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Improving Pressurized Water Reactor Performance Through Instrumentation: Application Case of Reducing Uncertainties on Thermal Power

Technical Report

Improving Pressurized Water Reactor Performance Through Instrumentation: Application Case of Reducing Uncertainties on Thermal Power

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REPORT SUMMARY

Reducing the cost of producing electricity is a major concern for nuclear power plants. One way to reduce cost is to improve plant performance by reducing uncertainty in safety margins. Improved instrumentation and more accurate analytical computations have potential to reduce these uncertainties, allowing, for example, increases in thermal power output. It is important to determine where improved instrumentation and computations can be used to obtain maximum benefits in relation to cost. An approach that assesses the benefits of improvements is described.

Background
The electric power industry is currently undergoing deregulation in many countries, including the United States. More emphasis is being put on cost-effective production of electricity by nuclear power plants to compete against other power generation sources. One way to reduce the cost of electricity production is to increase plant productivity by improving instrumentation and analytical calculations to reduce uncertainties that lead to less than optimal operation. Utilities are very interested in this approach since it is a way to produce more electricity without having to build new generation facilities.

Objectives
- To develop a systematic approach for assessing the benefits of improvements in instrumentation and analytical calculations for plant performance.
- To test the methodology for improvements to reduce the uncertainty of the calculated plant thermal power.

Approach
The project team developed a methodology to identify components contributing to the uncertainty in determining an operating function. This method first breaks up the uncertainty in the operating function into its various components. It then prioritizes these uncertainty components based on their importance to the overall uncertainty. Next, technical solutions to reduce the uncertainty components are determined. Finally, the cost and benefits of the solution are established. The project team tried out the methodology on the operating function of thermal power using values from the French 1450 MWe plant to demonstrate the results.

Results

This report describes a methodology for assessing benefits from improvements in instrumentation and computational methods. The methodology was used to look at different approaches to improve performance by reducing uncertainties in determining thermal power. It identified various components of the uncertainty to determine the importance of each. Solutions to address these uncertainty components were analyzed and the cost/benefits were established. This makes it very easy to identify which solutions achieve the best results. For example, improving flow rate measurement has the largest payback for thermal power. Improving differential pressure measurement and steam generator inlet temperature measurement both have early returns on investment.

EPRI Perspective

When nuclear power plants were licensed, safety margins were established to assure safe production of electricity by taking into account uncertainties. Many of these margins included uncertainties due to inaccuracy of instrumentation measurements of process variables and/or inaccuracy in calculations, such as for thermal power. These safety margins reduced the plant's operating power level to keep it within its licensed value. Reducing these uncertainties through improved instrumentation or computations is a cost-effective way to increase a plant's power output. The methodology described here shows how to determine components of uncertainty and consequences of improvements to establish the most cost-effective approaches for increasing performance.

Keywords

Instrumentation and control systems
Performance improvements
Instrumentation improvements
Thermal power
Pressurized water reactors
Uncertainty reduction

NOTATIONS

d	=	diameter of flowmeter throat [m]
ε	=	expansion factor
D	=	diameter of pipe [m]
H	=	enthalpy [kJ/kg]
h'	=	enthalpy with respect to saturation curve (water side), X = 1 [kJ/kg]
h''	=	enthalpy with respect to saturation curve (steam side), X = 0 [kJ/kg]
P	=	pressure [bar]
ΔP	=	differential pressure [bar]
Q	=	mass flow [kg/s]
s	=	estimate of standard deviation of a random population
e_X	=	expanded uncertainty of variable X
${}^{A}U_X$	=	type A expanded uncertainty of variable X
${}^{B}U_X$	=	type B expanded uncertainty of variable X
T	=	temperature [°C]
W	=	power [MW]
X	=	water content
α	=	discharge coefficient
β	=	ratio of diameter of flowmeter throat to diameter of pipe
ρ	=	density [kg/m^3]
μ	=	dynamic viscosity
$\bar{x}$	=	arithmetic mean of n_X measurements of variable X
t_0	=	temperature at which diameter of flowmeter throat was measured
t'_0	=	temperature at which diameter of pipe was measured
γ	=	expansion factor
$W_{th,reactor}$	=	thermal power of nuclear reactor
Pn	=	nominal power
EU	=	expanded uncertainty
Indices		
EE	=	steam generator inlet feedwater
SV	=	steam generator outlet steam-water mixture
SG	=	steam generator
P	=	steam generator blowdown
sat	=	thermodynamic properties of water at saturation
Exponents		
i	=	feedwater train i

EXECUTIVE SUMMARY

The electric power industry in the United States and many other countries is undergoing deregulation. Deregulation of the electric utilities is causing a major change in the way business is done in the electric utility industry. In order to compete against other generation sources, more emphasis is being put on cost-effective production of electricity by nuclear power plants. Reducing the cost of producing electricity is becoming the major concern for survival of the power plant. One way to improve plant productivity is to reduce uncertainty margins that were introduced in the past and are larger than necessary. Improved instrumentation and more accurate analytical computations have the potential to reduce these uncertainties. However, it is important to determine where improved instrumentation and computations can be used to maximize the benefits compared to the cost. To increase competitiveness, it is important to take advantage of the opportunities offered by modern technology to improve plant performance in both deregulated and regulated environments.

This report describes work that has been done as part of the study "Improving Plant Operation through Instrumentation". This study aims to identify potential performance improvements associated with instrumentation choices.

One part of this study is to develop a methodology that will allow the assessment of the benefits of improvements in instrumentation from a functional and economic standpoint. This methodology will be illustrated by looking for potential improvements in a specific area of PWR plants. Therefore, this report focuses on an analysis of the different approaches to improve plant performance in the specific field of the operating function of measurement of reactor thermal power via thermal balance of the secondary system for a 1450 MWe PWR plant. This same methodology could be applied to the analysis of other operating functions in other PWR plants.

The general methodology developed for this work has three steps :

- First is the calculation of the reactor thermal power and its associated uncertainty.
- Second, an analysis of the potential for improvement of the instrumentation and its impact on the measurement of reactor thermal power is performed. This analysis is made for the main components of operating function.
- Finally, the economic study of the solutions given in the previous analysis is developed.

The main components of the operating function uncertainty are: discharge coefficient of flow rate orifice plate, differential pressure measurement used for measuring flow rate and steam generator inlet temperature measurement. For each of these 3 components, a solution with its technical and economic aspects is presented. A payback period of approximately one year is the goal in all cases.

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1 INTRODUCTION

The electric power industry in the United States and many other countries is undergoing deregulation. Deregulation of the electric utilities is causing a major change in the way business is done in the electric utility industry. In order to compete against other generation sources, more emphasis is being put on cost-effective production of electricity by nuclear power plants. Reducing the cost of producing electricity is becoming the major concern for survival of the power plant. One way to improve plant productivity is to reduce uncertainty margins that were introduced in the past and are larger than necessary. Improved instrumentation and computations have the potential to reduce these uncertainties. However, it is important to determine where improved instrumentation and more accurate analytic computations can be used to maximize the benefits compared to the cost. To increase competitiveness, it is important to take advantage of the opportunities offered by modern technology to improve plant performance in both deregulated and regulated environments.

Instrumentation (sensors and data processing channels) in nuclear power plants is the primary element providing an image of the physical process. If the image is blurred or biased, the controls of the process are also biased because they use this image to determine actuation on the physical process. With this in mind, the design requirements of instrumentation and controls, as well as safety systems, in nuclear power plants made provisions for significant margins due to the uncertainties in the measured values and analyses.

Examples of some of these are described here:

- Safety margins were added to take into account the accuracy of available measurement channels. Safety margins are calculated with a conservative hypothesis. The measurements are taken in the unfavorable case (uncertainty is deducted from mean value). Consequently, a reduction of uncertainty would increase the mean value for a given criteria and associated safety margin.
- Conservatism due to computation capabilities at the time limited the estimation of accuracy of some of the most difficult physical parameters to be measured. Similarly to the description in the previous paragraph, these uncertainties intervene in the control of the process. The estimate of these uncertainties can undoubtedly be improved by the current means of simulation, making it possible to more accurately reproduce the real conditions.

The above observations indicate that there is a significant potential to improve the competitiveness of most nuclear plants by assessing the potential of operation improvement through improvements of instrumentation and computations.

For example, in the case of EDF's 1300 MWe units, the number of straight lengths on the upstream side of the flow orifice plate was not sufficient with regard to the standard (there was only 26.6 D on the upstream side, rather than 28 D as recommended by the standard). An additional uncertainty for the discharge coefficient should have been taken into account in the calculation of uncertainty of thermal power. Due to this, uncertainty with respect to the discharge coefficient would have been arithmetically increased by 0.5%. This would have increased the uncertainty with respect to reactor thermal power by 8.8 MWth. This uncertainty is taken into account in the control of core. In the case of operating with the maximum reactor thermal power, an increase of the flow rate measurement uncertainty leads a production loss of 2.9 MW in each of the 16 units. An experimental study using a full-scale mockup, and analysis via digital simulation was directed by EDF. This study showed the flow rate measurement with 26.6 D in straight lengths was as precise as that with 28 D. The additional uncertainty was therefore not necessary to be taken into account, thus avoiding for EDF a loss of FF 1.5 million per unit.

1.1 Objective : improving plant operation through value analysis instrumentation

This report describes work that has been done as part of the study "Improving Plant Operation through Instrumentation". This study aims to identify potential performance improvements associated with instrumentation choices.

One part of this study is to develop a methodology that will allow the assessment of the benefits of improvements in instrumentation from both a functional and economic standpoint. This methodology will be illustrated by looking for potential improvements in a specific area of PWR plants. If we define as the « operating function » any function that contributes to the production of megawatts (MWs) by the plant. Such a operating function may correspond to the control mechanism of thermal power in respect to the frequency on the network or the regulation level of steam generator. Therefore, this report focuses on an analysis of the different approaches to improve plant performance in the specific field of the operating function of the measurement of reactor thermal power via the thermal balance of the secondary system for a 1450 MWe PWR plant. This same methodology could be applied to the analysis of other operating functions in other PWR plants.

The principle of this methodology is based on the theory of « Value's Analysis ». The « Value's Analysis » is a process that is done to survey, to characterize, to arrange, to determine hierarchy, and to value the functions. This methodology consists of four stages. The first stage breaks up, in a systematic way, the operating function compared to all uncertainties of measurements. The second stage prioritizes the causes of the uncertainties having the most impact for the function of exploitation. The third stage determines the technical possibilities for improvements associated with the most significant causes. The fourth stage evaluates the economic and benefits of the technical solutions to reduce the uncertainties.

1.2 Background : secondary enthalpy balance is an accurate means to measure reactor power

The measurement of reactor thermal power by enthalpy balance on the secondary side serves as a reference for the periodic calibration of the continuous measurement of instantaneous power via in-core instrumentation (used for reactor control). High precision of this reference increases the output of the PWR as the instantaneous reactor power is well-known and margins for uncertainty can be reduced. Indeed, uncertainty on the thermal power of the reactor is deduced from the thermal power of design to obtain the maximum thermal power of production. The fact of reducing uncertainty on the reactor thermal power makes it possible to be below the maximum design value with a degree of confidence of 95% according to assumptions' described in the following paragraphs. There is no known method which enables direct and precise measurement of reactor thermal power. However, the total power supplied at the secondary side of the steam generators is measured with a high level of precision by means of an enthalpy balance. Then the reactor thermal power can be calculated with high accuracy from the total power supplied at the secondary side of the steam generators by adding the contributions of the primary circuit and their associated uncertainties.

1.3 Methodology adopted for this study

The general methodology developed for this work has three steps.

First is the calculation of the reactor thermal power and its associated uncertainty which will be explained in detail in chapter 2 using the case of a 1450 MWe typical French unit for numerical applications.

Second, an analysis of the potential for improvement of the instrumentation and its impact on the measurement of reactor thermal power is carried out in chapter 3. This analysis is made for the main components of operating functions.

Finally the economic study of the solutions given in the previous analysis is explained in chapter 4.

2
CALCULATION OF REACTOR THERMAL POWER AND OF ITS ASSOCIATED UNCERTAINTY

The calculation of the reactor thermal power along with its associated uncertainties will be described in this chapter.

These calculations consist of the following :

1. The calculation of the reactor thermal power along with the fundamental values needed to perform this calculation will be shown in section 2.1.

2. The calculation of the links between the reactor thermal power uncertainty and the uncertainties of fundamental values, are demonstrated in section 2.3.

3. The calculation needed to obtain the value of the reactor power from measurements and the main factors in the uncertainties of the measurements are also identified as described in section 2.3.

2.1 Measurement of reactor thermal power

There is no known method which enables direct and precise measurement of reactor thermal power. However, the total power supplied at the secondary side of the steam generators is measured with a high level of precision, usually less than 0.5% by means of an enthalpy balance.

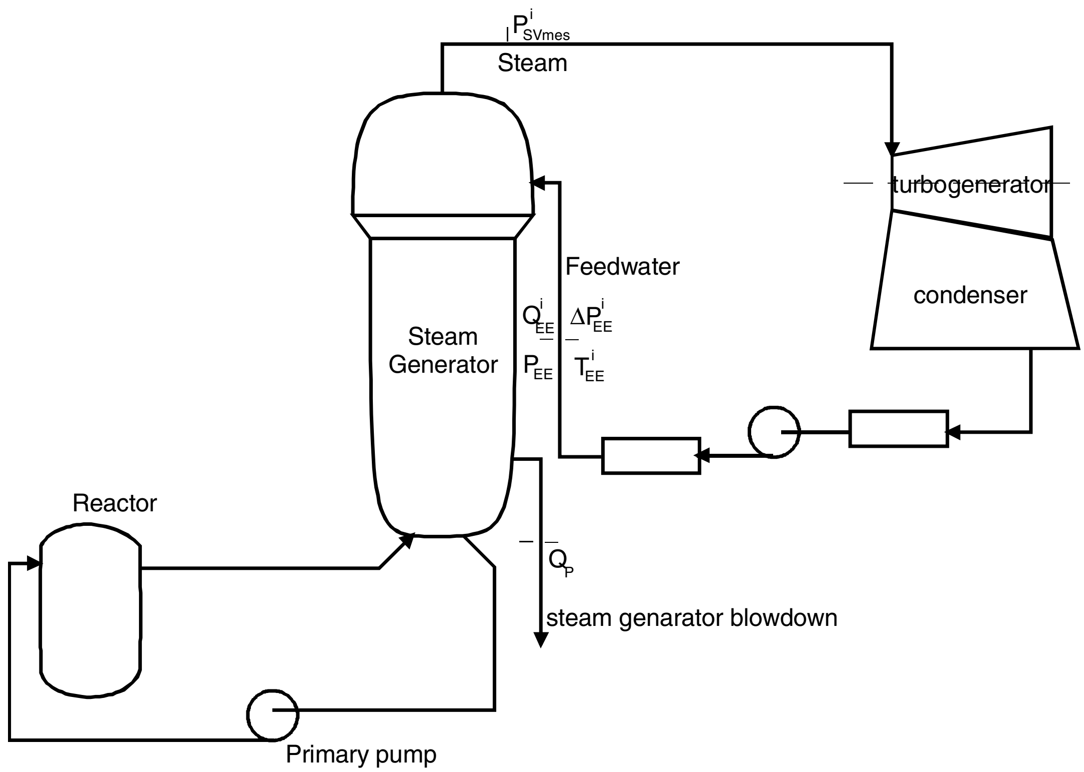

Figure 2-1
Plant system with measured quantities for heat balance.

The enthalpy balance calculation is based on measurements of feedwater, steam-flow from the steam generator, and steam generator blowdown rate. The measurements are typically made during a 20 minute time interval once a week in a EDF 1450 MWe plant. The measured values are checked compared to the expected values for 100% of power. The stability of the plant is checked on measurements of feedwater flow. If controls of ranges and stability are valid, the processing is carried out to calculate the thermal power of the steam generators and of the reactor with their uncertainties. If the difference on the reactor thermal power between the measurement by enthalpy balance on the secondary and the in-core measurement is higher than the uncertainty to the measurement by enthalpy balance on the secondary side, the in-core measuring equipment is readjusted.

The reactor thermal power is calculated from the total power supplied at the secondary side of the steam generators by applying the following equation:

$$W_{th,reactor} = W_{th,SG} - W_{th,primarysysteminput} \quad \textbf{Eq. 2-1}$$

where $W_{th,reactor}$ = thermal power of reactor

$W_{th,SG}$ = thermal power of steam generators

$W_{th,primarysysteminput}$ = thermal power from primary pump which is fixed at 20 MW for 1450 MWe units.

The primary input due to primary pumps is fixed at this value (20 MW) based on what was determined experimentally during acceptance tests of the steam generators.

For all of the steam generators of the PWR, the total power supplied at the secondary side of the steam generators is given by:

$$W_{th,SG} = \sum_{i=1}^{n_{loop}} \left[Q^i_{EE} \left(H^i_{SV} - H^i_{EE} \right) - \frac{Q_P}{n_{loop}} \times \left(H^i_{SV} - H^i_P \right) \right] \quad \textbf{Eq. 2-2}$$

where: n_{loop} = Number of loops (4 for 1450 MWe units)

Q^i_{EE} = Feedwater flow rate (cf. A.1.2.1)

Q_P = Steam generator blowdown flow rate (cf. A.1.2.2)

H^i_{EE} = Feedwater enthalpy at the steam generator inlet (cf. A.1.2.3)

H^i_{SV} = Steam generator outlet mixture enthalpy (cf. A.1.2.4)

H^i_P = Steam generator blowdown enthalpy (cf. A.1.2.5)

The calculation of the total reactor thermal power is given in more detail in Appendix A.1

2.2 Input data

As explained in Appendix A.1, the input data required to calculate the thermal power of the PWR are grouped into two categories. They are measured data and PWR unit data.

Data measured for a thermal balance calculation:

P^i_{SVmes} = measurement of absolute steam pressure at steam generator outlet

P_{EE} = measurement of absolute pressure of feedwater

T^i_{EE} = measurement of feedwater temperature

Q^i_{EE} = measurement of feedwater flow rate

Q_P = measurement of steam generator blowdown flow rate

Unit data:

ΔP^{i}_{SV} = pressure loss between instrument tap and steam dome outlet

X^{i}_{SV} = water content of steam generator outlet mixture

$Q^{i}_{SV_0}$ = steam flow at measurement of ΔP^{i}_{SV}

2.3 Uncertainty with respect to reactor thermal power

Uncertainty is a parameter associated with the result of a measurement, that characterizes the dispersion of the values which could reasonably be allotted to the measured data.

2.3.1 Definition of expanded uncertainties (EU)

The uncertainty or Expanded Uncertainty [4] (noted as EU hereafter) with respect to reactor thermal power defines an interval around the value of reactor thermal power for a given confidence level. At 95% confidence level, the expanded uncertainty is equal to twice the composite standard uncertainty on the assumptions of a Gaussian distribution. The composite standard uncertainty is the uncertainty with respect to the result obtained on the basis of the combination of values for other variables expressed in the form of a standard deviation. The other variables are used for the calculation of the value of reactor thermal power.

This expanded uncertainty is made up of a number of components, which can be grouped into two categories which are defined according to the type of data, and, ; result in differences in the method used to estimate the numerical value of the uncertainty.

- Type A, this data is continuously measured which allows uncertainty to be evaluated by using statistical methods on a given population of n-times repetition of the same piece of measurement.
- Type B, this data is not continuously measured, consequently uncertainty is evaluated by using other methods than for the type A uncertainty.

These categories are recommended by standards on the « calculation of measurement uncertainty ».

When a value Y is a function of other values (X_1, X_2,...., X_N) defined by a given functional relationship Y= f(X_1, X_2,..., X_N), the uncertainty (independent of its type) with respect to Y is given as a function of the U_{Xi} (i=1 to N) by the following equation:

$$U_Y^2 = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial Xi} \right)^2 U_{Xi}^2 \right) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial Xi} \frac{\partial f}{\partial Xj} U_{Xi} U_{Xj} \rho_{ij}$$

with U_Y = the uncertainty with respect to Y

U_{Xi} = the uncertainty with respect to Xi (i=1 to N)

$\frac{\partial f}{\partial Xi}$ = the partial derivative by Xi with respect to Y

ρ_{ij} = the correlation factor between U_{Xi} and U_{Xj}

Whether the different elementary uncertainties are either completely uncorrelated or completely correlated (ρ_{ij} = 0 or 1), the resulting uncertainty is either the quadratic sum or the linear sum of these elementary uncertainties taking account of the different partial derivatives which are called hereafter « coefficient of sensitivity ».

2.3.2 Application to the calculation of the uncertainty with respect to reactor thermal power

The main goal of the calculations given in Appendix section A.2 (Equations A-7 to A-16) is to determine the relations (especially coefficient of sensitivity, cf. Equations A-17 to A-28) between the expanded uncertainty with respect to reactor thermal power and the different expanded uncertainties (calculated in Appendix section A.3) with respect to the input data given in section 2.3. These expanded uncertainties depend themselves on different factors such as the acquisition system, environment, and other factors.

To demonstrate the entire uncertainty calculation, the following example is taken.

The expanded uncertainty with respect to reactor thermal power depends on uncertainties of type A and of type B. Here the uncertainty of type A is related to the temporal fluctuations of flow rate measurement. The uncertainty of type B is related to all elementary uncertainties of measurement, which are related to independent causes, and therefore the total uncertainty is expressed in the form of a quadratic sum of uncertainties of type A and type B.

$$U_{W_{th,reactor}} = \sqrt{{}^{A}U^{2}_{W_{th,reactor}} + {}^{B}U^{2}_{W_{th,reactor}}} \qquad \textbf{Eq. 2-3}$$

with ${}^{A}U^{2}_{W_{th,reactor}}$ = the type A uncertainty with respect to reactor thermal power (calculated in Eq. A-8)

${}^{B}U^{2}_{W_{th,reactor}}$ = the type B uncertainty with respect to reactor thermal power (calculated in Eq. A-9)

This is the starting point of the uncertainty calculation. Next, each term is broken up into the elementary uncertainties of the sensors, and of the measuring equipment. The first decomposition is shown here. The totality of the calculations is given in Appendix Section 2.

From Equation 2-1, the type B expanded uncertainty with respect to reactor thermal power is expressed as:

$$^{B}U_{W_{th,reactor}} = \sqrt{^{B}U^{2}_{W_{th,SG}} + {^{B}U^{2}_{W_{\text{th,primarysysteminput}}}}} \qquad \textbf{Eq. 2-4}$$

The type B expanded uncertainty with respect to calculation of the thermal power of the steam generators is expressed as:

$$^{B}U_{W_{th,SG}} = \sqrt{\sum_{i=1}^{n_{loop}} \left(^{B}U^{2}_{W_{th,SGi}}\right) + {^{B}U^{2}_{W_{th,SGcom}}} + {^{B}U^{2}_{W_{th,SGenv}}}} \qquad \textbf{Eq. 2-5}$$

with $^{B}U^{2}_{W_{th,SGi}}$ = type B EU, associated with the data common to the different loops is (Eq. A-16)

$^{B}U^{2}_{W_{th,SGcom}}$ = the type B EU, associated with the data specific to each loop (Eq. A-15)

$^{B}U^{2}_{W_{th,SGenv}}$ = type B EU, associated with the common environment of the sensors (Eq. A-11)

The whole of these calculations makes it possible with the help of the knowledge of the coefficients of sensitivity to determine the total uncertainty of the thermal calculation of power starting from the whole of elementary uncertainties on each data input.

The expanded uncertainty will be related to the measurement conditions (detector-type, environmental parameters such as external temperature, ...). This will be done for the following kind of values: flow rate value, differential pressure value, absolute pressure value, temperature value.

The calculations and results are detailed in Appendix Section A.3. From this point on, data coming from the instrumentation used in a French typical 1450 MWe are used.

The information provided by the sensors is collected by the real time acquisition software PATERN (developed by EDF and installed in each of its units) via an acquisition network. This acquisition system acquired electrical values associated with measurements and converted them into physical data according to calibration coefficients (pressure, temperature, flow,...). This data is controlled and used for reactor thermal power calculation and its uncertainty.

2.3.3 Quantification for 100% Power level

Appendix Section A.4 describes the results of the calculations described in sections 2.2, 2.3 and 2.4, based on a numerical application at 100% power level for a 1450 MWe French Unit (using some numerical parameters from the Unit).

The numerical results show which fundamental measurement uncertainties are critical for the reactor thermal power uncertainty. For the 100% power case in the 1450 MWe French plant, they are described in the following section and are listed in the following tables.

Uncertainties on the reactor thermal power can be gathered in 3 levels, according to their more or less direct connection with uncertainty on the thermal power.

Uncertainties related directly to uncertainty on the thermal power are:

Table 2-1
Direct uncertainty with respect to reactor thermal power at 100%Pn.

Origin of uncertainty X^i	**Expanded uncertainty** e_{X^i}	**Coefficient of sensitivity** $\frac{\partial W_{th,reactor}}{\partial X^i}$	**Product [MW]**		**Relative fraction [%]** $\frac{\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}{e_{W_{th,reactor}}^2}$
			one SG $e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}$	**all SGs** $\sqrt{\sum_i\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}$	
Random differential pressure variable	1.553 kg/s	1.774	2.756	5.513	10.29
Primary input				2.000	1.35
Common data				0.021	0.00
Common environment of sensors				2.655	2.39
Excluding common environment of sensors, associated with steam generators				15.934	85.97

For uncertainties related to the common data, with the common environment of the sensors and measurements related to the steam generators, uncertainties are broken up again. The relative ratio is given according to total uncertainty on the thermal power engine.

Table 2-2
Second level uncertainty with respect to reactor thermal power at 100% Pn.

Origin of uncertainty X^i	Expanded uncertainty e_{X^i}	Coefficient of sensitivity $\frac{\partial W_{th,reactor}}{\partial X^i}$	Product [MW] one SG $e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}$	Product [MW] all SGs $\sqrt{\sum_i\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}$	Relative fraction [%] $\frac{\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}{e_{W_{th,reactor}}^2}$
Common data					
Steam generator inlet water pressure	0.383 bar	-0.056		0.021	0.00
Blowdown flow rate	0.000 kg/s	-1.480		0.000	0.00
Atmospheric pressure	0.001 bar	-2.985		0.003	0.00
Common environment of sensors					
Temperature effect				1.597	0.86
Standard				1.827	1.13
Acquisition system				1.077	0.39
Excluding common environment of sensors, associated with steam generators					
Steam generator inlet temperature	0.500°C	-2.814	-1.407	2.814	2.68
Steam generator inlet water flow rate	4.416 kg/s	1.774	7.837	15.674	83.18
Steam outlet pressure	0.191 bar	-0.792	-0.151	0.302	0.03
Pressure difference between instrument tap and steam dome	0.300 bar	-0.792	-0.238	0.475	0.08
Steam dome moisture	0.000	-8.937	-0.004	0.007	0.00

Lastly, various uncertainties components uncertainty related to the measurement of feed water flow is given in the following table. The relative ratio is given according to total uncertainty on the reactor thermal power.

Table 2-3
Third level uncertainty with respect to reactor thermal power at 100% Pn.

Origin of uncertainty X^i	Expanded uncertainty e_{X^i}	Coefficient of sensitivity $\frac{\partial W_{th,reactor}}{\partial X^i}$	Product [MW]		Relative fraction [%] $\frac{\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}{e_{W_{th,reactor}}^2}$
			one SG $e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}$	all SGs $\sqrt{\sum_i\left(e_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}$	
Steam generator inlet water flow rate					
Discharge coefficient	0.00513	1493.264	7.665	15.330	79.57
Diameter of device	0.00001 m	9596.9	0.096	0.192	0.01
Diameter of pipe	0.00010 m	1831.4	0.183	0.366	0.05
Steam generator inlet temperature	0.500°C	-0.886	-0.443	0.886	0.27
Steam generator inlet pressure	0.383 bar	0.060	0.023	0.046	0.00
Differential pressure	0.00239 bar	652.512	1.558	3.116	3.29

Final uncertainty at 95% confidence:

$$W_{th,reactor} = 4250 \pm 17.2 \text{ MW } (0.40\ \%)$$

3
ANALYSIS OF POTENTIAL FOR IMPROVEMENT ASSOCIATED WITH INSTRUMENTATION

The calculation described above yielded the main components of uncertainty in the thermal power calculation.

3.1 Summary of main components

The main components with their relative contributions to the total calculated 17.2 MWth uncertainty are shown in descending order of magnitude in the following table. The contribution in MWth on the uncertainty of the reactor thermal power represents the ratio associated with each listed cause of uncertainty. It results from the product of elementary uncertainty due to a cause of uncertainty by the coefficient of sensitivity of the reactor thermal power compared to this cause of uncertainty. Given that the listed causes are independent, the contributions are added up quadratically to obtain total uncertainty (i.e., the square root of the sum of the squares of each contribution yields the total uncertainty) on the reactor thermal power.

Table 3-1
Summary of main components.

Origin of uncertainty	Contribution [MWth]	Relative fraction [%] of the 17.2 MWth
Discharge coefficient	15.33	79.57
Differential pressure	6.33	13.57
Steam generator inlet temperature	2.81	2.68
Primary input	2.00	1.35
Others uncertainties accumulated	2.98	3.00

3.2 Potential improvements

The study above identified the major contribution to uncertainty. In order to reduce the uncertainty which will allow increased power output, a number of solutions were developed and they are described below.

3.2.1 Improvement of flow rate measurement

Solution 1: One way of improving flow rate measurement is to produce a measuring tube (standardized flow orifice plate plus 6 m of machined piping) and to determine experimentally the uncertainty associated with its discharge coefficient. This measuring tube consists of the machined piping (10 D on the upstream side and 4 D on the downstream side) and the flow orifice plate. It is put in to replace the existing pipe at the time of a unit outage. The uncertainty associated with the discharge coefficient of the measuring tube is determined experimentally under flow conditions with a Reynolds number equivalent to the conditions of the desired flow rate measurement, and with the same flow conditions discontinuities. Discontinuities are all the elements which disturb the flow (e.g., elbow, diameter change). As a result, the uncertainty with respect to the discharge coefficient is reduced from 0.72 % to 0.4 % (minimum gain) where 0.72% is uncertainty with respect to the discharge coefficient imposed by flow rate measurement standard and where 0.4% is uncertainty with respect to the discharge coefficient determined experimentally with equivalent flow conditions. This leads to a contribution of 8.54 MWth of the uncertainty with respect to the discharge coefficient, instead of 15.33 MWth by taking account of the sensitivity coefficient of the reactor thermal power compared to this term. The final uncertainty with respect to reactor thermal power becomes 11.6 MWth, instead of 17.2 MWth. This gives the ability to achieve a gain in production of 1.9 MW electric based on cycle efficiency.

The case of feedwater trains in certain American power plants is worth emphasizing here. Measurement of feedwater flow rate displays a relative uncertainty of 1.4 % (venturi-type flow restrictor). Switching to a measuring tube with an orifice plate would almost certainly enable a very considerable gain. The target gain would be to reduce the uncertainty on discharge coefficient by 1%. The cost of a justification package covering experimental and instrumentation aspects would be paid off rapidly (within a year).

3.2.2 Improvement of differential pressure measurement

Solution 2: The dominant uncertainty term associated with the differential pressure transmitter is the random term due to fluctuations in flow rate over time. In the case of quantification at 100 % power, this is taken in the most penalizing case with a standard deviation equal to 4% of the mean differential pressure value. In general, this term is smaller. However, its value is strongly linked with the feedwater control channel. One way of achieving an improvement; therefore, is to have the power plant's Instrumentation and Control (I&C) Department improve this control to reduce fluctuations in flow rate over time. Fluctuation in flow rate over time corresponds in general to the response time of the loop of regulation of the level in the steam generators. While acting on this loop of regulation, it is possible to decrease the temporal fluctuations of the flow.

Solution 3: The stability term which corresponds to the transmitter drift over time can also be improved. Tracking the exact drift of the transmitters can be performed via double-calibration. The double-calibration consists in making a calibration to determine the coefficients of conversion and a second calibration by preserving the old coefficients of conversion in order to determine the drift of the transmitter. A statistical study carried out on 186 transmitters [9] induced that the stability was 1 mbar instead of the value 1.65 mbar given by constructors. The uncertainty with respect to differential pressure, excluding the common environment of the sensors and random uncertainty, falls from 2.39 mbar to 1.99 mbar. This leads to a contribution of 2.6 MWth instead of 3.1 MWth to the uncertainty with respect to reactor thermal power.

3.2.3 Improvement of steam generator inlet temperature measurement

Solution 4: The dominant term in the uncertainty with respect to the temperature measurement is the term associated with the representativeness of the measurement. The term of representativeness corresponds to the difference between the measured temperature and the real temperature of the fluid. This value is equal to 0.5°C with only one sensor, it was determined during the acceptance test. It is also possible to install a second sensor, thereby reducing to 0.35°C the uncertainty with respect to this measurement (cf. figure 3-1). A calibration of this also has to be provided for. This leads to a contribution of 2 MWth instead of 2.8 MWth to the uncertainty with respect to reactor thermal power.

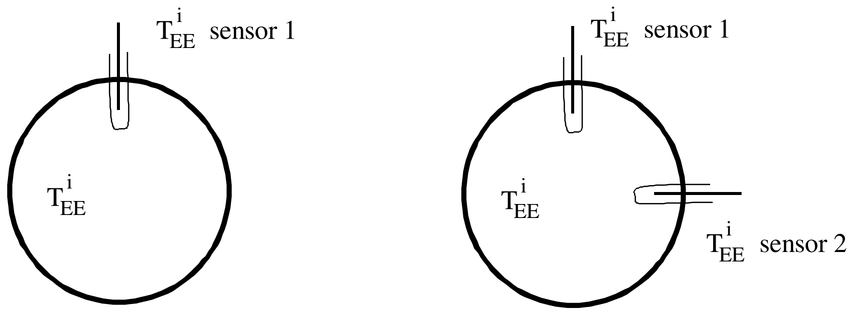

Figure 3-1
Temperature sensor position.

4
ECONOMIC STUDY OF THE IMPROVEMENT

In this chapter the costs of each solution described above are studied. The costs are presented in French Francs (FF) because they are corresponding to the French solution in the case of a French power plant with its organization constraint. The direct conversion to US dollars ($) would hide this aspect. The actual $ to FF conversion is about 1$ to 7.53FF at this time for reference purposes.

4.1 Improvement of flow rate measurement

Solution 1: The cost of the experimental study was FF 200,000. The cost of manufacturing a measuring tube was FF 75,000 [7]. The cost of installation and monitoring at the nuclear plant site was FF 60,000 for each measuring tube. The total cost for a 1450 MWe unit is FF 1,340,000. This may lead to a gain in production of 1.9 MW electric (i.e. FF 1,900,000 for a unit per year). The investment return period is thus about 1 year. The financial gain taken into account is the cost of substitution by other generating capacity, and not the sale cost.

4.2 Improvement of differential pressure measurement

Solution 2: The potential gain for this solution strongly depends on the ability of the Instrumentation & Control Department to reduce the fluctuations, and hence is difficult to evaluate.

Solution 3: Double calibration generates an additional cost of FF 1400 per transmitter per year(4 transmitters for a 1450 MWe PWR Unit). The gain of 0.1 MWth with respect to thermal power uncertainty produces a gain of FF 17,000 per unit per year. The operation is paid off within 4 months, and produces a gain of FF 170,000 over 10 years. This equates to FF 17 million over 20 years for the EDF nuclear power plant fleet (for an investment of FF 5.6 million).

4.3 Improvement of steam generator inlet temperature measurement

Solution 4: The second sensor costs FF 15,000, with a calibration cost of FF 500 per year. The gain of 0.11 MWth with respect to thermal power uncertainty produces a gain of FF 23,000 per unit per year. The cumulative gain over 20 years for 50 units is FF 23 million (for an investment of FF 4.25 million).

4.3.1 Summary of improvements

	Gain in MWth on the contribution to the reactor thermal power uncertainty.	Initial Contribution in thousands of FF	Annual Gain in thousands of FF	Investment return period in year
Solution 1	6.79	1340	1116	1.2
Solution 2	NA	NA	NA	NA
Solution 3	0.52	0	11.4	0
Solution 4	0.81	15	22.5	0.7

5
CONCLUSION

The methodology was applied to the operating function measurement of reactor thermal power. It led to 3 solutions of improvement having each one a time of return on investment of about a one year (the fourth solution was difficult to estimate due to the reason described above). These solutions were presented technically and economically. They represent a significant savings for the plant.

This methodology process can be applied to all other operating function or even to another means of production.

6 REFERENCES

1. Standard AFNOR NF-X 10-102, *Mesure de débit des fluides au moyen de diaphragmes, tuyères et tubes de venturi, (Measure flow of the fluids by means of diaphragms, conduits and tubes of venturi),* December 1970.

2. Standard NF ISO 5167-1, *Mesure de débit des fluides au moyen d'appareils déprimogènes Partie 1 : Diaphragmes, tuyères et tubes de venturi insérés dans des conduites en charge de section circulaire, (Measure flow of the fluids by means of pressure reducing apparatuses Part 1: Diaphragms, conduits and tubes of venturi inserted in charged mains of section circular).*

3. HERVAULT V. MELLIER J., *Concevoir et mettre en oeuvre une chaine de mesure de pression statique : Chaine type du département REME, (To design and implement a measuring equipment of static pressure: Chains standard of department REME),* HP-12/96/014/A September 1996.

4. Standard AFNOR XP X 07-020, *Guide pour l'expression de l'incertitude de mesure, (Guide for the expression of the uncertainty of measurement),* June 1996.

5. TOURNU É, *Spécifications du module de calcul du bilan thermique de centrales nucléaires REP (BIL TH 1.0), (Specifications of the module of calculation of the thermal balance of PWR nuclear power stations),* HP-17/97/046/B October 1997.

6. TOURNU É., *Quantification de la puissance thermique et de l'incertitude associée descentrales nucléaires REP basée sur le module BIL TH 1.0, (Quantification of the thermal power and uncertainty associated with the PWR nuclear power stations based on module BIL TH 1.0),* HP-17/98/013/B July 1998.

7. VEAU J., *La mesure de débit d'eau alimentaire - Comparaison des techniques utilisées dans les centrales REP, (The measurement of feedwater flow - Comparison of the techniques used in the PWR power stations),* HP-12/97/059/A April 1998.

8. VEAU J., *Mesure du débit d'eau alimentaire pour le BIL100 des REP : Evaluation de la nécessité d'une majoration de l'incertitude de débit, (Measure feedwater flow for the BIL100 of the PWR : Evaluation of the need for an increase of the uncertainty of flow.)* HP-12/94/026/A December 1994.

9. BARBÉ C. SOUCHOIS T., *Bilan thermique des REP (BIL 100) Analyse statistique des données d'étalonnage des capteurs de pression différentielle, (Thermal balance of PWR (BIL 100) The statistical analysis of the data of calibration of the differential pressure transmitter),* HP-12/98/082/A December 1998.

A
APPENDIX

A.1 Calculation of Reactor Thermal Power

A.1.1 Reactor thermal power for a typical 1450 MWe PWR unit

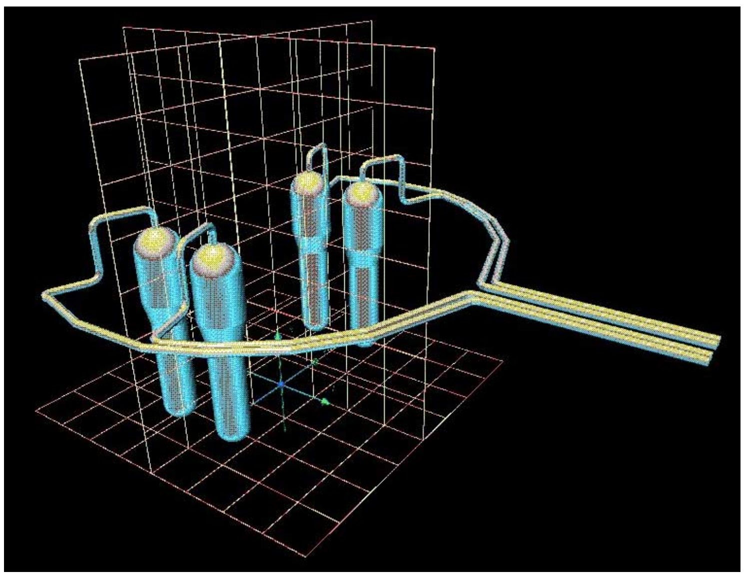

Figure A-1
Overall view of secondary side of steam generators.

The reactor thermal power is obtained from the total power supplied at the secondary side of the steam generators by applying the following equation:

$$W_{th,reactor} = W_{th,SG} - W_{th,primarysysteminput} \qquad \textbf{Eq. A-1}$$

where $W_{th,primarysysteminput}$ is fixed at 20 MW for 1450 MWe units.

For all the steam generators of the PWR Unit, the total power supplied at the secondary side of the steam generators is given by :

$$W_{th,SG} = \sum_{i=1}^{n_{loop}} \left[Q_{EE}^{i} \left(H_{SV}^{i} - H_{EE}^{i} \right) - \frac{Q_P}{n_{loop}} \times \left(H_{SV}^{i} - H_{P}^{i} \right) \right] \qquad \textbf{Eq. A-2}$$

where: n_{loop} = Number of loops (4 for 1450 MWe units)

Q^{i}_{EE} = Feedwater Flow rate (cf. A.1.2.1)

Q_{p} = Steam generator blowdown flow rate (cf. A.1.2.2)

H^{i}_{EE} = Feedwater enthalpy at the steam generator inlet (cf. A.1.2.3)

H^{i}_{SV} = Steam generator outlet mixture enthalpy (cf. A.1.2.4)

H^{i}_{P} = Steam generator blowdown enthalpy (cf. A.1.2.5)

A.1.2 Determination of fundamental variables

The fundamental values for the calculation of thermal power are Q^{i}_{EE}, Q_{P}, H^{i}_{EE}, H^{i}_{SV}, H^{i}_{P}, P^{i}_{SV}

A.1.2.1. Feedwater flow rate Q^{i}_{EE}

The feedwater flow rate $Q_{EE}{}^{i}$ is measured using a flow restrictor assembly, comprising an orifice plate with pressure taps at D and D/2 (cf. figure A-1).

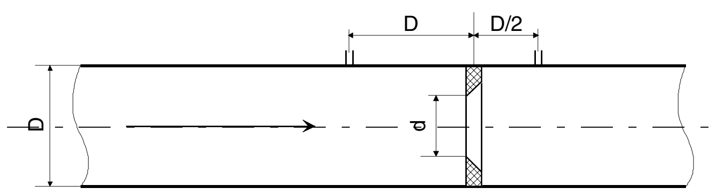

Figure A-2
Schema of a flow rate measurement

The feedwater flow rate is determined by PATERN in accordance with the formulation described in section A.4. The information provided by the sensors is collected by the real time acquisition software PATERN (developed by EDF and installed in each of its units) via an acquisition network. This acquisition system acquired electrical data from sensors of measurements and processing of physical data (pressure, temperature, flow,...)

A.1.2.2. Steam generator blowdown flow rate Q_{P}

For steam generator blowdown, the <u>*total*</u> flow rate is determined via a plant measurement. For this, it is assumed that the total flow rate is distributed equally across each steam generator, which can be verified by performing a local measurement of blowdown flow rate for each train. This measurement can be made by ultra sonic flow rate measurements.

A.1.2.3. Feedwater enthalpy H^i_{EE}

The feedwater enthalpy at the steam generator inlet $H_{EE}{}^i$ is calculated from steam tables on the basis of feedwater pressure P_{EE} and feedwater temperature $T_{EE}{}^i$.

$$H^i_{EE} = H\,(P_{EE}, T^i_{EE}) \qquad \textbf{Eq. A-3}$$

$T_{EE}{}^i$	=	feedwater temperature
P_{EE}	=	feedwater pressure
H	=	enthalpy given by steam tables

A.1.2.4. Steam generator outlet mixture enthalpy $H_{SV}{}^i$

The enthalpy at the steam generator outlet (at the steam dome outlet) $H_{SV}{}^i$ is determined on the basis of steam pressure $P_{SV}{}^i$ and the water content of the steam-water mixture $X_{SV}{}^i$. In general, there are no pressure measuring points at the steam dome outlet. The pressure can only be measured outside the reactor building. Therefore the steam generator outlet mixture pressure $P_{SV}{}^i$ takes account of the correction of the measured pressure by the pressure loss between the steam dome outlet and the measuring point (cf. A.1.2.6). The water content $X_{SV}{}^i$ is determined via water carryover rate tests.

$$H^i_{SV} = H\left(P_{SV}{}^i, X_{SV}{}^i\right) = X^i_{SV} \times h'\left(P^i_{SV}\right) + \left(1 - X^i_{SV}\right) \times h''\left(P^i_{SV}\right) \qquad \textbf{Eq. A-4}$$

$X_{SV}{}^i$	=	water content of the mixture at the steam generator outlet
$P_{SV}{}^i$	=	pressure of the steam-water mixture at the steam generator outlet (cf. A.1.2.6)
H	=	enthalpy given by steam tables
h’	=	water enthalpy given by steam tables
h’’	=	steam enthalpy given by steam tables

A.1.2.5. Steam generator blowdown enthalpy $H_P{}^i$

Finally, the steam generator blowdown is considered to be at saturation conditions at the steam dome pressure. The enthalpy $H_P{}^i$ is thus determined via knowledge of the steam dome pressure alone:

$$H^i_P = h'\left(P_{SV}{}^i\right) \qquad \textbf{Eq. A-5}$$

$P_{SV}{}^i$	=	pressure of steam-water mixture at the steam generator outlet

A.1.2.6. Steam generator outlet mixture pressure P_{SV}^{i}

As there are no pressure measuring points at the steam dome outlet. The steam generator outlet mixture pressure P_{SV}^{i} is calculated from the pressure measured outside the reactor building corrected by the pressure loss between the steam dome outlet and the measuring point:

$$P_{SV}^{i} = P_{SVmes}^{i} + \Delta P_{SV}^{i} \left(\frac{Q_{EE}^{i} - \frac{Q_P}{n_{loop}}}{Q_{SV_0}^{i}} \right)^2 \qquad \textbf{Eq. A-6}$$

P_{SVmes}^{i}	=	measurement of absolute pressure of steam dome outlet
ΔP_{SV}^{i}	=	pressure loss between the instrument tap and the steam dome outlet
$Q_{SV_0}^{i}$	=	steam flow at measurement of ΔP_{SV}^{i}
n_{loop}	=	number of steam generator

A.1.3. Input data

The input data required to calculate the thermal power of the steam supply system are grouped into two categories: data acquired, and PWR unit data.

Data measured for a thermal balance calculation:

P_{SVmes}^{i}	=	measurement of absolute steam pressure at steam generator outlet
P_{EE}	=	measurement of absolute pressure of feedwater
T_{EE}^{i}	=	measurement of feedwater temperature
Q_{EE}^{i}	=	measurement of feedwater flow rate
Q_P	=	measurement of steam generator blowdown flow rate

Unit data:

ΔP_{SV}^{i}	=	pressure loss between instrument tap and steam dome outlet.
X_{SV}^{i}	=	water content of steam generator outlet mixture
$Q_{SV_0}^{i}$	=	steam flow at measurement of ΔP_{SV}^{i} .

A.2. Uncertainty with Respect to Reactor Thermal Power

A.2.1 Determination of expanded uncertainties (EU)

The uncertainty or expanded uncertainty [4] (noted EU thereafter) with respect to reactor thermal power defines an interval around the reactor thermal power for which a given confidence level says. At 95% confidence, the expanded uncertainty is equal to twice the composite standard uncertainty. Composite standard uncertainty is the uncertainty with respect to the result obtained on the basis of the combination of values for other variables expressed in the form of a standard deviation.

This expanded uncertainty is made up of a number of components, which can be grouped into two categories according to the method used to estimate their numerical value:

- Type A, evaluated by using statistical methods on a given population of n-times repetition of the same piece of measurement.
- Type B, evaluated by using other methods than in the type A uncertainty.

When a value Y is function of another values (X_1, X_2,...., X_N) by following a given law Y= f(X_1, X_2,..., X_N), the uncertainty (independent of its type) with respect to Y is given in function of the U_{Xi} (i=1 to N) by the following equation

$$U_Y^2 = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial Xi} \right)^2 U_{Xi}^2 \right) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial Xi} \frac{\partial f}{\partial Xj} U_{Xi} U_{Xj} \rho_{ij}$$

with U_Y = the uncertainty with respect to Y

U_{Xi} = the uncertainty with respect to Xi (i=1 to N)

$\frac{\partial f}{\partial Xi}$ = the partial derivative by Xi with respect to Y

ρ_{ij} = the correlation factor between U_{Xi} and U_{Xj}

Whether the different elementary uncertainties are completely correlated or not at all (ρ_{ij} = 0 or 1), the resulting uncertainty is either the quadratic sum or the linear sum of these elementary uncertainties taking account of the different partial derivative which are called thereafter coefficient of sensitivity.

The main goal of the following calculations (Equations A-7 to A-16) is to determine the relations (especially coefficient of sensitivity, cf. Equations A-17 to A-28) between the expanded uncertainty with respect to reactor thermal power and the different expanded uncertainties (calculated in section A.4) with respect to the input data given in section A.2.3. These expanded uncertainties depend themselves on different factors (acquisition system, environment, ...) as shown in the following calculations.

The expanded uncertainty with respect to reactor thermal power is thus expressed as the following since the terms ${}^{A}U^{2}_{W_{th,reactor}}$ and ${}^{B}U^{2}_{W_{th,reactor}}$ are not correlated. They correspond to independent causes. Type A uncertainty corresponds to fluctuation over time of flow rate. Type B uncertainty corresponds to uncertainties of sensors, of acquisition system.

$$U_{W_{th,reactor}} = \sqrt{{}^{A}U^{2}_{W_{th,reactor}} + {}^{B}U^{2}_{W_{th,reactor}}} \qquad \textbf{Eq. A-7}$$

with ${}^{A}U^{2}_{W_{th,reactor}}$ = the type A uncertainty with respect to reactor thermal power (Eq. A-8)

${}^{B}U^{2}_{W_{th,reactor}}$ = the type B uncertainty with respect to reactor thermal power (Eq. A-9)

The only type A uncertainty taken into account is that associated with the random effect of both measuring noise (due to the measuring channel electronics) and process noise (due to fluctuations in the physical variables during the series of measurements) on the measurement of the differential pressure at the orifice plate for measuring feedwater flow rate.

Consequently, the type A expanded uncertainty with respect to reactor thermal power is expressed as:

$${}^{A}U_{W_{th,reactor}} = \sqrt{\sum_{i=1}^{n_{loop}} \left(\frac{\partial W_{th,SG}}{\partial Q^{i}_{EE}} \right)^{2} \times {}^{A}U^{2}_{Q^{i}_{EE}}} \qquad \textbf{Eq. A-8}$$

From Equation A-1, the type B expanded uncertainty with respect to reactor thermal power is expressed as:

$${}^{B}U_{W_{th,reactor}} = \sqrt{{}^{B}U^{2}_{W_{th,SG}} + {}^{B}U^{2}_{W_{th,primarysysteminput}}} \qquad \textbf{Eq. A-9}$$

Since the terms are not correlated because they are independent.

The type B expanded uncertainty with respect to calculation of the thermal power of the steam generators is expressed as:

$${}^{B}U_{W_{th,SG}} = \sqrt{\sum_{i=1}^{n_{loop}} \left({}^{B}U^{2}_{W_{th,SGi}} \right) + {}^{B}U^{2}_{W_{th,SGcom}} + {}^{B}U^{2}_{W_{th,SGenv}}} \qquad \textbf{Eq. A-10}$$

with ${}^{B}U^{2}_{W_{th,SGi}}$ = type B EU, associated with the data common to the different loops is (Eq. A-16)

${}^{B}U^{2}_{W_{th,SGcom}}$ = the type B EU, associated with the data specific to each loop (Eq. A-15)

${}^{B}U^{2}_{W_{th,SGenv}}$ = type B EU, associated with the common environment of the sensors (Eq. A-11)

Since the terms are not correlated because they are independent.

The type B expanded uncertainty with respect to calculation of the thermal power of the steam generators, associated with the common environment of the sensors (temperature effect, calibration and acquisition system) is:

$${}^{B}U_{W_{th,SGenv}} = \sqrt{{}^{B}U^{2}_{Temp_{W_{th,SG}}} + {}^{B}U^{2}_{Calib_{W_{th,SG}}} + {}^{B}U^{2}_{Acq\_sys_{W_{th,SG}}}}$$ **Eq. A-11**

Since the terms are not correlated because they are independent.

The type B expanded uncertainty with respect to the calculation of the thermal power of the steam generators, that is associated with the temperature effect is given by

$${}^{B}U_{Temp_{W_{th,SG}}} = \sum_{i=1}^{n_{loop}} \left(\frac{\partial W_{th,SG}}{\partial Q^{i}_{EE}} \times {}^{B}U_{Temp_{Q^{i}_{EE}}} + \frac{\partial W_{th,SG}}{\partial P^{i}_{SVmes}} \times {}^{B}U_{Temp_{P^{i}_{SVrel}}} \right) + \frac{\partial W_{th,SG}}{\partial P_{atmos}} \times {}^{B}U_{Temp_{P_{atmos}}} + \frac{\partial W_{th,SG}}{\partial P_{EE}} \times {}^{B}U_{Temp_{P_{EErel}}}$$

Eq. A-12

This is derived from Eq. A-2

with $\frac{\partial W_{th,SG}}{\partial Q^{i}_{EE}}$ = coefficient of sensitivity of thermal power of a steam generator in respect to feedwater flow rate of train i (Eq. A-17). For the other coefficients of sensitivity, the mean is similar and terms are defined in equation

${}^{B}U_{Temp_{Q^{i}_{EE}}}$ = the type B EU with respect to temperature effect on feedwater flow rate of loop i

The type B expanded uncertainty with respect to the calculation of the thermal power of the steam generators, that is associated with the calibration is given by :

$${}^{B}U_{Calib_{W_{th,SG}}} = \sum_{i=1}^{n_{loop}} \left(\frac{\partial W_{th,SG}}{\partial Q^{i}_{EE}} \times {}^{B}U_{Calib_{Q^{i}_{EE}}} \right)$$ **Eq. A-13**

The type B expanded uncertainty with respect to calculation of the thermal power of the steam generators, associated with the acquisition system :

$$^{B}U_{Acq\_sys_{W_{th,SG}}} = \sum_{i=1}^{n_{loop}}\left(\frac{\partial W_{th,SG}}{\partial Q_{EE}^{i}}\times {}^{B}U_{Acq\_sys_{Q_{EE}^{i}}} + \frac{\partial W_{th,SG}}{\partial P_{SVmes}^{i}}\times {}^{B}U_{Acq\_sys_{P_{SVrel}^{i}}}\right) + \frac{\partial W_{th,SG}}{\partial P_{atmos}}\times {}^{B}U_{Acq\_sys_{P_{atmos}}} + \frac{\partial W_{th,SG}}{\partial P_{EE}}\times {}^{B}U_{Acq\_sys_{P_{EErel}}} \quad \text{Eq. A-14}$$

The type B expanded uncertainty with respect to the calculation of the thermal power of the steam generators, associated with the data common to the different loops is:

$$^{B}U_{W_{th,SGcom}} = \sqrt{\left(\frac{\partial W_{th,SG}}{\partial P_{EE}}\right)^{2}\times {}^{B}U^{2}_{excl\_env_{P_{EErel}}} + \left(\frac{\partial W_{th,SG}}{\partial Q_{p}}\right)^{2}\times {}^{B}U^{2}_{Q_{p}} + \left(\frac{\partial W_{th,SG}}{\partial P_{atmos}}\right)^{2}\times {}^{B}U^{2}_{excl\_env_{P_{atmos}}}} \quad \text{Eq. A-15}$$

and the type B expanded uncertainty with respect to the calculation of the thermal power of the steam generators, associated with the data specific to each loop is:

$$^{B}U_{W_{th,SGi}} = \sqrt{\left(\frac{\partial W_{th,SG}}{\partial T_{EE}^{i}}\right)^{2}\times {}^{B}U^{2}_{T_{EE}^{i}} + \left(\frac{\partial W_{th,SG}}{\partial Q_{EE}^{i}}\right)^{2}\times {}^{B}U^{2}_{excl\_env_{Q_{EE}^{i}}} + \left(\frac{\partial W_{th,SG}}{\partial \Delta P_{SV}^{i}}\right)^{2}\times {}^{B}U^{2}_{\Delta P_{SV}^{i}} + \left(\frac{\partial W_{th,SG}}{\partial X_{SV}^{i}}\right)^{2}\times {}^{B}U^{2}_{X_{SV}^{i}} + \left(\frac{\partial W_{th,SG}}{\partial P_{SVmes}^{i}}\right)^{2}\times {}^{B}U^{2}_{excl\_env_{P_{SVrel}^{i}}}} \quad \text{Eq. A-16}$$

The term $Q_{SV_0}^{i}$ is not taken into account in the uncertainty calculation as it is a third order term ($\frac{\partial W_{th,SG}}{\partial Q_{SV_0}^{i}}\,{}^{B}U_{Q_{SV_0}^{i}} \approx 0.1\frac{\partial W_{th,SG}}{\partial \Delta P_{SV}^{i}}\,{}^{B}U_{\Delta P_{SV}^{i}}$).

A.2.2. Determination of partial derivatives

For the independent variables $Q_{EE}{}^{i}$, $T_{EE}{}^{i}$, P_{EErel}, $P_{SVrel}{}^{i}$, P_{atmos}, ΔP_{SV}^{i}, $X_{SV}{}^{i}$ and Q_{P}, the coefficients of sensitivity used in the previous equations are calculated from partial derivation of Equation A-2:

$$\frac{\partial W_{th,SG}}{\partial Q_{EE}^{i}} = H_{SV}^{i} - H_{EE}^{i} \quad \text{Eq. A-17}$$

$$\frac{\partial W_{th,SG}}{\partial T^i_{EE}} = -Q^i_{EE}\left(\frac{\partial H}{\partial T}\right)_{T^i_{EE},P_{EE}}$$ **Eq. A-18**

$$\frac{\partial W_{th,SG}}{\partial P_{EE}} = \sum_{i=1}^{n}\left\{-Q^i_{EE}\left(\frac{\partial H}{\partial P}\right)_{T^i_{EE},P_{EE}}\right\}$$ **Eq. A-19**

$$\frac{\partial W_{th,SG}}{\partial P^i_{SVmes}} = \left[\left(Q^i_{EE} - \frac{Q_P}{n_{loop}}\right)\times x^i_{sv} + \frac{Q_P}{n_{loop}}\right]\times\left(\frac{\partial h'}{\partial P}\right)_{P^i_{SV}} + \left(1 - x^i_{sv}\right)\times\left(Q^i_{EE} - \frac{Q_p}{n_{loop}}\right)\times\left(\frac{\partial h''}{\partial P}\right)_{P^i_{SV}}$$ **Eq. A-20**

$$\frac{\partial W_{th,SG}}{\partial \Delta P^i_{SV}} = \frac{\partial W_{th,SG}}{\partial P^i_{SVmes}}\left(\frac{Q^i_{EE} - \dfrac{Q_P}{n_{loop}}}{Q^i_{SV_0}}\right)^2$$ **Eq. A-21**

$$\frac{\partial W_{th,SG}}{\partial X^i_{SV}} = \left(Q^i_{EE} - \frac{Q_P}{n_{loop}}\right)\left[h'\left(P^i_{SV}\right) - h''\left(P^i_{SV}\right)\right]$$ **Eq. A-22**

$$\frac{\partial W_{th,SG}}{\partial Q_P} = \frac{\sum_{i=1}^{n}\left(H^i_P - H^i_{SV}\right)}{n_{loop}}$$ **Eq. A-23**

$$\frac{\partial W_{th,SG}}{\partial P_{atmos}} = \sum_{i=1}^{n_{loop}}\left\{\begin{array}{l}\left[\left(Q^i_{EE} - \dfrac{Q_P}{n_{loop}}\right)\times x^i_{sv} + \dfrac{Q_P}{n_{loop}}\right]\times\left(\dfrac{\partial h'}{\partial P}\right)_{P^i_{SV}} + \left(1 - x^i_{sv}\right)\times\left(Q^i_{EE} - \dfrac{Q_p}{n_{loop}}\right)\times\left(\dfrac{\partial h''}{\partial P}\right)_{P^i_{SV}} \\ Q^i_{EE}\left[\dfrac{H^i_{SV} - H^i_{EE}}{2\rho^i_{EE}}\times\left(\dfrac{\partial \rho}{\partial P}\right)_{T^i_{EE},P_{EE}} - \left(\dfrac{\partial H}{\partial P}\right)_{T^i_{EE},P_{EE}}\right]\end{array}\right\}$$

Eq. A-24

while the partial derivatives with respect to enthalpy determined on the basis of thermodynamic tables are as follows:

$$\left(\frac{\partial H}{\partial T}\right)_{T,P} = \frac{H(P, T+10) - H(P,T)}{10}$$ **Eq. A-25**

$$\left(\frac{\partial H}{\partial P}\right)_{T,P} = \frac{H(P+10, T) - H(P,T)}{10}$$ **Eq. A-26**

$$\left(\frac{\partial h'}{\partial P}\right)_P = \frac{h'(P+2)-h'(P)}{2}$$ **Eq. A-27**

$$\left(\frac{\partial h''}{\partial P}\right)_P = \frac{h''(P+2)-h''(P)}{2}$$ **Eq. A-28**

The uncertainty with respect to the formulation of the thermodynamic tables is disregarded.

A.2.3. Expanded uncertainties with respect to the independent variables

The different expanded uncertainties with respect to the input data given in section 2.3. are calculated in the following subsections

A.2.3.1. Expanded uncertainty with respect to steam moisture content

$${}^{B}U_{X^i_{SV}} = 0.1X^i_{SV}$$ **Eq. A-29**

A.2.3.2. Expanded uncertainty with respect to steam generator blowdown flow rate

$${}^{B}U_{Q_p} = 0.1Q_p$$ **Eq. A-30**

A.2.3.3. Expanded uncertainty with respect to pressure loss between instrument tap and steam dome outlet

$${}^{B}U_{\Delta P^i_{SV}} = 0.3bar$$ **Eq. A-31**

A.2.3.4. Expanded uncertainty with respect to value of primary system inputs

$${}^{B}U_{W_{\text{th,primarysysteminput}}} = 0.1W_{\text{th,primarysysteminput}}$$ **Eq. A-32**

A.2.3.5. Expanded uncertainty with respect to steam generator outlet steam pressure

${}^{B}U_{excl\_env_{P^i_{SVrel}}}$ (cf. Eq. A-91), ${}^{B}U_{Temp_{P^i_{SVrel}}}$ (cf. Eq. A-78 or 4-82 or 4-89) and ${}^{B}U_{Acq\_sys_{P^i_{SVrel}}}$ (cf. Eq. A-90) are determined in accordance with the formulae given in section 4.

A.2.3.6. Expanded uncertainty with respect to feedwater pressure

${}^{B}U_{excl\_env_{P_{EErel}}}$ (cf. Eq. A-91), ${}^{B}U_{Temp_{P_{EErel}}}$ (cf. Eq. A-78 or 4-82 or 4-89) and ${}^{B}U_{Acq\_sys_{P_{EErel}}}$ (cf. Eq. A-90) are determined in accordance with the formulae given in section 4.

A.2.3.7. Expanded uncertainty with respect to atmospheric pressure

${}^{B}U_{excl\_env_{P_{atmos}}}$ (cf. Eq. A-91) , ${}^{B}U_{Temp_{P_{atmos}}}$ (cf. Eq. A-78 or A-82 or A-89) and ${}^{B}U_{Acq\_sys_{P_{atmos}}}$ (cf. Eq. A-90) are determined in accordance with the formulae given in section 4.

A.2.3.8. Expanded uncertainty with respect to feedwater temperature

${}^{B}U_{T^{i}_{EE}}$ is determined in accordance with the formulae given in section 4 (cf. Eq. A-92).

A.2.3.9. Expanded uncertainty with respect to feedwater flow rate

${}^{A}U_{Q^{i}_{EE}}$, ${}^{B}U_{excl\_env_{Q^{i}_{EE}}}$, ${}^{B}U_{Temp_{Q^{i}_{EE}}}$, ${}^{B}U_{Acq\_sys_{Q^{i}_{EE}}}$ and ${}^{B}U_{Calib_{Q^{i}_{EE}}}$ are determined in accordance with the formulae given in section 4.

A.2.4. Input data

All the Expanded Uncertainties related to the previous calculation (Equations A-7 to A-16) may be considered as new input data (in addition to the input data for calculation of thermal power), which are required to calculate the uncertainty with respect to the thermal power of the steam supply system. Some of these uncertainties are associated with the acquisition system, the environment (and so on). In section 4, the calculation needed to obtain these uncertainties shall be explained.

The list of these new input data are given thereafter:

${}^{B}U_{X^{i}_{SV}}$ = expanded uncertainty with respect to steam moisture content (cf. Eq. A-29)

${}^{B}U_{Q_{p}}$ = expanded uncertainty with respect to steam generator blowdown flow rate (cf. Eq. A-30)

${}^{B}U_{\Delta P^{i}_{SV}}$ = expanded uncertainty with respect to pressure loss between the instrument tap and the steam dome outlet (cf. Eq. A-31)

$^{B}U_{W_{th,primarysysteminput}}$ = expanded uncertainty with respect to the value of primary system inputs (cf. Eq. A-32)

$^{B}U_{excl\_env_{P^{i}_{SVrel}}}$ = expanded uncertainty (excluding environment) with respect to steam generator outlet steam pressure (cf. Eq. A-91)

$^{B}U_{Temp_{P^{i}_{SVrel}}}$ = expanded uncertainty associated with temperature with respect to steam generator outlet steam pressure (cf. Eq. A-78 or A-82 or A-89)

$^{B}U_{Acq\_sys_{P^{i}_{SVrel}}}$ = expanded uncertainty associated with acquisition system with respect to steam generator outlet steam pressure (cf. Eq. A-90)

$^{B}U_{excl\_env_{P_{EErel}}}$ = expanded uncertainty (excluding environment) with respect to feedwater pressure (cf. Eq. A-91)

$^{B}U_{Temp_{P_{EErel}}}$ = expanded uncertainty associated with temperature with respect to feedwater pressure (cf. Eq. A-78 or A-82 or A-89)

$^{B}U_{Acq\_sys_{P_{EErel}}}$ = expanded uncertainty associated with acquisition system with respect to feedwater pressure (cf. Eq. A-90)

$^{B}U_{excl\_env_{P_{atmos}}}$ = expanded uncertainty (excluding environment) with respect to atmospheric pressure (cf. A-91)

$^{B}U_{Temp_{P_{atmos}}}$ = expanded uncertainty associated with temperature with respect to atmospheric pressure (cf. Eq. A-78 or A-82 or A-89)

$^{B}U_{Acq\_sys_{P_{atmos}}}$ = expanded uncertainty associated with acquisition system with respect to atmospheric pressure (cf. Eq. A-90)

$^{B}U_{T^{i}_{EE}}$ = expanded uncertainty with respect to feedwater temperature

$^{A}U_{Q^{i}_{EE}}$ = type A expanded uncertainty with respect to feedwater flow rate

$^{B}U_{excl\_env_{Q^{i}_{EE}}}$ = expanded uncertainty (excluding environment) with respect to feedwater flow rate (cf. Eq. A-43)

${}^{B}U_{Temp_{Q_{EE}^{i}}}$ = expanded uncertainty associated with temperature with respect to feedwater flow rate (cf. Eq. A-44)

${}^{B}U_{Acq\_sys_{Q_{EE}^{i}}}$ = expanded uncertainty associated with acquisition system with respect to feedwater flow rate (cf. Eq. A-46)

${}^{B}U_{Calib_{Q_{EE}^{i}}}$ = expanded uncertainty associated with calibration with respect to feedwater flow rate (cf. Eq. A-45)

A.3. Uncertainties with Respect to Measured Data

In the previous section relations between the expanded uncertainty with respect to reactor thermal power and the different expanded uncertainties have been detailed. Expanded uncertainties with respect to input data given in section 2.3 have been calculated. New expanded uncertainties in relation with the measurement conditions have appeared (cf. section 3.4). In the current section, the measurement required for data acquisition during a test and the associated expanded uncertainties will be determined for each kind of value: flow rate value, differential pressure value, absolute pressure value, temperature value.

A.3.1. Measurement of feedwater flow rate

A.3.1.1. Determination of flow rate value

The feedwater flow rate is determined using the following general formula [1], [2]:

$$Q_{EE}^{i} = \alpha^{i} \times \varepsilon^{i} \times \frac{\pi \times {d^{i}}^{2}}{4} \times \sqrt{2 \times \rho_{EE}^{i} \times \Delta P_{EE}^{i}} \qquad \textbf{Eq. A-33}$$

where:

Q_{EE}^{i} = mass flow

α^{i} = discharge coefficient (cf. Eq.. A-37 or A-38)

ε^{i} = expansion factor (equal to 1 in this case, as the fluid is incompressible)

d^{i} = diameter of flowmeter throat (cf. Eq.. A-35)

ρ_{EE}^{i} = density (cf. Eq.. A-34)

ΔP_{EE}^{i} = differential pressure via transmitter of the sensor used in the measurement

A.3.1.1.1. Determination of density

$$\rho^{i}_{EE} = \rho\left(P_{EE}, T^{i}_{EE}\right) \qquad \textbf{Eq. A-34}$$

$T_{EE}{}^{i}$ = feedwater temperature

P_{EE} = feedwater pressure.

A.3.1.1.2. Determination of pipe diameters

The pipe diameter D^i and flowmeter throat diameter d^i are obtained using the following formulae:

$$d^{i} = d^{i}(t_0)\left(1 + \gamma_d\left(T^{i}_{EE} - t_0\right)\right) \qquad \textbf{Eq. A-35}$$

$$D^{i} = D^{i}(t'_0)\left(1 + \gamma_D\left(T^{i}_{EE} - t'_0\right)\right) \qquad \textbf{Eq. A-36}$$

A.3.1.1.3. Determination of discharge coefficients

For an orifice plate with pressure taps at D and D/2

$$\alpha^{i} = \frac{0.5959 + 0.0312\beta^{2.1} - 0.1840\beta^{8} + 0.0029\beta^{2.5}\left(\frac{10^{6}}{Re^{i}_{D}}\right)^{0.75} + 0.0390\beta^{4}\left(1-\beta^{4}\right)^{-1} - 0.015839\beta^{3}}{\sqrt{1-\beta^{4}}}$$

Eq. A-37

For an orifice plate with vena contracta pressure taps

$$\alpha^{i} = \frac{0.5922 + 0.4252\left(\frac{0.3871}{D^{i^2}\beta^{2} + 0.254D} + \beta^{4} + 1.25\beta^{16}\right) + \left[0.00025 + 0.002325\left(\beta + 1.75\beta^{4} + 10\beta^{12} + 0.07874D^{i}\beta^{16}\right)\right]\sqrt{\frac{10^{6}}{Re^{i}_{D}}}}{\sqrt{1-\beta^{4}}} \qquad \textbf{Eq. A-38}$$

β = ratio of flowmeter throat diameter d^i to pipe diameter D^i.

Re^{i}_{D} = Reynolds number applied to pipe diameter (cf. Eq.. A-39).

$$Re^{i}_{D} = \frac{4Q^{i}_{EE}}{\pi\mu^{i}D^{i}} \qquad \textbf{Eq. A-39}$$

Given that Q^i_{EE} is dependent on α^i, α^i is dependent on Re^i_D, and Re^i_D is dependent on Q^i_{EE}, Q^i_{EE} is determined via an iterative calculation.

μ^I = dynamic viscosity

$$\mu^i = \mu\left(P_{EE}, T^i_{EE}\right) \qquad \textbf{Eq. A-40}$$

A.3.1.1.4. Input data

Data measured during a test:

P_{EE} = measurement of feedwater pressure

$T_{EE}{}^i$ = measurement of feedwater temperature

$\Delta P_{EE}{}^i$ = measurement of differential pressure at orifice plate

Orifice plate data:

t_0 = temperature at which the diameter of the flowmeter throat was measured

t'_0 = temperature at which the diameter of the pipe was measured

γ_d = dilatability of the flowmeter throat

γ_D = dilatability of the pipe

$d^i(t_0)$ = measurement of diameter of flowmeter throat (m)

$D^i(t'_0)$ = measurement of diameter of pipe (m)

A.3.1.2. Expanded uncertainty with respect to flow rate measurement

A.3.1.2.1. Determination of expanded uncertainties

Considering that the independent variables are α^i, d^i, D^i, $T_{EE}{}^i$, P_{EE} and $\Delta P_{EE}{}^i$, the expanded uncertainty with respect to flow rate measurement is as follows:

$$^{B}U_{Q^i_{EE}} = \sqrt{\begin{array}{l}\left(\frac{\partial Q^i_{EE}}{\partial \alpha^i}\right)^2 \times {}^{B}U^2_{\alpha^i} + \left(\frac{\partial Q^i_{EE}}{\partial d^i}\right)^2 \times {}^{B}U^2_{d^i} + \left(\frac{\partial Q^i_{EE}}{\partial D^i}\right)^2 \times {}^{B}U^2_{D^i} \\ + \left(\frac{\partial Q^i_{EE}}{\partial T^i_{EE}}\right)^2 \times {}^{B}U^2_{T^i_{EE}} + \left(\frac{\partial Q^i_{EE}}{\partial P^i_{EE}}\right)^2 \times {}^{B}U^2_{P^i_{EE}} + \left(\frac{\partial Q^i_{EE}}{\partial \Delta P^i_{EE}}\right)^2 \times {}^{B}U^2_{\Delta P^i_{EE}}\end{array}} \qquad \textbf{Eq. A-41}$$

$$ {}^{A}U_{Q_{EE}^{i}} = \sqrt{\left(\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}}\right)^{2} \times {}^{A}U^{2}_{\Delta P_{EE}^{i}}} $$ **Eq. A-42**

where : ${}^{A}U^{2}_{\Delta P_{EE}^{i}}$ is calculated in equation A-70

By grouping the terms not associated with the common environment of the sensors (temperature effect, calibration and acquisition system), the type B expanded uncertainty not associated with the environment is as follows:

$$ {}^{B}U_{excl\_env_{Q_{EE}^{i}}} = \sqrt{\begin{aligned}&\left(\frac{\partial Q_{EE}^{i}}{\partial \alpha^{i}}\right)^{2} \times {}^{B}U^{2}_{\alpha^{i}} + \left(\frac{\partial Q_{EE}^{i}}{\partial d^{i}}\right)^{2} \times {}^{B}U^{2}_{d^{i}} + \left(\frac{\partial Q_{EE}^{i}}{\partial D^{i}}\right)^{2} \times {}^{B}U^{2}_{D^{i}} \\ &+ \left(\frac{\partial Q_{EE}^{i}}{\partial T_{EE}^{i}}\right)^{2} \times {}^{B}U^{2}_{T_{EE}^{i}} + \left(\frac{\partial Q_{EE}^{i}}{\partial P_{EE}^{i}}\right)^{2} \times {}^{B}U^{2}_{excls\_env_{P_{EErel}^{i}}} + \left(\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}}\right)^{2} \times {}^{B}U^{2}_{excl\_env_{\Delta P_{EE}^{i}}}\end{aligned}} $$

Eq. A-43

The type B expanded uncertainty associated with the temperature of the environment is:

$$ {}^{B}U_{Temp_{Q_{EE}^{i}}} = \left(\frac{\partial Q_{EE}^{i}}{\partial P_{EE}^{i}}\right) \times {}^{B}U_{Temp_{P_{EErel}^{i}}} + \left(\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}}\right) \times {}^{B}U_{Temp_{\Delta P_{EE}^{i}}} $$ **Eq. A-44**

The type B expanded uncertainty associated with calibration is:

$$ {}^{B}U_{Calib_{Q_{EE}^{i}}} = \left(\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}}\right) \times {}^{B}U_{Calib_{\Delta P_{EE}^{i}}} $$ **Eq. A-45**

The type B expanded uncertainty associated with the acquisition system is:

$$ {}^{B}U_{Acq\_sys_{Q_{EE}^{i}}} = \left(\frac{\partial Q_{EE}^{i}}{\partial P_{EE}^{i}}\right) \times {}^{B}U_{Acq\_sys_{P_{EErel}^{i}}} + \left(\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}}\right) \times {}^{B}U_{Acq\_sys_{\Delta P_{EE}^{i}}} $$ **Eq. A-46**

A.3.1.2.2. Determination of partial derivatives

For the independent variables, the coefficients of sensitivity used in equations A-41 to A-46 are as follows:

$$\frac{\partial Q_{EE}^{i}}{\partial \alpha^{i}} = \frac{Q_{EE}^{i}}{\alpha^{i}}$$ **Eq. A-47**

$$\frac{\partial Q_{EE}^{i}}{\partial d^{i}} = \frac{2\,Q_{EE}^{i}}{d^{i}}\left(1+\frac{\beta_i^4}{1-\beta_i^4}\right)$$ **Eq. A-48**

$$\frac{\partial Q_{EE}^{i}}{\partial D^{i}} = \frac{Q_{EE}^{i}}{D^{i}}\left(\frac{2\beta_i^4}{1-\beta_i^4}\right)$$ **Eq. A-49**

$$\frac{\partial Q_{EE}^{i}}{\partial \Delta P_{EE}^{i}} = \frac{Q_{EE}^{i}}{2\,\Delta P_{EE}^{i}}$$ **Eq. A-50**

$$\frac{\partial Q_{EE}^{i}}{\partial T_{EE}^{i}} = \frac{Q_{EE}^{i}}{2\rho_{EE}^{i}}\left(\frac{\partial \rho}{\partial T}\right)_{T_{EE}^{i},P_{EE}}$$ **Eq. A-51**

$$\frac{\partial Q_{EE}^{i}}{\partial P_{EE}} = \frac{Q_{EE}^{i}}{2\rho_{EE}^{i}}\times\left(\frac{\partial \rho}{\partial P}\right)_{T_{EE}^{i},P_{EE}}$$ **Eq. A-52**

while the partial derivatives with respect to density determined on the basis of thermodynamic tables are:

$$\left(\frac{\partial \rho}{\partial T}\right)_{T,P} = \frac{\rho(P,T+10)-\rho(P,T)}{10}$$ **Eq. A-53**

$$\left(\frac{\partial \rho}{\partial P}\right)_{T,P} = \frac{\rho(P+10,T)-\rho(P,T)}{10}$$ **Eq. A-54**

A.3.1.3. Expanded uncertainties with respect to fundamental variables

A.3.1.3.1. Expanded uncertainty with respect to diameters

$${}^{B}U_{d^{i}} = 10^{-5}\,m$$ **Eq. A-55**

$${}^{B}U_{D^{i}} = 10^{-4}\,m$$ **Eq. A-56**

A.3.1.3.2. Expanded uncertainty with respect to discharge coefficients

$$^{B}U_{\alpha^i} = \begin{cases} 0.006\alpha^i \quad for \;\; \beta \leq 0.6 \\ \dfrac{\beta}{100}\alpha^i \quad for \;\; 0.6 < \beta \leq 0.75 \end{cases} \qquad \textbf{Eq. A-57}$$

A.3.1.3.3. Expanded uncertainty with respect to measurement of differential pressure

The calculations of the expanded uncertainties $^{A}U_{\Delta P^i_{EE}}$ and $^{B}U_{\Delta P^i_{EE}}$, $^{B}U_{excl\_env_{\Delta P^i_{EE}}}$, $^{B}U_{Temp_{\Delta P^i_{EE}}}$, $^{B}U_{Calib_{\Delta P^i_{EE}}}$ and $^{B}U_{Acq\_sys_{\Delta P^i_{EE}}}$ are given in the section on measurement of differential pressure.

A.3.1.3.4. Expanded uncertainty with respect to measurement of feedwater pressure

The calculations of the expanded uncertainties $^{B}U_{P^i_{EE}}$, $^{B}U_{excl\_env_{P_{EErel}}}$, $^{B}U_{Temp_{P_{EErel}}}$ and $^{B}U_{Acq\_sys_{P_{EErel}}}$ are given in the section on measurement of absolute or gauge pressure.

A.3.1.3.5. Expanded uncertainty with respect to measurement of feedwater temperature

The calculation of the expanded uncertainty $^{B}U_{T^i_{EE}}$ is given in the section on measurement of temperature.

A.3.2. Measurement of differential pressure

The calculation of the expanded uncertainty associated with a differential pressure measurement depends on the type of transmitter.

The following notations were selected for this section:

VM	=	measured value
ET	=	calibrated scale
EM	=	maximum measuring range of the instrument

Generally, all the parameters given concern a specific instrument and come from the manufacturer's data.

The type A and type B expanded uncertainties with respect to measurement of ΔP are combined quadratically.

$$U_{\Delta P} = \sqrt{{}^{A}U_{\Delta P}^{2} + {}^{B}U_{\Delta P}^{2}}$$ **Eq. A-58**

A.3.2.1 Type B expanded uncertainty

The type B expanded uncertainty results from four terms: the expanded uncertainty of the ΔP transmitter, the calibration precision, the precision of the acquisition system, and the 'sampling' error.

$${}^{B}U_{\Delta P} = \sqrt{{}^{B}U_{Sens}^{2} + {}^{B}U_{Calib}^{2} + {}^{B}U_{Acq\_sys}^{2} + {}^{B}U_{Samp\_freq}^{2}}$$ **Eq. A-59**

A.3.2.1.1 Expanded uncertainty of the digital transmitter Rosemount 3051CD2 or 3

The expanded uncertainty of the transmitter results from four terms (according to the manufacturer's data) :

- the intrinsic precision of the instrument. This includes non-linearity, hysteresis and repeatability errors;
- sensitivity to temperature;
- sensitivity to static pressure;
- stability over time.

$${}^{B}U_{Sens} = \sqrt{{}^{B}U_{Int}^{2} + {}^{B}U_{Temp}^{2} + {}^{B}U_{Pres}^{2} + {}^{B}U_{Stab}^{2}}$$ **Eq. A-60**

Intrinsic precision of sensor

The intrinsic precision of the sensor is equal to 0.075 % of the calibrated scale (according to the manufacturer's data).

At 95% confidence (2 standard deviations), the uncertainty due to sensor precision is thus (according to the manufacturer's data):

$${}^{B}U_{Int} = \frac{2}{3} \times \frac{0.075}{100} \times ET \;\; if \frac{EM}{ET} < 10$$ **Eq. A-61**

$${}^{B}U_{Int} = \frac{2}{3} \times \left(0.025 + 0.005\frac{EM}{ET}\right) \times \frac{ET}{100} \;\; if \frac{EM}{ET} > 10$$ **Eq. A-62**

Temperature effect

The temperature effect corresponds to the sensor error which occurs when the sensor is operating at a temperature which is different from that at which it was calibrated.

This effect is calculated by obtaining the arithmetical sum of two terms(according to the manufacturer's data):

- 0.025 % of the maximum measuring range per 28°C,
- 0.125 % of the calibrated scale per 28 °C.

The sensors frequently operate at ± 15°C of the calibration temperature. This means that they operate between 5 °C and 35 °C. The expanded uncertainty due to temperature will thus be as follows at 95% confidence (according to the manufacturer's data):

$$^{B}U_{Temp} = \frac{2}{3} \times \left(\frac{0.025}{100} \times \frac{15}{28} \times EM + \frac{0.125}{100} \times \frac{15}{28} \times ET \right)$$ **Eq. A-63**

Effect of static pressure

The effect of static pressure corresponds to the sensor error which occurs when the sensor is not operating at the calibration pressure. This effect is manifested at zero and on the slope (values according to the manufacturer's data) :

- at zero = 0.1 % of the maximum measuring range given 69 bar deviation,
- on the slope = 0.2 % of the measured value given 69 bar deviation

The sensors are considered to operate at ± 5 bar of their calibration pressure. The expanded uncertainty due to the line pressure will thus be as follows at 95% confidence:

$$^{B}U_{\mathrm{Pr}es} = \frac{2}{3} \times \left(\frac{0.1}{100} \times \frac{5}{69} \times EM + \frac{0.2}{100} \times \frac{5}{69} \times VM \right)$$ **Eq. A-64**

Effect of stability over time

The sensors are calibrated every six months. The manufacturer specifies a maximum drift of 0.1% of the maximum measuring range for this period.

The expanded uncertainty due to stability over time will be as follows at 95% confidence:

$$^{B}U_{Stab} = \frac{2}{3} \times \left(\frac{0.1}{100} \times EM \right)$$ **Eq. A-65**

A.3.2.1.2 Expanded uncertainty of the calibration standard

Sensors for thermal balance ΔP are handled by local calibration facilities.

$$^{B}U_{Calib} = 0.7 \text{ mbar}$$ **Eq. A-66**

A.3.2.1.3 Expanded uncertainty of the acquisition system

The equipment used varies considerably from unit to unit. However, one of the following four models is always used:

- HP 3497,
- HP 3852,
- ORION or SCORPIO (Schlumberger),
- IMP (Schlumberger).

The sensitivity of the voltmeter used impacts the physical variable scanned. Various studies carried out at REME have shown that the maximum error which results with these systems is approximately 0.07 % of the calibrated scale.

The following is thus applied regardless of the system:

$$^{B}U_{Acq\_sys} = \frac{2}{3} \times \frac{0.07}{100} \times ET \qquad \textbf{Eq. A-67}$$

A.3.2.1.4 Expanded uncertainty due to sampling

Regulation of the process causes fluctuations in flow rate Q^{i}_{EE}, in other words, in differential pressure ΔP. Acquisition of this dynamic signal must therefore be in compliance with the signal processing rules as follows:

- using a sufficiently high sampling frequency (Shannon rule)
- by inserting, upstream of the voltmeter, a filter with a cutoff frequency adapted to the selected acquisition frequency.

For technical reasons (limits of data loggers) and financial reasons (cost of filters), a waiver in respect of these rules was accepted, subject to incorporation of a ‘sampling error’ which is estimated, at 95% confidence, at 0.2 % of the mean value for 20 minutes’ acquisition at 0.2 Hz.

The following is thus obtained:

$$^{B}U_{Samp\_freq} = \frac{0.2}{100} \times VM \qquad \textbf{Eq. A-68}$$

A.3.2.2 Type B expanded uncertainty not associated with environment

By grouping the terms not associated with the common environment of the sensors (temperature effect, calibration and acquisition system), the type B expanded uncertainty not associated with the environment is as follows:

$$ {}^{B}U_{exl\_env_{\Delta P}} = \sqrt{{}^{B}U_{Int}^{2} + {}^{B}U_{\Pr es}^{2} + {}^{B}U_{Stab}^{2} + {}^{B}U_{Samp\_freq}^{2}} \qquad \textbf{Eq. A-69} $$

A.3.2.3 Type A expanded uncertainty

The uncertainty due to the random effect can only be calculated after acquisition of a series of measurements.

It will be recalled that the principle of the calculation is as follows:

The differential pressure lies in the interval

$\left(\overline{\Delta P} - \frac{s}{\sqrt{n}} t_{1-\frac{\alpha}{2}} ; \overline{\Delta P} + \frac{s}{\sqrt{n}} t_{1-\frac{\alpha}{2}}\right)$ with a probability of 1-α.

The standard deviation s is estimated via:

$S_{\Delta P} = \sqrt{\frac{\sum_{i=1}^{n}\left(\Delta P_i - \overline{\Delta P}\right)^2}{n-1}}$ where $\overline{\Delta P} = \frac{\sum_{i=1}^{n} \Delta P_i}{n}$ is the arithmetical mean.

The Student factor is equal to 2 for 95% confidence and over 20 measurements.

$$ A_{e\Delta P} = 2 \times \frac{S_{\Delta P}}{\sqrt{n}} \qquad \textbf{Eq. A-70} $$

A.3.3 Measurement of absolute or gauge pressure

A.3.3.1 Determination of pressure value for gauge pressure measurements

A.3.3.1.1 Feedwater pressure P_{EE}

$$ P_{EE} = P_{atmos} + P_{EErel} \qquad \textbf{Eq. A-71} $$

P_{atmos} = absolute measurement of atmospheric pressure via transmitter STA122 (cf. Annex Section 3.3.2.4)

P_{EErel} = gauge measurement, in comparison with atmospheric pressure, of feedwater pressure via transmitter 1151GP (cf. Annex Section 3.3.2.2)

A.3.3.1.2 Pressure of steam generator outlet mixture P_{SV}^{i}

$$P^{i}_{SVmes} = P_{atmos} + P^{i}_{SVrel}$$ **Eq. A-72**

P_{atmos} = absolute measurement of atmospheric pressure

P_{SVrel}^{i} = gauge measurement, in comparison with atmospheric pressure, of the steam generator outlet mixture pressure via transmitter 3051CG

The associated expanded uncertainty is as follows:

$$^{B}U_{P_{EE}} = \sqrt{{^{B}U_{P_{atmos}}}^{2} + {^{B}U_{P_{EErel}}}^{2}}$$ **Eq. A-73**

$$^{B}U_{P^{i}_{SVmes}} = \sqrt{{^{B}U_{P_{atmos}}}^{2} + {^{B}U_{P^{i}_{SVrel}}}^{2}}$$ **Eq. A-74**

A.3.3.2 Expanded uncertainty with respect to measurement of gauge or absolute pressure

The calculation of the expanded uncertainty associated with a gauge or absolute pressure measurement depends on the type of transmitter. The calculation is carried out for the transmitters currently used by the plants.

The following notations were selected for this section:

VM = measured value

ET = calibrated scale

EM = maximum measuring range of the instrument.

For absolute and gauge pressure measurements, the uncertainty associated with the random effect is negligible

Generally, all the parameters given concern a specific instrument and come from the manufacturer's data.

The type B expanded uncertainty results from two terms: the uncertainty of the ΔP transmitter and the precision of the acquisition system.

$$^{B}U_{P} = \sqrt{^{B}U^{2}_{Sens} + {^{B}U^{2}_{Acq\_sys}}}$$ **Eq. A-75**

A.3.3.2.1 Expanded uncertainty of transmitter

The expanded uncertainty of the transmitter results from three terms (according to the manufacturer's data):

- the intrinsic precision of the instrument. This includes non-linearity, hysteresis and repeatability errors;
- sensitivity to temperature;
- stability over time.

$$^{B}U_{Sens} = \sqrt{^{B}U_{Int}^{2} + {}^{B}U_{Temp}^{2} + {}^{B}U_{Stab}^{2}} \qquad \textbf{Eq. A-76}$$

A.3.3.2.2 Expanded uncertainty of the digital transmitter Rosemount 1151AP or GP

Intrinsic precision of sensor

The intrinsic precision of the sensor is equal to 0.25 % of the calibrated scale. The standard deviation corresponds to one-third of this value. At 95%, the expanded uncertainty due to sensor precision is thus as follows:

$$^{B}U_{Int} = \frac{2}{3} \times \frac{0.25}{100} \times ET \qquad \textbf{Eq. A-77}$$

Temperature effect

The temperature effect corresponds to the sensor error which occurs when the sensor is operating at a temperature which is different from that at which it was calibrated.

Given 56°C variation, this effect is calculated by considering two terms (values according to the manufacturer's data):

- for zero: 0.5 % of the maximum measuring range,
- for the slope: 0.5 % of the measured value.

The expanded uncertainty due to temperature will thus be as follows, for sensors operating at ± 15°C of the calibration temperature, at 95% confidence (values according to the manufacturer's data) :

$$^{B}U_{Temp} = \frac{2}{3} \times \left(\sqrt{\left(\frac{0.5}{100} \times \frac{15}{56} \times EM \right)^{2} + \left(\frac{0.5}{100} \times \frac{15}{56} \times VM \right)^{2}} \right) \qquad \textbf{Eq. A-78}$$

Effect of stability over time

The sensors are calibrated every six months. The manufacturer specifies a maximum drift of 0.25% of the maximum measuring range for this period.

The expanded uncertainty due to stability over time will be as follows, at 95% confidence:

$$^{B}U_{Stab} = \frac{2}{3} \times \left(\frac{0.25}{100} \times EM \right) \quad \textbf{Eq. A-79}$$

A.3.3.2.3 Expanded uncertainty of the digital transmitter Rosemount 3051CG

Intrinsic precision of sensor

The intrinsic precision of the sensor is equal to 0.075 % of the calibrated scale. The standard deviation corresponds to one-third of this value. At 95%, the expanded uncertainty due to sensor precision is thus as follows (values according to the manufacturer's data):

$$^{B}U_{Int} = \frac{2}{3} \times \frac{0.075}{100} \times ET \quad if \frac{EM}{ET} < 10 \quad \textbf{Eq. A-80}$$

$$^{B}U_{Int} = \frac{2}{3} \times \left(0.025 + 0.005 \frac{EM}{ET} \right) \times \frac{EE}{100} if \frac{EM}{ET} > 10 \quad \textbf{Eq. A-81}$$

Temperature effect

The temperature effect corresponds to the sensor error which occurs when the sensor is operating at a temperature which is different from that at which it was calibrated.

This effect is calculated by obtaining the arithmetical sum of two terms (values according to the manufacturer's data) :

- 0.025 % of the maximum measuring range per 28°C,
- 0.125 % of the calibrated scale per 28 °C.

The sensors frequently operate at ± 15°C of the calibration temperature. This means that they operate between 5 °C and 35 °C. The expanded uncertainty due to temperature will thus be as follows at 95% confidence (values according to the manufacturer's data) :

$$^{B}U_{Temp} = \frac{2}{3} \times \left(\frac{0.025}{100} \times \frac{15}{28} \times EM + \frac{0.125}{100} \times \frac{15}{28} \times ET \right) \quad \textbf{Eq. A-82}$$

Effect of stability over time

The sensors are calibrated every six months. For this period, the manufacturer specifies a maximum drift of 0.1% of the maximum measuring range for bands 2 and 3, and 0.2% of the maximum measuring range for bands 4 and 5.

The expanded uncertainty due to stability over time will be as follows at 95% confidence (values according to the manufacturer's data):

$$^{B}U_{Stab} = \frac{2}{3} \times \left(\frac{0.1}{100} \times EM \right) \text{bands 2 and 3} \quad \textbf{Eq. A-83}$$

$$^{B}U_{Stab} = \frac{2}{3} \times \left(\frac{0.2}{100} \times EM \right) \text{bands 4 and 5} \quad \textbf{Eq. A-84}$$

A.3.3.2.4 Expanded uncertainty of the digital transmitter Honeywell STA122

Intrinsic precision of sensor

The intrinsic precision of the sensor is equal to 0.1 % of the maximum measuring range.

At 95% confidence (2 standard deviations), the expanded uncertainty due to sensor precision is thus as follows:

$$^{B}U_{Int} = \frac{2}{3} \times \frac{0.1}{100} \times EM \;\; if \; \mathrm{ET} \geq 0.120 \text{ bar} \quad \textbf{Eq. A-85}$$

$$^{B}U_{Int} = \frac{2}{3} \times \left(0.05 + 0.05 \frac{0.120}{ET} \right) \times \frac{ET}{100} \;\; if \;\; ET < 0.120 \text{ bar} \quad \textbf{Eq. A-86}$$

Temperature effect

The temperature effect corresponds to the sensor error which occurs when the sensor is operating at a temperature which is different from that at which it was calibrated. This effect is equal to 0.175 % of the calibrated scale per 28 °C (values according to the manufacturer's data).

The sensors frequently operate at ± 15°C of the calibration temperature. This means that they operate between 5 °C and 35 °C. The expanded uncertainty due to temperature will thus be as follows at 95% confidence (values according to the manufacturer's data):

$$^{B}U_{Temp} = \frac{2}{3} \times \left(\frac{0.175}{100} \times \frac{15}{28} \times ET \right) \; if \; ET \geq 0.240 \text{ bar} \quad \textbf{Eq. A-87}$$

$$ {}^{B}U_{Temp} = \frac{2}{3} \times \left(0.125 + 0.05 \frac{0.240}{ET} \right) \times \frac{15}{28} \frac{ET}{100} \;\; \text{if } ET < 0.240 \text{ bar} \qquad \textbf{Eq. A-88} $$

Effect of stability over time

The manufacturer makes no specification regarding this effect. The drift is considered to be identical to that specified by the other manufacturers.

The expanded uncertainty due to stability over time will be as follows at 95% confidence:

$$ {}^{B}U_{Stab} = \frac{2}{3} \times \left(\frac{0.1}{100} \times EM \right) \qquad \textbf{Eq. A-89} $$

A.3.3.2.5 Expanded uncertainty of the acquisition system

The equipment used varies considerably from unit to unit. However, one of the following four models is always used:

- HP 3497,
- HP 3852,
- ORION or SCORPIO (Schlumberger),
- IMP (Schlumberger).

The sensitivity of the voltmeter used impacts the physical variable scanned. Various studies carried out at REME have shown that the maximum error which results with these systems is approximately 0.07 % of the calibrated scale.

The following is thus applied regardless of the system

$$ {}^{B}U_{Acq\_Syst} = \frac{2}{3} \times \frac{0.07}{100} \times ET \qquad \textbf{Eq. A-90} $$

A.3.3.3 Expanded uncertainty not associated with environment

By grouping the terms which are not associated with the common environment of the sensors (temperature effect, acquisition system), the expanded uncertainty not associated with the environment is obtained as follows:

$$ {}^{B}U_{excl\_env_{P}} = \sqrt{{}^{B}U_{Int}^{2} + {}^{B}U_{Stab}^{2}} \qquad \textbf{Eq. A-91} $$

A.3.4 Measurement of temperature

A.3.4.1 Expanded uncertainty with respect to temperature measurement

The temperatures are measured using calibrated Pt100 1/3 DIN platinum resistance temperature detectors.

The expanded uncertainty with respect to measurement results from three terms:

- representativeness of the instrument tap,
- uncertainty of the calibrated temperature detector,
- uncertainty of the instrumentation channel.

A.3.4.1.1 Representativeness error

The representativeness error is estimated at 0.5 °C (values according to the manufacturer's data).

A.3.4.1.2 Temperature detector uncertainty

The expanded uncertainty of the calibrated temperature detector is estimated at 0.1 °C.

A.3.4.1.3 Instrumentation channel uncertainty

The maximum error arising due to the voltmeters used in the power plants is 15 E-4 V, giving a maximum expanded uncertainty of 0.045 °C for a 0-10V measurement corresponding to 0-300°C.

A.3.4.1.4 Total expanded uncertainty

The expanded uncertainty with respect to temperature measurement is thus:

$$ {}^{B}U_{T} = \sqrt{0.5^2+0.1^2+0.045^2} \cong 0.5°C \qquad \textbf{Eq. A-92} $$

A.4 Quantification for 100 % Power

This chapter describes the results of the different uncertainty calculations and their relative contributions to the operating function 'measurement of reactor thermal power via thermal balance of the secondary system'. The impact of various potential modifications is also described.

To simplify the description of results, it is assumed that the steam generators operate in identical fashion.

A.4.1. Operating conditions

Table A-1
Rated values at 100% Pn

	Unit	Value
Steam outlet pressure	bar	71.5
Steam dome pressure	bar	73.2
Steam dome Delta P	bar	1.7 ± 0.3
Steam dome moisture	%	0.40 ± 0.04
Steam generator inlet water pressure	bar	75.5
Steam generator inlet temperature	° C	229.5 ± 0.5
Differential pressure	bar	0.818
Steam generator inlet water flow rate	kg/s	601.6
Steam generator blowdown flow rate	kg/s	0.0 ± 0.0

A.4.2. Uncertainties with respect to measurements

A.4.2.1. Uncertainty with respect to steam outlet pressure and inlet water pressure

The calculation parameters for measurement of steam outlet pressure, it will be recalled, are as follows:

Transmitter type = ROSEMOUNT 3051 CG
Maximum measuring range = 0 - 138 bar
Calibrated scale = 0 - 100 bar

Table A-2
Uncertainty with respect to measurement of steam outlet pressure at 100% Pn.

Origin of uncertainty X^i		Expanded uncertainty U_{X^i} [mbar]	Relative fraction $\frac{U_{X^i}^2}{U_{P_{SV}^i}^2}$ [%]
Transmitter	Intrinsic precision of sensor	50	6
	Stability	184	81
	Temperature effect	57	8
Acquisition system		47	5

At 95% confidence, therefore, the following is obtained: $P^{i}_{SV} = 71.5 \pm 0.204$ bar (0.29 %)

The calculation parameters for measurement of steam generator inlet water pressure are as follows:

Transmitter type = ROSEMOUNT 1151 GP
Maximum measuring range = 0 - 207 bar
Calibrated scale = 0 - 100 bar

At 95% confidence, therefore, the following is obtained: $P_{EE} = 75.5 \pm 0.433$ bar (0.57 %)

A.4.2.2. Uncertainty with respect to differential pressure

The calculation parameters, it will be recalled, are as follows:

Transmitter type = ROSEMOUNT 3051 CD
Maximum measuring range = 0 - 2.48 bar
Calibrated scale = 0 - 1.0 bar
Measured value = 0.818 bar
Measured standard deviation = 0. 03272 bar
Number of measurements = 240

Table A-3
Uncertainty with respect to measurement of ΔP^{i}_{EE} at 100% Pn

Origin of uncertainty X^i		Expanded uncertainty U_{X^i} [mbar]	Relative fraction $\frac{U_{X^i}^2}{U_{\Delta P^i_{EE}}^2}$ [%]
Transmitter	Intrinsic precision of sensor	0.500	1.0
	Stability	1.653	11.1
	Effect of static pressure	0.199	0.2
	Temperature effect	0.668	1.8
Calibration		0.700	2.0
Acquisition system		0.467	0.9
Sampling frequency		1.636	10.8
Random variable		4.224	72.2

At 95% confidence, therefore, the following is obtained: $\Delta P^{i}_{EE} = 818 \pm 4.97$ mbar (0.61 %)

A.4.2.3. Uncertainty with respect to flow rate

The calculation parameters, it will be recalled, are as follows:

Throat diameter = 303 ± 0.01 mm
Pipe diameter = 422 ± 0.1 mm

Table A-4
Uncertainty with respect to water flow rate at 100% Pn

Origin of uncertainty X^i	**Unit**	**Expanded uncertainty with respect to** X^i U_{X^i}	**Coefficient of sensitivity** $\frac{\partial Q^i_{EE}}{\partial X^i}$	**Product [kg/s]** $U_{X^i} \frac{\partial Q_{EE}}{\partial X^i}$	**Relative fraction [%]** $\frac{\left(U_{X^i} \frac{\partial Q^i_{EE}}{\partial X^i}\right)^2}{U_{Q^i_{EE}}^{\ 2}}$
Discharge coefficient		0.00513	841.536	4.320	84.5
Throat diameter	m	0.00001	5408.395	0.054	0.0
Pipe diameter	m	0.0001	1032.094	0.103	0.0
Steam generator inlet temperature	°C	0.500	-0.499	-0.250	0.3
Steam generator inlet pressure	bar	0.433	0.034	0.015	0.0
Differential pressure	bar	0.005	367.726	1.827	15.1

At 95% confidence, therefore, the following is obtained: $Q^i_{EE} = 601.6 \pm 4.70$ kg/s (0.78 %)

A.4.3. Uncertainty with respect to reactor thermal power

Table A-5
Uncertainty with respect to reactor thermal power at 100% Pn.

Origin of uncertainty x^i	Unit	Expanded uncertainty U_{X^i}	Coefficient of sensitivity $\frac{\partial W_{th,reactor}}{\partial X^i}$	Product [MW] one SG $U_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}$	Product [MW] all SGs $\sqrt{\sum_i\left(U_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}$	Relative fraction [%] $\frac{\left(U_{X^i}\frac{\partial W_{th,reactor}}{\partial X^i}\right)^2}{U_{W_{th,reactor}}^2}$
Random differential pressure variable	kg/s	1.553	1.774	2.756	5.513	10.29
Primary input					2.000	1.35
Common data					0.021	0.00
Steam generator inlet water pressure	bar	0.383	-0.056		0.021	0.00
Blowdown flow rate	kg/s	0.000	-1.480		0.000	0.00
Atmospheric pressure	bar	0.001	-2.985		0.003	0.00
Common environment of sensors					2.655	2.39
Temperature effect					1.597	0.86
Standard					1.827	1.13
Acquisition system					1.077	0.39
Excluding common environment of sensors, associated with steam generators					15.934	85.97
Steam generator inlet temperature	°C	0.500	-2.814	-1.407	2.814	2.68
Steam generator inlet water flow rate	kg/s	4.416	1.774	7.837	15.674	83.18
Discharge coefficient		0.00513	1493.264	7.665	15.330	79.57
Diameter of device	m	0.00001	9596.9	0.096	0.192	0.01
Diameter of pipe	m	0.00010	1831.4	0.183	0.366	0.05
Steam generator inlet temperature	°C	0.500	-0.886	-0.443	0.886	0.27
Steam generator inlet pressure	bar	0.383	0.060	0.023	0.046	0.00
Differential pressure	bar	0.00239	652.512	1.558	3.116	3.29
Steam outlet pressure	bar	0.191	-0.792	-0.151	0.302	0.03
Pressure difference between instrument tap and steam dome	bar	0.300	-0.792	-0.238	0.475	0.08
Steam dome moisture		0.000	-8.937	-0.004	0.007	0.00

Final uncertainty at 95% confidence:

$$W_{th,reactor} = 4250 \pm 17.2 \text{ MW } (0.40\ \%)$$

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