

ICONE-8083

Reconciliation of process data in Nuclear Power Plants (NPPs)

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ABSTRACT

This contribution presents an overall mathematical survey of the nuclear power plant (NPP) process in terms of functional redundancy in relation to performance measurements and reactor output calculations.

With the help of VALI software it has been possible to verify significant differences in the average coolant temperature (CT) values compared with the displayed values, in particular in respect of starting up the plant. Corrections in the operating mode, which were made on the basis of the reconciled data, have resulted in maximum output being achieved more quickly.

By tracking the trends of the component output data calculated from reconciled data, it has been possible to obtain direct indications of weaknesses in the process engineering. With the help of an examination of sensitivity, an incorrect measuring chain response can be identified. For this purpose, automatically generated report forms are produced and these are used to maintain the measuring chains.

The replacement of equipment calibration by functional redundancy in relation to the measured performance values results in potential savings in respect of maintenance activities such as recurrent tests (RT) and recurrent maintenance measures (RM) of approx. € 565,000 per LWR unit/year.

Introduction and Objective

A considerable amount of coolant must be circulated to transfer approx. 3,850 MW_{th} of thermal energy from the primary circuit to the secondary circuit via heat exchangers (steam generators). The thermal output of NPPs is subject to authorizations and therefore it must not be exceeded. As a result, it is in the interest of the plant operator to run the system as close to the limit as possible to obtain the maximum amount of electrical power and thus to produce a kilowatt-hour of electricity at the lowest specific cost.

Thermal reactor power is calculated on the basis of the performance measurement data using an empirical equation, although this figure is affected by measuring errors. Flow metering contains the greatest measuring errors. The error contained in pressure measurements is smaller. It is likely that the smallest measuring errors will occur with temperature measurements. These deviations may be magnified even further in the measuring chains upstream of the controls or the process control computers. This means that the calculated thermal reactor power is subject to measurement errors.

Device-related redundancy to record the actual operating parameters is currently "achieved" through extensive recurrent tests (RT) and recurrent maintenance measures (RMM) in instrumentation and control. These measures cost a great deal of money and can only be

carried out intermittently (mainly when the fuel elements are changed).

In order to assess the process, very accurate information is required on the operating parameters that occur during use and, in this case, particularly when the plant is restarted.

For this reason, device-related redundancy can be replaced by an overall mathematical survey of the plant processes - what is termed functional redundancy - which will verify the validity of the process data. This basis has been achieved at the jointly-operated nuclear power plant Neckarwestheim Unit 2 (GKN2, four LOOP plant) using the VALIII program (software from the company Belsim) /1/.

The mathematical basis for functional redundancy is described in the VDI2048 guideline /2/. The process data reconciliation works with process data generated by the plants measuring devices. This data is then merged functionally into a plants' model according to the process configuration. After further processing, the data represents an over-determined set of equations with respect to mass, energy and material balance. With the help of Gauss' compensation theorem, the most likely is determined. The principal way of this calculation is described on a simple example in the **APPENDICES 1 and 2**.

The results of the reconciliation calculations linked to the sensitivity analysis allow the operating data to be corrected online and over time also permit the trends for the functionality in the system of individual plant components to be recorded.

This paper will present a few examples to illustrate this point and will also consider how the data obtained is applied within the power plant organization. The effect it may have on maintenance costs is also covered.

Model structure

The data reconciliation model for GKN2 has been produced using the program VALIII/1/ and is shown in **APPENDIX 3** as a flow diagram and as a VALI chart in **APPENDIX 4**. The following systems have been modeled:

- the **primary circuit** with the reactor pressure vessel (RPV), four main coolant pumps (MCP), four steam generators (SG), the connecting pipes and the reactor water purification system (KBA system)
- the **secondary circuit** with the HP turbine, two LP turbines, two moisture separators/reheaters, two condensers, the condensate pump, two feed-water heater strings with a total of sixteen heat exchangers, the three feed water pumps, the feed water tank and the connecting piping systems, including the four blowdown pipes for the steam generator.

Input values

A total of

- 147 active measured values and
- 152 PSEUDO measured values

are entered in the reconciliation model. In order to obtain more process information and process data in addition to these values, for example

- Distribution of heat flows between the four steam generators,
- Main steam or feed water heat flows,
- Efficiency of pumps,
- Concentration of heat exchangers,
- Pressures, temperatures and mass flows in areas where no measurements are available,

a further 154 other variables are defined in addition.

Measured values are sent from the process computer to the model as mean hourly values.

PSEUDO measured values are values required for the reconciliation process but where there are no measurements available in the process at these points. Fixed start values are assigned to PSEUDO measured values.

The **other variables** are, for instance, calculated values such as the steam generator output or pressures, mass flows or temperatures at points in the process where no measurements are available.

The other variables are only required for analysis and, in comparison to the measured values and the PSEUDO measured values, do not have any influence on the reconciliation procedure.

Data flow and further processing

The data flow is shown in **APPENDIX 5**. The measured data record (mean hourly values) are read into the VALI model. As soon as the convergence criterion

Sum of the least squares less than 1×10^{-6}

has been satisfied, a REPORT FILE, required to indicate the trend, and – optionally – an SNS FILE containing the sensitivity analysis is produced.

Plotting flow sheets and trends

The REPORT FILE is read into an ACCESS database and optionally into an EXCEL flow sheet. The following data can be found in the REPORT FILE:

- The measured values or start values of PSEUDO measured values,
- The standard deviation of measured values,
- The reconciled values of measured values or the PSEUDO measured values,
- The standard deviation of the reconciled values and
- The PENALTY function.

The trend curves of individual data can be shown using the VALI RESULT BROWSER, which uses EXCEL as an interface: see **APPENDIX 6**.

The **PENALTY function** calculated with the VALI program can be taken as a measure indicating the quality of the model. It presents the following sum:

$$\sum_i \left(\frac{\text{Measured value}_i - \text{associated validated value}_i}{\text{Standard deviation of measured value}_i} \right)^2$$

The trend of the PENALTY function for this model structure is shown in **APPENDIX 7**. This chart also shows the electrical generator output in order to illustrate the relationship between the PENALTY functional value fluctuations of between 50 and 100 from the generator output. The sharp increase in the PENALTY function on June 1, 1998 can be attributed to a reduction in output to approx. 1100 MW (approx. 80 % of output).

APPENDICES 8 to 11 contain charts showing the start-up procedure on September 7, 1998 and how the trend developed until September 23, 1998

- The thermal reactor output
- The mean coolant temperature
- The electric generator output and
- The thermal outputs for blowdown, feed water and main steam.

The purpose of these charts is to be able to follow the start-up process practically online so that, if any problems do occur during the start-up process, indications on the reasons for the deviations from the expected values can be obtained as quickly as possible.

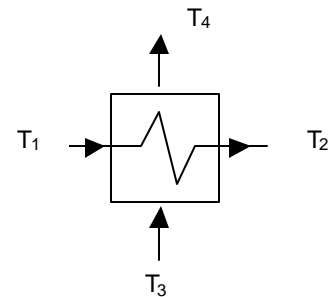
The lines plotted in the charts are the target values that need to be reached for 100% operation. Should individual values deviate from these target values, the cause in this area can be identified with the aid of further variables that can also be found in the database.

APPENDICES 12 and 13 contain charts showing the measured values and the reconciled values for feed water flows. Here it is possible to identify clear differences between the reconciled values and the measured values.

APPENDIX 14 shows the temperature difference ratio selected for evaluating heat exchangers in the case of a selected heat exchanger.

$$ETA_T = \frac{T_4 - T_1}{T_2 - T_1}$$

$T_2 > T_1$ and $T_4 < T_3$
and $T_{1,2,3,4}$ in [K]



APPENDIX 15 reveal a flow sheet. ... the primary loop with current measured and reconciled data. **APPENDIX 16** reveal a flow sheet of the secondary loop with current measured and reconciled data.

Sensitivity analysis

As an option, a **sensitivity analysis** can also be carried out. After processing, this is also loaded into the ACCESS database. Using this it is possible to select a criterion (individual PENALTY > as the selected criterion, e.g. 1) and to list all measuring points which satisfy this criterion and to show the relationships of other measuring points to the calculation of the reconciled values of these measuring points. In particular, this must be taken into account for calibration procedures that are to be initiated

by instrumentation and control. **APPENDIX 17** contains a sample report.

It can be seen that the reconciled value of measuring point JEC20CT003A is calculated on the basis of a total of seven measured values and these measured values are used in equal proportions (11.7 %) to determine the reconciled value. The sum of these parts amounts to 82%. The missing 18 % is made up of values which are calculated internally by VALI and are not indicated in the sensitivity analysis. (The sensitivity analysis only indicates measured values and PSEUDO measured values.)

Incorporation in the NPP organization

The process data gathered is reconciled by the "Instrumentation and Control" Department using a KRIS computer system. The reconciled data is either sent to the unit control room where it is displayed on a chart of the plant provided for this purpose so that significant deviations can be ascertained. Alternatively, it may be processed accordingly on a PC (in the "Operations" Department) so that the values can be displayed in the form of trend curves. In addition, individual values are grouped together in such a way that

- The thermal reactor power
- The efficiency of the system
- Power consumption and
- The efficiency of individual heat exchangers

are displayed/3/. This data is assessed by an operations engineer. Any deviations ascertained are discussed with the operations manager. It is then decided whether and in what form the system engineers or the maintenance team should become involved. Reports on measuring points with a large PENALTY function are generated automatically for the Instrumentation and Control Department in order to provide indications of where calibration work is required.

The purpose of this course of action is:

- Only to calibrate those measuring points where calibration is actually required and
- To optimize the VALI model.

The aim is to have penalty function during steady-state operation of below 40 in order to obtain a sensitive VALI model.

Should data reconciliation reveal deviations in the acquisition or processing of measured data, there are several options available to take corrective action:

- Recalibration of the measured values concerned
- Change in the measurement location
- Correction of measured values at a suitable point during measured value acquisition, e.g. in the process control computer.

The first option usually applies if a typical measuring error is involved, e.g. in the case of measuring transformer drifting. Data reconciliation can thus be used to change to a maintenance strategy for measuring chains which is genuinely "geared to the status".

Data reconciliation offers considerable potential for reducing costs in the short and medium term. Testing and maintenance measures involving the acquisition and processing of measured data currently cost approximately €1.13 million per power plant unit per year. Cost reductions in the order of 50% can be expected in the event of a systematic changeover to a future-orientated testing and maintenance strategy for measuring chains using data reconciliation.

As the majority of testing activities contained in the test and maintenance regulations for NPPs have been specified by the Authorities and Inspectors, the full potential of these savings can probably only be realized if Authorities and Inspectors accept data reconciliation as "functional redundancy" and thus as a "basis for calibration".

For some time now, this has been the case in Swiss Nuclear Power Plants. Corresponding initiatives will follow in Germany now that the trial phase has been successfully completed.

Once data reconciliation has been qualified, the third option can also be applied in some circumstances – measured value correction during measured value processing. For instance, the parameters for measuring power in the nuclear power plant at Leibstadt are corrected on the basis of data reconciliation in the process control computer. This is a simple option: it reduces the extent to which the personnel are exposed to radiation because no on-site work is required. All this is achieved without any reduction whatsoever in safety standards.

It has been known for a long time that – depending on the position of the measuring point - stratification in the medium can result in different temperatures being

displayed in certain areas, e.g. when loop temperatures are being measured. Where values cannot be calibrated during the downstream processing of measured values, data reconciliation can be used to identify those measuring sensors which are most likely to reflect the status of the plant and these can then be applied for conditioning tasks during the process. This application is a typical example for the second of the options listed above.

Conclusions

Functional redundancy in relation to performance measurements achieved as a result of reconciliation mean

- Process engineering deviations can be identified quickly and corrective measures initiated when starting up the unit
- Weaknesses developing in process equipment can be traced quickly by monitoring the trend data,
- The mode of operation can be optimized
- Calibration of measuring chains during operation is not complicated and
- There is considerable potential to reduce maintenance costs (RT, RMM).

The investment needed to install the reconciliation and analysis software amounting to €206,000 /4/ will therefore be recouped within months as a result of the parameters listed above.

The fact that the reconciliation of process data will also result in fundamental improvements in safety is a definite point in favor of the investment.

References

- /1/ Vali III USER GUIDE, BELSIM S.A., Liege, Belgium, September 1997
- /2/ VDI 2048 guideline; June 1999
- /3/ GKN 2 – Description and documentation of the changes made to the GKN2 VALI model to display the VALI results in graphic form
BTB-Jansky GmbH Report No. 760 dated August 5, 1998

- /4/ GKN I validation of performance measurements in nuclear power plants
BTB-Jansky GmbH Report No. 759 dated July 21, 1998

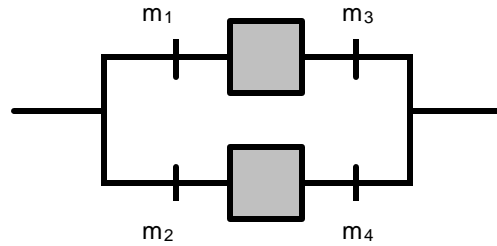
Overview of the Appendices

- Appendix 1:** Example
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Appendix 4: Overview of the GKN2-modell in VALI-charts
Appendix 5: Data flow
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Example - Calculation based on VDI 2048

Measurement values with specified standard deviations

$$m = \begin{bmatrix} m_1 = 250 \pm v_{x1} \text{ where } v_{x1} = 2 \text{ kg/s} \\ m_2 = 245 \pm v_{x2} \text{ where } v_{x2} = 2 \text{ kg/s} \\ m_3 = 270 \pm v_{x3} \text{ where } v_{x3} = 4 \text{ kg/s} \\ m_4 = 250 \pm v_{x4} \text{ where } v_{x4} = 4 \text{ kg/s} \end{bmatrix}$$



$$s_{xi}^2 = \left(\frac{v_{xi}}{t} \right)^2 \text{ with } t = 1,96 \text{ implying a 95\% confidence interval (1)}$$

Covariance matrix

$$S_x = \begin{bmatrix} s_{x1}^2 & s_{x1i} & s_{x1k} & s_{x1n} \\ s_{x1i} & s_{xi}^2 & s_{xik} & s_{xin} \\ s_{xk1} & s_{xki} & s_{xk}^2 & s_{xkn} \\ s_{xn1} & s_{xni} & s_{xnk} & s_{xn}^2 \end{bmatrix} \quad (2)$$

Vector of measured values

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \end{bmatrix} = \begin{bmatrix} 250 \\ 245 \\ 270 \\ 250 \end{bmatrix} \quad (3)$$

Restrictions

$$\begin{aligned} m_1 - m_3 &= 0 \\ m_2 - m_4 &= 0 \end{aligned} \quad (4)$$

Vector of restrictions

$$f(\bar{x}) = \begin{pmatrix} m_1 - m_3 \\ m_2 - m_4 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (5)$$

$f(\bar{x}) = f(x) + \frac{\partial f}{\partial x} \mathbf{n}$ where $f(x)$ - Vector of contradictions, v - Corrective vector applied to the present

example

$$\frac{\partial f}{\partial x} = \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{pmatrix} \text{ and } f(x) = \begin{pmatrix} m_1 - m_3 \\ m_2 - m_4 \end{pmatrix} = \begin{pmatrix} -20 \\ -5 \end{pmatrix} \quad (6)$$

and S_x

$$S_x = \begin{bmatrix} 1,0412 & 0 & 0 & 0 \\ 0 & 1,0412 & 0 & 0 \\ 0 & 0 & 4,1649 & 0 \\ 0 & 0 & 0 & 4,1649 \end{bmatrix} \quad (7)$$

The minimization problem

$$\mathbf{n} \cdot S_x^{-1} \cdot \mathbf{n} - 2\mathbf{l} \cdot f(\bar{x}) = \mathbf{x}_0 \rightarrow \text{Min} \quad (8)$$

yields, after a few adjustments and the linearization of $f(\bar{x}) = f(x) + \frac{\partial f}{\partial x} \mathbf{n}$ (9),

the corrective vector

$$\mathbf{n} = - \left(\frac{\partial f}{\partial x} S_x \right)^T \cdot \left(\frac{\partial f}{\partial x} S_x \cdot \left(\frac{\partial f}{\partial x} \right)^T \right)^{-1} \cdot f(x) \quad (10)$$

With the values specified above it can be calculated that

$$\left(\frac{\partial f}{\partial x} S_x \right)^T \cdot \left(\frac{\partial f}{\partial x} S_x \cdot \left(\frac{\partial f}{\partial x} \right)^T \right)^{-1} = \begin{bmatrix} 0,2 & 0 \\ 0 & 0,2 \\ -0,8 & 0 \\ 0 & -0,8 \end{bmatrix} \quad (11) \text{ and}$$

APPENDIX 1: Example

$$v = - \begin{bmatrix} 0,2 & 0 \\ 0 & 0,2 \\ -0,8 & 0 \\ 0 & -0,8 \end{bmatrix} \begin{bmatrix} -20 \\ -5 \end{bmatrix} = \begin{bmatrix} 4 \\ 1 \\ -16 \\ -4 \end{bmatrix} \quad (12)$$

As a result, the restriction fulfilling values yield

$$\bar{m} = \begin{bmatrix} \bar{m}_1 \\ \bar{m}_2 \\ \bar{m}_3 \\ \bar{m}_4 \end{bmatrix} = m + v = \begin{bmatrix} 250 \\ 245 \\ 270 \\ 250 \end{bmatrix} + \begin{bmatrix} 4 \\ 1 \\ -16 \\ -4 \end{bmatrix} = \begin{bmatrix} 254 \\ 246 \\ 254 \\ 246 \end{bmatrix} \quad (13)$$

The covariance matrix of corrections can be calculated as follows:

$$S_v = - \left(\frac{\partial f}{\partial x} S_x \right)^T \cdot \left(\frac{\partial f}{\partial x} S_x \cdot \left(\frac{\partial f}{\partial x} \right)^T \right)^{-1} \cdot \left(\frac{\partial f}{\partial x} S_x \right) \quad (14)$$

Implemented into the example it yields

$$S_v = \begin{bmatrix} 0,2082 & 0 & -0,83298 & 0 \\ 0 & 0,2082 & 0 & -0,83298 \\ -0,83298 & 0 & 3,3333 & 0 \\ 0 & -0,83298 & 0 & 3,3333 \end{bmatrix} \quad (15)$$

and the corrected covariance matrix

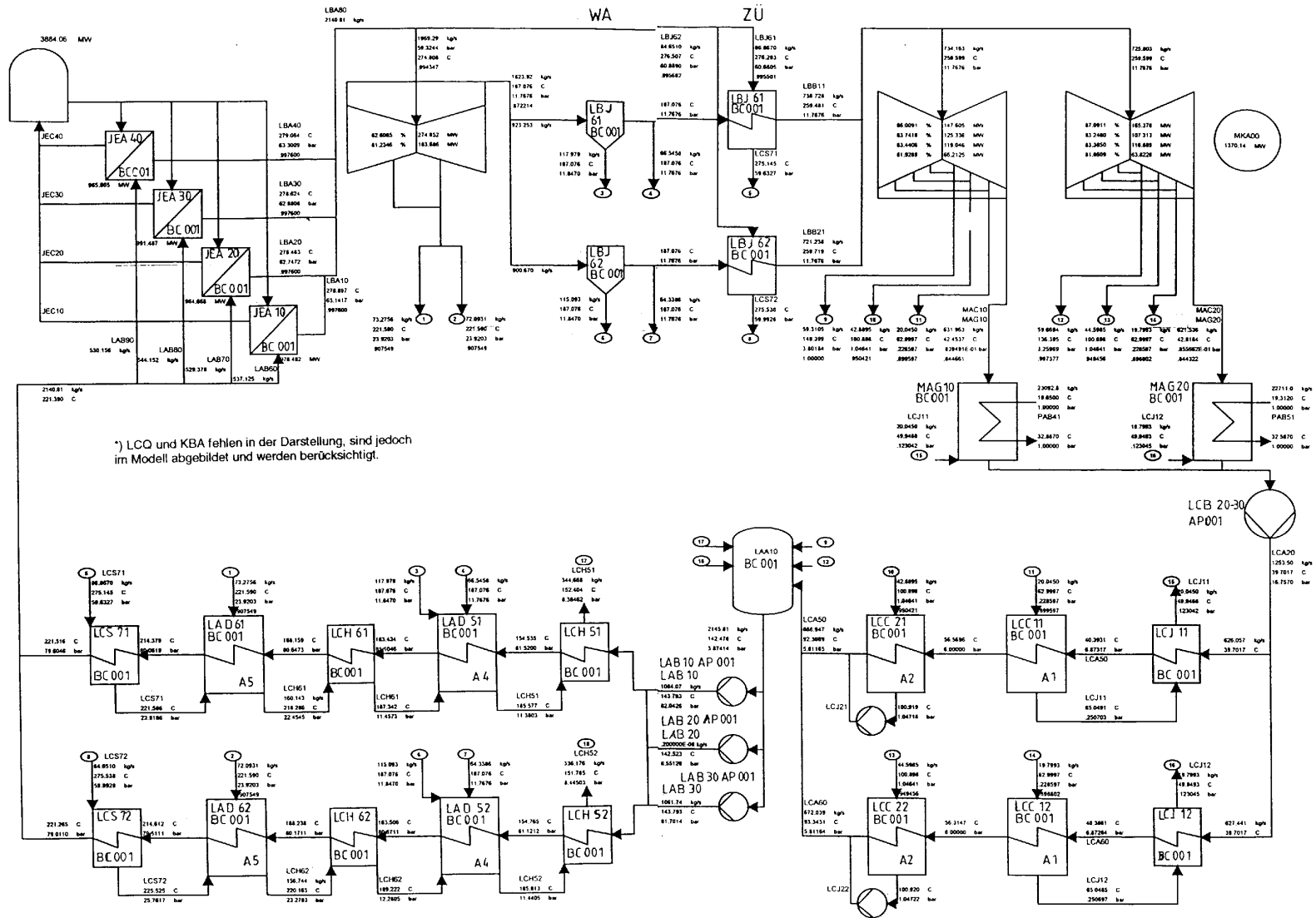
$$S_x^- = S_x - S_v = \begin{bmatrix} 1,0412 & 0 & 0 & 0 \\ 0 & 1,0412 & 0 & 0 \\ 0 & 0 & 4,1649 & 0 \\ 0 & 0 & 0 & 4,1649 \end{bmatrix} - \begin{bmatrix} 0,2082 & 0 & -0,83298 & 0 \\ 0 & 0,2082 & 0 & -0,83298 \\ -0,83298 & 0 & 3,3333 & 0 \\ 0 & -0,83298 & 0 & 3,3333 \end{bmatrix} =$$

$$S_x^- = \begin{bmatrix} 0,833 & 0 & 0,83298 & 0 \\ 0 & 0,833 & 0 & 0,83298 \\ 0,83298 & 0 & 0,831 & 0 \\ 0 & 0,83298 & 0 & 0,831 \end{bmatrix} \quad (16)$$

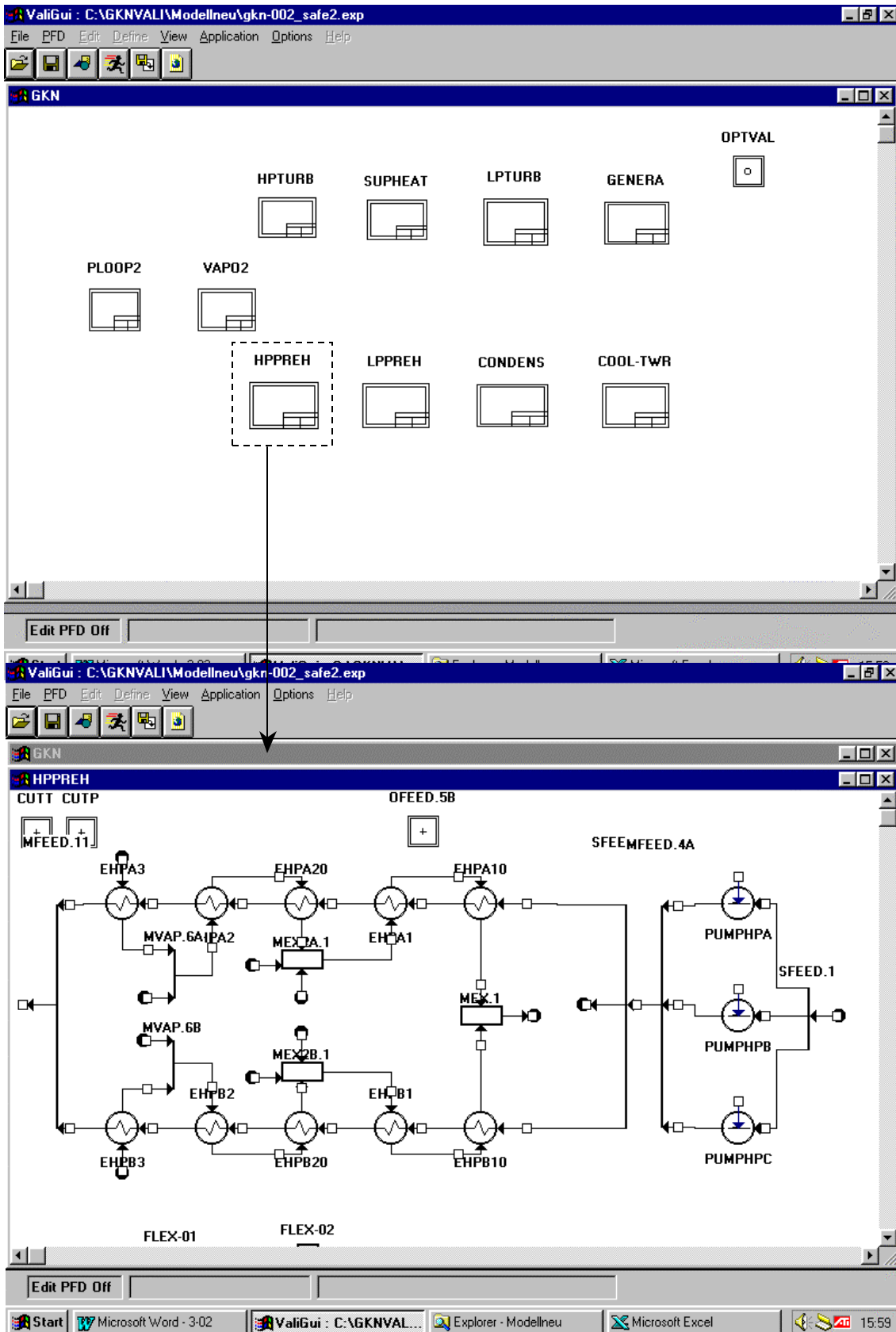
With the corrected covariance matrix and equation (1), the new corrected confidence intervals can be calculated. $v_{x_i} = \sqrt{s_{x_i}^2} \cdot t$ with $t = 1,96$ implying a 95% confidence interval (17) The example calculation yields $v_{x_i} = \pm 1,788869$. So you get the vector m_{NEW} without contradiction

$$m_{NEW} = \begin{bmatrix} 254 \pm 1,79 \text{ kg/s} \\ 246 \pm 1,79 \text{ kg/s} \\ 254 \pm 1,79 \text{ kg/s} \\ 246 \pm 1,79 \text{ kg/s} \end{bmatrix} \quad (18)$$

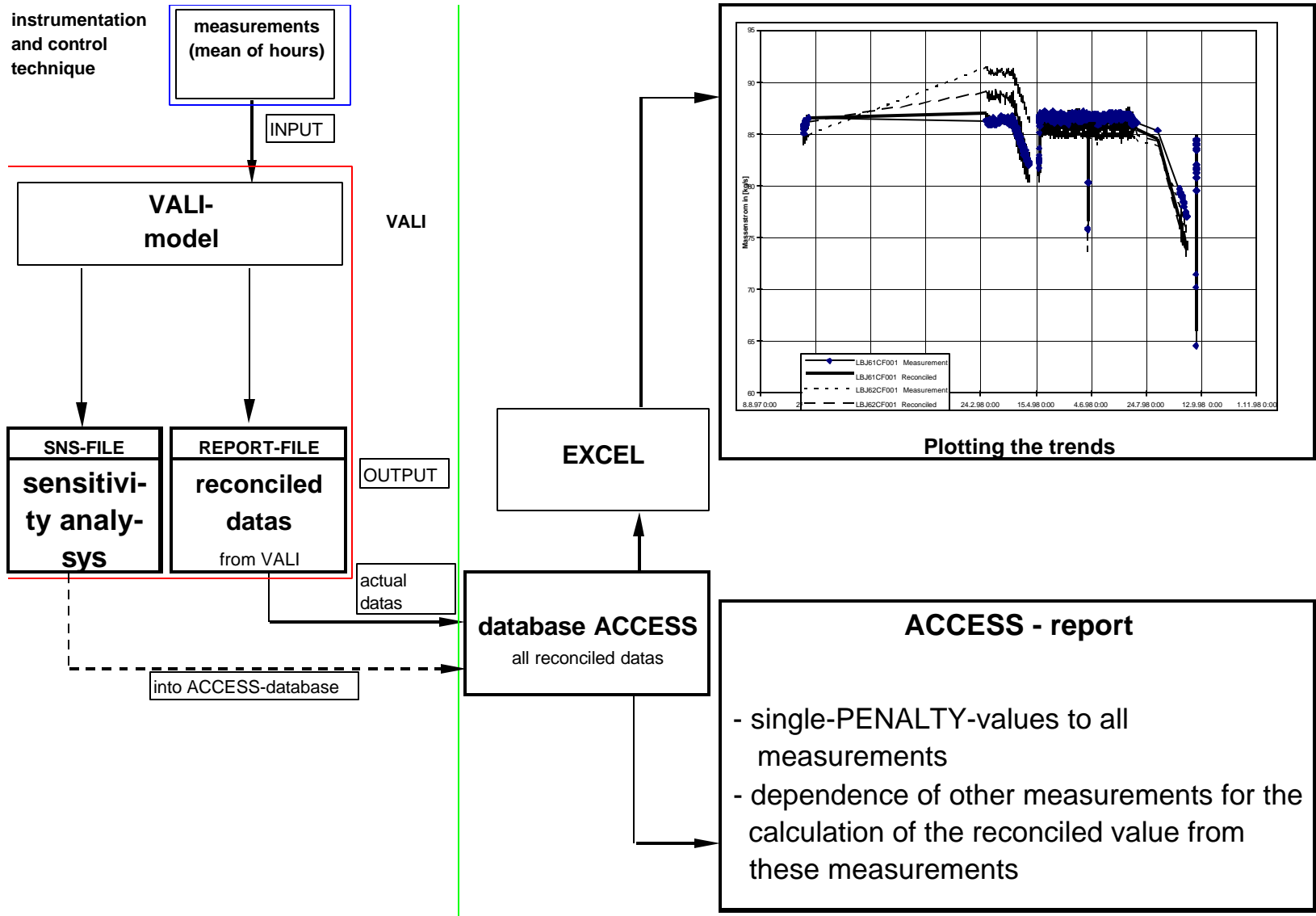
APPENDIX 2: Example-continue



APPENDIX 3: VAL-model of NPP GKN2



APPENDIX 4: Overview of the GKN2-modell in VALI-charts



APPENDIX 5: Data flow

GRAPH-VIEW - 01. Wärmemengenk2

File Database Runs Graph Tools Help

H8

gkn.mdb

Tag Name

P_ABSCH P_ABSCH P_FRISCH P_FRISCH P_SPW

Reconciled Measurement Reconciled Measurement

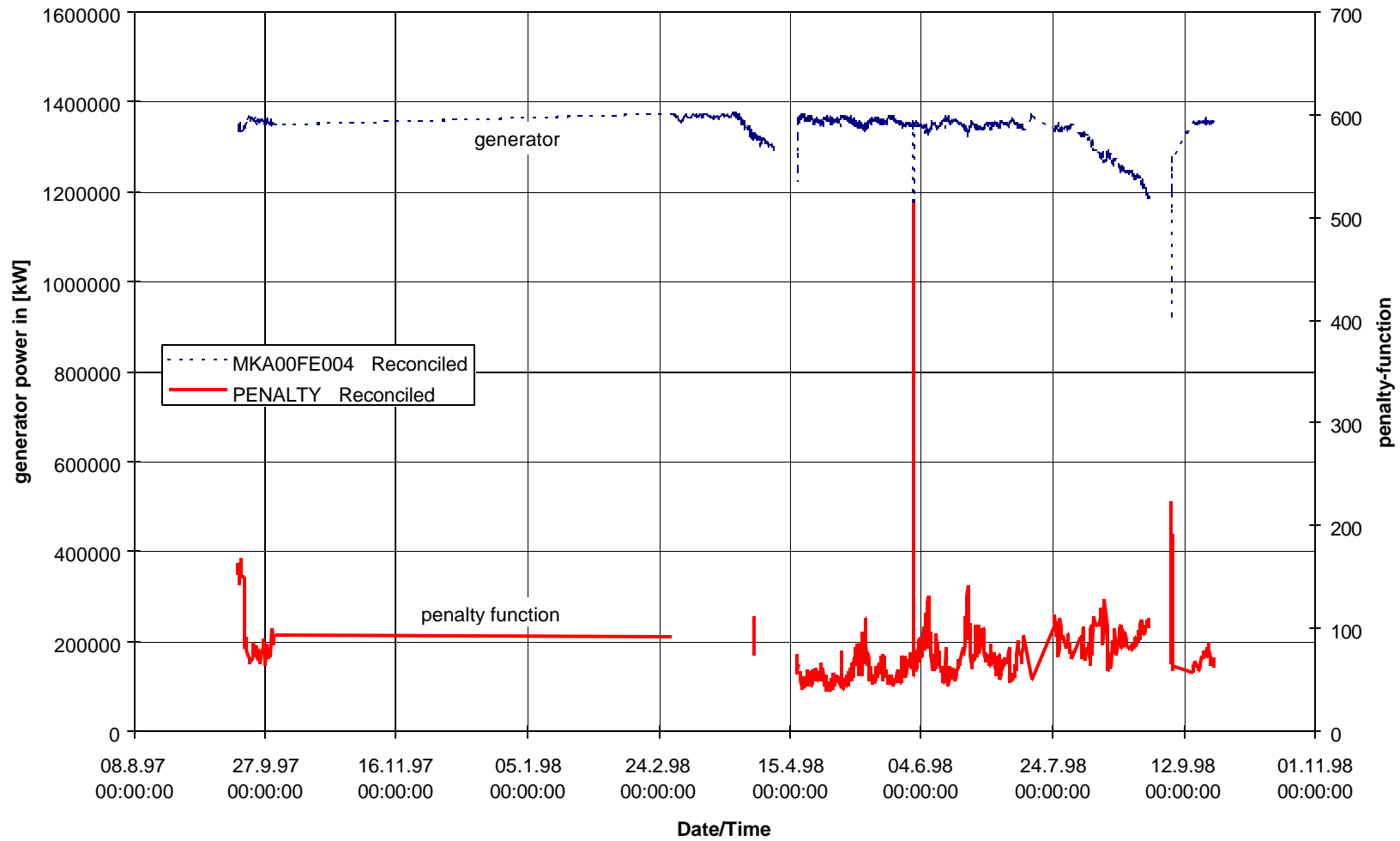
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1073	7.9.98 13:15				
1072	7.9.98 13:00				
1071	7.9.98 12:45				
1070	7.9.98 12:30				
1069	7.9.98 12:15				
1068	7.9.98 12:00				
1078	7.9.98 11:45				
1067	7.9.98 11:15				
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1062	7.9.98 9:30				
1077	7.9.98 9:00				
1076	7.9.98 8:45				
1061	7.9.98 8:00				
1060	7.9.98 6:45				

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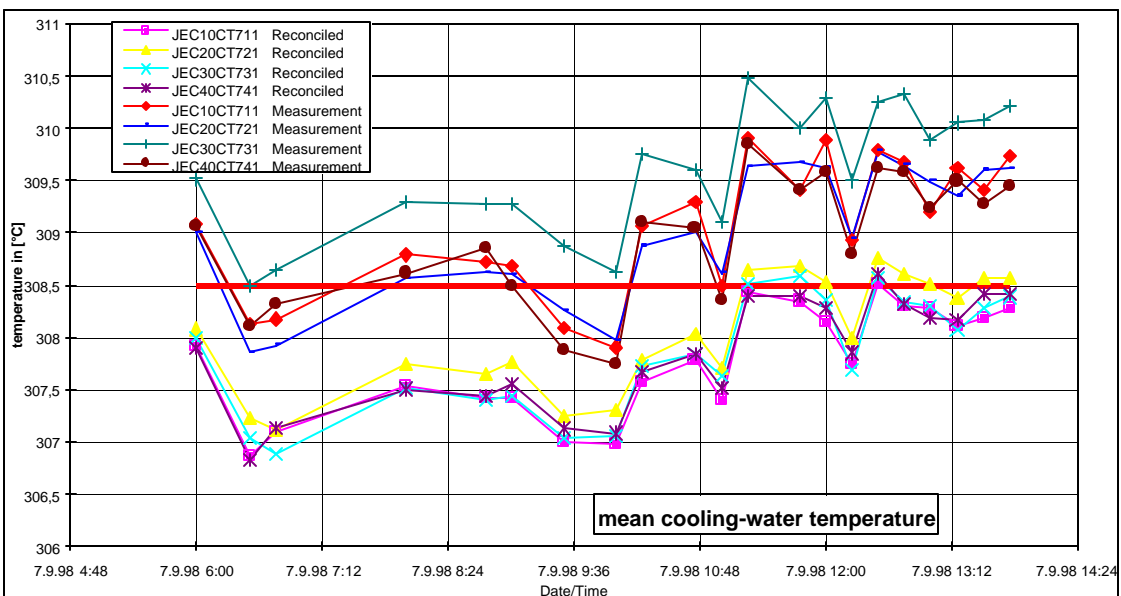
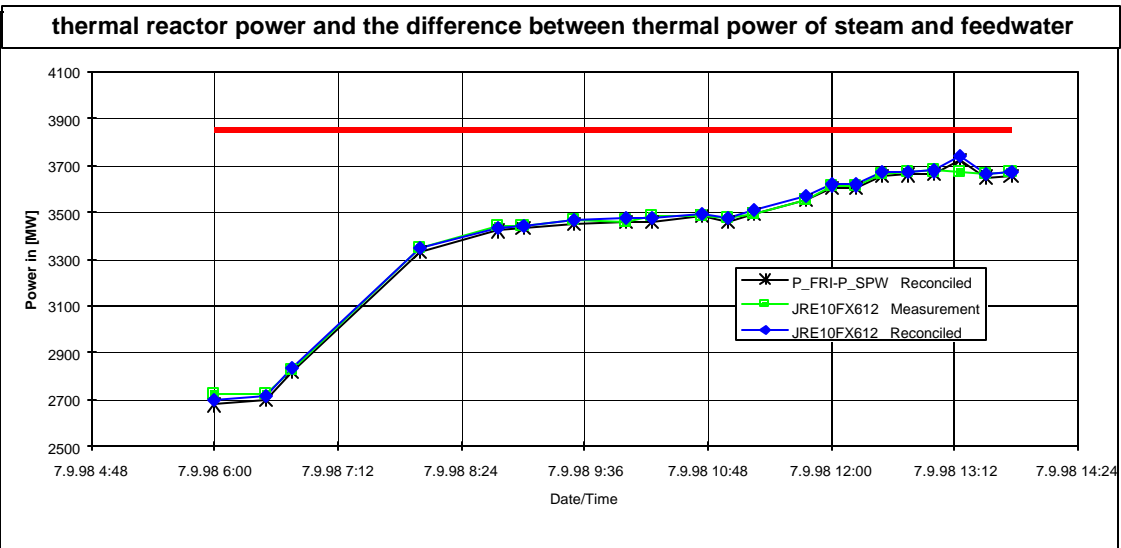
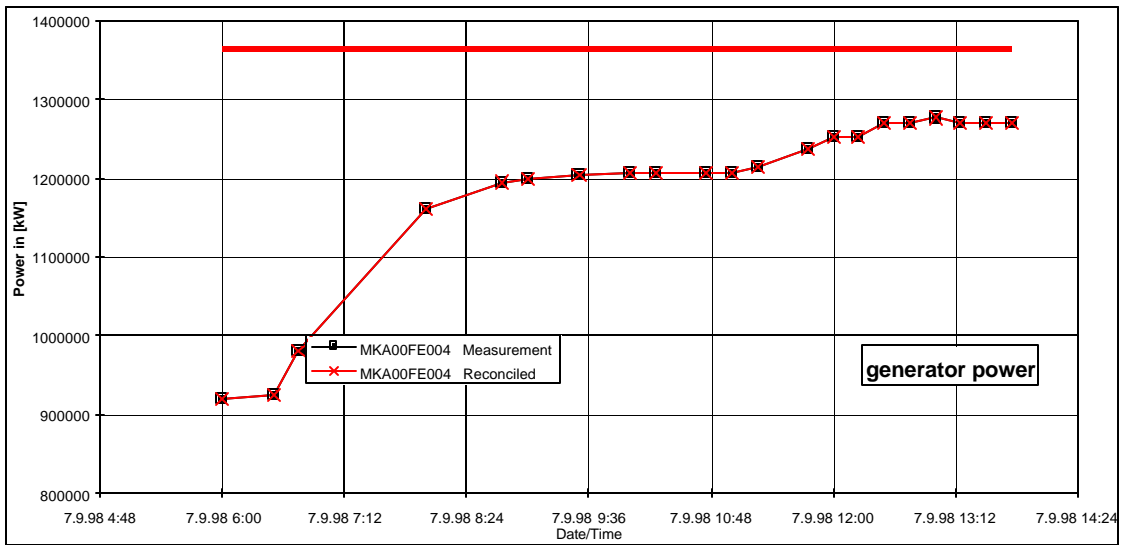
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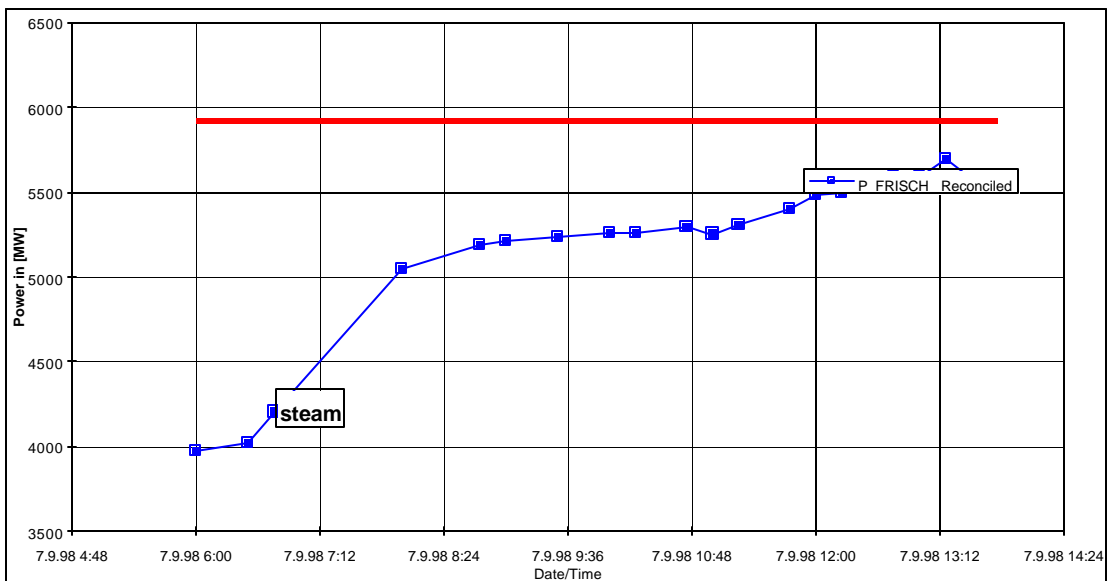
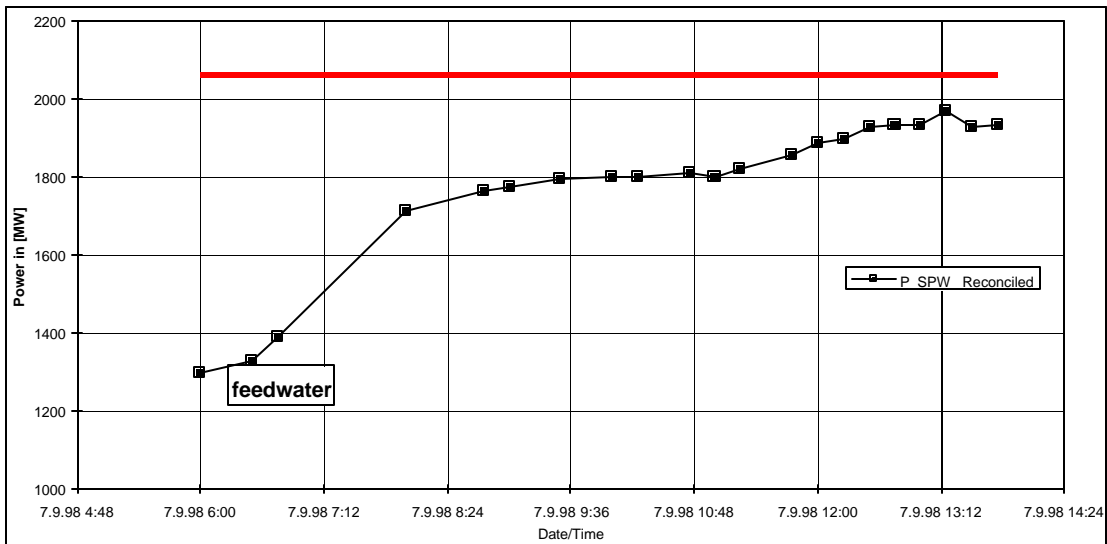
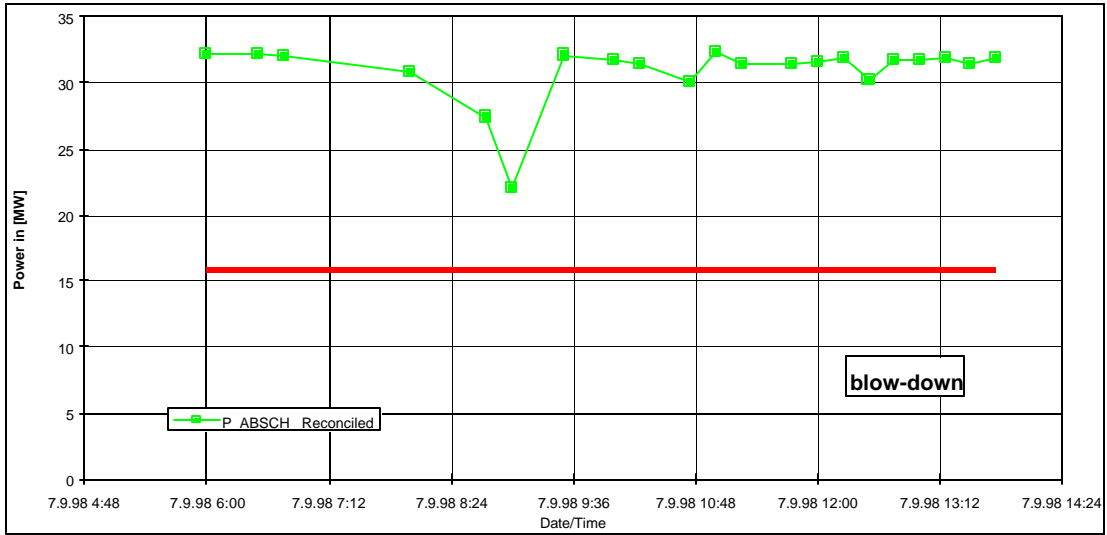
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APPENDIX 6: VALI-RESULT-BROWSER

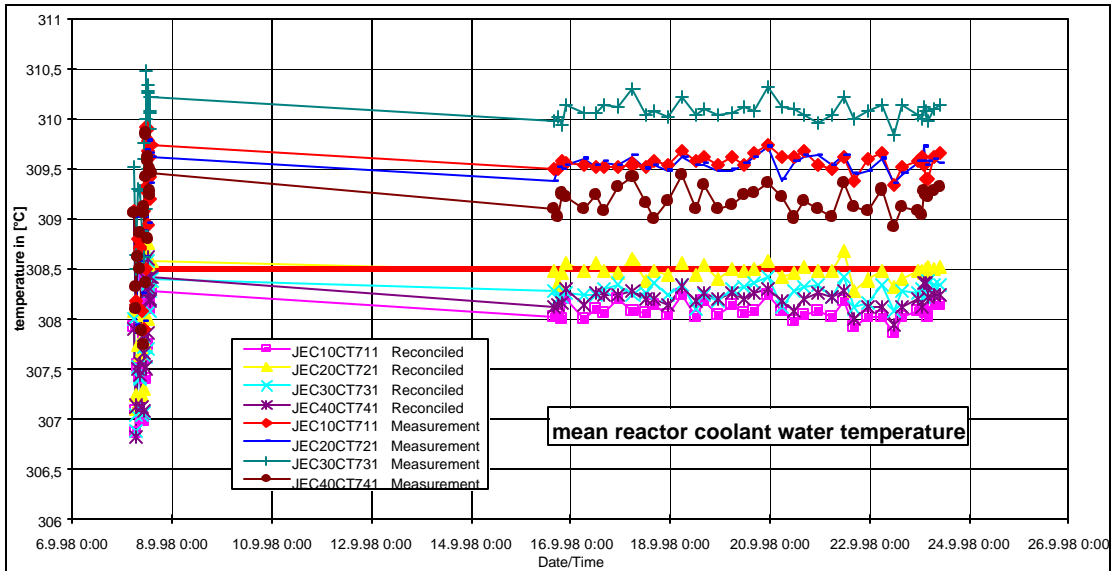
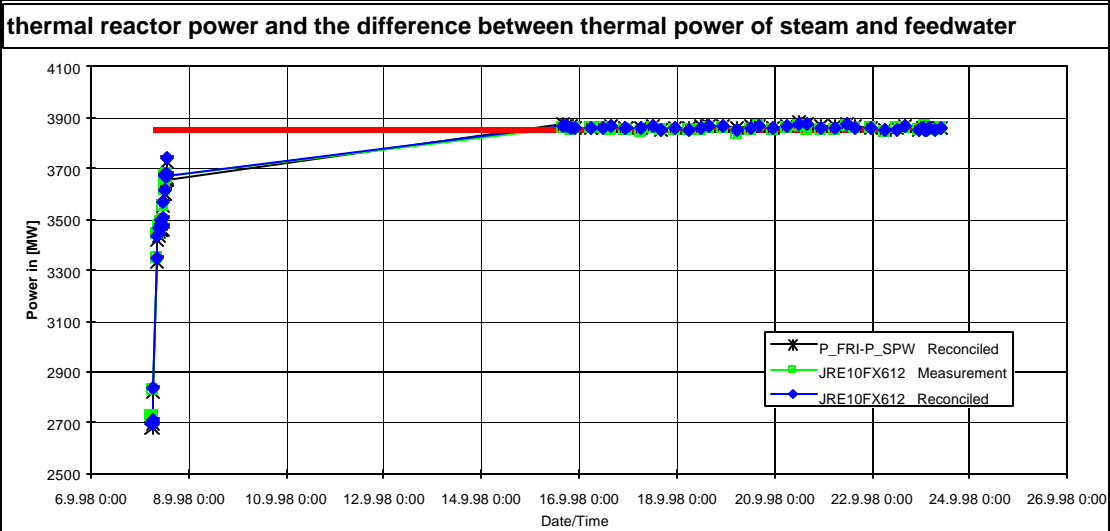
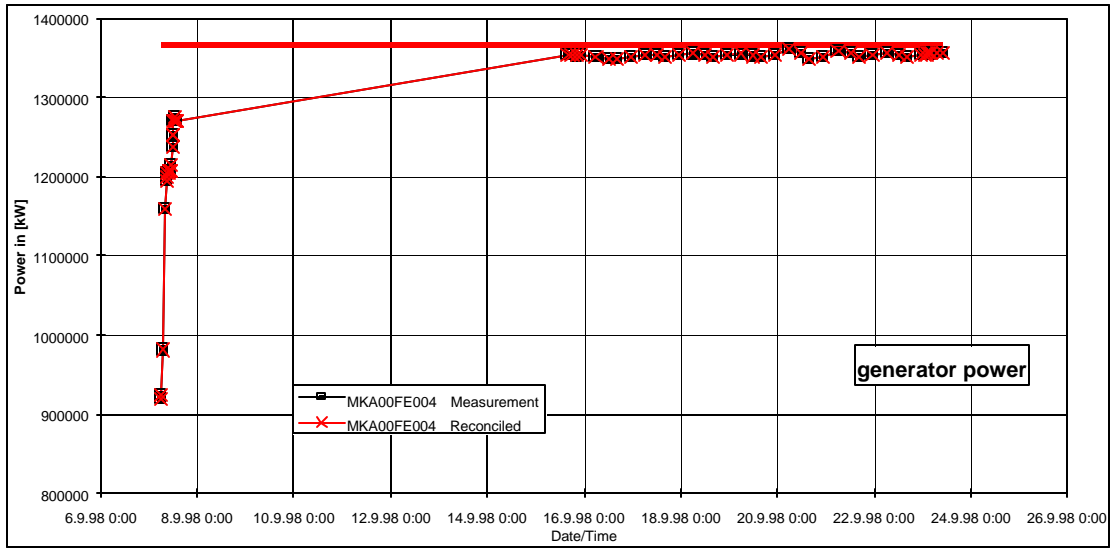


Appendix 7: Relationship between penalty-function and generator-power

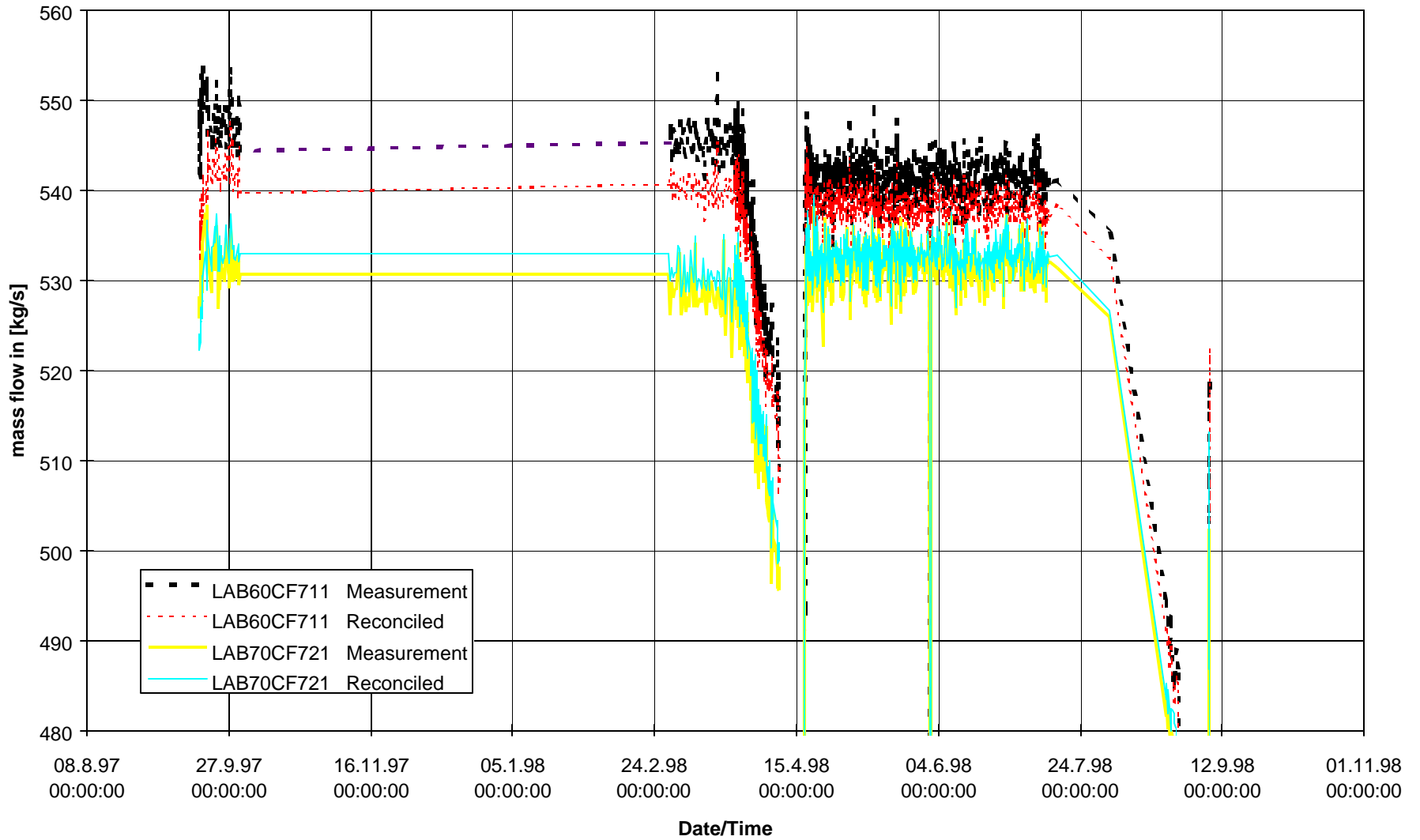




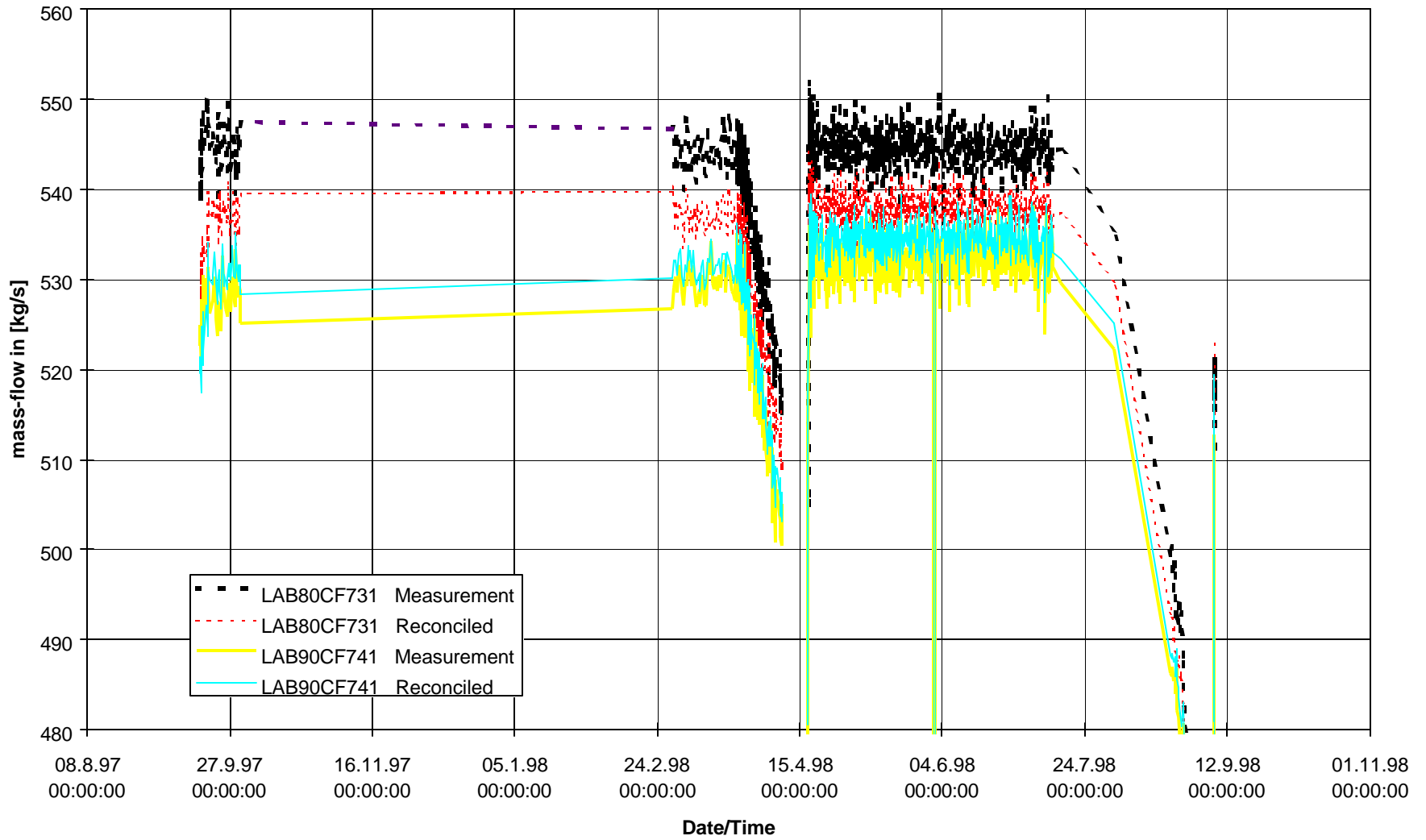
APPENDIX 9: Start-up 07.09.98



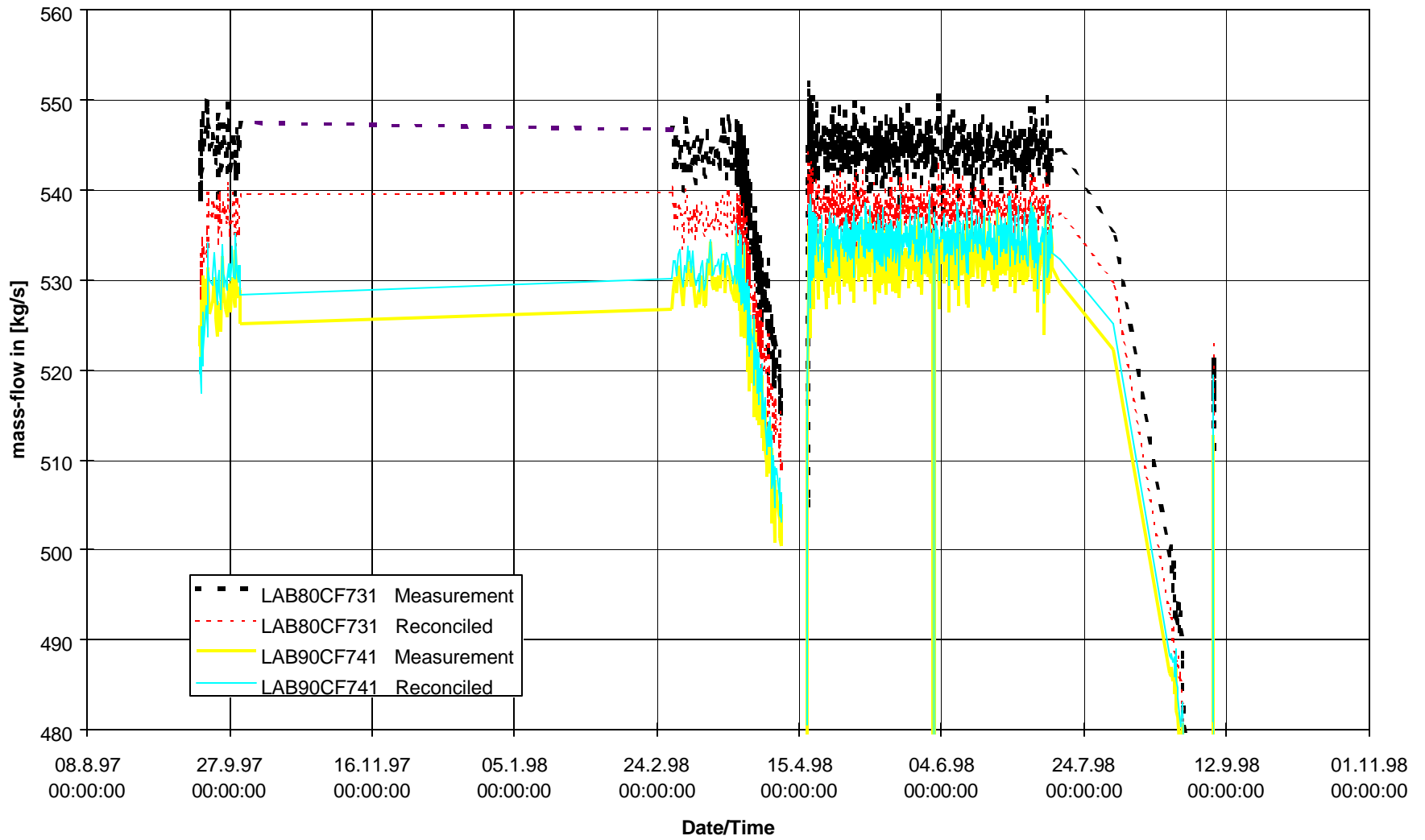
Appendix 10: Operating between 07.09.98 and 23.09.98



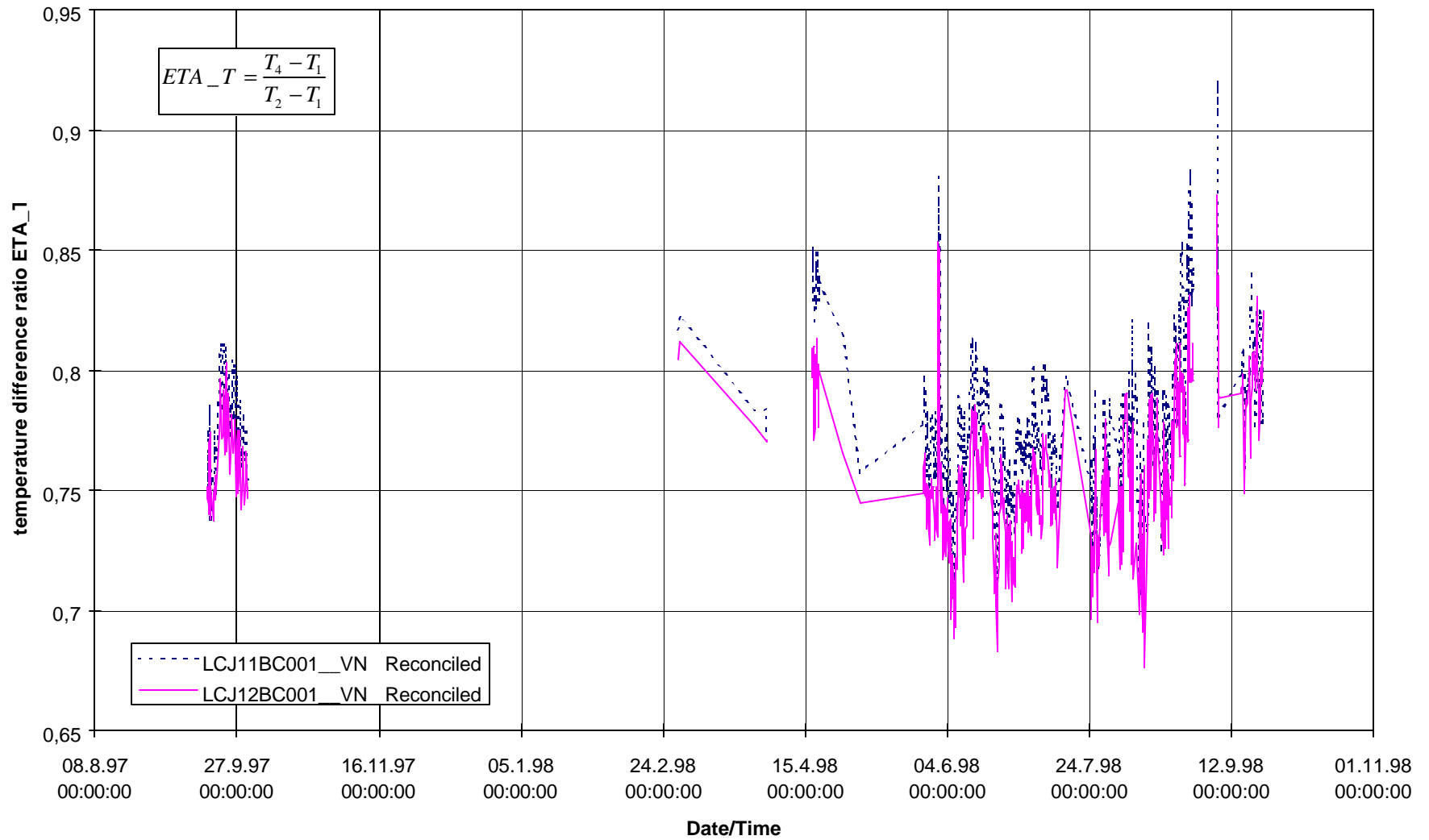
Appendix 12: Feedwater mass flow LAAB 60 and LAB 70



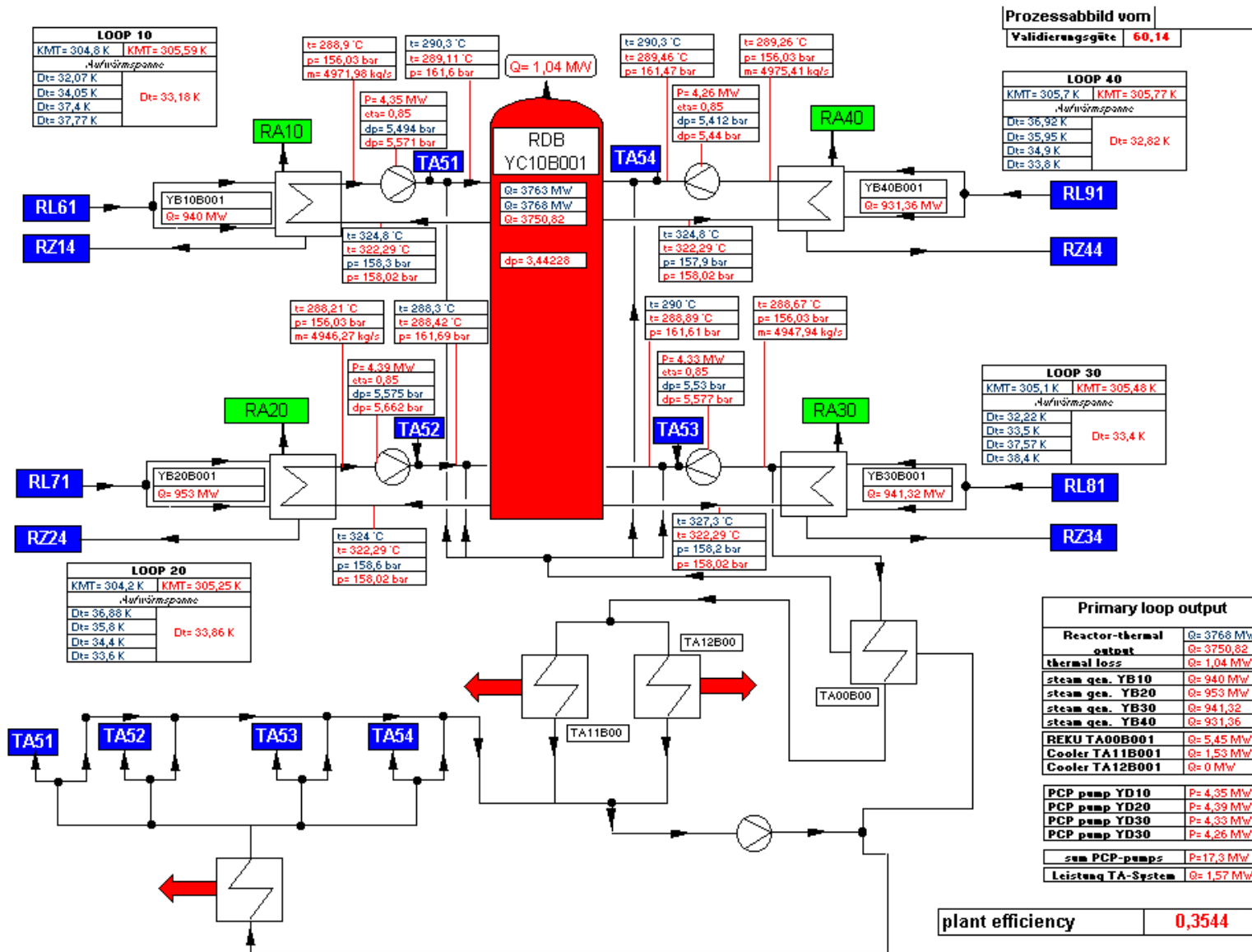
Appendix 13: Feedwater mass flow LAAB 80 and LAB 90



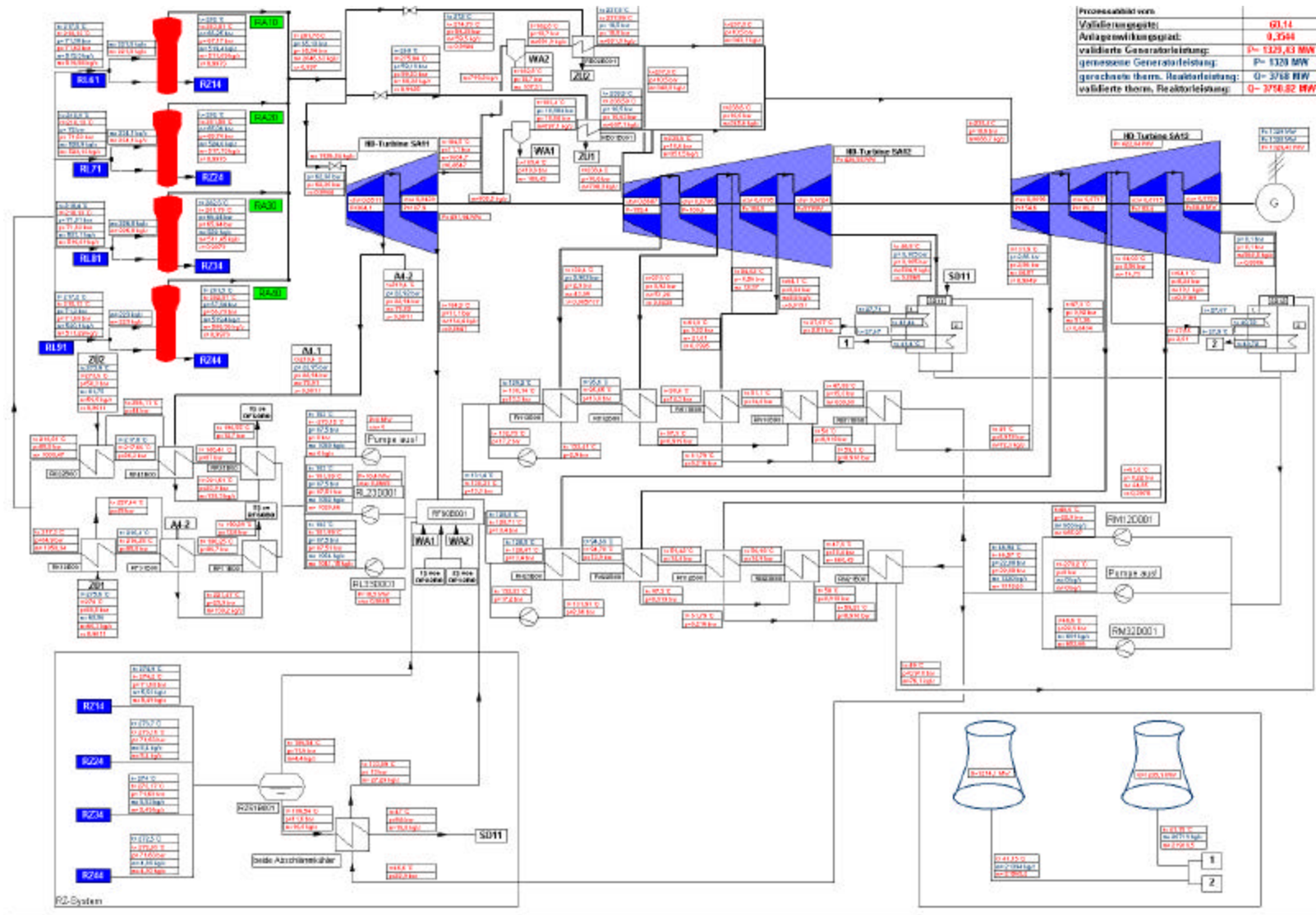
Appendix 13: Feedwater mass flow LAAB 80 and LAB 90



Appendix 14: Temperature difference ratio of two heat exchangers LCJ 11/21 B001



Appendix 15: Flowsheet primary loop



Appendix 16: Flowsheet secondary loop

SINLGE-Penalty > 4

Date: 23.09.98 10:00:00

1 Name	Single-PENALTY
JEC20CT003A	4,91
measurement:	323,84 C
reconciled value:	326,06 C

accuracy:
± 1,000 C

Contributors	portion in [%]
JEC10CT723	11.73 %
JEC20CT733	11.72 %
JEC40CT003	11.72 %
JEC40CT713	11.72 %
JEC30CT003A	11.72 %
JEC20CT003A	11.72 %
JEC10CT003A	11.72 %

2 Name	Single-PENALTY
MAG20CP005	4,66
measurement:	-0,90
reconciled value:	-0,91

accuracy:
± 0,005 -

Contributors	portion in [%]
MAG20CP005	48.73 %
MAC20CT017A	10.46 %
MAC10CT071A	10.40 %
MAG10CP005	8.82 %

PENALTY of the reconciliation	Sum of the selected measurements single-penalties	
72,61	9,57	13,18 %

Measurements with PENALTY > 4 2

Measurements with units °C, bar, barg, kg/s or without units (-).

The accuracies are absolute values of the measurements and is the standard deviation of the measurement.

APPENDIX 17: Report for measurements greater than the selected single-penalty criterion