SENSITIVITY ANALYSIS OF THE SECONDARY HEAT BALANCE AT KOEBERG NUCLEAR POWER STATION

by

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ABSTRACT

At Koeberg Nuclear Power Station, the reactor thermal power limit is one of the most important quantities specified in the operating licence, which is issued to Eskom by the National Nuclear Regulator (NNR). The reactor thermal power is measured using different methodologies, with the most important being the Secondary Heat Balance (SHB) test which has been programmed within the central Koeberg computer and data processing system (KIT). Improved accuracy in the SHB will result in a more accurate representation of the thermal power generated in the core. The input variables have a significant role to play in determining the accuracy of the measured power. The main aim of this thesis is to evaluate the sensitivity of the SHB to the changes in all input variables that are important in the determination of the reactor power. The guidance provided by the Electric Power Research institute (EPRI) is used to determine the sensitivity. To aid with the analysis, the SHB test was duplicated using alternate software. Microsoft Excel VBA and Python were used. This allowed the inputs to be altered so that the sensitivity can be determined. The new inputs included the uncertainties and errors of the instrumentation and measurement systems. The results of these alternate programmes were compared with the official SHB programme.

At any power station, thermal efficiency is essential to ensure that the power station can deliver the maximum output power while operating as efficiently as possible. Electricity utilities assign performance criteria to all their stations. At Koeberg, the thermal performance programme is developed to optimize the plant steam cycle performance and focusses on the turbine system. This thesis evaluates the thermal performance programme and turbine performance.

The Primary Heat Balance (PHB) test also measures reactor power but uses instrumentation within the reactor core. Due to its location inside the reactor coolant system, the instrumentation used to calculate the PHB is subject to large temperature fluctuations and therefore has an impact on its reliability. To quantify the effects of these fluctuations, the sensitivity of the PHB was determined. The same principle, which was used for the SHB sensitivity analysis, was applied to the PHB. The impact of each instrument on the PHB test result was analysed using MS Excel. The use of the software could be useful in troubleshooting defects in the instrumentation.

A sample of previously authorised tests and associated data were used in this thesis. The data for these tests are available from the Koeberg central computer and data processing system.

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DECLARATION

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Signed by candidate

Haydn Boyes

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NOMENCLATURE

T	Temperature	°C
P	Pressure	kPa
H	Enthalpy	kJ/kg
S	Entropy	kJ/kg.K
V	Specific Volume	m^3/kg
C_p	specific heat capacity	JkgK
Q	Flow	m^3/h
$\dot{m}$	Mass flow	kg/s
ρ	Density	kg/m^3
K	thermal conductivity	W mK
λ	expansion coefficient	
η	Dynamic Viscosity	Pa.s
ΔP	pressure difference	kPa
Re	Reynolds number	
W	Heat Energy	MW

ABBREVIATIONS

FW	Feedwater
ISO	International Organisation for standardisation
SHB	Secondary Heat Balance
PHB	Primary Heat Balance
KIT	Computer and data processing System
EPRI	Electric Power Research Institute
VBA	Visual Basic for applications
KBG	Koeberg Nuclear Power Station
RPN	Nuclear Flux Instrumentation system
SG	Steam Generator
APG	Blowdown System
RTD	Resistance Temperature Detector
SAR	Safety Analysis Report
NRC	National Regulatory Commission
USA	United States of America
ANN	Artificial Neural Networks
NPP	Nuclear Power Plant
UT	Ultrasonic
RCP	Reactor Coolant System

CHAPTER 1

INTRODUCTION

1.1 Plant Operation

At Koeberg Nuclear Power Station, the Reactor Coolant System (also called the primary system) is a three loop system and each loop consists of a common reactor vessel and pressurizer with separate steam generators and reactor coolant pumps. The primary function of the reactor coolant system is to transfer the heat from the fuel in the reactor vessel to the steam generators. Refer to Fig 1

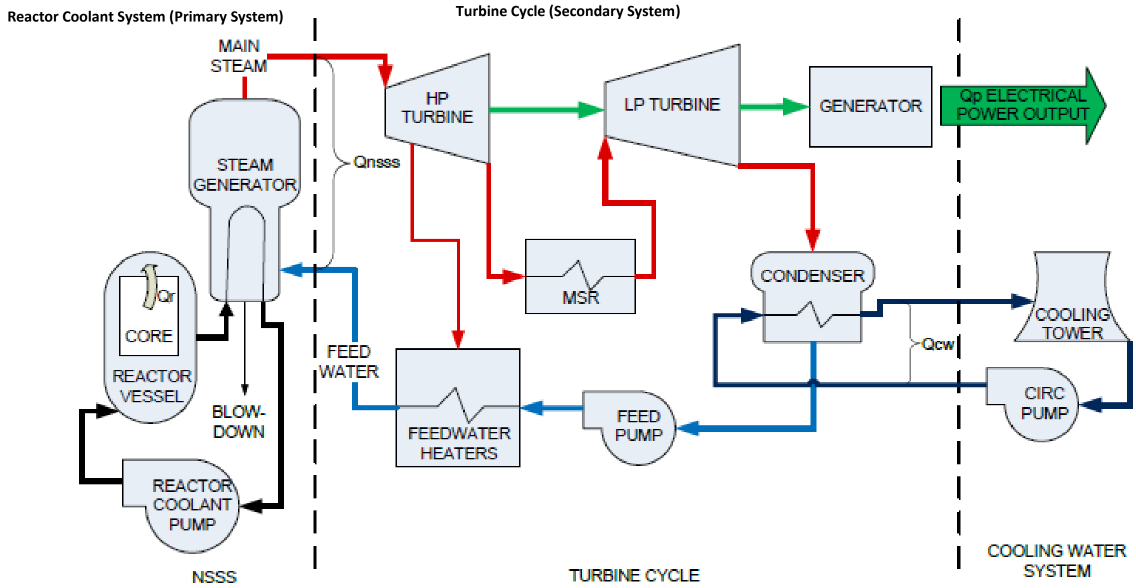

Figure 1.1: Nuclear Power Plant Operation

The turbine cycle or secondary system consists of the turbine, generator, condenser, feedwater heaters and pumps as well as all other components that assist in improving the system efficiency such as reheaters, steam drains etc. The secondary system is not in direct contact with the primary system and obtains its energy via the steam generators. The steam generator is a vertical, shell and tube heat exchanger, with primary water on the tube side. Enthalpy changes in the secondary water in the steam generator are based on the temperature of the feedwater and the properties of the exiting saturated steam.

1.2 Primary Heat Balance (PHB)

The reactor power is measured by using in-core instrumentation. The instrumentation used to calculate the PHB is subject to large temperature fluctuations and as a result, the PHB is not as accurate as other measurement systems.

1.3 Nuclear Flux Instrumentation System (RPN)

The reactor power can be measured by measuring the neutron flux, which is proportional to reactor power. Neutron detectors are placed outside the reactor pressure vessel. The detectors then measure the neutron flux leakage, which in turn is proportional to the neutron flux inside the reactor. Thus, by measuring the neutron flux leakage, it is possible to measure the power generated by the reactor. The detectors are used for control and protection functions. The bombardment of neutrons from the core on the detectors affects its accuracy and causes the readings to drift over time, requiring frequent calibration.

1.4 Secondary Heat Balance (SHB)

The Secondary Heat Balance is an energy balance across the steam generators, which are shell and U-tube type heat exchangers used to transfer the heat from the reactor to the turbine. The SHB uses sensors located on the secondary side of the steam generators and therefore are not subject to the large temperature fluctuations and neutronic disturbances that affect the PHB and RPN.

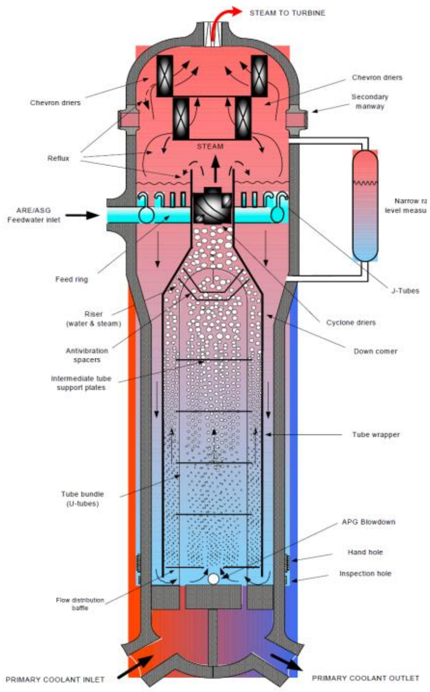

Figure 1.2: Steam generator design

1.5 Steam Generator (SG) Design

The steam generator (see figure 1.2) is a vertical shell and U-tube heat exchanger with integral moisture separating and drying equipment. The reactor coolant flows through the inverted U-tubes, entering and leaving through nozzles located in the hemispherical bottom or channel head, also called lower head or water box, which is divided into inlet and outlet chambers by a vertical partition plate.

Feedwater flows into the steam generator through the nozzle located in the upper head of the SG. It is distributed by means of the feedwater ring through inverted J-tubes, welded to the upper section of the feedwater ring. Steam is generated on the secondary side and flows upward past the tube bundle. It then flows through the moisture separator and chevron driers to the outlet nozzle at the top of the vessel. The tube sheet is a thick metal plate at the bottom of the SG, between the primary water boxes and the tube bundles. Two blowdown pipes are situated just above the main tubeplate to drain the liquid along with solid deposits which collect in this area. This blowdown system is beneficial for health of the SG, by eliminating impurities and reducing sludge buildup.

1.6 Calculation of thermal power

The thermal power of the reactor is determined from the enthalpy balance for each steam generator. Koeberg is a three loop PWR.

$$W_R = W_{SG1} + W_{SG2} + W_{SG3} - W_{\Delta PR} \tag{1.1}$$

W_R = Thermal power of reactor

W_{SG1} = Thermal power of steam generator 1

$W_{\Delta PR}$ = Thermal power added to the primary circuit by primary components.

The thermal power of one steam generator is:

$$W_{SG} = h_V\ (Q_E - Q_P) + h_P Q_P - h_E Q_E \tag{1.2}$$

Where:

h_P = Blowdown enthalpy

h_E = Feedwater enthalpy

Q_P = Blowdown flowrate

Q_E = Feedwater flowrate

h_V = Steam enthalpy,

These calculations are the basics of the enthalpy balance across the SGs. Further calculations (Appendix 2) will be performed to determine the feedwater densities, flow coefficients, etc.

1.7 Problem statement

Improved accuracies in the Secondary Heat Balance will result in a more accurate representation of the thermal power generated in the core. The input variables have a significant role to play in determining the accuracy of the measured power. Due to the dynamic thermal hydraulic characteristics of the secondary system, it is essential to understand the factors that affect each input variable measured by the instrumentation. The data acquisition system also affects the variable and performs an important function in producing highly accurate information. It is therefore vital that the quality of the data is not compromised during the process, when converting the recorded parameters into a digital format. Furthermore, the secondary system is interdependent on the primary system, which has unique thermal hydraulic properties. Considering that this test produces a result which is important to nuclear safety and vital for Koeberg's operating mandate as per the licence, it is prudent to understand the factors that could influence the measurement of reactor power. Once the factors are well understood, it will allow for the optimisation of output power, thereby providing the maximum amount of power to the transmission network for use by the general public.

Although the reactor power is measured by other systems besides the SHB i.e. the Primary Heat Balance (PHB) and Nuclear Flux Instrumentation System (RPN), the SHB uses sensors located on the secondary side of the steam generators and therefore are not subject to the large temperature fluctuations and neutronic disturbances that affect the PHB and RPN. These systems are calibrated using the SHB and therefore the inaccuracies associated with the SHB must be clearly understood.

The source code for the original Secondary Heat Balance content was written in ANSI Fortran 77, which is a very old programming code. Since Fortran was developed in the 1980s, it has been superseded by many programming codes. The version currently in use, is the KIT system which contains unique algorithms within the data processing software to compute the thermal power. Due to the age and obsolescence of the coding language, it is crucial that a newer software programme is used. Computer technology has developed significantly over the years and outdated software creates major challenges when newer hardware is purchased due to defects and failures.

The proposed research is to evaluate the sensitivity that the various inputs have on the Secondary Heat Balance result and other external factors that could influence the outcome, originating either from the secondary or primary systems. This will also aid in troubleshooting and predicting thermal performance should any defects occur on either the instrumentation, primary or secondary systems.

1.8 Objectives

It is intended that the following objectives will be met with the research project:

- Evaluate the current accuracy of the Secondary Heat Balance.
- Assess each input variable that could affect the accuracy of the measured power.
- Evaluate the data acquisition methodology and assess the factors which influence the quality of the data.
- Review the thermal hydraulic characteristics of the water and steam flow inside the steam generator and how it can affect the measurements.
- Review the Thermal Performance programme and its impact on the measurement of the SHB. The research will however focus more on the primary system and the intent of this section is to provide the context of the thermal balance across the steam generator.
- Evaluate the accuracies in the PHB and perform a sensitivity analysis of the PHB.
- The SHB software code will be re-written in Microsoft Excel VBA and Python.

1.9 Scope and Limitations

The research focusses on the Secondary Heat Balance and Primary Heat Balance methods used at Koeberg Nuclear Power Station which is a three loop Pressurised Water Reactor (PWR). There are various methods being used at other power stations in the world to measure reactor power. While many of the stations use a similar method as Koeberg, the assumptions and data used in this report is unique to Koeberg.

1.10 Organisation of the Report

Chapter 1 contains an introduction to the research

Chapter 2 contains the literature review with previous work done on instrumentation accuracy and sensitivity for nuclear plants. Various international standards and position papers are reviewed to ensure the methodology used in the report is in line with international norms.

Chapter 3 contains the details of the Thermal Performance Programme and the method used when calculating the energy balance of the turbine cycle. Even though the Thermal Performance Programme (TPP) is separate from the reactor thermal power programme, it shows how the heat energy from the reactor is used in the turbine cycle.

Chapter 4 shows how the energy balance across the reactor is determined using the Secondary Heat Balance method.

Chapter 5 evaluates the sensitivity of the Secondary Heat Balance to the instrumentation accuracy. It includes various uncertainties and shows the impact on the SHB result.

Chapter 6 looks at the thermal hydraulic effects of the steam generator and the factors that affect the performance of the steam generator. The Secondary Heat Balance test is reviewed by taking in to account these factors and the results are shown.

Chapter 7 provides details of how the PHB is determined and the uncertainties associated with it.

Chapter 8 contains information on the newly developed software programmes.

Chapter 9 contains conclusions based on the discussion, followed by recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Thermal Performance Programme

This programme is intended to maximize unit generator output and optimize plant steam cycle thermal performance under steady state operation while at full power. The programme focuses on turbine performance, efficient operation of the main steam, extraction steam, condensate, heater drains, feed water, and condenser cooling water systems; feed water performance; condenser performance and main generator power metering. While this programme directly interfaces with the core thermal power calculation (SHB/PHB), station service loads and equipment reliability, the administration and control of these technical areas is outside the scope of the thermal performance programme (Salie, 2019). Therefore, the thermal performance programme does not directly address core power calculations or system/component reliability monitoring.

2.2 SHB at Koeberg

The core thermal power is controlled by the operator based on the indications from the on-line (KIT/Ovation) PHB and RPN (ex-core detectors) systems. These indicators are calibrated using the SHB, which is the most accurate representation of core thermal power. An assessment for the need to calibrate the PHB and RPN is performed once a week. Although the SHB is a live, on-line system and provides real time information about the core power, this information cannot be used at random for calibrating the PHB and RPN channels. To use the SHB for calibration purposes, the operator has to ensure that during a selected time window the plant is operating in a stable state (Salie, 2013). The stable state is assessed by the SHB software on KIT and endorsed by the operator. If this has been the case, then the operator can generate the SHB test. To ensure further processing of the SHB test, the operator must state that no interventions have been performed that could affect the SHB test result, e.g. no dilution of the reactor, that could affect the power generated, has taken place over the SHB test time window. If the SHB is determined to be accurate then it will be authorised for use to calibrate the PHB and RPN.

At Koeberg, the PHB is averaged over 1 min and is used to determine whether the maximum core thermal power has been exceeded. The alarm setpoint is set at 100% Pn which equates to 2775 MW. When the PHB has drifted to more than 0.4% of the SHB measured value, it requires calibration because the PHB will be indicating a core thermal power that is greater than the actual value (Maroka, 2015). It is important to note that this does not mean that the PHB will at all times indicate a value greater than the SHB. Due to various parameters used in the calculation of the PHB, such as loop temperatures, RCP pump speeds, grid frequency and loop flow rates, it is very possible for this bias/offset to diminish or increase. The same goes for the SHB input parameters. The reason for the conservative calibration of the PHB is to prevent overpowering events. Koeberg is licensed to produce a maximum power of 2775 MWth and is not allowed to exceed this power level. With the PHB calibrated conservatively, this ensures no overpowering. The accuracy differences between the PHB and SHB will be valuable for later use.

2.3 SHB at other Nuclear Power Plants (NPPs)

Exelon Generation Company, based in the United States of America (USA) performed a calculation to determine the reactor core thermal power uncertainty. The purpose of this calculation was to determine the uncertainty of the calculation performed by the Plant Process Computer (PPC), similar to the SHB at Koeberg. By assessing the various instrument channel loop uncertainties, the total uncertainty could be calculated using the reactor heat balance relationship. It was found that the total uncertainty is 0.347 % of rated reactor thermal power. As per the nuclear regulator in the USA, the National Regulatory Commission (NRC) this uncertainty is considered acceptable because it is within the specified limit of 2%. This research has assisted nuclear plant owners to justify a smaller margin for power measurement uncertainty. This is usually associated with highly accurate feedwater flow measurement instrumentation that replaced older, less accurate instrumentation. The South African National Nuclear Regulator has also authorised a 2% error for power measurements, which is the threshold that is used for the sensitivity analysis in this thesis.

In another study, M. Jabbari et al. (2014) analysed the thermal power of a Russian VVER-1000 reactor by using the secondary heat balance procedure and compared it with other methods such as the in-core and ex-core neutron flux (power) monitoring systems. The calculated values of the reactor thermal power by the SHB method used in his research are comparable with the reactor power measured by the in-core and out-core instruments. In this study the SHB shows a smaller error in comparison with the other methods utilizing the neutron detectors. These detectors are widely used for reactor power measurement and are similar to the detectors used at Koeberg. These devices incorporate a material chosen for its relatively high cross section for neutron capture leading to subsequent beta or gamma decay. In its simplest form, the detector operates on directly measuring the beta decay current following capture of the neutrons. Compared to the stability of the SHB method, the neutron detectors are exposed to the continuous bombardment of neutrons from the core which affects its accuracy and causes the readings to drift over time.

In their research, Mesquita et al (2014) aimed to develop new methodologies for on-line monitoring of nuclear reactor power using other reliable processes besides neutron detectors. One method proposed is the temperature difference between an instrumented fuel element and the pool water below the reactor core. Another method consists of the steady-state energy balance of the primary and secondary reactor cooling loops. A third method is the calorimetric procedure whereby a constant reactor power is monitored as a function of the rate in temperature rise and the system heat capacity. These procedures, fuel temperature, energy balance and calorimetric were implemented in the IPR-R1 TRIGA nuclear research reactor at Belo Horizonte (Brazil) and has become the standard methodology used for the reactor power measurement. With an uncertainty of 4%, the method was proven to be fairly accurate and do not differ significantly from those obtained from conventional nuclear measuring channels using neutron flux. The uncertainty of the SHB method used at Koeberg will be compared to the 4% uncertainty of these methods.

2.4 Instrumentation accuracy

According to the International Atomic Energy Agency (IAEA, 2007), Online monitoring (OLM), involves comparing the steady state output of each channel with its process parameter to assess the deviation of the monitored value from the calculated value of the process variable. This is similar to the first step in traditional calibration methods. Each channel's deviation from its measured parameter represents its variation from the estimated value of the process. The amount of this variation is compared with pre-established acceptance criteria. The acceptance criteria are used to determine instrument performance and operability. Calculations for the acceptance criteria should be done in a manner consistent with the plant assumptions. The SHB should therefore be evaluated against the design assumptions of the plant. In the nuclear industry, the design is based on a worst case accident. It should be demonstrated that the SHB will at all times comply with the design basis. The SHB utilises a transient function that continually monitors deviations in the data from predetermined values.

With traditional calibration methods, instruments remain unattended for long periods. The possibility therefore exists that certain types of instrument failures may remain undetectable. It is therefore important to have the ability to re-analyse the test results if the calibrations show that the instruments were out of tolerance while in use. This is to show that the previous tests met the design assumptions through the full range of measurements.

At the Halden Reactor Project (Ruan D et al. 2002), they investigated available techniques aimed at enhancing the accuracy of flow measurements, and reducing the measurement uncertainty. It was found that in order to better estimate the feedwater flow, an integration of artificial neural networks (ANNs) and cross-correlation analysis can be beneficial. The idea is to develop a "virtual flow meter" based on neural cross-correlation of signals obtained from sensor pairs placed at spatially separated locations along the feedwater pipe. Inputs to the neural virtual flow meter will also include other plant measurements that have an influence on the velocity profile of the fluid in the pipe, e.g., temperature and pressure measurements. These techniques were experimentally developed in a laboratory and is intended to be used for a new type of sensor which will be able to provide better estimates of critical process parameters. One of the main intentions of this project was to enhance the operators' ability in identifying and rectifying problems that affect the thermal performance of nuclear plants and assess various computational intelligence approaches to flow measurements in NPPs.

Traditionally, due to limitations in technology, safety analysis of nuclear power plants were done by using conservative models and resulted in the overdesign of components and systems. In recent years, thanks to the accuracy of computational tools, safety analysis can be performed by using simulations which are more realistic of actual plant conditions. There are however, some uncertainties associated with these simulations and therefore these must be quantified. According to Gonzales (2018), the source of the uncertainties can be either the input parameter or the nuclear reactions (i.e reactivity) or thermo-hydraulic effects, all of which can affect the output. The research paper reviews the simulation tools SEANAP and COBAYA4 to analyse the accuracy of the simulations. This is done by interfacing with the physics and thermo-hydraulic codes as well as performing nodal analysis and predictive sampling. The research shows that uncertainties were around 0.5% for the reactivity simulations but increased to 7% if the reactor was unstable. It was found that the most significant contributor to the uncertainty was the feedwater temperature because it had the most significant effect on reactivity. The difference between this research and the uncertainty for the SHB, is that the reactivity does not impact on the SHB output because it uses instrumentation located on the secondary system and an increase (or decrease) in feedwater temperature will not significantly affect the other parameters on the secondary system. The feedwater temperature however has a major impact on reactivity in the primary system due to the moderator coefficient of the water.

In steam generators, special attention is given to preserving the boundary between the contaminated water in the primary reactor coolant system and the water-steam mixture in the secondary system. It is important for nuclear safety that these components are reliable and able to perform their function in accident conditions. Results obtained by using simulation software RELAP5, developed for safety analyses of NPPs, showed that the steam generator design is able to effectively transfer heat in accident conditions originating in the primary system or the secondary system (Sadek and Grgic 2017). It is therefore important that thermal energy measurements across the steam generator reflects the actual heat transfer so that the design assumptions are not challenged. This ensures that the steam generator is not over stressed which could affect the performance of the steam generator in the event of an accident.

One of the measurements which has a significant impact on SG thermal performance is the feedwater flow. The thermal power in the SG is very sensitive to the feedwater flow. This feedwater passes through the steam generator via a downcomer. The downcomer flow in SGs can provide unique fitness for service and performance indicators related to overall thermo-hydraulic performance and safety indicators. It highlights areas of degradation which is useful to the plant engineer, who can recommend alterations. Janzen et al. (2014) reviews the benefits of downcomer-flow measurements to nuclear power plant operators and describes methods that are commonly used. The research summarizes the history and state-of-the-art of technology such as non-intrusive ultrasonic (UT) systems as well as applications at nuclear power plants. These measurements can be used to determine the existence of steam carry over, assess the effectiveness of steam-generator cleaning and also provide useful information on transient/accident behaviour. In summary, the paper concludes a 10% level of uncertainty as appropriate for UT flow measurements. The results also suggest that the intrinsic accuracy of the UT measurements when optimized at room temperature may be somewhat better than 10%. The best results show a relative error of ±8 %. Considering that the SHB is sensitive to feedwater flow measurements, it is important to understand the impact that the uncertainty of the feedwater flow will have on the thermal energy measurement. At Koeberg, an orifice is used for feedwater flow measurements. The accuracy of the orifice will be compared against UT flow measurements.

The increasing age of existing NPPs are forcing the global nuclear power industry to confront the challenges of ageing in instrumentation. Temperature, humidity, radiation, electricity and vibration all contribute to ageing and affects most instrument & control components. The traditional aging management method is to replace equipment which requires the plant to be shut down. Recent ageing management technologies, collectively known as online monitoring (OLM), enable plants to monitor the condition and aging of their installed instrumentation while the plant is operating. OLM techniques include low and high-frequency methods for noise analysis or methods based on diagnostic sensors for vibration analysis or methods that inject a test signal into the component under test. Hashemian, (2010) reviewed the various OLM methods and investigated possible improvements.

OLM emerged in the 1980s as a way to extend the intervals between calibrations of pressure transmitters. In the 1990s, the nuclear industry adopted OLM techniques for equipment condition monitoring. This included the monitoring of reactor internals, detecting leaks, verifying the thermal performance of plants, measuring the stability of the reactor core, anticipating rotating equipment failures, checking that valves are operating correctly and identifying loose parts within reactor systems.

There are some OLM tools available for the protection of industrial monitoring systems against measurement errors but not all industries utilize them. Madron et al. (2015) concentrated on the protection of key results against systematic errors by using on-line monitoring techniques. It was found that errors can be hidden in flow measurements and in the properties of steam and water. The research attempted to identify errors while ensuring accurate measurements and proposed a simple method for OLM. This method is based on a linearization model and its success depends on the magnitude of the deviation from the non-linear calibrations. For the SHB sensitivity analysis, a similar method will be considered for the linearity analysis of the instrumentation.

The use of OLM methods for applications like monitoring the accuracy of pressure, level, and flow transmitters has been formally approved by the U.S. and British regulatory authorities. The Sizewell B plant in England anticipates significant savings per operating cycle when OLM technologies are fully implemented. Because OLM methods are non-intrusive and in situ (the instrument is not removed from the process), they can be used to monitor processes that are inaccessible while the plant is in-service and avoid unnecessary maintenance to instrumentation that show no ageing issues. OLM is making it easier to manage instrumentation ageing at NPPs. At Koeberg the SHB contains a watchdog function which is similar to an OLM tool. It automatically verifies the data that is extracted from KIT to ensure that data used in the SHB is accurate. This function will be evaluated.

2.5 International Standards

Nuclear Generation Group, Nuclear Engineering Standards (Vande Visse, 1997) provides the standard for the Analysis of Instrument Channel Setpoint Error and Instrument loop accuracy. According to them, the measurement process includes imperfections that causes errors in the test result. Errors may be of two types, random or systematic. Random error results from unpredictable variations and will be seen if there are repeated discrepancies in the measured parameter. Random errors of a measurement cannot be compensated by correction. They can be minimized or reduced by increasing the number of samples, increasing the accuracy of the instrument or by incorporating a measurement procedure that reduces the sources of error. Similarly, systematic error also cannot be eliminated. Systematic errors are from known sources and can be quantified. A correction factor may be applied to the measurement result to compensate for this type of error. An error in the test result is not the same as measurement uncertainty, and the two should not be confused. Both of these phenomena are considered in this thesis.

The Electric Power Research institute compiled the Thermal Performance Engineering Handbook (Mantey, 2013) where it provides guidance to thermal performance engineers when investigating the cause of energy losses. It also proposes new ways to increase electric power output. This report provides detailed descriptions of the components in the nuclear plant heat cycle and includes the various errors associated with the instrumentation associated with power measurement.

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. ISO 5167 is a standard that specifies the requirements for measuring flows using orifice plates. It covers the geometry, installation procedure and operating conditions of orifice plates when they are used to measure the flowrate in a pipe. This setup is utilised in the SHB. It also gives information for calculating the uncertainties that are associated with the configuration and equipment. Because the SHB is very sensitive to the measurement of the feedwater flow, this standard will be applied to the sensitivity analysis.

2.6 Statistical analysis

In order to quantify the uncertainty in instrumentation or systems, the analysis of the measured parameter must show some variation. By using numerical simulation tools such as Computational Fluid

Dynamics (CFD), these uncertainties can be computed. Otgonbaatar (2016) determined the uncertainty by using the normal probability distribution for the parameter which is measured. The normal probability distribution is the probability that an instrument will produce a certain value based on its manufactured accuracy. Additionally, a non-parametric formulation is used, which allows the quantification and integration of uncertainties that are not expressed by the normal probability distribution. As per the Wikipedia definition, "*Non-parametric models differ from parametric models in that the model structure is not specified but is instead determined from data. The term non-parametric is not meant to imply that such models completely lack parameters but that the number and nature of the parameters are flexible and not fixed in advance"* This methodology was based on the analysis of four industrial case studies where the measured parameters included mass flow rate, steam generator recirculation ratio, cooling tower deformation and NOx emissions. The research shows that these methods can be applied to all tests to express uncertainty. The methodology is however extremely complex and the coding should be obtained for its use. Contributing to the complexity is that the method must be used for each input parameter and the coding in CFD (eg Monte Carlo method) has not been developed for the other measurements in the SHB and is therefore beyond the scope of this thesis.

CHAPTER 3

CONTROL VOLUME ENERGY BALANCE OF THE TURBINE CYCLE

3.1 Thermal Performance Programme (TPP)

At any power station, thermal efficiency is essential to ensure that the power station can deliver the maximum output power while operating as efficiently as possible. Electricity utilities assign performance criteria to all their stations. At Koeberg the thermal performance programme is developed to optimize the performance of the steam cycle. This cycle includes the turbines and all steam systems linked to the turbine such as the extraction steam system, condensate system, heater drains system and feed water heating system.

The Thermal Performance Programme (TPP) is separate from the reactor power programmes. The measurement of the reactor thermal power is done using three different methodologies, namely the Primary Heat Balance (PHB), the Reactor Neutron Protection System (RPN) and the Secondary Heat Balance (SHB). Details of these were provided in Chapter 1. The difference between the TPP and the SHB is that the TPP is focussed on the secondary systems of the plant to ensure that the turbine and auxiliary systems perform as expected, whereas the SHB uses the secondary system parameters to determine the primary system power. This thesis will focus more on the primary system and the intent of this section is to provide the context of the thermal balance across the steam generator and how the steam system is managed.

The TPP consists of five elements that provide a holistic view of the thermal performance. These elements are necessary for the planning, execution and monitoring of a successful programme.

i. **Baseline and modelling**
Baseline values are required for key performance indicators. The baseline values are given below in table 3.1.

NSSS Power	%	25%	50%	75%	100%
Steam Flow	Kg/s	338.0	702.7	1098.6	1510.0
Final Feed Temperature	°C	167.9	186.8	205.8	219.3
MWe electric	MWe	205.7	472.6	734.1	997.4
HP exhaust pressure	Bar	2.7	5.6	8.3	11.5
Condensate flow	Kg/s	338.0	502.5	769.2	1043.6
Feed pump suction or discharge flow	Kg/s	338.0	702.7	1098.6	1510.3
Feed pump steam flow	Kg/s	3.4	6.5	9.7	13
Heating steam flow	Kg/s	53.4	87.5	108.7	120.3

Table 3.1: Baseline model for various power levels

The information in the table is from the turbine manufacture (Choquart, 2010), who also provides the baseline values for enthalpy and entropy diagrams. The calculations performed in this thesis are compared to the manufacturer supplied baseline values.

ii. **Performance goals**

The expected performance will differ at each station based on criteria set by the owner of the plant. At Koeberg, these performance goals are defined by Eskom and documented in the station performance contracts. Koeberg is accountable to the Eskom CEO on meeting these targets.

iii. **Monitoring and trending**

Monitoring consists of periodic reviews of thermal performance data. This is determine if current conditions are in line with expected targets. Monitoring is also used to verify the effectiveness of corrective actions. Trending comprises of specific trends that show the critical parameters which are used to ensure optimum thermal performance. Sufficient trending is the backbone of a good thermal performance programme.

iv. **Search and recovery**

Search and recovery is an aspect of the programme that is used only when there is an identified defect or deficiency in generation capacity. An investigation is initiated and specific troubleshooting tools are implemented to identify the root cause. When the investigation is concluded, it will specify a series of corrective actions which must be done to correct the deficiency.

v. **Communications/reporting**

All the elements of the programme require certain documentation. All documentation are kept for the life of the station and are subject to audits by the Quality Assurance department.

3.2 Turbine Performance

The turbine consists of a double flow high pressure (HP) cylinder and three double flow low pressure (LP) cylinders. From the SG, the main steam flows to the HP cylinder of the turbine. Inside the HP cylinder, steam is divided into two equal flows, each going through seven expansion stages. The expanded steam flows into reheaters before entering the three LP cylinders. Immediately after entering each LP cylinder, the steam flows through seven expansion stages and is exhausted into the condenser.

The turbine main steam system is a system of pipe-work and valves that is used to convey steam from the steam generator to the high-pressure and low-pressure cylinders of the main turbine. The route is described in three stages (refer to Figure 3.1):

- convey saturated steam from the SG to the turbine high-pressure cylinder (7),
- convey wet steam from the exhaust of the high-pressure cylinder to the Moisture Separator Reheater (8),
- convey superheated steam from the moisture separator re-heaters to the low-pressure cylinders of the turbine (9).

In addition to the main flow-path through the turbine, the steam system also supplies steam to various secondary consumers. We will not cover all the other steam flow paths in this thesis. What is important here, are the main processes, which are covered. Figure 3.1 is a simplified diagram of the cycle at Koeberg. The turbine reheat and feedwater systems are more complex than shown below but

Figure 3.1 is used as an illustration of the main steam system. Turbine performance is not the main focus of this thesis and therefore various processes have been simplified to show only certain components and the entry and exit enthalpies at those components (refer to Appendix 1). For example, at Koeberg, there are fourteen feedwater heaters but the diagram below only shows two. These two heaters represent the heat produced by all the other feedwater heaters. Key measurements were taken at the points indicated below to obtain the enthalpy values and the schematic represents the position of measured points. See figure 3.2 below. The analysis performed in Appendix 1 is compared with the data provided by the manufacturer of the turbine.

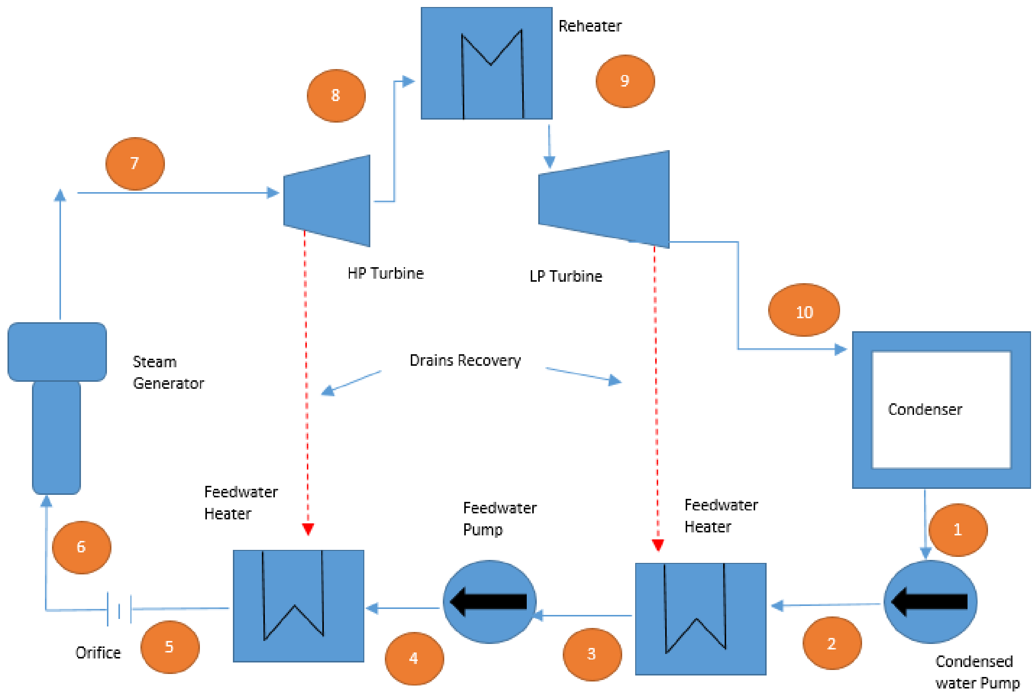

Figure 3.1: Schematic representing the secondary cycle

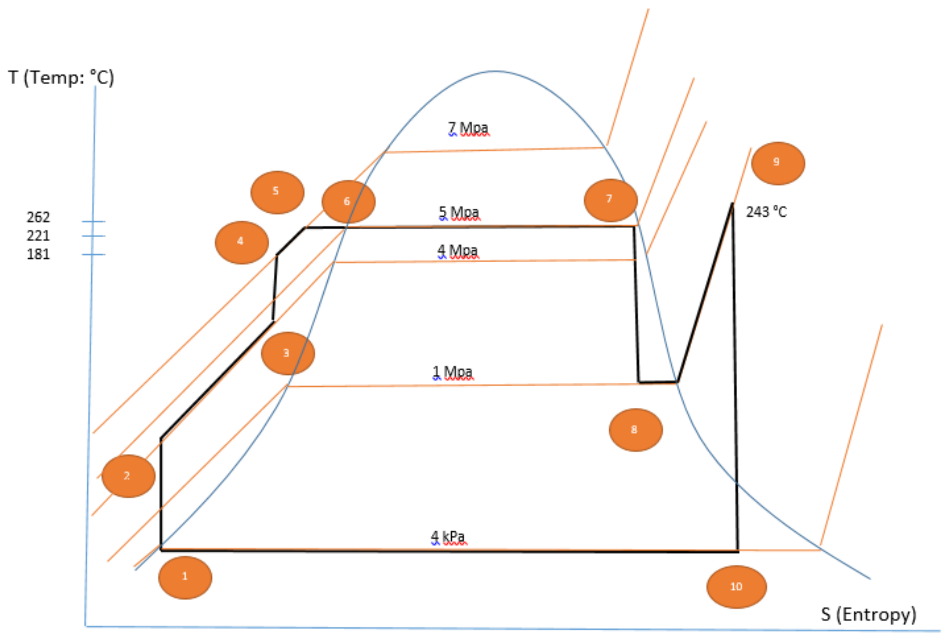

Figure 3.2: T-S diagram

Using actual plant, the Enthalpy at each point was calculated and compared to the manufacturer's specifications to determine current performance versus expected performance. The energy distribution within the Rankine cycle is clearly shown in the results. The results are shown below in Table 3.2. The manufacturer values (Alstom, 2010) can be found in Appendix 1.

Enthalpy (kJ/kg)			**Difference (%)**
At point	**Manual Calculation**	**Manufacturer supplied value**	
1	124.68	Not given	N/A
2	128.7	131.1	-1.83
3	767.7	770.0	-0.29
4	771.5	774.2	-0.34
5	948.3	949.2	-0.09
6	948.3	Not given	
7	2790.1	2792.9	-0.10
8	2513.6	2582	-2.64
9	2923	2924.3	-0.04
10	2092.4	2210.8	-5.35
		Average difference	-1.34

Table 3.2: Manual calculations versus manufacturer specifications

3.3 Conclusion

Thermal efficiency is essential to ensure that the power station can deliver the maximum output power while operating as efficiently as possible. The Thermal Performance Programme is focussed on the secondary systems of the plant to ensure that the turbine and auxiliary systems perform as expected. The TPP consists of five elements that provide a holistic view of the thermal performance of the plant. These include baseline modelling, performance goals, monitoring, search/recovery and reporting.

Manual calculations were performed to determine the energy balance at various stages within the cycle. These values were compared with the manufacturer supplied data. The average difference between the two was found to be -1.3 %. With a small difference like this, the data from the manual calculations can therefore be used for the development of other programmes. In Chapter 4 it will be seen how the manual calculations of the SHB can be used to develop Excel and Python programmes. These would be especially useful for fault finding troubleshooting within the cycle. For example, the input parameters for any of the feedwater heaters can be used to determine if the heater is producing the expected output energy. If not, then corrective actions can be developed to re-establish the expected performance.

CHAPTER 4

ENERGY BALANCE OF THE REACTOR

4.1 Background

The Reactor Coolant System (also called the primary system) consists of the reactor vessel, the steam generators, the reactor coolant pumps, a pressurizer, and the connecting piping (Eskom, 2019). A reactor coolant loop contains a reactor coolant pump, a steam generator and the piping that connects these components to the reactor vessel. The primary function of the reactor coolant system is to transfer the heat from the fuel to the steam generators which then converts the feedwater to steam.

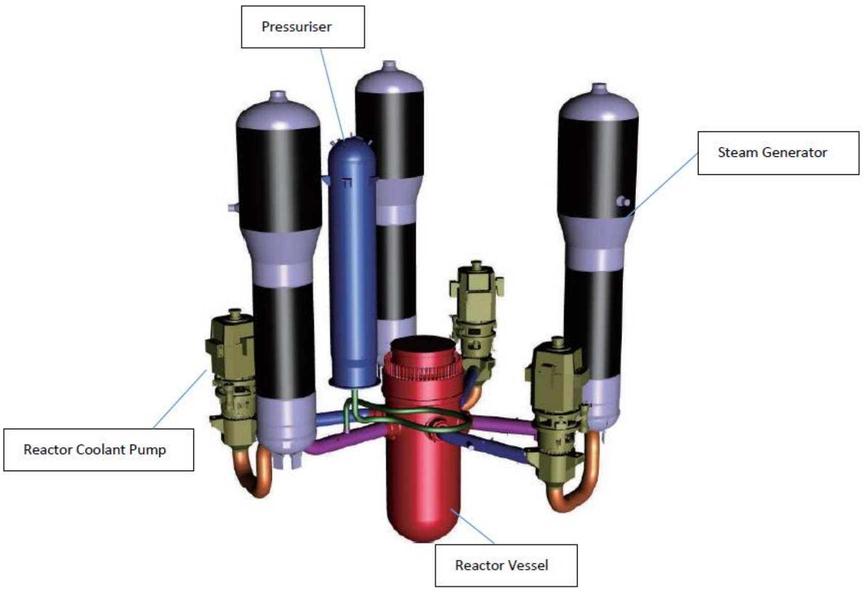

Fig 4.1: Layout of the reactor Coolant system of a three loop PWR
(Courtesy of Eskom)

4.2 Secondary Heat Balance

The thermal power of the reactor is determined from the enthalpy balance for each steam generator (Salie, 2013 ; Maroka, 2015).

$$W_R = W_{SG1} + W_{SG2} + W_{SG3} - W_{\Delta PR} \quad (4.1)$$

Where:

W_R = Thermal power of reactor

W_{SG1} = Thermal power of steam generator 1

$W_{\Delta PR}$ = Thermal power added to the primary circuit by primary components.

The thermal power of one steam generator is:

$$W_{SG} = h_V\,(Q_E - Q_P) + h_P Q_P - h_E Q_E \quad (4.2)$$

Where:

h_V = Steam enthalpy,

h_E = Feedwater enthalpy

Q_E = Feedwater flowrate

h_P = Blowdown enthalpy
Blowdown is the extraction of impurities from the tubesheet. This is done by allowing some feedwater to be extracted from a bleed off pipe located just above the tubesheet.

Q_P = Blowdown flowrate

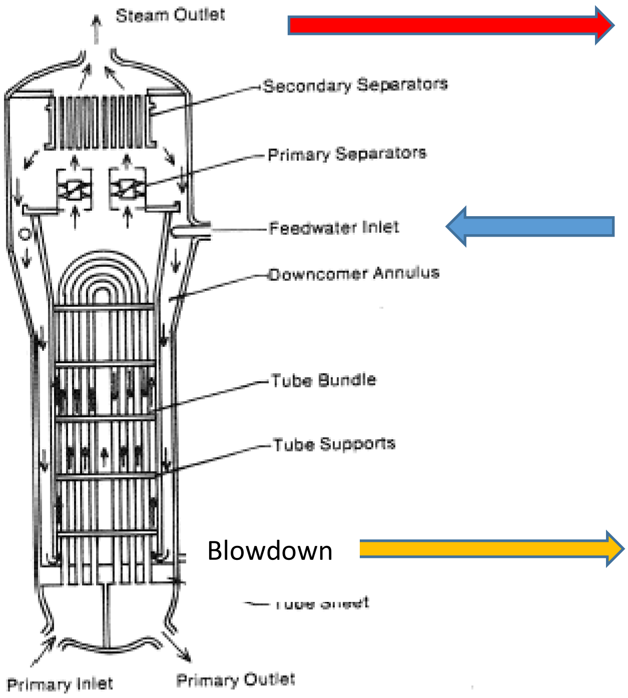

Fig 4.2: Steam Generator

The information used in this research was collected from actual plant data at Koeberg. The information was recorded from Reactor no. 2 (Unit 2) on 10 January 2020 at 23:59.

When these values were recorded, the reactor was at 100% power. The values used earlier in this thesis to calculate the thermal balance of the turbine, was at a similar plant state. The calculations based on Rawoot, 2015 is shown in Appendix 2. The measured inputs are shown below in Table 4.1. These values were used to perform the energy balance in the Secondary Heat Balance Equation.

Table 4.1: SHB measured inputs

Parameter	SG1	SG2	SG3
Feedwater Pressure (kPa)	5382.19	5382.19	5382.19
Feedwater Temp (°C)	220.39	220.34	220.43
Blowdown Flow (kg/s)	3.77	3.77	3.77
Steam Pressure (kPa)	5004.0	5005.4	5015.7
Steam Temp (°C)	263 .1	264.4	265.3
Steam quality	0.9975	0.9975	0.9975

4.2.1 Steam Enthalpy at SG_1 outlet (h_v)

The steam is wet saturated vapour (by interpolation):

$$h_v = h_f + x\, h_{fg} \tag{4.1}$$

Where:

h_f = saturated enthalpy

h_{fg} = Enthalpy difference

x = dryness fraction (refer to Safety Analysis report II-3.3.3.1.1

$$s_6 = s_f + x\, s_{fg} \tag{4.2}$$

Where:

s_f = *saturated liquid Entropy*

s_{fg} = *Entropy difference*

4.2.2 Feedwater Enthalpy at SG1 inlet (h_E)

Feedwater enthalpy is saturated liquid and found by interpolation

4.2.3 Feedwater Flowrate at SG_1 inlet (Q_E)

Feedwater flowrate is measured using a differential pressure transmitter fitted across an orifice plate which is located in the feedwater pipeline. The feedwater mass flowrate is the dominant factor in determining the power output for the steam generator. Slight changes in this parameter will influence the outcome significantly and therefore a lot of focus will be given to this parameter (Electricite de France, 2001). The sensitivity of the various elements in the feedwater flowrate equation will be evaluated later in this thesis.

As a guideline, the ISO Standard ISO 5167, 2003 was used for the calculation. This standard was adopted by the various utilities across the world. Koeberg was constructed by a French consortium and the French national utility EDF has also adopted the ISO standard for feedwater calculations.

$$Q_E = \alpha \varepsilon \pi \frac{d^2}{4} \sqrt{(2.\Delta P.\rho} \tag{4.3}$$

Where:

α = *Flow coefficient*

ε = Expansion coefficient = 1 for incompressible fluids

d = diameter of orifice

ΔP = Differential pressure across orifice plate

ρ= Density of feedwater

4.2.4 Diameter of orifice (d)

Due to high temperatures the diameter of the orifice will change due to thermal expansion. A fixed expansion coefficient for stainless steel is used.

$$d = d_0 (1+\lambda d(t_E - t_{d0}) \tag{4.4}$$

Where:

d_0 = measured diameter at room temp = 257,5 mm

λd = expansion coefficient for Stainless steel = 0,000019

t_E = Feedwater temperature

t_{d0}= room temperature = 23 °C

4.2.5 Inner diameter of pipe (D)

$$D = D_0 (1+\lambda D(t_E - t_{D0}) \tag{4.5}$$

Where:

D_0 = measured diameter at room temp = 369,4 mm

λD = expansion coefficient for Carbon steel = 0,0000128

t_E = Feedwater temperature

t_{d0}= room temperature = 23 °C

4.2.6 Diameter ratio (β)

$$\beta = \frac{d}{D} \tag{4.6}$$

4.2.7 Feedwater density (ρ)

At 220,3 °C

$$Density,\ \rho = \frac{mass}{Volume} \tag{4.7}$$

4.2.8 Flow coefficient (α)

$$\alpha = A + B.\sqrt{\frac{10^6}{Re_D}} \tag{4.8}$$

Where A and B are variables based on the diameter ratio.

4.2.9 Reynolds number (Re)

$$Re_D = \frac{4Q_E}{\pi\eta D} \tag{4.9}$$

Where

η = Dynamic Viscosity at 220 °C = 0,0001219 Pa.s

D = inner diameter of pipe = 370,33 mm

Q_E = Feedwater flowrate

The circular reference requires an iterative calculation to determine the flow coefficient, α. To determine the feedwater flowrate, we assume an initial value for α = 0,7. Continue to substitute α into the calculation for Q_E until the difference between successive values for α is smaller than 0,000001. Use the final Q_E value.

4.2.10 Blowdown Enthalpy at SG_1 (h_p)

There is however recirculation flow in the SG, due to the wet steam at the top of the SG as per the Koeberg Safety Analysis Report, mixing with the saturated feedwater. This mixing results in more heat energy being absorbed in the feedwater and consequently ejected through the blowdown line. Considering the recirculation flow, the enthalpy of the blowdown can be calculated using the saturated fluid in feedwater and multiplying it by a recirculation factor. The recirculation factor is calculated as a function of the relative thermal power. Appendix 16 shows the relationship between the Recirculation Ratio in the SGs and the level of relative thermal power. The equation for the curve is given by:

$$rf = 18.189 - (0.2582 * Qrel_{t-1}) + (0.0011 * Qrel^2_{t-1}) \quad (4.10)$$

where,

rf = the recirculation factor, unitless

Qrelt-1 = the relative thermal power calculated in the previous execution cycle, %

Blowdown Enthalpy

$$h_{BD} = ((h_{FW}+(rf \times h_f))/(1+rf) \quad (4.11)$$

where,

h_{BD} = the blowdown enthalpy

h_{FW} = the feedwater enthalpy (kJ/kg)

rf = the recirculation factor (unitless)

h_f = the enthalpy of the saturated fluid (kJ/kg)

4.2.11 Blowdown Flow rate at SG_1 (Q_p)

Blowdown flowrate is measured using a flowmeter:

After calculating all variables for Equations 4.1 to 4.9, the thermal power of one steam generator is:

$$W_{SG} = h_V\,(Q_E - Q_P) + \,h_P Q_P - \,h_E Q_E \tag{4.12}$$

The results of the manual calculations are shown below in Table 4.2. These results are given per steam generator.

Table 4.2: SHB results

SHB Manual Calculations (Unit 2 - 10 January 2020)			
Parameter	**SG 1**	**SG 2**	**SG 3**
Steam Enthalpy (kJ/kg)	2791.31	2792.18	2791.10
Blowdown Enthalpy (kJ/kg)	1108	1108.84	1107.9
Feedwater Enthalpy (kJ/kg)	945.0	946.07	946.48
Feedwater flow (kg/s)	504.83	505.89	495.27
TotalThermal Power (MW)	921.52	922.87	905.86
Primary pump power(MW)	10		
TOTAL	2740.25 MW (98.75%)		

4.3 Independent verification of the manual calculations

As per the license conditions, Koeberg is required to verify the thermal power every day and perform an independent verification with the SHB once per week. The plant operators in the main control room, continuously monitor the thermal power by using various indications available to them and perform an 'unofficial' SHB every day (Solomon, 2018). Understandably, it would be very tedious to manually calculate the SHB every day and therefore various software programmes are used. In this section we will compare the manual calculations performed in the previous section with the official SHB programme on KIT. Furthermore we will also perform independent verifications with alternate computer codes.

4.3.1 Comparison with the Official Secondary Heat Balance (SHB) software used

The same inputs used in Table 4.1 were used in this test to ensure that the results are comparable. Refer to Appendix 3 for an example of an SHB report that is produced on KIT. The first report is generated by the Operating Department and provides all the measured inputs and final results, as computed by KIT. The second report is generated by the testing department who evaluate the inputs and confirm if the results are acceptable as per the criteria specified in their procedure. They will determine if any plant parameters should be changed. Because the SHB uses sensors located on the secondary side of the steam generators, the test is not subject to the large temperature fluctuations and neutronic disturbances which affect the PHB and RPN systems. These systems will then be calibrated based on the results from the SHB. The third report is generated by the Engineering Department and provides an expert analysis of the SHB. The Engineers have information on the various programming variables and setpoints that could invalidate the test (Adams, 2004). These setpoints are checked to determine if any drift or software failures has occurred. They utilise an Excel spreadsheet to perform the analysis.

The results of the manual calculations performed in section 4.2 was compared with the results from the SHB programme. Table 4.3 contains the comparison.

Table 4.3: Comparison of results: Manual calculations versus SHB Programme

Parameter	SG 1		SG 2		SG 3	
	Calculated	SHB Prog	Calculated	SHB Prog	Calculated	SHB Prog
Steam Enthalpy (kJ/kg)	2791.31	2794.19	2792.18	2794.18	2791.10	2794.1
Blowdown Enthalpy (kJ/kg)	1108	1107.73	1108.84	1107.61	1107.9	1108.2
Feedwater Enthalpy (kJ/kg)	945.0	946.93	946.07	946.07	946.48	946.48
Feedwater flow (kg/s)	504.83	502.44	505.89	503.09	495.27	493.97
Thermal Power (MW)	921.52	919.74	922.87	921.37	905.86	904.31
TOTAL Thermal Power comparison	**Calculated: 2740.25 MW (98.75%)** **SHB Programme: 2735.4 MW (98.58%)** **Overall Difference: 0.17%**					

The difference between the manual calculations and the SHB programme is 0,17%. This shows a good correlation between the manual method and automated SHB.

4.4 Compilation of SHB using alternate coding systems

In order to provide more flexibility in the analysis of the SHB and to provide the capability for future development, the source code was re-written in Microsoft Excel VBA and Python. The new code will not replace the official SHB test on KIT but will assist with research and fault finding. It will also be used to identify improvement opportunities. One of the changes includes the use of different steam tables. Currently, the enthalpies, specific volume and dynamic viscosity are obtained from the ASME 1997 steam property calculations which are programmed in the automated SHB. Whereas Excel and Python uses later versions of the steamtables and therefore it is expected that the results will differ slightly (Verein Deutscher Ingenieure -VDI, 2010; Mantey, 2013).

4.4.1 Microsoft Excel VBA Code

The SHB was programmed into Excel using the formula presented earlier in this section. Appendix 17 contains additional detail and screenshots of the VBA code. This was done by following these steps:

- Importing of data
  The KIT system is a central computer system that interfaces with all plant instruments to provide data acquisition, processing and display of the data to plant personnel. Some parts of the system has a Human-Machine Interface (HMI) where the plant can be remotely operated. The SHB programme extracts data from KIT and then performs the calculations. To create a new programme, it should be able to extract the data from KIT. In order to achieve this, a query was written in Excel to perform a call-up function from the data in KIT.
- Once the data was imported to Excel, the average of each parameter was calculated. The average value was then used in a separate worksheet where all the averaged values were collated. These average values would be used as the SHB inputs.
- In order for Excel to use the steam tables it must be imported as an “Add-in”. The Add-in named “water97-v13” was loaded.
- The calculations were programmed in the Excel worksheet.
- A VBA code was compiled for the iterative calculation required for the feedwater flow.
- The results were compared with the official SHB programme and the manual calculations. Table 4.4 shows the comparison of the results.

Table 4.4: Comparison of results: Excel VBA vs manual calculations and SHB Programme for SG1

SG 1			
Parameter	**Calculated**	**SHB Prog**	**MS Excel VBA**
Steam Enthalpy (kJ/kg)	2791.31	2794.19	2794.19
Blowdown Enthalpy (kJ/kg)	1108	1107.73	1107.73
Feedwater Enthalpy (kJ/kg)	945.0	946.93	946.93
Feedwater flow (kg/s)	504.83	502.44	502.44
Thermal Power (MW)	921.52	919.74	919.74
TOTAL Thermal Power comparison (for 3 loops)	**2740.25 MW (98.75%)**	**2735.4 MW (98.58%)**	**2735.4 MW (98.57%)**

The results show that the Excel VBA code is comparable with the SHB programme showing a difference of 0.01% for the total thermal power. During the compilation, the following was noted for improvement:

i) The orifice and pipe diameters must be manually inserted. An improvement would be to include these parameters in KIT for automatic import into the SHB programme.
ii) The orifice and pipe thermal expansion coefficients must be manually inserted. An improvement would be to include these parameters in KIT for automatic import into the SHB programme.
iii) The blowdown recirculation factor must be manually inserted. An improvement would be to include these parameters in KIT for automatic import into the SHB programme.

4.4.2 Python Code

The SHB was programmed into Python using the formula presented earlier in this section. Appendix 18 contains further detail and screen shots of the Python coding. This was done by following these steps:

- Importing of data
  The KIT system is a central computer system that interfaces with all plant instruments to provide data acquisition, processing and display of the data to plant personnel. Some parts of the system has a Human-Machine Interface (HMI) where the plant can be remotely operated. The Python programme extracts data from KIT by using the same Excel file that was used in the VBA code. See 4.4.1.1 above.
- Once the data was imported to Excel, the average of each parameter was calculated. The average value was then used in the Python coding as the SHB inputs.
- In order for Python to use the steam tables it must be imported. The file “CoolProp” was used and imported.
- Various other files were needed for the functions associated with the equations and use of the Excel spreadsheets. Files “PropsSI”, “math”, “pi”, “xlsxwriter” and “xlrd” were inported.
- The Excel spreadsheet with the data was indexed for use
- The feedwater flow calculation was programmed using a while loop for the numerous iterations.
- The output was automatically written into an Excel file.

The results were compared with the official SHB programme, the manual calculations and the Excel VBA coding. Table 4.5 shows the comparison of the results.

Table 4.5: Comparison of results: Python versus the other methods for SG1

Parameter	SG 1			
	Calculated	**SHB Prog**	**MS Excel VBA**	**Python**
Steam Enthalpy (kJ/kg)	2791.31	2794.19	2794.19	2794.19
Blowdown Enthalpy (kJ/kg)	1108	1107.73	1107.73	1112.89
Feedwater Enthalpy (kJ/kg)	945.0	946.93	946.93	945.43
Feedwater flow (kg/s)	504.83	502.44	502.44	502.49
TotalThermal Power (MW)	921.52	919.74	919.74	920.6
TOTAL Thermal Power comparison	**2740.25 MW (98.75%)**	**2735.4 MW (98.58%)**	**2735.4 MW (98.57%)**	**2737.16 MW (98.64%)**

The results show that the Python code is similar to the SHB programme with a difference of 0.06%. During the compilation, the following was noted for improvement:

i) The Python code extracts data from Excel and therefore the Excel interface with KIT is still required.

ii) Similar to the Excel VBA programming, the orifice and pipe diameters as well as the thermal expansion coefficients must be manually inserted. An improvement would be to include these parameters in KIT for automatic import into the SHB programme. The blowdown recirculation factor must also be manually inserted.

4.5 SHB accuracy

The total accuracy of the SHB measurement system is dependent upon the combined accuracy of each instrument. The measurement uncertainty will largely depend on the instrumentation and therefore it is important to estimate the accuracy of the instrumentation and other factors. Measuring and test equipment is only beneficial if they provide information that is reliable and precise. Each measured parameter in the SHB system must produce meaningful results. It is therefore important to review instrument behaviour for the quality of the desired overall results. This will be evaluated further in Chapter 5.

4.6 Conclusion

An energy balance was performed across the steam generators by using the SHB methodology. The SHB calculations were firstly performed manually to ensure that the methodology for determining the SHB was correct. When compared to the official SHB reports, the difference between the automated SHB and the manual calculations was found to be 0.17% which showed a good correlation.

In order to provide more flexibility in the analysis of the SHB the source code was written in Microsoft Excel VBA and Python.. The results show that the Excel VBA code is comparable with the SHB programme showing a difference of 0.01% for the total thermal power. The Python code is similar to the SHB programme with a difference of 0.06%. These small differences are beneficial and could be further developed to replace the now ageing SHB software. Alternatively it could be used for fault-finding and research. Both the new programming methods had opportunities for improvement such as manually inserting information from the physical plant structures (i.e orifice and pipe diameters etc) into the programmes. It is important to review the accuracy of the instrumentation used in the SHB.

CHAPTER 5

ANALYSIS OF SHB SENSITIVITY TO INSTRUMENTATION ACCURACY

5.1. Accuracy of the Measurement System

The total accuracy of the SHB measurement system is dependent upon the combined accuracy of the instruments and other variables used in the system. In this chapter, we will determine the uncertainty of the SHB system by evaluating each variable that inputs to the test. The magnitude of each independent variable's uncertainty is estimated by evaluating the following accuracies. These accuracies contribute to the total uncertainty:

1. Systematic or Bias Uncertainty
2. Random or Precision error
3. Sensitivity analysis

The combination of these effects will provide a holistic view of the combined accuracy and uncertainty of the SHB measurement system. It is important that the data collected is accurate. Each parameter in the system has data requirements that must be satisfied if valid system performance is to be measured. Measuring the parameter must consider the measurement location as this could affect the measurement due to pressure differences, height, ambient temperature etc. Sampling frequency is considered for the accuracy of the data logger. A parameter that has a greater measurement uncertainty should be taken into account with respect to the ability of the instrument to affect thermal performance. It is therefore important to review instrument behaviour for the quality of the desired overall results. The measurement uncertainty of a data point is usually stated as a range and a probability. It is the result of two types of error: random error and systematic error. The total measurement system (or loop) uncertainty is typically found by calculating the square root of the sum of the squares of the uncertainties caused by random and systematic error as shown in the following equation:

$$Total\ Error = \sqrt{Error_{Systematic}^2 + Error_{Random}^2} \qquad (5.1)$$

5.1.1 Systematic or Bias Uncertainty

The systematic or bias uncertainty is a constant error that can be accounted for by calibration. This error is an indication of accuracy or bias in the instrument and be corrected because it is usually repeatable. Systematic uncertainty is associated with the following items:

- Linearity of the instrument
- Reference error (Inherent Instrument error)
- Drift of the instrument over time
- Error of the calibration equipment

The Secondary Heat Balance uses the instruments listed in Table 5.1.

Table 5.1: List of instrumentation used in the SHB

Measured Parameter	Instrument Label	Input Range	Calibration Range	Nominal Value at 100% P_n	Unit
Feedwater flow: Loop 1	ARE 051 MD	4-20 mA	0 – 200	115	kPa
Feedwater flow: Loop 2	ARE 052 MD	4-20 mA	0 – 200	115	kPa
Feedwater flow: Loop 1	ARE 053 MD	4-20 mA	0 – 200	115	kPa
Steam Pressure: Loop 1	VVP 017 MP	4-20 mA	4040 – 6940	5000	kPa
Steam Pressure: Loop 1	VVP 018 MP	4-20 mA	4040 – 6940	5000	kPa
Steam Pressure: Loop 1	VVP 019 MP	4-20 mA	4040 – 6940	5000	kPa
Feedwater Temp: Loop 1	ARE 005 MT	4-20 mA	0 – 300	220	ºC
Feedwater Temp: Loop 1	ARE 006 MT	4-20 mA	0 – 300	220	ºC
Feedwater Temp: Loop 1	ARE 007 MT	4-20 mA	0 – 300	220	ºC
Feedwater Pressure: Loop 2	ARE 003 MP	4-20 mA	4000 – 8000	5250	kPa
Blowdown Flow	APG 004 MD	4-20 mA	0 – 40	40	T/hr

5.1.1.1. Linearity of the instrument

Zero and span errors are corrected by performing a calibration. Most instruments are provided with a means of adjusting the zero and span of the instrument, along with instructions for performing this adjustment. The zero adjustment is used to produce a parallel shift of the input-output curve. The span adjustment is used to change the slope of the input-output curve. Linearity may be corrected if the instrument has a linearization adjustment. If the magnitude of the nonlinear error is unacceptable and it cannot be adjusted, the instrument must be replaced. Madron et al (2015) proposed a simple method for OLM. This method is based on linearization of the nonlinear model and its success depends on the magnitude of the deviation from the linear model. A similar method will be considered for the instrumentation linearity analysis.

For all the instruments listed above, the calibration certificates states the error obtained for each measurement point. An example of the calibration certificate is shown in Appendix 4. The SHB programme uses a data logging system to collect and store the data obtained from the instruments. At Koeberg this data logging system is called "KIT". It is important that the error of the KIT system is taken into account determining the thermal power. So to align the instrumentation, KIT and SHB programme values, a linearity assessment tool is used to ensure that there are no discrepancies between the measured values and the KIT calculations. The true input and actual output values obtained from the calibration certificates are used to determine the linearity error. These values are used in the tool to calculate the actual slope (gain) and actual intercept. Then the gain error (ratio) and intercept error (difference) are calculated. The coefficient calculation determines the straight line equation of the true values entered and then calculates the offset (A0) and gain (A1) in order for the KIT input to be calibrated to the true value.

Each instrument of the SHB is analysed for linearity. Below is an example, showing the linearity analysis for the feedwater temperature sensors. The information is extracted from the calibration certificate. See Appendix 5 for the analysis of all the instruments.

By plotting the values on a graph the calibration sequence is not perfectly linear(see figure 5.1). However, when the instrument is installed on the plant and measures a value between any two calibration values, it will predict a linear path and provide a reading that is not perfectly aligned with the calibration values. This prediction is shown in red. To correct the linearity, coefficients of linearity are used to adjust the signal so that the measured values are perfectly aligned with the calibration values, thereby reducing the uncertainty. These linearity coefficients are programmed into the data acquisition unit.

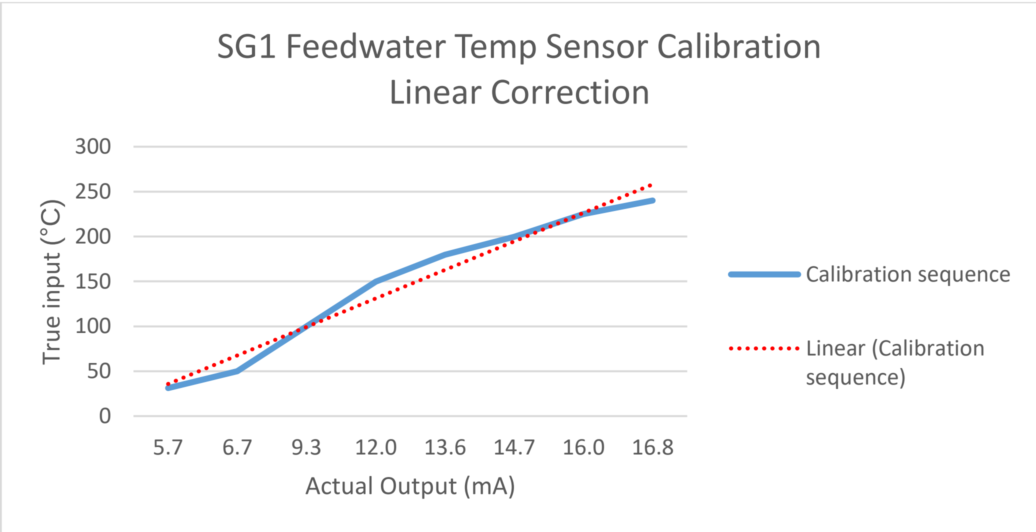

Figure 5.1: Linearity graph for SG1 Feedwater temperature sensor

To calibrate the linearity coefficients, the following method is used which is based on the straight line formula where the slope and intercept (or offset) are calculated. The intent is to solve the equation for the calibration sequence but use the linear equation parameters to obtain the coefficients.

The straight line (y_a) for the calibration sequence:

$$y_a = m_a.x + c_a \qquad (5.1)$$

From the table in Appendix 5, the following values are determined for the SG1 feedwater sensor (1ARE005MT):

Slope (m_a)= 18,7 ; intercept (c_a)= -74,85

The adjusted line (y_b) to the calibrated sequence line

$$y_b = y_a.A_1 + A_0 \qquad (5.2)$$

where:
$A_0 = Offset\ coefficient$
$A_1 = Multiplier\ coefficient$

The solutions are

A_0 = 0.0620 ; A_1 = 0.9988

And when substituted into equation 5.2, the resulting line will follow the calibration sequence.

From Appendix 5 at 30 °C nominal input

Applying the conversion coefficients to the standard instrumentation formula:

$$Temp = A_0 + A_1 \times \frac{Range}{mA} \times input - calibration\ constant \tag{5.3}$$

$$Temp = 0.0662 + 0.9988 \times \frac{300}{16} \times 5.612 - 75$$

= **30.252 °C**

The true input is 30.263 °C.

Table 5.2 Linearity analysis and Calibration coefficients for SG1 Feedwater

Instrument	Nominal Input °C	True Input during calibration	Actual output (mA)		Adjusted Output with coefficient	% error
			Increase	Ave		
Feedwater Temp Sensor	30	30.26	5.6120	5.6120	**30.25208**	0.036
	50	49.90	6.66180	6.66180	49.91310	-0.020
Input Range: 4-20mA	100	100.09	9.33850	9.33850	100.04324	0.049
	150	150.15	12.01690	12.01690	150.20523	-0.034
	180	180.08	13.61470	13.61470	180.12937	-0.022
	200	199.95	14.67390	14.67390	199.96643	-0.006
	225	224.96	16.00770	16.00770	224.94629	0.008
	240	239.85	16.80170	16.80170	239.81659	0.015
Ave error						**0.024**

As can be seen, this produces an output much closer to the actual input. From this output, an average error can be determined. For this instrument it was determined to be 0.024%. This is done for all the instruments and the results are included in Appendix 5. Each instrument will have unique design characteristics and calibration range that needs to be factored into the calculations. For example the range of the temperature transmitters are 0 to 300 °C while the differential pressure transmitters have a range of 0 to 200 kPa.

All the coefficients will be input to SHB programme to ensure the entire range is adjusted for the optimal output. For the purpose of this thesis, the average linearity error will be used to determine the overall error.

5.1.1.2 Reference Error

Reference Accuracy or Error is the baseline accuracy for many instruments and is the percentage of error associated with the instrument operating within design criteria under reference conditions. Stated as a percentage of span setting, most manufacturers include the combined effects of linearity, hysteresis and repeatability. Additionally, all manufacturers specify the reference conditions under which this performance applies. Because reference accuracy applies only to the stated conditions, it cannot be considered a measure of overall performance for industrial applications, where conditions vary. Reference accuracy represents transmitter performance only under “laboratory” conditions. As an example, Appendix 6 contains the manufacturer supplied data for the feedwater temperature sensor. Similar data sheets are supplied for all the instruments used in the SHB.

5.1.1.3 Drift

Drift is a source of uncertainty in measurement that should be included in the every uncertainty budget. It is an influence that you can calculate from your calibration data to see how much the error in your measurements changes over time. Essentially, drift determines how the error in your measurement process changes over time, and how much it can contribute to your estimate of uncertainty in measurement. Drift is determined by reviewing the calibration reports over an extended period, preferably more than three calibration periods. Hashemian, (2010) reviewed the impact of ageing and developed various OLM techniques. In the study it was found that vibration, humidity and temperature contributed to the ageing. It is therefore important that the equipment is located where these environmental effects are minimised. The location of the SHB instrumentation has been strategically positioned to reduce these effects. After reviewing the location of the SHB instruments, the main focus was the feedwater temperature and pressure sensors operate in a high ambient temperature environment of approximately 50 °C. This is however not a concern because the specifications of the transmitters allows for operation up to 85 °C.

5.1.1.4 Error in Calibration equipment

A calibration is a comparison of measuring equipment against a standard instrument of higher accuracy to detect, correlate, adjust, rectify and document the accuracy of the instrument being compared. The standard instrument will also have a reference error and should be taken into account.

5.1.1.5 Data acquisition error

As mentioned previously, the data processing system, KIT, processes the signals from the instrument to the user interface. The instrument loop of each SHB input was tested for both units. A Fluke 702 instrument calibrator was connected to the instrument loops in place of the instruments and used to inject currents across the measurement ranges. The SHB tests shows result which are within an accuracy of 0.15%.

A “watchdog function” is part of the SHB software and is an OLM tool that assists with verifying that the data used in the SHB is accurate. It provides an interface that determines if the application is running or not running and the actions to perform when the application is not running. The system also checks the validity of the SHB outputs. These are invalidated when the input values:

- Are invalid because it could cause the SHB to be invalid
- Falls outside its envelope limits (normal operating modes of the plant)
- Exceeds the limit for a transient condition (Each instrument type has its own transient criterion). The input is considered to be in transient mode when its instantaneous value (averaged over 10 seconds) differs from its 20 minute average value by more than a predefined limit.

5.1.2 Combined Systematic Uncertainty

The combined systematic uncertainty is a combination of all the items mentioned earlier in sections 5.1.1.1 to 5.1.1.5. As per Mantey, 2013, calculating the Total instrumentation loop (also called the Systematic error) requires the Root, Sum, Square (RSS) method. This is the square root of the sum of the squares of all individual uncertainties.

$$\text{Instrumentation loop error} = \sqrt{\sum_i Uncertainty\ (i)^2} \qquad (5.4)$$

For SHB:

$$\text{Instrumentation loop or Systematic error} = \sqrt{\text{Overall Transmitter error}^2 + Data\ acquisition^2}$$

$$= \sqrt{E^2_{thermowell} + E^2_{linearity} + E^2_{drift} + E^2_{accuracy} + E^2_{calibration} + E^2_{data\ logging}}^{\,2} \qquad (5.5)$$

The uncertainty values for the Feedwater Temperature Sensors is shown in Table 5.3. This is based on the manufacturers certificates and calculated values as shown in Section 5.1.1.

Table 5.3: Summary of errors and uncertainties for FW temp sensors

Parameter	Error
Thermowell	0.5°C = 0.167%
Transmitter Accuracy (Reference Error) (range 0-300°C)	0.2%
Drift	0.2%
Calibration	0.25%
Effect of temperature	IGNORE (as per manufacturer)
Linearity	0.024%
Data acquisition error	0.15%
Total error (using formula 5.5)	**0.439%**

The details of the systematic errors for the other instruments used in the SHB is shown in Appendix 7

5.2 Feedwater flow uncertainty

The feedwater flow is measured by fitting a differential pressure transmitter across an orifice plate. Differential pressure flow measurement is somewhat unique in that it involves the measurement of several independent variables, which together with the appropriate equation, calculate the flow rate. An uncertainty analysis can make it easier to predict the effect of uncertainties in the independent variables on the uncertainty of the measured flow.

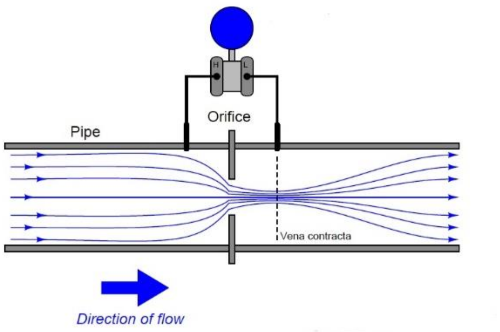

Figure 5.4: Schematic of Orifice type water Flowmeter

This method of flow measurement is often used because it eliminates the need for manual manipulation of data and can be automatically transmitted to an acquisition system. There are many international standards applicable to this method thereby ensuring that the accuracy of the method is repeatable.

The differential pressure tansmitters are sourced from Yokogawa who are leaders in the instrumentation field for these types of transmitters in an industrial application. These transducers were selected for their sensitivity and stability of performance with a quartz as the pressure -sensing material which gives excellent stability and reproducibility in pressure measurement.

The ISO standard 5167-1:2003, titled "*Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full",* provides the general principles and requirements applicable to these type of measurement systems. The standard provides the minimum uncertainty by which the measurement is unavoidable tainted, since the user has no control over these values. They occur mainly in the calculation of the discharge coefficient and the expansion factor because of small variations in the geometry of the piping etc.

As per the ISO standard the following equation is used:

$$Feedwater\ Flow\ Uncertainty = \sqrt{\left(\frac{\delta\alpha}{\alpha}\right)^2 + \left(\frac{\delta\varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\beta^4}{1-\beta^4}\right)^2\left(\frac{\delta D}{D}\right)^2 + \left(\frac{2}{1-\beta^4}\right)^2\left(\frac{\delta d}{d}\right)^2 + \frac{1}{4}\left(\frac{\delta\Delta p}{\Delta p}\right)^2 + \frac{1}{4}\left(\frac{\delta\rho_1}{\rho_1}\right)^2} \quad (5.6)$$

Where:

$\left(\frac{\delta\alpha}{\alpha}\right)$ = Discharge coefficient uncertainty

$\left(\frac{\delta\varepsilon}{\varepsilon}\right)$ = Expansion factor uncertainty

$\left(\frac{\delta D}{D}\right)$ = Pipe Diameter ratio uncertainty (0.4% max)

$\left(\frac{\delta d}{d}\right)$ = Orifice diameter ratio uncertainty (0.1% max)

$\left(\frac{\delta\Delta p}{\Delta p}\right)$ = Differential Pressure uncertainty

$\left(\frac{\delta\rho_1}{\rho_1}\right)$ = Fluid Density uncertainty

It is necessary to know the density and the viscosity of the fluid at the working conditions. In the case of a compressible fluid, it is also necessary to know the isentropic exponent of the fluid at working conditions. In this instance, K= 1 because water is considered incompressible.

Differential Pressure uncertainty is given by the manufacturer as the reference uncertainty and is already calculated as part of the systematic uncertainty. It will therefore be ignored in this calculation. Fluid Density uncertainty is based on the steam lookup tables and not measured so we can assume that there is no uncertainty.

Therefore:

$$Feedwater\ Flow\ Uncertainty = \sqrt{0.6546^2 + 0.0793^2 + \left(\frac{2 * 0.6926^4}{1 - 0.6926^4}\right)^2 * (0.4)^2 + \left(\frac{2}{1 - 0.6926^4}\right)^2 (0.1)^2}$$

= 0.583 %

The detailed calculations for the feedwater inaccuracy is provided in Appendix 8. Janzen et al. (2014) investigated feedwater flow measurements using ultrasonic flowmeters and found the best performance to have a relative error of ±8 %. In some cases the error was more than 10%. The orifice system in the SHB produces an uncertainty of 0.583 %, which is a significant improvement when compared to non-intrusive systems.

5.3 Random or Precision Error

Random uncertainty is a description of how much variation measurements have and is an indication of measurement device repeatability and the stability of measurement quality. Vande Visse (1997) provides the standard for the Instrument loop accuracy. Random error results from unpredictable variations and will be seen if there are repeated discrepancies in the measured parameter. Random errors of a measurement result cannot be compensated by correction. They can be minimized or reduced by increasing the number of samples, increasing the accuracy of the measurement device or by incorporating a measurement procedure that reduces sources of error.

It is important to have sufficient data to ensure an adequate calculation of random error. However larger samples could also introduce random errors. For example, an hour of data collected at a frequency of at least one data point per minute should be adequate to calculate the overall uncertainty. Collecting data over a full day would introduce random errors due to the increased possibility of an error occurring. It is therefore important that the data quality is good. Random uncertainty is calculated by applying the following equation:

$$Random\ uncertainty = \frac{S_t \times \frac{s}{\bar{x}}}{\sqrt{n}} \times 100 \quad (5.7)$$

Where:
St = student t-value (from chart)
S = standard deviation
$\bar{x}$ = mean
n = count

Using the SHB test from 9 Jan 2020, the random uncertainty calculations are tabulated in Appendix 9 showing that the random uncertainty for each instrument is much smaller that the systematic uncertainty. This is due to the large number of data points that is recorded in a SHB test. Over 3 hours, the KIT system records 1800 data points. Due to the large "n" count, the uncertainty in equation 5.7 is significantly reduced.

5.4 Influence Factor / Sensitivity

The influence factor or sensitivity is the impact which a measured parameter can have on the result. Different instruments in the SHB system have different sensitivities because the influence that they have on the outputs, differ. These sensitivities show the amount of change that occurs in the calculated result per unit change in the input variable. For example a 1% change in feedwater temperature has a smaller effect on the SHB result compared to a 1% change in feedwater flow. This provides valuable information, including:

- A prioritized list of instruments most significantly impacting performance parameters
- Recommendation for any instrument additions
- Recommendation for instrument replacements and improvements
- Recommendation for improvements in calibration techniques
- Recommendation for increased data collection frequency

The sensitivity of all the SHB instruments was checked to determine how much influence the errors and uncertainties could affect the SHB result. The test of 8 June 2020 was selected for analysis. The inputs, outputs and final results were recorded. The inputs were then varied by +1%, one input at a time. For each change, the SHB was recalculated. This analysis shows the change in SHB result when only a single input is varied by 1%. Table 5.4 shows the results of the sensitivity analysis. Refer to Appendix 10 for a more detailed breakdown of the results.

Table 5.4: Sensitivity Analysis

Parameter	Full Power value	Systematic Uncertainty (%)	Random Uncertainty (%)	% change in Reactor Power
SG1 Temp (°C)	220.03	0.439	0.0002	-0.240
SG2 Temp (°C)	220.02	0.439	0.0002	-0.236
SG3 Temp (°C)	220.27	0.439	0.0002	-0.236
Steam Press (kPa)	4864.40	0.406	0.0039	-0.007
Steam Press (kPa)	4851.10	0.406	0.0038	-0.007
Steam Press (kPa)	4865.90	0.406	0.0042	-0.007
FW Press (kPa)	5190.10	0.406	0.0036	-0.004
FW Diff Press (kPa)	117.64	0.489	0.0557	0.160
FW Diff Press (kPa)	112.69	0.489	0.0559	0.163
FW Diff Press (kPa)	114.79	0.489	0.0563	0.163
SG1 Orifice (m)	0.25601	0.583	-	0.92
SG2 Orifice (m)	0.25601	0.583	-	0.90
SG3 Orifice (m)	0.25601	0.583	-	0.88

The feedwater orifice diameter measurement has the highest impact when compared to the other instruments. When combining the sensitivity of the differential pressure transmitters and the uncertainties of the feedwater flow calculation, it is clear that errors associated with the feedwater flow measurement will have a significant effect on the SHB result.

When using the EPRI methodology (Mantey, 2013), the next part of the process to determine the overall uncertainty by combining the measurement error, uncertainties and sensitivity.

The overall uncertainty is determined by calculating the sum of the square root of each contributing uncertainty.

$$Total\ Uncertainty = Systematic\ contribution + Random\ contribution \qquad (5.8)$$

where

$$Systematic\ contribution = \left[\left(\frac{Systematic\ uncertainty}{2}\right) \times Sensitivity\right]^2 \qquad (5.9)$$

$$Random\ contribution = \left[\left(\frac{Random\ uncertainty}{\sqrt{sample\ size}}\right) \times Sensitivity\right]^2 \qquad (5.10$$

Using the student-t value from the random uncertainty which provides a probability assessment, the percentage error is determine by:

$$Percentage\ Uncertainty = S_t\sqrt{Total\ Uncertainty} \qquad (5.11)$$

Where S_t = student-t value available from a table in Mantey, 2013 Table 5.5 provides the total measurement uncertainty.

Table 5.5: Total Uncertainty

Parameter	Total Uncertainty (%)
SG1 Temp	0.002769
SG2 Temp	0.002686
SG3 Temp	0.002686
Steam Press	0.000002
Steam Press	0.000002
Steam Press	0.000002
FW Press	0.000001
FW Diff Press	0.001527
FW Diff Press	0.001597
FW Diff Press	0.001597
Percentage of Total Uncertainty, % (Eq 5.11)	**0.232**

The total uncertainty, based on full power equates to 6.387 MW.

5.5 Error analysis

Once all the errors and uncertainties have been determined, their impact needs to be evaluated. The overall test uncertainty includes all the errors and uncertainties and are added to produce a single value. This means that the overall uncertainty of the SHB is 0.23% (6.387 MW) even when all instruments are working perfectly and all test conditions (e.g flow orifices) are as expected. According to a report published by the IAEA (2008), the result must be evaluated against the expected plant's safety analysis, so that the assumptions in the design remain valid. Koeberg's SAR part 3, chapter 4 states the assumptions used in accident studies. In terms of core thermal power, to account for possible instrumentation errors, the initial power level is assumed to be equal to 102%Pn (Koeberg SAR, Eskom). Therefore the calculated error of 0.23% is within the allowed inaccuracy of 2% over nominal full power and does not invalidate any safety assumptions in the design basis. It is also similar to the uncertainty of 0.347% which was determined by Exelon (2009).

5.5.1 Instrument out-of-tolerance condition

Should an instrument be calibrated and found to be out of the manufacturer's specified tolerance, or any of the tolerances (systematic accuracy) described in section 5.1, the instrument should be evaluated for operability. This is done by evaluating how much the error impacted on the test result. The SHB is calculated with the error inserted into the affected variable (or input). To aid in this analysis, a tool was developed, using Excel VBA coding to programme the SHB test and automatically update the out of tolerance values. The results are contained in Appendix 11.

5.5.2 Adjustment of RPN and PHB

The RPN and PHB measurement systems are adjusted based on the results of the SHB (Salie, 2013). The errors of the SHB instrumentation will therefore be transferred to the RPN and PHB systems. It is important that the impact of this change is understood, especially if there are any instrumentation errors. This is because these measurements are related to the design power of the nuclear reactor and incorrect adjustments could impact on nuclear safety for the plant and environment. If the reactor power indication to the plant operator is lower than the actual power, then the condition is considered unsafe due to the potential for the operator to increase power and cause an actual power that is above 100%. In other words, the indicated power (read in the control room) is lower than the actual power. It is therefore important to distinguish between adjustments that are unsafe and those that are safe. In the nuclear industry these are referred to as conservative and non-conservative.

- Conservative Adjustments
  If the instrument error results in an SHB result that is higher than the actual power, then the adjustments on RPN and PHB will be from a lower value to a higher value. This higher value means that the actual power will be lower than the indicated power and result in the automatic reactor trip threshold (based on RPN) to be reached before the actual power is at the trip setpoint. This will cause the reactor to shutdown before an over-power condition is experienced.
- Non-conservative Adjustments
  If the instrument error results in a decreased SHB result, then the adjustments on RPN and PHB will be from a higher value to a lower value. This lower value means that the actual power will be higher than the indicated power. It will thus allow the operator to increase power based on the indication. This causes the actual power to be higher than the indicated power and possibly exceed the design criteria for an extended period of time.

5.6 Conclusion

The combination of various errors and uncertainty provides a holistic view of the combined accuracy and uncertainty of the SHB measurement system. These include the systematic uncertainty, random uncertainty and sensitivity. From all the parameters analysed in this research, it can be concluded that the total inaccuracy of the SHB is 6.387 MW or 0.232% of the full power value. The uncertainty analysis has many benefits for the power station such as evaluating which instruments most significantly impact on performance parameters, recommendations for any instrument improvements, as well as improvements in calibration techniques. Furthermore, the accuracy of data collection in terms of sampling and data acquisition can also be evaluated. Another benefit is the ability to analyse the impact on the SHB after an instrument was found to be out of tolerance when it is removed from service for calibration. In this way, the overall uncertainty can be evaluated while also checking the impact of one instrument in relation to the SHB result.

The data processing system, KIT, is very accurate (0.15%) and the random uncertainty is reduced due to the high volume of data. The system also checks the validity of the SHB outputs thereby ensuring high quality data. The feedwater flow uncertainty was quantified and found to be much better than non intrusive measurement methods.

The RPN and PHB measurement systems are adjusted based on the results of the SHB and the errors of the SHB instrumentation will therefore be transferred to the RPN and PHB systems. Once the instrumentation uncertainty is quantified and understood, then the adjustments can be made in the conservative direction to ensure nuclear safety is maintained.

CHAPTER 6

STEAM GENERATOR THERMAL HYDRAULIC EFFECTS

6.1 Factors affecting performance in the Steam Generator

In PWR plants, there are several types of steam generators which may be used. In a feedring U-tube type of steam generator, like those at Koeberg, the feedwater enters a downcomer region and flows up past the tubes. Over most of the tubes, the secondary flow is saturated. Nearly dry saturated steam exits from the top of the steam generator after passing through a moisture separator section in the steam dome. The moisture that is separated from the saturated steam recirculates with the feedwater. The moisture return path is via the downcomer region between the tube wrapper and the outer steam generator shell. Figure 4.2 shows the design details of a typical feedring steam generator. The downcomer flow in SGs can provide unique fitness for service and performance indicators related to overall thermo-hydraulic performance and safety indicators. (Janzen et al.,2014)

Plant thermal performance can be affected by the capability of PWR steam generators to transfer heat from the reactor coolant to the secondary system. This thermal capability can be reduced by several degradation mechanisms, the three most important being the quantity of plugged tubes, accumulation of deposits on the inside and outside tube surfaces and degradation or overloading of the moisture separators. Typically Steam Generators are built to maintain design performance with an allowable amount of tubes plugged (i.e., 10%). Fouling of the moisture separators increases pressure drop and allows more moisture carryover. Erosion or bypasses around the moisture separators and increased velocity due to power uprates or pressure reductions also increase moisture carryover. The number of plugged tubes should be accounted for and trended. The effect of deposit accumulation is determined by calculation. The resistance to heat transfer of a SG tube is the sum of the conductive resistance of the tube wall, the boundary layer resistance of the primary and secondary fluids, and the resistances resulting from the accumulation of any deposit layers on the inside and outside tube surfaces. The effect of increased resistance requires an increase in reactor coolant temperature or a decrease in secondary side temperature, that is, steam pressure to continue transferring the same amount of heat from the reactor. The thermal resistance of SG tubes varies locally throughout the tube bundle, depending on local coolant conditions and local deposit accumulation. It can be shown that a mean thermal resistance can adequately account for local variation and can be used to evaluate and trend the performance of steam generators.

Results obtained from the research done by Sadek and Grgic (2017) showed that the steam generator design is able to effectively transfer heat in accident conditions. It is therefore important that thermal energy measurements across the steam generator reflects the actual heat transfer so that the design assumptions are not challenged. This ensures that the steam generator is not over stressed which could affect the performance of the steam generator in the event of an accident.

At Koeberg, the fouling is minimal due to strict chemistry specifications and the effective use of the blowdown system. In refuelling shutdowns at Koeberg, the deposit layer is removed through a process called sludge lancing. Sometimes towards the end of an operational cycle, an increase in thermal resistance can be seen. There are however, no abnormal trends which have been reported from the eddy current inspections, sludge lancing activities and endoscopic inspections (Allie, 2018). The SGs will be replaced in 2021 and the clean tubes will improve thermal efficiency.

6.2 Recirculation Flow in the Steam Generator

In the previous version of the SHB, the enthalpy of the blowdown fluid was determined by simply calculating the enthalpy of the saturated fluid present in the steam generator from the feedwater line. There is however recirculation flow in the SG, due to the wet steam at the top of the SG, mixing with the saturated feedwater. This mixing results in more heat energy being absorbed in the feedwater and consequently ejected through the blowdown line. Considering the recirculation flow, the enthalpy of the blowdown can be calculated using the saturated fluid in feedwater and multiplying it by a recirculation factor. This recirculation factor (rf) is calculated using the relative thermal power. See Appendix 2 for equations related to the blowdown.

The recirculation factor is calculated as a function of the relative thermal power. Appendix 16 shows the relationship between the Recirculation Ratio in the SGs and the level of relative thermal power. The equation for the curve is given by:

rf = 18.189 – (0.2582 * Qrelt-1) + (0.0011 * Qrel2t-1) (4.10)

$$rf = 18.189 - (0.2582 * Qrel_{t-1}) + (0.0011 * Qrel^2_{t-1}) \qquad (6.1)$$

where,

rf = the recirculation factor, unitless

$Qrel_{t-1}$ = the relative thermal power calculated in the previous execution cycle, %

Blowdown Enthalpy

$$h_{BD} = \frac{(h_{FW} + (rf \times hf)}{1 + rf} \qquad (6.2)$$

where,

h_{BD} = the blowdown enthalpy

h_{FW} = the feedwater enthalpy (kJ/kg)

rf = the recirculation factor (unitless)

hf = the enthalpy of the saturated fluid (kJ/kg)

The SHB programme was modified to include this factor

6.3 Oscillations

Thermal hydraulic characteristics of the water and steam flow inside the steam generator causes fluctuations at various intervals. The current test method uses a real time programme to continuously calculate the instantaneous thermal power output of the reactor, but there is evidence that the water and steam flow oscillate in cycles to produce predictable fluctuations. The data used for the SHB is based on the average of all recorded parameters over a three hour period. The SHB test was analysed to determine the effect of the oscillations. Otgonbaatar (2016) determined the uncertainty by using the normal probability distribution for the parameter which is measured. This is however a very complex methodology but some of the statistical principles were applied to this thesis.

The data from the test on 16 March for Unit 2 was reviewed and analysed by performing the following steps:

1. The data from each of the recorded parameters over the 3 hour sampling period was reviewed:
   - The average value was determined
   - The standard deviation was calculated
   - The maximum value was recorded
   - The minimum value recorded

2. The data was divided into three sections, with each section representing one hour of the sampling time. For each of the three sections, the same four parameters were recorded as in point 1 above.

3. The recorded values from each of the three sections were individually compared to the calculated values from the data of the 3 hour period.

Refer to Appendix 15 for the results of the analysis. One of the parameters that were analysed is the SG differential pressure. Figure 6.1 shows the average for the SG differential pressure taken for the three periods and subtracted from the average of the full 3hr period.

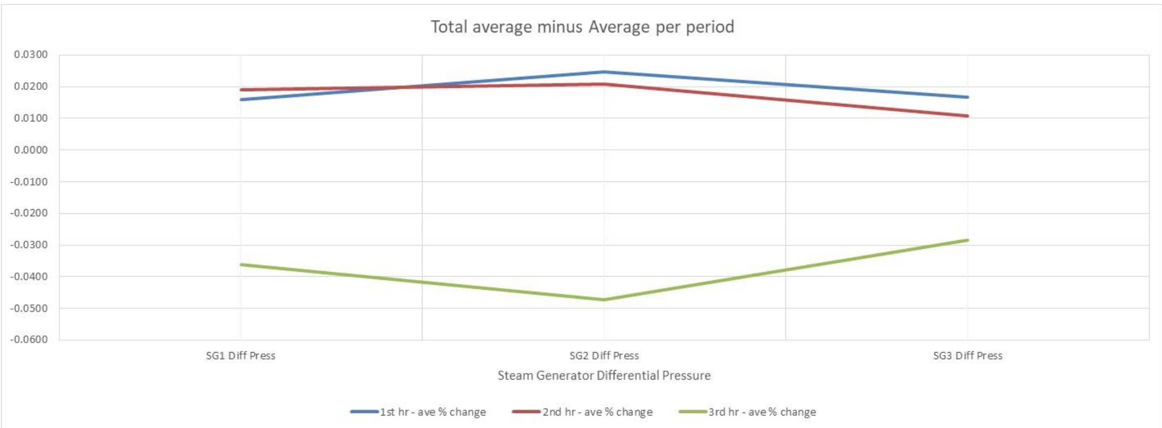

Figure 6.1: Total average minus Average per period for SG Pressures

When investigating the differential pressure measurement of the three steam generators it can be seen that the difference between the overall average value and the average value for the third hour shows a negative result, compared to a positive result for the first two hours. This indicates that the third hour showed a reduction in differential pressure for all SGs. The differential pressure measurement is used to determine the flow rate. When looking at the other parameters in Appendix 15, it is evident that all the parameters show a significant change in trend for the third period. This indicates that even though the plant was stable and there was no input by the operators, there was a more significant change in plant parameters in the third hour which impacts on the overall result. Further work is required in this area to fully understand the contributing factors. Additional testing is required to determine if this oscillations are systemic or unpredictable. Once these tests have been performed and the statistical analysis completed, the cause of these oscillations should be determined.

When studying the trend for the standard deviation of the SG differential pressure, it is expected that the trends are inverse to the trends for the average values. This is because the standard deviation is the difference between the average value and the value furthest away from the average value in that specific data set. This means that if the average is low, then the standard deviation would naturally be high. In figure 6.2 we can see that the percentage change for the first hour is different to the other second and third hours.

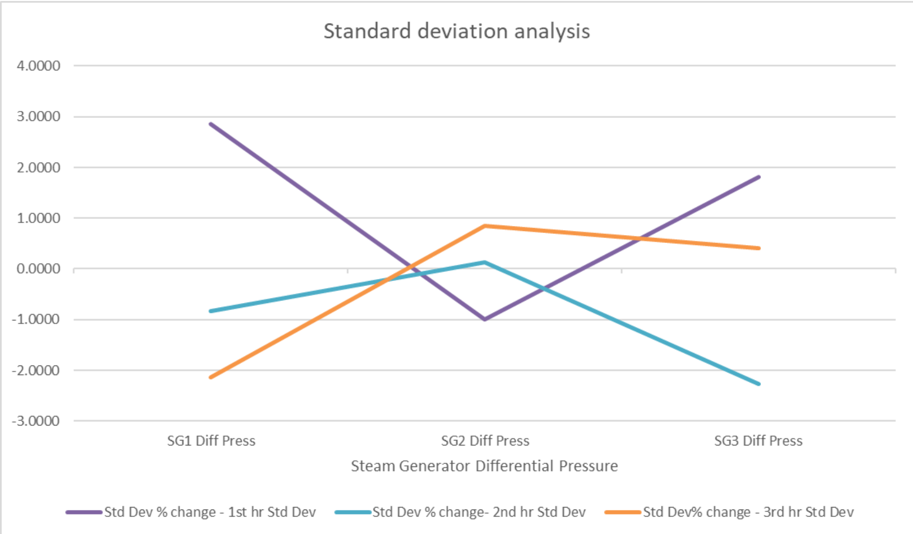

Figure 6.2: Standard deviation Analysis for SG Differential pressures

The statistical analysis of the data requires further testing and examination to ensure that the quality of the data that is collected is good and to identify areas for improvement.

6.4 Conclusion

Plant thermal performance can be affected by the capability of PWR steam generators to transfer heat from the reactor coolant to the secondary system. At Koeberg, there are no abnormal trends which have shown that the SGs are significantly affected by the degradation mechanisms mentioned earlier. Their replacement in 2021 will allow the plant life to be extended beyond the original 40 year period and will improve the plant thermal efficiency. Recirculation flow in the SG, results in more heat energy being absorbed in the feedwater and consequently ejected through the blowdown line. This flow must be taken into consideration when calculating thermal performance of the SGs. Thermal hydraulic characteristics of the water and steam flow inside the steam generator causes fluctuations at various intervals. It was found that there are differences in the various intervals. One example noted was the differential pressure measurement. There was a change in the recorded plant parameters for the third period when compared to the first two periods. This phenomenon should be further investigated to identify the root cause.

CHAPTER 7

PRIMARY HEAT BALANCE

7.1 Measurement of PHB

As mentioned earlier, the reactor thermal power is also measured using the Primary Heat Balance (PHB) method. The PHB method measures the reactor power by using instrumentation within the reactor core as part of the reactor coolant system. The instrumentation used to calculate the PHB is subject to large temperature fluctuations and as a result, is not as stable or accurate as other measurement systems. The PHB instrumentation is located in the reactor coolant system which is in the reactor building. While at power, the reactor building is not accessible and therefore the instruments can not be calibrated. There are however important elements associated with the PHB which influence the thermal performance calculations. These will be investigated. Also, the PHB and SHB are performed simultaneously and the result compared, so it is important to understand the elements which influence the PHB result.

An important element is that the PHB calculations assume either steady-state conditions or conditions that are steadily changing; i.e., little variation in rate-of-change of system temperature from one minute to the next. The fluctuations in the various primary parameters would therefore influence the PHB result and therefore the sampling rate is an important factor to consider.

Thermal hydraulic characteristics of the primary system are influenced by various factors. The reactivity in the core is affected by core life, control rod position, dilution and boration. The dynamic effect of the primary loop flow could also impact the PHB result. The parameters use various instruments and their accuracy must be considered. This includes the primary pump speed error because it is dependent on grid frequency as well as the water density that is dependent on temperature.

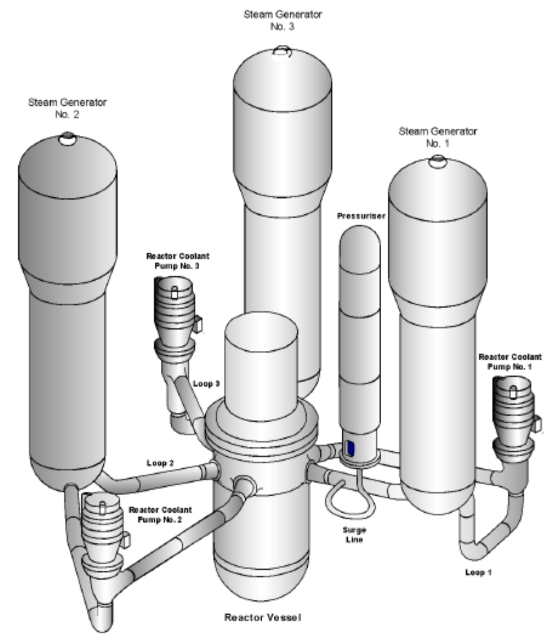

Figure 7.1: Spatial layout of the Reactor Coolant System
(Courtesy of Eskom)

The PHB method calculates the specific enthalpy of each hot leg (piping from the reactor) and cold leg (piping returned to the reactor) using Steam Table functions. The specific enthalpy difference between the hot leg and the cold leg is calculated by subtracting the specific enthalpy of the cold leg from the specific enthalpy of the hot leg for a given loop. The density of the cold leg is found from the steam tables based on the pressure and temperature in the cold leg. The reactor thermal power for a given loop is calculated by subtracting the specific enthalpies between the hot leg and cold leg and then multiplying it by the density and volumetric flow. Refer to figures 7.1 and 7.2 for a graphical representation of the hot and cold legs.

In their research, Mesquita et al (2014) developed various methods to measure the thermal power. One method was similar to the PHB whereby a constant reactor power is monitored as a function of the rise in temperature over time and the system heat capacity. These procedures, fuel temperature, energy balance and calorimetric were implemented in a nuclear research reactor and obtained an accuracy of 4%.

The SHB uses sensors located on the secondary side and are not subject to the various effects of the primary system which impact on the reliability of the PHB and RPN systems. The sensitivity of the PHB is however still important to understand because the PHB is used for continuous monitoring by the control room staff. It is compared with the SHB on a daily basis and is calibrated every week by performing an adjustment on the digital circuitry in the data logger. The instruments can not be calibrated because they are located inside the reactor core. Different instruments in the PHB system have different sensitivities because of the influence which the measured parameters have on the result.

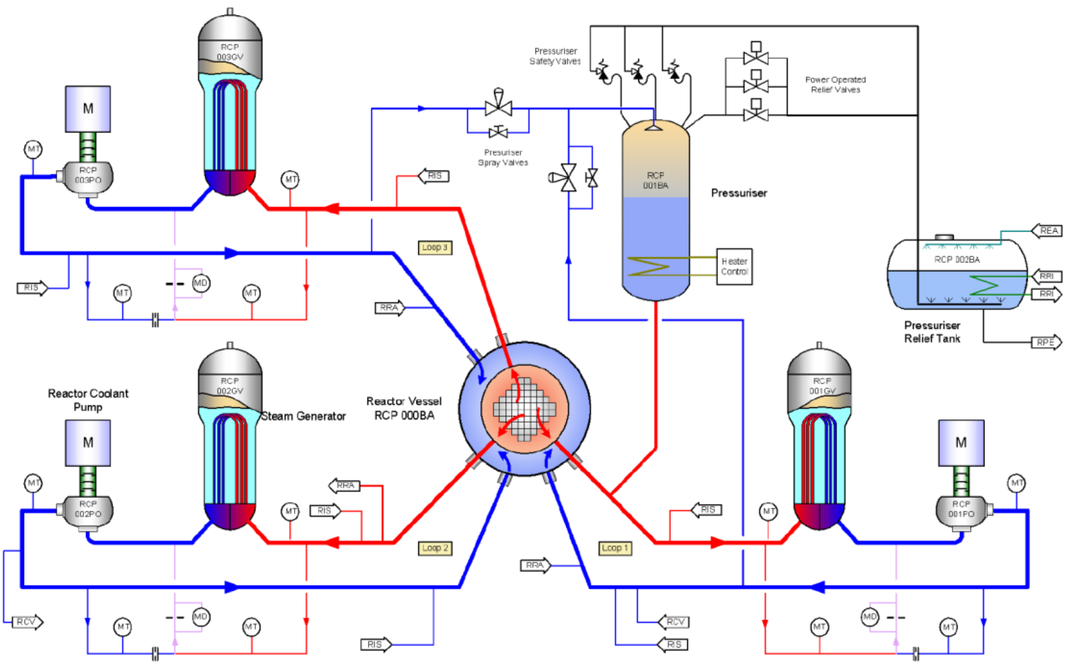

Figure 7.2: Loop layout of Reactor Coolant System.

(Courtesy of Eskom)

The PHB calculations provide the core thermal power transferred to each loop, the reactor thermal power, and the relative thermal power as a percentage of the rated thermal power. The calculations, taken from Glath (2012) assume steady-state conditions and therefore the parameters must be maintained stable during the test.

7.1.1 Reactor Thermal Output

$$W_{loop} = C * W_F \tag{7.1}$$

Where:

W_{loop} = the loop reactor thermal output

C = calibration constant for fine tuning

W_F = the power based on volumetric flow, cold leg density, and delta enthalpy per loop,

$$W_{CORE} = \Sigma\, W_{loop} \text{ for loops 1 to 3}$$

7.1.2 Thermal Power to SGs

$$W_{SG} = W_{loop} + W_{pump} \tag{7.2}$$

where,

W_{SG} = thermal power transferred to SG (MWt)

W_{loop} = the loop reactor thermal output

W_{pump} = pump heat less NSSS heat losses for loop

$$\textbf{Total Thermal Power} = \boldsymbol{W_T} = \sum W_{SG} \tag{7.3}$$

$$\textbf{Relative Thermal Power} = \boldsymbol{W_R} = \frac{\boldsymbol{W_T}}{\boldsymbol{W_{rated}}} * \mathbf{100} \tag{7.4}$$

where,

W_R = the relative thermal power delivered by core to the reactor coolant, %Pn

W_T = the reactor thermal power, MWt

W_{RATED} = the rated thermal power, MWt

7.1.3 Loop thermal power

$$\boldsymbol{W_{loop}} = (F_{VOL} * D * dh) / 3.6E6 \tag{7.5}$$

Where:

W_{loop} = the loop power based on volumetric flow, cold leg density, and delta enthalpy

F_{VOL} = the volumetric flow in the loop m^3/h

D = the fluid density in the cold leg, kg/m^3

dh = the delta enthalpy in the loop KJ/kg

3.6E6 = the unit conversion factor

7.1.4 Loop Flow Rate

$$Fvol = W_{loop} – P_h * SV / dh * C \quad (7.6)$$

W_{loop} = Loop Thermal Power

P_h = Pump Heat Losses

SV = Specific Volume

dh = Specific Enthalpy Difference

C = Conversion Factor (unitless)

The detail of the PHB calculations are given in Appendix 12. Table 7.1 shows the results of the calculations.

Parameter	Abr.	Loop1	Loop2	Loop3
Hot Leg temperature	T_{HL}	303.54	304.62	303.03
Cold Leg Temperature	T_{CL}	274.31	273.93	273.91
Pressuriser Pressure	P_{pzr}	15389.27	15389.27	15389.27
Cold leg press	P_{CL}	15389.69	15389.69	15389.69
Cold leg volumetric flow (Corrected)	Fvol	24372.76	23103.83	23949.86
Cold Leg Specific Volume	V_{CL}	0.001291	0.001291	0.001291
Cold leg density	D_{CL}	774.06	774.70	774.74
Cold Leg Enthalpy	h_{CL}	1203.30	1201.4	1201.28
Hot Leg Enthalpy	h_{HL}	1356.40	1362.44	1353.58
Enthalpy difference	dh	153.09	161.04	152.29
Loop Thermal	W_{loop}	802.32	800.67	784.97
Reactor Power	MW	**2397.97**		
	%	**86.41**		

Table 7.1: PHB manual results

7.1.5 PHB: Comparison with Official PHB

These calculations were compared with the official PHB test for 16 March 2020 which calculated a PHB thermal power of 86.13% (Figure 7.3). The difference between the manual calculations above (86.41%) and the automated system is 0.28%.

Summary of Results (3 Hour Averages)

	MWt	%Pn
Total SHB Thermal Power	2381.5	85.82
Total PHB Thermal Power	2390.2	86.13

Figure 7.3: Snapshot of PHB report

7.1.6 Programming of PHB using Excel VBA

A similar exercise was performed for the PHB, as was done for the SHB regarding the programming of Excel using VBA code. This was to provide more flexibility with the source code and even though it will not replace the official PHB test on KIT it will assist with research and fault finding. It will also be used to identify improvement opportunities. The same steps as explained in section 4.4 were performed for the PHB. Appendix 19 contains additional detail and screenshots of the VBA code. This was done by following these steps:

The Importing of data

- Importing the data from the KIT system.
- Once the data was imported to Excel, the average of each parameter was calculated.
- In order for Excel to use the steam tables it must be imported as an “Add-in”. The Add-in named “water97-v13” was loaded.
- The calculations were programmed in the excel worksheet.

For the analysis, the same test used in section 7.1.5, was used as the input data for the Excel programme. The result of the VBA code was 86.41% which is a 0.28% difference between the automated PHB result and the VBA code. Refer to Appendix 19.

7.2 PHB Uncertainty

The uncertainty of the PHB should be considered so that if adjustments are required, the effect will not exceed the allowable tolerances. The PHB is adjusted based on the results of the SHB and the uncertainties of the SHB and PHB play a role in the accurate measurement of the reactor power. The uncertainties in the PHB are due to the following factors:

- Uncertainty due to the physical measurement device (transducer/transmitter),
- Error of the data acquisition unit (KIT) when resistors are used to convert current to voltage

An example of a measurement device used in the PHB is a RTD (Resistance Temperature Detector) which is used for temperature measurement in the primary system. This is a unique type of temperature sensor because it consist of a length of fine wire (the resistor) wrapped around a ceramic or glass core. The RTD wire is a pure material, typically platinum, nickel, or copper. The material has a resistance/temperature relationship which is used to provide an indication of temperature and is able to withstand high temperatures. Refer to Appendix 13 for the calculation of the PHB uncertainties associated with all the instruments used for the PHB.

The uncertainty of the test developed by Mesquita et al (2014) was 4% however at Koeberg, the uncertainty was found to be 0.903% (Equation A13.4). In comparison with the uncertainty of the SHB (0.232%), the PHB is less accurate and have more factors that contribute to the total uncertainty.

7.3 PHB Sensitivity analysis

The influence factor or sensitivity is the impact which a measured parameter can have on the result. Different instruments in the PHB system have different sensitivities because of the influence which the measured parameters have on the result. These sensitivities show the amount of change that occurs in the calculated result per unit change in the input variable. The same analysis was done for the PHB as was done for the SHB. The sensitivity of all the PHB instruments were checked to determine how much influence the errors and uncertainties could affect the result. Detail of the sensitivity analysis are contained in Appendix 14. A summary of the results per loop are shown below in Table 7.2.

Parameter	Sensitivity: Effect of error (%)
Hot Leg Temperature	0.6307
Cold Leg Temperature	-0.5794
Pressurizer Pressure	-0.0355
Specific Volume	0.0258
Hot Leg Enthalpy	0.2820
Cold Leg Enthalpy	-0.2628
Reactor Coolant Pump Speed	0.2100

Table7.2: Sensitivity analysis of loop

Using the same formula used for the SHB analysis (5.8 – 5.11), we find that the sum of the combined uncertainties equate to 0.305 % and is equivalent to 8.45 MW in total (Table A14-2). When compared with the uncertainty for the SHB, which is 6.38 MW (from Table 5.4), it can be concluded that the uncertainty and sensitivity of the PHB is higher in comparison to the SHB.

7.4 Reactor Coolant Pump

The reactor thermal output for a given loop is found by multiplying the specific enthalpy difference for the hot leg and cold leg by the density and by the loop volumetric flow (calculated as a function of the ratio between nominal and current reactor coolant pump speed), see Equation 7.5. It can clearly be seen that a change in reactor coolant pump speed affects the loop flow calculation. A change in the pump speed during the 3 hour average will therefore alter the PHB. According to Maroka (2015) the PHB is consistently higher than the SHB and due to various parameters used in the calculation of the PHB, including the reactor coolant pump speeds, it will affect the relation between the PHB and SHB.

Based on the sensitivity analysis, shown in Table 7.1, the sensitivity of the pump speed is 0.21%. The parameter with the highest impact on the PHB result, is the hot leg temperature, with a sensitivity of 0.63%. This is unlike the SHB, where the measurement of the feedwater flow has the greatest impact on the SHB result as opposed to the feedwater temperature (refer to Section 5.2). With a lower sensitivity, the changes in speed due to grid transients will not exceed the allowed error and will still be smaller than the error contributed by the RTDs which measure the hot and cold leg temperatures.

The pump speed accuracy is shown as 0.14% which equates to 3.09 rpm. See Appendix 13. The pump speed was analysed and the standard deviation over the three hour period (which consists of 1937 data points) was found to be only 4.24 rpm while operating at a nominal speed of 1490 rpm. This standard deviation is only slightly higher than the speed accuracy. The deviations in the speed will therefore not have a major impact on the accuracy of the PHB and therefore will not significantly affect relationship between the PHB and SHB.

7.5 Conclusion

The instrumentation used to calculate the PHB is subject to large temperature fluctuations and as a result, is not as accurate as other measurement systems such as the SHB. An important element is that the PHB calculations assume either steady-state conditions or conditions that are steadily changing. The PHB was calculated manually for a period at steady state conditions and the results were compared with the official computed PHB test. The results showed a good correlation with a difference of 0.28%. The PHB was programmed in Excel for use as a trouble shooting and fault finding tool. The benefit is that each instrument can be individually altered to show the expected change in the result. This is useful for when instruments become defective and the impact on the PHB needs to be determined. It will also assist with estimating the uncertainty due to thermohydraulic effects.

The instrument and KIT errors were used to determine the PHB uncertainty which was calculated as per EPRI, Mantey (2013). It was found that the sum of the combined uncertainties was found to be 0.903% and is less accurate than the SHB.

The combination of the sensitivity and the uncertainties equate to 0.305 % which is equivalent to 8.45 MW of full power. This is higher than the combined value for the SHB, which is 6.38 MW. This shows that the PHB is more sensitive and have more uncertainties, in comparison to the SHB.

The primary pump speed sensitivity was evaluated in terms of the accuracy and standard deviation and found to be smaller than other inputs to the PHB such as the hot leg temperature.

CHAPTER 8

SUMMARY AND RECOMMENDATIONS

The Secondary Heat Balance at Koeberg nuclear power station is an energy balance across the steam generators which are used to transfer the heat from the reactor to the turbine. The SHB uses instrumentation located on the secondary system of the steam generators as opposed to the instruments for other power measurement systems which are located inside the reactor core. Improved accuracies in the SHB will result in a more accurate representation of the thermal power generated in the core. This thesis analysed the accuracy of the instrumentation, the sensitivity of the results and the uncertainties in SHB system.

The SHB calculations were firstly performed manually to ensure that the methodology for determining the SHB was correct. The difference between the official SHB programme and the manual calculations performed in this thesis was found to be 0.17%

In order to provide more flexibility in the analysis of the SHB and for future development, the source code for the SHB was written in Excel VBA and Python. The new code will be used in research, fault finding and to identify improvement opportunities. The manual calculations were used to develop the Excel VBA code and showed a difference of 0.01% between them. The Python code shows a difference of 0.06%. These small differences show that the programming software could be beneficial to further develop and replace the now ageing SHB software.

The SHB is important to nuclear safety and the accuracy must comply to the license conditions as issued by the National Nuclear Regulator. The combination of various errors and uncertainty provides a holistic view of the combined accuracy and uncertainty of the SHB measurement system. These include the systematic uncertainty, random uncertainty and sensitivity. From all the parameters analysed in this research, it can be concluded that the total inaccuracy of the SHB is 6.387 MW or 0.232% of the full power value. This is in line with the current expectations from the NNR who have specified a total inaccuracy of 2%.

The data processing system, KIT shows good accuracy and the random uncertainty is reduced due to the high volume of data. The system also checks the validity of the SHB outputs thereby ensuring high quality data. The feedwater flow uncertainty was quantified and found to be much better than non intrusive measurement methods.

Thermal hydraulic characteristics of the water and steam flow inside the steam generator causes fluctuations at various periods. It was found that there are variations in the data for the different periods within a test. One example noted was the differential pressure measurement. There was a change in the recorded plant parameters for the third period when compared to the first two periods of the test duration. This phenomenon should be further investigated to identify the root cause.

The RPN and PHB measurement systems are adjusted based on the results of the SHB and the errors of the SHB instrumentation will therefore be transferred to the RPN and PHB systems. To analyse these errors, the PHB was calculated manually at steady state conditions and the results were compared with the official computed PHB test. The results showed a good correlation with a difference of 0.28%. The PHB was programmed in Excel for use as a trouble shooting and fault finding tool, similar to the method used for the SHB. This is beneficial in that each instrument can be individually altered to show the expected change in the result. If adjustments are made based on a defective SHB result, this tool can be used to calculate the PHB with the induced error of the defect.

It will also assist with estimating the uncertainty due to thermohydraulic effects. The combination of the sensitivity and the uncertainties equate to 0.305 % which is equivalent to 8.45 MW of full power. This is higher than the combined value for the SHB, which is 6.38 MW. This shows that the PHB is more sensitive and have more uncertainties, in comparison to the SHB.

The accurate measurement of power generated by the reactor core provides confidence that the plant is operating safely within its design capability. This ensures that the personnel, plant and public are protected at all times. Nuclear safety is a key objective in the nuclear industry and the SHB helps in achieving this objective.

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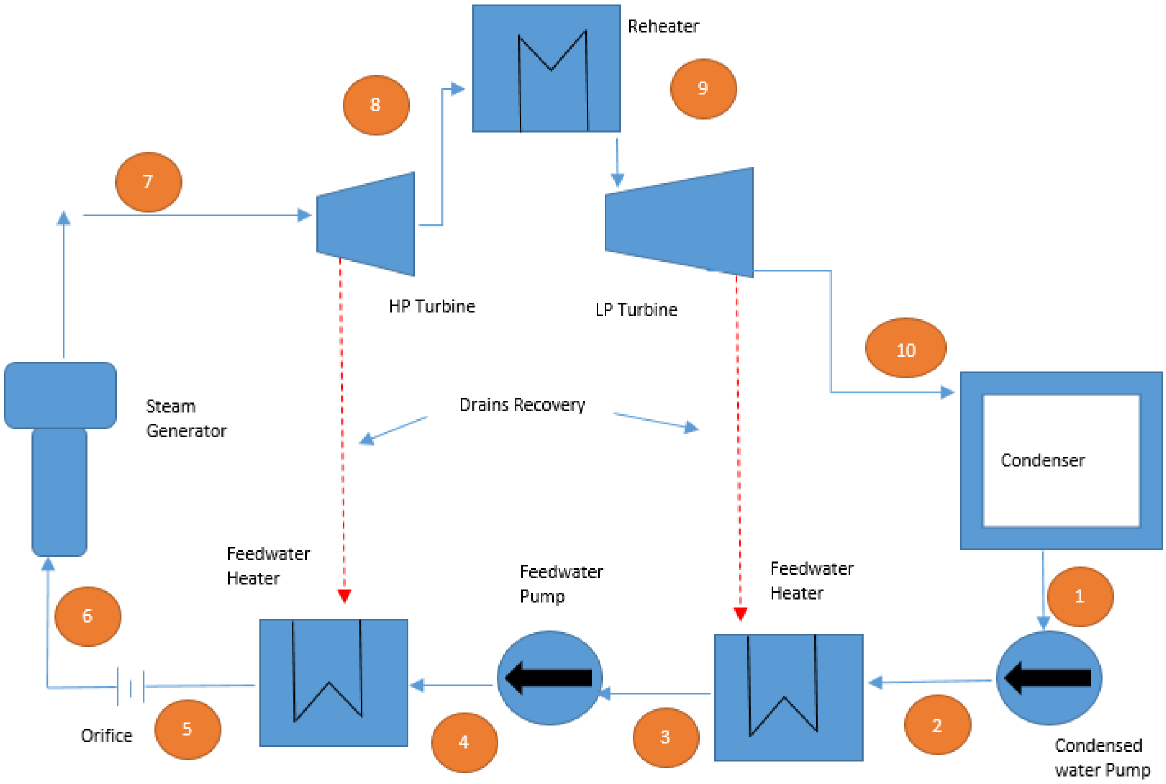
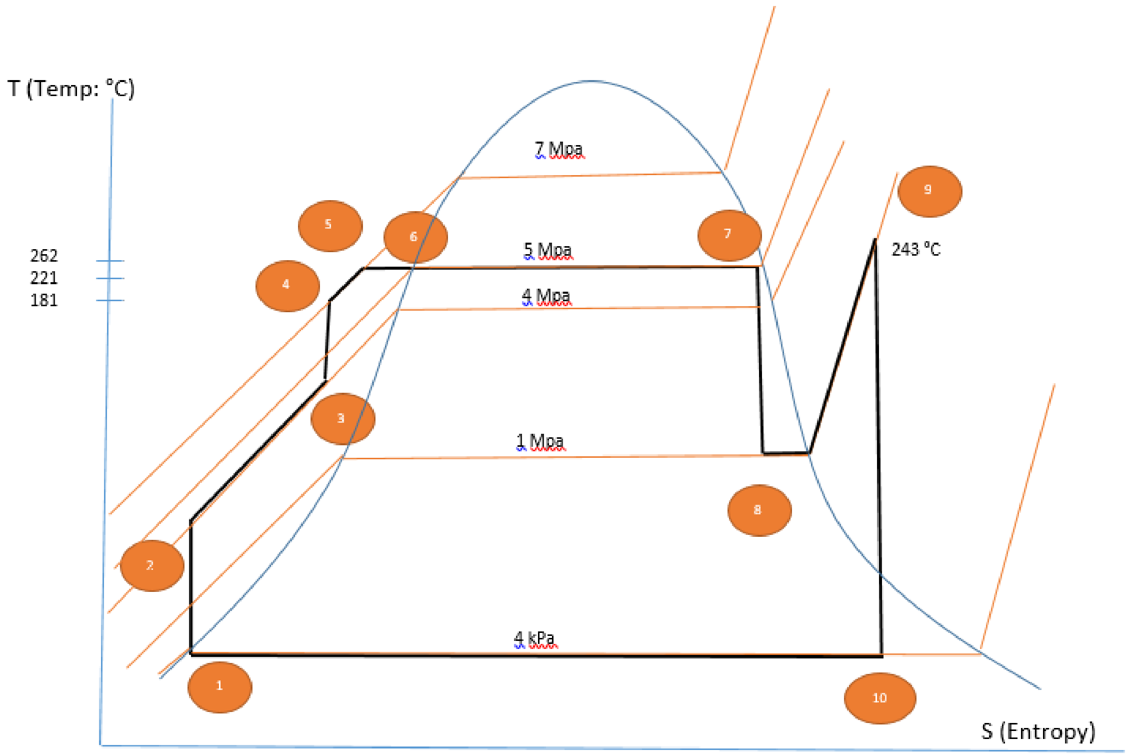
APPENDIX 1

CALCULATIONS OF CONTROLLED VOLUME ANALYSIS





At Point 1 (Saturated Liquid)

T_1= 30 °C (measured)

P_1 = 4.2 kPa (measured)

$h_1 = h_{f1}$ = 124.68 kJ/kg (by interpolation)

$V_1 = V_f$ = 0.0001004 m^3/kg

At Point 2

T_2 = 30.4 °C (measured)

P_2 = 4 MPa (measured)

Wpump in	$= V_1(P_2-P_1)$	(A1.1)
	= (0,001004) (4000 – 4.2)	
	= **4.01 kJ/kg**	
h_2	$= h_1$ + Wpump	
	= 124.68 + 4,01	
	= 128.69 kJ/kg	

At Point 3 (Sub-cooled liquid)

T_3 = 181 °C (measured)

P_3 = 4 MPa (measured)

h_3= 767.7 kJ/kg (interpolation)

At Point 4 (Sub-cooled liquid)

T_4 = 181 °C (measured)

P_4 = 7.4 MPa (measured)

h_4= 943.62 kJ/kg (interpolation)

Wpump in	$= V3(P_4-P_3)$	(A1.2)
	= (0.001128) (7400-4000)	
	= **3.84 kJ/kg**	

$$h_4 = h_3 + W_{pump} \quad \text{(A1.3)}$$

$$= 767.7 + 3.84$$

$$= \mathbf{771.5\ kJ/kg}$$

At Point 5 (Sub-cooled liquid)

T_5 = 221 °C (measured)

P_5 = 7.4 MPa (measured)

H_5= 948.3 kJ/kg (interpolation)

At Point 6 (Saturated liquid)

T_5 = 221 °C (measured)

P_5 = 5 MPa (measured)

H_5= 948.3 kJ/kg (interpolation)

At Point 7 (Wet steam)

T_6 = 262 °C (measured)

P_6 = 5 MPa (measured)

x = 0.9975 (determined during commissioning tests)

$$h_6 = h_f + x\, h_{fg} \quad \text{(A1.4)}$$

$$= 1154.23 + (0.9975)(1640.1)$$

$$= \mathbf{2790.1\ kJ/kg}$$

$$s_6 = s_f + x\, s_{fg} \quad \text{(A1.5)}$$

$$= 2.92 + (0.9975)(3.0553)$$

$$= 5.96\ kJ/kg\ K$$

At Point 8 (Wet steam)

P_7 = 1.1 MPa (measured)

$$s_7 = s_6 = s_{f7} + x\, s_{fg7} \quad \text{(A1.6)}$$

$$5.96 = 2.179 + x(4.374)$$

$$\mathbf{x = 0.866}$$

$$h_7 = h_f + x\,h_{fg} \quad (A1.7)$$

$$= 781.34 + (0.866)(2000.4)$$

$$= \mathbf{2513.6\ kJ/kg}$$

<u>At Point 9 (Superheated steam)</u>

T_8 = 243 °C (measured)

P_8 = 1.1 MPa (measured)

h_8 = 2923 kJ/kg (double interpolation)

s_8 = 6.88 kJ/kg.K (double interpolation)

<u>At Point 9 (Wet steam)</u>

P_9 = 4.2 kPa (measured)

$$s_9 = s_8 = s_{f9} + x\,s_{fg9} \quad (A1.8)$$

$$6.88 = 0.432 + x(8.024)$$

$$\mathbf{x = 0.81}$$

$$h_9 = h_f + x\,h_{fg} \quad (A1.9)$$

$$= 124.86 + (0.81)(2429)$$

$$= \mathbf{2092.4\ kJ/kg}$$

APPENDIX 2

SECONDARY HEAT BALANCE CALCULATIONS

Showing all calculations for SG1 from SHB test performed on Unit 2 on 10 January 2020. The same calculations are repeated for SG2 and SG3 and the results are provided at the end of this Appendix.

Table A2-1: SHB measured inputs

SG1	
Parameter	**Value**
Feedwater Pressure	5382 kPa
Feedwater Temp	220.3 °C
Blowdown Flow	3.77 kg/s
Steam Pressure	5004 kPa
Steam Temp	263 °C
Steam quality	0.9975

3.3.1 Steam Enthalpy at SG_1 outet (h_v)

At 5004 kPa the steam is two phase saturated vapour (by interpolation):

$$h_v = h_f + x\, h_{fg} \tag{A2.1}$$

$= 1155,7 + (0,9975)(1639)$

$=$ **2791,31 kJ/kg**

$$s_6 = s_f + x\, s_{fg} \tag{A2.2}$$

$= 2,92 + (0,9975)(3,0553)$

$= 5,96$ kJ/kg K

Feedwater Enthalpy at SG_1 inlet (h_E)

Feedwater enthalpy is sub cooled liquid at 220,3 °C (by interpolation)

$h_E = h_f = 945$ kJ/kg

Feedwater Flowrate at SG_1 inlet (Q_E)

$$Q_E = \alpha\varepsilon\pi\frac{d^2}{4}\sqrt{(2.\Delta P.\rho} \tag{A2.3}$$

Where:

α = *Flow coefficient*

ε = Expansion coefficient = 1 for incompressible fluids

d = diameter of orifice

ΔP = Differential pressure across orifice plate

ρ= Density of feedwater

Diameter of orifice (d)

Due to high temperatures the diameter of the orifice will change due to thermal expansion. A fixed expansion coefficient for stainless steel is used.

$$d = d_0\,(1+\lambda d(t_E - t_{d0}) \qquad \text{(A2.4)}$$

$$= 0{,}2575\ [1+(0{,}000019)(220{,}3-23)]$$

$$= 258{,}46 \text{ mm}$$

Where:

d_0 = measured diameter at room temp = 257,5 mm

λd = expansion coefficient for Stainless steel = 0,000019

t_E = Feedwater temperature

t_{d0}= room temperature = 23 °C

Inner diameter of pipe (D)

$$D = D_0\,(1+\lambda D(t_E - t_{D0}) \qquad \text{(A2.5)}$$

$$= 0{,}3694\ [1+(0{,}0000128)(220{,}3-23)]$$

$$= 370{,}33 \text{ mm}$$

Where:

D_0 = measured diameter at room temp = 369,4 mm

λD = expansion coefficient for Carbon steel = 0,0000128

t_E = Feedwater temperature

t_{d0}= room temperature = 23 °C

Diameter ratio (β)

$$\beta = \frac{d}{D} \qquad \text{(A2.6)}$$

$$\beta = \frac{0{,}25846}{0{,}37033}$$

= 0,698

Feedwater density (ρ)

At 220,3 °C

$$Density,\ \rho = \frac{mass}{Volume} = \frac{1}{0{,}001190} = 840{,}3\ kg/m^3 \quad \text{(A2.7)}$$

Flow coefficient (α)

$$\alpha = A + B.\sqrt{\frac{10^6}{Re_D}} \quad \text{(A2.8)}$$

Where A and B are variables based on the diameter ratio. The origin of these variables will be explained later in this thesis.

$$A = 0{,}5922 + 0{,}4252\ \left[\frac{0{,}3871}{(D^2 x \beta^2 + 0{,}254D)} + \beta^4 + 1{,}25\beta^{16}\right] \quad \text{(A2.9)}$$

= 0,69316

$$B = 0{,}00025 + 0{,}002325(\beta + 1{,}75\beta^4 + 10\beta^{12} + 0{,}07874D(\beta^{16}) \quad \text{(A2.10)}$$

= $3{,}3165 \times 10^{-3}$

Reynolds number (Re)

$$Re_D = \frac{4Q_E}{\pi \eta D} \quad \text{(A2.11)}$$

Where

η = Dynamic Viscosity at 220 °C = 0,0001219 Pa.s

D = inner diameter of pipe = 370,33 mm

Q_E = Feedwater flowrate

The circular reference requires an iterative calculation to determine the flow coefficient, α. To determine the feedwater flowrate, we assume an initial value for α = 0,7.

i. Assign an arbitrary value for alpha: α = 0,7.

$$Q_E = \alpha\varepsilon\pi\frac{d^2}{4}\sqrt{(2.\Delta P.\rho} \qquad \text{(A2.12)}$$

$$Q_E = (0,7)(1)\pi\frac{0,258^2}{4}\sqrt{(2)(112x10^3)(840,3)}$$

= 502,07 kg/s

Where ΔP=112kPa (measured)

ii.

$$Re_D = \frac{4Q_E}{\pi\eta D} \qquad \text{(A2.13)}$$

$$Re_D = \frac{4(499,8)}{\pi(0,0001219)(370,33)}$$

Re_D = 14085,6

iii.

$$\alpha = A + B.\sqrt{\frac{10^6}{Re_D}} \qquad \text{(A2.14)}$$

$$\alpha = 1,728 + 3,04x10^{-3}\sqrt{\frac{10^6}{14085,6}}$$

= 0,7211

Continue to substitute α into the calculation for Q_E until the difference between successive values for α < 0,000001. Use the final Q_E value.

In this calculation it is 504,83 m³/hr

Blowdown Enthalpy at SG_1 (h_p)

rf = 18.189 – (0.2582 * $Qrel_{t-1}$) + (0.0011 * $Qrel^2_{t-1}$) (A2.15)

= 18.189 – (0.2582 * 98.69) + (0.0011 * 98.69^2)

= 3.42

where,

rf = the recirculation factor, unitless

Qrelt-1 = the relative thermal power calculated in the previous execution cycle, %

$$h_{BD} = \frac{h_{FW}+(rf\times h_f)}{1+rf}$$

$$h_{BD} = \frac{945 +(3.42\times 1155.72)}{1+3.42}$$

= 1108 kJ/kg

where,

hBD = the blowdown enthalpy

hFW = the feedwater enthalpy (kJ/kg)

rf = the recirculation factor (unitless)

hf = the enthalpy of the saturated fluid (kJ/kg)h_p = h_f = 1155,72 kJ/kg

Blowdown Flow rate at SG_1 (Q_p)

Blowdown flowrate is measured using a flowmeter:

Qp = 3,7 kg/s

After calculating all variables for Equation 2 based on results from 3.3.1 to 3.3.11

The thermal power of one steam generator is:

$$W_{SG} = h_V\ (Q_E - Q_P) + \ h_P Q_P - \ h_E Q_E \qquad \text{from 4.2}$$

= (2791,3)(502,49 - 3,7) + (1108)(3,7) – (945) (502,49)

= **921,52 MW**

The primary pump adds an extra 10 MW to the reactor coolant system and must therefore be subtracted from the result to obtain the power produced by the reactor. The design full power is 2775MW. The above calculations were performed for loops 2 and 3. Below are the results

Table A2-2: SHB Manual calculations

SHB Manual Calculations (Unit 2 - 10 Jan 2020)			
Parameter	**SG 1**	**SG 2**	**SG 3**
Steam Enthalpy (kJ/kg)	2791.31	2792.18	2791.10
Blowdown Enthalpy (kJ/kg)	1108	1108.84	1107.9
Feedwater Enthalpy (kJ/kg)	945.0	946.07	946.48
Feedwater flow (kg/s)	504.83	505.89	495.27
TotalThermal Power (MW)	921.52	922.87	905.86
Primary pump power(MW)	10		
TOTAL	2740.25.64 MW (98.75%)		

APPENDIX 3

EXAMPLE OF SECONDARY HEAT BALANCE REPORTS

SECONDARY HEAT BALANCE DATA SHEET

UNIT: 2 TEST NUMBER: 003/2020 DATE : 09-Jan-20 TIME : 11:59 PM W/O No 721109116

TYPE OF TEST: WEEKLY TEST

TEST DATA

TIME	MWe	STR	APG	CVI	CRF	VAC
0	965	0.53	41	1 2 3 5 6	14.27	4.89
5	965	"	"	"	14.27	4.89
10	965	"	"	"	14.27	4.89
15	965	"	"	"	14.27	4.89
20	965	"	"	"	14.27	4.89

GPV GOVERNOR VALVE POSITION (%

21VV	22VV	23VV	24VV	25VV	26VV
73.9	74.4	74.3	74.4	74.7	74.1

T ave	AUX Pn
295.88	38.85

SUMMARY OF RESULTS

SHB RESULT:	98.58 %	2736 MW		
[illegible]RESULT (RCP5[illegible]EUZ	98.96 %	2746 MW		

SHB/ PHB DIFFERENTIAL 0.3820 % (L[illegible] B[illegible]WEEN 0 AND + 0.4% : 11MW)

	10MA		[illegible]		30MA		40MA	
RPN CHANNEL READINGS :	98.83	%	[illegible]	%	98.88	%	98.85	%
SHB/RPN DIFFERENTIAL :	0.25	%	[illegible]	%	0.30	%	0.27	%

LIMITS:
DURING STRECH-OUT +/- 1.0%
NORMAL OPERATION +/- 0.6%
DURING START-UP +/- 0.6%

SHB PARAMETERS	SG 1	SG 2	SG 3
POWER (MW)	916.3	918.3	900.8
FEEDWATER FLOW (t/h)	1808.8	1811.8	1778.1
FEEDWATER TEMP (C)	220.5	220.3	220.4
PHB (MWth)	919.4	921.5	905.2

INSTRUMENTATION USED	SG 1	SG 2	SG 3
FEEDWATER TEMPERATURE	ARE005MT	ARE006MT	ARE007MT
FEEDWATER PRESSURE	N/A	ARE003MP	N/A
STEAM PRESSURE	VVP017MP	VVP018MP	VVP019MP
FEEDWATER DIFF. PRESSURE	ARE051MD	ARE052MD	ARE053MD

TEST RESULT

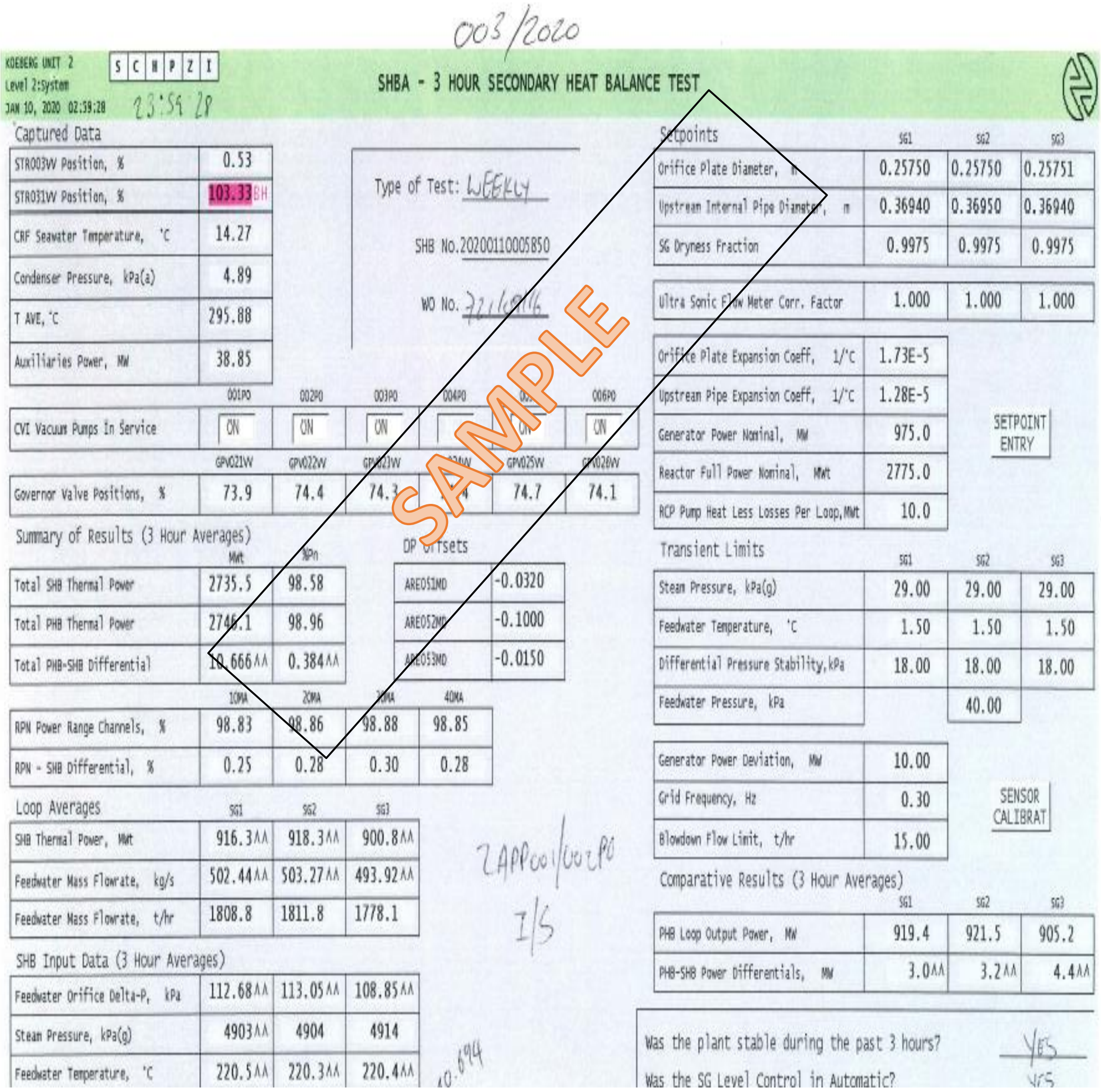
SHB/PHB DIFFERENTIAL: Acceptable

SHB/RPN DIFFERENTIAL: Acceptable

TEST COMMENTS

2APP001PO and 2APP002PO in service.

Figure A3-1: SHB Report Part A



003/2020

KOEBERG UNIT 2
Level 2:System
JAN 10, 2020 02:39:28 23:59:28

S | C | H | P | Z | I

SHBA - 3 HOUR SECONDARY HEAT BALANCE TEST

Captured Data

STR003VV Position, %	0.53
STR031VV Position, %	103.33 BH
CRF Seawater Temperature, °C	14.27
Condenser Pressure, kPa(a)	4.89
T AVE, °C	295.88
Auxiliaries Power, MW	38.85

Type of Test: WEEKLY

SHB No. 20200110005850

WO No. [illegible]

	001PO	002PO	003PO	004PO	[illegible]	006PO
CVI Vacuum Pumps In Service	ON	ON	ON		ON	ON

	GPV021VV	GPV022VV	GPV023VV	[illegible]	GPV025VV	GPV026VV
Governor Valve Positions, %	73.9	74.4	74.3	[illegible]	74.7	74.1

Summary of Results (3 Hour Averages)

	MWt	%Pn
Total SHB Thermal Power	2735.5	98.58
Total PHB Thermal Power	2746.1	98.96
Total PHB-SHB Differential	10.666 AA	0.384 AA

DP Offsets

ARE051MD	-0.0320
ARE052MD	-0.1000
ARE053MD	-0.0150

	10MA	20MA	30MA	40MA
RPN Power Range Channels, %	98.83	98.86	98.88	98.85
RPN - SHB Differential, %	0.25	0.28	0.30	0.28

Loop Averages

	SG1	SG2	SG3
SHB Thermal Power, MWt	916.3 AA	918.3 AA	900.8 AA
Feedwater Mass Flowrate, kg/s	502.44 AA	503.27 AA	493.92 AA
Feedwater Mass Flowrate, t/hr	1808.8	1811.8	1778.1

SHB Input Data (3 Hour Averages)

Feedwater Orifice Delta-P, kPa	112.68 AA	113.05 AA	108.85 AA
Steam Pressure, kPa(g)	4903 AA	4904	4914
Feedwater Temperature, °C	220.5 AA	220.3 AA	220.4 AA

2APP001/002PO

I/S

Setpoints

	SG1	SG2	SG3
Orifice Plate Diameter, m	0.25750	0.25750	0.25751
Upstream Internal Pipe Diameter, m	0.36940	0.36950	0.36940
SG Dryness Fraction	0.9975	0.9975	0.9975
Ultra Sonic Flow Meter Corr. Factor	1.000	1.000	1.000

Orifice Plate Expansion Coeff, 1/°C	1.73E-5
Upstream Pipe Expansion Coeff, 1/°C	1.28E-5
Generator Power Nominal, MW	975.0
Reactor Full Power Nominal, MWt	2775.0
RCP Pump Heat Less Losses Per Loop, MWt	10.0

SETPOINT ENTRY

Transient Limits

	SG1	SG2	SG3
Steam Pressure, kPa(g)	29.00	29.00	29.00
Feedwater Temperature, °C	1.50	1.50	1.50
Differential Pressure Stability, kPa	18.00	18.00	18.00
Feedwater Pressure, kPa		40.00	

Generator Power Deviation, MW	10.00
Grid Frequency, Hz	0.30
Blowdown Flow Limit, t/hr	15.00

SENSOR CALIBRAT

Comparative Results (3 Hour Averages)

	SG1	SG2	SG3
PHB Loop Output Power, MW	919.4	921.5	905.2
PHB-SHB Power Differentials, MW	3.0 AA	3.2 AA	4.4 AA

Was the plant stable during the past 3 hours? YES

Was the SG Level Control in Automatic? YES

SAMPLE

Figure A3-2: SHB Report Part B

APPENDIX 4

EXAMPLE OF CALIBRATION CERTIFICATE

TRIGRAM No: 1ARE003MP

CALIBRATION DATE : 2019/10/06

SER No : A300-578

JOB No : 719326894

AMBIENT CONDITIONS

Temp	23.8°C
Humidity	41%
Atmos.	1016 mBar

EQUIPMENT USED	MTE NUMBER
D. W. Tester	KIL200006
Standard DMM	KIL300990
Power Supply	KIL401090
Aneroid Barometer	KIL200620

MFR : ROSEMOUNT
TYPE : PRESSURE TRANSDUCER
MODEL : 1151
RANGE : 4000 kPa to 8000 kPa.
TOLER. : ± 0.25% of Span (16 mA)

INCREASING

NOMINAL INPUT kPa	TRUE INPUT kPa	DESIRED OUTPUT (mA)	[BEFORE ADJUST] ACTUAL OUTPUT	ERROR %	[AFTER ADJUST] ACTUAL OUTPUT	ERROR %
4000	3995.363	3.9815	3.97724	-0.0266%		
5000	4994.204	7.9768	7.97971	0.0182%		
6000	5993.045	11.9722	11.9798	0.0475%		
7000	6991.886	15.9675	15.9769	0.0588%		
8000	7990.727	19.9629	19.9895	0.1662%		

DECREASING

8000	7990.727	19.9629	19.9895	0.1662%		
7000	6991.886	15.9675	15.9882	0.1294%		
6000	5993.045	11.9722	11.9971	0.1556%		
5000	4994.204	7.9768	8.00068	0.1492%		
4000	3995.363	3.9815	3.99821	0.1044%		

Comments:

CORRECTIVE ACTION/FOLLOW-UP, use "***" YES : [ ] NO : ***

No action required.

RESPONSIBLE PERSON	SIGNATURE	DATE
RM DAVIS		2019/10/06
VERIFIER	SIGNATURE	DATE
R AHAMED		2019/10/06

APPENDIX 5

LINEARITY ANALYSIS

KIT input M&TE no. Due date	Cal date Input range CAP no.	Nom. full power	Nom. Input	True input	Actual output Incr.	 Decr.	 Avg.	Conversion coefficients		Range check	% Error
1ARE051MD	05-Oct-19		0	0.00000	3.99950	3.99830	3.99890	lr int	-49.97814251	0.01465	#DIV/0!
27E641632	4-20mA		40	39.95190	7.19270	7.19300	7.19285	lr sl	12.50162702	39.94422	0.019
1RO	164		80	79.91430	10.38840	10.39300	10.39070	lr rsq	0.999999935	79.92255	-0.010
		115	120	119.87188	13.58000	13.58800	13.58400			119.84400	0.023
			160	159.82887	16.77800	16.78500	16.78150	A0	0.0284	159.81795	0.007
			200	199.79310	19.98100	19.98100	19.98100	A1	1.0001302	199.81691	-0.012
1ARE052MD	05-Oct-19		0	0.00000	3.99960	3.99900	3.99930	lr int	-50.00020633	-0.00135	#DIV/0!
27E641636	4-20mA		40	39.95190	7.19490	7.19480	7.19485	lr sl	12.5019119	39.94914	0.007
1RO	165		80	79.91430	10.39150	10.39600	10.39375	lr rsq	0.999999926	79.94150	-0.034
		115	120	119.87188	13.58000	13.59200	13.58600			119.85073	0.018
			160	159.82887	16.77800	16.78600	16.78200	A0	0.0074	159.80685	0.014
			200	199.79310	19.98200	19.98200	19.98200	A1	1.000153	199.81297	-0.010
1ARE053MD	05-Oct-19		0	0.00000	3.99740	3.99600	3.99670	lr int	-49.95821811	0.00385	#DIV/0!
27E641637	4-20mA		40	39.95190	7.19240	7.19100	7.19170	lr sl	12.50083399	39.94401	0.020
1RO	166		80	79.91430	10.38810	10.39300	10.39055	lr rsq	0.999999961	79.93230	-0.023
		115	120	119.87188	13.58100	13.58800	13.58450			119.85934	0.010
			160	159.82887	16.77800	16.78300	16.78050	A0	0.0451	159.81201	0.011
			200	199.79310	19.98000	19.98000	19.98000	A1	1.0000667	199.80842	-0.008
1VVP017MP	06-Oct-19		4040	4035.25800	3.95310	3.99015	3.97163	lr int	3314.016877	4035.05576	0.005
A300-195	4-20mA		4770	4764.40100	7.97528	8.00583	7.99056	lr sl	181.5475983	4764.68284	-0.006
1RO	172	5000	5500	5493.54400	11.98730	12.02180	12.00455	lr rsq	0.999999958	5493.41397	0.002
			6220	6212.69900	15.95760	15.97790	15.96775			6212.92340	-0.004
			6940	6931.85400	19.92680	19.92680	19.92680	A0	-6.4261	6931.67940	0.003
								A1	1.0016419		
1VVP018MP	06-Oct-19		4040	4035.25000	3.95556	3.99238	3.97397	lr int	3312.979169	4034.10015	0.028
A300-197	4-20mA		4770	4764.39200	7.98890	8.02123	8.00507	lr sl	181.4610577	4765.58694	-0.025
1RO	173	5000	5500	5493.53400	12.00320	12.03360	12.01840	lr rsq	0.999999314	5493.85099	-0.006
			6220	6212.68700	15.97600	15.98800	15.98200			6213.09007	-0.006
			6940	6931.84100	19.93870	19.93870	19.93870	A0	-5.8810	6931.07707	0.011
								A1	1.0011645		
1VVP019MP	06-Oct-19		4040	4035.24700	3.94051	3.97228	3.95640	lr int	3319.64469	4034.56446	0.017
A300-198	4-20mA		4770	4764.38900	7.98207	8.01558	7.99883	lr sl	180.6997955	4765.03074	-0.013
1RO	174	5000	5500	5493.53000	12.01280	12.05170	12.03225	lr rsq	0.999999771	5493.86982	-0.006
			6220	6212.68300	15.99870	16.02320	16.01095			6212.82011	-0.002
			6940	6931.83600	19.98760	19.98760	19.98760	A0	14.7077	6931.39996	0.006
								A1	0.9969644		
1ARE005MT	16-May-20		30	30.26300	5.61200		5.61200	lr int	-74.85140829	30.25208	0.036
9815109	4-20mA		50	49.90300	6.66180		6.66180	lr sl	18.72834061	49.91310	-0.020
1Y	161		100	100.09200	9.33850		9.33850	lr rsq	0.999999804	100.04324	0.049
			150	150.15400	12.01690		12.01690			150.20523	-0.034
			180	180.08900	13.61470		13.61470	A0	0.0620	180.12937	-0.022
			200	199.95400	14.67390		14.67390	A1	0.9988448	199.96643	-0.006
		220	225	224.96500	16.00770		16.00770			224.94629	0.008
			240	239.85200	16.80170		16.80170			239.81659	0.015
1ARE006MT	14-May-20		30	31.31500	5.69400		5.69400	lr int	-75.3730417	31.51078	-0.625
9815108	4-20mA		50	49.90600	6.66620		6.66620	lr sl	18.77129852	49.76024	0.292
1Y	162		100	99.68700	9.31700		9.31700	lr rsq	0.999996713	99.51919	0.168
			150	149.90900	12.00070		12.00070			149.89572	0.009
			180	179.70700	13.60100		13.60100	A0	-0.2878	179.93543	-0.127
			200	199.65100	14.64950		14.64950	A1	1.0011359	199.61714	0.017
		220	225	225.09300	16.00440		16.00440			225.05037	0.019
			240	240.04100	16.80190		16.80190			240.02048	0.009
1ARE007MT	14-May-20		30	31.23000	5.69100		5.69100	lr int	-75.05558431	31.55874	-1.053
79914	4-20mA		50	49.99100	6.66590		6.66590	lr sl	18.73384781	49.82237	0.337
1Y	163		100	99.71600	9.32210		9.32210	lr rsq	0.999994378	99.58322	0.133
			150	149.91800	12.00350		12.00350			149.81616	0.068
			180	179.69300	13.58630		13.58630	A0	-0.1202	179.46809	0.125
			200	199.65300	14.66860		14.66860	A1	0.9991386	199.74374	-0.045
		220	225	225.08900	16.02640		16.02640			225.18056	-0.041
			240	240.05800	16.82680		16.82680			240.17513	-0.049
1ARE003MP	06-Oct-19		4000	3995.36300	3.97724	3.99821	3.98773	lr int	2999.291598	3995.16899	0.005
A300-578	4-20mA		5000	4994.20400	7.97971	8.00068	7.99020	lr sl	249.7357623	4994.72884	-0.011
1RO	93	5250	6000	5993.04500	11.97980	11.99710	11.98845	lr rsq	0.999999782	5993.23605	-0.003
			7000	6991.88600	15.97690	15.98820	15.98255			6990.70561	0.017
			8000	7990.72700	19.98950	19.98950	19.98950	A0	2.4625	7991.38427	-0.008
								A1	0.998943		
1APG004MD			0	0.00000	4.01400	4.01700	4.01550	lr int			
15750	0-500mV		15	10.00000	8.00200	8.02200	8.01200	lr sl			
	6		30	20.00000	11.99600	12.03900	12.01750	lr rsq			
	40	40	45	30.00000	16.00400	15.99700	16.00050				
			60	40.00000	19.97800	19.97800	19.97800	A0	0.0000		
								A1	1		

The straight line (y_a) for the calibration sequence:

$$y_a = m_a.x + c_a \tag{A5.1}$$

From the table in Appendix 5, the following values are determined for the SG1 feedwater sensor (1ARE005MT):

Slope (m_a)= 18,7 ; intercept (c_a)= -74,85

The adjusted line (y_b) to the calibrated sequence line

$$y_b = y_a.A_1 + A_0 \tag{A5.2}$$

where:
$A_0 = Offset\ coefficient$
$A_1 = Multiplier\ coefficient$
This equates to

$$A_0 = c_b - \frac{m_b}{\frac{300}{16}}\left(0 - \frac{300}{16} \times 4\right)$$

and

$$A_1 = \frac{16}{300} \times m_b$$

APPENDIX 6

MANUFACTURER SUPPLIED DATA FOR FEEDWATER TEMPERATURE SENSOR

Specifications and Reference Data

FUNCTIONAL SPECIFICATIONS

Inputs

Models 444RL, LL, and LM
100 Ω R_0 platinum RTD per IEC 751.

Model 444T
Thermocouple types E,J,K,T,R, and S per NIST (grounded or ungrounded).

Model 444MV
Millivolt input (grounded or ungrounded) source impedance les 100 Ω.

R-numbers, specials
Special inputs other than standards, consult factory.

Spans

RTD

Platinum	45 to 135 °F (25 to75 °C). 125 to 380 °F (70 to 210 °C). 360 to 1080 °F (200 to 600 °C).
Copper	180 to 540 °F (100 to 300 °C).
Nickel	45 to 360 °F (25 to 200 °C).

Thermocouples

Type J, K, E, T	180 to 540 °F (100 to 300 °C).
Type J	504 to 1458 °F (280 to 810 °C).
Type K, E	504 to 1510 °F (280 to 840 °C).
Type K	845 to 2540 °F (470 to 1410 °C
Type R, S	1467 to 3000 °F (815 to 1670 °C).

Millivolt
5 to 15 mV.
15 to 45 mV.

Outputs
Linear with temperature for RTD inputs.
Linear with millivolt input signal for thermocouple or millivolt i thermocouple and millivolt models input/output isolated to 500 V

Models 444RL, T, MV
4–20 mA.

Model 444LL
0.8–3.2 V dc.

Model 444LM
1.0–5.0 V dc.

Rosemount Model 444 Alphaline Temperature Transmitters

Output Limits (approximate)

Models 444RL, T, MV
Low: 3.9 mA dc.
High: 30.0 mA dc.

Model 444LL
Low: 0.1 V dc.
High: 4.2 V dc.

Model 444LM
Low: 0.125 V dc.
High: 6.2 V dc.

Power Supply

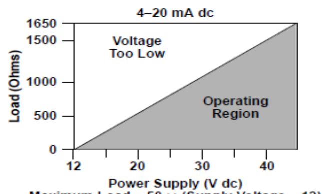
Models 444RL, T, and MV
12 to 45 V dc at terminals of transmitter.

Model 444LL
5 to 12 V dc (overvoltage protected to 24 V dc)
max current = 1.5 mA.

Model 444LM
8 to 12 V dc (overvoltage protected to 24 V dc)
max current = 2.0 mA.

Load Limits

Models 444RL, T, and MV
4–20 mA.



Maximum Load = 50 × (Supply Voltage – 12)

Span and Zero
Continuously adjustable, as defined in the ordering table. Adjustments are accessible from the terminal side of the transmitter housing.

Transmitter Temperature Limits
–13 to 185 °F (–25 °C to 85 °C), transmitter operates within specifications.
–40 to 212 °F (–40 °C to 100 °C), transmitter operates without damage.
–58 to 248 °F (–50 °C to 120 °C), storage.
–13 to 149 °F (–25 °C to 65 °C), transmitter operates within specifications for meter option.

Loss of Input
Upscale burnout indication standard for RTD inputs, downscale burnout indication optional. Upscale burnout indication standard for thermocouple and millivolt inputs; downscale burnout indication or no indication optional.

Turn-on Time
2 seconds. No warm-up required.

PERFORMANCE SPECIFICATIONS

Accuracy
±0.2% of calibrated span (or, for thermocouple and millivolt inputs, ±0.02 millivolts, whichever is greater). ±0.5% for copper, nickel, and isolated RTD inputs, 0.1% for differential RTD inputs. Includes combined effects of transmitter repeatability, hysteresis, linearity (conformity instead of linearity for thermocouple input), and adjustment resolution. Does not include sensor error.

Stability
±0.2% of calibrated span for six months.

Ambient Temperature Effect
Errors for 50 °F (28 °C) change in ambient temperature.

RTD Inputs
Zero: ±0.17 °C,
plus
Span: ±0.22%,
plus
Elevation/Suppression: ±0.083% of base temperature in °C.

T/C Inputs (Includes Effect of Cold Junction)
Zero: ±1.38 °C,
plus
Span: ±0.28% of span,
plus
Elevation/Suppression: ±0.11% of base temperature in °C.

Millivolt Inputs
Zero: ±0.038 mV,
plus
Span: ±0.28% of span,
plus
Elevation/Suppression: ±0.11% of base input in mV.

Input Impedance (Thermocouple and mV Inputs)
More than 1 megohm—burnout resistors disconnected.

Power Supply Effect
±0.005% per volt.

Load Effect
No load effect other than the change in voltage supplied to the transmitter.

Vibration Effect
±0.05% of span per g to 200 Hz in any axis for 3 g's up to 33 Hz, 2 g's from 33 to 70 Hz and 1 g from 70 to 200 Hz.

Mounting Position Effect
None.

APPENDIX 7

SYSTEMATIC ERRORS FOR ALL INSTRUMENTS USED IN THE SHB

$$\text{Instrumentation loop error} = \sqrt{\sum_i Uncertainty\ (i)^2}$$

For SHB:

$$\text{Instrumentation loop or Systematic error} = \sqrt{\text{Overall Transmitter error}^2 + Data\ acquisition^2}$$

$$= \sqrt{E_{thermowell}^2 + E_{linearity}^2 + E_{drift}^2 + E_{accuracy}^2 + E_{calibration}^2 + E_{data\ logging}^2} \qquad \text{(A7.1)}$$

For feedwater sensors

$$= \sqrt{0.167^2 + 0.024^2 + 0.2^2 + 0.25^2 + 0.2^2 + 0.15^2}$$

= 0.439 %

Table A7-1: Systematic errors for SHB

Parameter	FW Temp	FW Pres	FW DP	SG Steam Press	Feedwater flow
Thermowell	0.5°C (0.167%)	N/A	N/A	N/A	N/A
Linearity	0.024 %	0.009 %	0.014 %	0.004 %	N/A
Transmitter Accuracy	0.2 %	0.2 %	0.040 %	0.2 %	N/A
Drift	0.2 %	0.2 %	0.1 %	0.2 %	N/A
Calibration accuracy	0.25 %	0.25 %	0.145 %	0.25%	N/A
Static Pressure effect	N/A	N/A	0.145 %	N/A	N/A
Effect of temperature	IGNORE	IGNORE	0.425 %	IGNORE	N/A
Data acquisition error	0.15 %	0.15 %	0.15 %	0.15 %	N/A
Orifice Plate	N/A	N/A	N/A	N/A	0.583 %
TOTAL ERROR	**0.439 %**	**0.406 %**	**0.489 %**	**0.406 %**	**0.583 %**

APPENDIX 8

FEEDWATER FLOW UNCERTAINTIES

$$Feedwater\ Flow\ Uncertainty = \sqrt{\left(\frac{\delta\alpha}{\alpha}\right)^2 + \left(\frac{\delta\varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\beta^4}{1-\beta^4}\right)^2\left(\frac{\delta D}{D}\right)^2 + \left(\frac{2}{1-\beta^4}\right)^2\left(\frac{\delta d}{d}\right)^2 + \frac{1}{4}\left(\frac{\delta\Delta p}{\Delta p}\right)^2 + \frac{1}{4}\left(\frac{\delta\rho_1}{\rho_1}\right)^2}$$

Where:

Discharge coefficient uncertainty $\left(\frac{\delta\alpha}{\alpha}\right)$:

For $0.6 < \beta < 0.75$

Then $\frac{\delta\alpha}{\alpha}$ = (1.667β - 0.5) %

= (1.667*0.692 – 0.5)

= **0.6546 %**

Expansion factor uncertainty $\left(\frac{\delta\varepsilon}{\varepsilon}\right)$ = 3.5*$\frac{dP}{p1*K}$ %

= 3.5*$\frac{117.67}{5190*1}$

= **0.0793 %**

Where κ = isentropic exponent $= \frac{C_p}{C_v}$ across the orifice. It is necessary to know the density and the viscosity of the fluid at the working conditions. In the case of a compressible fluid, it is also necessary to know the isentropic exponent of the fluid at working conditions. In this instance, K= 1 because water is considered incompressible and therefore:

$Pipe\ Diameter\ ratio\ uncertainty$: $\left(\frac{\delta D}{D}\right)$ = 0.4% max

$Orifice\ diameter\ ratio\ uncertanty$: $\left(\frac{\delta d}{d}\right)$ = 0.1% max

$Differential\ Pressure\ uncertainty$: $\left(\frac{\delta\Delta p}{\Delta p}\right)$ is given by the manufacturer as the reference uncertainty and is already calculated as part of the systematic uncertainty. It will therefore be ignored in this calculation.

$Fluid\ Density\ uncertainty$ $\left(\frac{\delta\rho_1}{\rho_1}\right)$ is based on the steam lookup tables and not measured so we can assume that there is no uncertainty.

Therefore:

$$Feedwater\ Flow\ Uncertainty = \sqrt{0.6546^2 + 0.0793^2 + \left(\frac{2 * 0.6926^4}{1 - 0.6926^4}\right)^2 * (0.4)^2 + \left(\frac{2}{1 - 0.6926^4}\right)^2 (0.1)^2}$$

= 0.583 %

APPENDIX 9

RANDOM UNCERTAINTIES

Applying to the SG1 FW Temp

$$Random\ uncertainty \ = \frac{S_t \times \frac{s}{\bar{x}}}{\sqrt{n}} \times 100$$

Where:
St = student t-value (from chart)
α = confidence level
S = standard deviation
$\bar{x}$ = mean
n = count

$$Random\ uncertainty_{(SGFWTemp1)} = \frac{2.045 \times \frac{0.009}{220.5}}{\sqrt{1800}} \times 100$$

= 0.0002%

Applying the above calculations to all the instruments

Table A9-1: Random Uncertainties

	SG1 DP	SG2 DP	SG3 DP	SG1 FW TEMP	SG2 FW TEMP	SG3 FW TEMP	SG1 PRESS	SG2 PRESS	SG3 PRESS	SG2 FW PRESS
St $_{(n-1, \alpha/2)}$	2.045	2.045	2.045	2.045	2.045	2.045	2.045	2.045	2.045	2.045
avg	81.77	81.89	78.33	213.1	212.9	213.0	4605.6	4604.7	4616.2	4919.0
stdev	0.945	0.950	0.915	0.009	0.006	0.008	3.735	3.631	3.978	3.657
max	84.48	84.76	81.30	213.09	212.95	213.04	4615.08	4614.39	4625.72	4928.16
min	79.18	78.94	75.46	213.05	212.90	213.00	4591.64	4590.28	4600.24	4905.60
max - min	5.30	5.82	5.85	0.05	0.05	0.05	23.44	24.10	25.48	22.56
Count	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Random uncertainty	0.0557	0.0559	0.0563	0.0002	0.0001	0.0002	0.0039	0.0038	0.0042	0.0036

Table A9-1: Random Uncertainties

APPENDIX 10

SENSITIVITY ANALYSIS FOR THE SHB

Table A10-1: Sensitivity Analysis of SHB instruments

Parameter	Initial values of test			New values			% change in Loop Power	% change in Reactor Power
	Input value	Loop power	Reactor power	Input value +1%	Loop power	Reactor power		
SG1 Temp (°C)	220.03	928.4	2753.1	222.23	921.77	2746.5	-0.71	-0.24
SG2 Temp (°C)	220.02	908.6	2753.1	222.22	902.11	2746.6	-0.71	-0.24
SG3 Temp (°C)	220.27	916.1	2753.1	222.47	909.56	2746.6	-0.71	-0.24
SG1 Press (kPa)	4864.40	928.40	2753.10	4913.04	928.21	2752.90	-0.02	-0.01
SG2 Press (kPa)	4851.10	908.60	2753.10	4899.61	908.41	2752.90	-0.02	-0.01
SG3 Press (kPa)	4865.90	916.10	2753.10	4914.56	915.92	2752.90	-0.02	-0.01
FW Press (kPa)	5190.10	908.60	2753.10	5241.90	908.42	2753.00	-0.02	0.00
SG1 Flow (kPa)	117.64	928.40	2753.10	118.80	933.00	2757.50	0.50	0.16
SG2 Flow (kPa)	112.69	908.60	2753.10	113.82	913.16	2757.60	0.50	0.16
SG3 Flow (kPa)	114.79	916.10	2753.10	115.94	920.50	2757.60	0.48	0.16
SG1 Orifice (m)	0.25601	928.40	2753.10	0.25866	954.05	2778.50	2.76	0.92
SG2 Orifice (m)	0.25601	908.60	2753.10	0.25866	933.57	2778.00	2.75	0.90
SG3 Orifice (m)	0.25601	916.10	2753.10	0.25856	940.20	2777.30	2.63	0.88

$$Total\ Uncertainty = Systematic\ contribution + Random\ contribution \qquad (A10.1)$$

where

$$Systematic\ contribution = \left[\left(\frac{Systematic\ uncertainty}{2}\right) \times Sensitivity\right]^2 \qquad (A10.2)$$

$$Random\ contribution = \left[\left(\frac{Random\ uncertainty}{\sqrt{sample\ size}}\right) \times Sensitivity\right]^2 \qquad (A10.3)$$

Using the student-t value from the random uncertainty which provides a probability assessment, the percentage error is determine by:

$$Percentage\ Uncertainty = S_t\sqrt{Total\ Uncertainty} \qquad (A10.4)$$

Where S_t = student-t value available from a table in Mantey, 2013

Table A10-2: Combining error and Sensitivity SHB instruments

Combining error and Sensitivity							
Parameter	FP value	Systematic Uncertainty	Random Uncertainty	Sensitivity	Combined		Total Uncertainty
					Systematic Contribution	Random Contribution	
SG1 Temp	220.03	0.439	0.0002	-0.240	0.002769	1.654E-12	0.002769
SG2 Temp	220.02	0.439	0.0002	-0.236	0.002686	1.604E-12	0.002686
SG3 Temp	220.27	0.439	0.0002	-0.236	0.002686	1.604E-12	0.002686
Steam Press	4864.40	0.406	0.0039	-0.007	0.000002	5.376E-13	0.000002
Steam Press	4851.10	0.406	0.0038	-0.007	0.000002	5.082E-13	0.000002
Steam Press	4865.90	0.406	0.0042	-0.007	0.000002	6.070E-13	0.000002
FW Press	5190.10	0.406	0.0036	-0.004	0.000001	1.129E-13	0.000001
FW Diff Press	117.64	0.489	0.0557	0.160	0.001527	5.289E-08	0.001527
FW Diff Press	112.69	0.489	0.0559	0.163	0.001597	5.566E-08	0.001597
FW Diff Press	114.79	0.489	0.0563	0.163	0.001597	5.649E-08	0.001597
			Sum of Total Uncertainty, % (Eq 5.8)				**0.013**
			Percentage of Total Uncertainty % (Eq 5.11)				**0.232**
				Average corrected output, MW			**2753.100**
				Test uncertainty, MW			**6.387**

APPENDIX 11

EXCEL PROGRAMME WITH AUTOMATIC ERROR

Test No :		start	end					
Date :	16-Mar-2020	23:55:00	02:55:00					RESET ALL
	U2 Secondary Heat Balance				U2 SHB error analysis			
Parameter	**SG1**	**SG2**	**SG3**		**SG1**	**SG2**	**SG3**	
offset dp	-0.032	-0.100	-0.015	kPa				
uncorrected dP	81.772	81.888	78.332					
Feed Water dP (z corrected)	81.74	81.79	78.32	kPa	81.74	81.79	78.32	DP1 + error; DP1 - error; DP2 + error; DP2 - error; DP3 +error; DP3 - error — Increase results in positive
Feed Water Temp	213.08	212.93	213.03	°C	213.08	212.93	213.03	FW1 temp + error; FW1 temp - error; FW2 temp +error; FW2 temp - error; FW3 temp -error; FW3 temp - error — Increase results in negative
Feed Water Pressure	5020.29	kPa(abs)			5020.29			Fwpress +error; Fwpress - error — Increase results in positive
Steam Pressure	4706.9	4706.1	4717.5	kPa(abs)	4706.9	4706.1	4717.5	
Impulse line water head	0.0	kPa (pgh)			0.0			
Steam Pressure (corrected)	4706.9	4706.1	4717.5	kPa(abs)	4706.9	4706.1	4717.5	
Steam Quality	0.9975	0.9975	0.9975		0.9975	0.9975	0.9975	
Total Blowdown Flow	39.53	t/hr			39.53			
Blowdown Flow per Loop	3.66	3.66	3.66	kg/s	3.66	3.66	3.66	
Intermediate Results								
Feed Water Volumic Mass	851.43	851.62	851.49	kg/m³	851.43	851.62	851.49	
Feed Water Enthalpy	912.77	912.10	912.54	kJ/kg	912.77	912.10	912.54	
Steam Saturated Enthalpy	2796.53	2796.54	2796.46	kJ/kg	2796.53	2796.54	2796.45	
Water Saturated Enthalpy	1135.79	1135.74	1136.48	kJ/kg	1135.80	1135.74	1136.48	
Steam Wet Enthalpy	2792.38	2792.39	2792.31	kJ/kg	2792.38	2792.39	2792.31	
Blowdown Enthalpy	1095.97	1135.74	1136.48	kJ/kg	1135.80	1135.74	1136.48	
Feed Water Dynamic Viscosity	0.00012643	0.00012652	0.00012646	kg/s.m	0.00012643	0.00012652	0.00012646	
Orifice Diameter	0.25750	0.25750	0.25751	m	0.25750	0.25750	0.25751	
Pipe Diameter	0.36940	0.36950	0.36940	m	0.36940	0.36950	0.36940	
Beta	0.69707634							
Results					430.24	430.34	421.20	FW flow
Feed Water Flow	430.24	430.34	421.20		430.24	430.34	421.20	FW1 + uncertainty; FW2 + uncertainty; FW3 + uncertainty; FW1 - uncertainty; FW2 - uncertainty; FW3 - uncertainty — increase results in positive
Feed Water Flow	1548.9	1549.2	1516.3	t/hr	1548.9	1549.2	1516.3	
Flow Coefficient (alpha)	0.6956	0.6955	0.6956		0.6955	0.6955	0.6955	
SG Thermal Power (incl PP)	**802.47**	**803.09**	**785.69**	MWth	**802.62**	**803.09**	**785.69**	
Reactor Thermal Power (excl PP)	**799.14**	**799.76**	**782.36**	MWth	**799.28**	**799.76**	**782.36**	
	86.39%	86.46%	84.58%		86.41%	86.46%	84.58%	
	0.58%	0.65%	-1.23%		0.60%	0.65%	-1.23%	
Power Transfer with RCP	**10**	MWth			**10**			
Total Reactor Thermal Power	**2381.3**	**MWth**			**2381.4**			
% Full Power	**85.81**	**% Pn**			**85.82**	The RPN channels and PHB are calibrated based on the SHB result		

APPENDIX 12

PRIMARY HEAT BALANCE

Reactor Thermal Output

$W_{loop} = C*W_F$ MWt

Where:

W_{loop} = the loop reactor thermal output

C = calibration constant for fine tuning

W_F = the power based on volumetric flow, cold leg density, and delta enthalpy per loop,

$$W_{CORE} = \Sigma W_{loop} \text{ for loops 1 to 3} \quad \text{(A12.1)}$$

Thermal Power to SGs

$$W_{SG} = W_{loop} + W_{pump} \quad \text{(A12.2)}$$

where,

W_{SG} = thermal power transferred to SG (MWt)

W_{loop} = the loop reactor thermal output

W_{pump} = pump heat less NSSS heat losses for loop

$$\textbf{Total Thermal Power} = \mathbf{W_T} = \sum W_{SG} \quad \text{(A12.3)}$$

$$\textbf{Relative Thermal Power} = \mathbf{W_R} = \frac{\mathbf{W_T}}{\mathbf{W_{rated}}} * \mathbf{100} \quad \text{(A12.4)}$$

where,

W_R = the relative thermal power delivered by core to the reactor coolant, %Pn

W_T = the reactor thermal power, MWt

W_{RATED} = the rated thermal power, MWt

Loop thermal power

$$W_{loop} = (F_{VOL} * D * dh) / 3.6E6 \quad \text{(A12.5)}$$

Where:
W_{loop} = the loop power based on volumetric flow, cold leg density, and delta enthalpy
F_{VOL} = the volumetric flow in the loop m^3/h
D = the fluid density in the cold leg, kg/m^3
dh = the delta enthalpy in the loop KJ/kg

3.6E6 = the unit conversion factor

Loop Flow Rate

$$Fvol = W_{loop} – P_h * SV / dh * C \qquad (A12.5)$$

W_{loop} = Loop Thermal Power

P_h = Pump Heat Losses

SV = Specific Volume

dh = Specific Enthalpy Difference

C = Conversion Factor (unitless)

Loop Specific Enthalpy Difference

$$dh = h\ [Hot\ leg] – h\ [Cold\ leg] \qquad (A12.6)$$

where,

dh = the delta enthalpy in the loop, kJ/kg

h = the specific enthalpy from the Steam Table, as a function of temperature and pressure, kJ/kg

T_h = the temperature in the ith hot leg, °C

P = the pressurizer pressure, Bar(g)

T_C = the temperature in the ith cold leg, °C

P_C = the cold leg pressure, Bar(g)

P_{atm} = the atmospheric pressure constant, Bar(g)

Cold Leg Volumetric Flow

$$Q_{VOLcold} = (A * B)(\ Q_{REL})]/100 \qquad (A12.7)$$

where,

$Q_{VOLcold}$ = volumetric flow in cold leg, m^3/h

A = nominal full power RCP loop flow, m^3/h

B = loop Nominal Flow Multiplier, unitless

Q_{REL} = the relative flow in the cold leg, percent of nominal

Cold leg density:

$$D_{CL} = 1 / SV[\text{ Cold Leg }] \qquad (A12.8)$$

where,

D_{CL} = fluid density in cold leg, kg/m^3

SV = a Steam Table function which provides specific volume as a function of temperature and pressure

Cold Leg Pressure:

$$P_{CL} = P_{pzr} + E$$

where,

PC = the calculated cold leg pressure, Bar(g)

P_{pzr} = the pressurizer pressure, Bar(g)

E = an amendable constant to correct for pressure drop across the reactor vessel = 4.2 Bar

The test of 16 March was used for analysis. Below are the results of the calculations are shown below

Table A12-1: Summary of PHB results

Parameter	Abr.	Loop1	Loop2	Loop3
Hot Leg temperature	T_{HL}	303.54	304.62	303.03
Cold Leg Temperature	T_{CL}	274.31	273.93	273.91
Pressuriser Pressure	P_{pzr}	15389.27	15389.27	15389.27
Cold leg press	P_{CL}	15389.69	15389.69	15389.69
Cold leg volumetric flow (Corrected)	Fvol	24372.76	23103.83	23949.86
Cold Leg Specific Volume	V_{CL}	0.001291	0.001291	0.001291
Cold leg density	D_{CL}	774.06	774.70	774.74
Cold Leg Enthalpy	h_{CL}	1203.30	1201.4	1201.28
Hot Leg Enthalpy	h_{HL}	1356.40	1362.44	1353.58
Enthalpy difference	dh	153.09	161.04	152.29
Loop Thermal	W_{loop}	802.32	800.67	784.97
Reactor Power	MW	**2397.97**		
	%	**86.41**		

APPENDIX 13

PRIMARY HEAT BALANCE UNCERTAINTIES

RTD accuracy (from manufacturer)

Reference accuracy: 0.1 °C

Influence of operating pressure (used at 15 Mpa but calibrated at atmospheric pressure): 0.07 °C

Repeatability: 0.11 °C

Utilising the root square method to determine the Total RTD Uncertainty:

$$\Delta T_{RTD} = \sqrt{0.1^2 + 0.07^2 + 0.11^2} = \mathbf{0.1644\ °C}$$

Data acquisition:

Data acquisition accuracy = 0.1%

Hot Leg and Cold Leg Span = 70 °C

Uncertainty due to data acquisition at hot/cold leg = 70*0.1% = +/- 0.07 °C

Combined Uncertainty = $\sqrt{0.07^2 + 0.07^2}$ = 0.09899 °C (for both the hot and cold leg)

Combined data acquisition and RTD error = $\sqrt{0.1644^2 + 0.09899^2}$ **= 0.191831°C**

Specific Volume Error:

Total Uncertainty = **+/- 0.015%**

(IAPWS Thermodynamic Properties of Water and Steam, 2007)

Pressurizer Pressure Error

Reference error : 2.03% of Span for range 11.1 to 18.1 MPa (as per manufacturer)

Total Uncertainty = 0.0681 MPa / 15.41 MPa = **+/- 0.4419%**

Enthalpy Error

For Hot Leg: Temperature = 321 °C, Pressure = 15.41 MPa

Uncertainty = 0.5 kJ /kg (IAPWS Thermodynamic Properties of Water and Steam, 2007)

At full power: Uncertainty = 0.5 / 1423.8 *100= **0.0351%**

For Cold Leg: Temperature = 286.6 °C, Pressure = 15.41 bar

At full power: Uncertainty = 0.5 / 1273 *100= **0.03927%**

Total Enthalpy uncertainty =$\sqrt{\text{Hot leg}^2 + \text{Cold leg}^2}$ = $\sqrt{0.0351^2 + 0.03927^2}$ **= 0.05267%**

Primary Pump Speed:

0.14% (Manufacturer)

Uncertainty = 0.0014 * 1800 = +/- 2.52 RPM

Total Uncertainty = $\sqrt{1.82^2 + 2.52^2}$ **= 3.09684 RPM**

Final PHB error

$$Final\ error = \sqrt{\frac{(\text{Total Enthalpy error})^2 + (\text{Cold leg error})^2 + (\text{Hot leg error})^2 +}{(\text{Specific Volume})^2 + (\text{Pressuriser Pressure error})^2 + (\text{Primary pump speed})^2}} \quad \text{(A13.1)}$$

= 1.56493%

Full power per loop = 925 MW Per Loop

Loop Error = 925 * 1.56493% (A13.2)

= 925 * 0.0156493

= 14.4756 MW

Each loop percent error = Loop error / full power * 100% (A13.3)

= (14.4756 / 2775)*100

= 0.5216 %

$$\text{Total error} = \sqrt{\sum Loop\ error^2} \text{ *100\%} \quad \text{(A13.4)}$$

$$= \sqrt{\sum_0^3 0.00521643^2} \text{ * 100\%}$$

$$= \sqrt{\sum_1^3 0.00521643^2}$$

= 0.903513 %

APPENDIX 14

PRIMARY HEAT BALANCE SENSITIVITY ANALYSIS

Table A14-1: PHB instruments Systematic Errors

Parameter	Full Power value	Error (%)	Value after error	Loop Power	Loop Power	Sensitivity:
Hot Leg Temperature	312.4	0.1918 (°C)	312.208	928.6	934.45	0.6307
Cold Leg Temperature	279.2	0.1918 (°C)	279.008	928.6	923.22	0.5794
Pressurizer Pressure	15.41	0.4419	15.477	928.6	928.27	0.0355
Specific Volume	765.8	0.0150	765.950	928.6	928.84	0.0258
Hot Leg Enthalpy	1406.94	0.0351	1407.443	928.6	931.21	0.2820
Cold Leg Enthalpy	1227.832	0.0392	1228.320	928.6	926.16	0.2628
Reactor Coolant Pump Speed	1485	0.210	1481.881	928.6	930.55	0.2100

Table A14-2: PHB instruments combining Systematic Errors and Uncertainty

Parameter	Full Power value	Systematic Uncert	Random uncert	Sensitivity	Systematic Contribution	Random Contribution	Combined contribution
Hot Leg Temperature	321	0.1918	0.0017	0.630734	0.003659	7.955E-10	0.003659
Cold Leg Temperature	286.6	0.191831	0.0009	0.579367	0.003088	1.935E-10	0.003088
Pressurizer Pressure	15.41	0.44	0.0008	0.035537	0.000061	5.182E-13	0.000061
Specific Volume	752.3709	0.015	0.0000	0.025845	0.000000	0.000E+00	0.000000
Hot Leg Enthalpy	1459.2	0.052	0.0000	0.282037	0.000054	0.000E+00	0.000054
Cold Leg Enthalpy	1266.5	0.052	0.0000	0.262761	0.000047	0.000E+00	0.000047
Reactor Coolant Pump Speed	1485	0.21	0.0000	0.209994	0.000486	0.000E+00	0.000486
			Sum of Total Uncertainty, % (Eq 5.8)				**0.022**
			Percentage of Total Uncertainty % (Eq 5.11)				**0.305**
			Average corrected output				**2775**
			Test uncertainty (MW)				**8.452**

APPENDIX 15

DATA ANALYSIS

	SG1 FEEDWATER DIFFERENTIAL PRE	SG2 FEEDWATER DIFFERENTIAL PRE	SG3 FEEDWATER DIFFERENTIAL PRE	SG1 FEEDWATER TEMP	SG2 FEEDWATER TEMP	SG3 FEEDWATER TEMP	SG1 STEAM PRESS	SG2 STEAM PRESS	SG3 STEAM PRESS	SG2 FEEDWATER PRESS	HIGH T AVG (403EU)	010MA AVERAGE FLUX	020MA AVERAGE FLUX	030MA AVERAGE FLUX	040MA AVERAGE FLUX
	2ARE051MD	2ARE052MD	2ARE053MD	2ARE005MT	2ARE006MT	2ARE007MT	2VVP017MP	2VVP018MP	2VVP019MP	2ARE003MP	2RGL409CA	2RPN413EU	2RPN414EU	2RPN415EU	2RPN416EU
avg	81.77	81.89	78.33	213.1	212.9	213.0	4605.6	4604.7	4616.2	4919.0	288.6	86.1	86.0	86.1	86.1
stdev	0.945	0.950	0.915	0.009	0.006	0.008	3.735	3.631	3.978	3.657	0.043	0.327	0.316	0.327	0.324
max	84.484	84.760	81.309	213.099	212.952	213.048	4615.084	4614.392	4625.722	4928.168	288.762	87.246	87.070	87.510	87.217
min	79.187	78.944	75.462	213.053	212.907	213.002	4591.646	4590.287	4600.242	4905.608	288.501	84.873	85.049	85.137	84.814
max - min	5.30	5.82	5.85	0.05	0.05	0.05	23.44	24.10	25.48	22.56	0.26	2.37	2.02	2.37	2.40
Random Uncertainty	0.0556	0.0558	0.0562	0.0002	0.0001	0.0002	0.0039	0.0038	0.0041	0.0036					
First 1hr															
Ave	81.7594	81.8679	78.3192	213.0792	212.9317	213.0289	4607.3440	4606.4396	4618.0301	4920.7631	288.6540	86.1277	86.0268	86.1555	86.1435
StdDev	0.9184	0.9592	0.8986	0.0084	0.0068	0.0088	3.1434	2.9222	3.3101	2.9924	0.0347	0.3355	0.3229	0.3261	0.3273
Max	83.9654	84.2865	80.5454	213.0989	212.9523	213.0476	4615.0845	4614.3921	4625.7217	4927.8633	288.7623	87.2461	86.8945	87.3047	87.2168
Min	79.1870	78.9443	75.6296	213.0531	212.9295	213.0247	4597.3950	4597.8062	4609.1040	4911.7056	288.5006	85.2246	85.0488	85.2539	84.9902
2nd 1hr															
Ave	81.7568	81.8709	78.3238	213.0805	212.9308	213.0290	4604.3537	4603.4888	4614.9087	4917.7984	288.6260	86.1132	85.9749	86.1095	86.1257
StdDev	0.9533	0.9484	0.9361	0.0096	0.0055	0.0089	4.3018	4.3487	4.6447	4.2604	0.0460	0.3308	0.3224	0.3390	0.3239
Max	84.4845	84.0575	81.3088	213.0989	212.9523	213.0476	4615.0845	4612.6230	4624.6138	4928.1680	288.7530	86.8945	86.8945	87.5098	87.0410
Min	79.4160	79.0359	75.5991	213.0531	212.9066	213.0247	4591.6460	4590.2871	4600.2417	4905.6084	288.5100	84.8730	85.0488	85.1367	84.8145
3rd 1hr															
Ave	81.8020	81.9268	78.3545	213.0739	212.9282	213.0245	4605.1147	4604.2565	4615.6894	4918.3192	288.6107	86.1139	85.9797	86.1176	86.1224
StdDev	0.9657	0.9416	0.9116	0.0081	0.0052	0.0045	2.9079	2.6832	3.0747	2.7968	0.0353	0.3142	0.3003	0.3125	0.3211
Max	84.3623	84.7596	81.0950	213.0989	212.9295	213.0476	4612.2095	4610.8535	4623.7280	4924.8145	288.7249	86.8945	87.0703	87.0117	87.1289
Min	79.1870	79.0817	75.4617	213.0531	212.9066	213.0018	4594.9624	4595.8154	4606.6670	4910.1816	288.5006	85.0781	85.1367	85.1953	84.9609
Total Ave% change - 1st hr ave	0.0158	0.0246	0.0166	-0.0006	-0.0007	-0.0006	-0.0377	-0.0371	-0.0393	-0.0365	-0.0082	-0.0109	-0.0382	-0.0324	-0.0149
Total Ave % change- 2nd hr ave	0.0190	0.0209	0.0107	-0.0012	-0.0002	-0.0007	0.0273	0.0270	0.0283	0.0238	0.0016	0.0059	0.0221	0.0211	0.0057
Total Ave % change- 3rd hr ave	-0.0363	-0.0473	-0.0284	0.0019	0.0010	0.0014	0.0107	0.0103	0.0114	0.0132	0.0069	0.0051	0.0166	0.0117	0.0095
Std Dev % change - 1st hr Std Dev	2.8594	-0.9962	1.8176	8.4967	-12.5131	-10.1534	15.8415	19.5112	16.7904	18.1710					
Std Dev % change- 2nd hr Std Dev	-0.8271	0.1378	-2.2736	-4.4509	9.6402	-11.5446	-15.1699	-19.7771	-16.7606	-16.5039					
Std Dev% change - 3rd hr Std Dev	-2.1391	0.8529	0.3997	11.8293	14.2037	43.3005	22.1486	26.0948	22.7081	23.5183					

APPENDIX 16

RECIRCULATION FACTOR

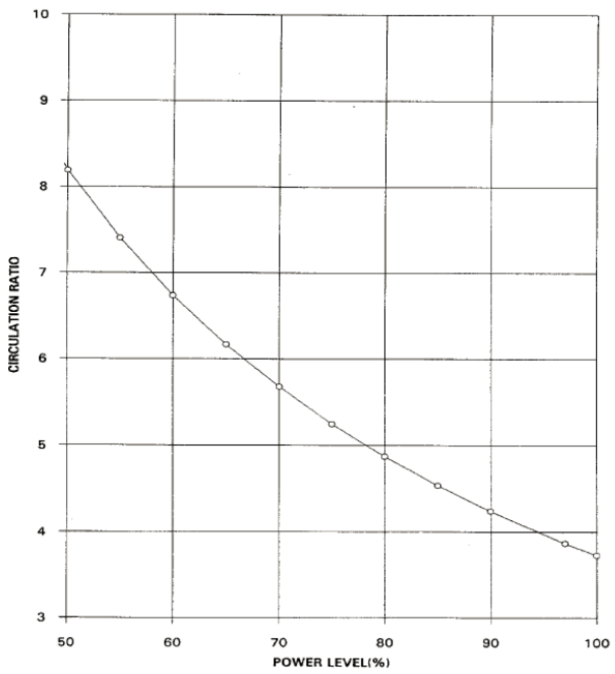
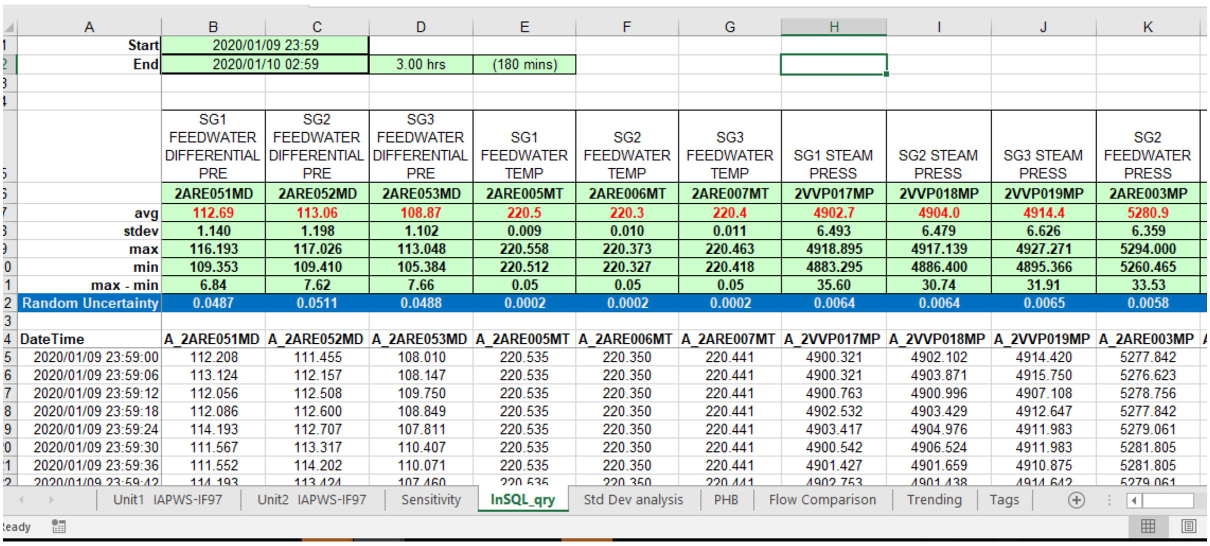


Figure 3.2-1. Circulation Ratio versus Relative Thermal Power

Coutesy – Glath, J (2012) *Primary Plant Performance Functional Specification,* Westinghouse

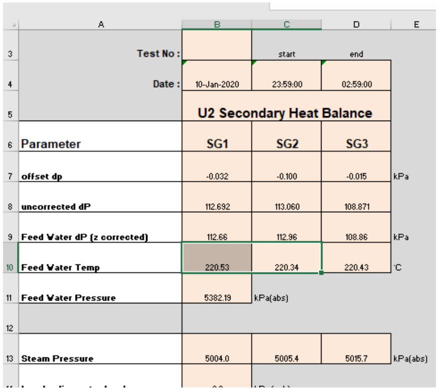
APPENDIX 17

SHB PROGRAMME USING EXCEL VBA CODE



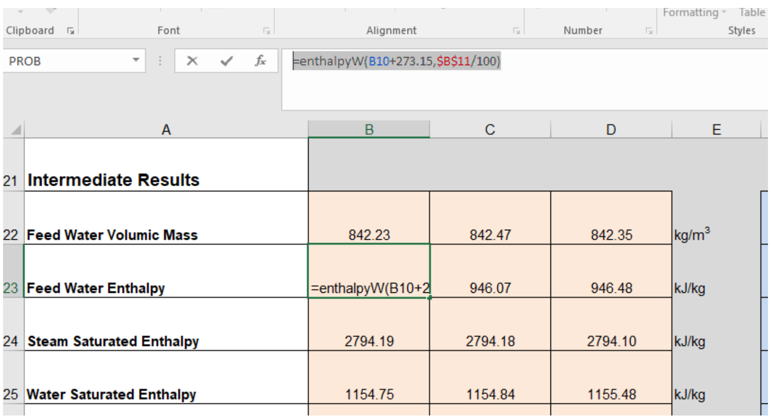
	A	B	C	D	E	F	G	H	I	J	K
1	Start	2020/01/09 23:59									
2	End	2020/01/10 02:59		3.00 hrs	(180 mins)						
3											
4											
5		SG1 FEEDWATER DIFFERENTIAL PRE	SG2 FEEDWATER DIFFERENTIAL PRE	SG3 FEEDWATER DIFFERENTIAL PRE	SG1 FEEDWATER TEMP	SG2 FEEDWATER TEMP	SG3 FEEDWATER TEMP	SG1 STEAM PRESS	SG2 STEAM PRESS	SG3 STEAM PRESS	SG2 FEEDWATER PRESS
6		2ARE051MD	2ARE052MD	2ARE053MD	2ARE005MT	2ARE006MT	2ARE007MT	2VVP017MP	2VVP018MP	2VVP019MP	2ARE003MP
7	avg	112.69	113.06	108.87	220.5	220.3	220.4	4902.7	4904.0	4914.4	5280.9
8	stdev	1.140	1.198	1.102	0.009	0.010	0.011	6.493	6.479	6.626	6.359
9	max	116.193	117.026	113.048	220.558	220.373	220.463	4918.895	4917.139	4927.271	5294.000
10	min	109.353	109.410	105.384	220.512	220.327	220.418	4883.295	4886.400	4895.366	5260.465
11	max - min	6.84	7.62	7.66	0.05	0.05	0.05	35.60	30.74	31.91	33.53
12	Random Uncertainty	0.0487	0.0511	0.0488	0.0002	0.0002	0.0002	0.0064	0.0064	0.0065	0.0058
13											
14	DateTime	A_2ARE051MD	A_2ARE052MD	A_2ARE053MD	A_2ARE005MT	A_2ARE006MT	A_2ARE007MT	A_2VVP017MP	A_2VVP018MP	A_2VVP019MP	A_2ARE003MP
15	2020/01/09 23:59:00	112.208	111.455	108.010	220.535	220.350	220.441	4900.321	4902.102	4914.420	5277.842
16	2020/01/09 23:59:06	113.124	112.157	108.147	220.535	220.350	220.441	4900.321	4903.871	4915.750	5276.623
17	2020/01/09 23:59:12	112.056	112.508	109.750	220.535	220.350	220.441	4900.763	4900.996	4907.108	5278.756
18	2020/01/09 23:59:18	112.086	112.600	108.849	220.535	220.350	220.441	4902.532	4903.429	4912.647	5277.842
19	2020/01/09 23:59:24	114.193	112.707	107.811	220.535	220.350	220.441	4903.417	4904.976	4911.983	5279.061
20	2020/01/09 23:59:30	111.567	113.317	110.407	220.535	220.350	220.441	4900.542	4906.524	4911.983	5281.805
21	2020/01/09 23:59:36	111.552	114.202	110.071	220.535	220.350	220.441	4901.427	4901.659	4910.875	5281.805
22	2020/01/09 23:59:42	114.193	113.424	107.460	220.535	220.350	220.441	4902.753	4901.438	4914.642	5279.061

Figure A17-1: Worksheet showing data imported from KIT



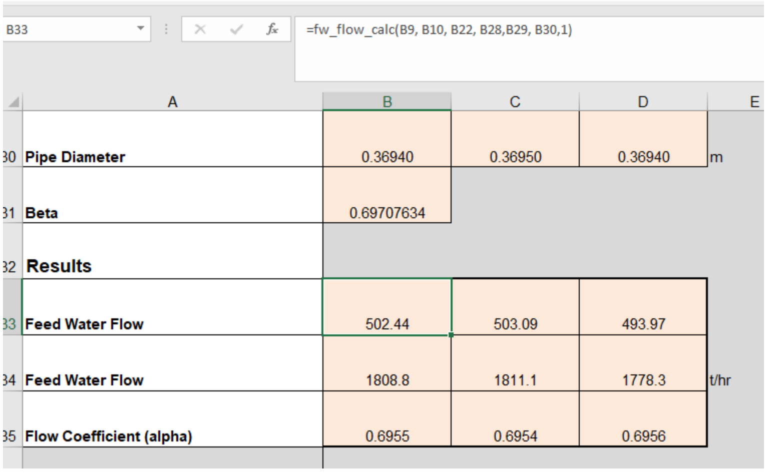
	A	B	C	D	E
3	Test No :		start	end	
4	Date :	10-Jan-2020	23:59:00	02:59:00	
5		U2 Secondary Heat Balance			
6	Parameter	SG1	SG2	SG3	
7	offset dp	-0.032	-0.100	-0.015	kPa
8	uncorrected dP	112.692	113.060	108.871	
9	Feed Water dP (z corrected)	112.66	112.96	108.86	kPa
10	Feed Water Temp	220.53	220.34	220.43	°C
11	Feed Water Pressure	5382.19	kPa(abs)		
12					
13	Steam Pressure	5004.0	5005.4	5015.7	kPa(abs)

Figure A17-2 Average values from KIT used as SHB Inputs



	A	B	C	D	E
21	Intermediate Results				
22	Feed Water Volumic Mass	842.23	842.47	842.35	kg/m³
23	Feed Water Enthalpy	=enthalpyW(B10+2	946.07	946.48	kJ/kg
24	Steam Saturated Enthalpy	2794.19	2794.18	2794.10	kJ/kg
25	Water Saturated Enthalpy	1154.75	1154.84	1155.48	kJ/kg

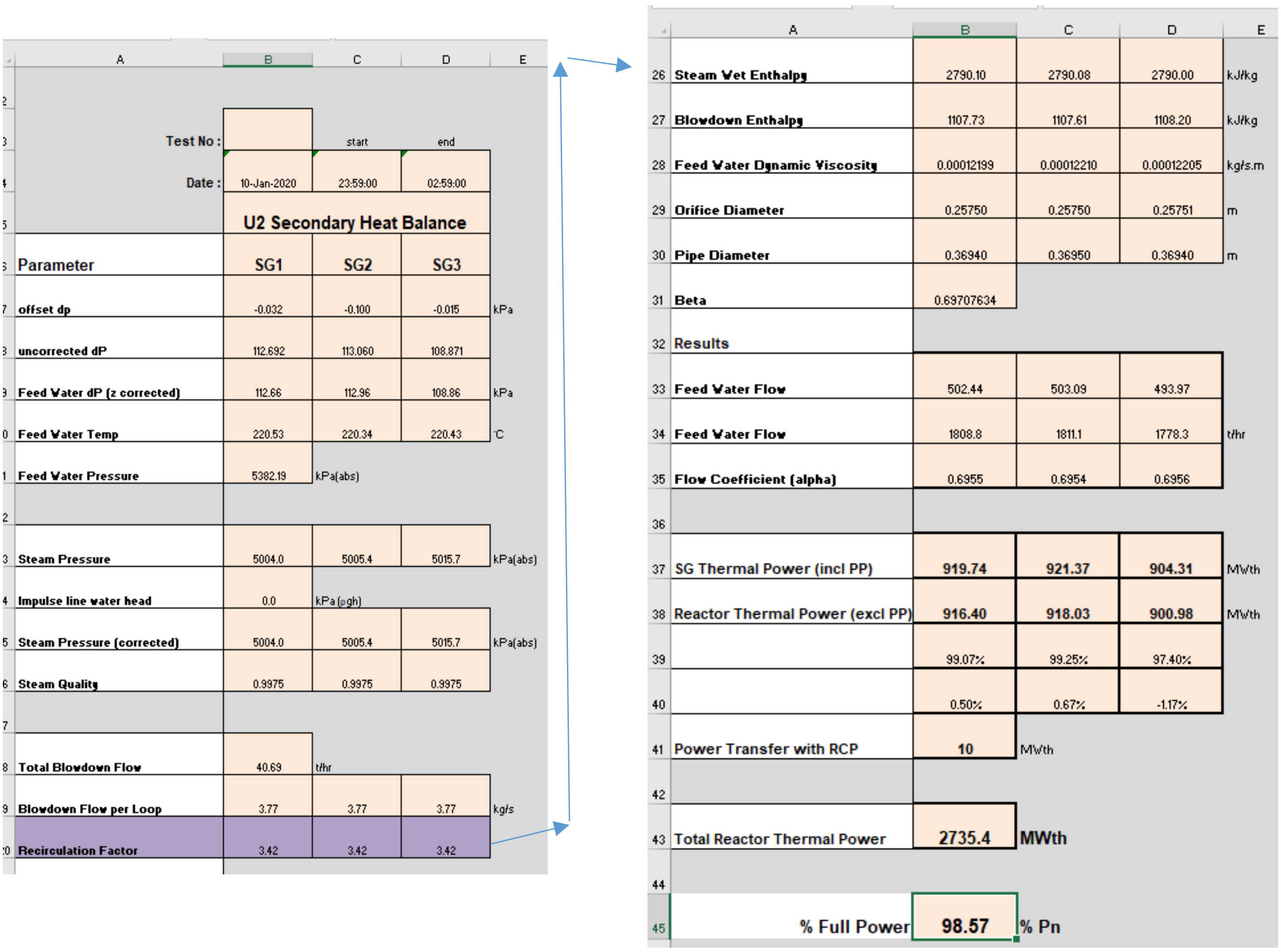
Figure A17-3: Calculation of feedwater enthalpy using the add-in named “water97-v13”



B33 =fw_flow_calc(B9, B10, B22, B28,B29, B30,1)

	A	B	C	D	E
30	Pipe Diameter	0.36940	0.36950	0.36940	m
31	Beta	0.69707634			
32	Results				
33	Feed Water Flow	502.44	503.09	493.97	
34	Feed Water Flow	1808.8	1811.1	1778.3	t/hr
35	Flow Coefficient (alpha)	0.6955	0.6954	0.6956	

Figure A17-4: The VBA code for the feedwater iterative calculation was compiled and used in the worksheet



	A	B	C	D	E
2					
3	Test No :		start	end	
4	Date :	10-Jan-2020	23:59:00	02:59:00	
5		U2 Secondary Heat Balance			
6	Parameter	SG1	SG2	SG3	
7	offset dp	-0.032	-0.100	-0.015	kPa
8	uncorrected dP	112.692	113.060	108.871	
9	Feed Water dP (z corrected)	112.66	112.96	108.86	kPa
10	Feed Water Temp	220.53	220.34	220.43	C
11	Feed Water Pressure	5382.19	kPa(abs)		
12					
13	Steam Pressure	5004.0	5005.4	5015.7	kPa(abs)
14	Impulse line water head	0.0	kPa (ρgh)		
15	Steam Pressure (corrected)	5004.0	5005.4	5015.7	kPa(abs)
16	Steam Quality	0.9975	0.9975	0.9975	
17					
18	Total Blowdown Flow	40.69	t/hr		
19	Blowdown Flow per Loop	3.77	3.77	3.77	kg/s
20	Recirculation Factor	3.42	3.42	3.42	

	A	B	C	D	E
26	Steam Wet Enthalpy	2790.10	2790.08	2790.00	kJ/kg
27	Blowdown Enthalpy	1107.73	1107.61	1108.20	kJ/kg
28	Feed Water Dynamic Viscosity	0.00012199	0.00012210	0.00012205	kg/s.m
29	Orifice Diameter	0.25750	0.25750	0.25751	m
30	Pipe Diameter	0.36940	0.36950	0.36940	m
31	Beta	0.69707634			
32	Results				
33	Feed Water Flow	502.44	503.09	493.97	
34	Feed Water Flow	1808.8	1811.1	1778.3	t/hr
35	Flow Coefficient (alpha)	0.6955	0.6954	0.6956	
36					
37	SG Thermal Power (incl PP)	919.74	921.37	904.31	MWth
38	Reactor Thermal Power (excl PP)	916.40	918.03	900.98	MWth
39		99.07%	99.25%	97.40%	
40		0.50%	0.67%	-1.17%	
41	Power Transfer with RCP	10	MWth		
42					
43	Total Reactor Thermal Power	2735.4	MWth		
44					
45	% Full Power	98.57	% Pn		

FigureA17-5: Screen shot of Excel Worksheet containing SHB calculations

APPENDIX 18

SHB PROGRAMME USING PYTHON CODE

Core Thermal Power Calculations Unit 2-Considering recirculation factor -

Core Thermal Power Calculations

```
In [1]: from CoolProp.CoolProp import PropsSI
        from math import pi
        import xlsxwriter
        import xlrd
```

Figure A18-1: The imported files for the various functions

InSQL Data Retrieval

```
In [2]: book = xlrd.open_workbook(r'C:u2_shb_9 Jan 2020xls - new.xlsm')
        InSQL = book.sheet_by_index(3)
```

Feedwater Flow Calculations

```
In [3]: #Parameters

        ε = 1 #Expansion coefficient
        α = 0.7 #Initial flow coefficient guess
        λd = 17.30e-6 #Temperature expansion coefficient of stainless steel orifice in 1/degC
        λD = 12.80e-6 #Temperature expansion coefficient of pipe in 1/degC
        Tod = 20 #Room temperature in degC
        WPR = 10 #Thermal power exchanged with the reactor coolant excluding the core in MW
```

Figure A18-2: The data retrieval from Excel

Unit 2 - Steam Generator 1

```
In [5]: #Input original orifice and pipe diameters before thermal expansion

Pdiff = (InSQL.cell(6, 1).value + InSQL.cell(6, 40).value)*1000 #Differential pressure across flow orifice plate in P
Te = (InSQL.cell(6, 5).value + InSQL.cell(6, 6).value)/2 #Feedwater temperature degC
Pf = InSQL.cell(6, 10).value + 101.325 #Feedwater pressure in kPa
Qp = ((InSQL.cell(6, 11).value)*(1000/3600))/3 #Blowdown flow rate in kg/s. Defined only for the first steam generato
SP = InSQL.cell(6, 7).value + 101.325 #Steam pressure in kPa
do = 0.25750 #Orifice plate diameter in m
Do = 0.36940 #Pipe diameter in m


vis = PropsSI('V', 'T', (Te + 273.15), 'P', (Pf * 1000), 'IF97::Water')#Temp in Kelvin and pressure in Pa
ρ = PropsSI('D', 'T',(Te + 273.15) , 'P', (Pf * 1000), 'IF97::Water')#Temp in Kelvin and pressure in Pa


d = do * (1 + λd*(Te - Tod)) #Thermal expansion calculation for orifice plate diameter in m
D = Do*(1 + λD*(Te - Tod)) #Thermal expansion calculation for pipe diameter in m


x = 1 #Arbritray place holder for while loop to run


while x > 0.0000001:
    Qe = α*ε*pi*((d**2)/4)*((2*Pdiff*ρ)**(1/2))
    Dnew = D*1000
    β = d/D
    A = 0.5922 + 0.4252*(((0.3871)/((Dnew**2) * (β**2) + 0.254*Dnew)) + β**4 + 1.25*β**16)
    B = 0.00025 + 0.002325 * (β + 1.75*(β**4) + 10*(β**12) + 0.07874*Dnew*(β**16))
    Re = (4*Qe)/(pi*vis*D)
    α = A + B*(((10**6)/Re)**(0.5))
    Qe_new = α*ε*pi*((d**2)/4)*((2*Pdiff*ρ)**(0.5))
    x = abs(Qe - Qe_new)
print(α)
print(Qe_new,"Kg/s")

#Steam Enthalpy Calculation
```

Figure A18-3: The calculations for feedwater

```
X = 0.9975 #Fraction
hvs = PropsSI('H', 'P', SP*1000, 'Q', 1 , 'IF97::Water')/1000 #Saturated steam enthalpy in kJ/kg
hes = PropsSI('H', 'P', (SP* 1000), 'Q', 0, 'IF97::Water')/1000 #Saturated water enthalpy in kJ/kg
hwet = PropsSI('H', 'P', (SP * 1000), 'Q', 0.9975, 'IF97::Water')/1000 #Wet steam enthalpy in kJ/kg
he = PropsSI('H', 'T', (Te + 273.15), 'Q', 0, 'IF97::Water')/1000 #Feedwater enthalpy in kJ/kg
rf = 4
hp = (he + rf*hes)/(1 + rf)

# Thermal power of steam generator 1 of unit 2

Wsg1 = (hwet*(Qe_new - Qp) + hp*Qp - he*Qe_new)/1000


workbook = xlsxwriter.Workbook('coolpropSG1.xlsx')
worksheet = workbook.add_worksheet()

worksheet.write('B2', ρ)
worksheet.write('B3', he)
worksheet.write('B4', hvs)
worksheet.write('B5', hes)
worksheet.write('B6', hwet)
worksheet.write('B7', hes)
worksheet.write('B8', vis)
worksheet.write('B9', do)
worksheet.write('B10', Do)
worksheet.write('B11', Qe_new)
worksheet.write('B12', Qe_new*3.6)
worksheet.write('B13', α)
worksheet.write('B14', Wsg1)
worksheet.write('B16', Pdiff)
worksheet.write('B17', Te)
worksheet.write('B18', Pf)
worksheet.write('B19', SP)
worksheet.write('B20', Qp)
worksheet.write('B21', hp)

workbook.close()
```

Figure A18-4: The outputs into Excel

APPENDIX 19

PHB PROGRAMME USING EXCEL

Loop 1 Hot Leg Temperature, °C, five-second average	Loop 1 Cold Leg Temperature, °C, five-second average	Loop 2 Cold Leg Temperature, °C, five-second average	Loop 2 Hot Leg Temperature, °C, five-second average	Loop 3 Cold Leg Temperature, °C, five-second average	Loop 3 Hot Leg Temperature, °C, five-second average	Pressuriser Pressure	Loop 1 cold leg volumetric flow - corrected	Loop 2 cold leg volumetric flow - corrected	Loop 2 cold leg volumetric flow - corrected
2RCP032MT	2RCP035MT	2RCP050MT	2RCP047MT	2RCP062MT	2RCP059MT	2KIT-TAP001	2KIT-STP118	2KIT-STP119	2KIT-STP120
303.544	274.319	273.937	304.629	273.914	303.035	153.893	24372.764	23103.832	23949.863
0.109	0.053	0.055	0.077	0.054	0.049	0.036	0.000	0.000	0.000
303.898	274.454	274.073	304.816	274.044	303.197	154.015	24372.764	23103.832	23949.863
303.253	274.133	273.727	304.252	273.710	302.889	153.794	24372.764	23103.832	23949.863
0.65	0.32	0.35	0.56	0.33	0.31	0.22	0.00	0.00	0.00
0.0017	0.0009	0.0010	0.0012	0.0009	0.0008	0.0011	0.0000	0.0000	0.0000
A_2RCP032MT-AVL	A_2RCP035MT-AVL	A_2RCP050MT-AVL	A_2RCP047MT-AVL	A_2RCP062MT-AVL	A_2RCP059MT-AVL	A_2KIT-TAP001	A_2KIT-STP118-Y0	A_2KIT-STP119-Y0	A_2KIT-STP120-Y0
303.573	274.283	273.903	304.662	273.851	303.090	153.903	24372.764	23103.832	23949.863
303.436	274.279	273.898	304.658	273.856	303.009	153.912	24372.764	23103.832	23949.863
303.633	274.287	273.903	304.688	273.856	303.009	153.913	24372.764	23103.832	23949.863
303.688	274.274	273.864	304.774	273.907	303.090	153.920	24372.764	23103.832	23949.863
303.539	274.261	273.851	304.718	273.881	303.090	153.918	24372.764	23103.832	23949.863
303.526	274.274	273.907	304.769	273.864	303.112	153.912	24372.764	23103.832	23949.863
303.714	274.244	273.911	304.680	273.881	303.035	153.902	24372.764	23103.832	23949.863
303.517	274.300	273.907	304.680	273.881	303.124	153.909	24372.764	23103.832	23949.863
303.693	274.257	273.894	304.573	273.860	303.124	153.898	24372.764	23103.832	23949.863
303.714	274.287	273.924	304.568	273.856	302.992	153.906	24372.764	23103.832	23949.863
303.752	274.253	273.920	304.714	273.851	303.060	153.914	24372.764	23103.832	23949.863
303.500	274.236	273.885	304.607	273.830	303.065	153.880	24372.764	23103.832	23949.863
303.633	274.249	273.877	304.680	273.830	303.060	153.871	24372.764	23103.832	23949.863
303.509	274.279	273.915	304.735	273.843	303.043	153.892	24372.764	23103.832	23949.863
303.398	274.270	273.890	304.739	273.830	303.120	153.884	24372.764	23103.832	23949.863

Figure A19-1: The data imported to Excel from KIT

A	B	C	D	E
		Loop1	Loop2	Loop3
	Thot	303.5440094	304.6287	303.0346
	Tcold	274.3192644	273.9368	273.9136
	Ppzr	15389.2734	15389.27	15389.27
0	Cold leg press	15389.6934	15389.69	15389.69
1	cold leg volumetric flow (Corrected)	24372.76367	23103.83	23949.86
2	Cold Leg Specific Volume	0.001291881	0.001291	0.001291
3	Cold leg density	774.0650533	774.7028	774.7415
4				
5	CL Enth©	1203.308907	1201.4	1201.285
6	HL enthalpy	1356.407107	1362.443	1353.583
7	Enthalpt diff	153.0982005	161.0429	152.2986
8	Loop Thermal	802.3240738	800.6786	784.9702
9				
0	Wreactor	2397.972944		
1	Power	86.41343943		

Figure A19-2: The Excel Worksheet with the PHB calculations