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# International Agreement Report

# Assessment of RELAP5/MOD2 Against a Natural Circulation Experiment in Nuclear Power Plant Borssele

Prepared by
L. Winters

Ministry of Social Affairs
Nuclear Inspectorate (KFD)
Netherlands Energy Research Foundation ECN
P.O. Box 1
1755 ZG Petten
The Netherlands

**Office of Nuclear Regulatory Research**
**U.S. Nuclear Regulatory Commission**
**Washington, DC 20555**

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Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Thermal-Hydraulic Code Assessment
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ABSTRACT

As part of the ICAP (International Code Assessment and Applications Program) agreement between ECN (Netherlands Energy Research Foundation) and USNRC, ECN has performed a number of assessment calculations for the thermohydraulic system analysis code RELAP5/MOD2/36.05. This document describes the assessment of this computer program versus a natural circulation experiment as conducted at the Borssele Nuclear Power Plant. The results of this comparison show that the code RELAP5/MOD2 predicts well the natural circulation behaviour of Nuclear Power Plant Borssele.

The work has been sponsored by the Dutch Licensing Authority and ECN.

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## 1. INTRODUCTION

Following a reactor scram and trip of the reactor coolant pumps in a pressurized water nuclear power plant (PWR), decay heat removal may be established by means of natural circulation. The natural circulation phenomena have been investigated experimentally by many international research organisations. Well known natural circulation experiments have been conducted in the LOFT, Semiscale, PKL and LOBI facilities. In general these facilities are scaled down versions of commercial plants, however, all have their specific limitations with respect to natural circulation. The LOFT facility has been equiped with one steam generator while the elevations of the components are a-typical. Semiscale, PKL and LOBI have component elevations comparable with a commercial plant while volumes have been scaled down drastically. The resulting small pipe diameters may strongly influence the natural circulation phenomena. For this reason natural circulation experiments in full size installations are usefull to confirm the data from the experimental facilities.

Theoretical considerations suggest that the natural circulation flow in a loop will stagnate under certain conditions. A stagnating flow in a loop of a nuclear power plant is not desirable due to possible deboration in the core and consequential reactivity effects after stagnation is discontinued. Another point of concern is the formation of a steam bubble in the stagnant loop during depressurization due to the relative hot water in the loop.

In Borssele Nuclear Power Plant (KCB) a natural circulation experiment has been performed with the objective to investigate the natural circulation phenomena and the possible occurance of flow stagnation in the event of an isolated steam generator. ECN has performed assessment calculations based on the available experimental data using the thermohydraulic system analysis code RELAP5/MOD2/36.05, ref. [1].

The outline of this document has been chosen in accordance with the recommendations as given in NUREG-1271, ref. [2]. A description of the experiment is given in chapter 2 while the RELAP5 input model has been described in chapter 3. Chapter 4 and 5 respectively present the results of the analyses and a comparison with the experimental data.

## 2. NATURAL CIRCULATION EXPERIMENT AT NPP BORSSELE

### 2.1. Description of the Nuclear Power Plant

Nuclear Power Plant Borssele (KCB) is a two-loop, 1365 $MW_{th}$ Pressurized Water Reactor (PWR) designed by Kraftwerk Union (KWU) and owned by the Provinciale Zeeuwse Energie Maatschappij (PZEM). The plant is located near the town of Vlissingen in the South West part of the Netherlands, and operating since 1973. A schematic picture of the plant including relative elevations is given in figure 2.1. The inside diameter of the primary loop piping is 0.8 m. The nuclear core has 121 fuel elements with a heated length of 2.65 m. The two steam generators are U-tube steam generators with a total production at full power of 734 kg/s dry steam at a pressure of 5.7 MPa. Each steam generator has 4234 Incoloy U-tubes with a total surface of 3600 $m^2$. The internal diameter of a U-tube is 0.0196 m and the wall thickness is equal to 0.0012 m. Table 2.1 gives some important nominal system parameters of KCB.

### 2.2. Natural circulation experiment

A description of the natural circulation experiment is given in ref. [3] and [4]. Before execution of the natural circulation test the KCB plant had been in operation almost continuously for a period of 10 months. On February 5, 1983 at 01h. 00m., shutdown of the plant was started in preparation for refueling. At 06h. 00m. the reactor became subcritical. The natural circulation experiment started at 13h. 45m. the same day by tripping the two reactor coolant pumps. The test lasted about 4 hrs during which different actions were taken in order to establish the right conditions for the test.

The sequence of events of the experiment is given in table 2.2 (the step numbers are shown also in figure 2.2 and 2.3). In this table two times are given viz. the actual time (hrs, m, s) and the relative time with respect to the start of the experiment (s). In figure 2.2 and 2.3 the measured secondary side pressures and the temperature differences across the loops are given.

During the experiment the Volume Controle System (VCS) was in operation. The temperature of the VCS injection water as a function of time is given in table 2.3. There is no measurement of the VCS mass flow available.

## 2.3. Experimental data

Because there was no opportunity to install additional measuring instruments only the signals of selected plant process instruments were recorded. The signals recorded by the process instrumentation and the location of the measuring devices are given in table 2.4. The location in the table gives the loop identification (Cold Leg (CL) and Hot Leg (HL) loops 01 and 02), the location of the measurement device on the main coolant pipe (0° = top of the pipe) and the distance of the device to the centerline of the reactor vessel (RV) or bottom of the steam generator pipe plate (main coolant pipe vertical).
All temperature measurements have been performed using Ni-Cr thermocouples, the system pressure by a so-called Bourdon cell and the liquid level in steam generators and pressurizer by means of a pressure difference measurement. No possibility exists to measure mass flows in the main loops of the primary system. In the experiment the occurence of natural circulation can be demonstrated by evaluation of the different temperature measurements. All the signals have been recorded on paper charts only. In order to make a comparison with calculated data easy the measured data of the strip charts was digitized by hand and stored on magnetic tape.

There is no qualification and uncertainty analysis of measured and recorded data available. Also some important information to understand discrepancies in the test is missing or not well documented.

Table 2.1. KCB system parameters

| | |
|---|---|
| Nuclear power | 1365.6 $MW_{th}$ |
| System pressure | 15.5 MPa |
| Total core mass flow | 10000 kg/s |
| Vessel outlet temperature | 588 K |
| Number of fuel elements | 121 |
| Core average heat flux | 615000 $W/m^2$ |
| Steam generator outlet pressure | 5.70 MPa |
| Total steam mass flow | 734 kg/s |

Table 2.2. Sequence of events of natural circulation test

1. Time 13.45.00 (t = 0.0 s).
   Both reactor coolant pumps are tripped. A few minutes later a stable natural circulation flow is established in both loops.
2. Time 13.59.00 (t = 840 s).
   Steam generator 01 is isolated by closing the feedwater and the main steam valves.
3. Time 14.50.00 (t = 3900 s).
   During 360 s the primary system is cooled down with a gradient of 100 K/hr (in accordance with the procedures). The cooling down is created by a depressurization of about 0.02 MPa/min of the secondary side of steam generator 02.
4. Time 14.54.00 (t = 4140 s).
   Injection of auxiliary feedwater into steam generator 02 during 540 s.
5. Time 15.15.00 (t = 5400 s).
   Isolation of steam generator 01 discontinued by reconnecting the steam generator to the feedwater and steam lines. Due to the connection line between the main steam lines the pressure on the secondary side of the steam generators is balanced again.

6. Time 15.37.00 (t = 6720 s).
   Isolation of steam generator 02 by closing the feedwater and main steam valves.
7. Time 15.56.00 (t = 7860 s). The primary system is cooled down during 2100 s at a gradient of 50 K/hr. The cooling down is created by a controlled depressurization of the secondary side of steam generator 01.
8. Time 16.52.00 (t = 11220 s).
   Isolation of steam generator 01 by closing the feedwater and main steam valves. At this point both steam generators are isolated.
9. Time 17.22.00 (t = 13020 s).
   Isolation of both steam generators is discontinued by reconnecting each to the main steam and feedwater lines.
10. Time 17.34.00 (t = 13740 s).
    Isolation of steam generator 01 by closing the feedwater and main steam valves.
11. Time 17.54.00 (t = 14940 s).
    Discontinuation of isolation of steam generator 01 by reconnecting it to the main steam and feedwater line.
12. Time 18.00.00 (t = 15300 s).
    End of the test.

Table 2.3. Water temperature of the VCS

| Time interval | Temperature (K) |
|---|---|
| start - 14.42.00 | 513 |
| 14.42.00 - 14.50.00 | 503 |
| 14.50.00 - 15.15.00 | 502 |
| 15.15.00 - 15.37.00 | 494 |
| 15.37.00 - 16.56.00 | 490 |
| 16.56.00 - 17.22.00 | 469 |
| 17.22.00 - end | 473 |

Table 2.4. Recorded signals

| | Sensor | Measurement | Location |
|---|---|---|---|
| * | YA01T090 | temperature | CL01, -30°, 10.470 m to ℄ RV |
| * | YA02T090 | temperature | CL02, -30°, 10.470 m to ℄ RV |
| * | YA01T098 | temperature | HL01, 30°, 8.424 m to ℄ RV |
| * | YA02T098 | temperature | HL02, 30°, 8.424 m to ℄ RV |
| | YA01T011/01 | temperature | CL01, NA 3.0140 m to SG pipe plate |
| | YA01T011/02 | temperature | HL01, - 75°, 8.424 m to ℄ RV |
| | (YA01T011 | avg. temp. | avg. of YA01T011/01 and YA01T011/02) |
| | YA02T011/01 | temperature | CL02, NA 3.0140 m to SG pipe plate |
| | YA02T011/02 | temperature | HL02, - 75°, 8.424 m to ℄ RV |
| | (YA02T011 | avg. temp. | avg. of YA02T011/01 and YA02T011/02) |
| | YA01T054/01 | temperature | CL01, - 60°, 10.970 m to ℄ RV |
| | YA01T054/02 | temperature | HL01, - 25°, 8.424 m to ℄ RV |
| * | (YA01T054 | temp. diff. | YA01T054/02-YA01T054/01) |
| | YA02T054/01 | temperature | CL02, - 60°, 10.970 m to ℄ RV |
| | YA02T054/02 | temperature | HL02, - 25°, 8.424 m to ℄ RV |
| * | (YA02T054 | temp. diff. | YA02T054/02-YA02T054/01) |
| * | YA01P002 | pressure | HL01, 120°, 9.335 m to ℄ RV |
| * | RA01P001 | pressure | main steam line loop 01 |
| * | RA02P001 | pressure | main steam line loop 02 |
| * | YB01L051 | liquid level | steam generator 01 |
| * | YB02L051 | liquid level | steam generator 02 |
| * | YP01L101 | liquid level | pressurizer |

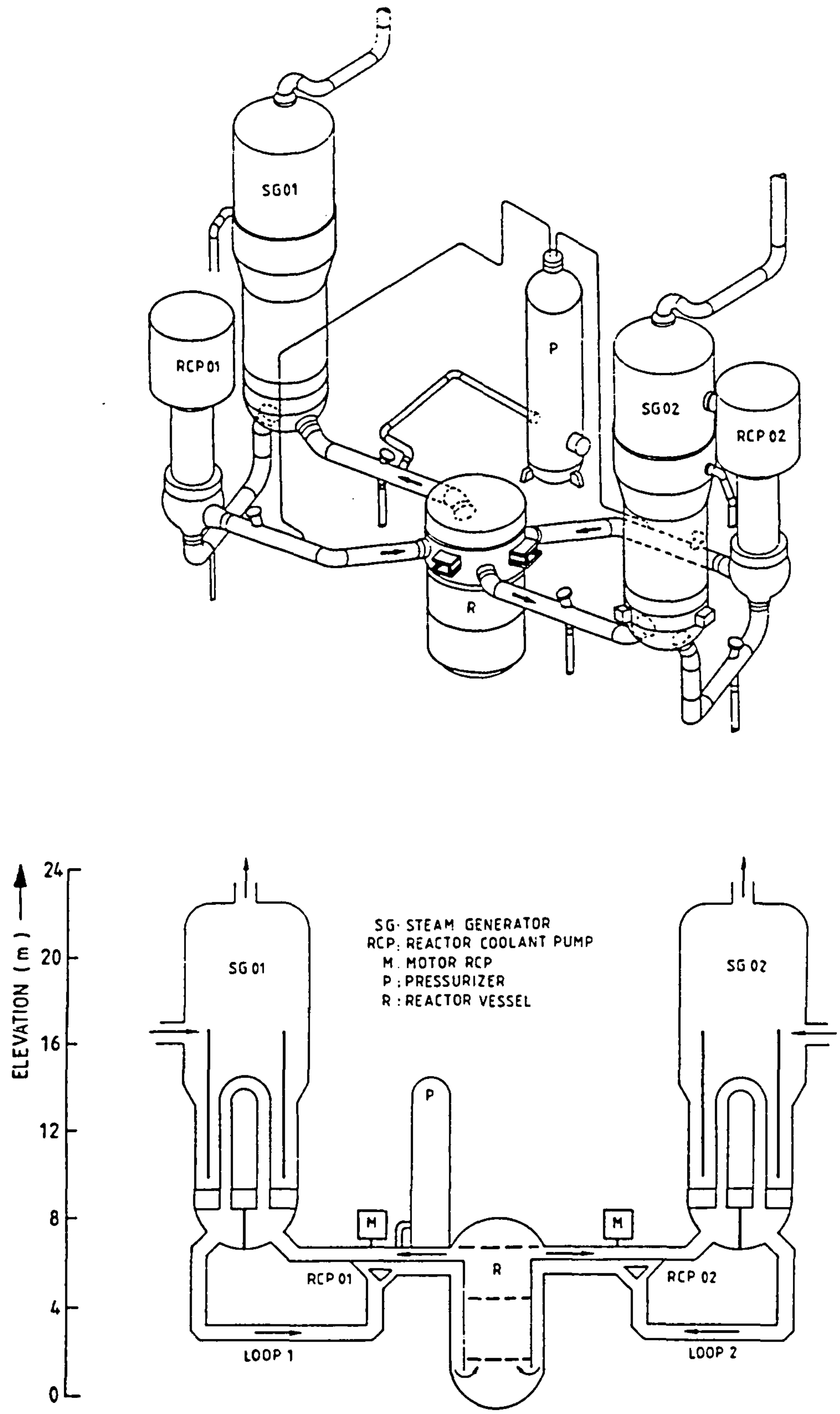


Fig. 2.1. Nuclear Power Plant Borssele:

(a) schematic

(b) elevation of components

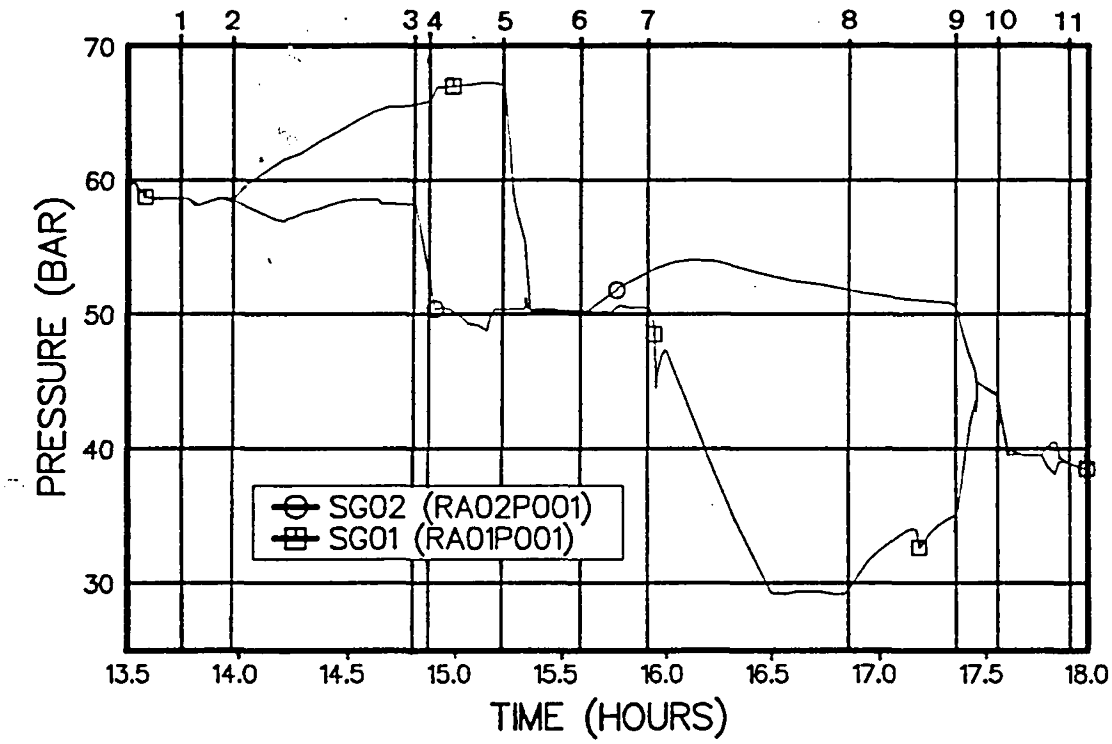


Fig. 2.2. Measured secondary side pressure transient during natural circulation experiment. Ref. [3].

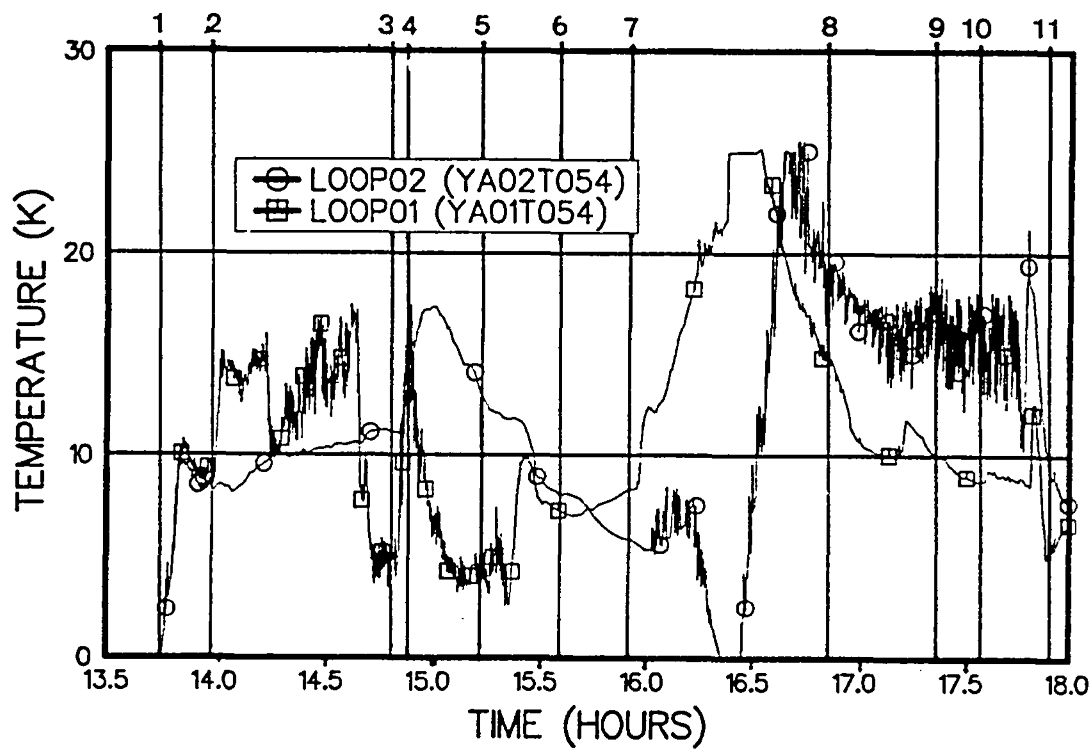


Fig. 2.3. Measured temperature difference between hot and cold legs during natural circulation experiment. Ref. [3].

## 3. RELAP5/MOD2 INPUT MODEL

### 3.1. Thermal hydraulic and control system model

As part of a cooperative program between ECN and the Dutch Licensing Authority (KFD) the Netherlands Energy Research Foundation has developed a RELAP5/MOD2 input model for the Borssele NPP.
The model has extensively been used for the purpose of transient analyses sponsored by the KFD and the operator of the plant (PZEM).
The same input model has been used for analysis of the natural circulation experiment.

The RELAP5 input model consists of 142 volumes, 160 junctions and 85 heat structures. The corresponding nodalization diagram is shown in figure 3.1. The two primary loops have been modelled separately and are designated as loop 01 and 02. The pressurizer is connected to loop 01 and the pressurizer spray lines are attached to the outlet of the two reactor coolant pumps. The reactor coolant pumps are modelled with the pump component of RELAP5. The homologous curves to describe the pump behaviour under two phase conditions have been obtained from manufacturers data as well as scaled experiments using similar pumps.

In the reactor vessel two leakage paths are represented: bypass of the fuel elements in the core and leakage from downcomer inlet to upperhead.

The secondary sides of the two steam generators are modelled identically. The separators and the dryers in the steam generators are represented within one single volume, at the separator location. The steam lines from the steam generator to the turbine have been modelled separately. The system boundaries for this part of the model are the steam bypass valves, the relief valves and the turbine valves.
The feedwater piping has been modelled starting off with the feedwater pumps.

The Emergency Core Cooling (ECC) system of the Borssele NPP makes use of combined injection into the primary loops (ECC water enters both the hot and cold legs). The simplified RELAP5 ECC model injects half of the total ECC flow in each loop and the flow is than equally divided across both injection points.

The Volume Control System (VCS) has been modelled and is connected to the reactor coolant pump inlet and outlet of both loops.

Heat structures are included to simulate the different heat sources, heat transfer areas and stored energy. The structures connected to the vessel model represent the fuel rods as well as the metal mass of the reactor vessel internals and vessel wall. The heat slabs connected to the pressurizer simulate the pressurizer wall and the heater elements. For the secondary side of the steam generators the heat slabs represent the internals structures (separator, steam dryer, inner shell), the steam generator outer shell as well as the U-tube heat transfer area between primary and secondary side. The wall of the piping of the primary circuit has not been included in the model.

The RELAP5/MOD2 input model includes control systems for the steam generator water level, the primary pressure as well as the pressurizer level. In the analysis of the natural circulation experiment however the steam generator control system for the liquid level has not been activated. A detailed description of the RELAP5 input model for KCB is given in ref. [5]. A brief description of the input model is presented in Appendix A.

## 3.2. Initial conditions

Just prior to the start of the natural circulation experiment in NPP Borssele the decay heat in the core was estimated at 13 MW and both reactor coolant pumps were running. Because of a known deficiency in the code concerning the dissipation of pump energy within the primary system the heat generation in the core is slightly modified for the calculation of steady initial conditions. The RELAP5/MOD2 code only accounts for wall friction dissipation while the form loss energy is neglected. In the RELAP5 model for NPP Borssele about 54% of the pump energy is lost in this way. In order to get a correct energy balance 54% of the power of the main coolant pumps is added to the power production in the core and the steam bypass valve is controlled to an opening sufficient to remove decay heat and total pump energy. For the steady state calculation is the steam generator feedwater flow balanced with the steam flow so the collapsed level is kept constant at the desired value. The steady state plant conditions as calculated by RELAP5/MOD2 have been compared against plant data as shown in table 3.1. The experimental values for the initial condition are obtained from the recorded plant data just prior to the start of the natural circulation experiment. The calculated initial conditions are in good agreement with the measured initial conditions.

## 3.3. Assumptions for the simulation

Based on the calculated steady state conditions the next assumptions have been made in order to simulated the experiment adequately.

- At time zero when the reactor coolant pumps are tripped, the core power is reset to the desired value of 13 MW. At the same time the steam bypass valve has been reset to a value sufficient to remove core power and the feedwater is balanced with the steam flow. There is no direct measurement to confirm the reset position of the steam bypass valve. Because after the main coolant pump trip the pressure measurement of the secondary side pressure shows an almost constant pressure it is assumed that the opening of the steam bypass valve is just sufficient to remove the decay heat.

- In the simulation model the feedwater control is strongly simplified. At time zero the feedwater mass flow has been reset to the steam mass flow in order to keep the steam generator liquid level constant. During the analysis the feedwater flow is kept constant when feedwater is available and the feedwater flow is set to zero when the steam generator has been isolated.

- There is no information available on the behaviour of the primary system pressure controller during the experiment. Because relatively small pressure changes do have only minor influence on the natural circulation behaviour a simplified pressure control is modelled. For this purpose the pressure controller in the RELAP5 model is replaced by a simple time-dependent volume which keeps the system pressure during the test at a constant level.

- Due to lack of information about the mass flows of the Volume Control System it is assumed that the primary system liquid level controller is not in operation. The mass flows of the Volume Control System are constant during the simulation, charge and discharge flows are balanced at 4.4 kg/s per loop.

Table 3.1. Experimental and calculated initial conditions

| Parameter | Experiment | RELAP5 |
|---|---|---|
| Core thermal power | 13.00 MW | 13.00 MW |
| Hot leg pressure | 15.35 MPa | 15.32 MPa |
| Cold leg temperature | 549.0 K | 548.4 K |
| Core temperature difference | -- | 0.3 K |
| Core mass flow | -- | 9623 kg/s |
| Pressurizer water level | 4.44 m | 4.45 m |
| Steam generator outlet pressure | 5.86 MPa | 5.84 MPa |
| Feedwater mass flow | -- | 5.8 kg/s |
| Feedwater temperature | -- | 489.2 K |
| Steam generator water inventory | -- | 44300 kg |
| Steam generator liquid level | 7.85 m | 7.96 m |

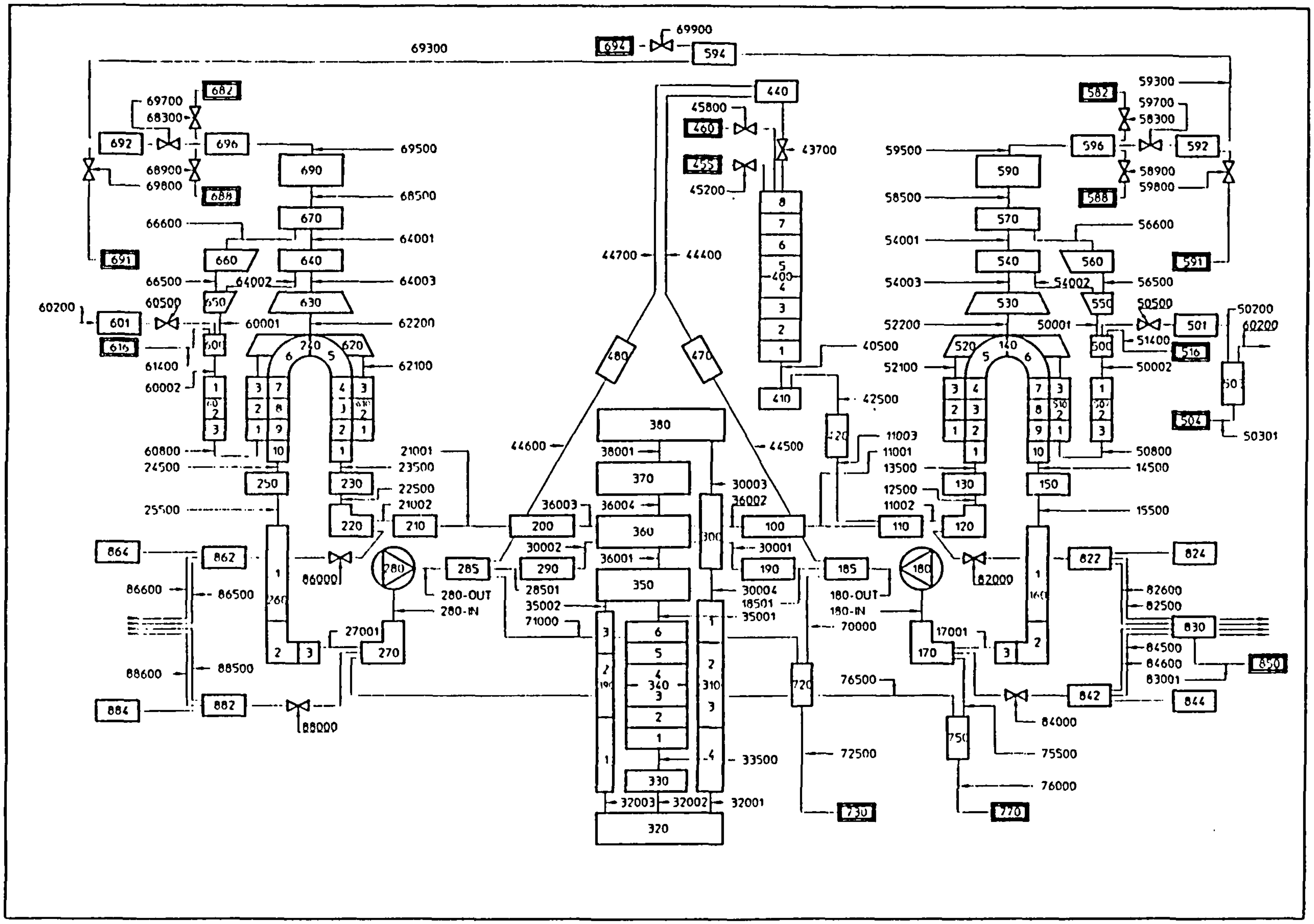


Figure 3.1. RELAP5 nodalization of KCB

## 4. RELAP5/MOD2 ANALYSIS OF THE NATURAL CIRCULATION EXPERIMENT

In this chapter the RELAP5/MOD2 results are presented as obtained from the analysis of the natural circulation experiment. Furthermore an explanation of the occuring phenomena is given.

The analysis starts with the steady state condition for KCB at nominal flow conditions and a core thermal power of 13 MW. The sequence of events of the analysis is given in table 4.1 while the main parameters of analysis are presented in figure 4.1 through 4.7.

The main driving forces for natural circulation are the differences in hydrostatic fluid pressure between downcomer and core within the reactor pressure vessel and between the upward and downward legs of the steam generator U-tubes and in the loop seal. The hydrostatic pressure difference terms are given by summation of the "$\rho gh$" terms for each of the three vertical components. In Appendix B a more comprehensive explanation of the driving forces is given.

An explanation of the calculated system behaviour will be given next for the different periods as defined in table 4.1 . In the analysis of the results the figures 4.1 through 4.7 are extensively used but no reference is given in the text.

0-840 s.

After trip of the reactor coolant pumps at time zero, the pumps coast down and a natural circulation mass flow of about 165 kg/s is established in both loops. The temperature difference across the core increases from 0.3 K towards 7.7 K. The driving force for the natural circulation is generated inside the core and in both steam generators. Heat transfer into and out of the primary system are balanced; almost 95% of the total energy generated in the core is removed equally by the steam generators while the remaining 5% is lost in the Volume Control System. At the end of this period almost steady state conditions exist inside the primary system.

840-3900 s.

At time = 840 s steam generator 01 is being isolated (closure of the main steam isolation valve and interruption of feedwater). The secondary pressure in steam generator 02 is kept constant by the pressure control system in the model. After isolation decreases the heat transfer to steam generator 01 to zero and all the heat generated in the core is removed from the system through steam generator 02. After redistribution of the heat transfer is established the system converges to a steady state with equal hot leg temperatures in the loops and no driving force in steam generator 01. The pressure at the secondary side of the isolated steam generator levels out close to the saturation pressure of the hot leg temperature. The natural circulation in loop 01 is caused only by the driving force from the reactor vessel while in loop 02 a larger natural circulation is established due to the existence of a driving force from reactor vessel core and steam generator 02. The mass flows in loop 01 and 02 resp. level out at 96 kg/s and 202 kg/s.

3900-4260 s.

During this period the primary system is cooled down at a rate of 100 K/hr by depressurizing steam generator 02. The cooling down in steam generator 02 causes an almost immediate increase of the driving force in steam generator 02 (outlet of steam generator 02 decreases in temperature while the inlet has a constant temperature). The colder fluid moving through loop 02 causes delayed also an increase in driving force in the core. Again somewhat later in time the colder fluid arrives at the inlet of steam generator 01. Because the outlet of the isolated steam generator is constant and the inlet temperature decreases, a decrease to a negative driving force in steam generator 01 is created. This negative driving force in steam generator 01 compensates the net driving force of the core resulting in a stagnation in loop 01. The 360 s cooling down time is not sufficient to reach a steady state condition. Due to the relative long "refresh" time of the loops and the core (due to the small mass flows it lasts long to replace the water in a component) the effect goes on after discontinuation of the cooling down.

4260-5400 s.
At time = 4260 s the cooling down of the primary system is discontinued and the secondary side pressure is controlled constant at its last value. The maximum negative driving force in the steam generator 01 is set by the temperature difference between the secondary sides of the two steam generators. The primary fluid entering steam generator 01 has a temperature equal to the secondary side fluid of steam generator 02 while the fluid leaving steam generator 01 has a temperature equal to the secondary side fluid of steam generator 01. The maximum (negative driving force) will not be reached because a smaller temperature difference already causes a negative driving force resulting in an almost stagnant mass flow in loop 01. At the end of the period an almost steady state condition is reached with a mass flow in loop 01 of 5 kg/s and in loop 02 of 222 kg/s.

5400-6720 s.
At time = 5400 s the isolation of steam generator 01 is discontinued and a return to the situation described in time frame 0-840 s is observed. Discontinuation of the isolation causes a rapid decrease of the primary fluid temperature in the U-tubes of steam generator 01. The effect of this temperature decrease is a shrinkage of the fluid followed by a change of the temperature gradient in the U-tubes. Due to the shrinkage there is an immediate increase of the mass flow through steam generator 01. The resulting change of the temperature gradient in steam generator 01 causes an increase of the driving force and this again gives another increase of mass flow in loop 01. After some oscillations in driving forces in core and steam generator region, due to "refresh" time of the components of the primary system, a steady state condition is established. The steady state mass flow in both loops is 163.5 kg/s and the core temperature difference is 7.8 K. This condition is very close to the mass flows in the loops and the core temperature difference observed at the end of time frame 0-840 s.

6720-7860 s.
At time = 6720 s steam generator 02 is being isolated (closure of the main steam isolation valve and interruption of feedwater). The obser-

ved behaviour is symmetric compared to the behaviour in the period 840-3900 s. The total time in this period (1140 s) is to short to reach a steady state condition but the system behaviour is a reflection of the observed behaviour in period 840-3900 s. The loop mass flows at the end of the period are 188 kg/s and 117 kg/s while the core temperature difference 8.3 K is.

7860-9960 s.

At time = 7860 s the primary system is cooled down with a gradient of 50 K/hr during 2100 s by means of depressurization of steam generator 01. The behaviour during this cooling down phase is similar to the system behaviour during the time interval 3900-4260 s. Cooling down of steam generator 01 causes a temperature decrease of the fluid in the hot leg of loop 02. The decreasing fluid temperature at the inlet of steam generator 02 and the constant fluid temperature at the outlet causes a decreasing driving force in steam generator 02 and so a decreasing mass flow in loop 02. Due to the small mass flow in loop 02 and the injection of relatively cold water from the Volume Control System into the cold leg, a strong increase of the temperature difference across loop 02 is observed.

Just prior to the end of the period the driving force in steam generator 02 starts to increase while the driving force of loop seal 02 starts to decrease. This effect is caused by the onset of a negative mass flow in loop 02. An additional analysis in which the boundary conditions are maintained beyond t = 9960 s shows the following behaviour. The slow decreasing fluid temperature at the inlet of steam generator 02 causes a decreasing mass flow. When the mass flow gets negative it sudden decreases to about -35 kg/s and then increases back to zero and stagnates. This all happens in the time between 9750 s and 10150 s. The mass flow behaviour can be explained by the driving forces in loop 02. The reversed flow causes, due to cold water of the Volume Control System, a negative driving force in the loop seal of loop 02 and an increasing driving force in steam generator 02. For the positive driving force in steam generator 02 and the core it is impossible to overcome the large negative driving force in loop seal 02 resulting in a stagnant mass flow.

9960-11220 s.

At time = 9960 s the cooling down of the primary system by means of steam generator 01 is interrupted and the pressure on the secondary side of the steam generators is kept constant. In this period the system behaviour is more or less a reflection of the behaviour during time period 4260-5400 s and moreover a continuation of the behaviour observed at the end of the previous period. A small reversed mass flow in loop 02 pushes cold water from the Volume Control System inlet into the steam generator leg of the loop seal causing a decreasing driving force in the loop seal. Moreover, relatively cold water is pushed into the downward leg of steam generator 02 causing an increase in driving force in this region. The result of the driving forces in core, steam generator 02 and loop seal 02 region is a very small (1-2 kg/s) negative mass flow in loop 02. The time period is to short to reach a steady state condition in loop 01, but the system moves towards a zero mass flow in loop 02. Due to the decrease in driving force in loop 01 (less heat transfer in steam generator 01) the mass flow in loop 01 decreases from 250 kg/s to 223.5 kg/s.

11220-13020 s.

At time = 11220 s steam generator 01 is also isolated. During this part of the transient both steam generators have been isolated and the heat generated in the core is added to the primary system. After both steam generators have been isolated the fluid temperatures in loop 01 and the secondary side of steam generator 01 increase. Due to the heating up of the secondary side of steam generator 01 decreases the driving force in steam generator 01 drastically. This driving force added to the driving force of the core maintains a smaller natural circulation in loop 01 (180 kg/s). The stagnant loop 02 is not affected by the heating up of the primary and secondary side of loop 01.

13020-13740 s.

At time = 13020 s isolation of steam generators 01 and 02 is discontinued by opening of both main steam isolation valves and restoring the feedwater flow. After the main steam isolation valves have been opened the pressure on the secondary side of the steam generators is kept constant. By coincidence are the secondary side pressures of both isolated steam generators equal just prior to discontinuation of the isolation (t = 13020 s). So the reconnection of the steam generators to the main steam line does not give a large discontinuity in heat transfer in one of the steam generators. Because steam generator 02 has a stagnant flow all the heat produced in the core must be removed by steam generator 01. The increasing heat transfer in steam generator 01 causes an increase in driving force and so in mass flow in loop 01. The time period is to short to reach a steady state condition but the natural circulation mass flow in loop 01 is of the magnitude of 215 kg/s. In contrast with the system behaviour at time = 5400 s is the mass flow in the stagnant loop not restored. The main reason for the difference in system behaviour is the pressure level at the secondary side of the steam generators at which discontinuation of the isolation takes places. The main steam isolation valve is being closed when the two secondary side pressures are almost identical and so a discontinuity in the primary system fluid temperature is avoided.

13740-14940 s.
After discontinuation of the isolation of the steam generators in the previous time period remains the mass flow in loop 02 stagnated. In order to restore the mass flow steam generator 01 is being isolated. The behaviour of the system is a copy of the system behaviour after time = 840 s. However due to stagnation in loop 02 all the heat has to be removed by steam generator 02. This causes a more rapid increase of the primary system temperature in loop 01 and secondary pressure of steam generator 01.

14940-15900 s.
At time = 14940 s the isolation of steam generator 01 is discontinued. The pressure at the secondary side of steam generator 01 drops to the setpoint value of the pressure controller and a strong cooling down by steam generator 01 is introduced.
The cooling down of primary system fluid in steam generator 01 causes shrinkage and a strong increase of the driving force in the steam generator resulting in an increasing mass flow in loop 01. The increasing mass flow causes an increasing driving force in the core

resulting in a positive mass flow in loop 02. This mass flow ends the negative driving force of the loop seal in loop 02 resulting in an increasing mass flow. After some oscillations the natural circulation in both loops is re-established. At the end of the period the mass flow is 158 kg/s in both loops.

The general behaviour of the primary coolant system during the natural circulation experiment can be characterized as follows:
After the trip of the reactor coolant pumps natural circulation is established in the loops. After a steady state condition has been established in the primary system a simple relation exists between the natural circulation mass flow and the heat production in the core.

$\dot{m} = C\, Q^{1/3}$

$\dot{m}$ = natural circulation mass flow in the core

Q = heat production in the core

C = constant

The relation exists when all the heat produced in the core is removed equally by the steam generators. In Appendix B a derivation of the relation is presented.

Isolation of a steam generator while keeping the average primary system temperature constant (all the heat produced in the core is removed by the non-isolated steam generator) maintains a natural circulation mass flow in the loops of the primary system. The analysis shows, at an almost constant core mass flow, a redistribution of the mass flows over the loops. The redistribution of the mass flows over the loops strongly depends on the distribution of the hydraulic resistances over the system.

Cooling down of the primary system by depressurizing one of the steam generators results in the RELAP5 analysis in stagnation of the mass flow in the other loop. The cooling down rate sets the time to get to flow stagnation.

Possibilities to restore the mass flow in a stagnant loop depend strongly on the temperature distribution in the loop. In the analysis this sensitivity is shown by the influence of the location of the Volume Control System injection line. Cold water is added close to the loop seal and the temperature distribution in this vertical oriented part of the system is important for the driving force. A negative driving force in this part of the primary system has to be overcome by the rest of the driving forces in order to restore mass flow in the loop. The analysis shows that a sudden increase of heat transfer in one of the steam generators (depressurization of the steam generator) is able to restore the natural circulation in the stagnant loop. Probably a sudden decrease of heat transfer to a steam generator will show the same effect. However, a sudden pressure increase on the secondary side of the steam generator is hard to realize.

Table 4.1. Sequence of events for simulation of the natural circulation experiment

| Time(s) | Event |
|---|---|
| 0.0 | Reactor coolant pumps tripped. |
| 840.0 | Main steam valve on steam generator 01 closed and the feedwater of steam generator 01 turned off (isolation of steam generator 01). |
| 3900.0 | Cooling down of steam generator 02 with 100 K/hr. A controlled pressure reduction with a constant feedwater mass flow in the affected steam generator provides cooling down of the primary system. |
| 4140.0 | Injection of auxiliary feedwater. This step is neglected in the analysis due to lack of information about the auxiliary feedwater mass flow. |
| 4260.0 | Discontinuation of the cooling down of the primary system. |
| 5400.0 | Isolation of steam generator 01 discontinued by opening of the main steam valve and re-establishing the feedwater flow. |
| 6720.0 | Main steam valve of steam generator 02 closed and feedwater off (isolation of steam generator 02). |
| 7860.0 | Cooling down of steam generator 01 with 50 K/hr A controlled reduction of the pressure in the steam generator provides the cooling down of the primary system. |
| 9960.0 | Discontinuation of the cooling down of steam generator 01. |
| 11220.0 | Main steam valve steam generator 01 closed and feedwater discontinued (isolation of steam generator 01). At this point both steam generators are isolated. |
| 13020.0 | Isolation of steam generator 01 and 02 discontinued by opening of the main steam valves and restoring the feedwater flow. |
| 13740.0 | Isolation of steam generator 01 (compare event at t = 840 s). |
| 14940.0 | Isolation of steam generator 01 discontinued (compare event at t = 5400 s). |
| 15300.0 | End of test. |
| 15900.0 | End of the calculation. |

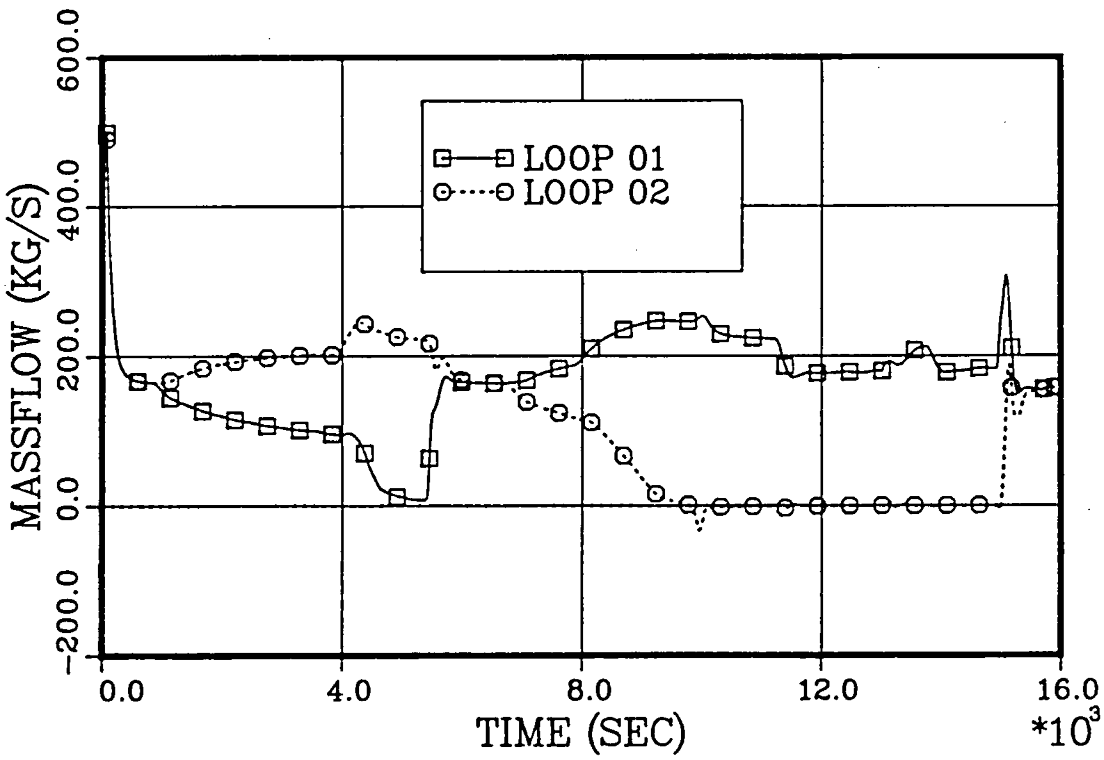


Figure 4.1. RELAP5 mass flow rate inside loop 01 and 02

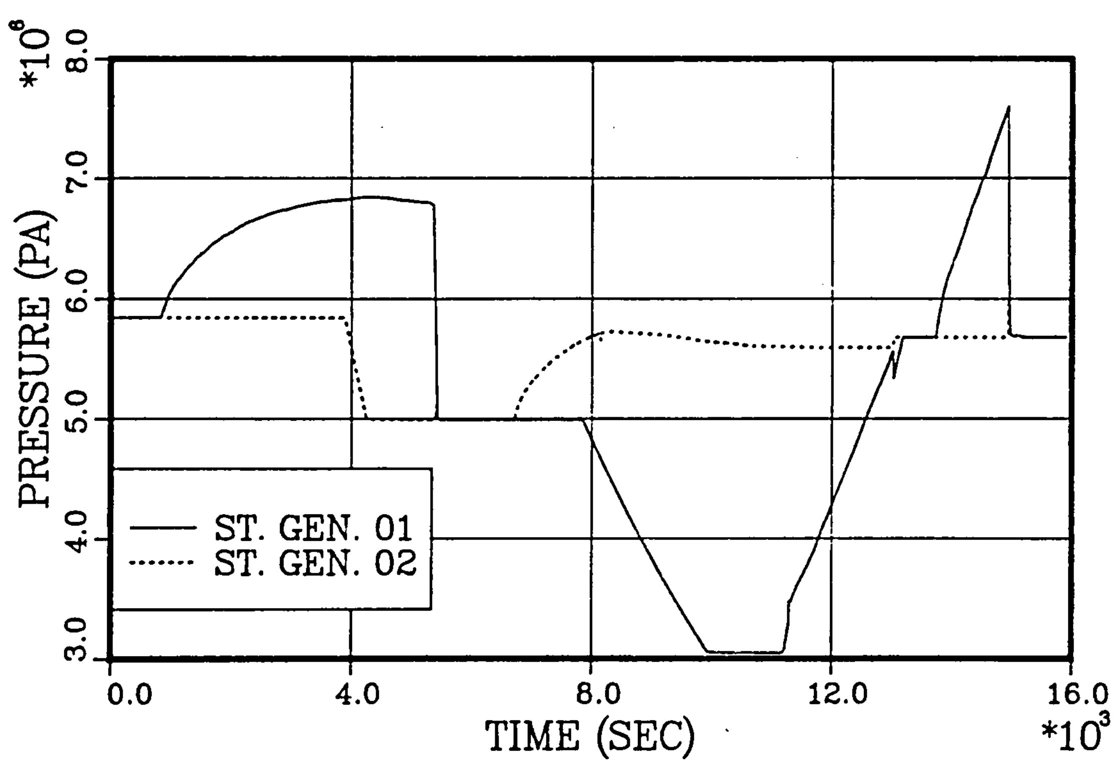


Figure 4.2. RELAP5 steam generator secondary side pressures

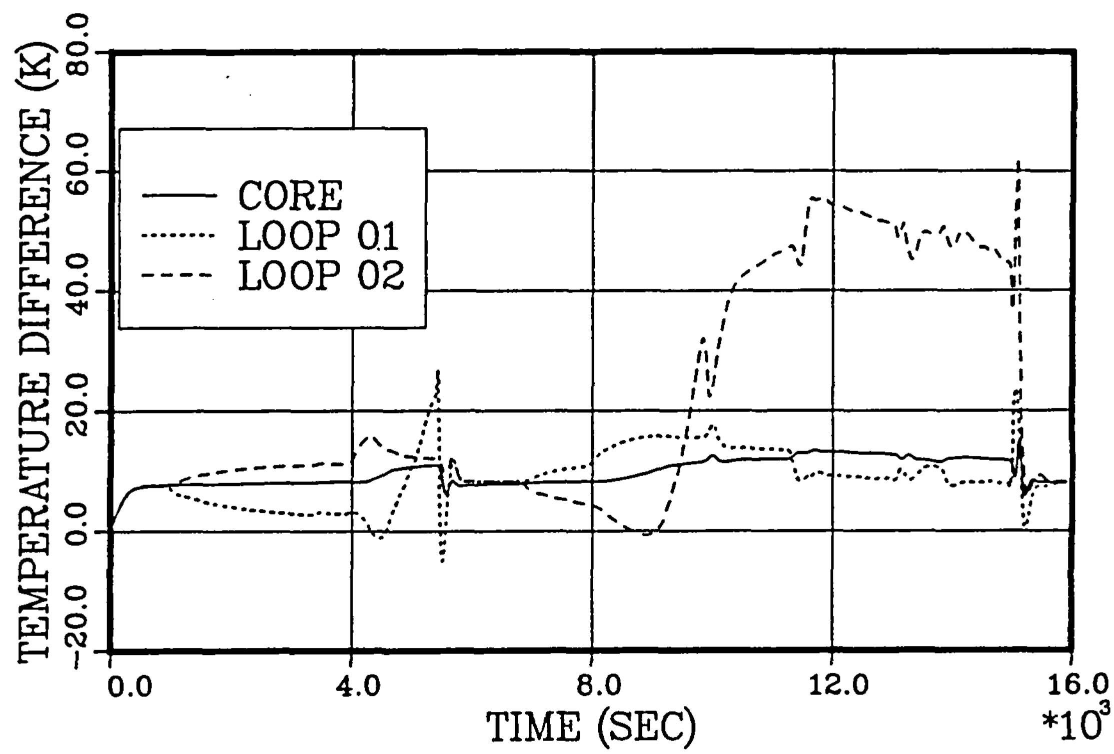


Figure 4.3. RELAP5 temperature gradients in primary system loops and core

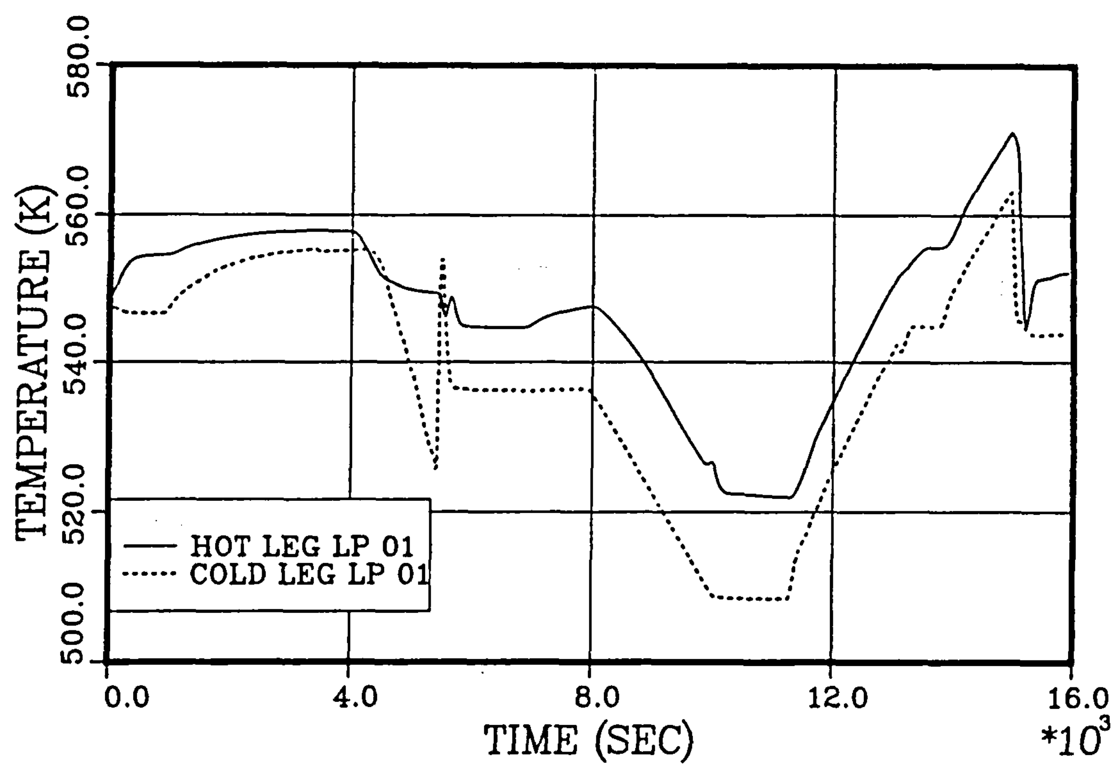


Figure 4.4. RELAP5 hot and cold leg fluid temperatures in loop 01

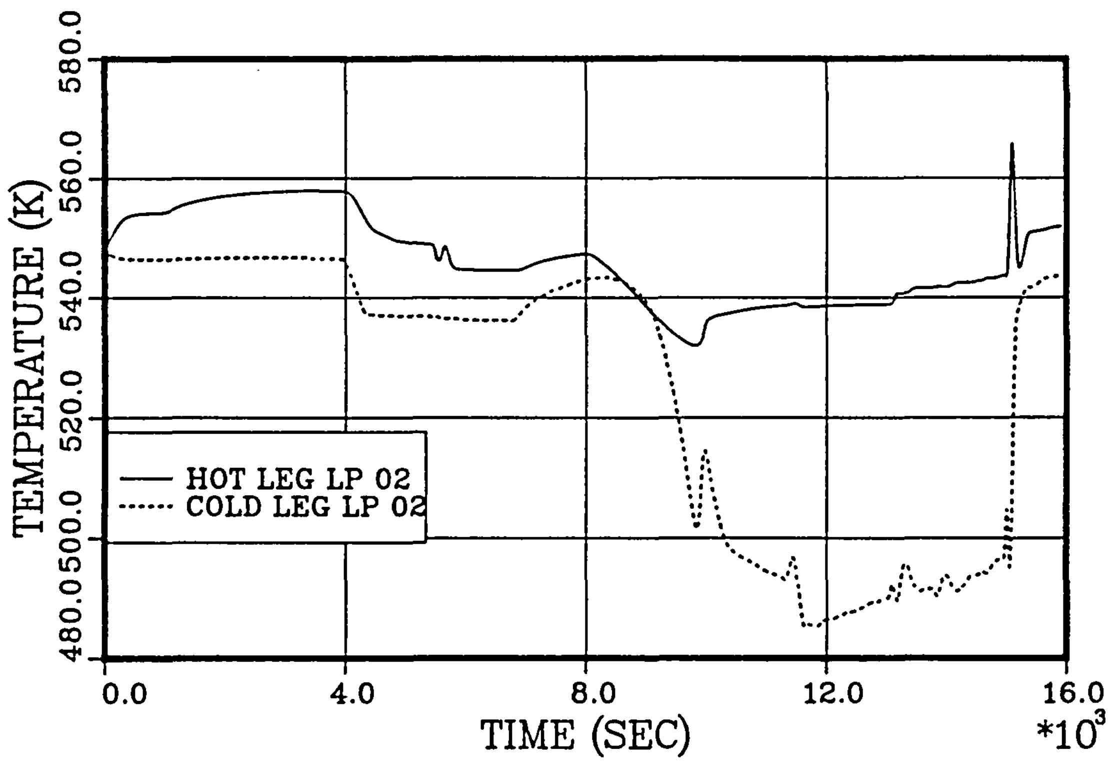


Figure 4.5. RELAP5 hot and cold leg fluid temperatures in loop 02

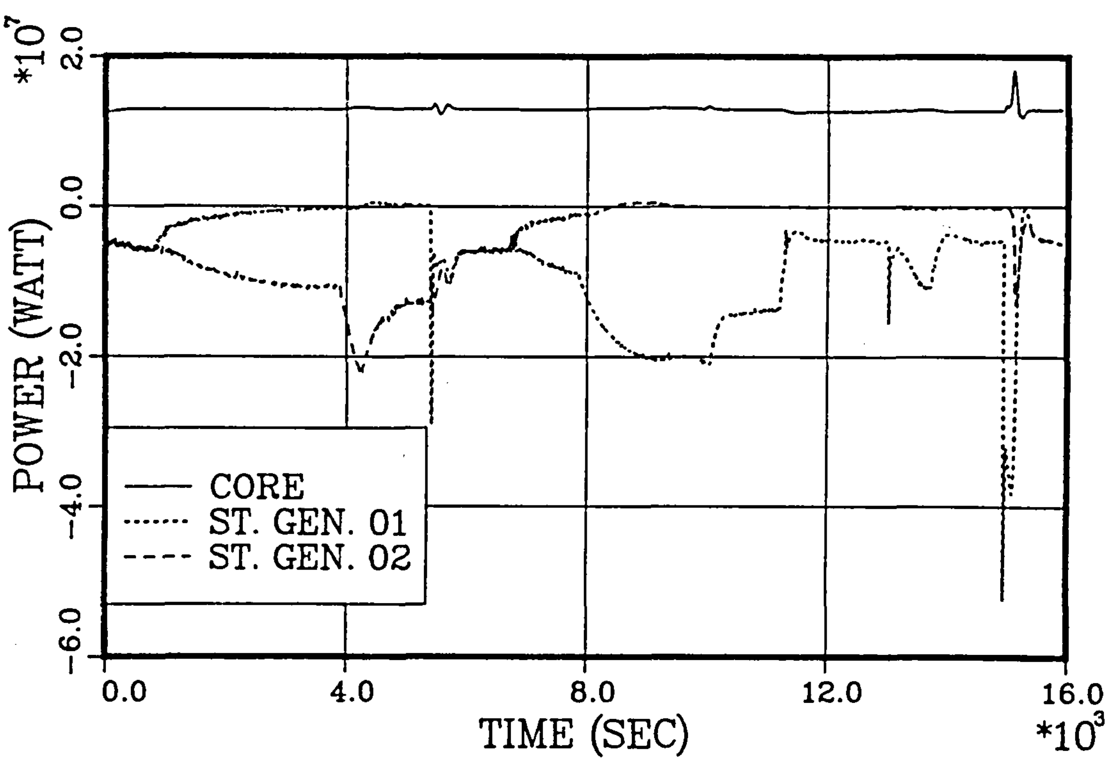


Figure 4.6. RELAP5 energy balance for primary system

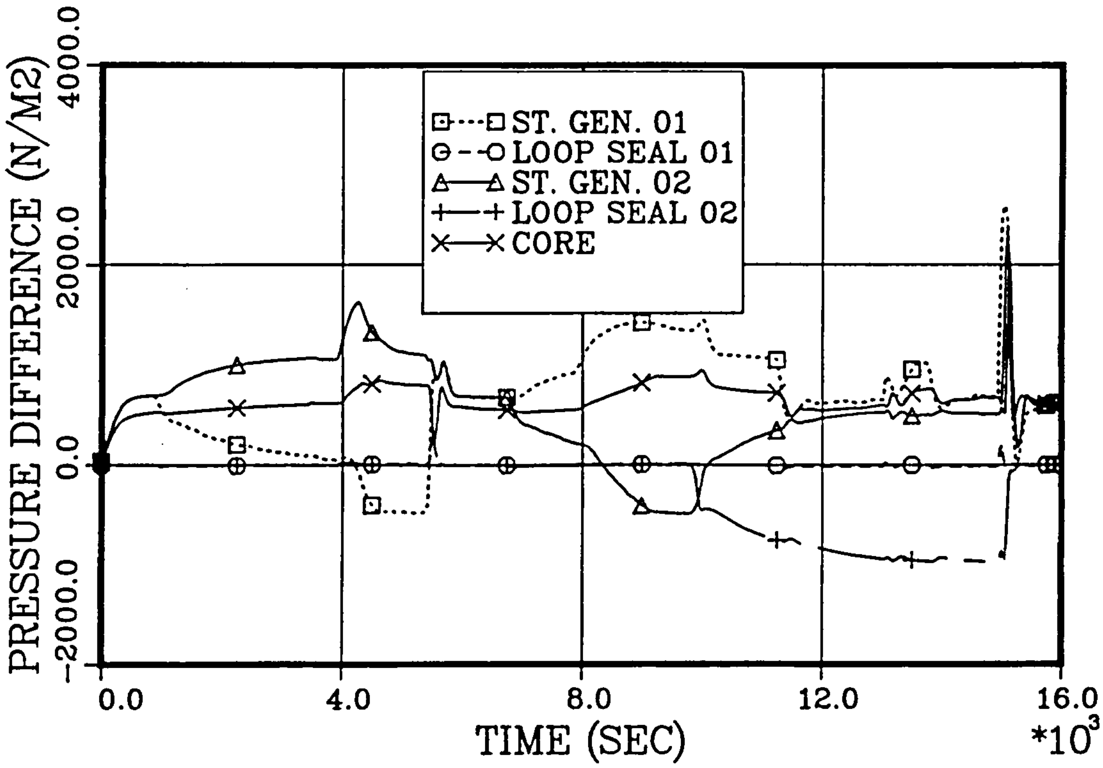


Figure 4.7. RELAP5 driving forces for natural circulation in steam generators, loop seals and core

## 5. COMPARISON OF RELAP5 CALCULATIONS TO EXPERIMENTAL DATA

A quantitative comparison of the measured data and the calculated results is presented in this section. The comparison can not be very detailed due to the limited number of measurements and the construction, location and measurement range of the devices. Moreover there is no data qualification of the measured data available. The data channels which are available from the strip charts are given in table 2.4. From the available data channels presented in table 2.4 the marked (*) ones did not show major problems during the test and will be used for comparison with the RELAP5 calculations.

In table 5.1 the designation of the calculated and experimental data is given together with the figure numbers where the comparison is presented. Fig. 5.1 through 5.12 show overlays of the measured and calculated data. The parameter labels in the figures are described in tables 2.4 and 5.1. For completeness are the measured and calculated liquid levels in the steam generators and the system pressure presented. However, lack of information made it necessary to simplify the controllers and for this reason the comparisons are not meaningful for assessment purposes.

A short description of the comparisons for the different time periods will be given next.

Time 0-840 s.
The temperature behaviour during this first period in the calculation and in the experiment is very similar. There is an increase in hot leg temperature and an almost constant cold leg temperature.

Time 840-3900 s.
The calculated temperature behaviour during this period is in reasonable agreement with the measured values. An exception is the deviation in the temperatures in the hot leg of loop 01. An explanation for this deviation is an excessive spray into the pressurizer during part of this period. Because of the spray hot water from pressurizer

is pushed into the hot leg of the primary system. At the end of the period the spray is turned off, but there is no measured confirmation of the spray flowrate and the timing of the discontinuation of the flow. In general the calculated secondary side pressure in the isolated steam generator 01 increases to fast. A possible reason for this deviation is the heat loss from the wall of the steam generator to the environment. This effect is not modelled in the RELAP5 calculation.

Time 3900-4260 s.
In the calculation the temperature decrease during this time frame is controlled by the depressurization rate of steam generator 02. At the secondary side of steam generator 02 the calculated temperature is very close to the measured value. Due to the small mass flow in the loop of the isolated steam generator the cooling down effect on the fluid temperature in this loop is delayed into the next time frame. The calculated liquid level in the pressurizer decreases faster (about double) than the measured level. A possible cause of this deviation is an uncertainty in the control function for the mass flow of the Volume Control System.

Time 4260-5400 s.
During this time frame the cooling down effect of the previous period is shown in the fluid temperatures in loop 01. A strong temperature decrease is observed in the calculated cold leg temperature of loop 01. This decrease is caused by the injection of relatively cold water from the Volume Control System into the cold leg. The calculated temperatures in loop 02 are close to the experimental values.

Time 5400-6720 s.
During this part of the transient (natural circulation in both loops) the experimental and calculated values are very close.

Time 6720-7860 s.
The pressure and temperature behaviour in steam generator 02 and in the loops is identical to the behaviour for steam generator 01 and the opposite loops during the period 840-3900 s. The calculated pres-

sure increase in steam generator 02 is during this period also fast compared to the experimental value and is being caused by the same effect as in period 840-3900 s.

Time 7860-9960 s.
The calculated and measured temperatures in loop 01 are in good agreement. However, a significant deviation is observed in the fluid temperatures in loop 02. The calculated temperature decrease in the hot leg of loop 02 is relatively small while the cold leg temperature decrease is relatively large. A reason for this different temperature behaviour is the very small and decreasing mass flow in loop 02 and the injection of cold water from the Volume Control System into the cold leg. The liquid level in the pressurizer again decreases too fast compared to the measured one.

Time 9960-11220 s.
The calculated temperatures in loop 01 are close to the measured temperatures. In loop 02 however deviations in the fluid temperatures still exist due to the same reasons as described in previous period.

Time 11220-end.
The temperature and pressure comparisons after about 11000 s are not realistic. In the experiment the nature and timing of the different events are not well described and hence a comparison of calculated and measured data is not meaningful.

In Appendix B an analytical solution of natural circulation in a simplified model is presented together with a comparison of the analytical and with RELAP5 calculated solution. The Appendix shows that RELAP5 calculates the natural circulation mass flow well. With the assumption that 80% of the heat is transferred in the upward leg of the steam generators the maximum error in the calculated mass flow due to nodalization is about 3%. Also presented in Appendix B is the importance of the initial temperature distribution and nodalization on the mass flow behaviour.

Although there is no direct measurement of the mass flow in the core or in the loops a thorough investigation of all the measured temperatures confirms stagnation of the mass flow during some parts of the transient, ref. [3]. The mass flow stagnation is observed at the same location and time as in the calculation.

A general conclusion of the comparison between calculated and measured data is the good agreement in the temperatures in the non-stagnant loop. In the loop with a small or stagnant mass flow deviations between the calculated and measured fluid temperatures are observed. Reasons for the deviations are the injection of relatively cold water of the Volume Control System and a probable stratification of the mass flow close to the measuring device.
Isolation of a steam generator results for the RELAP5 analysis in a too fast increase of steam generator secondary side pressure and primary system temperature. Heat loss from the steam generator to the environment and uncertainties in the mass inventories of the steam generators are reasons for the deviations. Another uncertainty is the decay heat in the core. The power in the calculation is fixed to 13 MW but there is no confirmation by a measurement of the power.

The behaviour of the calculated liquid level in the pressurizer is close to the measured value. However the calculation shows a more pronounced control action than is observed in the test. A reason for the deviation is uncertainties in the controller and pump characteristics of the Volume Control System.

Table 5.1. Designation of experimental and calculated date

| Experiment | RELAP5 | Figure no. |
|---|---|---|
| YA01T090 | TEMPF 185010000 | 5.10 |
| YA02T090 | TEMPF 285010000 | 5.12 |
| YA01T098 | TEMPF 110010000 | 5.9 |
| YA02T098 | TEMPF 210010000 | 5.11 |
| YA01T054 | CNTRLVAR 4090 | 5.7 |
| (YA01T054/01 - YA01T054/02) | (TEMPF 110010000 - TEMPF 185010000) | |
| YA02T054 | CNTRLVAR 4091 | 5.8 |
| (YA02T054/01 - YA02T054/02) | (TEMPF 210010000 - TEMPF 285010000) | |
| YA01P002 | P 110010000 | 5.1 |
| RA01P001 | P 596010000 | 5.5 |
| RA02P001 | P 696010000 | 5.6 |
| YB01L051 | CNTRLVAR 109 | 5.3 |
| YB02L051 | CNTRLVAR 110 | 5.4 |
| YP01L101 | CNTRLVAR 108 | 5.2 |

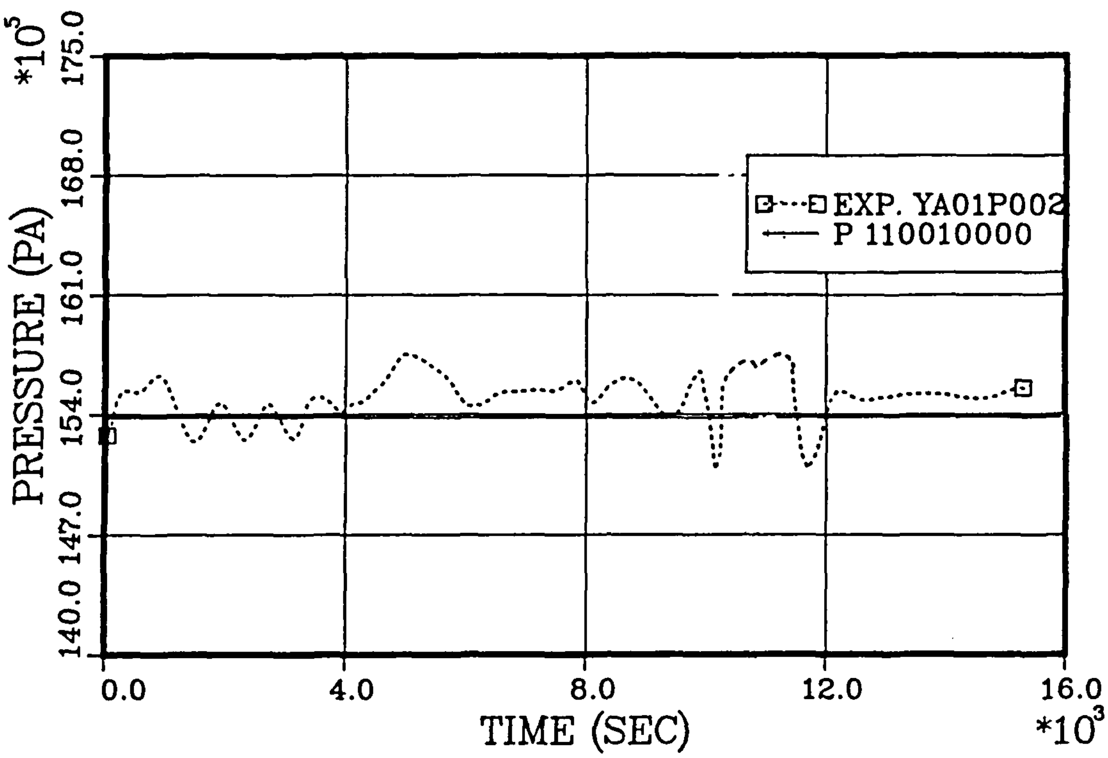


Figure 5.1. Comparison of calculated and measured system pressures

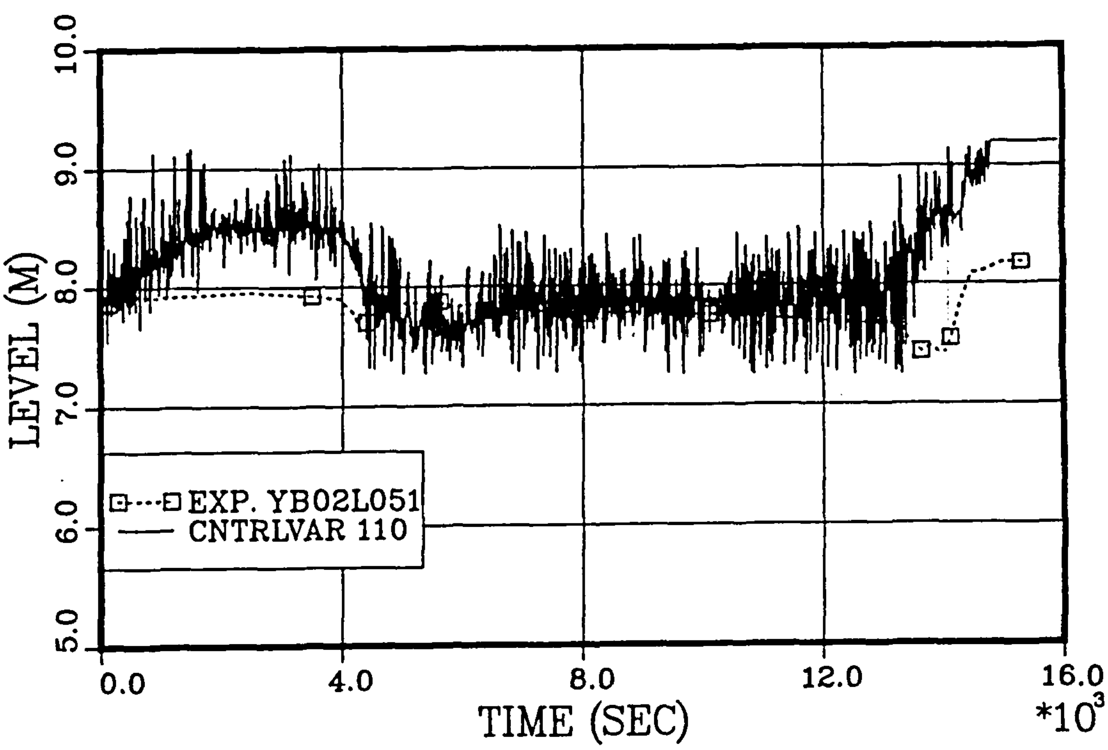


Figure 5.2. Comparison of calculated and measured collapsed liquid levels in the pressurizer

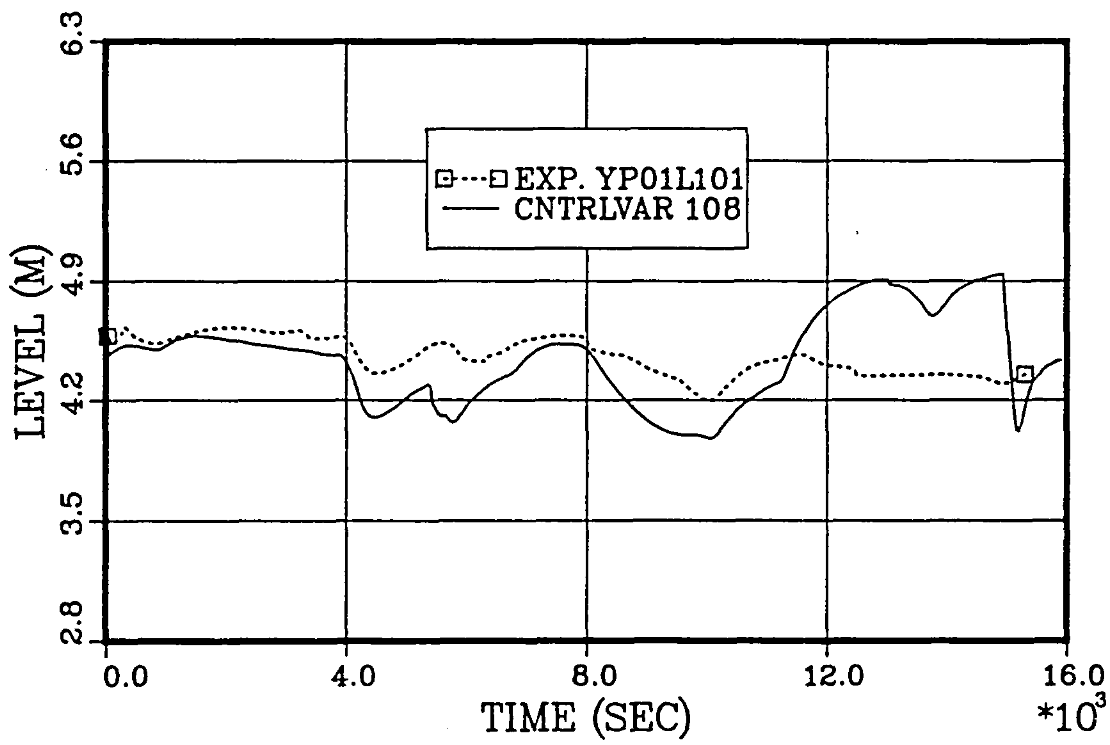


Figure 5.3. Comparison of calculated and measured collapsed liquid levels in steam generator 01

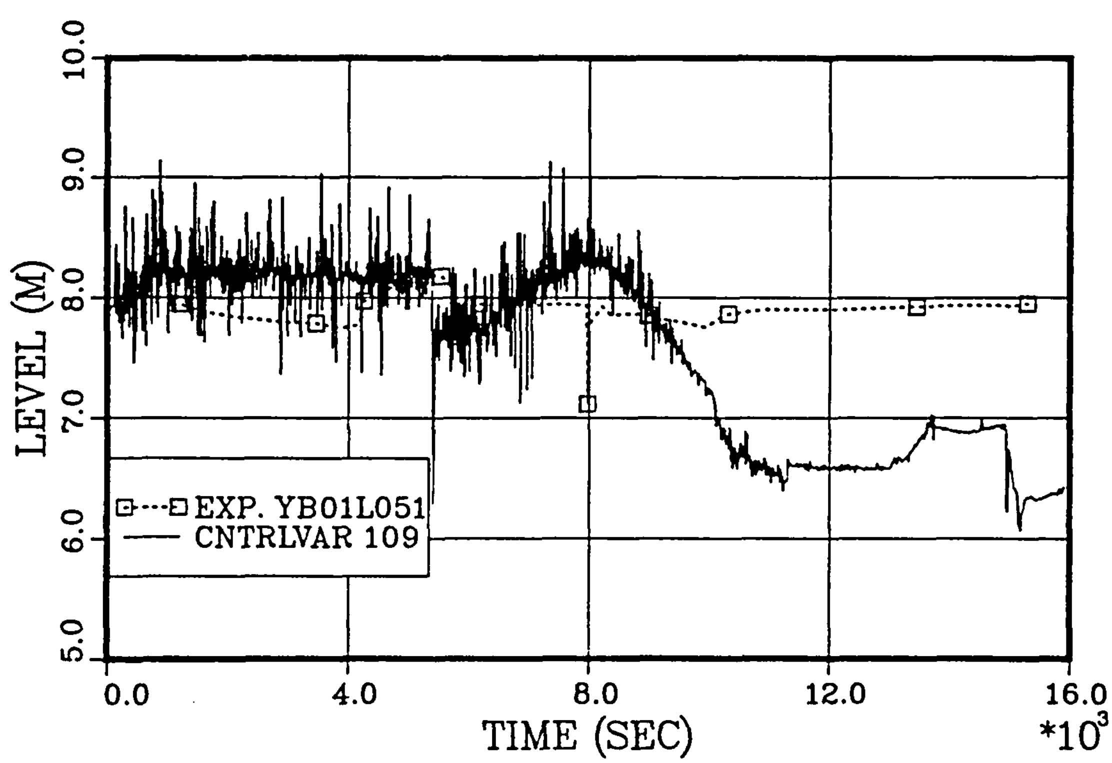


Figure 5.4. Comparison of calculated and measured collapsed liquid levels in steam generator 02

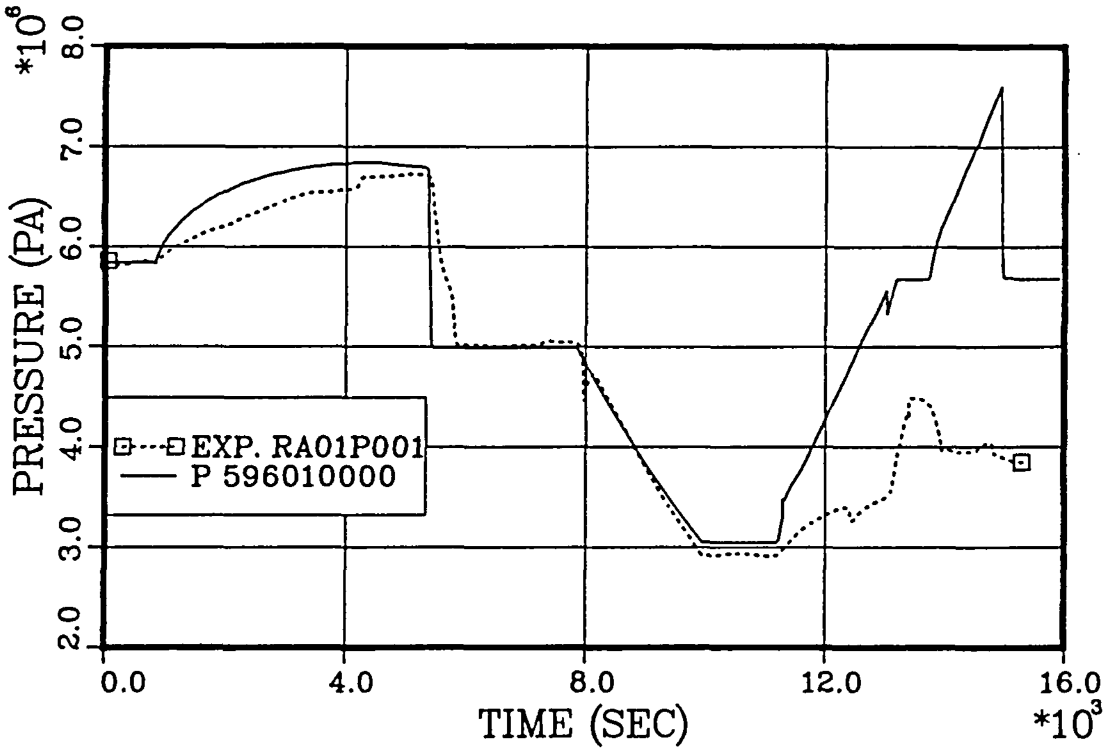


Figure 5.5. Comparison of calculated and measured pressures at secondary side of steam generator 01

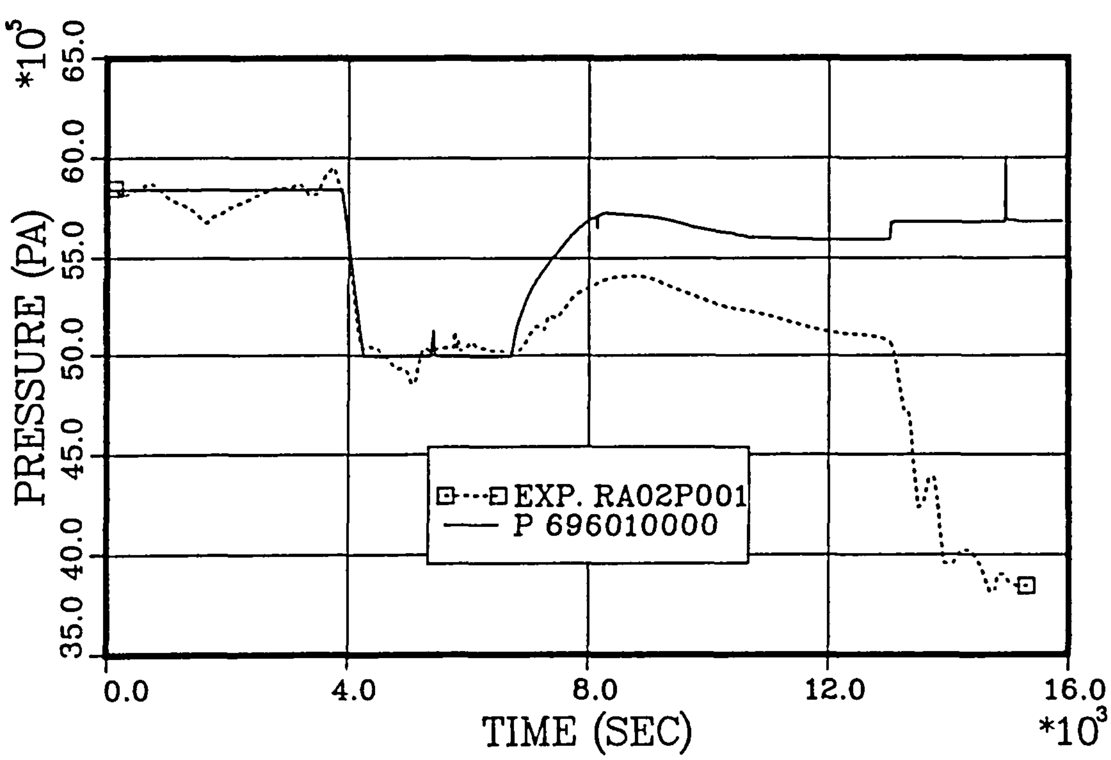


Figure 5.6. Comparison of calculated and measured pressures at secondary side of steam generator 02

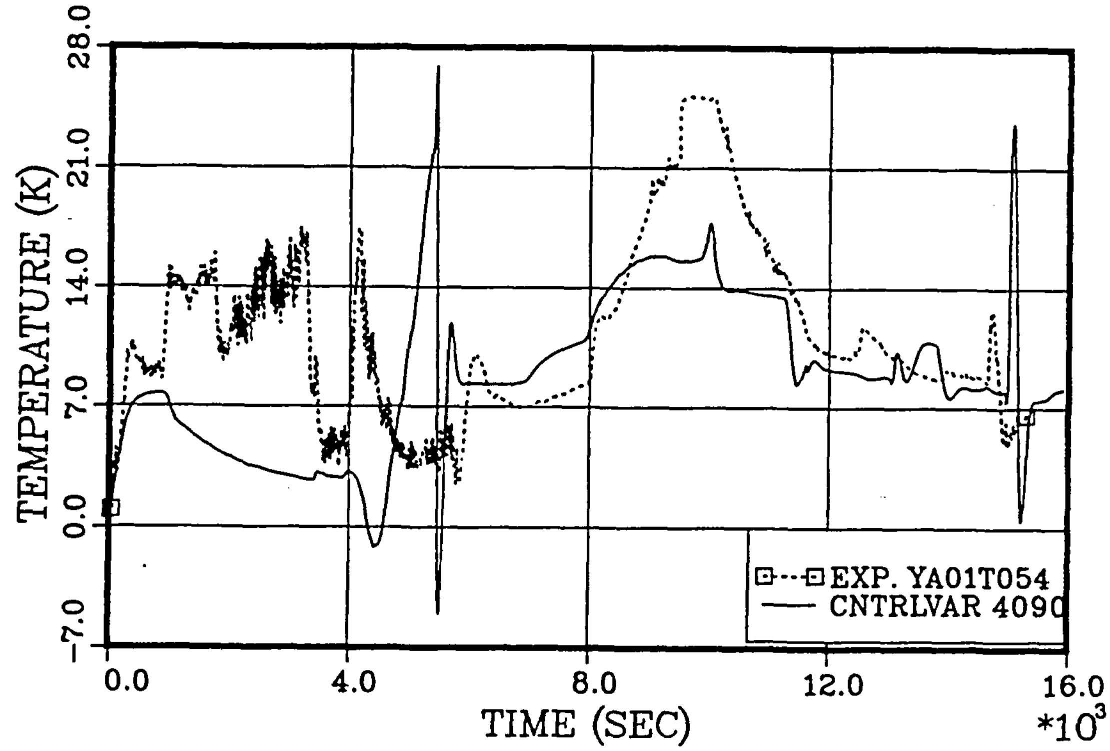


Figure 5.7. Comparison of calculated and measured temperature differences across loop 01

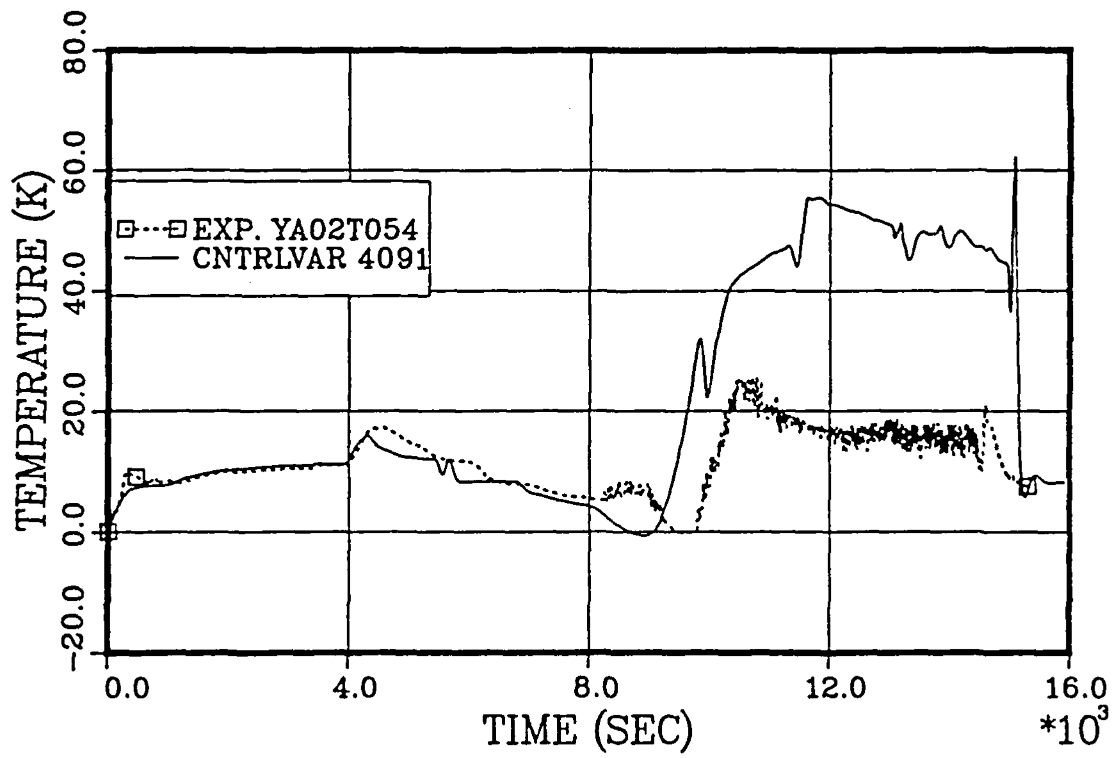


Figure 5.8. Comparison of calculated and measured temperature differences across loop 02

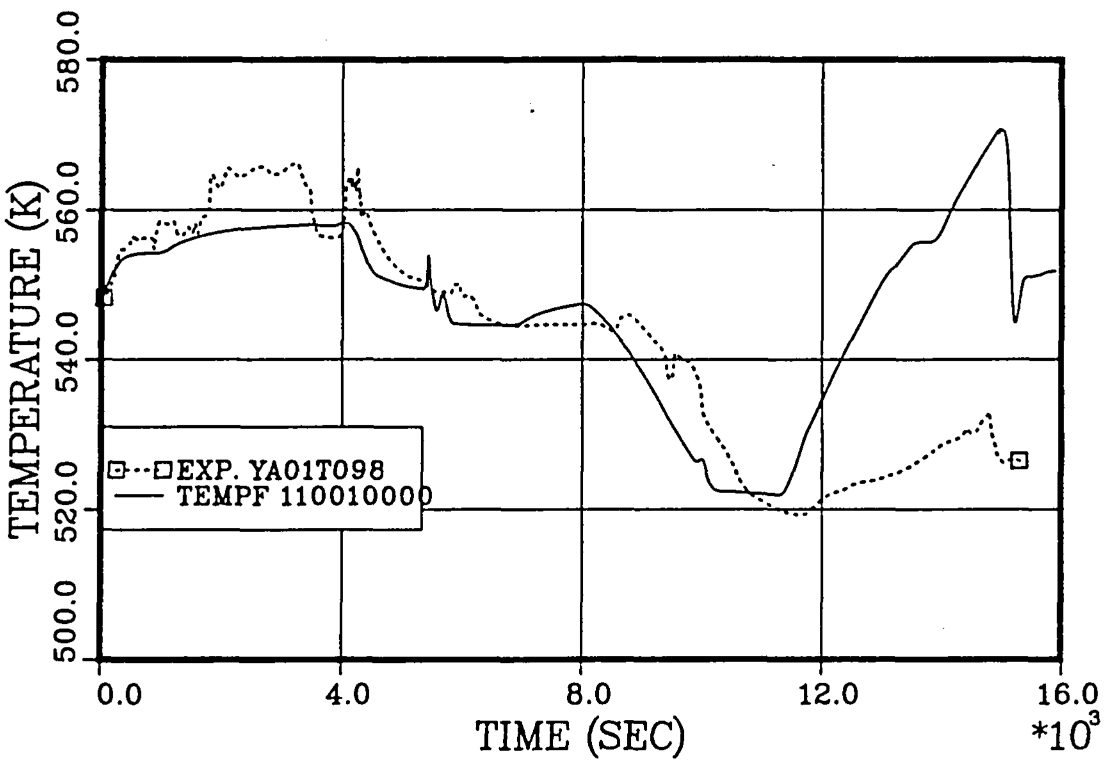


Figure 5.9. Comparison of calculated and measured fluid temperatures in the hot leg of loop 01

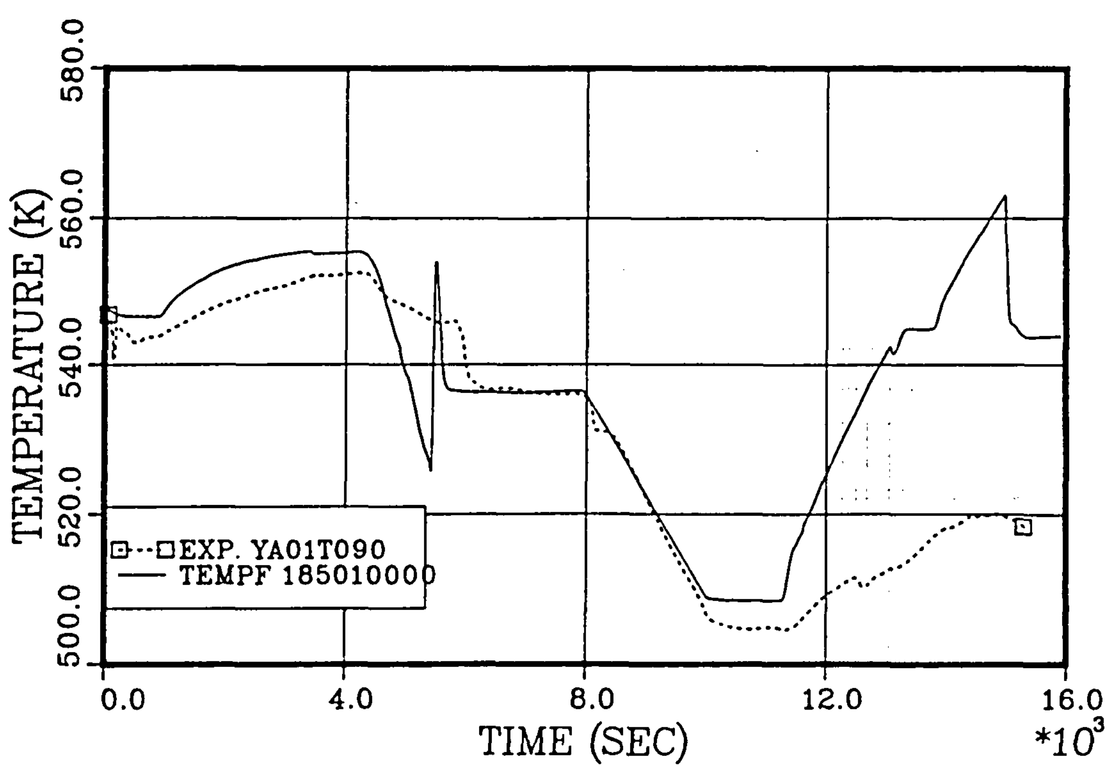


Figure 5.10. Comparison of calculated and measured fluid temperatures in the cold leg of loop 01

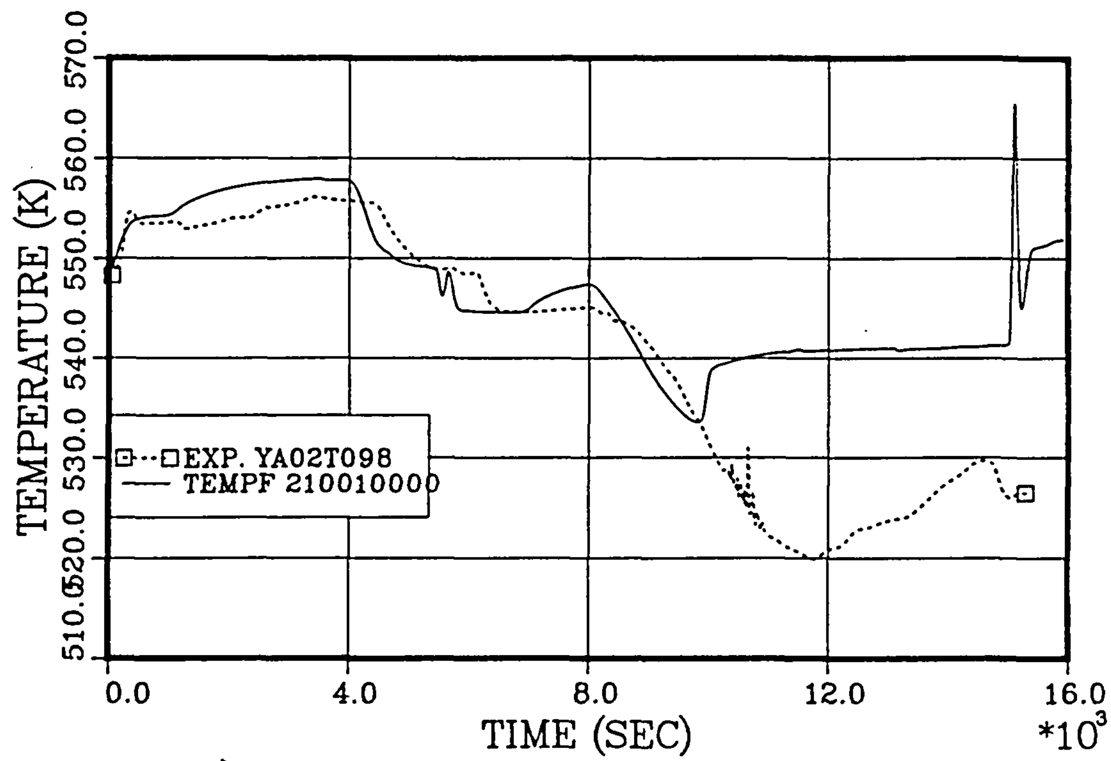


Figure 5.11. Comparison of calculated and measured fluid temperatures in the hot leg of loop 02

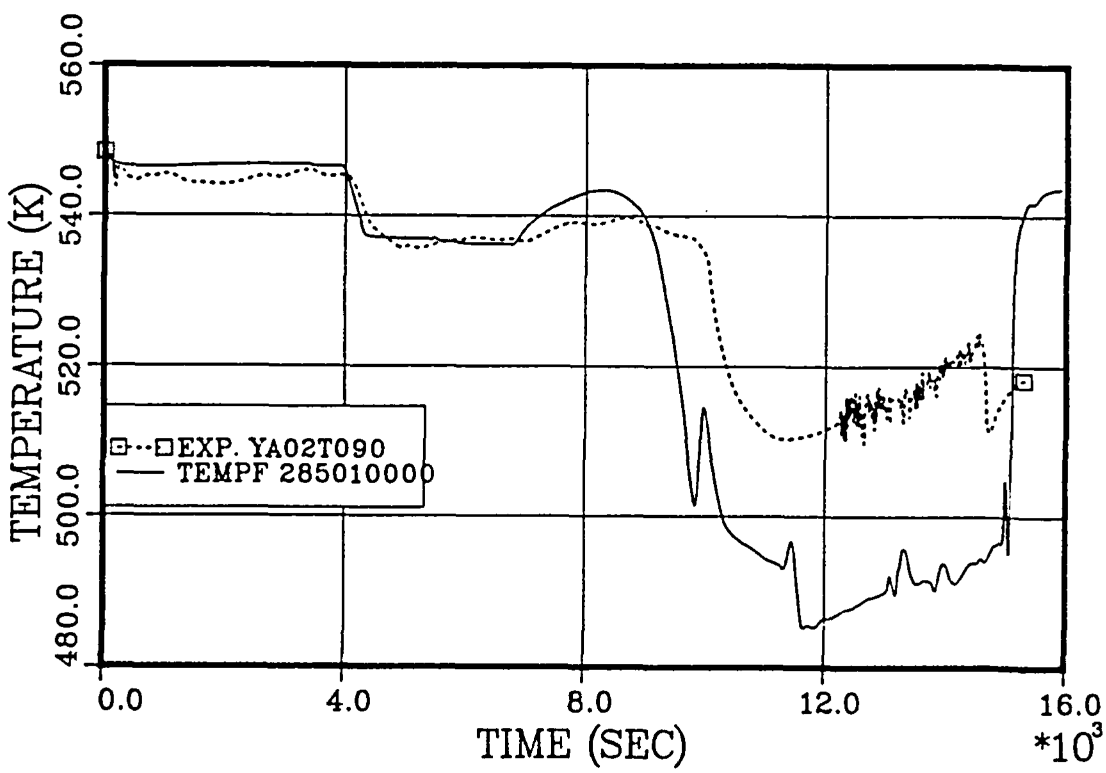


Figure 5.12. Comparison of calculated and measured fluid temperatures in the cold leg of loop 02

## 6. CONCLUSIONS

Generallly the RELAP5 analyses of the natural circulation experiment in Nuclear Power Plant Borssele showed qualitatively good agreement with the test data. However, lack of qualified and relevant data from the test (typical for plant transients) prevented a quantitative assessment.

A deficiency in the energy equation in RELAP5 causes a deviation in energy balance and steady-state. Adding part of the "pump power" to the "core power" solved the problem.

RELAP5/MOD2 simulates the primary system behaviour under natural circulation conditions in Nuclear Power Plant Borssele adequate. The calculated mass flow and temperature difference across the loops agree in general well. Also the observed mass flow stagnation in the experiment is well predicted by the code. In general mass flow stagnation in a loop with an isolated steam generator occurs when the system is cooled down by the intact steam generator. Restoration of the mass flow in a loop requires a large and sudden heat transfer increase in one of the steam generators.

The comparison of measured and calculated temperatures shows a good agreement as long as a mass flow exists, during stagnation the temperatures deviate. The observed temperature differences are probably caused by uncertainties in the Volume Control System behaviour. Also stratification at the location of the measuring devices can play a role.

The secondary side pressure behaviour during isolation is identical in calculation and experiment. The slower increase of the pressure at the secondary side of the steam generator during isolation is probably caused by uncertainties in feedwater and steam mass flows, heat losses from the steam generators to the environment and mass inventory uncertainties of the steam generators. A comparison between an analytical solution and a RELAP5 calculation for a simplified reactor model shows that the used RELAP5 nodalization in core and steam generators generates a nodalization error less than 3%.

## 7. REFERENCES

[1] Ransom, Victor H. et al.: RELAP5/MOD2 Code manual. Volume 1: Code Structure, Systems Models and Solution Methods. Volume 2: Users Guide and Input Requirements.
NUREG/CR-4312.

[2] Guidelines and Procedures for the International Code Assessment and Applications Program
U.S. Nuclear Regulatory Commission.
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[3] Kalverboer, C. (PZEM): Natural Circulation and Heat Transfer Tests in the Borssele Nuclear Power Plant;
KVB/IB/NCIRC, July 11, 1983. (Internal report)

[4] Technical Note: Natural Circulation Tests in the Borssele Nuclear Power Plant;
Nuclear Safety, Vol. 25, No. 3, May-June 1984.

[5] L. Winters: RELAP5 model KCB (in progress).

Appendix A. Description of the RELAP5 model for KCB

## Introduction

This Appendix gives a brief description of the RELAP5 model for Nuclear Power Plant Borssele (KCB). A comprehensive description of the model with assessment calculations is in progress (ref. [5]). The model was developed at ECN for the Dutch Licensing Authority (KFD). The model has been used succesfully for different transient calculations with the simulation code RELAP5.

## Reactor coolant system

The overall RELAP5 nodalization scheme of KCB is presented in figure 3.1 of the report. A more detailed nodalization of the different components is given in figure. A-1 through A-5. In the figures the correspondence between the physical and the mathematical components is shown by means of a schematic drawing of the component and the corresponding RELAP5 nodalization scheme. The loops are designated as loop 01 and 02 with the pressurizer connected to loop 01. Figure A-1 gives the nodalization scheme for loop 01. Loop 02 is identical to loop 01 except that loop 01 has a connection with the pressurizer through the surge line. The pressurizer is represented in figure A-2. The heater elements in the pressurizer provide a maximum power of 1.660 MW. The Pilot Operated Relief Valves (PORV) and the safety valves on the pressurizer are represented in the model by a servo valve. The pressurizer spray valves are modelled as a servo valve with six different opening positions, which are controlled by the primary system pressure. The maximum spray capacity is about 24 kg/s.

Figure A-3 shows the RELAP5 vessel configuration and nodalization. Two minor flow paths are modelled viz. the bypass of the core and the leak path from inlet annulus of the downcomer to the upper head. The flow through the two leak paths is resp. 5.9% and 1.5% of the total mass flow through the reactor vessel.

The steam generator primary and secondary sides are represented in figure A-4. The separators and the dryers in the steam generator are modelled in one separator model at the seperator location. The steam line with its components (safety valves, relief valves, steam bypass station and turbine valves) are all modelled. The feed water pumps and the feed water control valves are also included in the model. The auxiliary feed water system is simplified and modelled as a single fill junction. In the model the turbine valves and the feedwater tanks represent the boundaries of the steam generator.

Added to the model of the primary system are the Volume Control System (VCS) and the Emergency Core Cooling System (ECCS) (figure A-5). The VCS is represented in 4 time dependent junctions (charge flow in bottom of the loop seal). The ECCS includes the High Pressure Injection System (HPIS), accumulators and the Low Pressure Injection System (LPIS). The ECCS is connected to both hot legs (connection between reactor vessel and steam generator) and the cold legs (lowest part of the loop seal).

Heat structures are added to the model to represent the fuel rods, the wall of reactor vessel and steam generators and internals in the steam generators and the reactor vessel.

## Control systems

Added to the RELAP5 model are the most important reactor control systems viz. primary system pressure control system, level control system in the pressurizer and the level control system in the steam generators.

The pressure in the primary system is controlled by the heater elements and the spray in the pressurizer. The adjustment of these components is set by control elements which have the primary system pressure as input signal.

The liquid level in the pressurizer is controlled by the mass flows of the Volume Control System. Signals representing the Volume Control System charge- and discharge flow and the actual level in the pressurizer are used as input for a proportional integral controller. This PI-element controls the position of the discharge flow valve of the Volume Control System. The charge flow of the Volume Control System is constant.

The level control in the steam generators is similar to the pressurizer level control. The feed water valves are controlled by a PI-controller which has as input signals the feed water mass flow, the steam flow and the deviation of the steam generator actual level and the level setpoint.

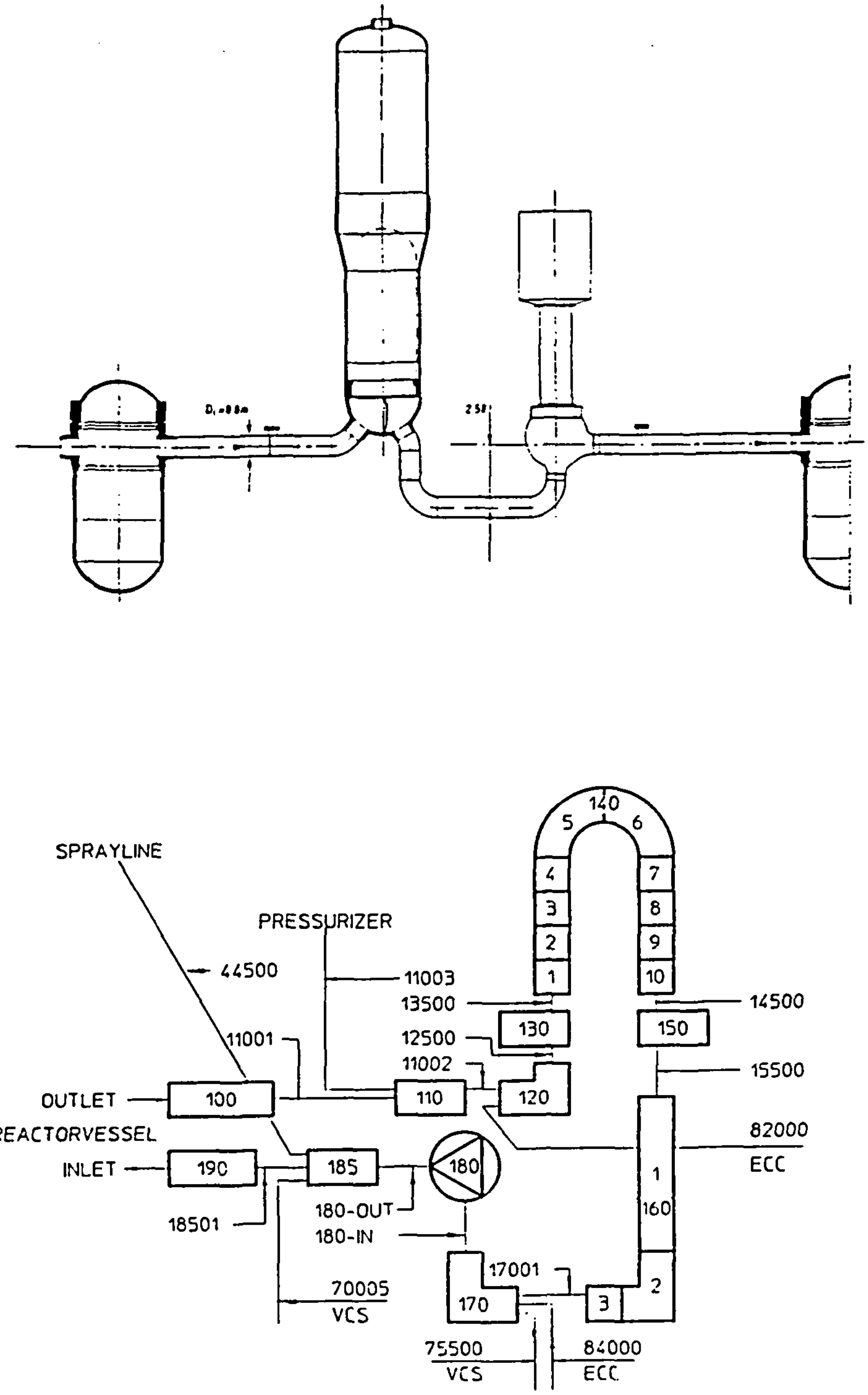


Figure A-1. Representation of loop 01

a) Configuration

b) RELAP5 nodalization diagram

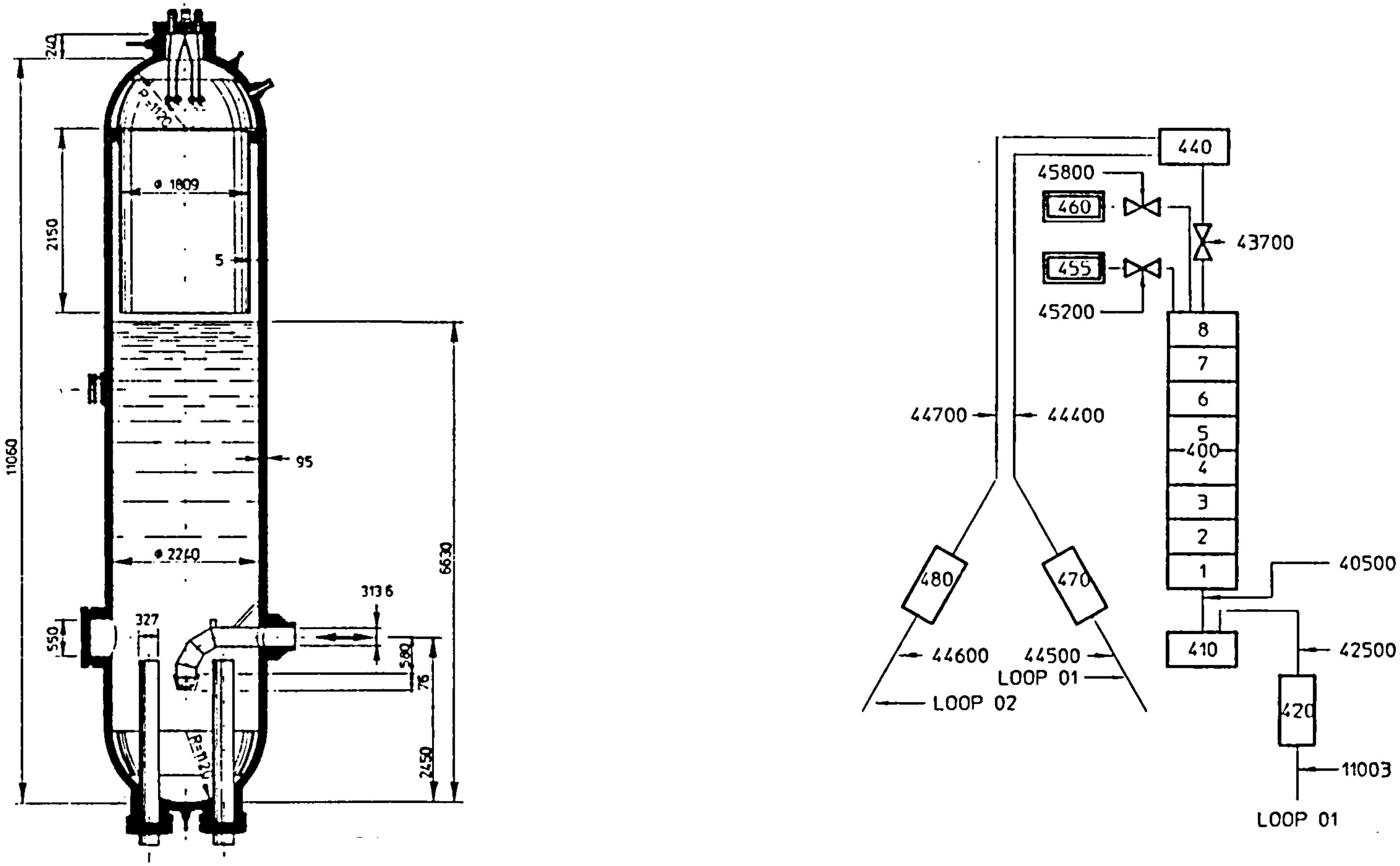


Figure A-2. Representation of the pressurizer

a) Configuration

b) RELAP5 nodalization diagram

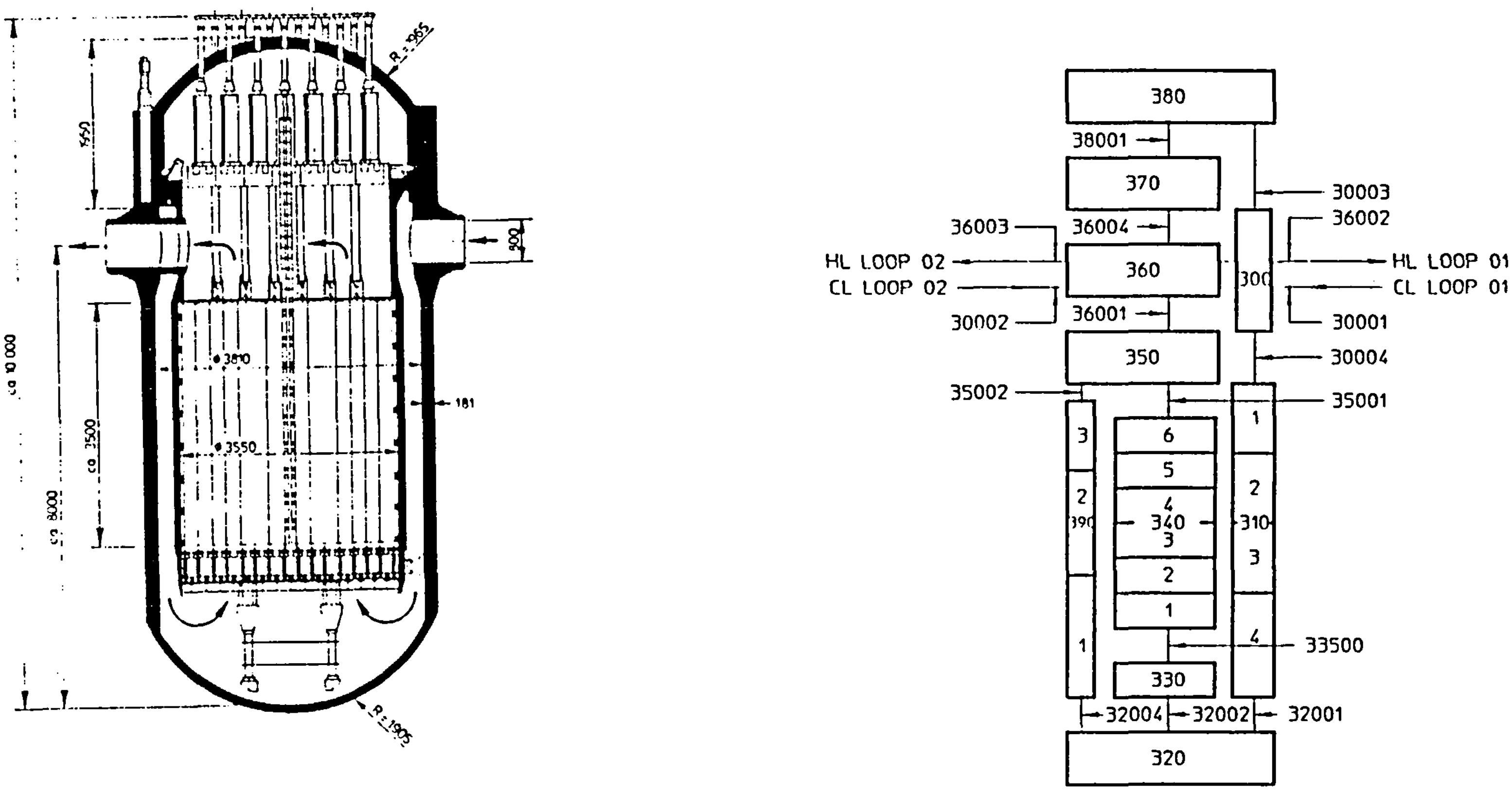


Figure A-3. Representation of the reactor vessel

a) Configuration

b) RELAP5 nodalization diagram

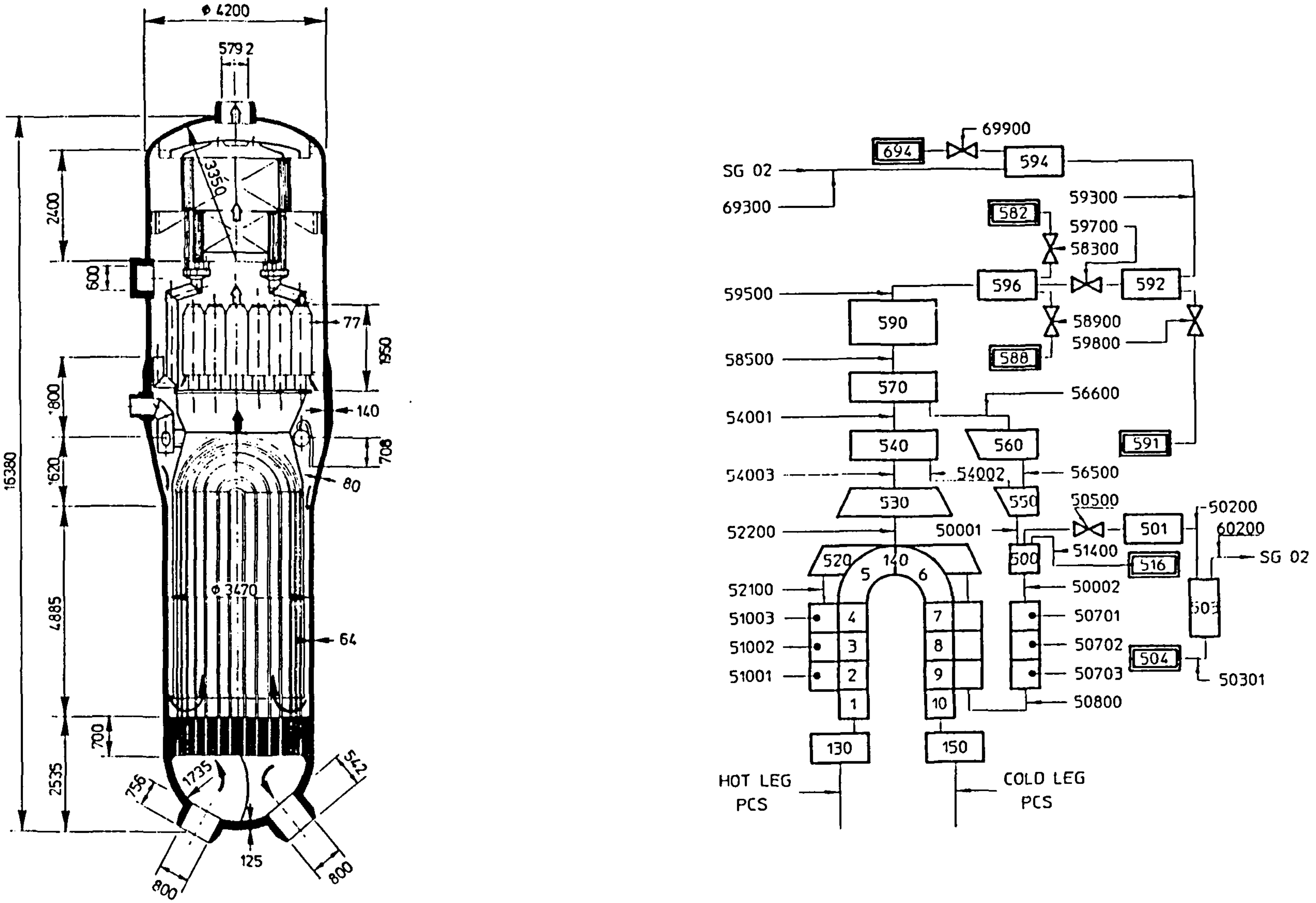


Figure A-4. Representation of the steam generator

a) Configuration

b) RELAP5 nodalization diagram

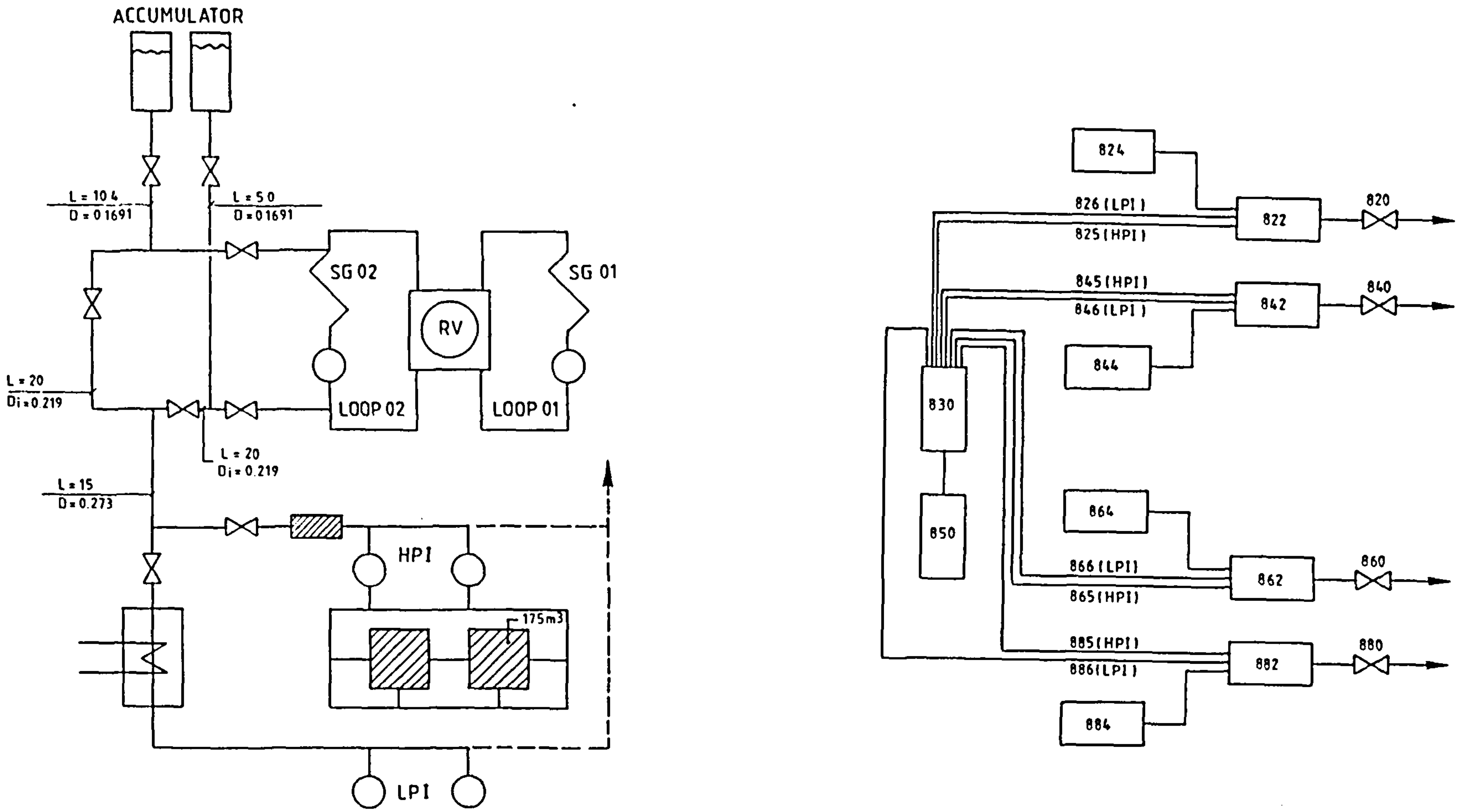


Figure A-5. Representation of ECC system

a) Configuration

b) RELAP5 nodalization diagram

## Appendix B. Analytical model for natural circulation

In a single loop a simple relation exists between the steady state natural circulation mass flow and the heat production. Figure B-1 is a schematic simplified representation of one loop of a reactor system. In the core the generated heat (Q) is added to the fluid and in the steam generators $Q_1$ (upward leg) and $Q_2$ (downward leg) is transfered from the primary system fluid to the secondary side of the steam generator. During steady state conditions is the generated heat equal to the removed heat ($Q_1 + Q_2 = Q$). The driving force for the natural circulation is given by

$$\Delta P = \int \rho g dz \qquad \text{(B.1)}$$

where:

$\Delta P$ = driving pressure ($N/m^2$)
$\rho$ = density of the fluid ($kg/m^3$)
g = acceleration due to gravity (9.81 $m/s^2$)
z = vertical ordinate (m)

In evaluating the integral (B.1) the next relations are important

$$\Delta \rho = - \beta \rho \Delta T \qquad \text{(B.2)}$$

$$\Delta T = Q / \dot{m} C_p \qquad \text{(B.3)}$$

$$\Delta P = \tfrac{1}{2} (k + k_f) \dot{m}^2 / \rho A^2 \qquad \text{(B.4)}$$

where:

$\Delta \rho$ = change in density due to temperature change ($kg/m^3$)
$\beta$ = coefficient of thermal expansion ($K^{-1}$)
$\Delta T$ = temperature change (K)
$\dot{m}$ = mass flow (kg/s)
Q = heat transfer (J/s)
$C_p$ = specific heat capacity of the fluid at constant pressure (J/kg K)
k = total form loss coefficient of the circuit
$k_f$ = total loss factor due to friction
A = flow area in relation to loss factor ($m^2$)

For a RELAP5 calculation the schematic loop of fig. B-1 has to be divided into subvolumes (fig. B-2). Assume the "core" is subdivided in $N_c$ volumes and both the upward and downward leg of the "steam generator" in N volumes.

For the analysis the RELAP5 assumption is important that the fluid density in a volume is defined by the outlet condition of the volume. Evaluating the above mentioned integral (B.1) according to the RELAP5 code, with the assumption of a clockwise directed mass flow, gives the next relation for the driving force.

$$\Delta P = -\frac{\bar{\beta}\,\bar{\rho}\,g}{\dot{m}\,\bar{C}_p}\left\{\left(\frac{h_c}{2} + h + \frac{h_s}{2}\right) Q + \frac{h_s}{2}\,\frac{Q_1 - Q_2}{N} + \frac{h_c}{2}\,\frac{Q}{N_c}\right\} \qquad \text{(B.5)}$$

$\bar{\beta}$, $\bar{\rho}$ and $\bar{C}_p$ are mean physical constants for the fluid in the system and h, $h_c$ and $h_s$ are resp. height of hot leg, core and steam generator (fig. B-2). Starting from eq. (B.5) and using the relations (B.2), (B.3) en (B.4) the natural circulation mass flow is given by:

$$\dot{m}^3 = -\frac{2\,\bar{\beta}\,\bar{\rho}^2\,A^2 g}{(k + k_f)\bar{C}_p}\left\{\left(\frac{h_c}{2} + h + \frac{h_s}{2}\right) Q + \frac{h_s}{2}\,\frac{Q_1 - Q_2}{N} + \frac{h_c}{2}\,\frac{Q}{N_c}\right\} \qquad \text{(B.6)}$$

The first term in this relation represents the analytical solution and the last two terms represent an error introduced by the RELAP5 code. The error is caused by the fact that the system is subdivided in discrete volumes in connection with the RELAP5 assumption with respect to the volume density. The last two terms disappear and so the error goes to zero when N and $N_c$ get infinite.

With the simple model of figure B-2 two sets of RELAP5 calculations are performed.

1. One set of calculations with different nodalization in core and steam generators.
2. One set of calculations with different power distributions for $Q_1$ and $Q_2$ in the steam generators.

**Ad 1. Nodalization sensitivity**

Table B-1 gives the results of a RELAP5 calculation and the analytical solution according to eq. (B.6) for the mass flow for different nodalizations. The power distribution for all the cases is set fixed viz. Q = 13.0 MW, $Q_1$ = 6.5 MW and $Q_2$ = 6.5 MW and the different heights are $h_c$ = 2.6 m, h = 3.6 m and $h_s$ = 7.6 m. The system fluid temperature is 530 K. The analytical solution of eq. (B.6) is based on the next average physical properties:

$\beta$ = 1.74 $10^{-3}$ $K^{-1}$
$(k_f + k)/A^2$ = 36.9 $m^{-2}$
g = 9.8 $m/s^2$
$C_p$ = 4795 J/kg
$\rho$ = 795 $kg/m^3$

The solution of eq. (B.6) and the RELAP5 mass flow calculation are identical for different nodalizations (small deviations are due to the averaging proces of the physical properties). The analytical solution for the simple model is 239.6 kg/s (eq. (B.6) with N, $N_c \rightarrow \infty$).

The nodalization of the steam generators and the core in the standard RELAP5 model for Nuclear Power Plant Borssele (N = 4, $N_c$ = 6) is based a.o. on efficiency considerations. The applied nodalization mesh size is a good choice, a maximum error of 1.5% can be expected due to nodalization.

**Ad 2. Variation in power distribution**

Table B-2 gives the results of a RELAP5 calculation and the analytical solution according to eq. (B.6) for the mass flow for different power distributions. The nodalization is the standard one $N_c$ = 6 (core divided in 6 subvolumes) and N = 4 (up and downward side of the steam generator divided in 4 volumes). The calculation started with relatively cold water at the steam generator outlet and hot water at the core outlet resulting in an average fluid temperature of about 530 K.

Table B-2 shows that the analytical and RELAP5 solutions are identical. The analytical solution according to eq. (B.6) and with N and $N_c \rightarrow \infty$ for this problem is 239.6 kg/s, based on average fluid physical properties. Assuming ($0,25 < Q_1/Q < 0,75$) a maximum deviation of about 15% can be seen between the RELAP5 calculated mass flow and the analytical solution for the mass flow.

Combining the seperate effects of nodalization and power distribution shows a maximum nodalization error of 3%.

Important in the RELAP5 analysis of a single loop is the possibility to calculate a reversed natural circulation flow. A reversed flow in the simple model will be calculated by starting with an isothermal system and $Q_1 >> Q_2$.

Table B-1. Steady state natural circulation mass flow for different nodalization schemes

| number of volumes in the core $N_c$ | number of volumes in steam generator N | mass flow RELAP5 (kg/s) | mass flow eq. (B.6) (kg/s) |
|---|---|---|---|
| 1 | 1 | 251.1 | 251.1 |
| 2 | 2 | 245.2 | 245.1 |
| 4 | 4 | 242.1 | 242.7 |
| 6 | 6 | 241.1 | 241.7 |

Table B-2. Steady state natural circulation mass flow for different power distributions.

| heat fluxes (MW) Q | $Q_1$ | $Q_2$ | RELAP5 mass flow (kg/s) | mass flow eq. (B.6) (kg/s) |
|---|---|---|---|---|
| 13 | -- | 13 | 248.9 | 250.0 |
| 13 | 3.25 | 9.75 | 245.1 | 245.9 |
| 13 | 6.5 | 6.5 | 241.1 | 241.7 |
| 13 | 9.75 | 3.25 | 237.1 | 237.3 |
| 13 | 13 | -- | 232.9 | 232.8 |

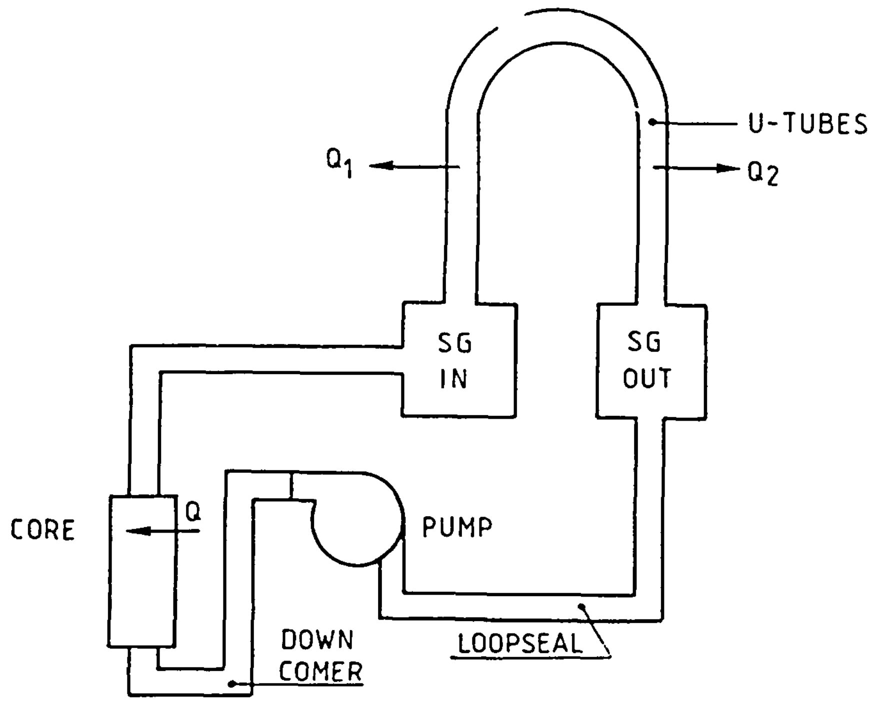


*FIG. B-1 SCHEMATIC OF A LOOP OF A PWR*

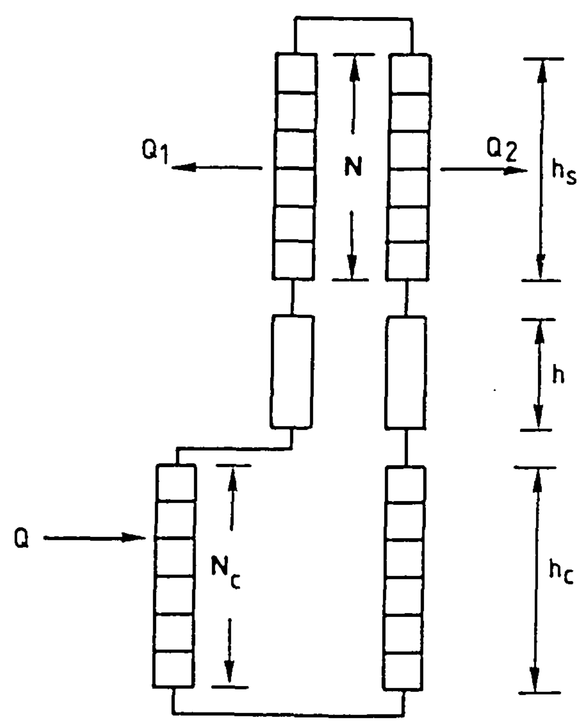


*FIG. B-2 RELAP 5 MODEL OF A LOOP OF A PWR*

Appendix C. Run statistics

The version of the simulation code used was RELAP5/MOD2, CY36.05. The code is implemented on a CDC Cyber 170-855 computer at the Technical Computing Center (ENR) at Petten, The Netherlands.
The run statistics for the documented analysis are given by the next numbers:

| | | |
|---|---|---|
| CPU | = total execution time(s) | = 9241 |
| C | = number of volumes | = 140 |
| DT | = number of time steps | = 18912 |
| RS | = millisec. per volume per time step | = 3.490 |

In figure C-1 the CPU-time is given as a function of the transient time. The CPU-time parameter in RELAP5 is reset to zero for each restart job. This explains the several drops back to zero in the CPU-time history.
In figure C-2 the time step size is given as a function of the transient time. The specified maximum time step size for the entire transient was 10 s.

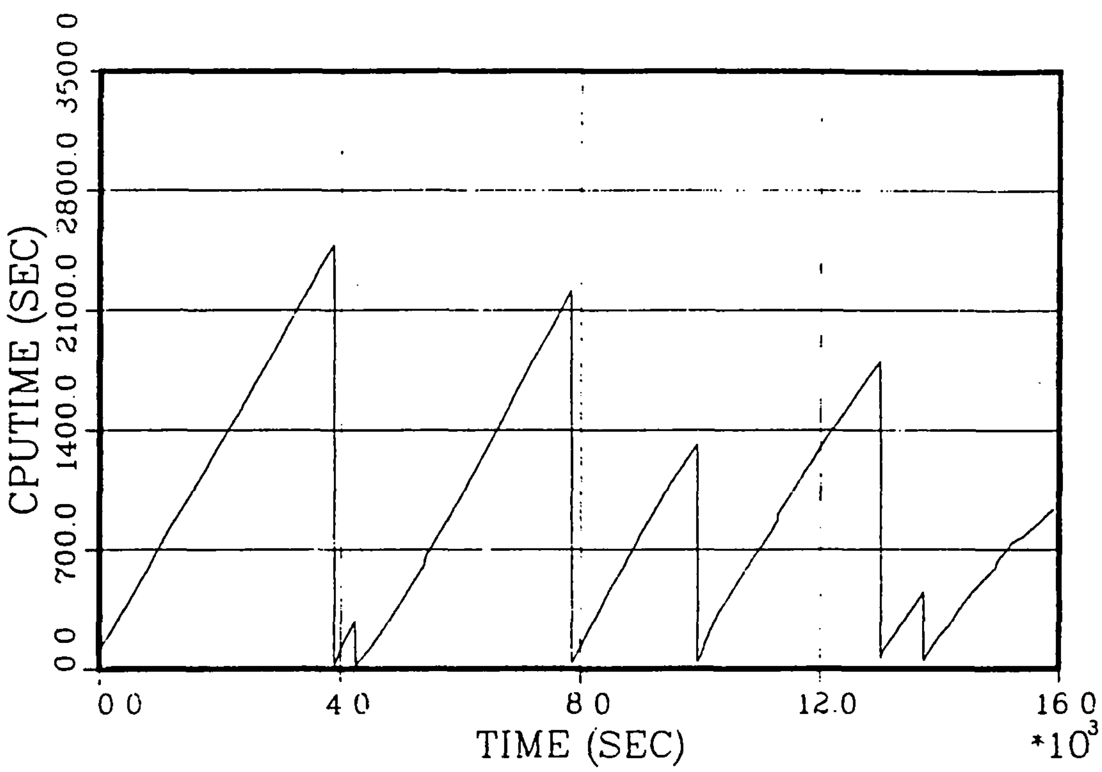


Fig. C-1. CPU-time as a function of real time

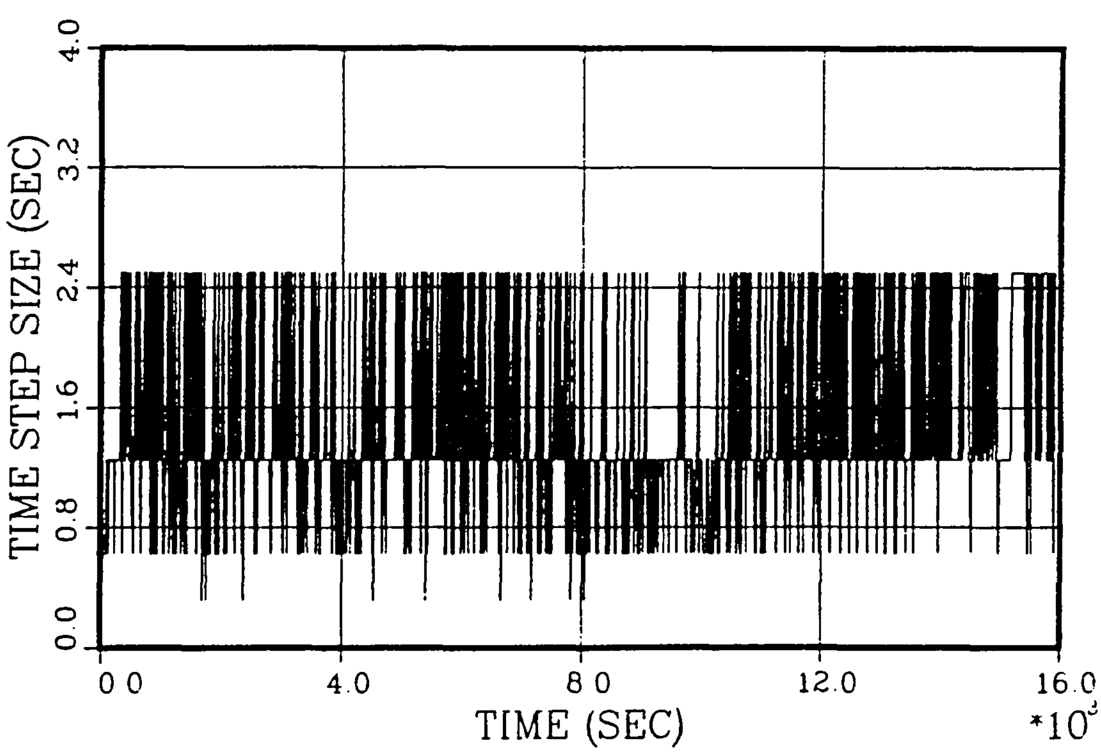


Fig. C-2. Time step size as a function of real time

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

As part of the ICAP (International Code Assessment and Applications Program) agreement between ECN (Netherlands Energy Research Foundation) and USNRC, ECN has performed a number of assessment calculations for the thermohydraulic system analysis code RELAP5/MOD2/36.05. This document describes the assessment of this computer program versus a natural circulation experiment as conducted at the Borssele Nuclear Power Plant. The results of this comparison show that the code RELAP5/MOD2 predicts well the natural circulation behaviour of Nuclear Power Plant Borssele.

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