay ratio are low, whereas the period displays no discrepancies.

6.3.2 74.5p42f

The state point of 74.5p42f was designed to stress the point of 64.5p42f by increasing the power; and thus the instability. The results from this section are located in appendix 10.

The state point demonstrates a stable behavior give the disturbance, it is though more unstable then the point of 64.5p42f seen in the slower decay of the APRM (figure 1). The differences in the APRM (figure 2) are low at a start but are increasing as the period of the two oscillations are different for the three models. A minute difference in the pressure drop over the steam separators can be seen (figure 3, 4). The carry under (figure 5, 6) demonstrates a reverse order in comparison to the 64.5p42f state point; where the reference has the lowest carry under of the three models. The difference in carry under is though low for the models.

Table 7

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.595</td>
<td>Period=1.680</td>
<td>Decay.R. =0.564</td>
</tr>
<tr>
<td>Standard.D=0.903E-02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The decay ratio differences are low whereas the period difference is within the standard deviation as visible in table 8.

6.3.3 43p25f

The figures of this section are located in appendix 11. This state point of the reactor is stable as is visible in the APRM (figure 1). The differences cannot be displayed in this state point due to different calculations times in POLCA-T. The difference in the APRM is low as is visible in the decay ratio in table 9 below.

Table 8

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.605</td>
<td>Period=1.653</td>
<td>Decay.R. =0.875</td>
</tr>
<tr>
<td>Standard.D=0.813E-3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The pressure drop (figure 2) displays minute differences along wise the carry under (figure 3).
6.3.4 53p25f

The APRM (figure 1, 2) in appendix 13 demonstrates that the state point of 53p25f is an unstable state point. After the disturbance of the control rods the amplitude of the oscillation increases for the APRM. As the APRM does not have identical periods the difference between the models for the APRM increases as the amplitude increases. The APRM is increased prior to the control rod disturbance; the reason for this is that the steady state in not completely converged. If a long time series would be performed this would not be ideal for the analysis, but for a stability comparison between different models with the same steer up in power this has no importance; the vital part is difference between the models not the models behaviors.

The steer up of the model is visible in the pressure drop over the steam separators (figure 3, 4) that oscillate prior to the control rod disturbance; the high velocity of the fluctuation generates a high difference. As the model approaches a more steady state the control rod disturbance is made visible. For the carry under (figure 5, 6), the reference case displays the lowest carry under.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.521</td>
<td>Freq =0.526</td>
<td>Freq =0.531</td>
</tr>
<tr>
<td>Period =1.920</td>
<td>Period =1.903</td>
<td>Period =1.884</td>
</tr>
<tr>
<td>Standard.D=0.522E-2</td>
<td>Standard.D=0.485E-2</td>
<td>Standard.D=0.380E-2</td>
</tr>
</tbody>
</table>

Table 10

Visible in table 10 is that the difference of the period and the decay ratio are minute.

6.3.5 Conclusion

This study for the state points done on the BWR-1 demonstrated no significant differences between the models. The decay ratio was not within the standard deviation; however the general behavior of the parameters, except the carry under, were the same for all state points.

6.4 PARAMETER STUDY OF CONTROL ROD PATTERN FOR BWR-1

A parameter study of the control rod pattern (or rather radial power distribution) is presented in this section. Utilized is the 53p25f state point since it is unstable and thus alterations might be easier to notice.

6.4.1 Line

The line control rod pattern was generated to split the power shape of the core in two halves. The figures referred to in this section are located in appendix 13.

The APRM (figure 1, 2) displays a stable behavior in that the amplitude is decreasing over time. As mentioned the state point utilized was 53p25f which was unstable, but since a number of control rods have been inserted the reactivity of the core has been reduced. The APRM displays low differences most visible during the high derivative changes of the APRM due to a lag in phase by the three rings and the five rings model.
Visible in table 11 are the differences of the decay ratio and the period, which are low.

The steer up in power is visible prior to the control rod disturbance at one second. This steer up generates the same behavior of the pressure drop over the steam separators (figure 3, 4), and the carry under (figure 5, 6), as seen for the 53p25f state point.

### 6.4.2 Ring

The control rod ring distribution was generated to increase the power locally in the middle of the core in comparison to the outer of the core. The case utilized was the 53p25f as in the control line distribution. The figures of this section are located in appendix 14.

The APRM (figure 1, 2) displays an unstable behavior with low differences. The differences are occurring due to the lag of the three and the five rings model in the oscillation. The carry under (figure 3, 4) and the pressure drop (figure 5, 6) over the steam separators displays the same general behavior seen for the 53p25f state point. No large differences in decay ratio or frequency occur as is visible in table 12.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.522</td>
<td>Period =1.915</td>
<td>Decay.R.=0.961</td>
</tr>
<tr>
<td>Freq =0.524</td>
<td>Period =1.910</td>
<td>Decay.R.=0.937</td>
</tr>
<tr>
<td>Freq =0.524</td>
<td>Period =1.909</td>
<td>Decay.R.=0.950</td>
</tr>
</tbody>
</table>

### 6.4.3 Circle

The figures of this section are located in appendix 15. The APRM (figure 1, 2), the carry under (figure 5, 6) and the pressure drop over the steam separators (figure 3, 4) all display the same behavior as the ring control rod pattern. Visible in table 13 is the decay ratio and the period; both with low deviations.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.522</td>
<td>Period =1.905</td>
<td>Decay.R.=1.244</td>
</tr>
<tr>
<td>Freq =0.527</td>
<td>Period =1.897</td>
<td>Decay.R.=1.211</td>
</tr>
<tr>
<td>Freq =0.529</td>
<td>Period =1.890</td>
<td>Decay.R.=1.216</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.537</td>
<td>Period =1.863</td>
<td>Decay.R.=1.311</td>
</tr>
<tr>
<td>Freq =0.540</td>
<td>Period =1.853</td>
<td>Decay.R.=1.293</td>
</tr>
<tr>
<td>Freq =0.541</td>
<td>Period =1.847</td>
<td>Decay.R.=1.268</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.537</td>
<td>Period =1.863</td>
<td>Decay.R.=1.311</td>
</tr>
<tr>
<td>Freq =0.540</td>
<td>Period =1.853</td>
<td>Decay.R.=1.293</td>
</tr>
<tr>
<td>Freq =0.541</td>
<td>Period =1.847</td>
<td>Decay.R.=1.268</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
<th>Five rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.525</td>
<td>Period =1.905</td>
<td>Decay.R.=1.244</td>
</tr>
<tr>
<td>Freq =0.527</td>
<td>Period =1.897</td>
<td>Decay.R.=1.211</td>
</tr>
<tr>
<td>Freq =0.529</td>
<td>Period =1.890</td>
<td>Decay.R.=1.216</td>
</tr>
</tbody>
</table>

Table 11

Table 12

Table 13
6.4.4 Conclusion

No significant differences could be seen in the parameter study of the control rod pattern since the behavior of the models where the same.

6.5 STABILITY ANALYSIS FOR BWR-2

The control rod disturbance for the BWR-2 plant was tested for fresh fuel and for the cycle burn-up at 6000 EFPH. Different state points where tested for each cycle burn-up. For this study the reference model refers to the BWR-2 base model and the three ring model refers to a model with three radial rings in the steam separators. The three rings model has a separate upper plenum connected to specific fuel channels and radial cross sectional flows in the upper plenum.

This simulation was conducted for longer time periods; whereas the standard deviation of the decay ratio evaluation decreases.

6.5.1 BOC

The following state points are tested for fresh fuel in the core. Three different state points were tested for this cycle burn-up.

6.5.1.1 91.3p29.22f

The figures referred to in this section are located in appendix 16. The APRM (figure 1) displays that this state point is unstable; the step disturbance starts an oscillation that increases in amplitude until a steady amplitude is reached. The APRM difference (figure 2) demonstrates an increasing difference as the simulation progresses due to that the frequencies of the oscillations are not precisely matched.

The behavior of the pressure drop over the steam separators (figure 3) demonstrates the same behavior as the APRM.

The carry under (figure 5) is high with values around 6 percent, this due to the high effect and the low flow state point used. A steady state difference is visible for the carry under between the models; reflected in the value that the oscillations are oscillating around. The oscillations in the carry under are not in the same period, which increases the carry under difference (figure 6) oscillations as the simulation progresses. The decay ratio and the period are visible in table 14.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq = 0.696</td>
<td>Freq = 0.695</td>
</tr>
<tr>
<td>Period = 1.437</td>
<td>Period = 1.440</td>
</tr>
<tr>
<td>Decay.R. = 1.015</td>
<td>Decay.R. = 1.015</td>
</tr>
<tr>
<td>Standard.D = 0.906E-2</td>
<td>Standard.D = 0.887E-2</td>
</tr>
</tbody>
</table>

Table 14

6.5.1.2 91.3p26.62f

The figures referred to in this section are located in appendix 17. The APRM (figure 1) of this state point demonstrates an unstable behavior that leads to the model being unable to simulate
past 25 seconds. Due to a difference in iterations the differences will not be displayed for this section.

The APRM displays the same behavior for both the models, whereas the pressure drop over the steam separators (figure 2) shows minute difference. The same behavior of the carry under (figure 3) as in the 91.3p23.22f state point can be seen. As in the previous state point the decay ratio and the frequency is within the standard deviation; as shown in table 15.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq = 0.673</td>
<td>Freq = 0.673</td>
</tr>
<tr>
<td>Period = 1.487</td>
<td>Period = 1.487</td>
</tr>
<tr>
<td>Decay.R. = 1.184</td>
<td>Decay.R. = 1.187</td>
</tr>
<tr>
<td>Standard.D = 0.897E-2</td>
<td>Standard.D = 0.872E-2</td>
</tr>
</tbody>
</table>

Table 15

6.5.1.3 96.6p28.87f

The figures referred to in this section are located in appendix 18. The state point of 96.6p28.87 is stable as seen in the behavior of the APRM (figure 1, 2) that displays minute differences between the models. The pressure drop (figure 3, 4) and the carry under (figure 5, 6) shows the same behavior as the other state points of the burn up point. No significant differences are visible in neither the decay ration nor the frequencies as visible in table 16.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq = 0.684</td>
<td>Freq = 0.683</td>
</tr>
<tr>
<td>Period = 1.462</td>
<td>Period = 1.464</td>
</tr>
<tr>
<td>Decay.R. = 0.957</td>
<td>Decay.R. = 0.961</td>
</tr>
<tr>
<td>Standard.D = 0.982E-2</td>
<td>Standard.D = 0.952E-2</td>
</tr>
</tbody>
</table>

Table 16

6.5.1.4 Conclusion

For the BWR-2 plant at BOC the tested state point demonstrated minute differences. There is no need to utilize a parallel steam separator model for these conditions with the utilized construction of the upper plenum.

6.5.2 6000 EFPH

Two of the state points tested for the fresh fuel where utilized in the testing of the 6000 EFPH burn-up.

6.5.2.1 91.3p29.22f

The figures referred to in this section are located in appendix 19. The state point behaves in the same way as it did at BOC; the APRM (figure 1, 2) and the pressure drop over the steam separators (figure 3, 4) behaves identically, whereas a drift the in the carry under (figure 5, 6) can be seen.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq = 0.586</td>
<td>Freq = 0.584</td>
</tr>
<tr>
<td>Period = 1.707</td>
<td>Period = 1.714</td>
</tr>
<tr>
<td>Decay.R. = 1.020</td>
<td>Decay.R. = 1.018</td>
</tr>
<tr>
<td>Standard.D = 0.932E-2</td>
<td>Standard.D = 0.999E-2</td>
</tr>
</tbody>
</table>
The decay ratio difference is within the standard deviation as visible in table 17.

6.5.2.2  91.3p26.62f

The behavior at the BOC and 6000 EFPH are the same as is visible in the APRM (figure 1, 2) in appendix 20. For the 6000 EFPH burn-up the simulation is possible above 25 seconds, but the behavior of the cycle points is very similar to the point of the numerical failure at BOC. The similarities in behavior apply to the pressure drop over the steam separators (figure 3, 4) as well as for the carry under (figure 5, 6). As in the previous state points the difference in pressure drop over the steam separators and the APRM displays minute differences, whereas the carry under displays significant differences.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Three rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq =0.555</td>
<td>Freq=0.554</td>
</tr>
<tr>
<td>Period = 1.803</td>
<td>Period=1.807</td>
</tr>
<tr>
<td>Decay.R. = 1.000</td>
<td>Decay.R. =1.000</td>
</tr>
<tr>
<td>Standard.D = 0.867E-2</td>
<td>Standard.D=0.835E-2</td>
</tr>
</tbody>
</table>

The decay ratio is within the standard deviation as visible in table 18.

6.5.2.3  Conclusion

The conclusion from the 6000 EFPH cycle point is that it behaves in the same way as the fresh fuel point. The differences between the models are small for the general behavior although the difference in carry under is high as for all previous conducted analysis. There is no significant reason to utilize the parallel steam separator model for the later cycle points in the BWR-2 model for the tested state points.

7  CONCLUSIONS AND SUMMATION

7.1  SUMMATION

The goal of this study was to examine if a simulation of the steam separators would induce a difference in the behavior of studied dynamic behaviors. Two different differences where theorized to be visible from the alteration of the model into having separate upper plenums and separate steam separators. The first theorized difference was that the difference in coolant mass in the upper plenum and the stand pipes that would lead to a difference in the velocity of the reduction of the water level for certain transients. The second theorized difference was that the stability parameters of the model would alter when the steam separators where more accurately modeled.

The first study conducted was whether an increase in the number of axial nodes of the steam separators would induce a difference in behavior of the models. The differences were insignificant; except for the carry under. The behavior of the carry under shifted with significant levels even though the difference of the void and the mass flow was minute in the increased axial node model; proving that the carry under is sensitive and that the variable requires to be tuned for each change in the model to fit the experimental values. The carry under is thus solely not an indication of that the behavior of a model has shifted.
Initially a more simple approach of simulating a three dimensional steam separator was utilized where only the steam separators where divided in three rings for the BWR-1. This model approach proved no significant changes from the reference model.

To allow for a difference in the behavior of the void and the mass flux in the upper plenum, and thus to have a larger difference in the behavior of the model; the upper plenum was divided. Each ring of the upper plenum was connected to the corresponding fuel channels and the corresponding stand pipes. Radial cross flows where connected to allow for homogenization of the void and the mass flow in the upper plenum. The BWR-1 proved to have for steady state a high degree of homogenization to the extent that a difference between the models was likely to be small. The BWR-2 model proved to be poor in homogenization, the issue might be the relatively small difference in mass flow and void at the state point. The void and the mass flow into the steam separators were still relatively homogenous in the BWR-2 case.

For the BWR-1 a model without radial cross flows was generated to have a more extreme behavior of the void and the mass flux in the upper plenum and the steam separators. The model displayed large differences of void and mass flow as expected. The model had the theorized difference in mass of the upper plenum and the stand pipes; where the alternated model had more coolant than the reference model. The difference was theorized to increase as the number of radial rings increases and the void distribution in the core of the state points becomes more extreme. The model approach was abandoned since the differences in void and mass flow rendered the model impossible to utilize in longer simulations.

Low level transients where tested for the BWR-1 for three radial rings and five radial rings with radial cross flows. The transients proved radial differences in void and mass flow as expected. The differences where though small and induced no significant deviations in the behavior of the model from the reference model. The transient analysis proved little difference between the five rings and the three ring model, implying that the need for more radial rings in the model is not necessary.

The stability analysis for the BWR-1 proved no significant differences for the behavior of the models neither for the three rings model nor for the five rings model.

The BWR-2 model proved no significant discrepancies in the behavior of the stability analysis. The fact that the same conclusion was the product of an analysis conducted in a second plant model implies that the plant model in question is not significant for the general behavior of implying the model with radial cross flows.

7.2 CONCLUSION

The model without radial cross flows in the upper plenum demonstrated significant differences from the reference model and displayed that the theorized difference in coolant mass of the upper plenum and the steam separators can be modeled. The simulation approach was though unstable due to the extreme void and mass flux distribution whereas the model approach could not be further examined.

The model with radial cross flows in the upper plenum demonstrated no significant differences from the reference model neither for the transient analysis nor the stability analysis. For the stability analysis no differences could be seen regardless of state point, model, cycle point and plant model, this implies that the utilized model with divided upper plenum and steam
separators has no significant effect. The transient behavior demonstrated no significant
difference for the models utilized. The expected difference in behavior of the water level
decrease was not seen in results due to the effective homogenization of the void in the upper
plenum.

The effect rendering the divide of the steam separators with radial cross flows in the upper
plenum insignificant is the homogenization that takes place in the upper plenum. The physical
behavior is with all likeliness in between the two extremes of on one hand the total
homogenized presently used model and on the other the divided upper plenum without radial
cross flows. The utilized model in this study was located so close in behavior to the original
model in void and mass distribution that no significant differences could be located. Prior to
experimental results of radial void and mass flow distribution in the upper plenum being
generated simulations of a separate steam separator model is speculative at best.
REFERENCES

[1] WCAP-16747-P rev 0; POLCA-T: System Analysis Code with Three-Dimensional Core Model; Ulf Bredolt, Dobromir Panayotov, Mats Thunman, Camilla Rotander, Staffan Söderholtz; March 2007

[2] ISSN 0347-1071; Methods to identify stability properties for a thermohydraulic channel and from reactor noise measurements; Camilla Rotander; Stockholm 1999

Generally used references

SES 04-170 rev 0; NOG – Förstudie, förbättrad ångseparatormodel for dynamiska analysprogram; Ingemar Greis, Ulf Bredolt; 2005-04-07
Appendix 1: Control rod placement for stability analysis for the BWR-1

Figure 1: Power for reference case steady state

Figure 2: Control rod line distribution

Figure 3: Power for control rod line distribution for steady state
Appendix 1: Control rod placement for stability analysis for the BWR-1

Figure 4: Control rod pattern circle

Figure 5: Power of control rod pattern circle for steady state

Figure 6: Control rod pattern circle

Figure 7: Power of control distribution circle for steady state
Appendix 2: Axial node increase for BWR-1

Figure 1: CPR

Figure 2: CPR difference
Appendix 2: Axial node increase for BWR-1

Figure 3: Pressure fall over steam separators

Figure 4: Pressure fall difference over steam separators
Appendix 2: Axial node increase for BWR-1

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 2: Axial node increase for BWR-1

Figure 7: Mass flow in upper plenum highest node

Figure 8: Mass flow difference in upper plenum highest node
Appendix 2: Axial node increase for BWR-1

Figure 9: Heat generated in core

Figure 10: Heat difference
Appendix 3: Separate steam separators for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 3: Separate steam separators for BWR-1

Figure 3: CPR

Figure 4: CPR difference
Appendix 3: Separate steam separators for BWR-1

Figure 5: Pressure fall over steam separators

Figure 6: Pressure fall difference over steam separators
Appendix 3: Separate steam separators for BWR-1

Figure 7: Carry under

Figure 8: Carry under difference
Appendix 4: Upper plenum without cross flows for BWR-1

Figure 1: APRM

Figure 2: CPR
Appendix 4 : Upper plenum without cross flows for BWR-1

Figure 3: Pressure fall over steam separators

Figure 4: Carry under
Appendix 4: Upper plenum without cross flows for BWR-1

Figure 5: Mass flow in the highest node of upper plenum for five rings

Figure 6: Mass flow in the highest node of the upper plenum for model without cross flows
Appendix 4: Upper plenum without cross flows for BWR-1

Figure 7: Difference between actual mass flow and the area proportional mass flow for five rings

Figure 8: Difference between actual mass flow and area proportional mass flow for model without cross flows
Appendix 4: Upper plenum without cross flows for BWR-1

Figure 9: Void in upper plenum highest node for five rings

Figure 10: Void in upper plenum highest node for model without cross flows
Figure 1: APRM

Figure 2: APRM difference
Appendix 5: LRNBP 102p90f for BWR-1

Figure 3: CPR

Figure 4: CPR (minimum enhancement)

Figure 5: CPR difference
Figure 6: CPR placement

Figure 7: CPR placement (minimum enhancement)
Appendix 5: LRNBP 102p90f for BWR-1

Figure 8: Pressure fall over steam separators

Figure 9: Pressure fall difference over steam separators
Figure 10: Carry under

Figure 11: Carry under difference
Appendix 5: LRNBP 102p90f for BWR-1

Figure 12: Mass flow in highest node of the upper plenum for five rings

Figure 13: Mass flow in the highest node of upper plenum for three rings

Figure 14: Difference between actual mass flow and area proportional mass flow for three rings
Appendix 5: LRNBP 102p90f for BWR-1

Figure 15: Mass flow in the highest node of the upper plenum for five rings

Figure 16: Mass flow in the highest node of the upper plenum for five rings

Figure 17: Difference between actual mass flow and area proportional mass flow for five rings
Appendix 5: LRNBP 102p90f for BWR-1

Figure 18: Void in upper plenum highest node for three rings

Figure 19: Void in upper plenum highest node for five rings
Figure 20: Void in second ring of upper plenum for three rings

Figure 21: Void in second ring of the upper plenum for five rings
Appendix 5: LRNBP 102p90f for BWR-1

Figure 22: Water level

Figure 23: Water level difference
Figure 1: APRM

Figure 2: CPR
Appendix 6: LRNBP 64.5p42f for BWR-1

Figure 3: CPR (minimum enhancement)

Figure 4: CPR placement
Appendix 6 : LRNBP 64.5p42f for BWR-1

Figure 5: Pressure fall over steam separators

Figure 6: Carry under
Appendix 6: LRNPB 64.5p42f for BWR-1

Figure 7: Mass flow in the highest node of the upper plenum for three rings

Figure 8: Mass flow in the highest node of upper plenum for three rings

Figure 9: Difference between actual mass flow and the area proportional mass flow for three rings
Appendix 6: LRNBP 64.5p42f for BWR-1

Figure 10: Mass flow in the highest node of the upper plenum for five rings

Figure 11: Mass flow in the highest node of the upper plenum for five rings

Figure 12: Difference between actual mass flow and the area proportional mass flow for five rings
Figure 13: Void in upper plenum highest node for three rings

Figure 14: Void in upper plenum highest node for five rings
Appendix 6: LRNBP 64.5p42f for BWR-1

Figure 15: Void in the second ring of the upper plenum for three rings

Figure 16: Void in the second ring of the upper plenum for five rings
Figure 17: Water level
Appendix 7: LOAFW 102p90f for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 7: LOAFW 102p90f for BWR-1

Figure 3: CPR

Figure 4: CPR (minimum enhancement)
Figure 5: CPR difference

Figure 6: CPR placement
Figure 7: Pressure fall over steam separators

Figure 8: Pressure fall difference over the steam separators
Figure 9: Carry under

Figure 10: Carry under difference
Appendix 7: LOAFW 102p90f for BWR-1

Figure 11: Mass flow in the highest node of the upper plenum, three rings

Figure 12: Mass flow in the highest node of the upper plenum for three rings

Figure 13: Difference between actual mass flow and area proportional mass flow for three rings
Appendix 7: LOAFW 102p90f for BWR-1

Figure 14: Mass flow in the highest node of the upper plenum for five rings

Figure 15: Mass flow in the highest node of the upper plenum for five rings

Figure 16: Difference between actual mass flow and area proportional mass flow for five rings
Appendix 7: LOAFW 102p90f for BWR-1

Figure 17: Void in upper plenum highest node for three rings

Figure 18: Void in upper plenum highest node for five rings
Figure 19: Void in the second ring of the upper plenum for three rings

Figure 20: Void in the second ring of the upper plenum for five rings
Appendix 7 : LOAFW 102p90f for BWR-1

Figure 21: Water level

Figure 22: Water level differences
Figure 1: APRM

Figure 2: APRM differences
Appendix 8 : LOAFW 64.5p42f

Figure 3: CPR

Figure 4: CPR (minimum enhancement)
Figure 5: CPR difference

Figure 6: CPR placement
Figure 7: Pressure fall over the steam separators

Figure 8: Pressure fall difference over the steam separators
Figure 9: Carry under

Figure 10: Carry under
Figure 11: Carry under difference

Figure 12: Carry under difference (enhanced)
Appendix 8: LOAFW 64.5p42f

Figure 13: Mass flow in the highest node of the upper plenum for three rings

Figure 14: Mass flow in the highest node of the upper plenum for three rings

Figure 15: Difference between actual mass flow and area proportional flow for three rings
Appendix 8: LOAFW 64.5p42f

Figure 16: Mass flow in the highest node of the upper plenum for five rings

Figure 17: Mass flow in the highest node of the upper plenum for five rings

Figure 18: Difference between actual mass flow and the area proportional mass flow for five rings
Figure 19: Void in the second ring of the upper plenum for three rings

Figure 20: Void in the second ring of the upper plenum for five rings
Figure 21: Void in upper plenum highest node for three rings

Figure 22: Void in upper plenum highest node for five rings
Figure 23: Water level (Narrow range monitor)

Figure 24: Water level difference (Narrow range monitor)
Figure 25: Water level (Wide range monitor)

Figure 26: Water level difference (Wide range monitor)
Appendix 9: Control rod disturbance 64.5p42f for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 9: Control rod disturbance 64.5p42f for BWR-1

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Appendix 9 : Control rod disturbance 64.5p42f for BWR-1

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 10: Control rod disturbance

Figure 1: APRM

Figure 2: APRM difference
Appendix 10: Control rod disturbance

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separator
Appendix 10: Control rod disturbance 74.5p42f

Figure 5: Carry under

Figure 6: Carry under difference
Figure 1: APRM

Figure 2: Pressure fall over the steam separators
Figure 3: Carry under
Appendix 12: Control rod disturbance 53p25f

Figure 1: APRM

Figure 2: APRM difference
Appendix 12: Control rod disturbance 53p25f

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Figure 5: Carry under

Figure 6: Carry under difference
Appendix 13: Control rod disturbance for line control rod pattern for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 13: Control rod disturbance for line control rod pattern for BWR-1

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Appendix 13: Control rod disturbance for line control rod pattern for BWR-1

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 14: Control rod disturbance for ring control rod pattern for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 14: Control rod disturbance for ring control rod pattern for BWR-1

Figure 3: Pressure fall over steam separators

Figure 4: Pressure fall difference over steam separators
Appendix 14: Control rod disturbance for ring control rod pattern for BWR-1

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 15: Control rod disturbance for circle control rod pattern for BWR-1

Figure 1: APRM

Figure 2: APRM difference
Appendix 15: Control rod disturbance for circle control rod pattern for BWR-1

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Figure 5: Carry under

Figure 6: Carry under difference
Appendix 16: Control rod disturbance for 91.3p29.22f for BWR-2 with EFPH 0

Figure 1: APRM

Figure 2: APRM difference
Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Appendix 16: Control rod disturbance for 91.3p29.22f for BWR-2 with EFPH 0

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 17: Control rod disturbance for 91.1p26.62f for BWR-2 with EFPH 0

Figure 1: APRM

Figure 2: Pressure fall over the steam separators
Figure 3: Carry under
Appendix 18: Control rod disturbance for 96.6p28.87f for BWR-2 with EFPH 0

Figure 1: APRM

Figure 2: APRM difference
Appendix 18: Control rod disturbance for 96.6p28.87f for BWR-2 with EFPH 0

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Figure 5: Carry under

Figure 6: Carry under difference
Appendix 19: Control rod disturbance for 91.3p29.22f for BWR-2 with EFPH 6000

Figure 1: APRM

Figure 2: APRM difference
Appendix 19: Control rod disturbance for 91.3p29.22f for BWR-2 with EFPH 6000

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Appendix 19: Control rod disturbance for 91.3p29.22f for BWR-2 with EFPH 6000

Figure 5: Carry under

Figure 6: Carry under difference
Appendix 20: Control rod disturbance for 91.3p26.62f for BWR-2 with EFPH 6000

Figure 1: APRM

Figure 2: APRM difference
Appendix 20: Control rod disturbance for 91.3p26.62f for BWR-2 with EFPH 6000

Figure 3: Pressure fall over the steam separators

Figure 4: Pressure fall difference over the steam separators
Appendix 20: Control rod disturbance for 91.3p26.62f for BWR-2 with EFPH 6000

Figure 5: Carry under

Figure 6: Carry under difference