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TRACER MEASUREMENTS COMPARED TO PROCESS DATA RECONCILIATION IN ACCORDANCE WITH VDI 2048

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ABSTRACT

The feed water mass flow is the key measured variable used to determine the thermal reactor output in a nuclear power plant. Usually this parameter is recorded via venturi nozzles or orifice plates. The problem with both principles of measurement, however, is that an accuracy of below 1 % cannot be reached. In the case of nuclear power plants and depending on the size of the plant, this corresponds to an electrical output of 4 MWel to 16 MWel.

In order to make more accurate statements about the feed water amounts recirculated in the water-steam circuit, tracer measurements [1 - 4] that offer an accuracy of up to 0.2 % are used. A drawback of this method is that this measuring principle is suitable only for providing an instantaneous picture but does not provide continuous operating information about the feed water mass flow.

Process data reconciliation based on VDI 2048 [5, 6] is a mathematical-statistic process that makes use of redundant process information. The uncertainty of reconciled feed water flow rates and the thermal reactor output calculated on this basis can be reduced to 0.4 %. The overall process monitored continuously in this manner therefore provides hourly process information of a quality equal to that obtained with acceptance measurements [7 – 13].

In the NPP Beznau both methods have been used in parallel to determine the feed water flow rates in 2004 (unit 1) and 2005 (unit 2). Comparison of the results shows that a high level of agreement is obtained between the results of the reconciliation and the results of the tracer measurements. For this reason it was decided that no future tracer measurements will be conducted anymore. A a result of the findings of this comparison, a high level of acceptance of process data reconciliation based on VDI 2048 was achieved.

PRINCIPLE OF PROCESS DATA RECONCILIATION BASED ON VDI 2048

Theoretical backround

All measured values are subject to distortions caused by avoidable, systematic or random errors (DIN 1319). For more than 200 years the Gaussian correction principle that is complemented by taking boundary conditions into account has been available as an estimation method in the statistical-mathematical sense that allows these measurement errors to be detected.

The basic idea of this method is to use not only the minimum quantity of measured variables required to obtain a solution but to record all accessible measured variables along with the respective variances and covariances. Additionally the true values of the measured variables must meet the boundary conditions:

- Mass balances,
- energy balances and
- material balances (stoichiometric laws).

This method is described in VDI 2048 [5, 6] and is the best possible quality control method available to detect serious measurement errors. This methodology allows consistent estimations of the true values of the measured variables to be derived from conflicting measured values. The consistent estimated values thus obtained correspond to the true values with a 95% probability.

Gaussian correction principle

Corrections ν are made to the measured values x in accordance with equation 1 in order to obtain estimated values (reconciled values) $\bar{x}$.

$$\bar{x} = x + v \qquad \textbf{(1)}$$

The corrections ν must be determined in such a manner that the quadratic form

$$\xi_0 = v^T \cdot S_X^{-1} \cdot v \Rightarrow \text{Min} \qquad \textbf{(2)}$$

ξ_0 ... square form of errors

S_X^{-1} ... inverse empirical covariance matrix

becomes a minimum. The empirical covariance matrix S_X is the estimated value for the uncertainty of the measured variables X. This general formulation also covers the existence of covariances, i. e. the interdependencies of the measuring points. The improved covariance matrix $S_{\bar{x}}$ is calculated from the empirical covariance matrix S_x and the covariance matrix of the improvements S_v as follows:

$$S_{\bar{x}} = S_x - S_v \qquad (3)$$

Quality control

As a quality-control measure, two criteria must be fulfilled for process data reconciliation based on VDI 2048. For one thing, the square form of errors ξ_0 contained in Equation 2 must be smaller than $\chi^2_{95\%}$ (95% quantile of CHI square).

VDI 2048 criterion 1: $\xi_0 < \chi^2_{95\%}$ (4)

The 95% quantile of CHI square is a statistical measure for the number of model redundancies (degrees of freedom) and is included e.g. in [14] as a table. The number of model redundancies is dependent both on the number of equations contained in the model and on the number of embedded measured values and reflects the overdetermined character of the system. The relationship between the square form of errors and CHI square is referred to as reconciliation quality, see Equation 5. Generally the following applies: The smaller the reconciliation quality, the better is the quality of the model/measured values.

Reconciliation quality = $\xi_0 / \chi^2_{95\%}$ (5)

Additionally the value of the individual penalty must be smaller than the statistical coefficient of 1.96. The value of the individual penalty of a measuring point is the ratio of the square of the improvement v_i to the difference between the estimated uncertainty of the measured value $s_{x,ii}$ and the calculated standard deviation of the reconciled measured value $s_{\bar{x},ii}$, see Equation 6.

VDI 2048 criterion 2: $\frac{|v_i|}{\sqrt{s_{x,ii} - s_{\bar{x},ii}}} = \frac{|v_i|}{\sqrt{s_{v,ii}}} \le 1.96$ **(6)**

This criterion must be complied with for all measured values i. If it is not complied with, a serious fault exists for the corresponding measuring point i or for the estimated value of the associated uncertainty.

In this case the reconciled measured value as well as the measured value itself is questionable. If both of the above criteria are complied with, the reconciled measured values $\bar{x}$ correspond to a 95% probability of the true physical state variables.

Consequences for an industrial process

If process data reconciliation based on VDI 2048 is applied to an industrial process, measured temperatures, mass flows and pressures lose their singular character. The physical relationships between the measured parameters generated via secondary conditions such as mass balance and energy balance result in a process image that corresponds to the physical basis of the process as closely as possible. The relationships thus generated can be represented via the correlation coefficients that result from the improved covariance matrix; also refer to [5].

Principle of the tracer measurement

With this measurement method [3, 4] a substance (tracer) that is soluble only in the liquid phase is metered to the flow. The mass flow can be determined by comparing the concentration of the substance after sufficient mixing in the sample taken at the place of measurement with the concentration in the metering solution. This method is to ensure that no tracer losses occur, e.g. due to deposits on tube walls, leaks, diverted flows, water drains or blowdowns that would affect the results of the measurement. Additionally provisions must be made to ensure that the tracer is distributed evenly in the liquid phase up to the point of extraction (mixing section).

The method used in the Beznau NPP is the "method with constant metering mass flow", see Fig. 1.

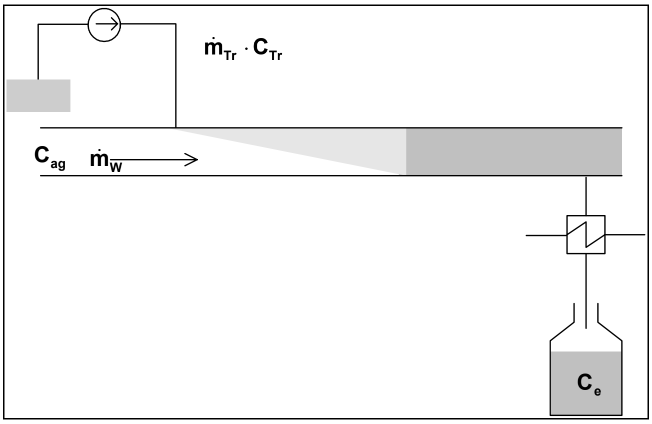

Figure 1: Principals of the tracer measurement method

The tracer solution of concentration C_{tr} and with a constant injection rate m_{tr} is injected into the feed water. After the tracer solution has been mixed thoroughly with the mass flow to be determined, a sample of concentration C_e is taken. Additionally the original concentration of tracer C_{ag} – if available – will have to be taken into account as well. The quantity m_W to be determined is then calculated as follows:

$$m_W = m_{tr} \bullet \frac{C_{tr} - C_e}{C_e - C_{ag}} \qquad (7)$$

Radioactive sodium (Na^{24}) is used as the tracer substance as this substance can be measured reliably even at extremely low concentrations. The resulting overall accuracy of the mass flow to be determined is between 0.2 % and 0.5 %, depending on the specific measuring conditions in the respective power plant.

Tracer measurement and process data reconciliation in the Beznau NPP

HISTORY AT BEZNAU

From 1994 to 2005, a tracer calibration of the feed water orifices and feed water venturis was performed by ABB using radioactive tracer substance Na^{24}. In the initial stages of the tracer measurements (from 1994), larger deviations (of up to 1%) were detected at the venturi nozzles. The orifice measurements were far more stable.

After changing over the water chemistry of the secondary plant to a pH value of 9.8 in the feed water, only small deviations were observed at the venturi nozzles. Magnetite formation and the resulting deposits were reduced significantly.

Continuous process data reconciliation based on VDI 2048 was introduced in NPP unit 1 in 2004 and in NPP unit 2 in 2005. No further tracer measurements were performed after the final tracer measurements made in unit 1 (2004) and unit 2 (2005) as a good match with the reconciliation results had been obtained.

DESCRIPTION OF THE TRACER MEASURING LAYOUT

Fig. 2 shows the tracer injection locations (i1 to i4) and the extraction locations (e1 to e6) used to determine the respective concentrations. The original concentration c_{ag} is extracted at points e1 (BG) and e2 (BG).

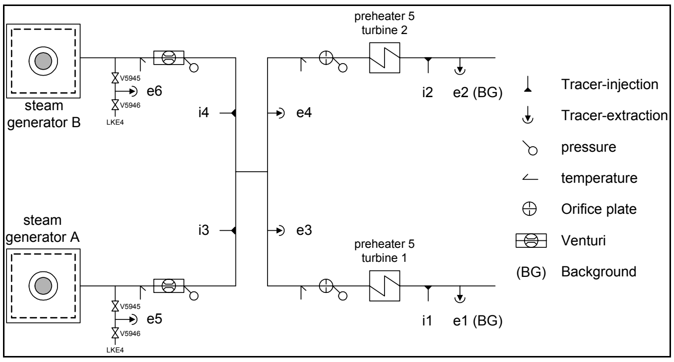

Figure 2: Injection and extration positions for the tracer

DESCRIPTION OF THE RECONCILIATION MODELS

The reconciliation models of both units at Beznau were built up using the VALI program certified as per VDI 2048 [15, 16]. A total of 260 measured values per unit are taken into account. The number of redundancies is 166 which corresponds to a $\chi^2_{95\%}$ of 197.07.

The plant model includes the following process areas:

- **Primary circuit** with reactor pressure vessel, two steam generators, two main coolant pumps, the pressurizer, the reactor water cleaning/volume control system and the connecting pipework.
- **Secondary circuit** with two HP and four LP turbines, four water separator/intermediate superheaters, two condensers, main condensate pumps, two LP preheater sections, two feed water tanks, feed water pumps, two HP preheating sections, the steam generator blowdown system, two generators including generator cooling, district heat extraction system and the connecting pipework.

Fig. 3 shows an example of the plant model for the primary circuit of unit 2.

As an example of the interdependencies with other measured values that are produced via the boundary conditions after a reconciliation run, Table 1 shows the “sensitivity analysis” for the entire thermal reactor output; this sensitivity analysis can be derived from the improved covariance matrix [5] following a reconciliation. The correlation coefficients shown may be between –1 and + 1 and are a measure for the dependence on the respective measured value. It can be seen clearly that the best correlation is found with the more accurate orifice measurements. However, the correlation with the condensate amounts, the measurements at the venturi nozzles and the feed water temperatures is also clearly evident. The 95% confidence interval of the thermal reactor output is 0.58 % for this data set (equivalent to 6.52 MW_{th}).

Comparison of the results

The position of the measuring levels is shown in Fig. 4. The venturi flow measurements are located ahead of the steam generators whereas the orifice measurements are found downstream of the HP preheating sections.

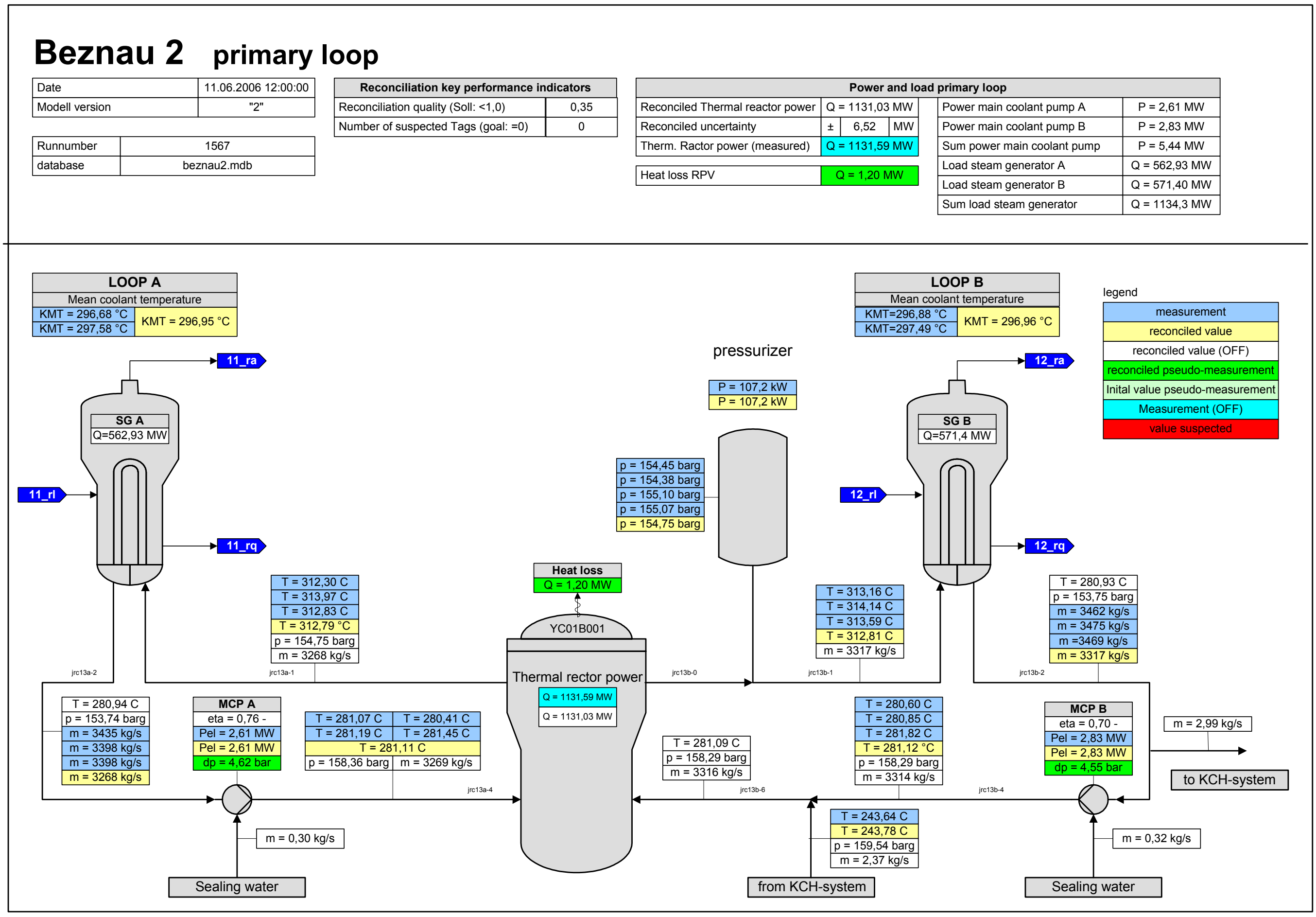

Figure 3: Visualisation of primary loop results

measurement	reconciled value	uncertainty (abs.)	uncertainty (rel.)	Unit
QPP0004P therm reactor pow.	1131	6,52	0,58%	MW

correlation coefficients to other measurements....

measurement	correlation coefficient	unit	remark
FFL1620P	0,6666	kg/s	orifice plate
FFL1610P	0,6529	kg/s	orifice plate
FB24270P	0,511	kg/s	condensate 1
FA24270P	0,5019	kg/s	condensate 2
FFL1220P	0,2801	kg/s	SG-A steam 1
FFL1221P	0,2801	kg/s	SG-A steam 2
FFL1222P	0,2801	kg/s	SG-A steam 3
FFL1121P_V	0,2796	kg/s	SG-B Venturi feedwater 1
FFL1122P_V	0,2796	kg/s	SG-B Venturi feedwater 2
FFL1123P_V	0,2796	kg/s	SG-B Venturi feedwater 3
FFL1210P	0,2724	kg/s	SG-B steam 1
FFL1211P	0,2724	kg/s	SG-B steam 2
FFL1212P	0,2724	kg/s	SG-B steam 3
FFL1113P_V	0,2719	kg/s	SG-A Venturi feedwater 1
FFL1111P_V	0,2719	kg/s	SG-A Venturi feedwater 2
FFL1112P_V	0,2719	kg/s	SG-A Venturi feedwater 3
TA03222P	-0,1439	°C	feedwater temperature
TB03222P	-0,1439	°C	feedwater temperature
TA03221P	-0,1439	°C	feedwater temperature
TB03221P	-0,1439	°C	feedwater temperature

Table 1: Correlation coefficients for the thermal reactor power

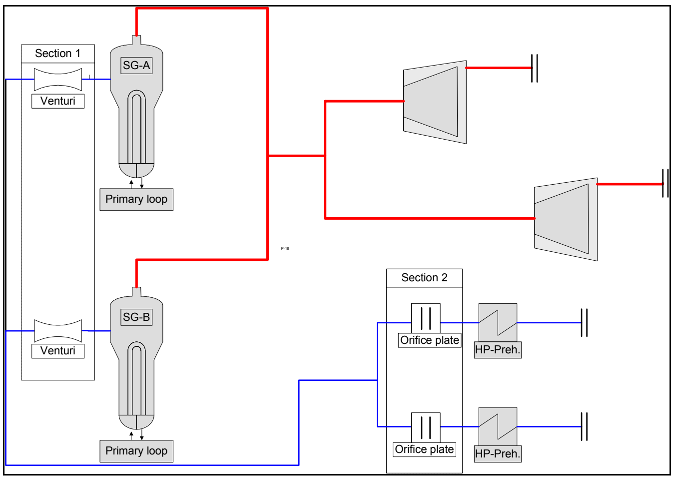

Figure 4: Measurement sections for feed water mass flow

The tracer measurements on measuring planes 1 and 2 were performed on different days. As the reactor output had not been exactly identical, the sum of the orifice measurements deviates slightly from the sum of the nozzle measured values. A conversion of the VALI data to the respective operating point during the tracer measurement was therefore required. The reconciliation results shown here are hourly mean values. The tracer measurement was performed for a period of 0.5 hours only.

Figs. 5 to 8 provide a graphic representation of the results for both units. Figs. 6 and 7 show that the trend is the same both for the tracer measurement and the reconciliation compared to the measured value of the ANIS system. This, however, is not the case in Figs. 5 and 8 as the reconciliation here rather confirms the measured value of the ANIS system.

Overall the sum of the deviations between the tracer measurement and the reconciliation results is approx. 0.054 % (orifices) and 0.064 % (venturis) for unit 1. For unit 2 the deviations are approx. 0.003 % (orifices) and 0.064 % (venturis). This means that the largest absolute deviation was 0.4 kg/s.

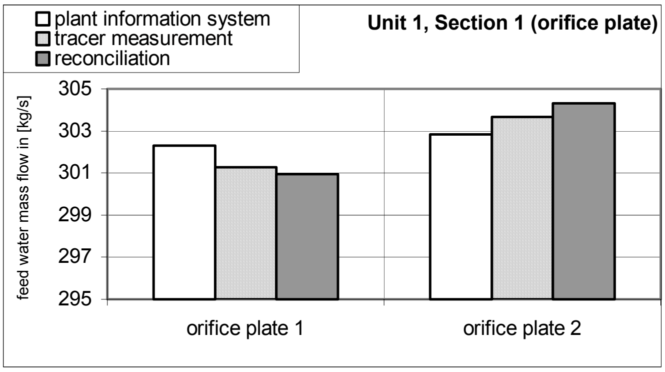

Fig. 5: Comparison of venturis for unit 1

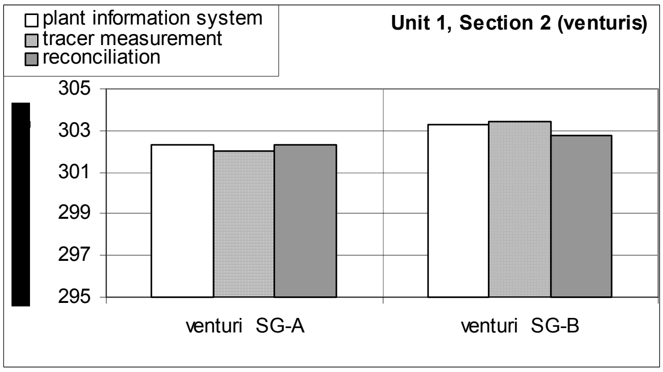

Fig. 6: Comparison of orifices for unit 1

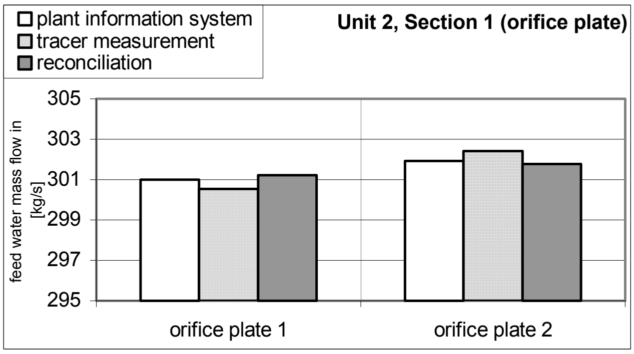

Fig. 7: Comparison of venturis for unit 2

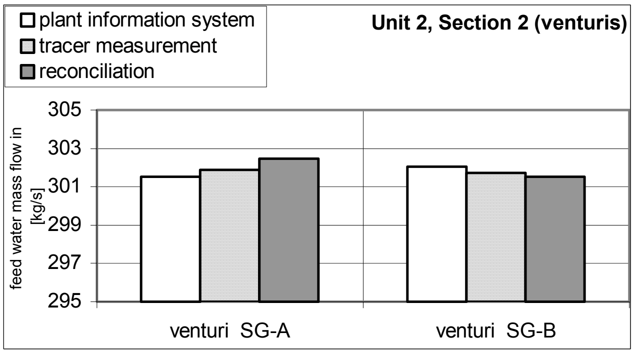

Fig. 8: Comparison of orifices for unit 2

Subsequent action and consequences

As a result of the excellent agreement between the results of the reconciliation and the measurement results of the tracer measurements it was decided to dispense with further tracer measurements. Continuous monitoring will now be performed exclusively using the process data reconciliation method based on VDI 2048.

This offers numerous benefits:

- Hourly quality control inspections both of the overall process and of the individual components are possible with a quality equivalent to that of an acceptance measurement,
- handling of radioactive tracer substances can be avoided,
- state-oriented maintenance of the measurement instrumentation can be implemented.

As an example of monitoring the measured values, Fig. 9 shows the thermal reactor output and the deviation between the "measured" and reconciled reactor output in a graphic manner. Corrective action will be taken when the deviation between the reconciled and the "measured" values exceeds 2 MW_{th}.

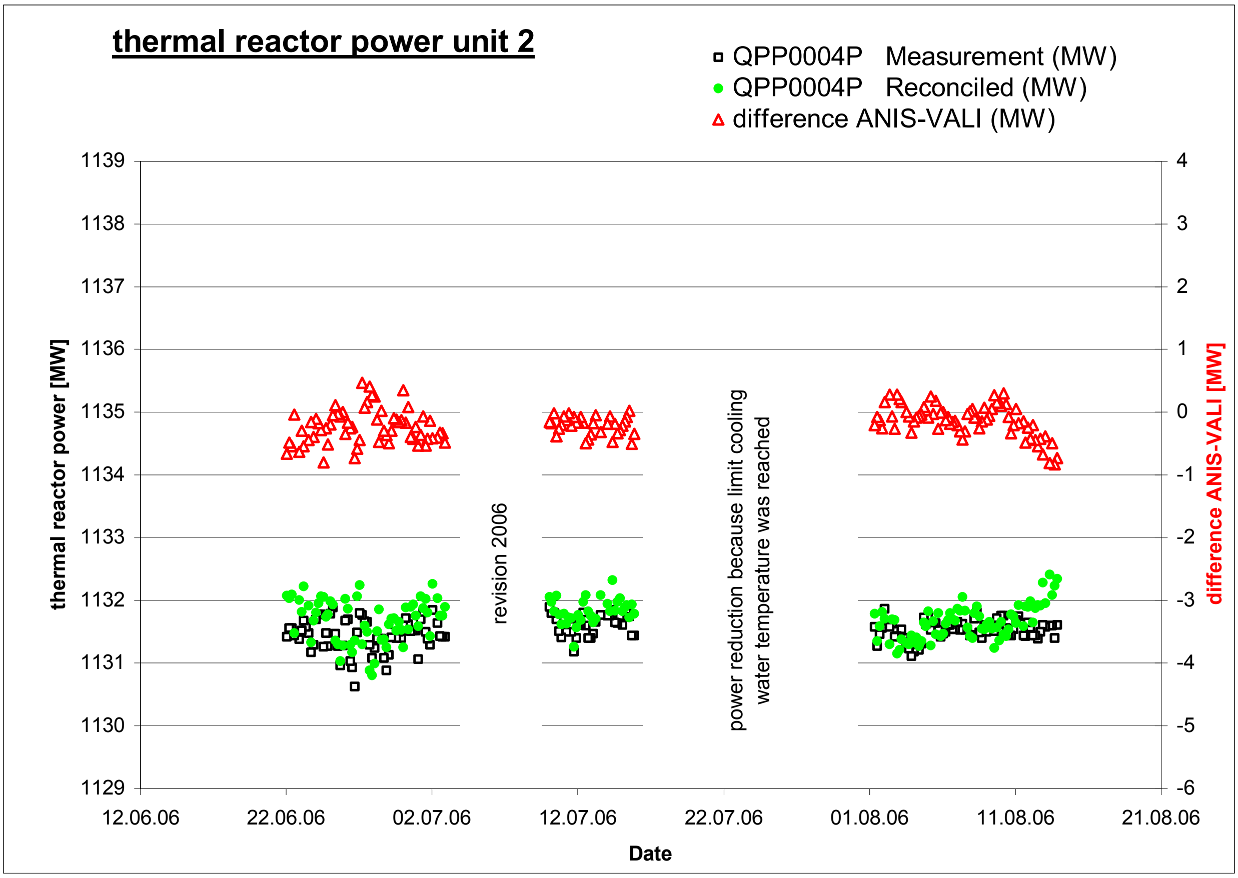

Fig. 9: Thermal reactor output

Conclusions

When performed correctly, the tracer measurement method is the most accurate method currently available for instantaneously determining the feed water flow rates. The comparisons show that process data reconciliation based on VDI 2048 provides comparable results. When a continuous monitoring system using process data reconciliation is implemented, the safety required for determining the thermal reactor output will also be maintained under continuous operation conditions.

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