ChemPlant Technology s.r.o.

Report CPT- 348-15

Date of issue: 15.7.2015

This report has 62 pages.

Monitoring Nuclear Reactor Thermal Power

Strategy of NR power assessment, data reconciliation, validation and instrumentation optimization

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Ústí nad Labem *July 2015*

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Summary

1. A general approach towards a NR power assessment is described in Chapter 2. The NR power assessment is based on the mass and energy balance of the Nuclear Steam Supply System which can be complemented by the system of the feed water preheat train.
2. Chapter 3 deals with mass and heat balancing of steam generators. The assessment of the SG power can be enhanced by data reconciliation and by the inclusion of the phase equilibrium.
3. Most of industrial reactor blocks contain several steam generators. The power calculation can be also improved by including the feed water preheat train. Modeling such complex system is described in Chapter 4.
4. The precision of the assessed NR power can be improved by the optimization of the instrumentation system (Chapter 5). Two areas of optimization are studied: instrumentation placement and a precision improvement of individual instruments.
5. The accuracy of results is composed of the instrumentation precision (influence of random measurement errors) and of the influence of systematic and gross errors. Chapter 6 explores how to protect a NR power monitoring against gross measurement errors.
6. In Chapter 7 are explained two main mechanisms of the NR power precision improvement: Data Reconciliation and Streams' Splitting.
7. Appendix 1 contains a very brief description of Data Reconciliation
8. Appendix 2 describes input data and result files from a part of a real NPP calculated with the aid of the mass and energy balance program RECON
9. The report is complemented by an Excel file containing archive of 10 days process data extracted from a PWR NPP (hourly averages). This Excel file can be directly linked as the external data source with the program RECON for automatic data processing (balancing with data reconciliation, gross error detection, viewing trends, etc.) to simulate a real industrial data processing in practice.
10. All examples present in this report can be solved with the aid of the Light or the Academic versions of the program RECON, version 11. The automatic data processing of the archive data requires the Professional version of the RECON software.
11. Real plant data can be viewed via the Demo example available free at http://84.242.83.242/pdis_web/MainPage.aspx?dst=S&syst=k&schema=index&user=DEMO (the access password is "demo").

1. Introduction

One of the most important KPIs in Nuclear Power Plants (NPP) is the nuclear reactor thermal power. For electric power generation in NPPs it is typical its low OPEX but very high CAPEX. It is therefore lucrative to run NPPs at the highest achievable power while at the same time the maximum thermal power of industrial nuclear reactors is strictly licensed by authorities. It is therefore very important to know the real NR thermal power (further denoted shortly as *NR* power) with the highest possible accuracy (minimal uncertainty), as this uncertainty of the measured power must be deduced from the licensed power.

There exists no method of a direct measurement of the NR power. All methods available are based on a detailed mass and energy balance of a reactor cooling. This document concerns a pressurized light water reactor (PWR), where the cooling is achieved by a Nuclear Steam Supply System (NSSS). NSSS consists of the reactor, the reactor coolant pumps, steam generators and associated piping. The overall system balanced can include also a feed water preheat train and some other equipment in the primary circuit (containment).

This report has the following structure:

- A general approach towards a NR power assessment is described in the next Chapter 2
- The most important balanced equipment is a steam generator (Chapter 3)
- Most of industrial reactor blocks contain several steam generators. The power calculation can be also improved by including the feed water preheat train. Modeling of such complex system is described in Chapter 4.
- The precision of the assessed NR power can be improved by the optimization of the instrumentation system (Chapter 5)
- The accuracy of a result is composed of the instrumentation precision (influence of random measurement errors) and of the influence of systematic and gross errors. Chapter 6 therefore explores how to protect a NR power monitoring against gross measurement errors.
- Appendix 1 contains a very brief description of Data Reconciliation
- Appendix 2 describes input data and result files from a part of a real NPP calculated with the aid of the mass and energy balance program RECON
- The report is complemented by an Excel file containing 10 days of process data extracted from a PWR NPP (hourly averages). This Excel file can be directly linked as the external data source with the program RECON for automatic data processing (balancing with data reconciliation, gross error detection, viewing trends, etc.) to simulate a real industrial data processing in practice.

Examples solved in this report were calculated by the mass and energy balancing program with data reconciliation and validation RECON [10]. The thermodynamic properties of water and steam are based on the method IAPWS Industrial Formulation 1997 (IAPWS-IF97) [11].

2. NR power assessment

2.1. Nuclear Steam Supply System

NSSS for a PWR consists of the reactor and the reactor coolant pumps, steam generators and further equipment in the containment with associated piping. There exists the ASME document [2] which is the Performance Test Code targeted at procedures for conducting tests to determine the thermal performance of a NSSS including assessment of the NR power. Even if this document is no longer an American National Standard or an ASME approved document, it can serve as a good starting point for a NSSS analysis. Further on in this chapter will be analyzed a hypothetical NPP with one NR and one SG. A more realistic description of a PWR NPP can the reader find in a very good report [17].

A NSSS with one reactor and one steam generator is shown in the next Fig. 2.1:

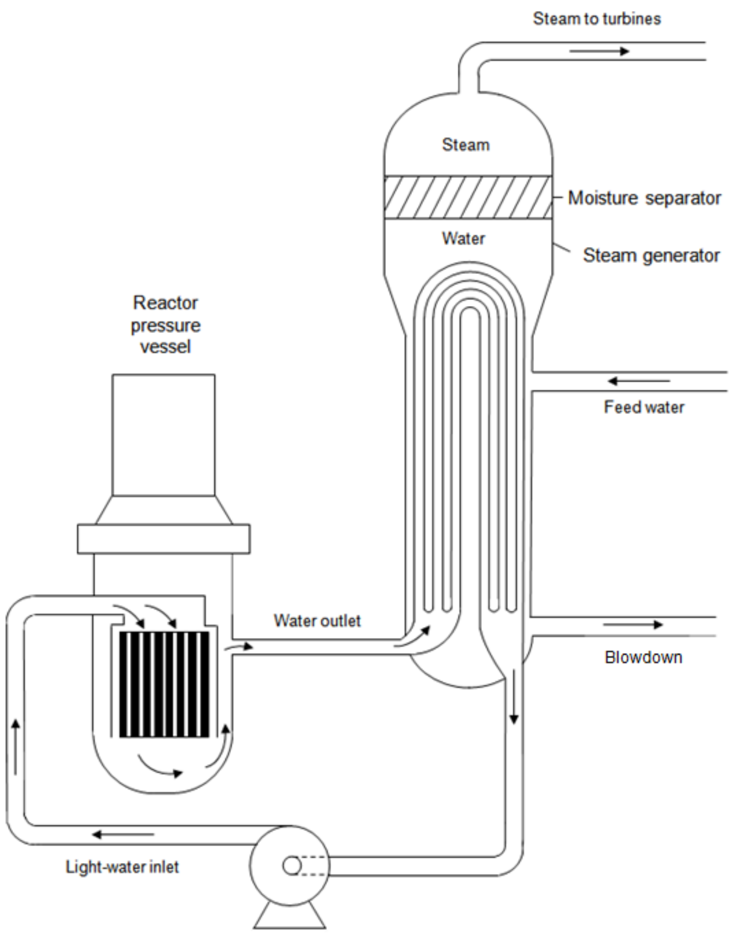

Fig. 2.1: A simple NSSS in a NPP

The most simple is the case of the overall balance of the NR containment, which contains a NR and a steam generator shown in Fig. 2.1. The balance envelope is in the next Fig. 2.2:

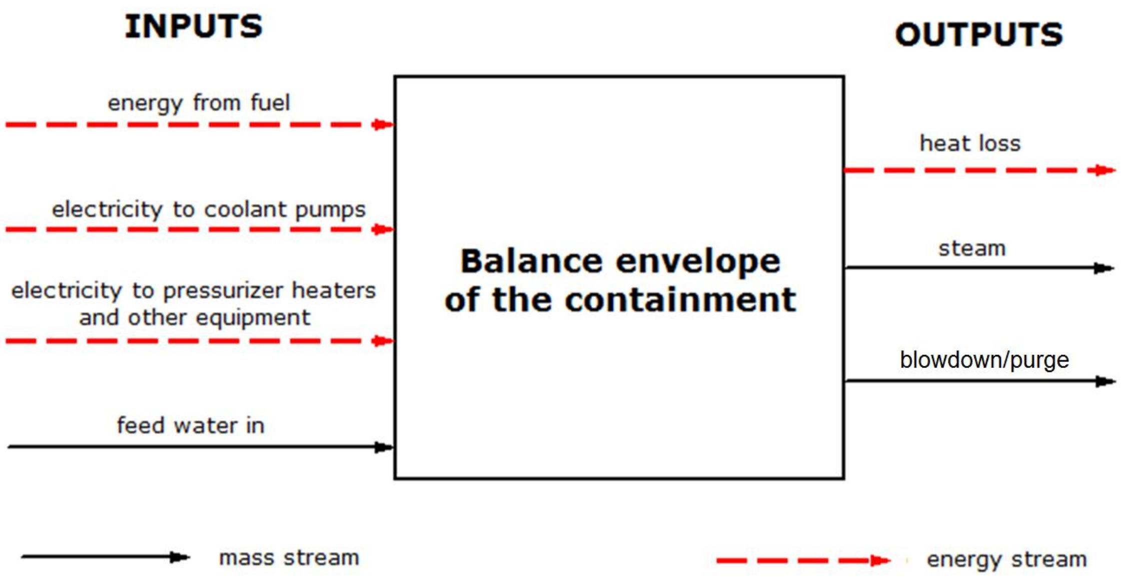

Fig. 2.2: Balance envelope of the containment

The NR power is denoted here as "energy from fuel". The mass and heat balance around this envelope generates 2 equations (one mass and one energy balance). In [2] the steam flow is supposed to be unmeasured and is calculated from the mass balance (the measurement of a wet steam is problematic). So, the remaining energy balance equation can be used for calculating the directly unmeasurable energy flux from the fuel, which is the NR power.

Inside this balance envelope there can be some measurements on the steam generator. Let's try to use them in the NR monitoring. In the next Fig. 2.3 is a more detailed flowsheet:

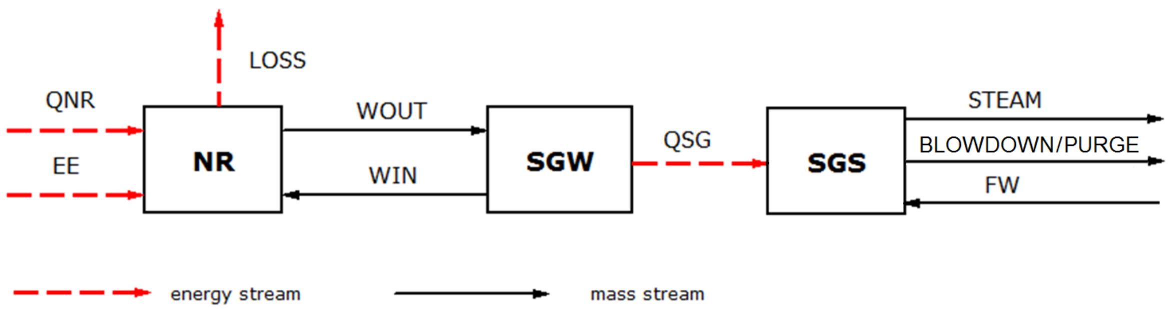

Fig. 2.3: Detailed balance flowsheet of the containment

There are 3 balance nodes: SGW – water side of a steam generator, SGS – steam side of a steam generator and NR – the rest of the containment. QNR – thermal power of the NR, EE – sum of the electrical energy inputs (pumps, etc.), QSG – thermal power of the SG, WOUT and WIN – flows of the pressurized water, FW – feed water. Note that such system generates 6 balance equations, but only 5 of them are independent (the mass balance equations around nodes NR and SGW are the same). It is (for example) possible to calculate QNR, QSG, WIN, WOUT and STEAM streams (without their measurement) or we can have redundancy if some of these streams are measured.

2.2. Practical considerations

Energy loss can't be calculated from the balance as its stream is parallel with the QNR stream. This is a well known result from theory of linear balances. This means that the loss must be determined (estimated) independently on the energy balancing proper (from the containment construction and air conditioning). The overall loss can be considered almost constant as the temperature differences between the equipment and the containment atmosphere is relatively constant.

A major problem in balancing NPPs is that the steam leaving steam generators is somewhat wet. Contrary to classical power stations, this is not only the general problem of the whole Rankine cycle in NPPs (turbines), but also the problem of steam leaving steam generators, as the moisture separation there is never perfect. This fact brings two problems:

- Determination of the steam enthalpy
- Measurement of the steam flow by orifices or similar devices, which are designed for a single-phase flow.

There are several methods of measuring a steam quality (moisture, wetness) which are mentioned in [2] and also in [3], p. 230 – 233. These methods range from a calorimetric measurement to radioactive tracing, but these methods are suitable for specially designed NPP tests, not for the on-line monitoring.

The problem of measuring a wet steam is addressed only in a few papers, for example in [4,16].

In practice it is reasonable to accept values of the steam wetness, measured for example during NPPs acceptance tests, with some reasonably high value of uncertainty for these values.

The Fig. 2.2 does not include additional mass streams entering and leaving the containment balancing envelope. This can be acceptable for sealless main coolant pumps. If this is not the case, also some seal and make up water must be taken into account.

3. Steam generators

This report deals with monitoring of thermal power in a *pressurized light water* nuclear reactor (PWR). Steam generators (SG) in such nuclear power plant (NPP) convert a hot water into steam from heat generated in the NR core. As there exists no method of a direct measurement of the NR power, the thermal power assessment is based on a detailed mass and energy balance of SGs. In words (see the previous chapter), the NR power can be expressed as:

NR power = SG power – Electric Energy inputs + Loss , (3-1)

where the SG power (heat flux) is dominant. This is the reason why this chapter is devoted fully to the SG balancing.

SG is usually a vertical or horizontal shell and tube heat exchanger where the hot water flows in tubes and steam is generated in the shell space (recall Fig. 2.1). The important part of the SG is a moisture separator.

3.1. SG modeling

The thermodynamic state at the boiling proper inside the generator can be defined by temperature or pressure. One here assumes phase equilibrium between liquid and vapor phases.

This unit operation can be modeled as a heat exchanger. As the steam generator in a nuclear power plant will be the subject of a more extensive study below, let us now prepare this model for further use.

Heat is supplied to the steam generator (SG) by the high-pressure hot water circulating between the nuclear reactor and the high pressure water part of the SG (SGW). Into the shell part of a SG (SGS) is supplied preheated feed water, the outputs are steam and blowdown (purge) water, which can be both continuous and periodic. The steam always contains a small amount of a liquid phase. The balance model is shown in the next Fig. 3.2:

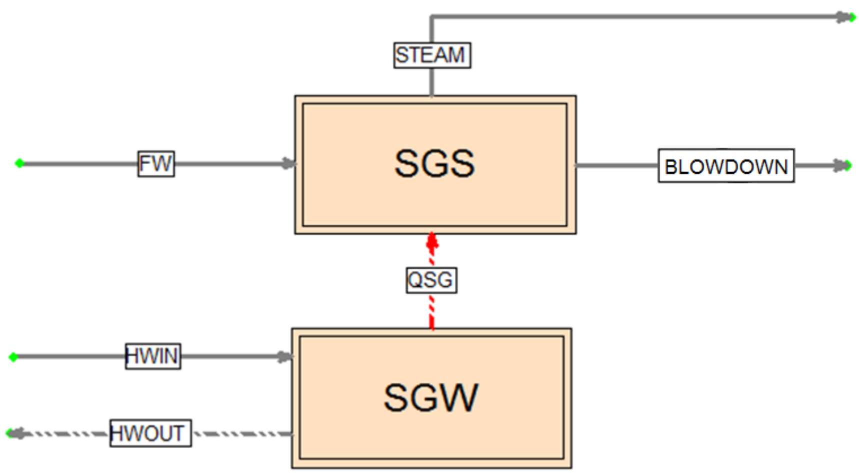

Fig. 3.2: Balancing scheme of a steam generator drawn in RECON

Note: While the term *blowdown* is in this case more appropriate the term *purge,* we use in this report systematically the second one because it is shorter.

The feed water stream FW is characterized by its temperature t_{FW} and pressure p_{FW}, STEAM and PURGE will be further characterized by the SG temperature t_{SGS} and their water contents X. PURGE is 100 % saturated water and STEAM is a mixture of a saturated steam and liquid water expressed as % of the wetness (moisture). Hot water is characterized by its pressure p_{HW} and temperatures t_{HWIN} and t_{HWOUT}. The QSG stream represents a heat flux in the SG between the tube and shell spaces (the SG heat power). The model equations are:

SGS mass balance:

$$F_{FW} - F_{STEAM} - F_{PURGE} = 0 \qquad (3\text{-}2)$$

SGS energy balance:

$$F_{FW}\, h(t_{FW},p_{FW}) - F_{STEAM}\, h(t_{SGS},X_{STEAM}) - F_{PURGE}\, h(t_{SGS},X_{PURGE}) + QSG = 0 \qquad (3\text{-}3)$$

SGW mass balance:

$$F_{HWIN} - F_{HWOUT} = 0 \qquad (3\text{-}4)$$

SGW energy balance:

$$F_{HWIN}\, h(t_{HWIN},p_{HW}) - F_{HWOUT}\, h(t_{HWOUT},p_{HW}) - QSG = 0 \qquad (3\text{-}5)$$

In this model, altogether 4 balance equations can be generated (2mass and 2 energy balances). If we measure the flowrates of all mass streams connected with the steam space and the hot water flowrate at the inlet into the high-pressure water space, we have altogether 2 unknown streams, viz. hot water outlet F_{HWOUT} and the heat flux QSG. If we further measure all temperatures and pressures, two degrees of redundancy are available for reconciliation and data validation. In the case of NRs, sometimes the hot water flow is not measured (insufficient length of tubes ahead of flowmeters in the containment). In this case the degree of redundancy is 1.

3.2. SG data reconciliation

Example 3.1: Mass and energy balance of a steam generator

In the following case study we will suppose that the hot water stream input flow is measured.

INPUT DATA:

Besides the mass and heat flowrates, the problem involves 4 temperatures (hot water temperatures HWIN and HWOUT, temperature in the steam generator SG, equal for the outlet steam and purge, and temperature of feed water FW). Further involved are two pressures (FW for feed water and HW for hot water). In addition, we here have two wetness values for liquid water (WATER) and (wet) steam (STEAM).

In the next Table 3.1 is the input data not only for the Example 3.1 but also for other examples concerning the simple SG shown in the Fig. 3.2:

Table 3.1: Measured variables and their uncertainties

Variable	**Stream**	**Meas.unit**	**Value**	**Max.error (uncertainty)**
Flow	FW	kg/s	444.5	1%
Flow	STEAM	kg/s	445.0	1%
Flow	BLOWDOWN/PURGE	kg/s	6.12	5%
Flow	HWIN	kg/s	5650	5%
Temperature	FW	°C	221.6	1
Temperature	SGS (STEAM and BLOWDOWN)	°C	257.6	1
Temperature	HWIN	°C	295.2	1
Temperature	HWOUT	°C	265.8	1
Pressure	FW	kPag	4600	0.5%
Pressure	SGS	kPag	4500	0.5%
Pressure	HW	kPag	9600	0.5%
Wetness	STEAM	%	0.25	0.1

Data were processed by RECON with the following results. The meaning of the individual abbreviations is:

MC	Measured variable (Corrected, reconciled)
NO	Nonmeasured variable Observable
F	Fixed variable (constant)
INP.VALUE	Input value (measured or a guess for nonmeasured variables)
REC.VALUE	calculated value
ABS.ERROR	absolute error (uncertainty) of a result

RESULTS

```
Task: SG (Balance of steam generator)

 Balance: [19.02.2014 23:00; 19.02.2014 24:00)

 I T E R A T I O N S

 Iter           Qeq            Qx             Qy            Qmin
 -----------------------------------------------------------------
 START     2.0623E+08
    1      7.8884E+04    2.4049E+01      5.4461E+06      4.5920E+00
    2      6.7629E+00    1.2412E-01      2.9315E+03      4.5516E+00
    3      6.1005E-05    1.0636E-05      2.5630E-01      4.5516E+00
    4      2.6987E-07    9.5904E-11      2.3546E-06      4.5516E+00

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function
```

G L O B A L   D A T A

Number of nodes	2
Number of heat nodes	2
Number of streams	6
Number of energy streams	1
Number of components	1
Number of temperatures	4
Number of pressures	2
Number of measured variables	11
Number of adjusted variables	11
Number of non-measured variables	2
Number of observed variables	2
Number of non-observed variables	0
Number of free variables	0
Number of equations	4
Number of independent equations	4
Number of user-defined equations	0
Degree of redundancy	2
Mean residue of equations	2.6987E-07
Qmin	4.5516E+00
Qcrit	5.9900E+00
Status (Qmin/Qcrit)	0.759860

S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	444.500	445.699	4.181	KG/S
HWIN	MC	5650.000	5447.986	198.162	KG/S
HWOUT	NO	5000.000	5447.986	198.162	KG/S
PURGE	MC	6.120	6.115	0.306	KG/S
STEAM	MC	445.000	439.585	4.189	KG/S

E N E R G Y   S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
QSG	NO	800000.000	810886.366	8008.238	KW

T E M P E R A T U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	221.600	221.566	0.999	C
HWIN	MC	295.200	294.683	0.859	C
HWOUT	MC	265.800	266.209	0.888	C
SG	MC	257.600	257.597	1.000	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	4600.000	4599.999	23.000	KPA
HW	MC	9600.000	9600.169	48.000	KPA

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
STEAM	MC	0.250	0.249	0.100	%
WATER	F	100.000	100.000		%

Calculations lasted 00:00:0.052

Note that the calculated value of QSG is 810 886 kW with the uncertainty 8008 kW (0.988 %).
Additional information:

A sole SG is a very simple model. In the next Table 3.2 is the additional information about DR results:

Table 3.2: Further results of data reconciliation

```
Task: SG (Balance of steam generator)

REPORT ON CLASSIFICATION OF VARIABLES
 =====================================

R E D U N D A N T   M E A S U R E M E N T S

 Type Variable      Adjustability          Threshold value               Unit
                                    Beta: 90%        95%         99%
 ----------------------------------------------------------------------------
  MF  FW                 0.059442       23.772       26.262       30.912  KG/S
  MF  HWIN               0.298541      719.967      795.371      936.205  KG/S
  MF  PURGE              0.000266       24.092       26.615       31.327  KG/S
  MF  STEAM              0.686186       25.539       28.214       33.209  KG/S
  P   FW                 0.000000   890328.858   983575.215  1157734.345  KPA
  P   HW                 0.000005    26685.755    29480.620    34700.678  KPA
  T   FW                 0.000605       52.226       57.696       67.912  C
  T   HWIN               0.140659        3.552        3.924        4.619  C
  T   HWOUT              0.112151        3.947        4.361        5.133  C
  T   SG                 0.000005      583.098      644.168      758.229  C
  X   STEAM              0.000078        1.802        1.991        2.344  %

 Legend:
  Adjustability   = relative cut of error due to reconciliation
  Threshold value = gross error that will be detected with 90% probability

  MF  Mass flow
  P   Pressure
  T   Temperature
  X   Steam wetness
```

Let us further discuss the individual results.

Adjustability (see the Appendix 1 and the Section 6.1 for details) gives the relative decrease of a result uncertainty due to the reconciliation. For example for the flow HWIN, this decrease (precision enhancement) is ca by 30 %. Some variables have the adjustability close to zero (almost nonadjustable variables). The latter are those which are measured with high absolute precision (with respect to the other variables); this is for example the case of the PURGE flow. Its relative uncertainty is 5 % but its absolute value small (the absolute uncertainty 0.3 kg/s in comparison with the uncertainty value 4.4 kg/s for the FW).

The further case is represented by temperatures that are also of relatively high precision and in addition are, as steam temperatures, of minor importance in the heat balance. This important fact will be discussed in details also in the Section 5.2 in connection with the optimization of the instrumentation precision optimization. The same holds for pressures which have very small influence on streams' enthalpy.

Threshold value (TV, more about it will be in Chapter 6) gives the minimum value of gross error that will be detected with probability Beta. In the Table 3.2 there are

Threshold values for Beta = 90 %, 95 %, and 99 %. Thus for example the value TV = 795 for the flow HWIN means that the gross error must be at least 795 kg/s so as to be detected with probability 95 % (for information, the flowrate of this stream is 5650 t/h, so the threshold value represents some 14 % of the nominal stream value).
It follows from the theory that the threshold value is closely connected with the adjustability of the variable. The smaller the adjustability, the higher is the threshold value (hence also the chance for gross error detection is smaller). Thus for example for almost nonadjustable purges (stream PURGE), the threshold value is several times greater than the nominal one. TVs informs us for which measured variables the gross error detection is efficient and for which measured variables other independent methods must be used (frequent calibration, etc). More about gross error detection will be presented in Chapter 6.

Note that threshold values for pressures are very high. This is typical for almost nonadjustable measured variables. The values presented in the table above just inform us that there is no chance to detect gross errors for such variables (the numbers calculated from the linearized model are not probably completely valid). See also further discussion on this problem in the Chapter 6.

Next result table presents information about parametric sensitivity of the SQ heat power (heat flux QSG).

```
REPORT ON PARAMETRIC SENSITIVITY
 ================================

Task: SG (Balance of steam generator) ... Balance [19.02.2014 23:00; 19.02.2014 24:00)

 Type Variable
 -------------
  HF  QSG

 GIVEN VARIABLE IS SENSITIVE TO:

 Type Variable             Sensitivity    Unit
 ----------------------------------------------
  MF  FW                      1626.592  [KJ/S] / KG/S
  MF  HWIN                       2.795  [KJ/S] / KG/S
  MF  PURGE                  -1458.363  [KJ/S] / KG/S
  MF  STEAM                    181.093  [KJ/S] / KG/S
  P   FW                        -0.118  [KJ/S] / KPA
  P   HW                        -0.075  [KJ/S] / KPA
  T   FW                     -2013.316  [KJ/S] / C
  T   HWIN                     566.552  [KJ/S] / C
  T   HWOUT                   -509.755  [KJ/S] / C
  T   SG                      -180.235  [KJ/S] / C
  X   STEAM                  -7224.772  [KJ/S] / %

 Legend:

  MF  Mass flow
  P   Pressure
  T   Temperature
  X   Steam wetness
```

Parametric sensitivity gives the sensitivity of the thermal power to the changes of individual variables values. Thus, e.g., the value 1627 for stream FW means that if the measured value of feed water FW increases by 1 kg/s , the thermal power QSG value increases by 1627 kJ/s. More about parametric sensitivity can be found in [1], Section 3.10.

3.3. Phase equilibrium in the SG

The important assumption in modeling steam generators is that the steam and the purge states are on the saturation line. We can then select the temperature or the pressure as the variable from which the stream enthalpies will be calculated (the temperature in the preceding section). If both temperature and pressure are available, we can try to exploit this information for increasing redundancy.

Theoretically it is possible to the Equation (3-3) add the new one written in the term of SG pressure. But this is not enabled in the RECON's GUI. Instead of this we can use the equivalent solution which is based on writing the equation of the phase equilibrium.

Let us now suppose that besides the temperature, also pressure has been measured in the SG. The relation between temperature and pressure is not configured in the graphical editor, but in the editor of user defined equations. There are now two possibilities – either express temperature as function of pressure, or pressure as function of temperature. The result is, however, practically independent of this choice.

Example 3.2: Mass and energy balance of a steam generator with a phase equilibrium (compare with the Example 3.1).

In the original model, altogether 4 balance equations were generated, the phase equilibrium assumption generates the fifth. There are two unmeasured variables in the problem, so three degrees of redundancy are at hand for data reconciliation and validation.

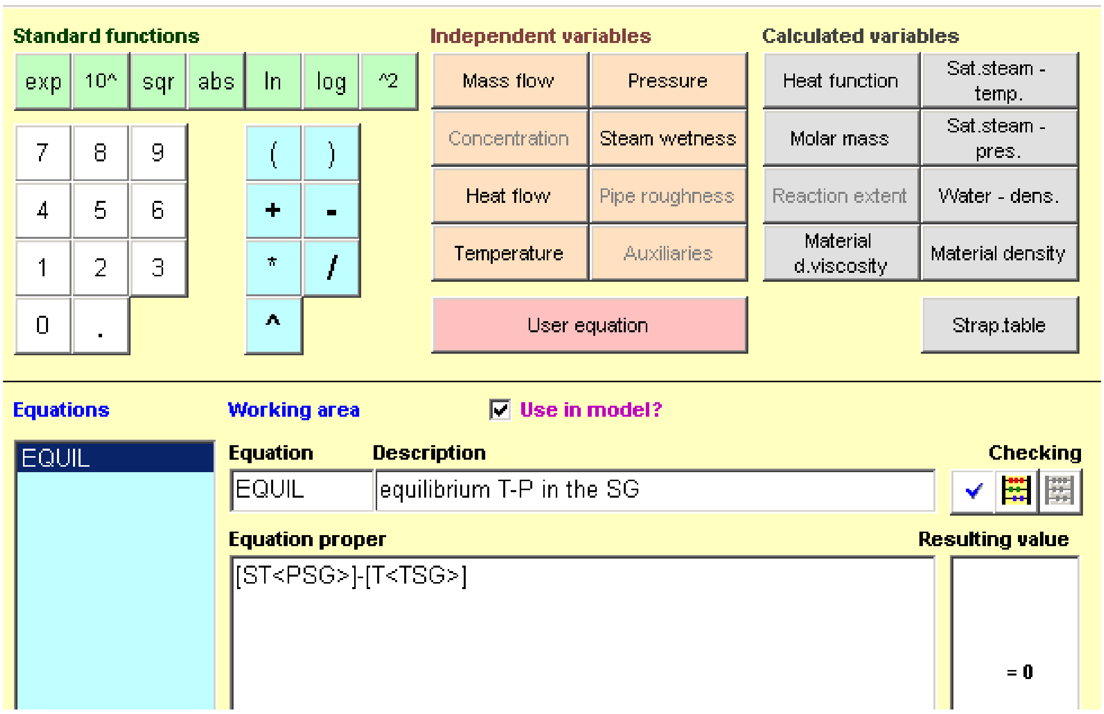

Fig. 3.3: Editor of user defined equations (demo Example E-11)

Equation EQUIL represents here the relation between measured temperature *T* and equilibrium temperature *T**, which is a function of pressure.

$T^* = \mathrm{T}(P)$ (3-6)

In the editor, the equation is of the form

[ST<PSG>]-[T<TSG>] , (3-7)

which is the Eq. (3-6) rewritten with zero right-hand side. Here in sharp brackets <> are the tag names of temperature and pressure variables. Function ST (Saturated Temperature) invoked by button „Saturated steam – temp.“ has the argument of measured pressure PSG. The second term in the equation is the measured temperature TSG.

INPUT DATA

We will use the input data presented in the Table 3.1. This data will be enriched by the SG pressure PSG (measured value 4 500 MPa with the uncertainty 0.5 %).

RESULTS

```
Task: SG-EQUIL (Balance of SG with phase equilibrium)

 I T E R A T I O N S

 Iter           Qeq            Qx              Qy            Qmin
 -----------------------------------------------------------------
 START     1.6499E+08
    1      6.3171E+04    8.5276E+01      5.4593E+06      4.6792E+00
    2      5.4040E+00    1.1408E-01      3.1750E+03      4.6388E+00
    3      4.7851E-05    9.7659E-06      2.5572E-01      4.6389E+00
    4      1.2839E-07    1.4167E-10      2.1220E-06      4.6389E+00

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function


 G L O B A L   D A T A

 Number of nodes                                         2
 Number of heat nodes                                    2
 Number of streams                                       6
 Number of energy streams                                1
 Number of components                                    1
 Number of temperatures                                  4
 Number of pressures                                     3

 Number of measured variables                           12
 Number of adjusted variables                           12
 Number of non-measured variables                        2
 Number of observed variables                            2
 Number of non-observed variables                        0
 Number of free variables                                0
 Number of equations (incl. UDE)                         5
 Number of independent equations                         5
 Number of user-defined equations (UDE)                  1

 Degree of redundancy                                    3

 Mean residue of equations                      1.2839E-07
 Qmin                                           4.6389E+00
 Qcrit                                          7.8100E+00
 Status (Qmin/Qcrit)                              0.593963
```

S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	444.500	445.699	4.181	KG/S
HWIN	MC	5650.000	5448.078	198.162	KG/S
HWOUT	NO	5000.000	5448.078	198.162	KG/S
PURGE	MC	6.120	6.115	0.306	KG/S
STEAM	MC	445.000	439.585	4.189	KG/S

E N E R G Y   S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
QSG	NO	800000.000	810912.240	8006.699	KW

T E M P E R A T U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	221.600	221.566	0.999	C
HWIN	MC	295.200	294.684	0.859	C
HWOUT	MC	265.800	266.209	0.888	C
TSG	MC	257.600	257.453	0.292	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	4600.000	4599.999	23.000	KPA
HW	MC	9600.000	9600.169	48.000	KPA
PSG	MC	4500.000	4500.989	21.523	KPA

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
STEAM	MC	0.250	0.249	0.100	%
WATER	F	100.000	100.000		%

Note that the calculated value of QSG is 810 912 kW with the uncertainty 8007 kW (0.987 %).
If we will compare this result with the Example 3.1, we can see that there is practically no improvement in the QSG precision.
The major change appears in the following table of adjustabilities and threshold values:

Task: SG-EQUIL (Balance of SG with phase equilibrium) ...

REPORT ON CLASSIFICATION OF VARIABLES

R E D U N D A N T   M E A S U R E M E N T S

Type	Variable	Adjustability	Threshold value Beta: 90%	Beta: 95%	Beta: 99%	Unit
MF	FW	0.059441	25.173	27.709	32.431	KG/S
MF	HWIN	0.298546	762.385	839.176	982.187	KG/S
MF	PURGE	0.000266	25.515	28.085	32.871	KG/S
MF	STEAM	0.686186	27.044	29.768	34.841	KG/S
P	FW	0.000000	943574.548	1038616.210	1215615.714	KPA
P	HW	0.000005	28259.191	31105.602	36406.575	KPA
P	PSG	0.043654	149.404	164.453	192.479	KPA
T	FW	0.000605	55.298	60.868	71.240	C
T	HWIN	0.140659	3.761	4.140	4.845	C
T	HWOUT	0.112152	4.180	4.601	5.385	C
T	TSG	0.707765	2.011	2.214	2.591	C
X	STEAM	0.000078	1.909	2.101	2.459	%

Table 3.3: Adjustabilities and threshold values for Examples 3.1 and 3.2.

Variable	Name	Adjustability		Threshold value (95 %)	
Example		**3.1**	**3.2**	**3.1**	**3.2**
Temperature	TGS	0.000005	0.708	644	2.2
Pressure	PGS	-	0.043	-	164

The major difference in the Examples 3.1 and 3.2 is in the possibility to validate temperature and pressure in the steam space of the steam generator. For example the gross error of the steam temperature 2.2 °C will be detected with the probability 95 %. These facts will be discussed also in the Chapter 5.

Note: If we created a user defined equation for phase equilibrium and temperature or pressure were not measured, this would only serve for computing the unmeasured variable without changing the degree of redundancy. In this case, RECON would only serve as a calculator for equilibrium temperature or pressure. Let us note in addition that in the panel „Node balance“, the unmeasured temperatures and/or pressures under phase equilibrium conditions are available for the user automatically, even without defining any user defined equation. ♦

4. Industrial NR power monitoring

The optimal assessment of a real NR power is more complex than the simple system of one NR and one SG presented in the Chapter 2. Modern NPPs has more SGs connected with one NR (typically 4 or 6). The mass and energy balance of such systems can be enhanced (from the point of view of data validation) by incorporating the balance of the feed water preheat system. The high pressure preheat of the feed water is usually well equipped by instrumentation and can increase the data redundancy of the NR power determination.

4.1. The feed water preheat train

Let us consider the scheme given in the following Fig. 4-1a; it represents a two stage system of a feed water preheat.

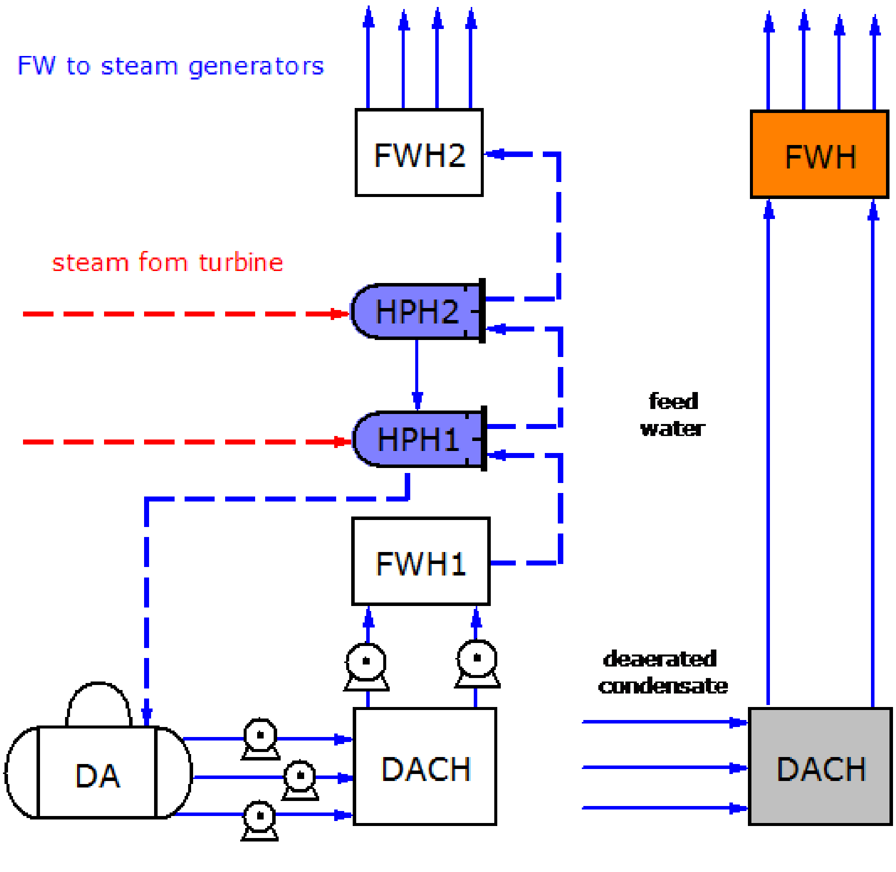

Fig. 4.1: The feed water preheat. ——— measured flow, - - - - - unmeasured flow

The deaerated condensate in the Fig. 4.1 a) is pumped from the deaerator (DA) to the deaerated condensate head (DACH). From this point the feed water is pumped to the feed water header FWH1 and then goes to the system of the two stage high pressure preheating system (High Pressure Heaters HPH1 and HPH2), where the feedwater is heated by the extraction steam from the turbine. Finally the feed water enters the feed water header FWH2. From the FWH2 the FW is distributed to the individual steam generators.

A detailed mass and energy balancing of the whole system is not easy and not essential for the NR power determination. This system contains a lot of unmeasured streams and also the state of the extraction steams is not clear due to their wetness.

In the Fig. 4.1 b) is the reduced balancing scheme. Around the node DACH can be set up only the mass balance as the temperatures around this node are not measured. Around the feed water header FWH can be set up mass and heat balance as all temperatures around this node are measured Altogether 3 balance equations can be generated here: the mass balance around DACH and mass and heat balances around FWH.

4.2. NR balancing system

The reduced balance scheme 4.1 b) can be now incorporated in the system of the steam generation.

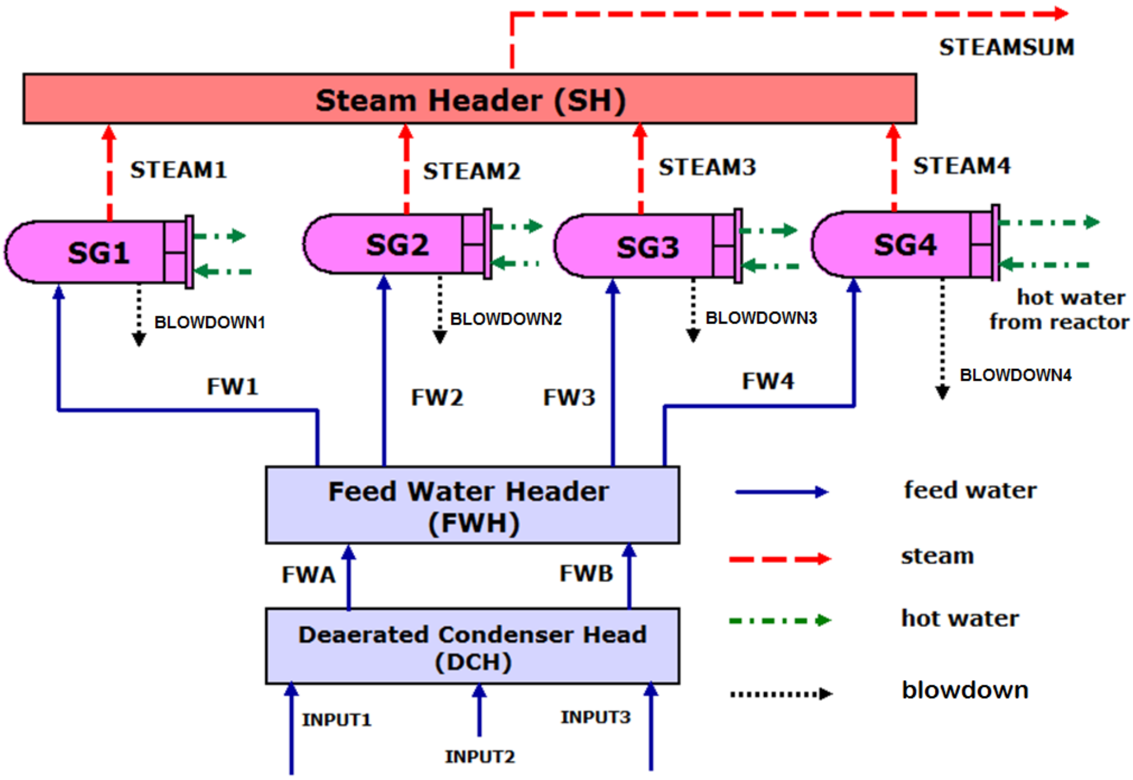

Fig. 4.2: Feed water preheat and steam generation

We have here 3 measured streams of condensate (INPUT1-3), supplied to condensate head DCH. From here, the condensate is pumped via two measured streams (FWA and FWB) into the feed collector FWHEAD. It is then distributed into 4 steam generators SG1-4. There are further 4 measured streams of purge (PURGE1-4). In each SG, the measured stream of steam STEAM1-4 is generated. Steam is led into the steam header SH, from where it goes by the measured stream STEAMSUM to the turbine.

Temperatures are measured for all streams of the feed water and steam. The purge temperatures are assumed to be the same as the steam temperatures in the respective SG. The deaerated condensate temperatures are not measured. For this reason, no energy balance around node DCH is created in the model.

Steam generators are connected with the NR by streams of the pressurized water – see the next Fig. 4.3:

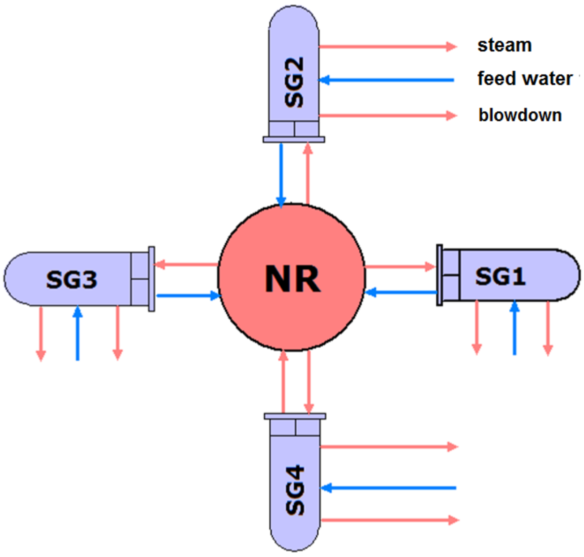

Fig. 4.3: A nuclear steam supply system with 4 steam generators

One problem is that in our case flows of the circulating water between the NR and SGs are not measured. The mass and heat balance around SGs can only serve for calculation of these unmeasured flows, but this does not increase the redundancy of the system. Therefore we need not include the subsystem of hot water from the nuclear reactor into the balancing system (we can balance only the steam side of SGs and exclude the hot water balance from our system). Let's recall the balancing flowsheet with one steam generator described in the Chapter 2:

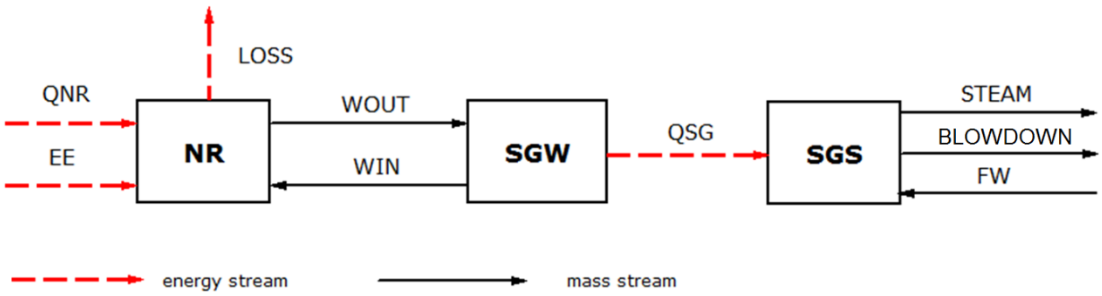

Fig. 4.4: Detailed balance flowsheet of the containment with one SG

Example 4.1: NSSS with FW preheat

It is possible to merge nodes NR and SGW into one node. The streams of pressurized water then vanishes and the final balancing flowsheet is shown in the next Fig. 4.5, where is the flowsheet drawn in the program RECON

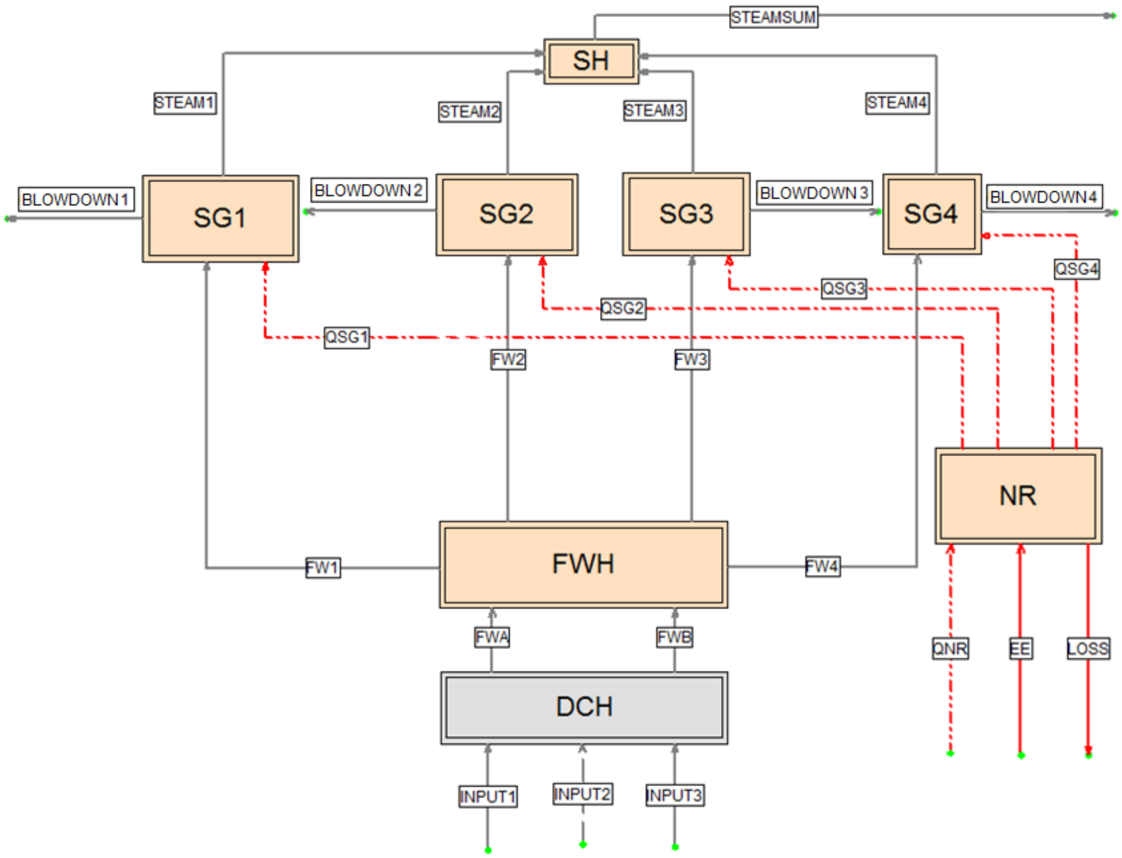

Fig. 4.5: Balance schema in program RECON

The heat supply to individual SG is modeled by four heat flows QSG1-4 that come from node NR representing the nuclear reactor. Stream QNR then represents the whole thermal power of the reactor. All losses (LOSS) and electric energy inputs (EE) are concentrated in the NR node. QNR is the key variable to be identified.

Flowrates and temperatures are measured with the following uncertainties:

Table 4.1: Measurement uncertainties

Type	Stream	Uncertainty
Temperature	All	1 °C
Flow	STEAM	3 %
Flow	PURGE	5 %
Flow	INPUT	1.5 %
Flow	FW	1 %
Pressure	All	0.5 %
Electricity input	EE	2%
Heat loss	LOSS	20 %
Wetness	STEAM	0.1 %

For the majority of nodes, the model creates 2 equations – mass and energy balances. The following nodes make an exception:

- DCH – here, the inlet temperatures are not available and only mass balance equation is created
- NR – mass flowrates are absent and only energy balance is created.

Altogether, there are 14 equations. There are 5 unmeasured variables (heat fluxes QNR and heat powers of the individual steam generators) in the problem. The degree of redundancy is therefore 14 – 5 = 9.

4.3. Main results

The main results of a typical data set are

```
Task: NRPOWER4SG (NPP with 4 steam generators)

I T E R A T I O N S

 Iter           Qeq            Qx              Qy            Qmin
 -----------------------------------------------------------------
 START     4.9596E+06
    1      3.6378E+02    6.5756E-01      1.1039E+07      8.3513E+00
    2      3.2742E-03    3.0913E-05      7.9708E+02      8.3490E+00
    3      1.0531E-07    1.5539E-09      3.5928E-04      8.3490E+00

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function


 G L O B A L   D A T A

 Number of nodes                                    8
 Number of heat nodes                               7
 Number of streams                                 25
 Number of energy streams                           7
 Number of components                               1
 Number of temperatures                            11
 Number of pressures                                1

 Number of measured variables                      32
 Number of adjusted variables                      30
 Number of non-measured variables                   5
 Number of observed variables                       5
 Number of non-observed variables                   0
 Number of free variables                           0
 Number of equations                               14
 Number of independent equations                   14
 Number of user-defined equations                   0

 Degree of redundancy                               9

 Mean residue of equations                 1.0531E-07
 Qmin                                      8.3490E+00
 Qcrit                                     1.6900E+01
 Status (Qmin/Qcrit)                         0.494024


 S T R E A M S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 FW1              MC          370.566        369.875          3.350  KG/S
 FW2              MC          396.429        394.132          3.546  KG/S
 FW3              MC          394.181        393.542          3.542  KG/S
```

FW4	MC	397.208	396.437	3.565	KG/S
FWA	MC	776.776	780.760	6.176	KG/S
FWB	MC	769.340	773.226	6.151	KG/S
INPUT1	MC	761.812	761.785	8.679	KG/S
INPUT2	F	0.00E+0	0.00E+0		KG/S
INPUT3	MC	792.230	792.201	8.752	KG/S
PURGE1	MC	1.913	1.912	0.096	KG/S
PURGE2	MC	2.477	2.479	0.124	KG/S
PURGE3	MC	1.169	1.169	0.058	KG/S
PURGE4	MC	1.602	1.602	0.080	KG/S
STEAM1	MC	370.739	367.963	3.351	KG/S
STEAM2	MC	381.984	391.654	3.547	KG/S
STEAM3	MC	396.862	392.372	3.542	KG/S
STEAM4	MC	398.246	394.835	3.565	KG/S
STEAMSUM	MC	1532.050	1546.824	5.698	KG/S

E N E R G Y   S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
EE	MN	5.015	5.015	0.100	MW
LOSS	MN	1.596	1.596	0.319	MW
QNR	NO	2820.438	2854.141	11.229	MW
QSG1	NO	703.492	679.971	6.433	MW
QSG2	NO	707.889	722.485	6.800	MW
QSG3	NO	709.531	726.057	6.810	MW
QSG4	NO	699.526	729.048	6.842	MW

T E M P E R A T U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FWA	MC	220.500	220.304	0.815	C
FWB	MC	222.000	221.805	0.818	C
FWSG1	MC	220.800	220.894	0.962	C
FWSG2	MC	221.600	221.700	0.956	C
FWSG3	MC	220.400	220.500	0.956	C
FWSG4	MC	221.000	221.100	0.956	C
SG1	MC	259.200	259.186	0.976	C
SG2	MC	258.600	258.586	0.974	C
SG3	MC	257.000	256.987	0.978	C
SG4	MC	259.800	259.785	0.971	C
steamsum	MC	258.600	258.656	0.447	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	4.733	4.733	0.024	MPAG

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
SGsteam	MC	0.100	0.100	0.100	%
water	F	100.000	100.000		%

Calculations lasted 00:00:0.044

The sum of squares of adjustments Q_{min} = 8.35, critical value of chi-square distribution with 9 degrees of freedom at the significance level 0.05 [$\chi^2_{0.95}(9)$] = 16.90. Since

8.35 < 16.90,

no gross error presence has been detected.

We have found the value of the reactor thermal power *QNR* = 2854 MW with uncertainty 11.2 MW (which represents 0.39 % from the computed value).

4.4. Further information

By its extent, this case study already approaches real problems met with in practice. It will thus be useful to give further interesting results that can be considered typical of this kind of problems.

For the sake of brevity, let us give the results in abridged form. We'll use the fact that our scheme is symmetric around the vertical axis. The values of parallel variables (e.g. parallel stream flowrates) are nearly equal and the same holds for their further properties). So not single results, but only those for the representatives will be given. The results for adjustabilities, threshold values and parametric sensibilities are given in the following table.

REPORT ON CLASSIFICATION OF VARIABLES
=====================================

All unmeasured variables observable

R E D U N D A N T   M E A S U R E M E N T S

Type	Variable	Adjustability	Threshold value Beta: 90%	95%	99%	Unit
MF	FW1	0.095917	19.710	21.498	24.799	KG/S
MF	FWA	0.204919	29.112	31.753	36.629	KG/S
MF	INPUT1	0.240463	39.933	43.556	50.244	KG/S
MF	PURGE1	0.000035	25.608	27.931	32.219	KG/S
MF	STEAM1	0.698680	26.514	28.919	33.360	KG/S
MF	STEAMSUM	0.876035	105.287	114.838	132.471	KG/S
P	FW	0.000000	412704.330	450143.298	519264.024	MPAG
T	FWA	0.184967	3.923	4.279	4.936	C
T	FWSG1	0.038478	8.274	9.024	10.410	C
T	SG1	0.024109	10.415	11.359	13.104	C
T	steamsum	0.552629	2.542	2.772	3.198	C
X	SGsteam	0.000000	2.273	2.479	2.860	%

Legend:
Adjustability   = relative cut of error due to reconciliation
Threshold value = gross error that will be detected with 90% probability

MF Mass flow
P   Pressure
T   Temperature
X   Steam wetness

Let us further discuss the individual results.

Adjustability gives the decrease of result uncertainty due to the reconciliation. For example at stream INPUT1, this decrease (precision enhancement) is by 24 %. The average value of adjustabilities of all variables is 0.24. This roughly corresponds to the experience from practice, where one gives the result precision enhancement by some 30 % on the average for well instrumented systems. However, one can see here even substantially better adjustability values over 60 %, and also practically nonadjustable variables. The latter are those which are measured with high absolute precision (with respect to the other variables); this is the case of the purges (see also the discussion in the previous case study). Further case is represented by temperatures that are also of relatively high precision and in addition are, as steam temperatures and the pressure of the FW, of minor importance in the heat balance (also already discussed in the previous Chapter).

Threshold value gives minimum value of gross error that will be detected with some probability. Thus for example the value TV = 43.6 for stream INPUT1 means that the gross error must be at least 43.6 t/h so as to be detected with probability 95 % (for information, the flowrates of this stream are ca. 790 t/h, so the threshold value represents some 5 % of the nominal stream value).

It follows from the theory that the threshold value is closely connected with the adjustability of the variable. The smaller the adjustability, the higher is the threshold value (hence also the chance for gross error detection is smaller). Thus for example for almost nonadjustable purges (stream PURGE), the threshold value is many times greater than the nominal one.

4.5. Detection and identification of gross errors

Balancing flowsheets of Chapters 2 and 3 are too simple for showing detection and identification of gross errors (low redundancy). The scheme shown in the Fig. 4.2 contains enough redundancy in this respect. Let us now give two examples from the domain of gross errors detection and identification. We introduce artificially a gross error into our data and our aim is to find it.

Let us begin with an error in the feed water flowrate FW1. According to the report on classification above, the threshold value for this variable is 21.5 t/h. The gross error will be chosen somewhat greater, say 25 t/h. The measured value 370.566 t/h will be increased to 395.566 t/h and the new reconciliation carried out.

During the DR process we get the following message:

```
ERRORS/WARNINGS
===============

S U S P E C T   M A S S   I M B A L A N C E S

NODE:
  [ FWH ]

INPUTS:
Stream     From node  To node              Value           Error
-------------------------------------------------------------------
FWA        DCH        FWH                776.776          7.7678 KG/S
FWB        DCH        FWH                769.34           7.6934 KG/S
                                  ----------------
           Sum of inputs:               1546.116

OUTPUTS:
Stream     From node  To node              Value           Error
-------------------------------------------------------------------
FW1        FWH        SG1                395.566          3.9557 KG/S
FW2        FWH        SG2               396.4295          3.9643 KG/S
FW3        FWH        SG3               394.1805          3.9418 KG/S
FW4        FWH        SG4                397.208          3.9721 KG/S
                                  ----------------
           Sum of outputs:              1583.384

           Imbalance:                    -37.268 (-2.4%)
           Test (should be < 1.96):       5.4114

NODE:
  [ SG1 ]
```

```
INPUTS:
Stream     From node  To node                Value           Error
------------------------------------------------------------------
FW1        FWH        SG1                  395.566          3.9557 KG/S
                                     ----------------
           Sum of inputs:                  395.566

OUTPUTS:
Stream     From node  To node                Value           Error
------------------------------------------------------------------
STEAM1     SG1        SH                   370.739         11.1222 KG/S
PURGE1     SG1        ENVIRON                1.9125         0.0956 KG/S
                                     ----------------
           Sum of outputs:                372.6515
           Imbalance:                      22.9145 (6%)
           Test (should be < 1.96):         3.8045
```

RECON evaluates not only the complex mass & energy balance but also evaluates mass imbalances. Of course, the gross error in FW1 causes significant imbalances in nodes FWH and SG1. This information helps with analyzing the gross errors identification problem.

After the DR process has ended, we have the new result:

$$Q_{min} = 48.9 \quad ,$$

which exceeds the critical value Q_{crit} = 16.89. So the gross error has been correctly detected. We further apply program RECON menu *Results – Gross errors.* As a result, we have the following message.

```
REPORT ON GROSS ERRORS
 ======================

 S U S P E C T   M E A S U R E M E N T S

 Type Variable           Norm.adjust.    G.e.(abs)    G.e.(rel)
 --------------------------------------------------------------
  MF  FW1                      -6.425        28.3            7 %
  MF  FW2                      -5.074        28.6            7 %
  MF  FWA                       4.398        41.4            5 %
  MF  FWB                       4.388        41.4            5 %
  MF  FW4                      -3.454        29.1            7 %
  MF  FW3                      -3.311        29.0            7 %
  MF  STEAM1                    3.173        37.8           10 %

 Adjustability >= 0.01

 Legend:
  Norm.adjust.= normalized adjustment
               (big value => suspect as gross error)
  G.e.(abs)   = estimated gross error (absolute value)
  G.e.(rel)   = estimated gross error (in % of measured value)

  MF  Mass flow
```

It is well known that the variables with great normalized adjustments are candidates for gross errors. We see that the program has found suspected variables and shown correctly the greatest suspect (placed as first, having greatest absolute value of normalized adjustment). There is also a great distance between the first and second variables. We can now continue with the method of elimination of suspect variables from the balance. The suspect variables are one by one put among the unmeasured ones and the DR process is repeated. The variables with the smallest *Qmin* are then possible candidates. Here is the report on the elimination:

Results of elimination

Type	Variable	Meas.	Calc.	Diff.	Qmin	Status
MF	FW1	396	367	28.8	7.619E+00	4.915E-01
MF	FW2	396	373	23.0	2.315E+01	1.494E+00
MF	FWA	777	806	-28.8	2.954E+01	1.906E+00
MF	FWB	769	798	-28.8	2.963E+01	1.911E+00
MF	FW4	397	381	15.9	3.696E+01	2.385E+00
MF	FW3	394	379	15.2	3.793E+01	2.447E+00
MF	STEAM1	371	390	-19.0	3.882E+01	2.505E+00

Legend:

Meas.	Measured value
Calc.	Calculated value
Diff.	Meas. – Calc
Qmin	Sum of least squares
Status	Qmin/Qcrit (should be < 1

Note that only the elimination of FW1 solves our problem, as the Status is < 1. We can see also that the calculated value of the flow (367) is very close to the measured value (about 368) before the introduction of the gross error.

Now, however, a less favorable situation will be arranged. We introduce a gross error into the flowrate FWA (feed water into feed water collector), of value +35 t/h (the threshold value is here 31.8 t/h, see report on classification of variables above). The measured value 776.776 t/h has thus been increased to 811.776 t/h. After reconciliation, one has found the value Q_{min} = 18.8 , with critical value 16.89 (Status = 1.114). A gross error has thus been again detected. We have further applied again the method for suspect values identification giving the following result.

```
REPORT ON GROSS ERRORS
 ======================

 S U S P E C T   M E A S U R E M E N T S

 Type Variable            Norm.adjust.    G.e.(abs)     G.e.(rel)
 --------------------------------------------------------------
  MF   FWB                      -3.647         20.8             3 %
  MF   FWA                      -3.638         20.8             3 %
  MF   STEAM2                    2.169         19.3             5 %
  MF   FW3                       1.982         14.4             4 %

 Adjustability >= 0.01

 Legend:
  Norm.adjust.= normalized adjustment
               (big value => suspect as gross error)
  G.e.(abs)    = estimated gross error (absolute value)
  G.e.(rel)    = estimated gross error (in % of measured value)
```

In this case, we already have not been that successful as in the preceding one. Now we have two suspects – both streams of the feed water with mutually close values of normalized adjustment. These two suspects cannot be further distinguished by the method used.

Even the application of the suspect measurements elimination method brings no breakthrough:

Results of elimination

Type	Variable	Meas.	Calc.	Diff.	Qmin	Status
MF	FWB	769	745	24.2	5.533E+00	3.570E-01
MF	FWA	812	788	24.2	5.600E+00	3.613E-01
MF	STEAM2	382	395	-13.3	1.412E+01	9.113E-01
MF	FW3	394	403	-9.12	1.490E+01	9.612E-01

Again, the elimination of any of the couple FWA and FWB is successful.

The impossibility of distinguishing the two streams follows from the fact that in the scheme, the streams are parallel and in the balance of the two nodes DCH and FWH, they make themselves equally valid. In the case of a linear mass balance only, the two parallel streams should have exactly the same normalized adjustment. In our case the situation is a little bit distorted by the existence of the nonlinear energy balance. The root of these problems is in the covariance matrix of adjustments. If two or more variables have their covariances equal to 1 or -1, they are deterministically correlated and are indistinguishable from the point of view of a gross error identification. However, problems can be encountered also in the cases of covariance close to 1 or -1.

In practice, more cases of similar (although not so obvious) situations can occur. One then often doesn't deal with one error only. As a consequence, the results of gross errors identification are not always unambiguous. Only another independent method could be applied (judging whether the increase in flow over the current limit is possible at all, or scrutinize the measurement system for the two streams).

4.6. System without FW preheat

Example 4.2: NSSS without FW preheat

For completeness, further is presented the NSSS without the FW preheat. It is roughly the balancing envelope of the containment. See the next Fig. 4.6:

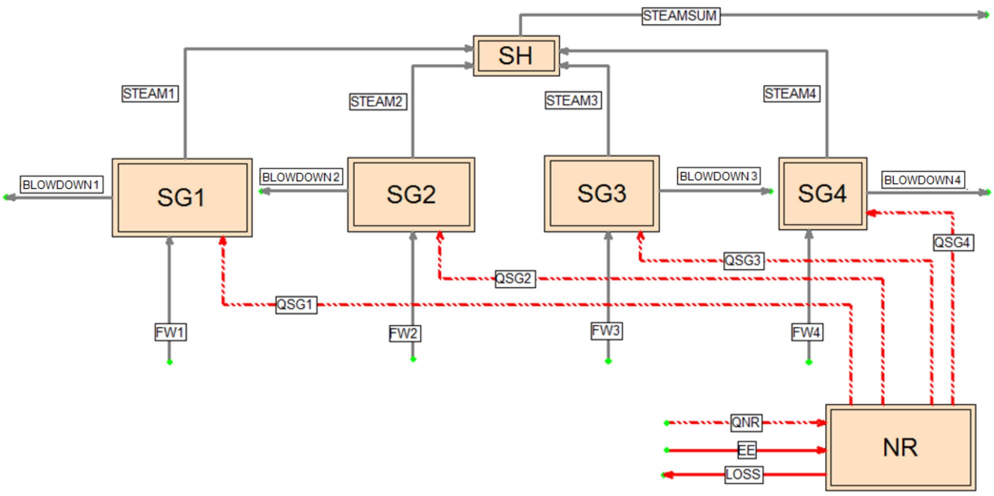

Fig. 4.6: NSSS without the FW preheat

Results of DR with this system follows (abridged). The degree of redundancy is 6. The QNR value is 2861 MW with uncertainty 14.2 MW (0.50 %).

These results will be also discussed in the Chapter 7.

Task: NRPOWER4SG WITHOUT PREHEAT (NPP with 4 steam generators without FW preheat)

G L O B A L   D A T A

Degree of redundancy	6
Mean residue of equations	6.1171E-07
Qmin	5.0324E+00
Qcrit	1.2600E+01
Status (Qmin/Qcrit)	0.399400

S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
FW1	MC	370.566	370.667	3.506	KG/S
FW2	MC	396.429	395.029	3.734	KG/S
FW3	MC	394.181	394.441	3.730	KG/S
FW4	MC	397.208	397.347	3.757	KG/S
PURGE1	MC	1.913	1.912	0.096	KG/S
PURGE2	MC	2.477	2.479	0.124	KG/S
PURGE3	MC	1.169	1.169	0.058	KG/S
PURGE4	MC	1.602	1.602	0.080	KG/S
STEAM1	MC	370.739	368.755	3.507	KG/S
STEAM2	MC	381.984	392.550	3.736	KG/S
STEAM3	MC	396.862	393.271	3.730	KG/S
STEAM4	MC	398.246	395.745	3.758	KG/S
STEAMSUM	MC	1532.050	1550.322	7.298	KG/S

E N E R G Y   S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
EE	MN	5.015	5.015	0.100	MW
LOSS	MN	1.596	1.596	0.319	MW
QNR	NO	2820.438	2861.306	14.192	MW
QSG1	NO	703.492	681.593	6.729	MW
QSG2	NO	707.889	724.321	7.157	MW
QSG3	NO	709.531	727.900	7.169	MW
QSG4	NO	699.526	730.910	7.206	MW

T E M P E R A T U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FWA	MN	220.500	220.500	1.000	C
FWB	MN	222.000	222.000	1.000	C
FWSG1	MN	220.800	220.800	1.000	C
FWSG2	MN	221.600	221.600	1.000	C
FWSG3	MN	220.400	220.400	1.000	C
FWSG4	MN	221.000	221.000	1.000	C
SG1	MC	259.200	259.186	0.976	C
SG2	MC	258.600	258.586	0.974	C
SG3	MC	257.000	256.987	0.978	C
SG4	MC	259.800	259.785	0.971	C
steamsum	MC	258.600	258.656	0.447	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MN	4.733	4.733	0.024	MPAG

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
SGsteam	MC	0.250	0.250	0.100	%
water	F	100.000	100.000		%

4.7. *Complete model with hot water streams*

For completeness, in the next Fig. 4.7 is the complete model of the NSSS which includes circulation of hot water between NR and steam generators.

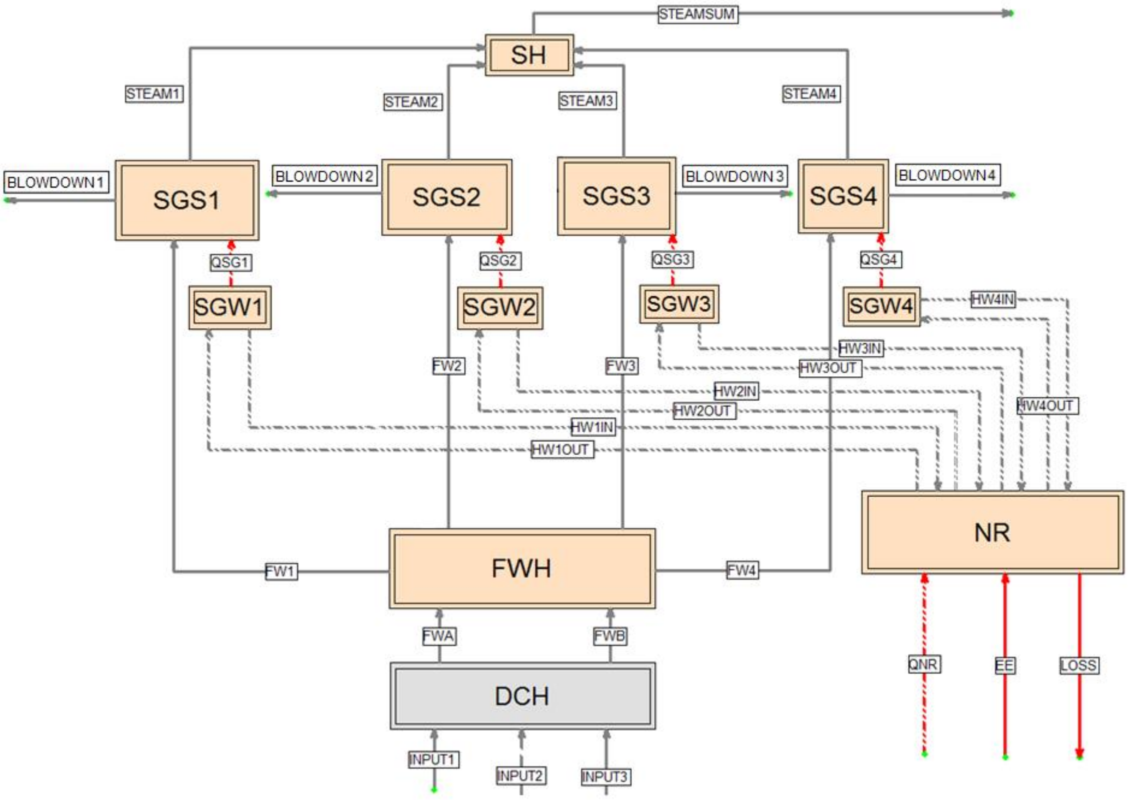

Fig. 4.7: A complete model of NSSS including hot water circulation

Note that steam generators now consist of two nodes – SGS* (steam water side) and SGW* (hot water side). All temperatures around steam generators are measured but all hot water flows are unmeasured. There are 8 more equations generated (mass and heat balances around SGW* nodes. As there are 8 new unknown variables (flows of hot water streams), the degree of redundancy remains equal to 9. This model enables one to calculate hot water circulation which is valuable in monitoring of the whole NSSS. It is clear that the final results (reconciled and calculated values) and all related information (uncertainties, gross error detection possibilities etc.) must be the same a in the case of the simplified model described in the Section 4.2.

5. NR power assessment optimization

There exists a vast literature about optimization of measurement systems, especially about selecting measuring points, see for example [8]. Some of the methods proposed are very sophisticated and powerful. Further on we will try to exploit the relative simplicity of our problem for finding some rules of thumbs in this area by a common sense.

There are several levels on which NR power measurement system can be optimized. Here we will mention two of them:

- Selection of measured variables from the set of all measurable variables. This variant is sometimes called the “instrumentation placement”
- Optimization of instrumentation precision and accuracy.

5.1. Instrumentation placement

Let’s start with the steam generator model presented in the Chapter 3. Now we'll describe in more detail the complex processing of data measured on one steam generator of a nuclear power station. Besides the balance proper and data reconciliation, we'll also give further information that can be deduced from the measured data.

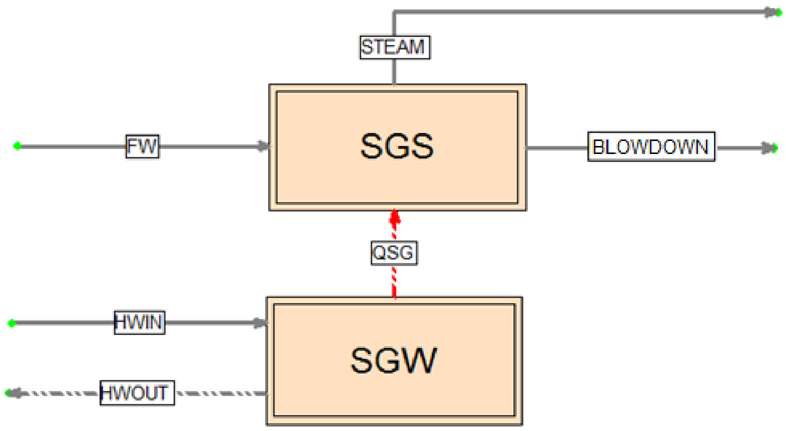

Fig. 5.1: Steam generator

Hot water (HW) circulates between the nuclear reactor and tube space denoted as SGW. Steam (containing 0.25 % wetness) is generated in the shell space SGS. From the shell space of SG, the purge is continuously withdrawn. The heat stream QSG represents the heat flux (thermal power) in SG. The following table gives measured values and their uncertainties.

Table 5.1: Measured variables and their uncertainties

Variable	Stream	Meas. unit	Value	Max.error (uncertainty)
Flow	FW	kg/s	444.5	1%
Flow	STEAM	kg/s	445.0	3%
Flow	PURGE	kg/s	6.12	5%
Flow	HWIN	kg/s	5650	5%
Temperature	FW	°C	221.6	1
Temperature	SGS (STEAM and PURGE)	°C	257.6	1
Temperature	HWIN	°C	295.2	1
Temperature	HWOUT	°C	265.8	1
Pressure	FW	kPag	4600	0.5 %
Pressure	HW	kPag	9 600	0.5 %

This basic variant of SG was already solved in the Chapter 3. We'll give below further results and analyses.

One of the important measurement results is the heat flux QSG, which plays the main role in the nuclear reactor thermal power identification. One speaks then of a *key variable* of the whole measurement. Usually, there are several different ways for its identification, based on the choice of measured variables and the measured values processing – it is so-called *strategy of measurement* and measured data processing.

Let us further review several variants, in order to show the importance of the strategy for measured data analysis. We here make use of the RECON program.

The individual variants (strategies) of the heat flux QSG identification follows.

1. From the mass and heat balances of hot water (balance around node SGW): One deals with direct calculation without data reconciliation on the nuclear reactor side. Data about SGS are ignored.
2. From the mass and heat balance of the steam part of the SG: One deals with direct calculation without data reconciliation on the steam generator side. Steam flowrate is considered unmeasured and it is calculated from the feed water and purge flowrates.
3. From reconciled mass and heat balances for the steam part of SG: Hot water balance is not taken into account.
4. From the reconciled balance of the whole system (model applied in the previous section).
5. Strategy No. 4 is made still more perfect on applying new pressure measurement in (the steam part of) SG, and this pressure is reconciled with the temperature in SG according to the phase equilibrium condition.

These strategies can be described by the following *instrumentation placement matrix*:

Table 5.2: Matrix of instrumentation placement

Variable	Stream	V1	V2	V3	V4	V5
Flow	**FW**	**0**	**1**	**1**	**1**	**1**
Flow	STEAM	0	0	1	1	1
Flow	PURGE	0	1	1	1	1
Flow	HWIN	1	0	0	1	1
Temperature	FW	0	1	1	1	1
Temperature	STEAM & PURGE	0	1	1	1	1
Temperature	HWIN	1	0	0	1	1
Temperature	HWOUT	1	0	0	1	1
Pressure	HW	1	0	0	1	1
Pressure	SGS	0	0	0	0	1
Pressure	FW	0	1	1	1	1

Here on the top of the table are the individual variants of the instrumentation placement. 1/0 means whether the individual variables are measured or not.

The results of the QSG assessment uncertainty are in the following table.

Tab. 5.3: Identification of flowrate QSG in different ways

Strategy No	QSG [MW]	Uncertainty [MW]	Uncertainty [%]	Degree of redundancy
1	868.7	60.5	7.0	0
2	808.6	8.49	1.05	0
3	809.8	8.08	0.98	1
4	810.9	8.01	0.99	2
5	810.9	8.01	0.99	3

The results are in good agreement with simple rules familiar to those which deal systematically with process measurement.

- The choice of the whole measurement strategy is of fundamental importance. Even if strategy No.1 looks very good as concerns the simplicity of the balance calculation, the result is not good. The hot water balance suffers from the fact that it is based on the evaluation of temperature difference of the hot water streams, which is a difference of two large numbers. In addition, there is a relatively great uncertainty of the hot water flowrate measurement.
- Considerably better is the result of strategy No.2 based on the SG steam side balance. The balance works with a relatively precise knowledge of the feed water flowrate. The measurement of temperatures has only marginal importance for setting up the heat balance. This strategy based on simple mass balance is often used in practice.
- Strategy No.3 is supported by the reconciliation of the mass balance around the SG steam side. Further, the result uncertainty is somewhat reduced. In addition, we here have the effect of data validation consisting in the possibility of gross errors detection.

- Strategy No. 4 does not bring any relevant diminishing of the result uncertainty. Two models (No.1 and 3) have been integrated and the degree of redundancy increased by 1. The model according to strategy No.1 brings itself, from the standpoint of thermal power identification, substantially less than model No.3. We here have an asset in enhancing the precision of flowrate measurement on the hot water circuit. More detailed analysis shows that the hot water flowrate uncertainty is lowered by ca. 30 % due to the reconciliation.
- Strategy No. 5 further increases the degree of redundancy, however without any sensible effect on the QSG uncertainty. One deals with reconciliation and temperature precision enhancement, and as shown above, the temperature of steam in SG is of minor importance for setting-up the energy balance. Still, the chance for the validation of temperature and pressure data in SG is then generally better (see the Section 3.4).

Differences of QSG uncertainties among strategies 2 – 5 are not very significant. This coheres with supposed uncertainties of FW and STEAM flows (1 % versus 3 %). For equal uncertainties of FW and STEAM the uncertainty of QSQ for strategy No. 2 would be higher by several tens of percent than for strategies 3 - 5.

5.2. Optimization of instrumentation precision and accuracy

Let’s continue with the steam generator balance. In the following example we'll deal with the propagation of measurement errors during data processing. The final target is to use this information for optimization of the instrumentation precision and maintenance.

Information in this respect is provided by the *vector of shares* introduced in [1], Section 3.9 *Propagation of errors at data processing and....* . Let us recall that this vector contains percentage shares of individual measured variables on the dispersion of the result. The program RECON offers the vector of shares in menu *calculations – Propagation of errors*.

Let us further concentrate on the thermal power of SG – variable QSG introduced in the Chapter 3.

```
Task: SG (Balance of steam generator)

REPORT ABOUT PROPAGATION OF ERRORS

Type Variable
-------------
 HF  QSG

THE VARIANCE OF GIVEN VARIABLE IS CAUSED MAINLY BY:

Type Variable                 Share
-----------------------------------
 MF  FW                        82 %
 MF  STEAM                      9 %
 T   FW                         6 %

 Sum                           97 %

Legend:
 MF  Mass flow
 T   Temperature
```

This list contains only variables with shares greater than 1 %. One can see that the dominant effect on the thermal power precision is due to the flowrates, and in particular those of feed water and steam constituting 91 % of the variance of the result. If we want to make the QSG still more precise, this would make sense just with these two variables. The others are of rather negligible impact. The other finding is that we can improve the QSG precision significantly by including the other FW measurements outside the containment balancing envelope presented in the Chapter 4.

Let us further put the question, why further variables make themselves less valid in the vector of shares. For instance, for the purge measurement, this measurement itself is (absolutely) very precise. While for the feed water measurement, absolute uncertainty is 4.4 kg/s (1 % of 444.5 kg/s), it is only 0.3 kg/s for the purge. For the hot water flowrate measurement, the reason is more complicated. The hot water balance suffers from the fact that it is based on the evaluation of a temperature difference, which is the difference of two large numbers.

Somewhat surprising is the small importance of measured temperatures. Why for example, in the list of relevant variables doesn't occur the temperature in SG, which determines the steam enthalpy, thus the main carrier of energy? One of the reasons is certainly the fact that the assumed uncertainty 1 °C is relatively small and possible impact on the energy balance is not great in these limits. More essential is however the fact that in the temperature domain typical for SG, the temperature dependency of saturated steam enthalpy is flat. This is shown in the next Fig. 5.4:

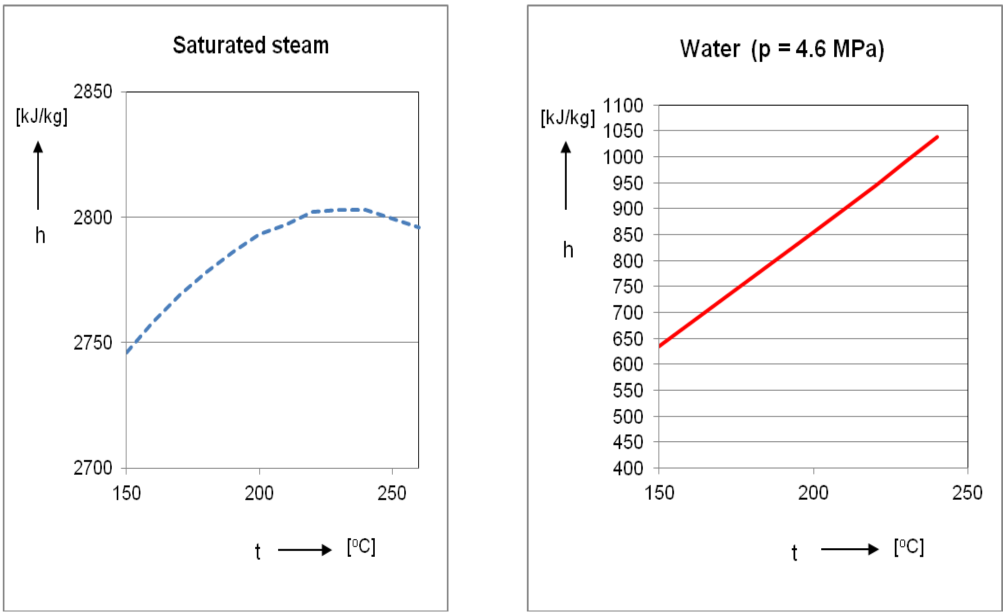

Fig 5.4: Specific enthalpy of the saturated steam and the water [kJ/kg]

The curve of the specific enthalpy in dependence of temperature reaches its maximum somewhere around 235 °C (it is clear that at the maximum the temperature has no influence on the enthalpy). Then the enthalpy falls with the raising temperature. For example at 257 °C the change of the specific enthalpy is ca. - 0.4 kJ/(kg deg C), which is only 0.02 % of the evaporation heat at this temperature.

For instance an error in steam temperature 10 °C (hence ten times the assumed uncertainty) results only in a several tenths per cent error in the stream enthalpy, thus substantially smaller than the flowrate measurement error. With a little bit of exaggeration we can say that for the purpose of balancing in this case the temperature inside the steam generator needn't be measured at all.

Somewhat different is the situation of the feed water. Its specific heat at pressure 4.6 MPa and 220 °C is ca. 4.6 kJ/(kg °C), which is about 10 times more than it was with the steam. Therefore, the feed water temperature occurs in the vector of shares (though still as an item of smaller importance).

For the same reason, in the vector of shares absent is the hot water pressure. The pressure dependency of liquid water enthalpy is even less pronounced than in the preceding case of saturated steam, so that even large errors at the water pressure measurement do not cause large errors in the balance. On the other side however, the chances for the detection of these errors are also bad.

Let's now apply this approach to the more complex system of NSSS with 4 SGs and the FW preheat train solved in the Chapter 4. The result of the propagation of errors analysis follows:

```
Task: NRPOWER4SG (NPP with 4 steam generators)

REPORT ABOUT PROPAGATION OF ERRORS

 Type Variable
 -------------
  HF  QNR

 THE VARIANCE OF GIVEN VARIABLE IS CAUSED MAINLY BY:

 Type Variable                  Share
 ----------------------------------
  MF  FW1                        11 %
  MF  FW2                        12 %
  MF  FW3                        12 %
  MF  FW4                        12 %
  MF  FWA                        12 %
  MF  FWB                        12 %
  MF  INPUT1                      5 %
  MF  INPUT3                      5 %
  X   SGsteam                     5 %

  Sum                            86 %

 Legend:
  MF  Mass flow
  X   Steam wetness
```

Here we can see that on the list of important measured variables are only flows, especially flows of the feed water. The only exception is the pseudomeasurement of the steam wetness.

We can deduce that the most important for the precise assessment of the NR power is the exact mass balance of steam generators, especially the exact assessment of the FW input.

We can conclude this section with the observation, that there is a class of important variables which should be properly measured and their instruments should be regularly maintained and calibrated. In warranted cases we should think about replacement of the existing instrumentation by a better one (with a lower uncertainty and greater reliability).

6. Protection of NR monitoring against gross errors

One of major benefits of Data Reconciliation and Validation is the possibility to protect monitoring systems of industrial Key Process Indicators against malfunctions of measurement systems and similar problems. This Chapter is the abridged version of the paper [12].

In essence, there are at least three major benefits of data reconciliation (DR):

1. Reconciled data are consistent with the model
2. Reconciled data are more precise than data directly measured
3. DR represents a solid basis for detection, identification and elimination of data corrupted by gross errors.

While the first two benefits need not too much discussion, the remaining one deserves a comment. Even if this benefit is often denoted in the literature as “invaluable”, the exact knowledge of strength of the DR method is quite scarce. This chapter will concentrate on evaluation of the last benefit in practice.

6.1. Precision of reconciled data

The precision of data can be characterized by their covariance matrices $\boldsymbol{F}$. Between covariance matrices of $\boldsymbol{x}^+$, $\boldsymbol{x'}$ and $\boldsymbol{v}$ holds the following relation [1]

$$\boldsymbol{F} = \boldsymbol{F}_{x'} + \boldsymbol{F}_v \qquad (6\text{-}1)$$

The precision of individual variables (elements of vectors) is characterized by their standard deviations σ_i, which are square roots of diagonal elements of respective covariance matrices

$$\sigma_i^2 = F_{ii} \quad . \qquad (6\text{-}2)$$

As $\sigma_{vi}^2 \geq 0$, the following inequality holds

$$\sigma_i \geq \sigma_{x'i} \qquad (6\text{-}3)$$

saying that there can be some improvement in precision due to DR. This improvement can be characterized for the *i*-th variable by the so-called *adjustability* a_i

$$a_i = 1 - \sigma_{x'i}/\sigma_i \qquad (6\text{-}4)$$

The adjustability of any measured variable represents the reduction of its imprecision caused by DR. As will be seen later, adjustabilities are remarkable variables having importance also in area of gross error detection. From the definition follows that any adjustability lies in the interval <0 ;1):

- value 0 represents the so-called *just determined variable,* which is not influenced by DR and is not adjusted at all (*nonredundant* variable)
- value in the interval (0;1) means *redundant variables* which are adjusted in the process of DR

Further it is supposed that covariance matrices of reconciled values ***x'*** and of estimated values of unmeasured variables ***y'*** are available (the already mentioned DR Engine) and thus providing uncertainties (confidence intervals) of reconciled values.

6.2. Gross measurement errors

Let's modify Equation (A1-5) in the Appendix 1 to the form

$$x^{+} = x + e + d \quad , \tag{6-5}$$

where d is a gross error (which is a constant). The most simple and frequently used method for detection of gross errors is the well known chi-square test [1,5,6,7,8,9] applied to Q_{min} defined by Eq. (A1-3). Q_{min} has the chi-square distribution with ν degrees of freedom. A gross error is detected when the following inequality holds:

$$Q_{min} > \chi^2_{1-\alpha}(\nu) \tag{6-6}$$

where $\chi^2_{1-\alpha}(\nu)$ is the critical value of the χ^2 distribution with ν degrees of freedom and the confidence level α (0.05 in our case).

6.3. Power of the χ2 test

As every statistical test, also the χ^2 test has its power characteristics shown in Fig. 6.1.

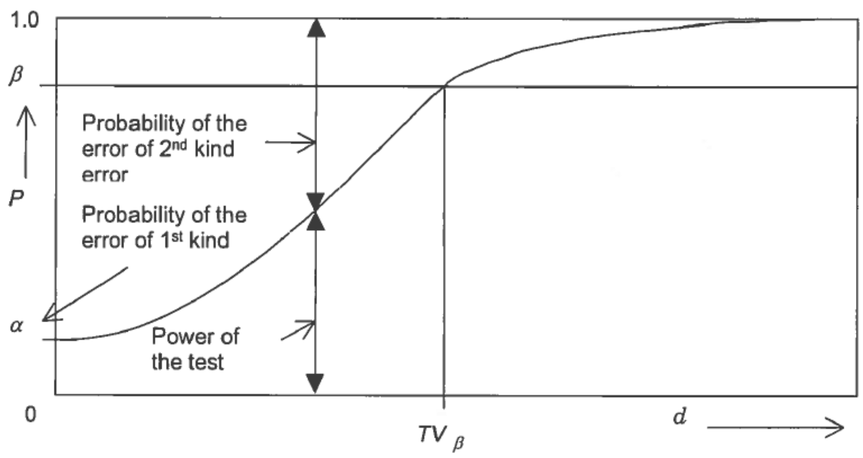

Fig. 6.1: Power characteristic of the χ2 test

On the *x*-axis there is the magnitude of a gross error. On the *y*-axis is the probability *P* that the gross error will be detected. The power characteristic for a measured variable equals the confidence level α in the absence of the gross error (d=0) and approaches 1 for high values of the gross error ($d \to \infty$). TV_β is the value of a gross error which will be detected with probability β (β = 0.95 further in this paper). TV_β is characteristic for every measured variable. The lower is TV_β, the better. It is clear that gross errors can be detected only for redundant measured variables.

Threshold values can be calculated from equation

$$q_i \;=\; \delta_\beta(\nu,\alpha)/[a_i(2-a_i)]^{1/2} \qquad (6\text{-}7)$$

where q_i is a dimensionless threshold value TV_i/σ, which means

$$q_i \;= TV_i/\sigma_i \qquad (6\text{-}8)$$

and $\delta_\beta(\nu,\alpha)$ is a constant characteristic for the confidence level of the *chi*-square test α, number of degrees of freedom ν and the probability that a gross error will be detected β.

Equation (6-7) is slightly re-arranged equation (4.143) from literature [5]. Values of $\delta_\beta(\nu,\alpha)$ are not available in standard statistical tables. Details about calculating threshold values and constants δ (for α=0.05, β=0.9 and ν = 1,2, … ,20) can be found in literature [1]. In this paper will be used the new equation (6-9) for the more convenient β=0.95. This equation approximates δ (for α=0.05) in the range of ν = 1,2, … ,400).

$$\delta_{0.95}(\nu,0.95) \;= 3.59399 \;+\; 0.471951 \ln(\nu) +\; 0.014197 \ln(\nu)^2 + 0.015074 \ln(\nu)^3 \qquad (6\text{-}9)$$

It is worth mentioning that threshold values are simple functions of adjustabilities defined by Eq. (6-4), see also the next graphical presentation of Eq. (6-9).

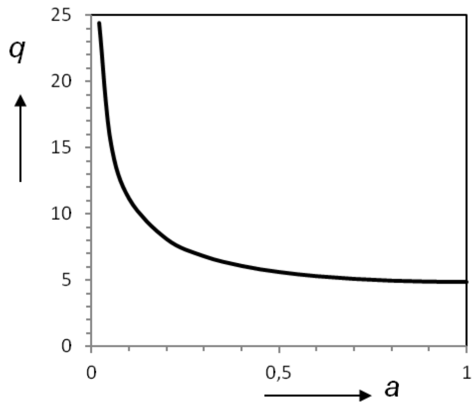

Fig. 6.2: Example of the dimensionless threshold value q as a function of adjustability a (for v = 9, α = 0.05 and β = 0.95)

Some simple conclusions can be deduced from this graph:

- the higher is the adjustability, the higher is the probability to detect a gross error (low value of the threshold value)
- for adjustabilities less than 0.1 the chance for detecting gross errors diminishes steeply

6.4. Target variables and their protection against gross errors

In practice, there always exist one or several variables, which are of key importance. They are the main reason why hundreds of other variables are measured, collected and processed. The measurement target can be for example a nuclear reactor heat output while errors can be hidden in measured flows and state variables of steam and water. The basic question is: “How are these target variables protected against gross errors of the measurement?”

We are successful if **A**: “A gross error is present and eliminated while maintaining an accurate value for the target variable.” We are unsuccessful if **B**: “A gross error is present but not identified and an inaccurate value for the target variable is determined.”

In analogy with statistics (power of statistical tests) we can define the probability of an event **A** as a power of the Monitoring System Self-Protection (MSSP).

Let’s further suppose that for a target variable h, we know (require) the *maximum acceptable error* e_{hmax}. This tolerance can be consumed by

1. a random error e_{hr} caused by random errors of all measured variables (further we suppose Gaussian errors with Normal distribution). As the random errors are not known, we will substitute e_{hr} by e_{hrmax} which represents the *tolerance* of h caused by random errors (the information provided by the DR Engine).
2. a constant gross error e_{hg} caused by a gross error of one measured variable d in the sense of Eq. (6-5)

We require that

$$e_{hmax} > e_{hrmax} + e_{hg} \quad . \tag{6-10}$$

Inequality (6-10) sets the upper limit on the error e_{hg} caused by the gross error, further denoted as e_{hgmax}

$$e_{hgmax} = e_{hmax} - e_{hrmax} \tag{6-11}$$

This means that both errors’ tolerances add to form the overall tolerance. The situation is illustrated in the next Fig. 6.3.

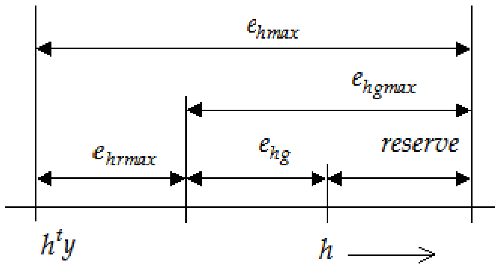

Fig. 6.3: The overall tolerance e_{hmax} consumed by random and systematic errors

It is clear that the *reserve* should be non-negative to satisfy our MSSP requirement (6-10).

The MSSP analysis will be based on a combination of two methods:

- gross error detection power described in the previous paragraph
- a parametric sensitivity of the target variable with respect to the individual measured variables.

Let's suppose that a target variable *h* is a function of measured variables in the sense of Eq. (A1-7).

$$h = h(\boldsymbol{x}^{+}) \tag{6-12}$$

In this case the function *h()* represents the whole DR process starting by collection of measured values and ending by calculations of target values.

A *parametric sensitivity* ζ_i of *h()* with respect to a measured variable x_i is defined as the partial derivative

$$\zeta_i = \partial h(\boldsymbol{x}^{+})/\partial x_i^{+} \tag{6-13}$$

The process consists of two steps, which are applied to all measured adjustable variables:

1. determination of the threshold value for the *i*-th measured variable
2. evaluation of the parametric sensitivity of the target variable with respect to the *i*-th measured variable.

The process is illustrated in the next Fig. 6.4, which is a continuation of Fig. 6.1. On the right hand side y axis there are errors of the target variable caused by a gross error of the *i*-th adjustable measured variable.

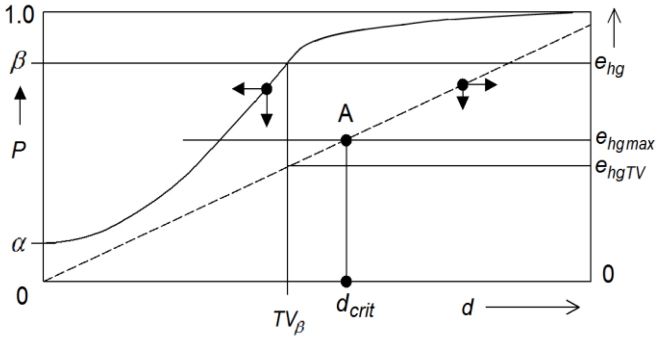

Fig 6.4: Power characteristics (full curve) and the parametric sensitivity (dashed straight line) for the i-th measured variable (the index i is omitted here for brevity)

It is supposed that the function (6-12) can be linearized and that a gross error of the *i*-th measured variable transforms to the error of the target variable according to Eq. (6-13)

$$e_{hg} = \zeta_i d_i \tag{6-14}$$

This equation is represented by the dashed straight line in Fig. 6.4. There are two important points on the x axis:

1. threshold value TV_β which informs that gross error was detected (with probability β)
2. critical value of the gross error d_{crit} . At this point e_{hg} reaches the maximum value e_{hgmax} and exhausts all tolerance available (point **A** in the Fig. 6.4).

$$e_{hgmax} = |\zeta_i| \, d_{crit,i} \tag{6-15}$$

or

$$d_{crit,i} = e_{hgmax} / |\zeta_i| \tag{6-16}$$

Now it is time to compare the power characteristic curve with the parametric sensitivity straight line. The most important is the relation between $d_{crit,i}$ and $TV_{\beta,i}$. If there holds the inequality

$$d_{crit,i} > TV_{\beta,i} \quad , \tag{6-17}$$

the gross error will be detected before causing unacceptable error in the target variable and the system is well protected against a gross error of the respective measured variable (this case is depicted in Fig. 6.4). In the opposite case an undetected gross error can devalue the target value significantly before it is detected.

The inequality (6-17) can be expressed also in the alternative way by substitution of $d_{crit,i}$ from (6-16) to (6-17):

$$e_{hgmax} \;>\; \left|\zeta_i\right| TV_{\beta,i} \tag{6-18}$$

saying that

The product of the parametric sensitivity and the threshold value should be less than the tolerance belonging to the gross error set a priori for the target variable.

The inequality (6-18) thus represents the only criterion for assessing whether the target variable is self protected by DR (and the following data analysis steps) against gross error(s) in the *i*-th measured variable. The inequality (6-18) must be checked for all measured variables.

6.5. Example: Nuclear Reactor heat power monitoring

The heat released in the nuclear reactor is not directly measurable, it is calculated from the mass and heat balance of the feed water and the steam generation systems.

The following example is a simplified version of the 1000 MWe PWR Nuclear Reactor (NR) heat balance problem described in the Chapter 4. The heat loss and the electricity consumption are for brevity neglected.

QNR is the **target variable** to be determined. The model generates 14 mass and heat balance equations among 28 measured variables and 5 unmeasured variables (heat fluxes QSG and QNR). The mass and enthalpy balances were set up around all nodes excluding the INPUT, where only the mass balance was used. The degree of redundancy is therefore 14 – 5 = 9. There are 9 degrees of redundancy available for DR and gross error detection.

Let's analyse the possibility to protect such system against gross measurement errors. **It is required that the overall error of *QNR* should not exceed 1.2 % of the nominal value, which is 3000 MW, i.e. 36 MW**.

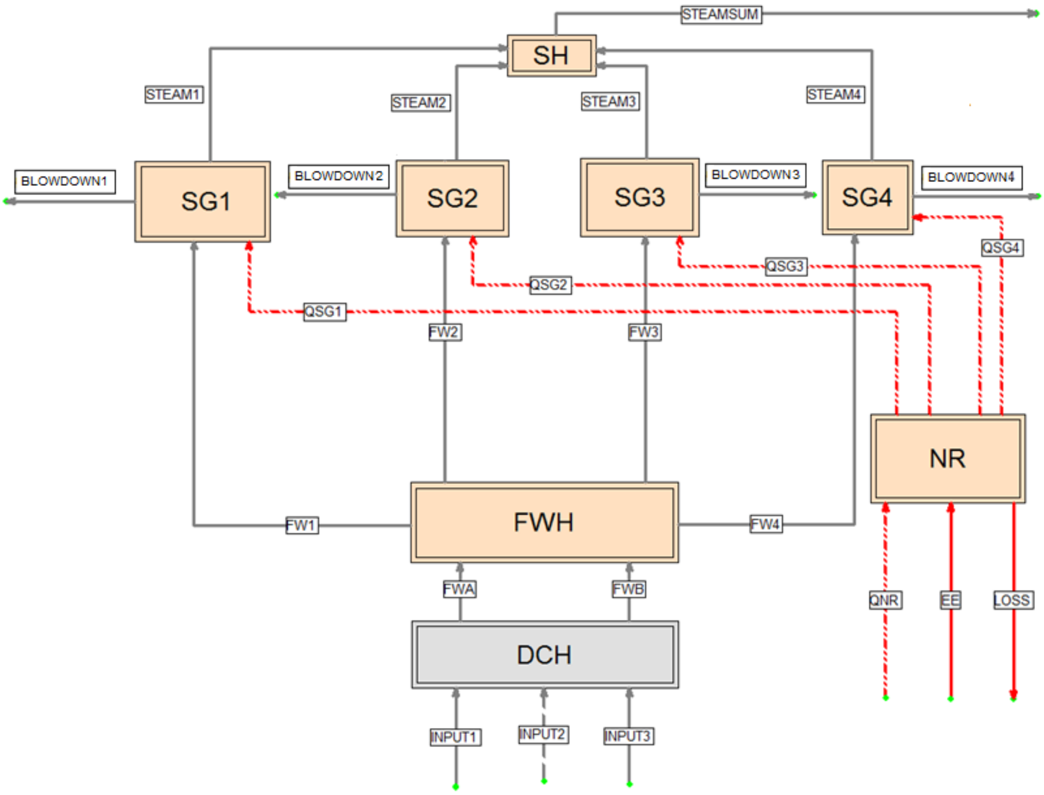

Fig. 6.5: The balancing flowsheet for the example

Flows and temperatures were measured with the following tolerances (maximum errors):

Table 6.1: Tolerances of measurement

Type	**Stream**	**Tolerance**
Temperature	All	1 °C
Flow	STEAM	3%
Flow	PURGE	5%
Flow	INPUT	1.5 %
Flow	FW	1%

The major results of data reconciliation were:

$$Q_{min} = 14.4$$

(the critical value $\chi^2_{0.95}$ (9) = 16.9, hence no gross error was detected). The calculated NR heat power

$$QNR = 2820.7 \pm 10.8 \text{ MW},$$

therefore the tolerance of *QNR* belonging to random errors e_{hrmax} equals 10.8 MW (0.38% of the calculated value).

As the maximum allowed tolerance is 36 MW, the undetected gross error should not cause greater error in *QNR* than 36 – 10.8 = 25.2 MW (according to Eq. 6-11).

Results of the analysis are summarized in the next Table 6.2. As the flowsheet is symmetrical, results will be presented only for the representatives of parallel streams (for example conclusions for all 4 STEAM streams are almost the same).

Table 6.2: Analysis of MSSP for the Example. TV = Threshold Value (the critical value of TV$|\zeta|$ is 25.2)

Type	**Stream**	**Adjusta-bility** *a*	***TV***	**Parametric Sensitivity** ζ	*TV* $\lvert\zeta\rvert$
Flow	INPUT1-3	0.26	43.3	0.220	9.5
Flow	FW1-4	0.10	21.9	0.989	21.7
Flow	FWA,B	0.21	31.6	0.498	15.7
Flow	PURGE	0.00012	29.1	-1.52	44.2
Flow	STEAM	0.70	30.0	0.110	3.3
Flow	STEAMSUM	0.88	114.8	0.028	3.2
T	FWA,B	0.18	4.3	-1.18	5.1
T	FW1-4	0.042	8.6	-1.17	10.1
T	STEAM	0.026	10.9	0.15	1.6
T	STEAMSUM	0.55	2.8	0.14	0.4
Flow	PURGE*	0.025	2.2	-1.23	2.7

* values after installation of the measurement of the sum of purges

The values in the last column are now compared with the limiting value, which is 25.2 MW according to the Inequality (6-18). From the Table 6.2 follows that the target variable *QNR* is quite well protected against gross errors for most of measured variables as they pass the Inequality (6-18). The only exceptions are the PURGE streams.

Really, any of the purge streams has very low adjustability (and therefore relatively high threshold value) and at the same time also high parametric sensitivity. The value from the last column of Table 6.2 is 44.2 MW which is almost twice the allowed tolerance for QNR (25.2 MW). This means that the system is not protected against gross errors in purge flow measurements.

Let's try to raise the redundancy of the instrumentation system. The redundancy of the purge streams is very low (they are checked only by the balance of steam generators, while feed waters and steam has its own redundant balancing sub-flowsheets). By adding the measurement of the sum of all purge streams (tolerance 5 % of the measured value), the problem is completely solved.

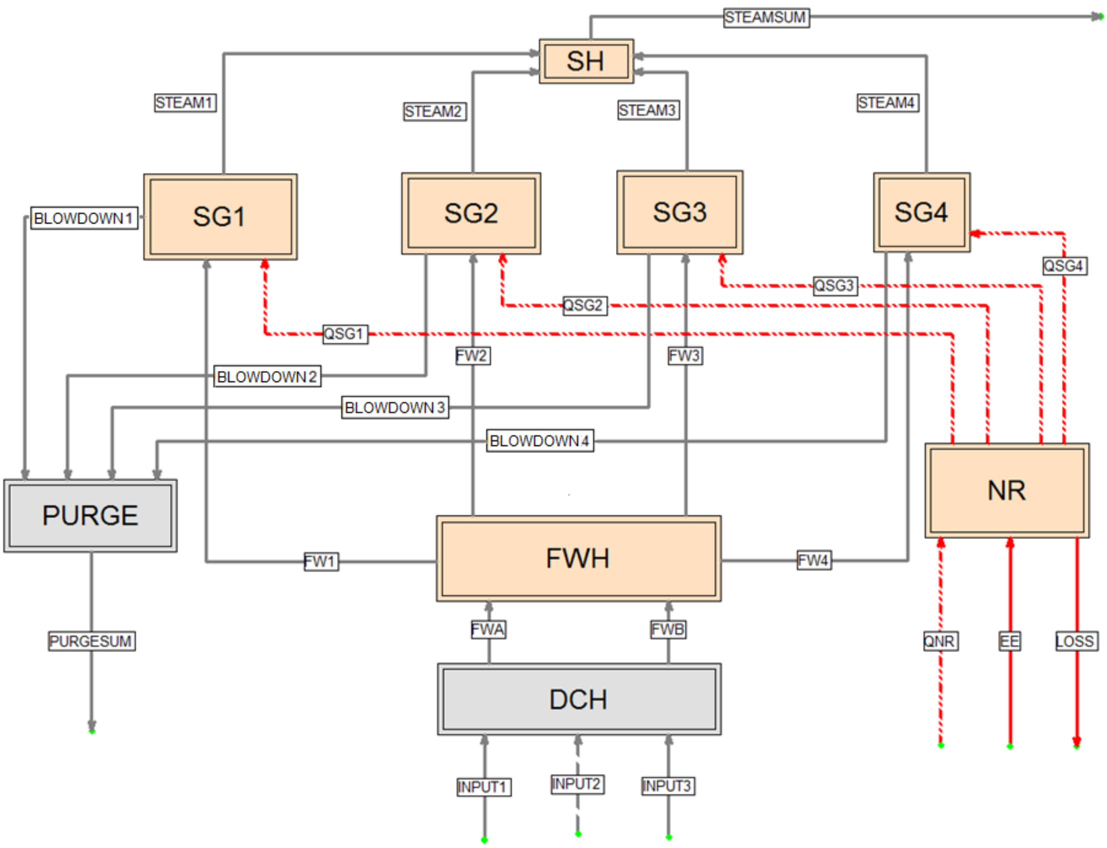

Fig. 6.6: The balancing flowsheet after adding the purge sum measurement

After this step the threshold values of all purge streams fell from 29.1 to 2.2 kg/s. The result is presented in the last row of Tab. 6.2. It can be seen that the adjustability of purges increased by more than two orders after the installation of the new measurement.

6.6. Interpretation of results and conclusions

Results of the Example can be interpreted in the following way. For the whole system we can conclude that it is (after installing the new measurement of the sum of purges) well self-protected against gross errors as concerns the target variable *QNR* and its required tolerance. Especially

The probability that any undetected gross error will impair the required tolerance of QNR (36 MW) is less than 5 %, provided that the measurement of the sum of purges is installed.

Otherwise the flowmeters of purges must be checked independently of the data validation and reconciliation procedure described above. Such interpretation can help in deciding which measured variables are self-protected by DR and which need independent checking, calibration or additional redundancy.

Let's briefly discuss some limitations of the proposed method. The solution is based on linearization of the nonlinear model. This is a general problem of the DR technology. It depends on how far from the point of the solution the linearization is applied. In our problem we should look how big the threshold values are, as applied in inequality (6-18). In practice, if the threshold values are up to 10 % of the flow or up to 10 centigrade in the case of temperatures, the errors introduced by linearization are small and smaller than the other errors (model errors, estimation of measurement precision, etc.). If the threshold values are bigger, it is possible to use the Monte Carlo simulation to check whether the linear model works well.

Conclusions drawn from the method proposed should be applied in the statistical sense. This means that they are valid for a large number of data sets, for example in the case of a continuous monitoring of an industrial process. Benefits of DR are of a statistical nature.

The proposed MSSP analysis is based on the assumption that only a single gross error may exist in the system. This should be the case of a well maintained monitoring system where the probability of multiple gross errors is low. In the case of simultaneous gross errors the problem starts to be more complex (not only for gross error detection but also for their localization).

The method proposed is quite simple and can be useful in the process of analysis of existing monitoring systems. It **makes possible to find which couples of target variables and measured variables are automatically protected** against gross error and which primary measurement needs independent checking or frequent calibration. This work can be also useful in the optimization of the instrumentation placement as was shown on example of measurement of the overall purge.

7. Discussion and conclusions

Some results were already discussed in the individual chapters. Here we will look at the overall problem of the QNR assessment uncertainty.

Let's recall 3 Cases in this report:

1. Assessment of the 1 SG power (QSG) in the Example 3.1. This is not the case of the full QNR assessment but very close to this problem (see the Equation (3-1)).
2. QNR of the 4 SGs without the feed water preheat train in the Example 4.2.
3. QNR of the 4 SGs with the feed water preheat train in the Example 4.1.

The uncertainties of measured variables are the same for all Cases. The most important results of these cases – thermal power uncertainties - are summarized in the next Table 7.1:

Table 7.1: Uncertainties of QSG and QNR in per cents of the power value

Case	Variable	Degrees of redundancy	Uncertainty (%)
1	QSG	2	0.99
2	QNR	6	0.50
3	QNR	9	0.39

Note that the uncertainty falls with the raising degree of redundancy which is in tune with the theory. A question is whether the uncertainty in the Case 3 is not too much optimistic? The uncertainty value of the QNR 0.39 % is substantially smaller than that of any of the measured flows. Moreover, also errors at setting-up the heat balance should play a role. Let's analyze this problem in details.

There are 2 major effects which must be taken into account.

- Precision improvement due to data reconciliation
- Precision improvement due to steam's splitting.

Further on in this chapter will be for simplicity supposed that

- The flowmeters used have the same relative uncertainty expressed in per cents, irrespective of the flow
- The random errors of flowmeters are uncorrelated
- This is the problem of the (linear) mass balance only.

In the next Fig. 7.1 there are two simple flowsheets illustrating this problem:

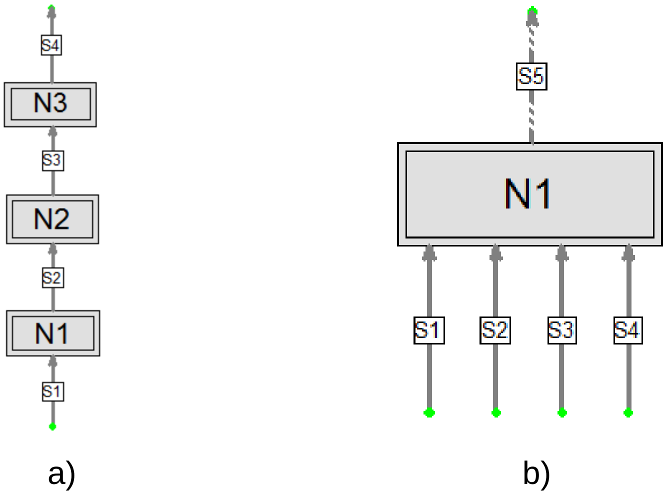

Fig. 7.1: Data reconciliation and stream's splitting

In the Fig. 7.1a) is the case of 4 flowmeters placed on one line (streams S1 – S4). Such system can be reconciled. There are 4 streams and 3 nodes. The degree of redundancy is 3. Let's suppose that the nominal flow in this system is 100 kg/s and its uncertainty is 10 % (10 kg/s). After the data reconciliation in the program RECON, the all reconciled values have the uncertainty 5 kg/s. This means that the DR cut the uncertainty by 50 %.

This simple example resembles the flowsheet in the Example 4.1. The FW streams are measured on 3 levels, the steam on two levels, similarly as in the Fig. 7.1a).

The next influence was probably not presented in the literature on industrial data processing. Imagine again that the overall flow in this system is 100 kg/s and the uncertainty of flowmeters available is 10 % (10 kg/s). There is the possibility to split this stream into the four same parts (S1 – S4), each flow 25 kg/s with the uncertainty 10 % (2.5 kg/s) see the Fig. 7.1b). The stream S5 is not measured but calculated from the balance as the sum of four streams. The final uncertainty of such calculated stream S5 in the program RECON is then again 5 kg/s, the same as in the preceding case of the DR. This benefit of 50 % precision improvement is not due to the DR but due the law of errors propagation during the S5 calculation:

$$S5 = S1 + S2 + S3 + S4 \qquad (7\text{-}1)$$

To explain it in words, when measuring the same thing (the flow of the S5 stream) by several instruments, the positive and negative errors can cancel in some extent.

This example also resembles the flowsheet in the Example 4.1. The FW and STEAM streams are measured on 3, 2, 4 and 4 parallel streams, this also enhances the final QNR uncertainty.

These two simple examples have shown that the precision improvement is enabled by two different mechanisms of the relatively same power, by DR and by stream's splitting.

Note: the cut of the uncertainty by 50 % in both cases is only incidental and holds only for this number of streams.

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List of abbreviations

ABS.ERROR	absolute error (uncertainty) of a result
CAPEX	CApital EXpenditure
DR	Data Reconciliation
F	Fixed variable (constant)
FW	Feed Water
GE	Gross Error
INP.VALUE	Input value (measured or a guess for nonmeasured variables)
KPI	Key Performance Indicator
MC	Measured variable (Corrected, reconciled)
NO	Nonmeasured variable Observable
NPP	Nuclear Power Plant
NR	Nuclear Reactor
NSSS	Nuclear Steam Supply System
OPEX	OPerating EXpenditure
PWR	Pressurized (light) Water Reactor
REC.VALUE	calculated value
RECON	Mass and heat balancing program: http://www.chemplant.cz/recon.asp
SG	Steam Generator
Status	Status of data quality, Qmin/Qcrit. The Status should be < 1 (no GE detected)

List of symbols

a	adjustability (6-4)
d	gross error (6-5)
d_{crit}	gross error causing error of a target variable equal to e_{hgmax} (Fig. 6-4)
e	random error with Normal (Gauss) distribution (A1-5)
e_h	error of a target variable h
e_{hmax}	maximum allowed error of a target variable
e_{hgmax}	maximum allowed error of a target variable due to a gross error
e_{hgTV}	error of a target variable due to a gross error equal to the threshold value
e_{hrmax}	tolerance of error of a target variable due to random errors
e_{max}	maximum value of e (1.96σ), tolerance
F	flow
$\boldsymbol{F}$	covariance matrix
$\boldsymbol{g()}$	column vector of functions (A1-1)
h	target variable

p	pressure
q	dimensionless gross error (6-8)
t	temperature
Q_{min}	quadratic form of adjustments (A1-3)
$\boldsymbol{v}$	*column* vector of adjustments (A1-4)
X	wetness of the steam (moisture content in mass %)
$\boldsymbol{x}$	column vector of measured variables
$\boldsymbol{y}$	column vector of unmeasured variables
$\boldsymbol{z}$	column vector of process variables
α	level of confidence, probability of the error of 1st kind (0.05 in this paper)
β	probability that a gross error will be detected (0.95 in this paper
ν	degree of redundancy
χ^2	chi-square distribution
σ	standard deviation

Upper index

‘	reconciled value
+	measured value
$^{-1}$	inverse of a matrix
^{T}	transposed matrix (vector)

Appendix 1: A very brief summary of Data Reconciliation

Throughout this report it is supposed that the reader is a little bit familiar with mass and energy balancing and data reconciliation and validation. In special problems we will refer to our report [1] which is available free on the Internet. There are also books dealing with this subject [5-9].

Now only very briefly: Data Reconciliation (DR) can be defined as an adjustment of measured data to obey some mathematical model (mostly a law of nature). The DR procedure minimizes the generalized sum of squares of adjustments constrained by

$$\boldsymbol{g(z')} = \boldsymbol{0} \quad , \tag{A1-1}$$

where $\boldsymbol{z}$ is a vector of process variables (flowrates, temperatures, …) and $\boldsymbol{g(z')}$ is a vector of generally nonlinear functions of $\boldsymbol{z}$. The vector $\boldsymbol{z}$ is partitioned

$$\boldsymbol{z'} = \boldsymbol{(y',x')} \quad , \tag{A1-2}$$

where $\boldsymbol{y'}$ is a subvector of unmeasured variables and $\boldsymbol{x'}$ that of measured variables.

The reconciled solution z' must obey the condition (A1-1) and minimizes the generalized sum of squares

$$Q_{min} = \boldsymbol{v^T F^{-1} v} \tag{A1-3}$$

where $\boldsymbol{F}$ is the covariance matrix of measurement errors and $\boldsymbol{v}$ the vector of adjustments of measured variables:

$$\boldsymbol{v} = \boldsymbol{x'} - \boldsymbol{x^+} \tag{A1-4}$$

where $\boldsymbol{x'}$ are the reconciled values and $\boldsymbol{x^+}$ the vector of measured values subject to random errors.

The solution is based on the assumption that true (unknown) values x are corrupted by random errors e.

$$x^+ = x + e \quad . \tag{A1-5}$$

Random errors are characterised by their standard deviations (sigmas). Sigma is calculated as the uncertainty of an instrument divided by 1.96.

The important notion is the *degree of redundancy* ν. If all unmeasured variables are observable, ν equals the difference between the number of equations and the number of unmeasured variables.

This is a brief statement of the DR problem which is used in industry since early sixties of the past century. The solution proper was described many times in the literature and will not be treated here. Further it is supposed that the reader is acquainted with basics of DR. For those not familiar with the DR technology, there is the *Balancing and Data Reconciliation Minibook* [15] available free on the Internet. DR is also mentioned in [13].

Further it is also supposed that there exists a software which is capable of doing all necessary DR activities connected with DR – the DR Engine depicted in the next Figure A1.1.

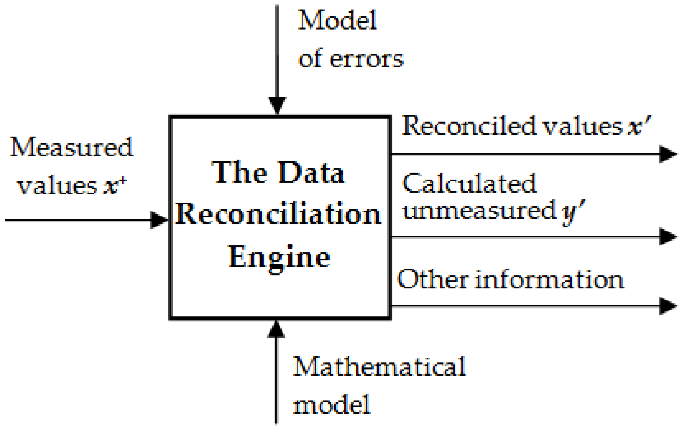


Fig. A1.1: The Data Reconciliation Engine

We can write symbolically

$$\boldsymbol{x'} = \boldsymbol{h_1(x^+)} \tag{A1-6}$$

$$\boldsymbol{y'} = \boldsymbol{h_2(x^+)} \quad , \tag{A1-7}$$

where $\boldsymbol{h_1(x^+)}$ and $\boldsymbol{h_2(x^+)}$ are functions of measured values. By the *"other information"* in the Fig. A1.1 we mean other detailed results needed for data analysis described later (mostly covariance matrices of $\boldsymbol{x'}$ and $\boldsymbol{y'}$).

The covariance matrices contain the all information about uncertainties of results. On their diagonals are squares of standard deviations (sigmas). The uncertainty is calculated as 1.96 times sigma. The uncertainties are in the RECON output reports denoted as "maximum errors".

Appendix 2: NPP data archive

In the next Fig. A2.1 is the P&I diagram of the NSSS:

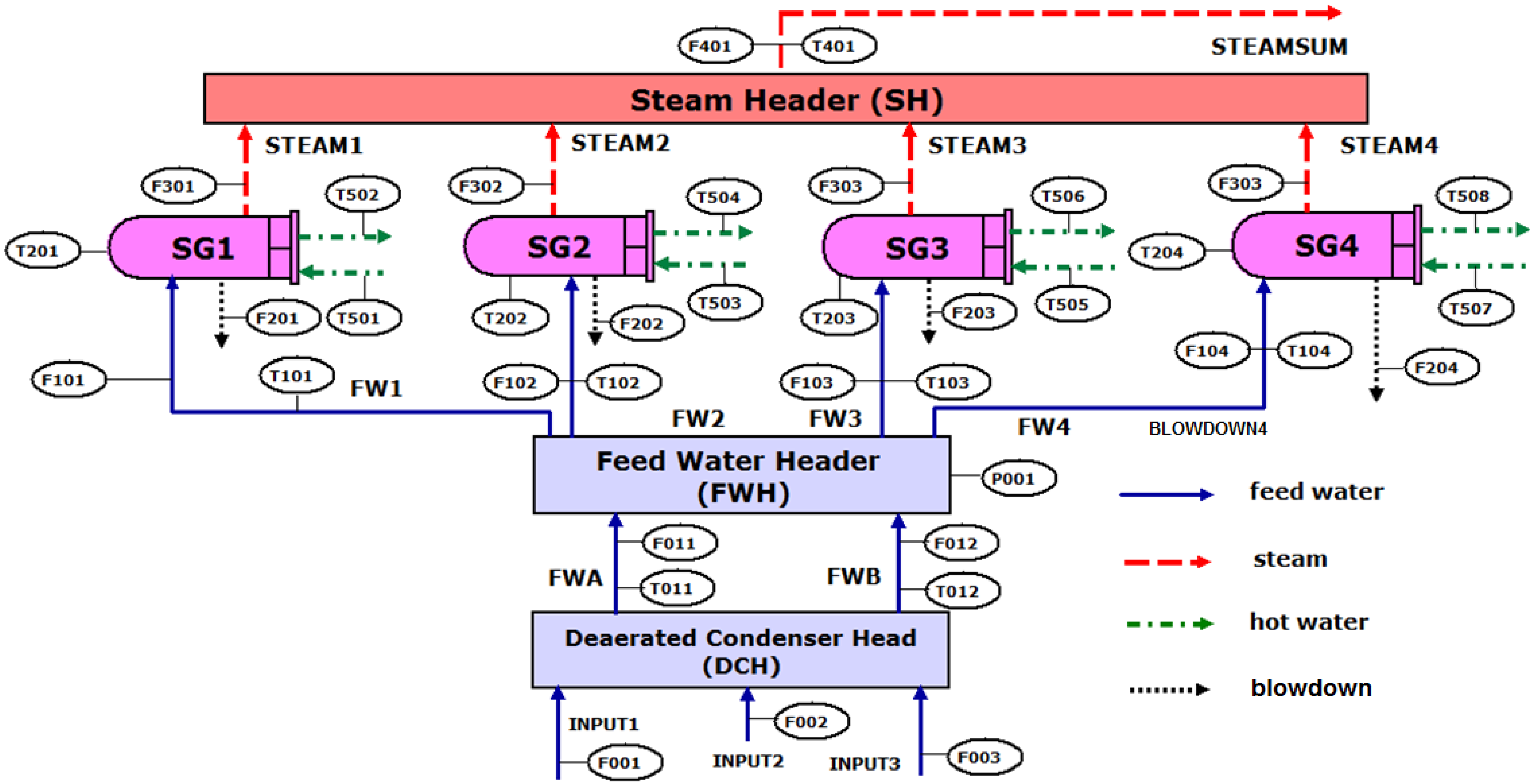


Fig. A2.1: P&I diagram. F – flow measurement, T – temperature measurement, P – pressure measurement

The directly measured variables shown in the Fig. A2-1 are accompanied by 3 other variables which are treated as measured with some uncertainty:

EE	total electric energy input measured at the containment balance envelope
LOSS	heat loss of the containment (constant)
SGsteam	wetness of the steam leaving a steam generator. This is a constant 0.25 % with the uncertainty 0.1 (a result of the NPP performance test)

A2.1 Processing of one data set

The summary of the one set of data (1 hour average) follows. Important are the uncertainties (column Max. error) given with sample values:

Task: NRPOWER4SG (NPP with 4 steam generators)
Input Data

Balance: [10.07.2014 23:00; 10.07.2014 24:00)

M A T E R I A L   S T R E A M S

ID	Type	Value	Max.error	
FW1	M	368.4900	1.0000%	KG/S
FW2	M	381.4650	1.0000%	KG/S
FW3	M	403.9550	1.0000%	KG/S
FW4	M	394.7860	1.0000%	KG/S
FWA	M	772.2000	1.0000%	KG/S
FWB	M	764.7640	1.0000%	KG/S
INPUT1	M	760.6770	1.5000%	KG/S
INPUT2	F	0.000E+0		KG/S
INPUT3	M	788.4845	1.5000%	KG/S
PURGE1	M	3.5673	5.0000%	KG/S
PURGE2	M	3.0647	5.0000%	KG/S
PURGE3	M	2.1686	5.0000%	KG/S
PURGE4	M	2.4090	5.0000%	KG/S
STEAM1	M	368.2305	3.0000%	KG/S
STEAM2	M	380.6000	3.0000%	KG/S
STEAM3	M	393.8345	3.0000%	KG/S
STEAM4	M	395.1320	3.0000%	KG/S
STEAMSUM	M	1532.0500	3.0000%	KG/S

E N E R G Y   S T R E A M S   [MW]

ID	Type	Value	Max.error
EE	M	5.1807	2.0000%
LOSS	M	1.5960	20.0000%
QNR	N	2820.4379	
QSG1	N	703.4922	
QSG2	N	707.8885	
QSG3	N	709.5314	
QSG4	N	699.5258	

T E M P E R A T U R E S   [C]

ID	Type	Value	Max.error
FWA	M	220.5000	1.0000
FWB	M	222.0000	1.0000
FWSG1	M	220.8000	1.0000
FWSG2	M	221.6000	1.0000
FWSG3	M	220.4000	1.0000
FWSG4	M	221.0000	1.0000
SG1	M	259.2000	1.0000

```
SG2         M           258.6000      1.0000
SG3         M           257.0000      1.0000
SG4         M           259.8000      1.0000
steamsum    M           258.6000      1.0000
```

P R E S S U R E S   [MPAG]

```
ID          Type           Value   Max.error
-------------------------------------------
FW          M             4.7260      0.5000%
```

W E T N E S S E S   [%]

```
ID          Type           Value   Max.error
-------------------------------------------
SGsteam     M             0.2500      0.1000
water       F           100.0000
```

Results of this sample data reconciliation are shown next:

```
RECON 11.2.9-Pro  [ChemPlant Technology s.r.o.]
 Task: NRPOWER4SG (NPP with 4 steam generators)

 Balance: [10.07.2014 23:00; 10.07.2014 24:00)
```

I T E R A T I O N S

```
Iter           Qeq            Qx              Qy             Qmin
-----------------------------------------------------------------
START     3.1388E+06
   1      4.4775E+02    3.6992E-01    1.0100E+07     5.9596E+00
   2      1.7052E-03    3.3679E-05    7.9223E+02     5.9569E+00
   3      7.0800E-08    2.3176E-10    1.9236E-04     5.9569E+00

Legend:

Qeq   mean residual of equations
Qx    mean increment of measured variables in iteration
Qy    mean increment of non-measured variables in iteration
Qmin  least-square function
```

G L O B A L   D A T A

```
Number of nodes                                      8
Number of heat nodes                                 7
Number of streams                                   25
Number of energy streams                             7
Number of components                                 1
Number of temperatures                              11
Number of pressures                                  1

Number of measured variables                        32
Number of adjusted variables                        30
Number of non-measured variables                     5
Number of observed variables                         5
Number of non-observed variables                     0
Number of free variables                             0
Number of equations                                 14
Number of independent equations                     14
Number of user-defined equations                     0

Degree of redundancy                                 9

Mean residue of equations                   7.0800E-08
Qmin                                        5.9569E+00
Qcrit                                       1.6900E+01
Status (Qmin/Qcrit)                           0.352478
```

S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
FW1	MC	368.490	368.093	3.331	KG/S
FW2	MC	381.465	380.908	3.436	KG/S
FW3	MC	403.955	402.251	3.606	KG/S
FW4	MC	394.786	394.225	3.543	KG/S
FWA	MC	772.200	776.509	6.140	KG/S
FWB	MC	764.764	768.968	6.115	KG/S
INPUT1	MC	760.677	758.901	8.654	KG/S
INPUT2	F	0.00E+0	0.00E+0		KG/S
INPUT3	MC	788.485	786.576	8.720	KG/S
PURGE1	MC	3.567	3.566	0.178	KG/S
PURGE2	MC	3.065	3.064	0.153	KG/S
PURGE3	MC	2.169	2.169	0.108	KG/S
PURGE4	MC	2.409	2.409	0.120	KG/S
STEAM1	MC	368.231	364.526	3.335	KG/S
STEAM2	MC	380.600	377.844	3.438	KG/S
STEAM3	MC	393.834	400.082	3.608	KG/S
STEAM4	MC	395.132	391.816	3.544	KG/S
STEAMSUM	MC	1532.050	1534.269	5.670	KG/S

E N E R G Y   S T R E A M S

Name	Type	Inp.value	Rec.value	Abs.error	
EE	MN	5.181	5.181	0.104	MW
LOSS	MN	1.596	1.596	0.319	MW
QNR	NO	2820.438	2827.722	11.156	MW
QSG1	NO	703.492	673.009	6.393	MW
QSG2	NO	707.889	696.183	6.582	MW
QSG3	NO	709.531	739.474	6.927	MW
QSG4	NO	699.526	722.641	6.792	MW

T E M P E R A T U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FWA	MC	220.500	220.298	0.815	C
FWB	MC	222.000	221.800	0.818	C
FWSG1	MC	220.800	220.896	0.961	C
FWSG2	MC	221.600	221.700	0.959	C
FWSG3	MC	220.400	220.506	0.954	C
FWSG4	MC	221.000	221.103	0.956	C
SG1	MC	259.200	259.188	0.976	C
SG2	MC	258.600	258.588	0.976	C
SG3	MC	257.000	256.989	0.977	C
SG4	MC	259.800	259.787	0.970	C
steamsum	MC	258.600	258.647	0.447	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
FW	MC	4.726	4.726	0.024	MPAG

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
SGsteam	MC	0.250	0.250	0.100	%
water	F	100.000	100.000		%

End of results

Calculations lasted 00:00:0.042

A2.2 Continuous data processing

This Section is about processing of long term data by the program RECON. RECON can process data from more sources in one task (process historians, LIMS, relational databases, Excel files, …). In the following case data are stored in one sheet of an Excel file.

The process data are stored in the file HISTORY.XLS attached at this report. A part of this file is shown below:

	A	B	C	D	E	F	G	H
1	TIME	F001	F002	F003	F011	F012	F101	F102
2	1.7.2014 0:00	760.7905	0	789.6195	773.916	766.48	369.009	382.7625
3	1.7.2014 1:00	760.677	0	789.8465	773.916	766.48	369.009	388.6445
4	1.7.2014 2:00	762.3795	0	791.549	775.632	768.196	369.6145	389.942
5	1.7.2014 3:00	762.8335	0	792.003	776.204	768.768	369.874	383.8005
6	1.7.2014 4:00	762.039	0	791.549	775.632	768.196	369.701	383.714
7	1.7.2014 5:00	762.266	0	792.1165	776.204	768.768	370.9985	384.752
8	1.7.2014 6:00	762.3795	0	792.457	776.776	768.768	372.296	385.8765
9	1.7.2014 7:00	761.585	0	791.322	775.632	768.196	371.777	385.3575
10	1.7.2014 8:00	760.677	0	790.0735	773.916	767.052	371.258	384.752
11	1.7.2014 9:00	763.7415	0	792.23	776.204	768.768	372.2095	385.79
12	1.7.2014 10:00	765.898	0	792.7975	777.348	769.912	372.5555	386.0495
13	1.7.2014 11:00	768.168	0	793.138	777.92	769.912	372.7285	386.309

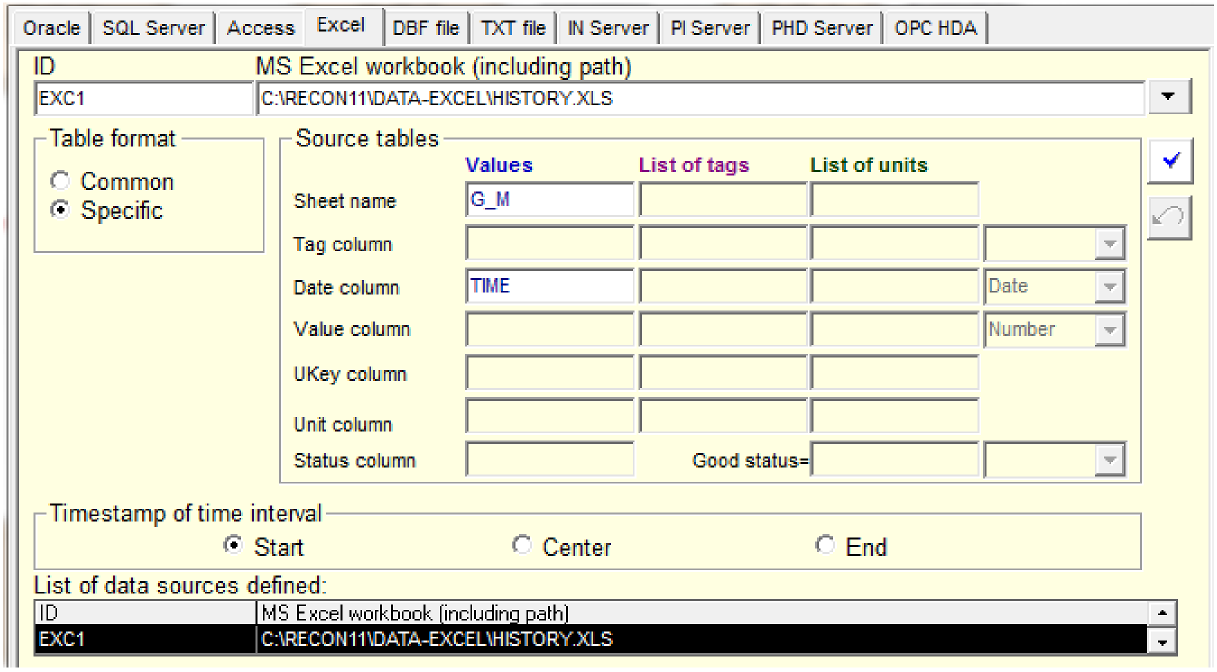
G_M List2 List3

The data format is as follows:

1. The first column contains the TIME information. For example, the time 1.7.2014 0:00 means the hourly average between 1.7.2014 0:00 and 1.7.2014 1:00
2. The first line contains tag names of variables
3. For the definition of this data structure are needed: Name of the time column (TIME in this case), the name of the Excel file (HISTORY.XLS in this case) and the name of the Excel sheet (G_M in this case).

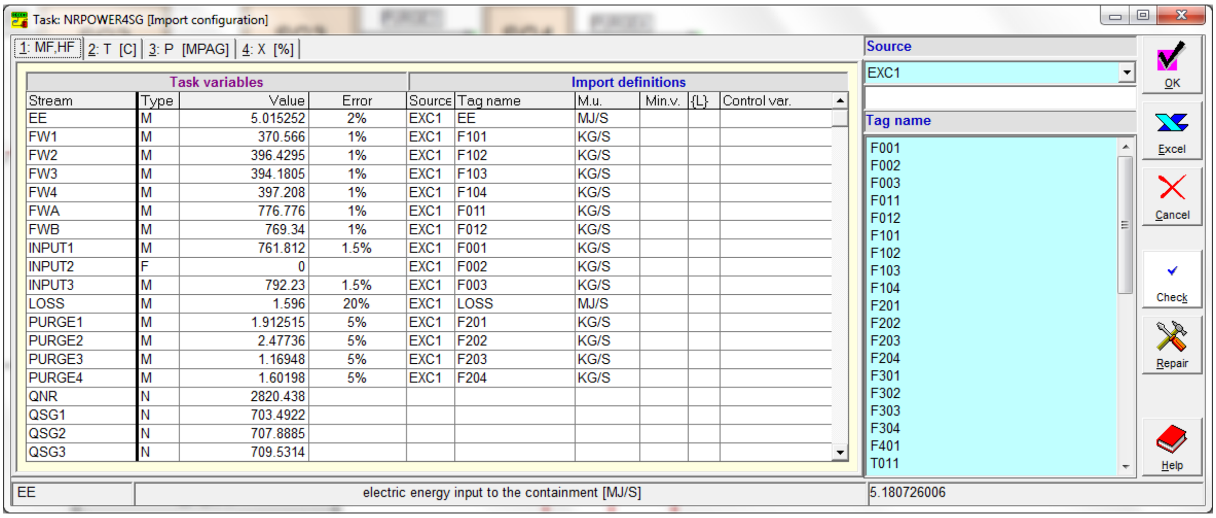
The data import is defined in several steps:

1. Definition of the data source on the following panel:



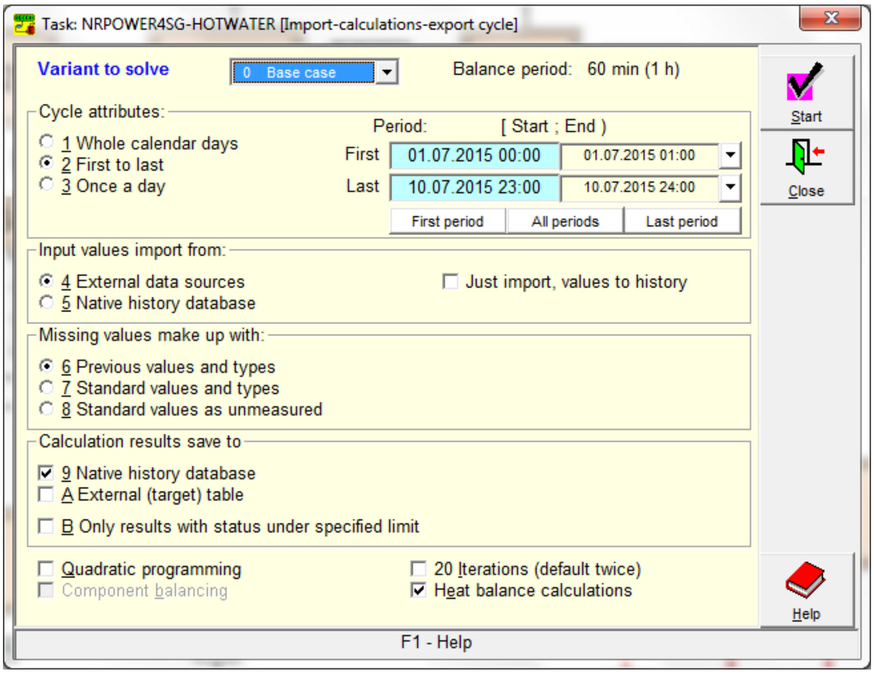
This panel defines the Excel file as a data source (EXC1), the sheet name and the time column name.

2. Configuration of the import is on the next panel:



Here the individual process variables are linked with the tag names in the HISTORY.XLS file.

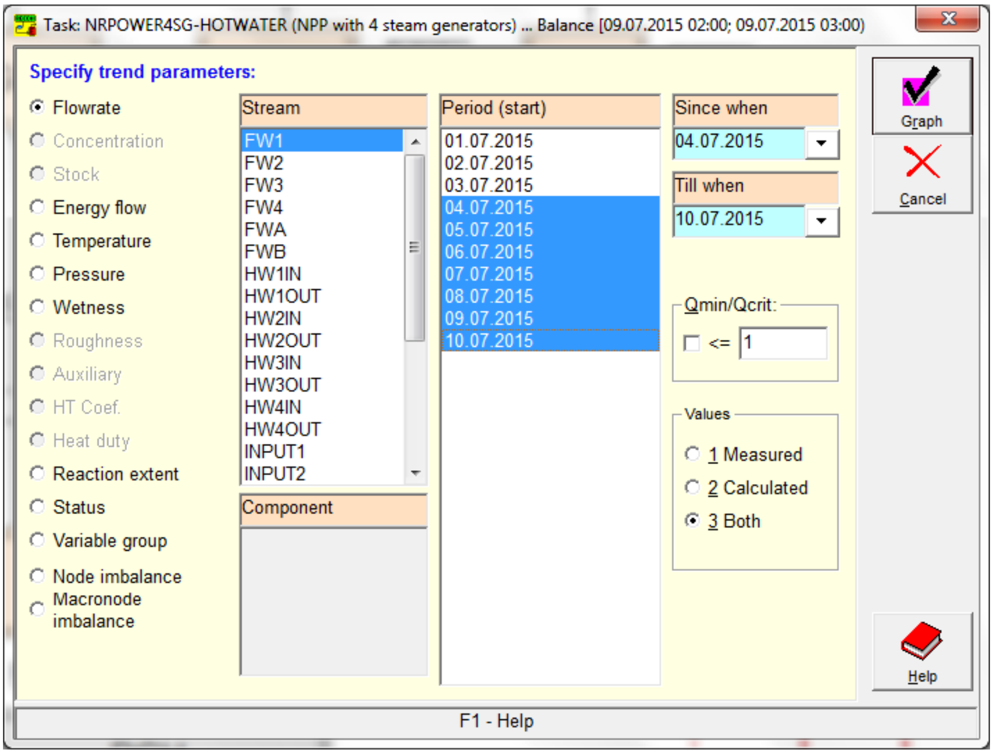
After this configuration data can be processed with the aid of the following panel:



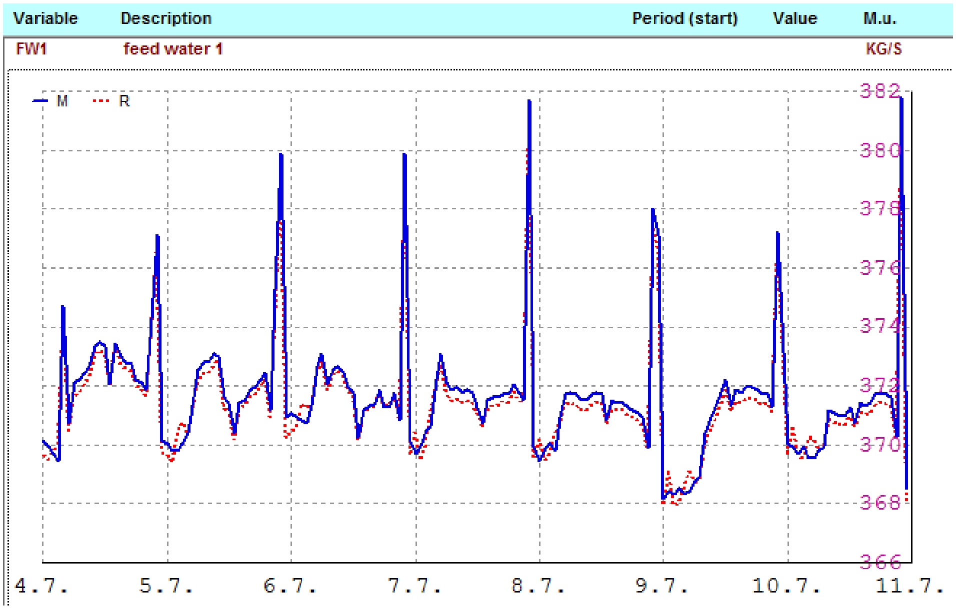
In general, data can be processed automatically for the selected time interval. In this case the input values are imported from the external data source (Excel file) and results are saved to the RECON's native database. It is also possible (in a different panel) to select just one data set for the interactive analysis of some special problems connected with data.

A2.3 Viewing and analyzing results

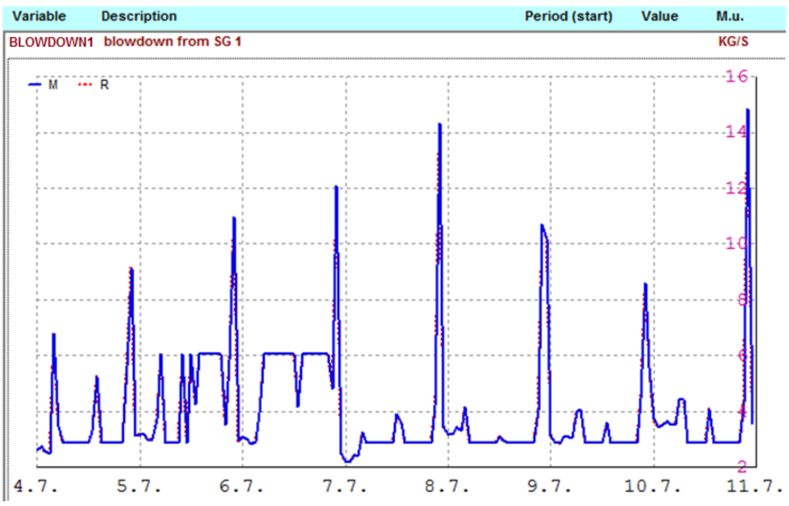
Trends of measured and reconciled variables are available in the RECON's trend manager. Trends are configured on the following panel:



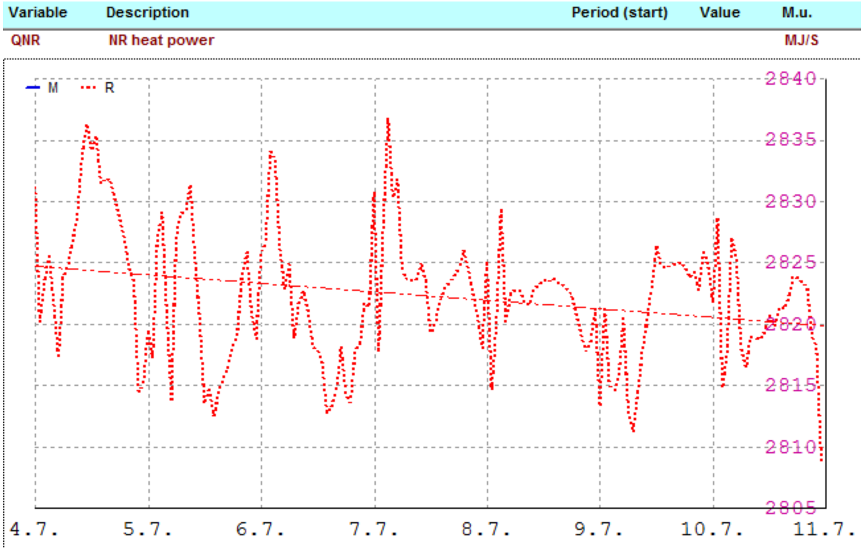
Variables can be selected from the list or a user can create his groups of variables. Some examples follow:



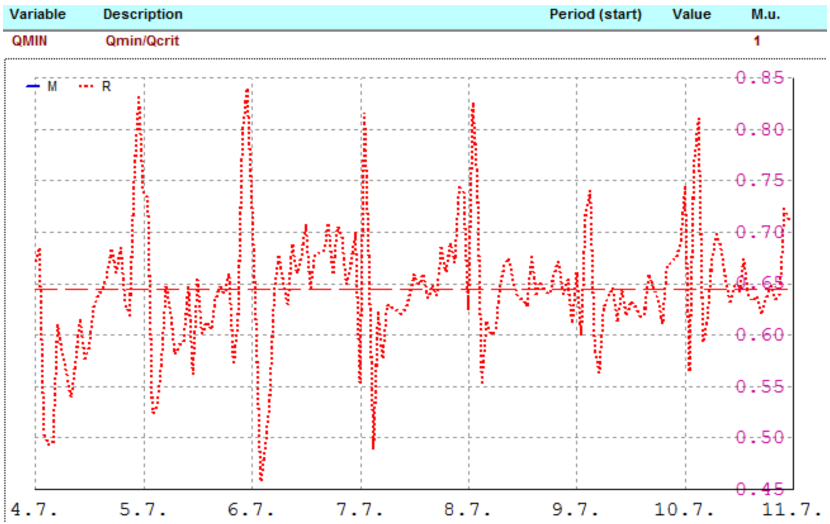
Trend of the FW1 flow. The blue line are the measured values, the red line are reconciled values. Peaks are caused by the periodic purge done usually once a day on the basis of the steam and condensate analyses. See the next figure:



In the next figure is the trend of the NR power. The dot-dashed straight line represents the linear regression showing that the NR power decays a little bit in time.



The next figure shows a trend of the Status of data quality (Status = Qmin/Qcrit, should be < 1). The dashed line is the mean value. It can be seen that in the time interval selected no gross error was encountered. The average value of the Status is about 0.64. Some peaks in the Status trend correlates with periodic purges which evokes the increase of the relatively cold feed water into steam generators with the sequential disruption of the stationary state. Anyway, these relatively small disturbances do not influence the Status significantly.



Let's now compare Status values with their theoretical mean value.

Qmin has the χ^2 distribution with ν degrees of freedom. The mean value of this distribution equals ν. In our case $\nu = 9$ and the critical value (95 percentile) is 16.919. The mean value of the Status then should be 9/16.919 = 0.53. We can see that the average Status value is not far from the expected vale.