

UNCERTAINTY ANALYSIS OF THE PBMR TURBO MACHINES

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ABSTRACT

The aim of this study was to quantify the amount of uncertainty that surrounds the design of the PBMR turbo machines. The PBMR plant is a first-of-a-kind engineering effort in which a closed loop intercooled Brayton cycle is used to extract nuclear energy from a pebble bed reactor. Until the plant has been successfully operated, uncertainty will exist as to the performance of key components.

The Monte Carlo method was selected for the uncertainty analysis. The analysis tools used for the study were Matlab and Flownex. Flownex is widely used in industry. It is a fast solving network CFD code that solves conservation of mass, energy and momentum equations. In order to automate the process of solving thousands of steady-states, another code developed in Matlab was used. Matlab was also used to process the data.

Six turbo machine variables were selected as evaluating criteria. These included the rotational speed of the turbo units, the surge margin of the compressors, the grid power produced and the net cycle efficiency. Four steady state operating points, which are spread within the plant operating envelope, were evaluated.

Plant parameters influencing the six turbo machine variables were identified and the degree to which they contribute to the uncertainty was justified. The uncertain parameters include pressure drop, to which the reactor and turbo machine intake and diffusers are the main contributors. Other uncertain parameters include leakage flows, turbo machine efficiency and flow area, reactor outlet temperature, manifold pressure and cooling water temperature.

The Monte Carlo results indicate that the PBMR design is fairly robust with regard to the turbo machine parameters. An adjustment with regard to the design surge margin of the Low Pressure Compressor can be made as a result of this study. This recommendation will further enhance the robustness of the PBMR plant while at the same time quantifying the uncertainty surrounding the design of the turbo machines. Abbreviated results of this study were presented at the HTR 2004 conference in Beijing, China.

UITTREKSEL

Die doel van hierdie studie is die vermindering van onsekerheid rakende die ontwerp van die PBMR turbo masjiene. Die PBMR projek is 'n eerste van sy soort ingenieursontwerp waar 'n geslote lus Brayton siklus met tussenverkoeling gebruik word om kernenergie vanuit 'n reaktor te onttrek. Tot tyd en wyl die aanleg gebou en bedryf word sal daar onsekerheid bestaan oor die werking van sleutelkomponente.

Die onsekerheidsanalise is volgens die Monte Carlo metode gedoen. Matlab, tesame met 'n termo-hidrolise kode genaamd Flownex, wat wyd in industrie aangewend word, is gebruik as analiese gereedskap. Flownex is 'n netwerk BVM kode wat die behoud van massa, energie en momentum baie vinnig oplos. Ten einde die duisende gestadigde toestande op te los is Matlab kode gebruik. Matlab is ook gebruik om die data te verwerk.

Ses turbomasjiene veranderlikes is gebruik as evaluasiekriteria. Dit sluit in die rotasie spoed van die turbo eenhede, die stuwings marge van die kompressors, elektrisiteitslewering aan die verspreidingsnetwerk en die siklus effektiwiteit. Vier gestadigde toestand bedryfspunte, wat die aanleg se bedryfsgebied omvat, is gebruik vir die analises.

Aanlegparameters wat die ses veranderlikes van die turbomasjiene beïnvloed is geïdentifiseer en die graad waarmee die veranderlikes tot die onsekerheid bydra is verdedig. Die parameters wat tot die onsekerheid bydra is onder andere drukval, waar die reaktor en turbomasjiene wat die grootste bydrae lewer. Ander parameters wat tot onsekerheid bydra sluit in lekvlouie, turbomasjiendoeltreffendheid en vloeiarea, reaktor uitlaat temperatuur, hulsdruk en verkoelwatertemperatuur.

Die Monte Carlo resultate wys dat die PBMR ontwerp met betrekking tot die turbomasjiene parameters redelik robuust is. Hierdie studie het uitgewys dat 'n klein verandering aan die Laedrukkompressor se stuwingsmarge nodig is. Hierdie voorstel sal die robuustheid van die PBMR aanleg verder verbeter en terselfdertyd die onsekerheid wat met die turbomasjiene ontwerp gepaard gaan, verminder. Verkorte resultate van hierdie studie is aangebied by die HTR 2004 konferensie in Beijing, China.

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“The management of uncertainty is the key to the understanding of complexity, its patterns, and the order and knowledge it hides.” – Jacek Marczyk, PhD.

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ABBREVIATIONS

Abbreviation or Acronym	Definition
AVR	Arbeitsgemeinschaft Versuchsreaktor (German for Jointly-operated Prototype Reactor)
BVM	Berekeningsvloeimechanika
CDF	Cumulative Density Function
CFD	Computational Fluid Dynamics
CWT	Cooling Water Temperature (Pre-cooler/Intercooler inlet water temperature)
EMB	Electromagnetic Bearing
Eskom	Eskom Holdings Limited – RSA
GUI	Graphical User Interface
HP	High Pressure
HPC	High-pressure Compressor
HPT	High-pressure Turbine
HPTU	High-pressure Turbo-unit
HTGR	High-temperature Gas-cooled Reactor
HTR	High-temperature Reactor
IAEA	International Atomic Energy Agency
KTA	Kerntechnischer Ausschuss (German Nuclear Safety Standards Commission)
LHS	Latin Hypercube Sampling
LP	Low Pressure
LPC	Low-pressure Compressor
LPT	Low-pressure Turbine
LPTU	Low-pressure Turbo-unit
MCR	Maximum Continuous Rating
MCRI	Maximum Continuous Rating Inventory
MHI	Mitsubishi Heavy Industries
MIT	Massachusetts Institute of Technology
MPS	Main Power System
MW	Megawatt
NGNP	New Generation Nuclear Plant
PBMM	Pebble Bed Micro Model
PBMR	Pebble Bed Modular Reactor
PBMR (Pty) Ltd	Pebble Bed Modular Reactor (Pty) Ltd
PC	Pre-cooler
PCU	Power Conversion Unit
PR	Pressure Ratio
PT	Power Turbine
PU for CHE	Potchefstroom University for Christian Higher Education
PWR	Pressurized Water Reactor
RBMK	Reaktor Bolshoy Moshchnosty Kanalny (High-Power Channel Reactor)

Abbreviation or Acronym	Definition
ROT	Reactor Outlet Temperature
rpm	Revolutions per minute
RPV	Reactor Pressure Vessel
RX	Recuperator
THTR	Thorium High-temperature Reactor
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America

1. INTRODUCTION

1.1 THE HISTORY OF THE PBMR

The PBMR project originated in the 1950's in Germany, when Dr. Rudolf Schulten conceived a new type of pebble fuel. The new fuel concept entailed that silicon carbide-coated uranium kernels (triso-particle) be compacted into hard billiard-ball-like spheres. The fuel pebbles thus formed could be used as fuel for high temperature reactors, cooled by helium. Coupled to an electrical power conversion plant, it meant that a new source of electrical energy generation was born [1].

The pebble fuel reactor idea took root in Germany and in due course the Arbeitsgemeinschaft Versuchsreaktor (AVR), a 15 MW_e (40 MW_{th}) demonstration pebble bed reactor was built. It was operated successfully for 21 years. During its life it was used to test different designs of fuel, fuel loading systems, and safety systems. In spite of the test programmes and despite being the first prototype, it produced power for 70 percent of its life. Several other reactors were built in Germany. The 300 MW thorium high-temperature reactor (THTR), a first of its kind plant intended to demonstrate the viability of different sub-system hardware designs, with specific emphasis on plant availability and maintainability. The THTR achieved 100 percent power performance on 23 September 1986, a year after going critical for the first time [1].

Then on 26 April 1986, the infamous Chernobyl reactor explosion destroyed all notions the world had that nuclear energy is safe. The Chernobyl was an RBMK light water graphite reactor and exploded when tests were being done with some necessary safety systems disabled. The world reacted in horror as 31 people died (28 due to radiation exposure) when the reactor exploded. Fear gripped the world as the wind blew light contaminated material over Ukraine, Belarus, Russia and to some extent over Scandinavia and Europe. As a consequence of the Chernobyl accident, all negotiations for buying new reactors broke off and the intense anti-nuclear sentiment that followed basically meant the end of nuclear programs in Europe, including the German pebble bed reactors.

South Africa's state owned electrical utility, Eskom, recognised that that it could gain access to millions of dollars worth of fully developed technology, which might otherwise lie idle. Eskom started with feasibility studies regarding the possibility of building a PBMR in South Africa in 1994. The design and costing studies showed that the PBMR has a number of

advantages over other potential power sources [2]. In 1999, Eskom obtained the right to access the HTR engineering database. The PBMR project is currently making huge strides in developing the technology for use in South Africa and elsewhere in the world ([3] and [4]).

1.2 INHERENT SAFETY FEATURES

The major challenge for any new nuclear plant is to be accepted as safe and free from risk to the environment and humans. It has to be economically competitive with traditional power generation plants, like coal-fired power stations, but this requirement pales in comparison to the huge emphasis placed on safety in a post-Chernobyl world.

In existing reactors, of which pressurized water reactors (PWR) is the most common, safety objectives are achieved by means of custom-engineered, active safety systems. In contrast, the PBMR is inherently safe as a result of the design, the materials used, the fuel and the physics involved. This means that, should a worst-case scenario arise, no human intervention is required in the short or medium term. The plant is said to be “walk away” safe.

Nuclear accidents are principally driven by the residual power generated by the fuel after the chain reaction is stopped (decay heat) caused by radio active decay of fission products. If this decay heat is not removed, it will heat up the nuclear fuel until its fission product retention capability is degraded and its radioactivity released [1].

In the PBMR, the removal of the decay heat is independent of the reactor coolant conditions. The combination of very low power density of the core ($1/30^{\text{th}}$ of the power density of a PWR) and the fuel’s resistance to high temperature, underpins the superior safety characteristics of this type of reactor [1].

The peak temperature that can be reached by the core, which is about 1600°C under the most severe conditions, is below the temperature that may cause damage to the fuel. This is because the radionuclides, which are the potentially harmful products of the nuclear reaction, are contained by two layers of pyrocarbon and a layer of silicon carbide that are extremely good at withstanding high temperatures.

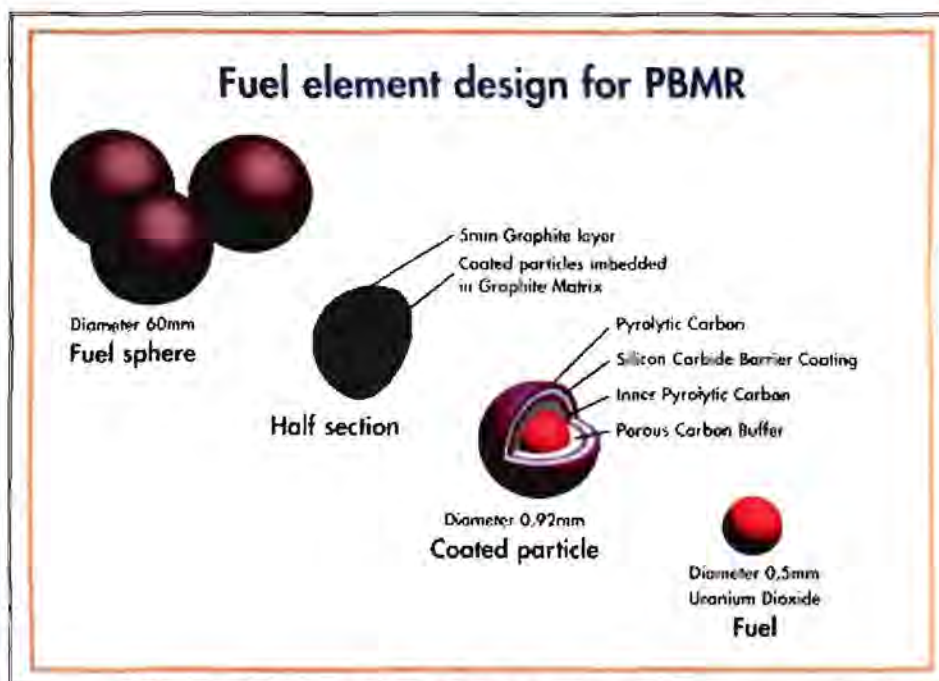


Figure 1: The PBMR fuel design.

The size of the PBMR core ensures a high surface area to volume ratio. This means that the heat that it loses through its surface (via the same mechanism that allows a cup of coffee to cool down) is more than the heat generated by the decay fission products in the core. The reactor therefore never reaches a temperature at which significant damage to the fuel can occur. The plant can never be hot enough for long enough to cause damage to the fuel.

In a world that is beginning to feel the pinch of energy shortages, this bodes well for future development. The PBMR concept with its inherently safe features makes it a very attractive alternative for electrical power generation. Fossil fuels are running out fast and the world needs to look for alternatives. The so-called green power generators, like wind, solar and wave power, among others, cannot provide the magnitudes of electrical power demanded by a growing economy, like that of South Africa. The PBMR concept however, can provide a long term, viable and safe solution to the looming energy crises. Pursuing this concept is thus a worthwhile effort, with lucrative possibilities.

1.3 THE POWER CONVERSION UNIT

In order to extract the electrical power from the reactor, a power conversion unit (PCU) of some sort is required. The cycle configuration directly influences the cycle efficiency, power output and cost, as well as maintenance, construction time and risk associated with the plant. Possible cycle configurations include the Rankine, Brayton and Combined cycles. The early

PBMR plants in Germany utilised the Rankine cycle with steam conditions fairly similar to modern fossil fuel plants. The drawback of the Rankine cycle is that it is not as thermally efficient as the Brayton cycle.

Combined cycles refer to a PCU where a standard Rankine cycle, using existing steam technology, is coupled to a small Brayton cycle. While combined cycles hold the promise of higher efficiency, the financial impetus thus gained should be weighed against the increase in capital cost. These cycles are under investigation for process heat applications, but are still at an early stage [5].

The Brayton cycle, used in a closed loop thermodynamic cycle could provide significant cost savings and gains in thermal efficiency, since advances in gas turbine technology can be applied directly [6]. Although Brayton cycle designs are well known in the gas turbine environment, the specific configurations and operating conditions that will be required for the PBMR plant, differ markedly. These differences introduce uncertainty, which is the subject of this investigation.

Research showed that a closed loop Brayton cycle layout with a three-shaft configuration would provide the optimal thermal efficiency for the PBMR plant. Figure 2 shows a simplified schematic diagram of the working of a Brayton cycle.

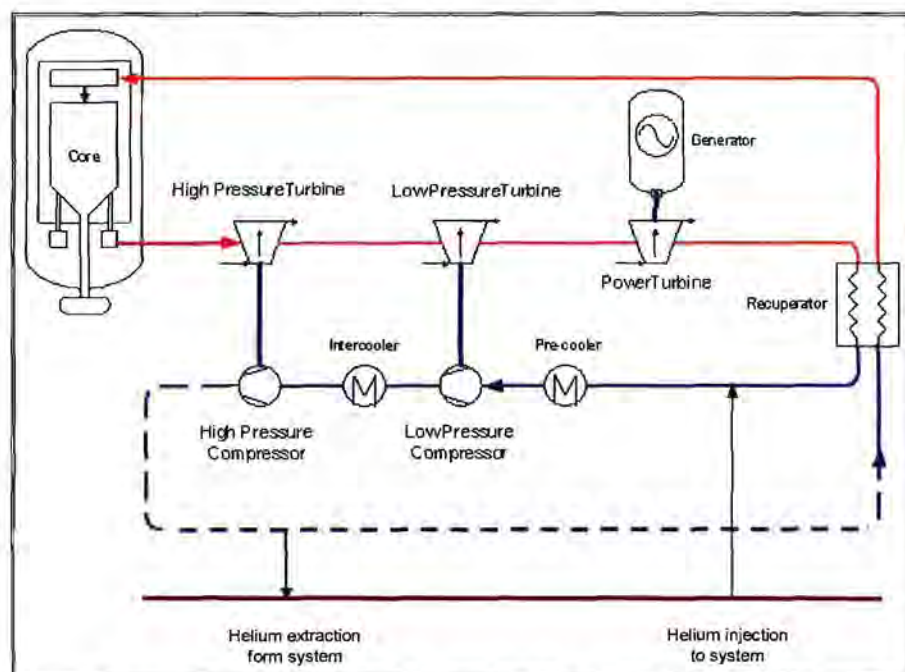


Figure 2: Simplified diagram of a direct Brayton cycle

The main components of the three-shaft Brayton cycle configuration are the reactor, which is the heat source, two turbo units, supplying the necessary pressure ratio to drive the cycle, a recuperator to recuperate heat that might otherwise be lost and a power turbine connected to the electrical generator, to generate electricity. In order to increase cycle efficiency, a pre-cooler and an intercooler is employed in front of the two compressors, as it is easier to compress a colder gas. Helium is used as coolant gas for the reactor and also serves as the working fluid of the turbines. A stepwise description of the working of the cycle is provided in the following paragraphs, starting at the reactor inlet [3].

Helium enters the reactor at a temperature of about 500 °C and a pressure of approximately 9 MPa [7]. It is conveyed to the top of the reactor via annular riser channels. The gas then moves downwards through the fuel spheres. During this process, helium removes heat from the fuel spheres, which were heated by the nuclear reaction. The heated helium exits the reactor at a closely controlled temperature of 900 °C.

The reactor outlet is connected to the HPT, which drives the HPC. Together, the HPT and HPC form the HPTU. The HPC provides the second stage of compression to reach the required pressure ratio to drive the cycle.

Next, the helium flows through the LPT, which drives the LPC. This unit is known as the LPTU. The LPC provides the first stage of compression in the Brayton cycle. Helium then flows from the LPT outlet to the PT, which drives the generator.

After the helium exits the PT, it is at a low pressure (approximately 3.0 MPa), but at a high temperature (approximately 500°C) [7]. During the next step of the cycle, the gas flows through the primary side of the recuperator where its heat is recuperated to the high-pressure helium entering the reactor (refer also to the last step of the process).

The pre-cooler cools the gas exiting from the recuperator (at approximately 120°C) before it passes through the LPC. The density of the helium is decreased due to the cooling, which results in a more efficient compression process.

The outlet of the LPC is connected to an intercooler, where the helium is cooled before entering the HPC. This compressor compresses the helium to 9.0 MPa. The cold (± 100 °C),

high-pressure helium then flows through the secondary side of the recuperator, where it is pre-heated before it returns to the reactor.

A three-shaft recuperative Brayton cycle had never been physically built before, and there was much scepticism surrounding this concept. It was labelled as an unstable cycle that would not be self-sustaining or controllable. In order to address the scepticism, a test rig, named the PBMM, operating on this cycle was built at then Potchefstroom University for Christian Higher Education (PU for CHE) in 2002. The project was a success and proved that this concept is feasible as the cycle bootstrapped as predicted and could be controlled without problems [8].

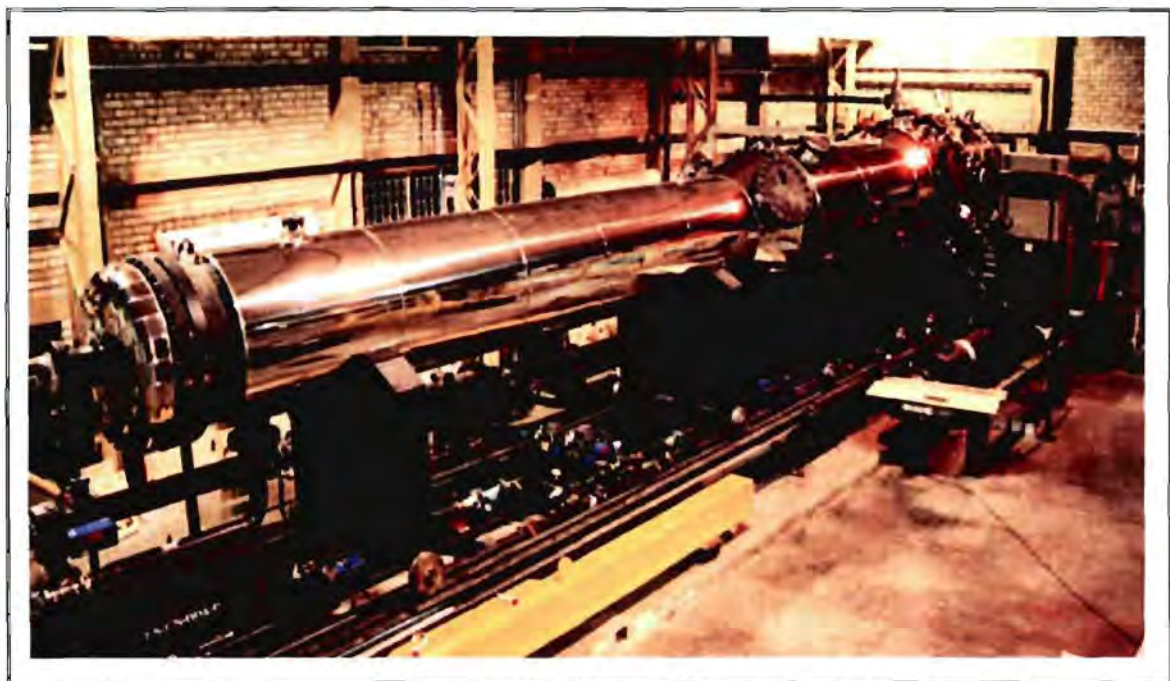


Figure 3: The PBMM built at the PU for CHE

1.4 PROBLEM STATEMENT

As stated previously, research indicated that a three-shaft recuperative Brayton cycle with intercooling, would result in the most cost effective design for the envisaged PBMR plant. Although the Brayton cycle is based on existing gas turbine technology, some uncertainty as to the operability and robustness of the design exists, particularly with regard to the required turbo machinery. The PBMM alleviated the concern that the closed loop Brayton cycle cannot be started and run in a stable fashion.

The purpose of this study is to quantify the uncertainty still surrounding the turbo machines of the PBMR plant. A set of uncertain input parameters was identified, each with a degree of uncertainty. These parameters were evaluated to find their impact on the following critical turbo machine and plant parameters:

- Turbo unit rotational speed,
- Compressor surge margin, and
- Power exported to the grid, as well as cycle efficiency.

The turbo machine supplier agreed that these output parameters are of importance and should be studied [9]. Analysing the impact on these parameters would make it possible to point out design flaws and deficiencies. Understanding the cycle dynamics at various operating points will ensure that the design is as robust and ultimately, as safe as possible.

1.5 OVERVIEW OF THIS STUDY

This dissertation is structured in the following manner:

- In Chapter 1 the history and importance of the PBMR plant was illustrated.
- Chapter 2 identifies Flownex as a suitable thermo-hydraulic code for simulating the PBMR plant. Several sampling methods were investigated for appropriateness, including the selected Monte Carlo method. The choice of the Monte Carlo method is justified.
- The parameters contributing to uncertainty are described and justified in Chapter 3.
- Chapter 4 describes the method of analysis and the results of the Monte Carlo study.

- An equivalent study done in May 2002 on a simplified model of a 300MW plant was used for validation purposes. The validation results are described in Chapter 5.
- The conclusions that can be drawn from this study are listed in Chapter 6, together with recommendations for further work.

2. LITERATURE REVIEW

2.1 INTRODUCTION

In order to address the problem stated in the previous chapter, the following has to be addressed. Firstly, an acceptable thermo-hydraulic code, capable of solving the PBMR Brayton cycle reliably needs to be identified. Secondly, a sampling method for the uncertainty analysis needs to be identified and substantiated.

2.2 SOLVING THERMO-HYDRAULIC NETWORKS

Although several thermo hydraulic codes exist, the Flownex code was chosen as the analysis tool for this study. It will be indicated that Flownex is suitable to solve the problem at hand.

2.2.1 The Development of Flownex

M-Tech Industrial developed Flownex over the past 15 years, in collaboration with the Faculty of Engineering at the then PU for CHE (now the North West University). Flownex is a general-purpose thermal-fluid network analysis code, i.e. an integrated system based 1D CFD analysis code based on a network approach. It solves flow, pressure and temperature distribution in large unstructured thermal-fluid networks and provides the engineer/designer with essential information on the interaction between network components and the behaviour of complex systems [10].

One of Flownex's outstanding features is its ability to handle a wide variety of network components, such as pipes, pumps, orifices, heat exchangers, compressors, turbines, controllers and valves. In addition to its fluid dynamics and heat transfer capabilities, Flownex features a one-dimensional solid heat transfer modelling capability, which allows the modelling of heat transfer through solids [10].

Flownex incorporates the following advanced turbo machinery features, which are of importance for this study [10]:

- Flownex features composite turbo machine elements that enable any number of compressors or turbines as well as external loads to be placed on a single shaft.

-
- The schematic diagram illustrates the components and flow of a gas turbine engine. The main flow path is indicated by a thick line: Inlet (1) → Compressor (2) → Combustion Chamber (3) → Turbine (4) → Exhaust (5). A fuel system (6, 7, 8, 9, 10, 11, 12, 13, 14) and a heat exchanger (15, 16) are also shown. The heat exchanger (15, 16) is located between the combustion chamber (3) and the turbine (4). The fuel system components include a fuel tank (6), fuel pump (7), fuel control valve (8), fuel nozzle (9), fuel filter (10), fuel line (11), fuel manifold (12), fuel injector (13), and fuel return line (14). The heat exchanger (15, 16) is a cross-flow heat exchanger that preheats the fuel before it enters the combustion chamber (3). The turbine (4) is connected to the compressor (2) and the fuel pump (7) via a common shaft. The exhaust (5) is shown exiting the engine.

User interaction with Flownex is through a user-friendly GUI, where networks are created and edited and where input data for networks are provided. A command line solver is also provided which can be called from external software (like Matlab) to solve a thermo-hydraulic network that was set-up using the GUI. Flownex is extensively validated against analytical solutions, other codes and experimental data [10].

2.2.2 Use of Flownex in industry

10

MHI is one of the world's leading manufacturers of heavy machinery, including industrial gas turbines for power generation. With a vast amount of practical experience and a high level of technological capability, MHI has been active in the nuclear industry for more than three decades. Since commencing research into and developing of nuclear power generation in the 1950s, MHI has taken part in the design, manufacture and construction of a large number of very successful PWR power plants [14].

Kobe Steel Ltd (Japan) uses Flownex for the simulation of air chilling units [15]. From comprehensive power generation plants to individual machines, the Plant Engineering Sector of Kobe Steel's Plant Engineering Company has the capability to fulfil a vast range of needs in such industries as iron and steel making, cement, energy and chemical-related fields.

Integrating excellent manufacturing and plant engineering capabilities, they are expanding their operations into a variety of business fields. In addition to their ability to produce the world's largest desulphurization reactors and oxygen generation plants for oil refining and petrochemical plants, they offer a wide range of power generation and gas supply facilities, nuclear equipment, and district heating and cooling systems [15].

The conceptual design of the PBMM, or test rig as it was referred to in Chapter 1, was done with the aid of Flownex. The PBMM started up and reached steady state operation as Flownex predicted. This was a major achievement, as it was the first time that a fully functional, properly controllable, robust plant based on a three-shaft, inter-cooled Brayton cycle was designed, built and commissioned. This was made possible to a large extent by the availability of the Flownex software that could simulate the integrated plant [16].

Flownex is also used by a number of academic institutions. MIT uses Flownex for design of the Brayton cycle [17] in their research into high temperature gas reactors and Cranfield University uses it for the simulation of compressor units [18] in their advanced turbo machinery research laboratory.

M-Tech also put procedures in place to ensure that the results produced by Flownex are accurate and trustworthy. These procedures cover the verification and validation of software [19], the project management for the design, development and maintenance of software [20], as well as the configuration management process definition for software [21]. Also at PBMR, the Flownex Nuclear Software Verification and Validation Plan [22] were put in place.

From the above it is clear that Flownex is widely used in the industry and by academic institutions for modelling and simulation of various thermal-fluid systems and networks. All the mentioned users of Flownex are well known in industry and academic fields. They have delivered reliable products and education. It can therefore be accepted that Flownex will be a reliable tool for performing the analysis required by this study.

2.3 MODELING THE PBMR PLANT IN FLOWNEX

An extensive model of the PBMR plant was set up in Flownex and is named V701 [23]. This model includes the following components:

- The reactor, which consists of a pebble bed element, critical volumes, as well as a simplified bypass leakage path,
- The core outlet pipe, which takes hot helium from the reactor to the HPT,
- The HPT, with pipe models for the intake and diffuser,
- The LPT, with pipe models for the intake and diffuser,
- The PT, with simplified pipe models for the intake and diffuser,
- The recuperator, followed by a connection to the pre-cooler,
- The pre-cooler, which consists of an outer and inner bundle,
- The LPC, with pipe models for the intake and diffuser,
- The intercooler, which also consists of an outer and inner bundle,
- The HPC, with pipe models for the intake and diffuser,
- The manifold, which is represented by pipe models,
- Helium flowing through the manifold reaches the HP side of the recuperator, from where the gas flows to the core inlet pipes,
- The core inlet pipes take the helium to the reactor inlet.
- The model includes gas cycle valve models, which is used to control the Brayton cycle, the start-up blower system, as well as power matching for the HPTU and LPTU.

The Flownex model shown in Figure 5 is used for all the analyses done for this study. The detail of how this model was used for analyses will be discussed in Chapter 4.

2.4 SAMPLING METHODS

This study attempts to quantify the uncertainty associated with the PBMR plant. A statistical method is therefore needed to address this requirement. Since uncertainty is associated with a number of variables, the combined effect of these uncertainties is really what needs to be determined.

Several statistical sampling methods have been devised already. These sampling methods include, among others, Latin Hypercube Sampling (LHS), the Taguchi method and of course Monte Carlo simulation. With Monte Carlo Simulation being the exception, the other sampling methods require that some or other rule and mathematical criteria be applied to the data before it is analysed so that the number of calculations can be minimised.

LHS is a stratified sampling technique where the random variable distributions are divided into equal probability intervals. A probability is randomly selected from within each interval for each basic event. Generally, LHS will require fewer samples than simple Monte Carlo simulation for similar accuracy. However, due to the stratification method, it may take longer to generate an answer than for a Monte Carlo simulation.

The Taguchi method was developed for designing experiments by optimising the input variables so that the variance of the response variable is a minimum. Its main objective can be divided into two categories namely: optimising the experiment and determining the variables with the biggest impact on the response. The Taguchi method is well described by Phadke [24].

Wang and Pan showed how the Taguchi method can be used to increase the stability of the two phase flow experiment in a natural circulation loop, by determining the inputs with the biggest impact on the response variable's variance [25]. They found that the variables suggested by Taguchi did in fact improve the stability and that they saved a great deal in experimental time.

In comparison to the Monte Carlo method, these other sampling methods can reduce the simulation time, but several time consuming mathematical modifications have to be applied to the data beforehand. For this study, a large number of input variables are identified, with

an even greater number of variables having an effect on the final solution. Choosing the Monte Carlo method as sampling technique therefore might mean longer calculation time, but it is very easy to implement.

2.5 MONTE CARLO METHODS

Monte Carlo methods can be loosely defined as statistical simulation methods. According to Woller, statistical simulations are defined in general terms to be any method that utilizes sequences of random numbers to perform a simulation [26].

In Monte Carlo methods, all of the available observations or variables are varied simultaneously with random numbers of realistic amplitude. Note that the set of results will be different every time due to the fact that random numbers are used. By repeating the experiment many times with different sets of random numbers for different variables, one obtains an impression of the forecast error that is due to the uncertainty in the observation.

Monte Carlo methods provide some major advantages in statistical analysis. These advantages include the following [27]:

- It can be implemented easily on complex systems,
- The physical process is simulated directly, there is no need to know the differential equations that describe the underlying mathematical system,
- It is approximation-free and provides an undistorted picture of reality.

According to Marczyk, Monte Carlo simulation makes one realise that once one leaves linearity and determinism, one is navigating a very broad ocean. Being a model-free approach, Monte Carlo simulation preserves all the complexity and subtleness of a physical system. It helps to understand uncertainty and to embrace the possibilities it offers rather than to fight it. Marczyk further describes Monte Carlo techniques as the basis of simulation. It is seen as the third form of knowledge generation besides theory and experimentation [27].

As was said earlier, available variables are varied simultaneously with random numbers. That is, input variables are given a random value. These random values describe all the possible values that the input variables can have, giving substance to the uncertainty surrounding the variable's actual value. The range of random numbers needs to be defined, as well as the probability that the input variable might take on a certain value.

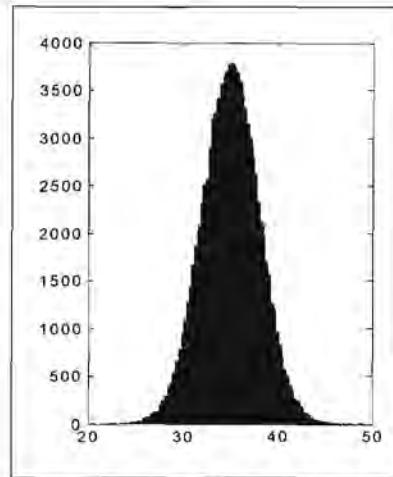


Figure 6: Normal/Gaussian Probability Density Function

The range and chance that a variable might take a certain value is described by its probability density function. Several probability density functions are possible, like the normal or Gaussian distribution, the block or uniform distribution, also tri-angular and skewed distributions. These functions can dictate infinite possible random numbers or a discrete set of possible values. The choice of distribution and the range of values for the distribution are the tools available to the Monte Carlo simulator. Figure 6 indicates the normal distribution where values tend be distributed about a mean value, while Figure 7 indicates a discrete, uniform distribution, meaning that there is equal chance that the random number can be any value within the discrete range.

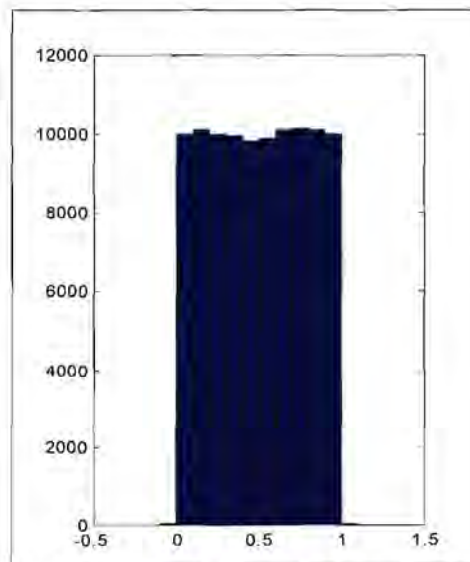


Figure 7: Uniform Probability Density Function

2.6 CONVERGENCE OF MONTE CARLO ANALYSIS

A controversial point when using Monte Carlo methods for uncertainty analyses is of course the number of random simulations to perform. Normally, 10 000 runs are considered to be sufficient for convergence by the statistical fraternity [28]. After this vast quantity of runs, it is thought that the cumulative standard deviation of the result stays constant. The standard deviation of a sample is calculated by the following equations:

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2.1)$$

With:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (2.2)$$

Where:

n = number of elements in the sample.

By calculating the cumulative standard deviation, one can see if the standard deviation of the sample has stabilized. If this would be the case, it would mean that sufficient Monte Carlo runs have been performed and that there would be nothing to gain by performing any more simulation runs. Figure 8, taken from [28], illustrate this concept graphically.

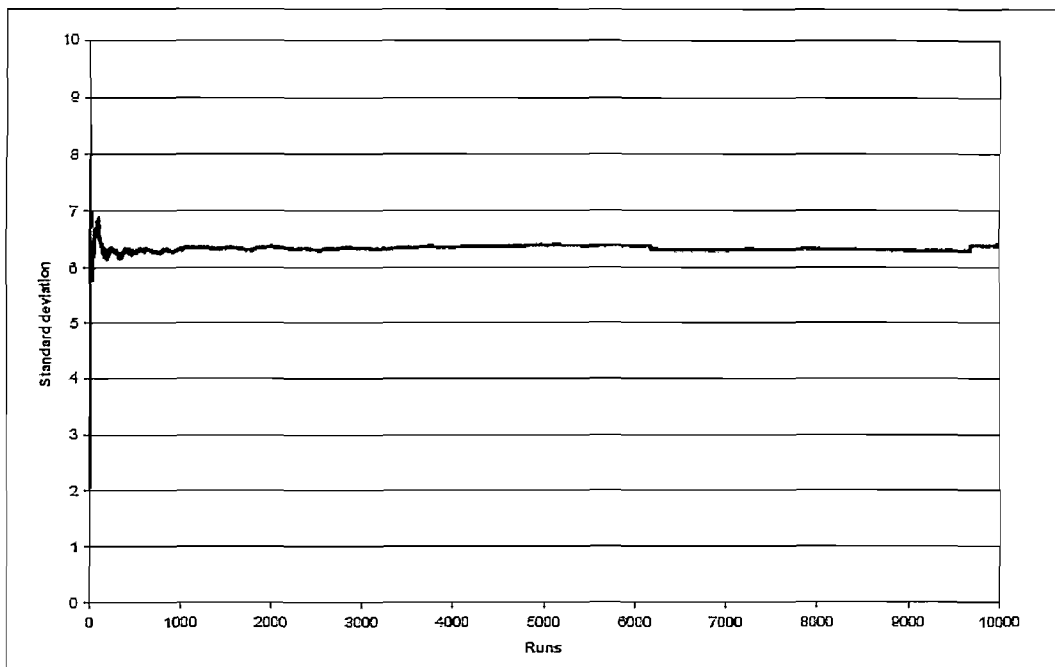


Figure 8: Example of a cumulative standard deviation graph

The problem with performing 10 000 runs for every Monte Carlo simulation, is that it is time consuming and expensive [29]. For the purpose of this study, the convergence of the Monte Carlo simulation will be tested by comparing results after performing 250, 1000 and 2000 runs (described in section 4.5). The cumulative standard deviation will also be plotted to indicate that the standard deviation has stabilized, meaning that sufficient runs have been performed.

2.7 CONCLUSION

It was shown that the Flownex thermo-hydraulic code is used extensively in industry to model various types of thermo-hydraulic applications, including the Brayton cycle, which is required for this study.

Different sampling methods for analyzing the uncertainty associated with the PBMR plant were investigated. Latin Hypercube and Taguchi sampling methods give the same accuracy as Monte Carlo methods in less simulation runs, but require complex manipulation of the data before any simulation work can start.

The Monte Carlo simulation method was found to be best suited for this study due to its simplicity and robustness. Monte Carlo simulation is used widely for uncertainty analyses in most fields imaginable, from bio-chemistry to finite element crash model validation in the automotive industry [30].

The convergence of Monte Carlo simulations was also investigated. The statistical norm is performing 10 000 runs, but this notion is analyzed later and it will be shown that fewer runs is adequate for this study.

3. PARAMETERS WITH UNCERTAINTY

3.1 INTRODUCTION

The previous chapter substantiated the use of the Flownex code to solve the thermo-hydraulic model of the PBMR. It also indicated that although there are many possible sampling methods for analyzing the uncertainty, the Monte Carlo method is a simple, yet powerful method. In this chapter the parameters with uncertainty will be pointed out and where possible, substantiated from literature.

The parameters to which uncertainty is attributed include the following:

- Pressure drop, mainly through the reactor, but also associated with the turbo machine intakes and diffusers,
- The effect of leakage flow bypassing the reactor and cooling flows to the turbines,
- Turbo machine efficiency,
- Turbo machine flow area,
- The reactor outlet temperature (ROT), which represents the highest gas temperature in the PBMR Brayton cycle,
- The manifold pressure, which is the highest pressure in the MPS, and
- The effect of cooling water temperature, which is the lowest temperature in the PBMR Brayton cycle,
- Heat exchanger effectiveness and the pressure drop.

These parameters were identified in consultation with the relevant system engineers who are responsible for the design, manufacture and integration of the MPS components. The nature of the uncertainty around each of the parameters will now be discussed.

3.2 PRESSURE DROP

An important thermo-hydraulic parameter for the design of the PBMR Brayton cycle is pressure drop. The LPC and HPC generate the PR required to overcome the pressure drops in the PBMR cycle. The power to drive these compressors is taken from the turbines, the LPT and HPT respectively. The greater the pressure drop and subsequently, the greater the required PR, the greater the power extracted from the HPT and LPT. This leaves less power for the PT to drive the generator. Correct prediction of pressure drop is therefore of great importance in the design of the PBMR and the prediction of plant performance and efficiency. The main contributors to uncertainty in cycle pressure drop are identified as the reactor and the turbo machine intakes and diffusers.

3.2.1 The Reactor

The PBMR reactor consists of various parts, e.g. the RPV, Core Structures, which are manufactured from graphite, and of course the fuel in the form of pebbles as described earlier. Figure 9 indicates a section through the reactor [31].

Helium enters the RPV and core structures at the inlet plenum, rises through riser channels to the inlet slots, turns and flows downward through the pebble bed where it is heated and exits through the outlet slots to the outlet plenum. This intricate flow path has been modelled extensively with aid of CFD [32].

The main helium flow path within the reactor is modelled in detail: inlet plenum, riser channels, inlet slots, pebble bed, outlet slots etc. Secondary flow paths (control rod cooling flow, lumped bypass flow and gaps in the top reflector) are also modelled. The reactor mass flow ratios and the pressure drop are calibrated according to CFD results [31].

Predicting the pressure drop and mass flow rates of the reactor correctly is important, since:

1. The reactor pressure drop influences the grid power generated and cycle efficiency,
2. The mass flow through the core determines the maximum fuel temperature.

All the leak flow paths in the reactor are not modelled in detail. Therefore, the reactor mass flow distribution (between the core flow and lumped bypass and leak flows) plus the reactor pressure drop are calibrated against CFD results in the Flownex model.

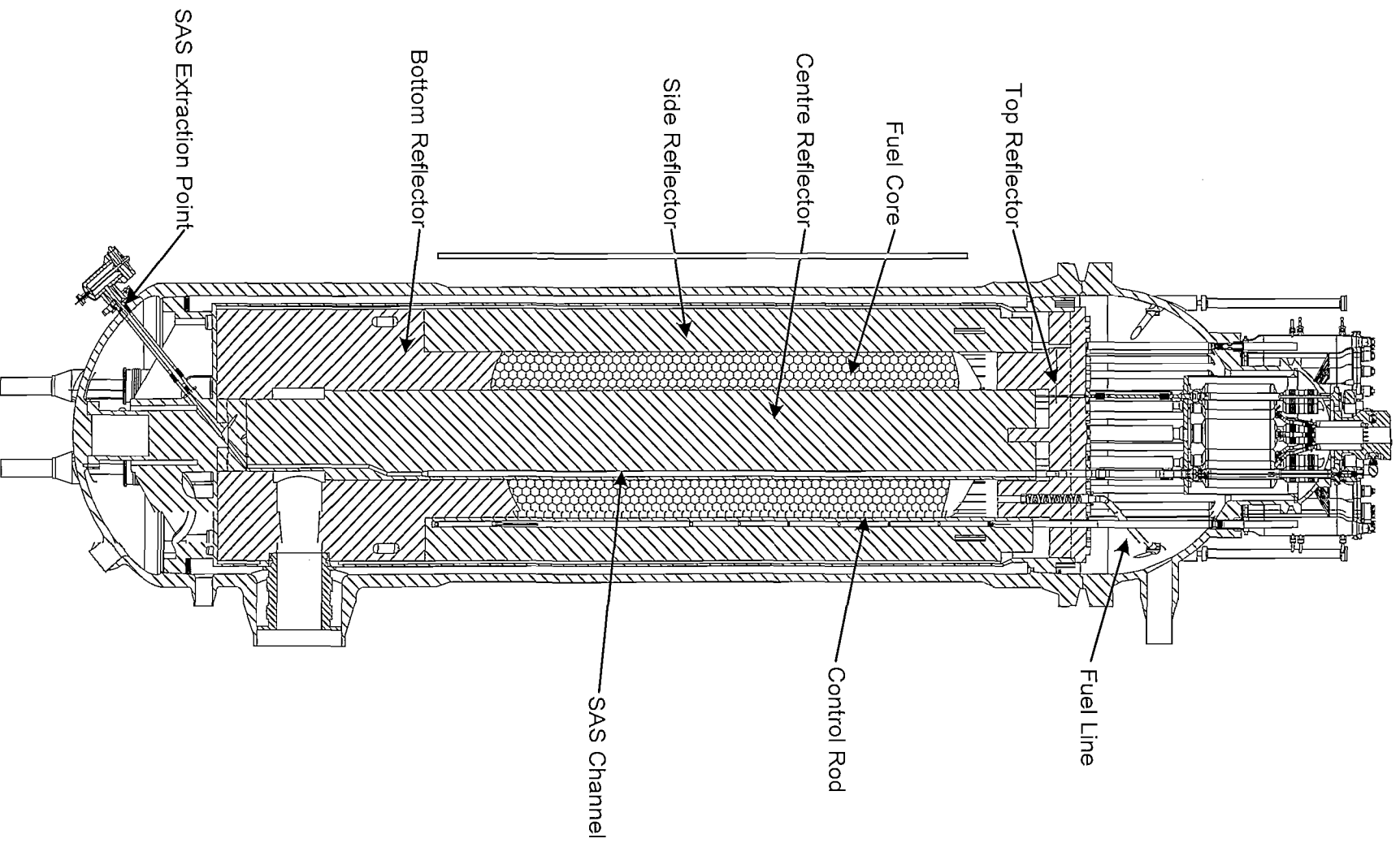


Figure 9: Vertical slice through reactor

Flownex uses an equation from [33] to calculate the pressure drop across the pebble bed of the reactor. This equation is also proposed for use in the German reactor safety standards for high temperature gas cooled reactors [34]. The equation states that the pressure drop is linear with respect to the height of the reactor.

According to [34], the uncertainty associated with the said equation is $\pm 15\%$, meaning that a 15% error can be made in calculating the pressure drop.

3.2.2 Implementation

To implement the $\pm 15\%$ uncertainty associated with the equation listed in [33] in this study, the height of the reactor was varied to reach the extremes of the pressure drop uncertainty range. The nominal pressure drop calculated by the Flownex model is 216.7 kPa. The upper and lower limit values are listed in Table 1.

Table 1: Input variation for pebble bed height

	-15%	Nominal	+15%
Pressure drop [kPa]	184.2	216.7	249.2
Height [m]	9.141	11	12.925

The uniform distribution is chosen for this input variable to be conservative. The uncertainty surrounding the calculated pressure drop value is deemed to be high and this variation implies that there is equal chance that any value in the input range can be obtained as input.

3.3 TURBO MACHINE INTAKES AND DIFFUSERS

Each turbo machine has an intake and diffuser. Simply put, the purpose of the intake is to accelerate the flow to the appropriate inlet blade axial velocity, whereas the diffuser accepts the flow from the last stage and decelerates the flow by enlarging the flow area in a process called diffusion, or in other words, pressure recovery from dynamic to static pressure.

In reality, the design of efficient turbo machinery intakes and diffusers is a complex exercise. It was principally the lack of understanding of diffusion that delayed the arrival of efficient

dynamic pumps and compressors until some decades into the previous century with viable gas-turbine engines only arriving in the mid-1930s [35].

A particular source of losses, i.e. pressure drop, is flow separation from the diffuser wall. This occurs when the angle of diffusion is too great for the particular flow condition. Flow separation is detrimental to the diffusion process, meaning that no pressure recovery can occur once flow separation has taken place. In most cases separation has to occur in only one place for complete flow breakdown to follow [35]. Good diffuser designs will prevent flow separation in all expected turbo machine flow conditions.

Turbo machine intakes on the other hand do not suffer from this proneness to flow separation. The flow area is in fact reduced (forcing the flow onto the wall) to accelerate the flow onto the first stage of the turbo machine. Dynamic pressure drop in an intake is can be related directly back to the velocity of the gas. However, pressure drop is proportional to the square of the velocity, so one cannot simply accelerate the flow without keeping close account of the losses incurred.

The intakes and diffusers of the PBMR turbo machines are being designed by the supplier. Models of the turbo machine intakes and diffusers are therefore required in the Flownex model of the PBMR plant. However, intakes and diffusers normally have quite complex geometries, whereas Flownex is only a one dimensional code. In an attempt to bridge the gap of modelling a complex geometry with a one dimensional code, intakes and diffusers can be modelled by using 2D or even 3D CFD.

CFD is used regularly in industry in an attempt to minimise the cost of developing efficient intakes and diffusers. Neve used CFD to analyse the diffuser performance in gas powered jet-pumps [36]. However, according to Klein, CFD does not have the final say in design, since the development of combustor diffusers is still mainly based on experimental work [37]. One reason for this is that CFD makes use of approximation models for flow turbulence, which can introduce inaccuracies and subsequently uncertainty as to the correctness of the result.

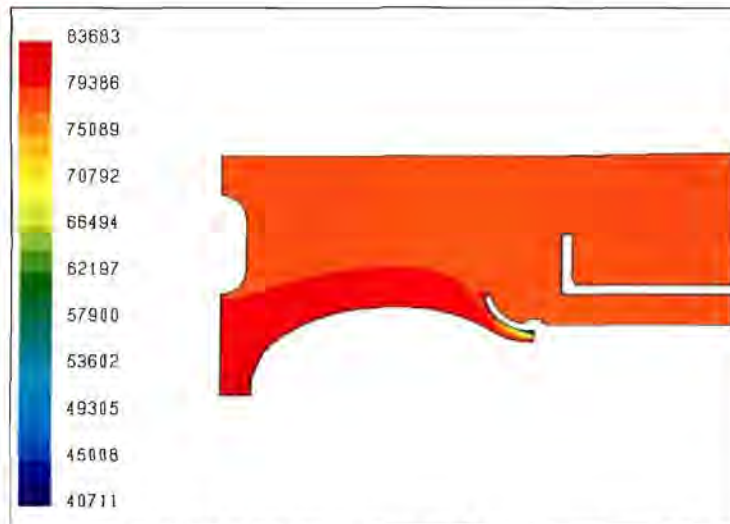


Figure 10: HPC Inlet contours of Total Pressure [Pa]

Once the losses of the intakes and diffusers have been analysed, the secondary loss factor (k-factor) in the Darcy-Weisbach [9] pressure drop equation can be determined from the CFD results [38]. This k-factor can then be used in a simplified, one dimensional pipe model of either the intake or diffuser in the relevant Flownex model. Good correlation is obtained between the CFD results and the Flownex results, but the uncertainty with regards to the CFD analysis still exists.

3.3.1 Implementation

In order to get a feel for the robustness of the PBMR plant design, the k-factors of turbine and compressor intakes and diffusers are varied between -10% to +50%. This variation attempts to indicate that there is a small chance that the pressure drop might be lower and a greater possibility that the pressure drop will be higher than the design value calculated by CFD. The expected variation is smaller than the range specified above, but the relative large variation in both positive and negative directions is an attempt at being conservative in light of large uncertainty associated with the calculated k-factors. This uncertainty range cannot be substantiated from literature for a first of a kind design and is based on engineering judgement.

3.4 LEAKAGE FLOW

Two types of leakage flow are present in the PBMR plant, which are cooling flows and leakage flow in the reactor. Cooling leakage flows are used to cool the turbine and hot gas piping. These cooling flows bypass the reactor, which is the heat source of the Brayton cycle. In order to drive the leakage flows, the compressors have to perform work on the working

fluid. The energy to perform the work is withdrawn from the hot gas stream leaving the reactor, meaning that less energy is available to drive the PT to generate electricity. Cooling leakage flow is thus detrimental to plant efficiency. The quantity of cooling leakage flow required is therefore a parameter that requires close attention from the design team.

Leakage flows in the reactor bypass the reactor core by leaking through the core structures. The bypass flow does not remove heat from the core. Therefore, less mass flow passes through the core to extract heat. The power level of the reactor is however a set value, meaning that the maximum fuel temperature needs to be higher to transfer the required heat to the helium flow passing through the reactor. The maximum fuel temperature is a nuclear safety concern, as higher fuel temperatures mean that more fission products are released that have to be contained.

The main leakage flows in the PBMR plant, are the cooling flows required by the turbines and the bypass flow in the reactor through the core structures. A leakage flow bypassing the LP side of the recuperator is also envisaged.

3.4.1 Turbine Cooling Flows

The cooling and leakage flow is utilised in the turbines for the following:

- Cooling the stator and casing to prevent warping due to thermal expansion,
- Cooling the turbine blade roots and discs for mechanical strength,
- Protecting and cooling the electro magnetic bearings (EMB), and
- Performing thrust balancing.

The stator and casing of the turbine support the internal rotating and stationary parts of the turbine. High temperature gas passes through the turbine which heats up the metal in the turbine, be it stationary or rotating, causing thermal expansion. However, parts like the bearings and dry gas seals, which operate on close tolerances, require that the turbine casing distorts as little as possible. It is therefore necessary to cool the stator and casing of the turbine to an acceptable temperature. This cooling flow path through the stator is very intricate and it is extremely difficult to predict the actual leakage flow until it has been tested.

The turbine blade is fixed in the turbine disc by a mechanical bond, referred to as the blade root. Figure 11 shows a typical bond known as a fir tree connection. This bond is designed to fail at a certain force, which is the last resort in an over speed situation, typically at 140% of nominal rotation speed. This connection is under tensile stress when the turbine is running due to the centrifugal force generated. The high temperatures found in the gas flow path heats the turbine blades, which is then conducted to the blade root. This causes the allowable tensile strength in the material to be reduced. In order to preserve the tensile strength of the material, it is necessary to cool the blade root to a temperature that is below some desired threshold temperature.

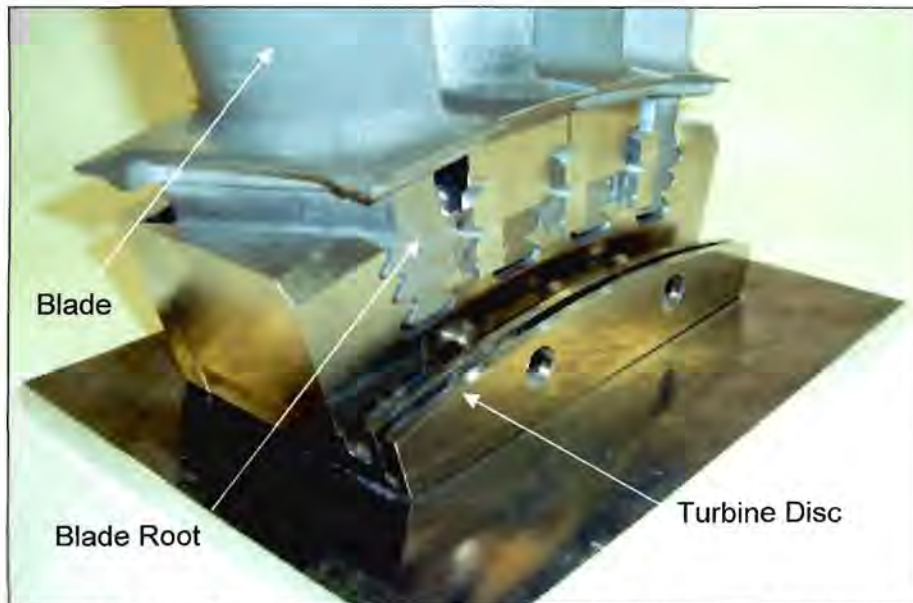


Figure 11: Section of a turbine disc indicating the root connection

The PBMR turbo machines use electro-magnetic bearings. Large currents flow through the coils of these bearings, which heats up the coils. This heat generation is called Joule losses and arises from resistance to electrical current flow in the conductors. Another source of heat is eddy current losses, also formed in coils of these types of bearings. The heat that is generated in the electro-magnetic bearings needs to be removed through cooling of some sort. Water cooling is possible, but this introduces a large risk to the system should a leak occur in the cooling circuits. It was therefore decided to cool the EMB by using cold helium extracted from the main Brayton cycle flow path. Figure 12 indicates the intricate flow path required to provide cooling to the lower electro-magnetic bearing of the HPC.

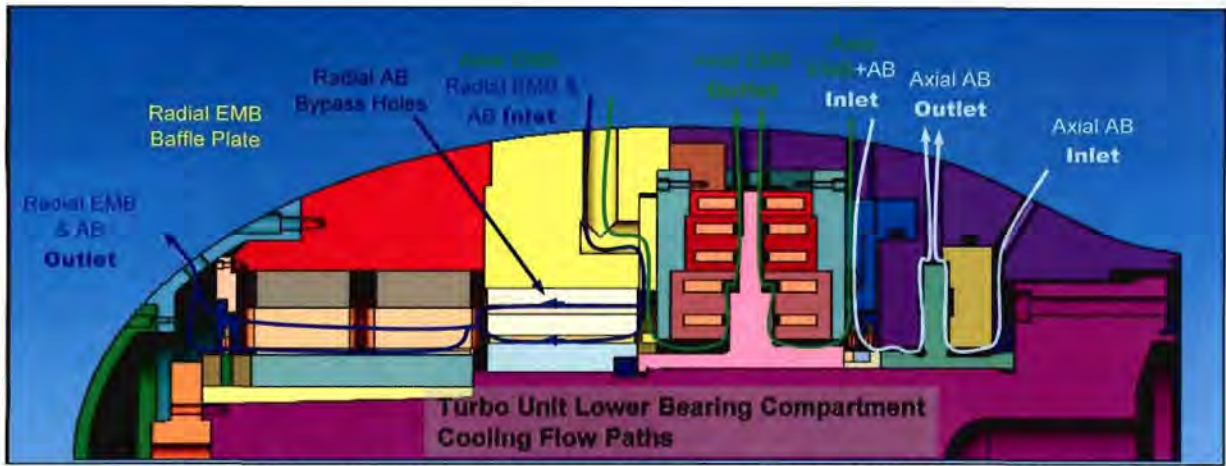


Figure 12: Lower HPC electro-magnetic bearing cooling flow paths

The change in pressure from inlet to outlet and the force on the blades due to the momentum change afforded by the blades on the gas, results in an axial thrust load on the machine shaft. It is the turbo machine designer's task to minimise this thrust force in order to make the thrust bearing load as small as possible. A typical design is to place a compressor and turbine back to back if they are located on the same shaft, i.e., the turbine is driving the compressor, which is the case for the HPTU and LPTU. In these machines, this thrust load is handled by an axial EMB, of which the maximum load is 15 tonne, which is a small design range. Figure 13 shows the thrust balancing scheme of the HPTU.

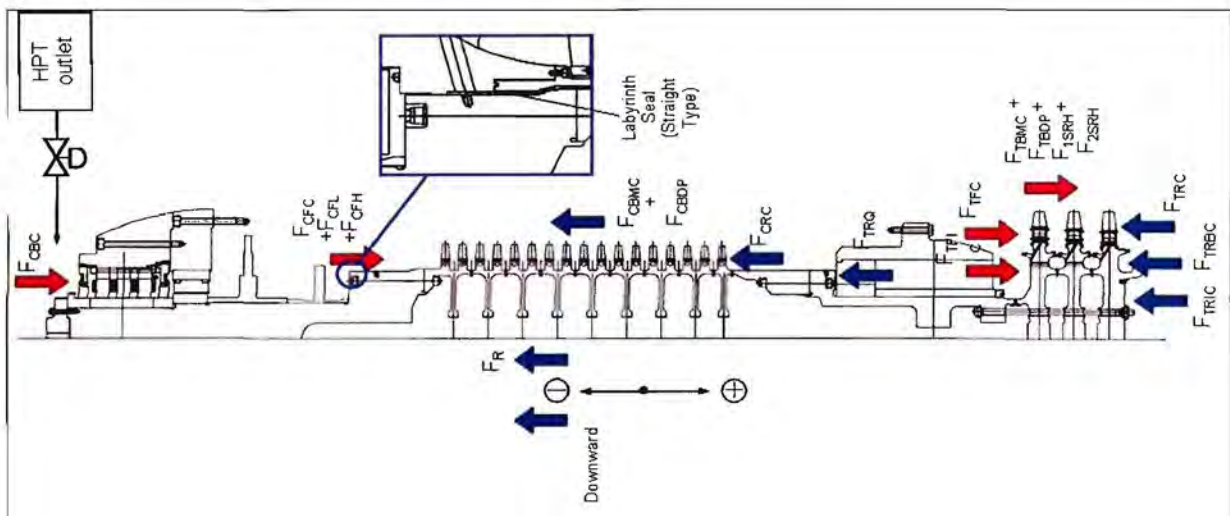


Figure 13: HPTU thrust balancing scheme

Figure 14 indicates the elaborate cooling flow path required to provide the cooling flow of the power turbine. It indicates the flow through the stator, the flow through the rotor discs to the blade roots, as well as the flow through the leaf seals which is part of the thrust balancing scheme.

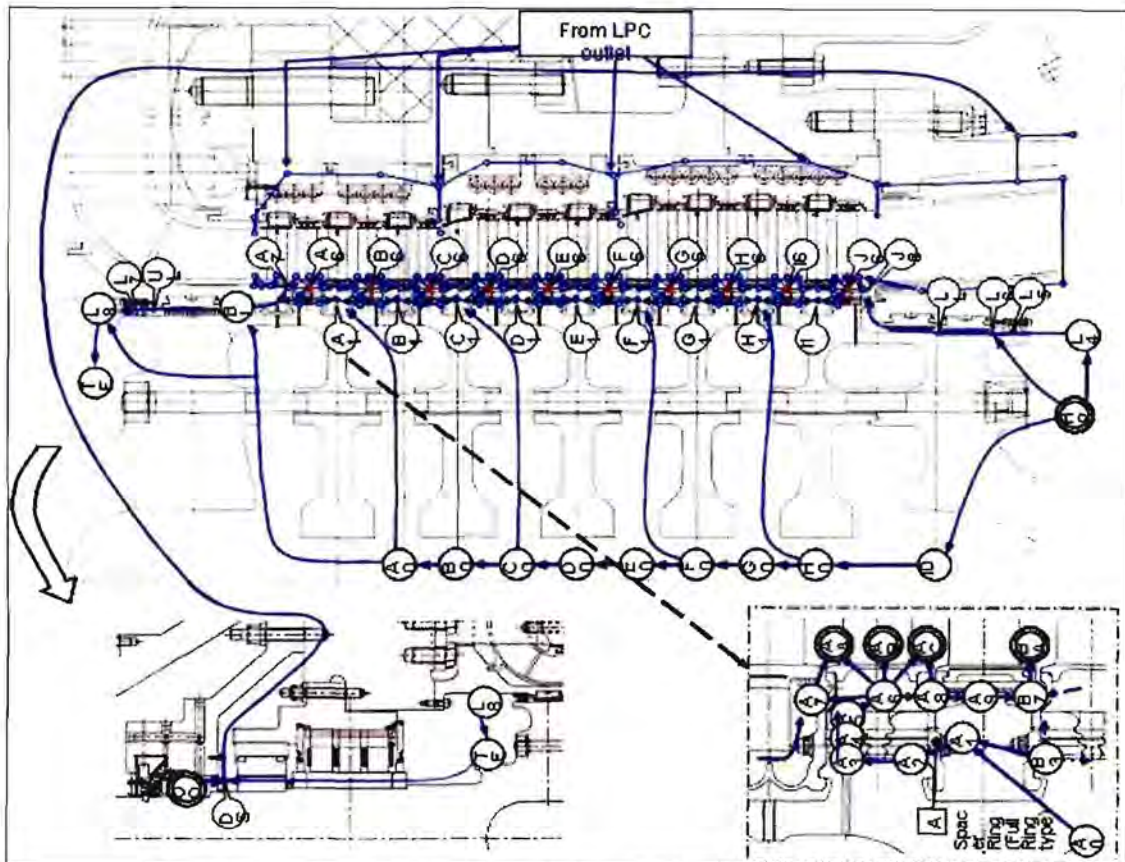


Figure 14: Power Turbine cooling flow paths

3.4.2 Reactor bypass leak

According to [31] the leakage flow paths that exist in the reactor are characterised with the aid of CFD. These leakage flow paths exist between the graphite blocks making up the core structures. Figure 15 indicates this leakage path in a layer of these graphite blocks. These blocks are designed to fit tightly together and not leak excessively when the reactor is hot. In the Flownex thermo-hydraulic model shown in Figure 5, this leakage flow path is further simplified to a single flow element, which might introduce uncertainty in off-design conditions.

One wants as much flow as possible to pass through the pebble bed, therefore the leakage flow that is passing through the core structures must be minimised. Remember that leakage flow in the reactor leads to higher fuel temperatures.

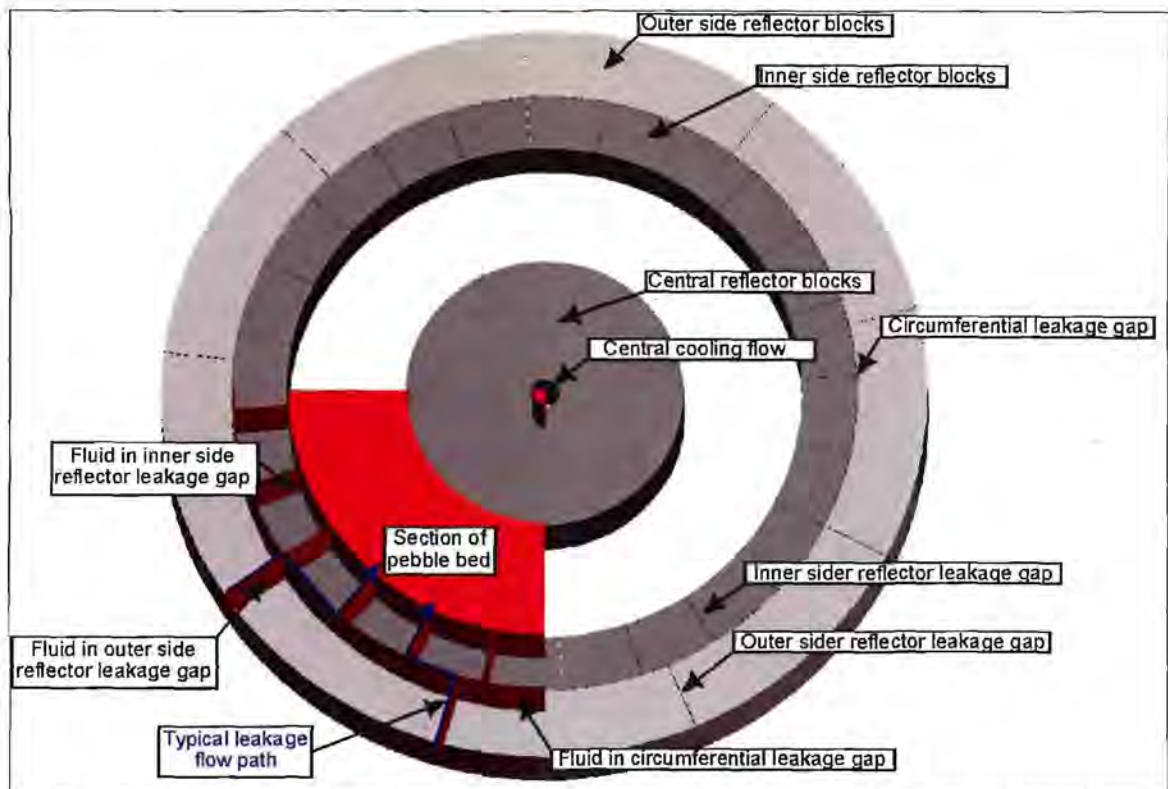


Figure 15: Typical reactor leakage flow path

3.4.3 Recuperator bypass leak

The recuperator is made up several plates which are welded together to form the heat exchange areas. Several sealing plates are required to force flow through the heat exchange matrix. It is possible that these plates do not perform the sealing function perfectly and therefore a bypass leakage flow is included in the model which bypasses the LP side of the recuperator. This bypass is detrimental to the cycle efficiency, as even less heat can now be recuperated to the HP side.

3.4.4 Implementation

From the preceding paragraphs, it can be seen that the turbo machine leakage flow is quite important and very necessary. However, in a first of a kind design, the question of whether or not the flow paths of these leakage flows will perform as designed is a great source of uncertainty. Until physical testing has been done, the uncertainty will remain.

Similarly, the core structures in the reactor are designed in such a manner that the leakage flow is minimised. The exact flow bypassing the reactor will only be known once the demonstration plant has been built and the reactor is operating at full power. Until then, the uncertainty can only be quantified by testing small modules and by CFD analysis.

The source of uncertainty with regards to the turbo machine cooling and leakage flow is therefore twofold. Firstly, is the cooling flow to the various parts of the turbine enough to perform the required cooling? Secondly, is the elaborate flow path required to get the flow to the various parts designed adequately? The turbo machine supplier is fairly experienced in designing for both of these uncertainties, but again, in a first of kind design, the uncertainty with regards to cooling and leakage flow will only be mitigated through extensive testing, which is only planned in a few years time. Uncertainty with regard to the reactor leakage flow stems from the accuracy of the predicted flow. Is the predicted bypass flow in the correct ball park, or is it substantially incorrect?

The leakage flow area variation for the turbines was estimated by the supplier to be -5% to +20% [39]. This variation indicates that there is a small chance that the leakage flow might be lower and a large possibility that the final leakage flow might be more than the present design values. The turbo machine leakage flows are modelled in Flownex by using the RD element [9]. The mass flow of an RD element is given by:

$$\dot{m} = M \cdot C_d \cdot A \cdot p_{01} \frac{\sqrt{\gamma}}{\sqrt{R \cdot T_{01}}} \left[1 + \frac{\gamma - 1}{2} \cdot M^2 \right]^{\frac{1(\gamma+1)}{2(\gamma-1)}} \quad (3.1)$$

Where:

M = Mach number in the throat,

C_d = Coefficient of discharge,

A = Physical throat area [m²],

p_{01} = Upstream total pressure [Pa],

γ = Ratio of specific heats,

R = Gas constant [J/kg.K], and

T_{01} = Upstream total temperature [K].

The product $C_d \times A$ gives the actual throat area of the formed vena contracta and it is this value that will be varied in Chapter 4 to achieve the required change in mass flow for turbine leakage flows. The equivalent upper and lower diameters were calculated from the actual area and used as input to the Monte Carlo simulation.

In the case of the reactor leakage flow, a large variation of $\pm 50\%$ is assumed to see the effect of this variation on the selected output parameters. The reactor bypass leak is also modelled in Flownex by an RD element. In this case the Flownex Optimiser functionality was used to determine the diameters that will create the specified $\pm 50\%$ variation.

As for distribution choices, the double triangular distribution (refer Appendix B) is chosen for the turbo machine leakage flow, as the input variation is skewed. The normal distribution was chosen for the variation in reactor leakage flow, as it is expected that this value will be evenly distributed about a central mean. A uniform distribution is chosen for the recuperator bypass leak to be conservative. This distribution implies that there is equal chance for the variable to take on any value in the input variation.

3.5 TURBO MACHINE EFFICIENCY

Turbo machine efficiencies compare the actual work performed to the work performed in an ideal process [35]. PBMR, the turbo machinery supplier and Flownex defines and uses the isentropic efficiency of the turbo machines. The turbo machine supplier predicts what the isentropic efficiency of each turbo machine will be by using their design software. However, experience has taught the supplier that until a machine has been tested, there will always be some risk attached to predicting its efficiency value. In the design of the PBMR plant, this efficiency value is of particular importance as it directly influences the performance of the plant.

The turbo machinery supplier takes the following approach when stating efficiency values. Three risk efficiency values are specified. The concept of “risk efficiency” is explained as follows: 90% risk efficiency implies that there is a 90% risk that the efficiency stated will not be reached, whereas 10% risk efficiency implies that there is only a 10% risk that the efficiency stated will not be reached. By implication, this means that the 90% risk efficiency is the highest value. Table 2 lists the risk efficiencies quoted at present (taken from [40], [41] and [42]).

Table 2: Turbo Machine Risk Efficiencies

Turbo Machine	10% Risk Efficiency [%]	50% Risk Efficiency [%]	90% Risk Efficiency [%]
HPT	86.6	87.6	88.6
HPC	87.5	89.0	90.5
LPT	89.9	90.9	91.9
LPC	87.5	89.0	90.5
PT	91.5	92.5	93.5

3.5.1 Implementation

The Demonstration plant analyses of the MPS utilises the 50% Risk Efficiency values for determining the plant design point. The 10% and 90% Risk Efficiency values is then used as the lower and upper bounds of the expected variation. In Flownex the E-factor (refer to [9]) is used to change the efficiency of turbo machines.

Although these values are symmetrical, the double triangular distribution was chosen for the variation of the input distribution. This distribution is finite and would force all the efficiency values to fall within the range specified by the supplier.

3.6 TURBO MACHINE BLADE FLOW AREA

Axial turbines and compressors are used in the MPS of the PBMR plant. Axial turbo machinery has numerous blades in rows, which are called stages. In-between the adjacent blades of a stage, a minimum flow area, often referred as the throat area can be found. Figure 16 (taken from [35]) indicates the throat area in red. The minimum flow area determines the quantity of mass flow which can be forced through a stage, given its pressure differential.

Turbo machinery blades are manufactured to a specific size tolerance and this causes a variation in the throat area. This means that the area can either be larger than designed, meaning a higher mass flow for a certain pressure differential, or conversely, smaller than designed, which will have the opposite effect on mass flow for a given pressure differential. According to the supplier, a variation flow area of -1% to +3% can be expected [39].

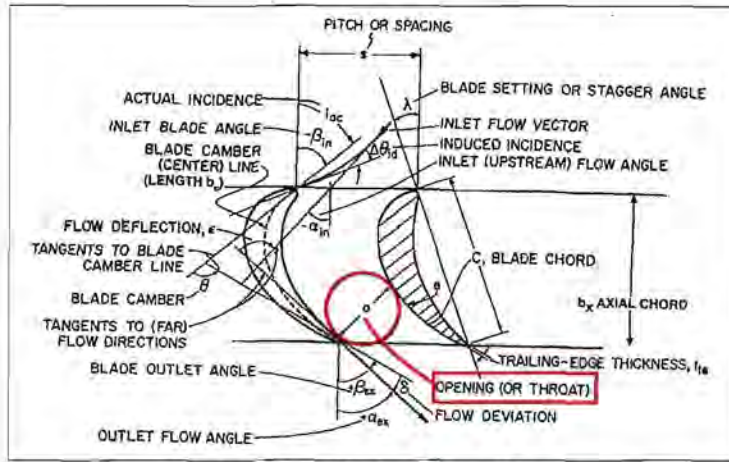


Figure 16: Blade Throat Area

3.6.1 Implementation

The mass flow scaling factor (B-Factor) is used to scale both performance maps i.e. the pressure ratio versus corrected mass flow map and the isentropic efficiency versus corrected mass flow map. The scaling is done by simply multiplying all the original values of corrected mass flow

mass flow $\left(\frac{\dot{m} \sqrt{T_{0i}}}{P_{0i}} \right)$ supplied in the chart with the value of the scaling factor. This means that

in effect the corrected mass flow axis of the map is **stretched** if the value of the scaling factor is greater than one and **shrunk** if the value of the scaling factor is less than one.

Suppose the corrected mass flow for the new, scaled map is denoted with $\left(\frac{\dot{m} \sqrt{T_{0i}}}{P_{0i}} \right)_{NM}$, while

the original is denoted as $\left(\frac{\dot{m} \sqrt{T_{0i}}}{P_{0i}} \right)_{OM}$, then:

$$\left(\frac{\dot{m} \sqrt{T_{0i}}}{P_{0i}} \right)_{NM} = B * \left(\frac{\dot{m} \sqrt{T_{0i}}}{P_{0i}} \right)_{OM} \quad (3.2)$$

where B denotes the mass flow factor. Figure 17 illustrates this concept for the pressure-corrected mass flow map of a typical compressor:

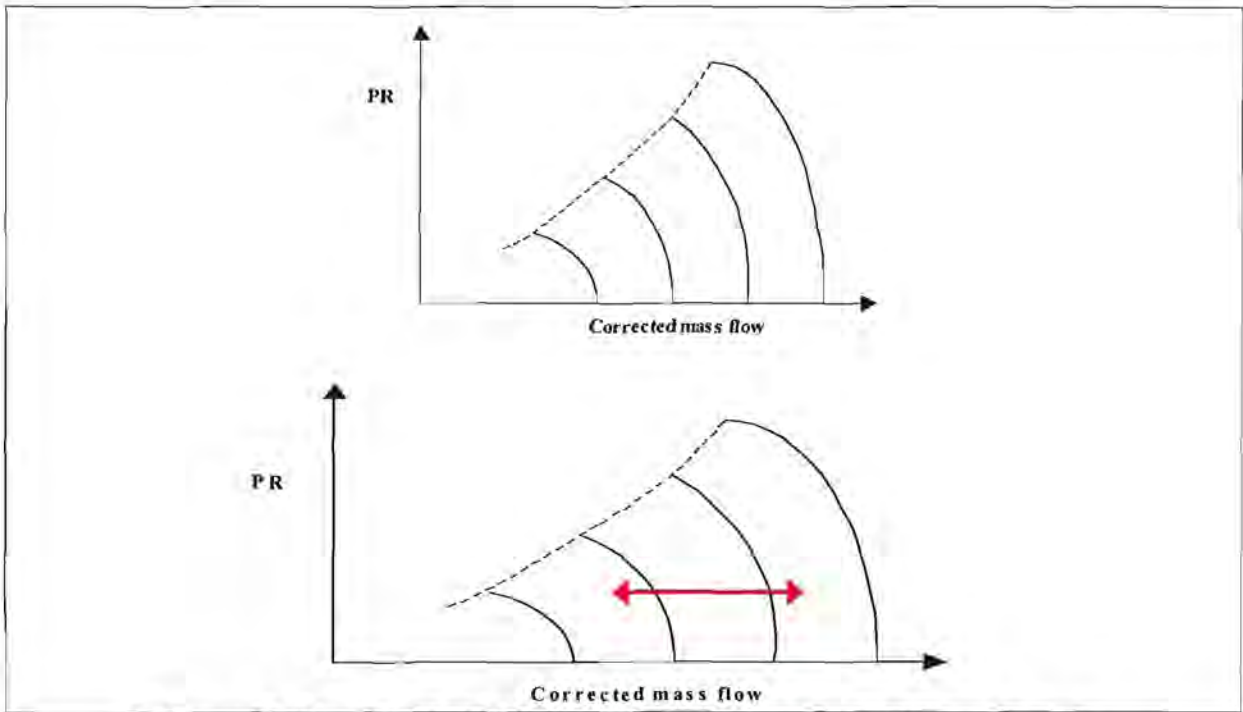


Figure 17: The effect of B-factor (>1) scaling on a performance map

$$\frac{\dot{m}\sqrt{RT_{0i}}}{D^2 P_{0i}}$$

The true non-dimensional mass flow is given by $\frac{\dot{m}\sqrt{RT_{0i}}}{D^2 P_{0i}}$. Notice that D is below the line in this equation. D represents some or other significant length and so, D^2 represents some or other significant area, like the throat area in turbo machines.

For the purpose of this study, it was necessary to determine the sensitivity to varying the

throat area. Flownex however uses the corrected mass flow given by $\frac{\dot{m}\sqrt{T_{0i}}}{P_{0i}}$, thus assuming that scaling of turbo machines will not occur between different gases (R assumed 1) and that the value of $D=1$. Subsequently, it is not possible to directly vary the throat area (or any other significant area).

In order to simulate a variation in the throat area, it is necessary to vary $1/B$ -Factor instead of the B-Factor alone. This will cause the variation to be inversely proportional. Thus, a larger B in this case, will cause a smaller corrected mass flow.

This type of variation is done to simulate the effect of the predicted speed line and the measured speed not coinciding accurately; possibly due to some or other manufacturing variation.

The double triangular distribution was chosen for the variation in throat area, since the variation specified by the supplier is skewed.

3.7 REACTOR OUTLET TEMPERATURE

The ROT has a significant influence on the efficiency of the Brayton cycle. For this reason, ROT should be as high as possible. However, a higher ROT has a negative influence on downstream component life. A compromise has therefore to be found between an efficient plant and required plant life.

In the plant, ROT will be accurately controlled so that the smallest possible variation in temperature is achieved. Variations in ROT are expected to originate from two sources, control uncertainty and measurement uncertainty. It is at this stage envisaged that a combined variation of $\pm 15^{\circ}\text{C}$ might be prevalent from these two sources. This variation is based on engineering judgement.

3.7.1 Implementation

The Flownex pebble bed element is used to simulate the heat generating pebbles in the reactor. In the Flownex pebble bed model, one can either specify the fluidic power or the exit temperature of the pebble bed. Normally the latter is specified in analysis, since this temperature will be controlled by a controller. In this study, the variation stated will be input in the study by manipulating the pebble bed exit temperature.

The normal distribution is chosen as input variation for this variable, as the expected variation due to controller fluctuation and measurement error is thought to be distributed evenly about a central mean.

3.8 MANIFOLD PRESSURE

A characteristic of the closed direct Brayton cycle of the PBMR is that it is possible to control the power output by varying the manifold pressure. The manifold pressure translates directly to the helium inventory level: the higher the inventory level, the higher the manifold pressure.

The plant modes and states [43] requires load following capability of between 100%-40%-100% MCRI. This means that the plant will be required to operate at any level between 100% and 40% of the inventory level. The manifold pressure will thus be tightly controlled and monitored in the plant. Engineering judgement was used to estimate that the variation in manifold pressure due to the pressure controller and measurement uncertainty should not be more than $\pm 1\%$.

3.8.1 Implementation

In the Flownex model of the MPS depicted in Figure 5, the pressure on node 78 is fixed to the appropriate pressure value for the required inventory level. This is done because Flownex requires the closed cycle to have a reference pressure. To implement the pressure variation of $\pm 1\%$, the fixed pressure on node 78 was adjusted to the appropriate value.

The normal distribution is chosen as input variation for this variable, as the expected variation due to controller fluctuation and measurement error is thought to be distributed evenly about a central mean.

3.9 COOLING WATER TEMPERATURE

The cooling water system cooling the pre- and intercooler, uses demineralised water, connected via an intermediate heat exchanger to the sea, which is the ultimate heat sink of the plant. All the heat rejected in the pre- and intercooler goes to the sea. This heat represents the unusable energy in the Brayton cycle.

The sea temperature at Koeberg varies throughout the year. According to [44], the sea temperature varies between 11.1°C (10% cumulative probability) and 15.2°C (90% cumulative probability). This variation in temperature is indicated in Figure 18.

The approach temperature of the seawater heat exchanger is 3°C, which means that the actual cooling water temperature at the inlet to the pre- and intercooler is 3°C higher than the seawater. This inlet temperature will vary with the same variation as the seawater.

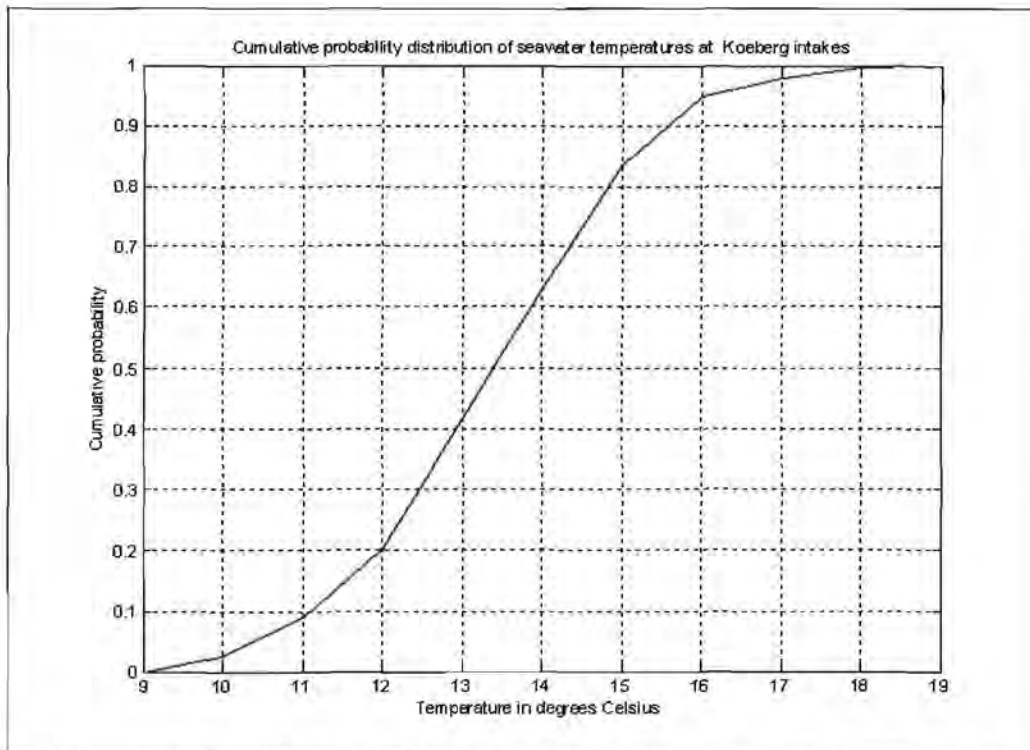


Figure 18: Cumulative probability of Koeberg sea water temperature

3.9.1 Implementation

In the Flownex MPS model of Figure 5, the cooling water temperature is fixed on the secondary side of nodes 99 and 106. The fixed temperature will be varied according to the seawater temperature variation with the 3°C approach temperature incorporated, which means that the actual input cooling water temperature range is between 14.1 °C and 18.2 °C.

The normal distribution is chosen as input variation for this variable, as the expected variation in seawater temperature is thought to be distributed evenly about a central mean.

3.10 HEAT EXCHANGER PARAMETERS

3.10.1 Heat Exchanger Effectiveness

The PBMR MPS has three heat exchangers: the pre- and intercooler and the recuperator. The pre- and intercooler are water-helium heat exchangers that remove heat from the Brayton cycle to an external heat sink. The recuperator on the other hand, takes heat that was not extracted in the turbines and pre-heats the helium that enters the reactor. The recuperator pushes up the efficiency of the Brayton cycle, since it provides better energy utilisation.

The pre-cooler is designed to have an approach temperature of 5°C. The intercooler will be an exact duplicate of the pre-cooler in order to save on design and manufacturing cost. This means that the intercooler will be slightly over sized for its required duty, but this will be offset by the subsequent efficiency gain of the Brayton cycle, since its approach temperature will be lower. Consequently, the intercooler will have a colder outlet temperature for the same inlet water temperature, meaning the HPC requires less power to compress the helium.

The recuperator is designed so that it has an effectiveness of 97%, as this was determined to be the most cost effective point when comparing cycle efficiency gain with the capital cost of the recuperator. The effectiveness is defined as the ratio of the actual heat exchanged to the theoretical maximum heat that can be exchanged. The effectiveness is therefore a measure of the physical size of the recuperator. Increasing the size and thus the heat exchange area of the recuperator, will increase its effectiveness, but also its cost.

$$\eta = \frac{T_{s,o} - T_{s,i}}{T_{p,i} - T_{s,i}} \dots\dots\dots(3.3)$$

Where:

η = Effectiveness;

$T_{s,o}$ = Secondary side outlet temperature;

$T_{s,i}$ = Secondary side inlet temperature; and

$T_{p,i}$ = Primary side inlet temperature.

Some uncertainty exists as to the performance of the heat exchangers. The pre- and intercooler are of a compact design in order to save on space and subsequently cost. This compact design has however never been built and tested by the supplier. Therefore uncertainty exists as to the heat transfer performance of the plate finned-tubes. The uncertainty will be mitigated by experimentally testing the tube arrangement, but until such a time, an estimation regarding the heat transfer performance has been made from [45]. This estimation is the source of the uncertainty, since an exact geometry match cannot be made.

As for the recuperator, uncertainty also exists as to the thermal performance, but to a somewhat lesser extent. The recuperator's fin geometry was chosen from [45], but no geometry in [45] was tested in helium, which has tremendously better heat transfer capabilities when compared to air. This risk introduced by this uncertainty will also be mitigated by experimentally testing the thermal performance of the recuperator in helium, but until such a time, the uncertainty remains.

3.10.2 Heat Exchanger Pressure Drop

Apart from the actual heat exchange occurring in the heat exchangers, the pressure drop across the heat exchangers is also an important parameter for plant efficiency. Every pressure drop in the cycle has to be overcome by the pressure ratio set up by the compressors. The more pressure drop that has to be overcome, the less efficient the plant becomes to run. Pressure drop should therefore be as low as possible, while still maintaining sufficient heat exchange.

For the recuperator, the total pressure drop should be less than 1% of the inlet pressure. This means that the pressure drop on the LP side can be 0.5% of the LP inlet pressure. Conversely, the pressure drop on the HP side can thus be no more than 0.5% of the HP inlet pressure.

3.10.3 Implementation

Given the extent of the estimations made with regards to the heat exchanger performance described in the previous section, it is clear that the possibility of a large variation exists. Several parameters play a role in the performance of a heat exchanger regarding the heat transfer and pressure drop characteristics. These two parameters are however interlinked, since both depend on the velocity through the heat exchanger. A larger velocity will have a higher pressure drop, but it will at the same time improve the outside heat transfer coefficient.

It was decided to implement the uncertainty associated with the pre- and intercooler, as well as the recuperator, by choosing a variation of $\pm 50\%$ on the heat exchange area of each of the heat exchangers. The heat exchange area is a parameter that is available in Flownex models and is therefore an obvious choice for manipulating the heat transfer and subsequently, the heat exchanger effectiveness. Also, the relatively large variation is an attempt to force the selected output parameters outside of their limits. This is a test of the robustness of the PBMR design.

The pressure drop associated with the pre- and intercooler and the recuperator can be related back to the hydraulic diameter of the heat exchanger. The hydraulic diameter is a function of the minimum free flow area, as well as the inlet and outlet area of a heat exchange bundle. The inlet and outlet area are input parameters to Flownex and are therefore the parameters to vary when attempting to manipulate the pressure drop.

For this study, it was decided to vary the inlet and outlet area of the recuperator by $\pm 10\%$. The same variation was applied to the inlet area of the inlet area of the inlet area only of the pre- and intercooler. The inlet area of the inner bundle is the outlet area of the outer bundle. The value of $\pm 10\%$ was chosen much larger than the anticipated real world variation (which is estimated to be less than 1%) in an attempt to force the results out of bounds.

The double triangular distribution was chosen for the variables mentioned in this section, as it is a finite distribution and would force all the variables to fall within the specified range. Since all the input variation ranges of this section are symmetrical, the double triangular distribution will approximate the normal distribution.

3.11 CONCLUSION

In this chapter the parameters with uncertainty have been listed and where possible, the uncertainty has been justified from literature. Where this was not possible, which was in most cases, as the PBMR plant is a first-of-a-kind design, engineering judgement was used, or the variation was chosen excessively large in order to test the robustness of the design and to be conservative with respect to uncertainty in the inputs.

The input variable distributions were chosen to reflect the nature of the input data as far as possible. The double triangular distribution was chosen for variables with skewed input variations, while the normal distribution was chosen where a central mean can be expected.

4. METHOD OF ANALYSIS AND RESULTS

4.1 INTRODUCTION

Previous chapters justified the use of Flownex as thermo-hydraulic analysis tool, as well as the Monte Carlo sampling method as being applicable for this study. The parameters with uncertainty were highlighted and the expected variations justified. In this chapter, the method of analysis will be discussed, followed by a discussion of the main results obtained from the study. The chapter begins with an explanation of the analysis envelope, followed by the implementation in Flownex and Matlab.

4.2 ANALYSIS ENVELOPE

4.2.1 The Demonstration Plant Operating Envelope

The PBMR plant will be required to operate continuously at several steady state operating points. The operating point is defined by the reactor outlet temperature, which can be any set temperature in the range 750°C to 900°C. Secondly, the operating point is determined by the inventory level or quantity of helium contained within the pressure boundary, which can be anywhere between 40% and 100%. The inventory level directly correlates to the power level, the higher the inventory level, the higher the grid power that will be produced. Bypass valves can be used to further reduce the power output, but for this study, bypass valve usage is not considered.

The operating points indicated in Figure 19 were chosen as they represent the bounding operating points for the PBMR plant operating envelope [43]. These points represent the maximum and minimum reactor outlet temperature, as well as the maximum and minimum inventory level.

The four operating points are:

- 900°C ROT, 100% MCR & 100%MCRI (Case A)
- 900°C ROT, 40% MCR & 40%MCRI (Case B)
- 750°C ROT, 61% MCR & 100%MCRI (Case C)
- 750°C ROT, 24% MCR & 40%MCRI (Case D)

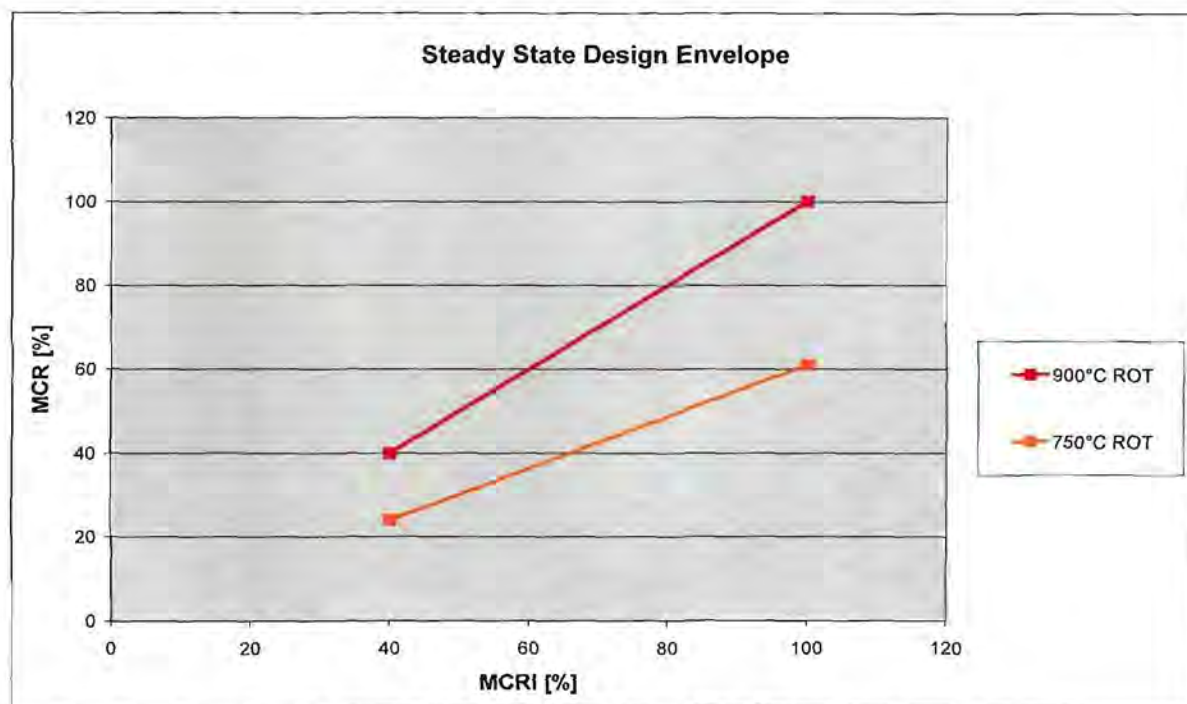


Figure 19: PBMR MPS Operating Envelope

For simplicity, the four operating points shall be referred to as Case A, B, C or D as indicated.

4.3 IMPLEMENTATION IN FLOWNEX AND MATLAB

Flownex does not have the built-in capability to perform the Monte Carlo analyses required for this study. Flownex does have a command line solver named Flownex Console, which is just the solver without the graphical user interface. It is possible to call the command line solver from other software to solve thermo hydraulic networks previously set up with the Flownex GUI.

The Monte Carlo sampling method requires that thousands of runs be performed consecutively. Software was therefore developed in Matlab by others to automate the Monte Carlo sampling, substituting the selected values in the designated Flownex model database and calling on Flownex Console to solve the thermo hydraulic model, as required by each run.

The Matlab software developed especially for this type of study is called Flownex Analyser [46]. Flownex Analyser uses an Excel spreadsheet as input file. This input file defines the quantity of runs required; as well the parameters to be changed, the upper and lower limits of

parameters, the nominal value and the input distribution curve to be used. The software then uses Matlab's random number functionality, which calls on the CPU's random number generator, to create the random input variables for each of the Monte Carlo runs. The input spreadsheets used in this study can be found in Appendix C.

Different types of input variables require different input distribution shapes. Some variables are expected to exhibit Gaussian behaviour, which means that the variables are distributed about a mean value. Other variables might require the use of a uniform distribution, which means that there is an equal chance that the variable can take on any value between the specified upper and lower limit.

Many of the identified parameters discussed in the previous chapter, have finite ranges and are skewed, meaning that it is not centred about a central mean value. A study done in May 2002 derived a double triangular distribution to fit this type of skewed, finite data range [47]. The defining equations and a graphical illustration of the double triangular distribution are given in Appendix B. Flownex analyser was programmed so that the input distribution choices listed in Table 3 are available:

Table 3: Distributions choices available

1	Double-Triangular (refer Appendix B)
2	Uniform (refer Figure 7)
3	Normal / Gaussian (refer Figure 6)

On completion of the specified number of runs, Flownex Analyser collates all the results from the Flownex results file and produces a result matrix that can then be further analysed in Matlab, using Matlab's built in statistical functions.

4.4 THE MONTE-CARLO SIMULATION

In Table 4, the inputs to the Monte Carlo runs are listed. The element or node number refers to the unique number in the Flownex MPS model. The varied parameter is indicated, as well as the nominal value, chosen variation and the type of input distribution to be used. The specific number of the input distributions is listed in Table 3 in the previous section.

Table 4 lists the inputs required for the 900°C, 100% MCR, 100% MCRI case. To achieve the other three bounding operating points, it is necessary to adjust the nominal value of both the reactor outlet temperature and the manifold pressure. The input variations of these variables are kept the same, hence slight variations in the percentages of the upper and lower limits of the variations shown in Table 5 to Table 7.

The double triangular and uniform distributions are finite, but the Gaussian distribution has infinite bounds. It is therefore possible for the random generated value calculated by the Gaussian function to fall outside the range listed in the input tables. However, these values represent only 5% of the total number of values generated and are not sufficient enough to influence the final results.

Table 4: The Monte Carlo input table

Item	Element or Node Number	Description	Parameter	Nominal Value	Variation	Distribution
1	150	HPT Intake	K-Factor	0.537676	-10% to +50%	1
2	11	HPT Diffuser	K-Factor	0.305818	-10% to +50%	1
3	133	Manifold to HPTi Leakage	Cd X A	0.025661	-5% to +20%	1
4	113	Manifold to HPTe Leakage	Cd X A	0.031878	-5% to +20%	1
5	9	High Pressure Turbine	E factor ⁽¹⁾	0.989773	-1.09% to +1.09%	1
6	9	High Pressure Turbine	1/B factor	1/1	-3% to +1%	1
7	152	LPT Intake	K-Factor	0.45795	-10% to +50%	1
8	19	LPT Diffuser	K-Factor	0.271482	-10% to +50%	1
9	182	Manifold to LPTi Leakage	Cd X A	0.018524	-5% to +20%	1
10	116	Manifold to LPTe	Cd X A	0.029185	-5% to +20%	1
11	17	Low Pressure Turbine	E factor	0.992773	-1.14% to +1.14%	1
12	17	Low Pressure Turbine	1/B factor	1/1	-3% to +1%	1
13	27	PT Intake	K-Factor	1.642882	-10% to +50%	1
14	33	PT Diffuser	K-Factor	0.183352	-10% to +50%	1
15	3874	25% PT Rotor Disk Cooling Flow	Cd X A	0.013823	-5% to +20%	1
16	3875	75% PT Rotor Disk Cooling Flow	Cd X A	0.017892	-5% to +20%	1
17	29	Power Turbine	E factor	0.988296	-1.09% to +1.09%	1
18	29	Power Turbine	1/B factor	1/1	-3% to +1%	1
19	39	Recuperator	Heat Area	28534.21	-50% to +50%	1
20	39	Recuperator	Primary inlet area	11.879	-10% to +10%	1
21	39	Recuperator	Primary outlet area	11.879	-10% to +10%	1
22	39	Recuperator	Sec inlet area	3.562	-10% to +10%	1
23	39	Recuperator	Sec outlet area	3.562	-10% to +10%	1
24	158	Recuperator (LP) to PC Connection	K-Factor	1.68	-10% to +10%	1
25	3899	RX(LP) Leakage	Area	0.0004	-10% to +10%	2
26	41	Pre-cooler outer bundle	Heat Area	5320.82	-50% to +50%	1
27	41	Pre-cooler outer bundle	Inlet Area	33.109	-10% to +10%	1
28	43	Pre-cooler inner bundle	Heat Area	4609.21	-50% to +50%	1
29	43	Pre-cooler inner bundle	Inlet Area	19.21	-10% to +10%	1
30	51	LPC Intake	K-Factor	0.28761	-10% to +50%	1
31	55	LPC Diffuser	K-Factor	2.489976	-10% to +50%	1
32	183	LPC Inlet Seal (Thrust Balance)	Cd X A	0.022015	-5% to +20%	1

Item	Element or Node Number	Description	Parameter	Nominal Value	Variation	Distribution
33	53	Low Pressure Compressor	E factor	0.984714	-1.68% to +1.69%	1
34	53	Low Pressure Compressor	1/B factor	1/1	-3% to +1%	1
35	61	Intercooler outer bundle	Heat Area	5320.82	-50% to +50%	1
36	61	Intercooler outer bundle	Inlet Area	33.109	-10% to +10%	1
37	63	Intercooler inner bundle	Heat Area	4609.21	-50% to +50%	1
38	63	Intercooler inner bundle	Inlet Area	19.21	-10% to +10%	1
39	71	HPC Intake	K-Factor	0.345796	-10% to +50%	1
40	75	HPC Diffuser	K-Factor	1.808044	-10% to +50%	1
41	181	HPC Inlet Seal (Thrust Balance)	Cd X A	0.018982	-5% to +20%	1
42	73	High Pressure Compressor	E factor	0.984777	-1.69% to +1.68%	1
43	73	High Pressure Compressor	1/B factor	1/1	-3% to +1%	1
44	1	Pebble bed reactor (400MW)	Length	11	-16.9% to +17.5% ⁽²⁾	2
45	1826	Core bypass leak	Diameter	0.1474	-30.7% to +25.1% ⁽³⁾	3
46	3828	Outlet slots (part1)	K-Factor	2	-15% to +15%	3
47 ⁽⁴⁾	1	Pebble bed reactor (400MW)	Fuel Exit T	1234.645 K	-1.31% to 1.31%	3
48	78	Manifold	Pressure	9000000 Pa	-1% to +1%	3
49 ⁽⁵⁾	99	Cooling water temperature	Temperature	291.15 K	-1.34% to +0.07%	3

NOTES:

1. The range for the E-factor was determined from the 10% and 90% risk efficiencies as supplied by the supplier. The 50% risk efficiency was used to determine the nominal value of the E-factor.
2. The range for item 44 was determined by manually varying the length to determine a -15% to +15% pressure drop across the pebble bed.
3. The range for item 45 was determined in the following manner: A $\pm 50\%$ range was suggested for the reactor bypass mass flow. The optimiser was used to specify the mass flow range and the corresponding diameters of the RD element (1826) were calculated.
4. The exit temperature of the reactor should vary $\pm 15^\circ\text{C}$.
5. This creates the actual cooling water temperature variation from 14.1°C to 18.2°C .

The same values listed in Table 4 were used as inputs to the 900°C ROT, 40%MCR & 40%MCRI network, except for the changes indicated in Table 5.

Table 5: Modified inputs for the 900°C ROT, 40%MCR & 40%MCRI case.

Item	Element or Node Number	Description	Parameter	Nominal Value	Variation	Distribution
47	1	Pebble bed reactor (400MW)	Fuel Exit T	1238.148K	-1.37% to +1.38%	3
48	78	Manifold	Pressure	3652215.51 Pa	-1% to +1%	3

The same values listed in Table 4 were used as inputs to the 750°C ROT, 61%MCR & 100%MCRI network, except for the changes indicated in Table 6.

Table 6: Modified inputs for the 750°C ROT, 61%MCR & 100%MCRI case.

Item	Element or Node Number	Description	Parameter	Nominal Value	Variation	Distribution
47	1	Pebble bed reactor (400MW)	Fuel Exit T	1067.1K	-1.56% to +1.56%	3
48	78	Manifold	Pressure	8421037.06 Pa	-1% to +1%	3

The same values listed in Table 4 were used as inputs to the 750°C ROT, 24%MCR & 100%MCRI network, except for the changes indicated in Table 7.

Table 7: Modified inputs for the 750°C ROT, 24%MCR & 40%MCRI case.

Item	Element or Node Number	Description	Parameter	Nominal Value	Variation	Distribution
47	1	Pebble bed reactor (400MW)	Fuel Exit T	1069.339K	-1.56% to +1.57%	3
48	78	Manifold	Pressure	3419393.16 Pa	-1% to +1%	3

4.4.1 Recorded Output Parameters

As stated at the outset, the following six parameters are being examined in this study:

- The rotational speed of the HPTU and LPTU,
- The surge margin of the HPC and LPC,
- The grid power produced, and
- The cycle efficiency.

The design point rotational speed for the HPTU is 6000 rpm, while the LPTU will run at 7000 rpm at the design point. These speeds are also referred to as the nominal rotational speed. It is convenient to convert the actual running speed to a percentage of the nominal rotational speed. The “percentage of nominal rotational speed” is the output parameter recorded in this study. This parameter is important as the supplier imposed an operating range of 80% to 105% of nominal running speed on both the HPTU and LPTU. Speeds outside of this range might cause blade excitation and subsequent failure.

The supplier imposes a minimum surge margin on the operating point of both the HPC and LPC. This means that no matter where the compressor is operating, there should be sufficient margin or “distance” to the actual surge line of the machine. The supplier uses its own definition for surge margin (referenced in [48]), which is not the same as the PBMR surge margin defined in [49]. The PBMR definition amounts to approximately half the definition of the supplier. If the supplier requests a surge margin of 20% it means that the

equivalent PBMR surge margin is 10%. This needs to be kept in mind when evaluating the results.

The **grid power** produced is a value that is calculated from the following equation:

$$\text{Grid Power} = ((P_{PT} \cdot \eta_{gen} \cdot \eta_{mech}) - HL) * \eta_{TX} \dots\dots\dots (4.1)$$

Where:

P_{PT} = Power turbine power available to drive the generator,

η_{gen} = Generating efficiency of the generator, which is assumed to be 0.985,

η_{mech} = Mechanical efficiency which takes windage and bearing losses into account. This value is assumed to be 0.99,

HL = House load is power required to drive plant auxiliaries, which is assumed to be 5MW,

η_{TX} = The transformer switching efficiency for passing the power onto the grid, which is assumed to be 0.99.

The **cycle efficiency** is also a calculated parameter:

$$\eta_{cycle} = \frac{\text{Grid Power}}{P_{\text{Reactor, Fluidic}} + P_{\text{Reactor, Fluidic losses}}} \dots\dots\dots (4.2)$$

Where:

$P_{\text{Reactor, Fluidic}}$ = the fluidic power added to the coolant gas in the reactor,

$P_{\text{Reactor, Fluidic losses}}$ = the heat lost to the surroundings by the reactor and subsequently not transferred to the coolant gas. This value is assumed to be 4 MW [31].

In summary, Table 8 lists all the variables that should be recorded to enable evaluation of the selected output parameters.

Table 8: Recorded output parameters

Parameter	Element Number
HPT rotational speed	9
LPT rotational speed	17
HPC Surge margin	73
LPC Surge margin	53
Power turbine power	29
Reactor fluidic power	1

4.5 CONVERGENCE OF MONTE CARLO RESULTS

The “convergence” of the Monte Carlo analyses needs to be checked. Different quantities of runs were performed, i.e.: 250 runs, 1000 runs and 2000 runs. The cycle efficiency results were deemed to be the best variable to examine for convergence, since it is a value that is calculated from different results. If the cycle efficiency results have “converged”, one can be rather confident that enough runs have been performed. The 900°C, 100% MCR and 100% MCRI results were evaluated and the following was found.

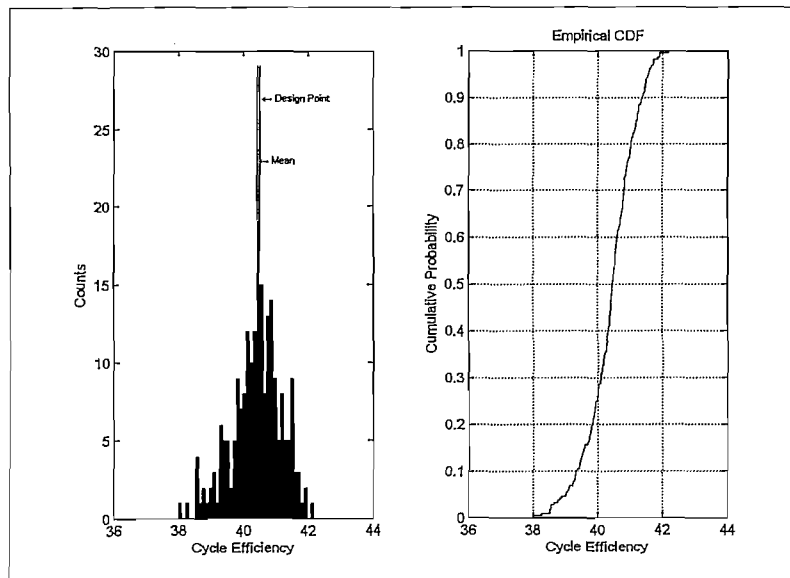


Figure 20: 250 Monte Carlo runs

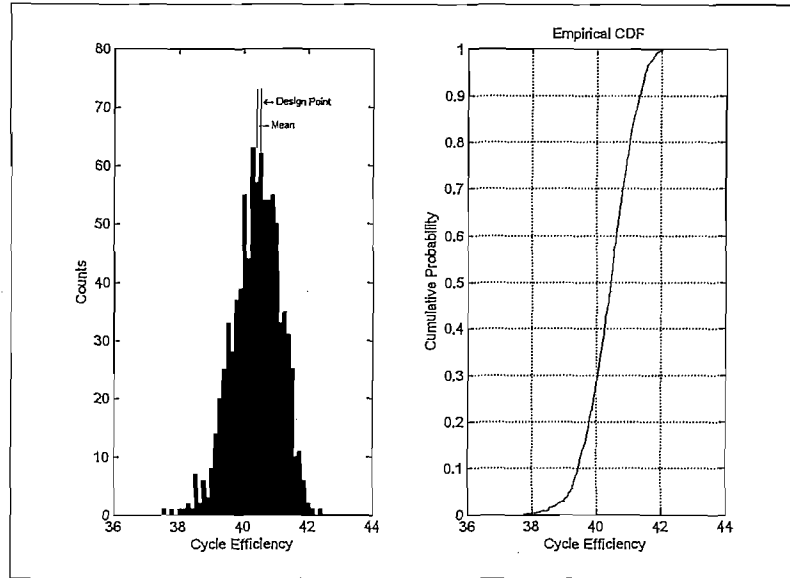


Figure 21: 1000 Monte Carlo runs

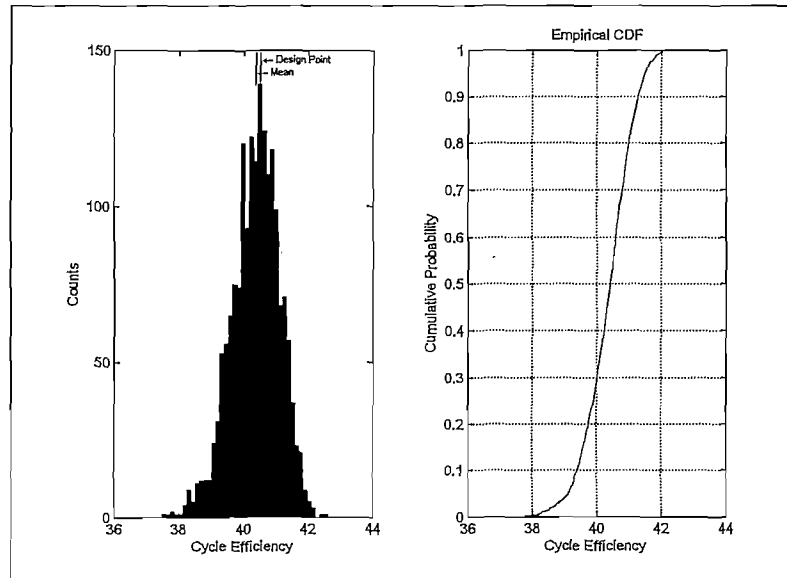


Figure 22: 2000 Monte Carlo runs

Visually, one can see from Figure 20 to Figure 22 that as the runs are increased, the distribution is packed with increasing density. (The number of “bins” was the same in all three graphs.) Also, the curve of the cumulative probability function becomes smoother as the number of runs is increased, as one would expect. The cumulative probability, cumulative distribution function (CDF), is simply the integral of the distribution, i.e. the area indicated in blue. If f is a probability density function for random variable X , the associated CDF F is:

$$F(x) = P(X \leq x) = \int_{-\infty}^{\infty} f(t) dt \quad (4.3)$$

The CDF of a value x , $F(x)$, is the probability of observing any outcome less than or equal to x .

Subsequently, one can use the data from the graphs to determine the level of "convergence". If one assumes that 2000 runs are sufficient, one can perform the comparisons listed in Table 9 and Table 10.

Table 9: Comparison between different quantities of runs

	Nom Cycle Efficiency	Mean	Lower Limit	Upper Limit	10% value	90% value
250 runs	40.5062	40.3997	37.9892	42.1769	39.3450	41.3875
1000 runs	40.5062	40.3948	37.4783	42.4378	39.4413	41.3191
2000 runs	40.5062	40.3671	37.4783	42.6122	39.4020	41.2900

Table 10: Percentage difference from 2000 runs

	Nom Cycle Efficiency	Mean	Lower Limit	Upper Limit	10% value	90% value
% Diff250 runs	0.000%	0.081%	1.363%	-1.022%	-0.145%	0.236%
% Diff1000 runs	0.000%	0.069%	0.000%	-0.409%	0.100%	0.070%
Base2000 runs	Base	Base	Base	Base	Base	Base

As can be seen from Table 10, the percentage of error made decreases as more runs are performed. What is also shown in the table is that the results obtained from 250 runs do not differ markedly from the results provided by 2000 runs. It is therefore a fair assumption that the results obtained from 1000 runs are acceptably accurate.

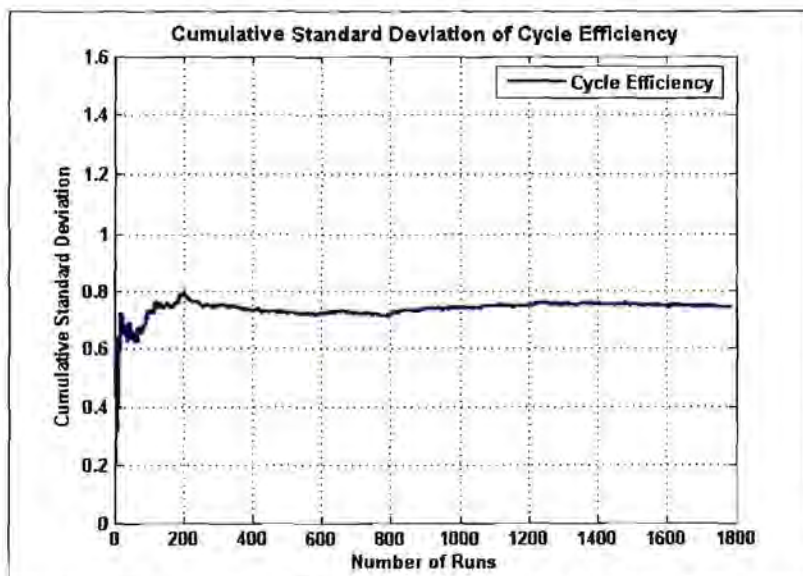


Figure 23: Cumulative Standard Deviation of Cycle Efficiency

The cumulative standard deviation (refer section 2.6) of the Cycle Efficiency was also plotted to check whether and where the standard deviation has stabilised. As can be seen from Figure 23, the value of cycle efficiency has started stabilising after about 400 runs. The standard deviation from 1000 runs onwards, changes very little. From this graph and the comparisons done in Table 10, it can be concluded that 1000 runs is a sufficient number samples for the purpose of this study.

Note that although Flownex Analyser has been asked to set up the number of runs referred to in the text above, the actual quantity of runs solved by Flownex Console is less. The reason for this is that in some cases the combination of input variable values selected randomly, caused numerical instability in the Flownex solver and hence these runs are not solved. The unsolved runs are then simply ignored when processing the results. Table 11 indicates the number of runs which did not solve for each of the cases analysed for this study. It can be seen that Case A is the most unstable of the four Flownex models used and is therefore the best candidate to use for “convergence” evaluation.

Table 11: Number of Monte Carlo runs that did not solve

Analysis case	Number of Runs	Number of Unsolved Runs
Case A	250	33 (13.2%)
Case A	1000	122 (12.2%)
Case A	2000	216 (10.8%)
Case B	1000	53 (5.3%)
Case C	1000	2 (0.2%)
Case D	1000	4 (0.4%)

4.6 LIMITATIONS OF THE STUDY

It is important to consider the limitations of this study at this point. As stated in previous sections, a total of 1000 steady state simulation runs were performed on each of the four steady state operating points. These Monte Carlo runs were however performed by incorporating some assumptions, which impose some limitations on the study.

- The results listed below indicate that the reactor power varies between 105.93 to 434.61 MW. In reality, the power will be limited to 400 MW. For the purposes of the simulation, this limit was purposely ignored to see what the power variation would be and the subsequent level of control that is required to control the reactor power.

- It is believed that, to some extent, the efficiency and leak flow variations stipulated by the supplier are design uncertainties, rather than manufacturing tolerances. As such, they are probably more conservative than what will be achieved during manufacture. The variation in the results must be considered in this light.
- All the parameters that were varied during the analyses were assumed to be capable of varying independently of each other. This is not necessarily true, especially considering the turbo-machine parameters. It is doubtful for example, that it may be possible to improve the efficiency of the turbines and have complete flexibility regarding the flow area size of the machine, which is what the Monte-Carlo assumes. For the simulation, it was assumed that cross-coupling effects such as these have a non-material effect on the results.
- Any effects that exhibit auto-correlation have been neglected in the analysis. Thus, effects such as reduction in turbine efficiency as a function of time (due to wear and tear) have not been considered. In addition, the analysis is only performed around the full power operating point. Separate analyses must be performed to assess the results around different operating points.
- Flownex solver or code uncertainty was ignored in this study. It is assumed that the code verification and validation referred to in Chapter 2 will reduce this uncertainty to an insignificant level when compared to the inputs used in this study.

A total of 40 “bins” were used when drawing each Monte Carlo distribution listed in this document. Some experimentation showed that this value gives a good balance between spread and number of counts per bin. More bins would have created sparser filled bins on the edges, while fewer bins would produce inaccurate values for 10% and 90% probability values. The number of “bins” used does not alter the results, it is purely for visual display.

4.7 RESULTS

The following paragraphs list the results of the Monte Carlo Analyses. Only Case A histograms and summary tables are included here. The histograms of Cases B to D are included in Appendix A.

4.7.1 Rotational speed results

The shaft speed results are indicated as a percentage of nominal speed. Table 12 displays the HPTU results.

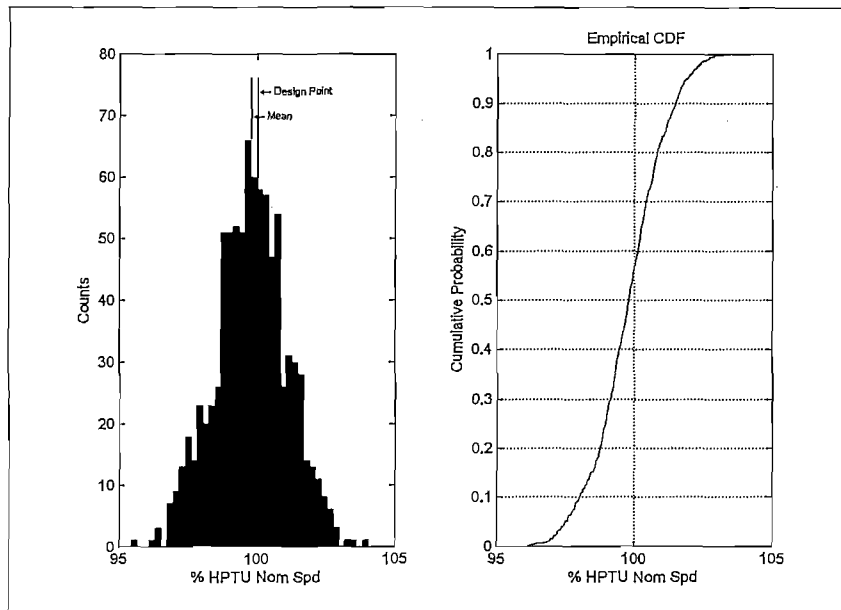


Figure 24: HPTU % of Nominal Design Speed (Case A)

Table 12: HPTU Rotational Speed Results

	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	99.78%	95.5%	104.1%	98.0%	101.5%
Case B	99.8%	96.1%	103.7%	98.3%	101.5%
Case C	91.7%	88.7%	95.2%	90.3%	93.2%
Case D	91.8%	88.3%	96.1%	90.3%	93.3%

The following results were obtained for the LPTU:

Table 13: LPTU Rotational Speed Results

	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	99.7%	92.7%	106.9%	97.3%	102.3%
Case B	100.6%	94.3%	107.0%	98.3%	103.2%
Case C	85.8%	80.9%	91.3%	83.8%	87.9%
Case D	86.4%	81.0%	92.9%	84.4%	88.6%

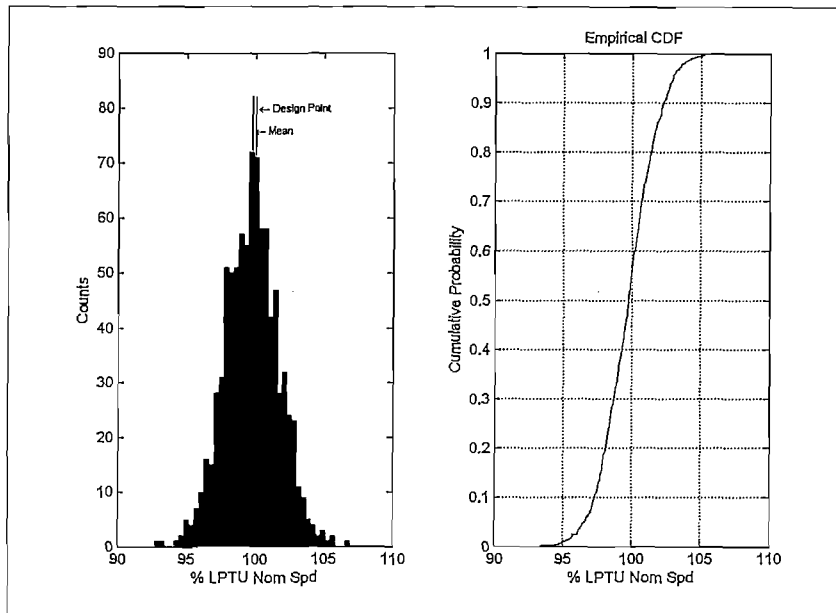


Figure 25: LPTU % of Nominal Design Speed (Case A)

From Table 12 it can be seen that for all the performed runs, the nominal HPTU rotational speed stayed within the allowable operating range of 80% to 105% of nominal speed for the cases analysed. The lower limit was 88.3%, while the upper limit was 104.1%. By implication this means that the 10% and 90% values lie comfortably within the allowable range. Remember that these values represent 80% of all possible speed values.

Table 13 reveals that the LPTU stayed above the lower limit of 80% for all the runs, whereas the upper limit of 105% of nominal rotational speed was exceeded in two of the cases. The lower limit was 92.7%, while the upper limit was recorded to be 107.0%. The 10% and 90% values lie within the allowable operating range.

4.7.2 Compressor Surge Margins

Table 14 displays the results for the HPC Surge Margin.

Table 14: HPC Surge Margin Results

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	11.681%	11.240%	7.715%	14.202%	9.736%	12.598%
Case B	11.162%	10.721%	7.289%	13.162%	9.396%	12.063%
Case C	15.146%	14.733%	11.337%	17.121%	13.424%	16.000%
Case D	14.846%	14.385%	11.272%	17.028%	13.018%	15.670%

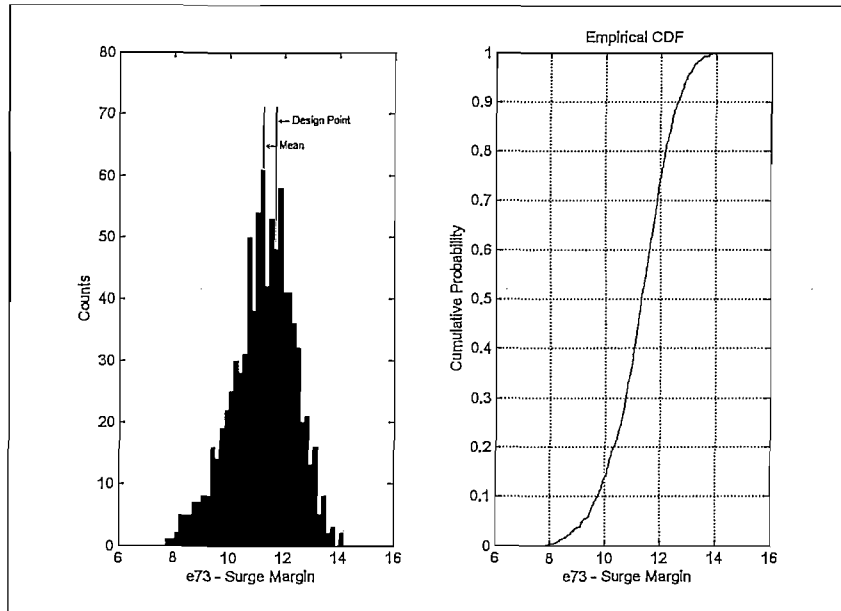


Figure 26: HPC Surge Margin (Case A)

The results for the LPC Surge Margin are listed in Table 15.

Table 15: LPC Surge Margin Results

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	11.236%	10.877%	5.584%	15.187%	8.852%	12.767%
Case B	11.792%	11.582%	6.519%	15.153%	9.779%	13.447%
Case C	4.765%	4.379%	-0.086%	8.319%	2.419%	6.324%
Case D	5.189%	4.778%	0.124%	9.481%	2.901%	6.678%

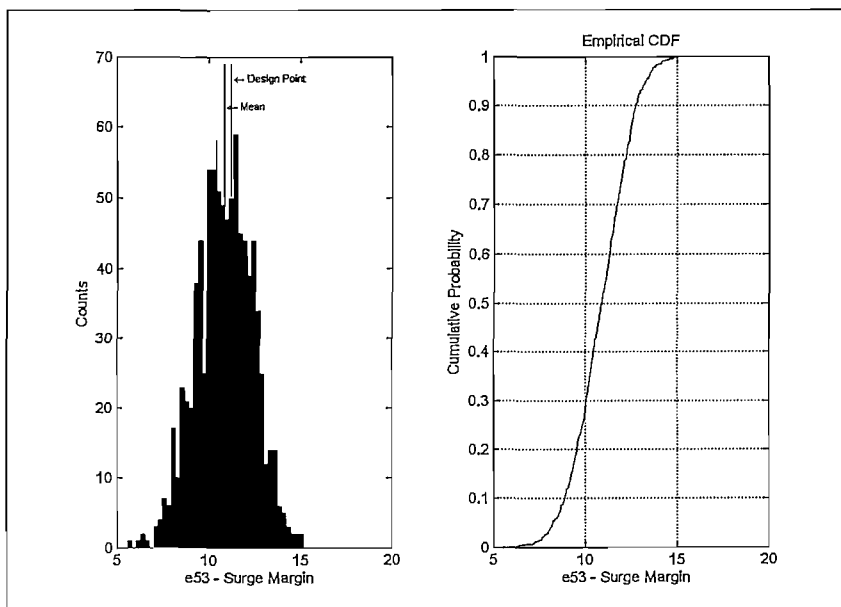


Figure 27: LPC Surge Margin (Case A)

The surge margin results of the HPC indicate a lowest mean value of 10.721%. This value should be doubled to compare it with the minimum value of 20% set by the supplier, which is then slightly surpassed. The lowest 10% value is 9.396%, which means that this value is below the lower limit set by the supplier. The upper limit and 90% values are listed for completeness.

Table 15 shows the surge margin results for the LPC. The Case C lower limit indicates that the compressor is surging. The lowest 10% value is, even when doubled, well below the limit set by the LPC supplier. Interesting to notice is that the spread of lower to upper limit for the HPC varies by 9.832%, while the same variation for the LPC is 15.273%. This means that the LPC is more prone to surging than the HPC.

4.7.3 Grid Power Results

Grid power is calculated by using equation (4.1). The results are indicated in Table 16:

Table 16: Grid Power Results

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	162.0	162.4	141.5	184.9	154.1	170.2
Case B	64.8	65.1	56.9	72.3	62.0	68.3
Case C	99.6	99.4	84.5	113.4	93.5	105.4
Case D	38.7	38.9	32.9	45.8	36.5	41.3

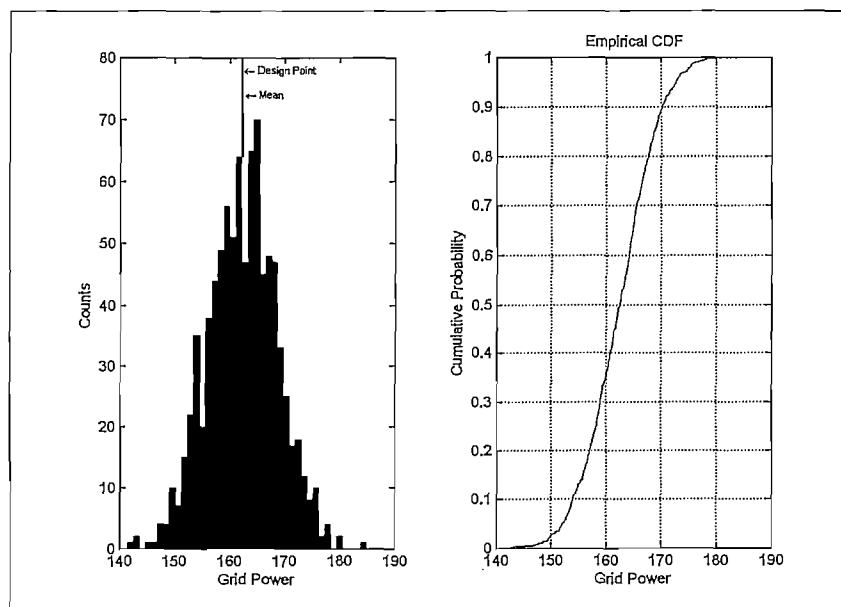


Figure 28: Grid Power (Case A)

The grid power results of Case A are the most significant. The nominal (best estimate) value is 162.0MW. The median value of the Case A analysis is 162.4MW, which compares very favourably with the best estimate value. Inspection of the other mean values also indicates good correlation with the best estimate value.

4.7.4 Cycle Efficiency Results

The cycle efficiency is calculated from equation (4.2). Table 17 lists the cycle efficiency results for the four cases.

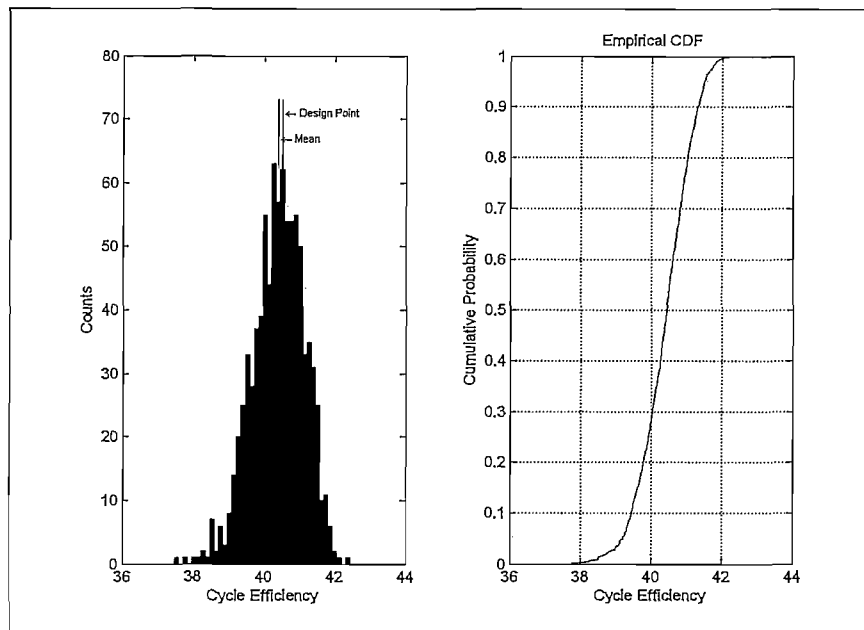


Figure 29: Cycle Efficiency (Case A)

Table 17: Cycle Efficiency Results

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
Case A	40.5062	40.3948	37.4783	42.4378	39.4413	41.3191
Case B	38.8283	38.7654	36.7297	40.6952	37.9221	39.5503
Case C	34.8572	34.6546	31.8051	37.4462	33.5265	35.7547
Case D	32.3733	32.3354	29.7776	34.7458	31.3274	33.2737

Again, the results of Case A are the most significant. The mean compares favourably with the nominal (best estimate) value, which is also the true for the other cases under consideration.

4.8 CONCLUSION

The four cases under consideration were analysed with Flownex and Flownex Analyser developed in Matlab. It was found that 1000 runs are sufficient for Monte Carlo convergence. This notion was further substantiated by looking at the cumulative standard deviation for the cycle efficiency, which indicates that suitable convergence is achieved after about 500 runs.

The rotational speed results indicated that the HPTU ran well within the allowable operating range (80% - 105%) set by the supplier. The LPTU ran above the lower limit, but ran above the upper limit in two of the cases. Should this extreme situation arrive once the plant is commissioned, the LPC bypass valves can be used to lower the LPTU speed to the operating limit of 105%. The 10% and 90% values were within the required range.

The surge margin results of the HPC indicate that its surge margin should be increased slightly (say by 5% according to PBMR's definition) to be sufficiently far away from the limit set by the supplier. The LPC results indicate that its surge margin needs to be increased in the order of 10% (according to PBMR's definition) to ensure that the LPC stays above the supplier's limit.

It was found that the mean value of each case correlates quite well to the nominal grid power value. This gives an indication as to the robustness of the PBMR plant, as the large variations employed as input, could not budge the mean grid power from its nominal (best estimate) value, which also increases the confidence with regards to the best estimate value.

The cycle efficiency results also showed a very good correlation to its nominal value for each of the cases. The 10% to 90% range of cycle efficiency values are also above the required plant efficiency value of 39%, which enhances the confidence in the best estimate value. Input variations were purposely overestimated. This could however not force a significant change in the cycle efficiency of the plant. This is again an indication that the plant layout as it is now constitutes a fairly robust design.

5. VALIDATION OF RESULTS

5.1 INTRODUCTION

The previous chapters described the theory and usefulness of the Monte Carlo method in analysing the uncertainty associated with the PBMR plant. The implementation of the Monte Carlo method in Matlab was described, together with the operating envelope that was analysed. The Matlab program together with Flownex was used to perform the required analyses. It is the purpose of this chapter to compare these results with a previous study on the PBMR plant to show that a good correlation exists between the studies.

5.2 SIMILAR FLOWNET 5 STUDY

5.2.1 Background

Reference [47] describes sensitivity and Monte Carlo analyses that were performed on a previous design of the PBMR plant in May 2002. Although this layout of the PBMR plant is also based on the three-shaft Brayton cycle, the maximum reactor power was only 300MW. All equipment included in this cycle layout is therefore sized approximately 75% smaller. Furthermore, the thermo-hydraulic model was built in Flownet 5 code, which is the forerunner to the Flownex code used in the study described in this document.

The thermo-hydraulic model analysed was also a simplified model. The model was stripped of detail that was deemed unnecessary. Resistances in series were combined into a single resistance and leak flow paths were also simplified. Detail regarding piping and valves that did not form part of the main flow path during normal operation, were also removed. Figure 30 indicates the simplified network.

The simplified network was deemed to be representative of the PBMR PCU. The analysis was not intended to provide a comprehensive review of the PBMR PCU, but rather, it was intended to highlight the most important areas that can affect steady state performance of thermo-hydraulic networks similar to the PBMR network. The objective of the study was twofold:

- Firstly, the purpose was to list the factors that are likely to vary, or are uncertain at present, and determine which parameters the network is most sensitive to.
- Secondly, the purpose of the Monte-Carlo simulation was to give an indication of the kind of variation that can be expected in key system parameters.

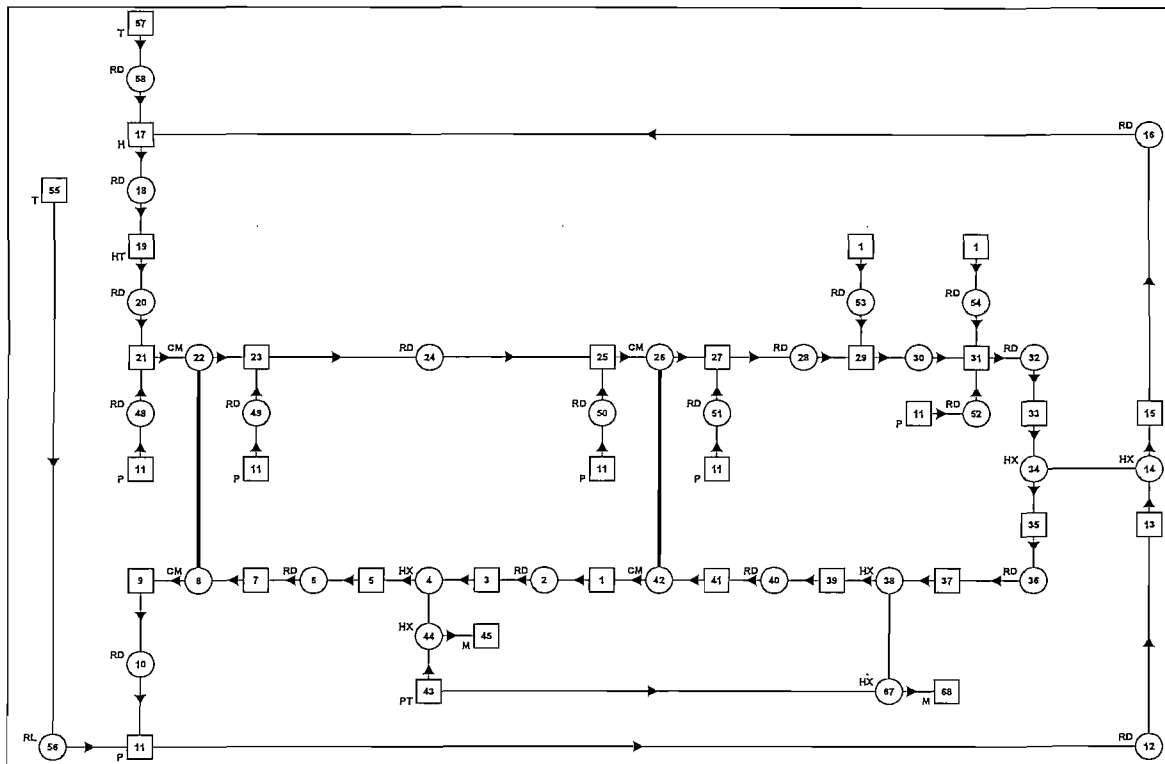


Figure 30: A layout of the simplified network

The first part of the May 2002 study, which considered individual sensitivities, will be ignored altogether in the results validation. The second part, which is the Monte Carlo analysis, will be used. The output parameters of this study will be compared to similar parameters of the May 2002 study, namely the turbo unit rotational speeds, compressor surge margins, grid power and cycle efficiency. Other parameters were recoded, but these are not of interest for validation purposes.

5.2.2 Similarities and Differences

The study in described in this document is in essence a repeat of the May 2002 study, noting the following differences that had to be checked:

- The May 2002 study considered only the 100% MCR 100% MCRI case, which is similar to Case A described earlier. The latest study checked the limits of the operating envelope (Case A to Case D).
- As was said earlier, the simplified model's reactor was operated at maximum 300MW thermal power, compared to 400MW for the four cases described earlier. This limit was however not enforced in the May 2002 study, for the same reason as in this study.

- The turbo machines in the May 2002 study used Alstom maps. The MHI turbo-machines maps have with different curvatures to the Alstom maps, due to different design philosophies employed by these companies. This can cause a significant difference when comparing the results for validation purposes.
- The May 2002 study did not calculate the grid power of the cycle efficiency values. These values will therefore not be compared between the two studies.

This study also had similarities to the May 2002 study:

- All the parameters that were varied during the May 2002 study were also assumed to be capable of varying independently of each other. (Refer to the limitations stated in section 4.6.)
- Any effects that exhibit auto-correlation have been neglected in the May 2002 study. (Refer to the limitations stated in section 4.6.)

5.3 COMPARING RESULTS

5.3.1 Shaft Speed Results

The shaft speed results are compared in Table 18 and Table 19, while the May 2002 results are graphically illustrated in Figure 31 and Figure 32.

Table 18: HPTU Speed Results Comparison

	Nominal Speed [RPM]	Mean*	Lower Limit*	Upper Limit*	10% value*	90% value*
May 2002	11496	93.5%	84.0%	101.3%	90.2%	96.7%
Case A	6000	99.8%	95.5%	104.1%	98.0%	101.5%
Difference	N/A	6.3%	11.5%	2.8%	7.8%	4.8%

*Percentage of Nominal Speed

Table 19: LPTU Speed Results Comparison

	Nominal Speed [RPM]	Mean*	Lower Limit*	Upper Limit*	10% value*	90% value*
May 2002	11244	89.4%	78.4%	104.6%	84.4%	95.2%
Case A	7000	99.7%	92.7%	106.9%	97.3%	102.3%
Difference	N/A	10.3%	14.3%	2.3%	12.9%	7.1%

*Percentage of Nominal Speed

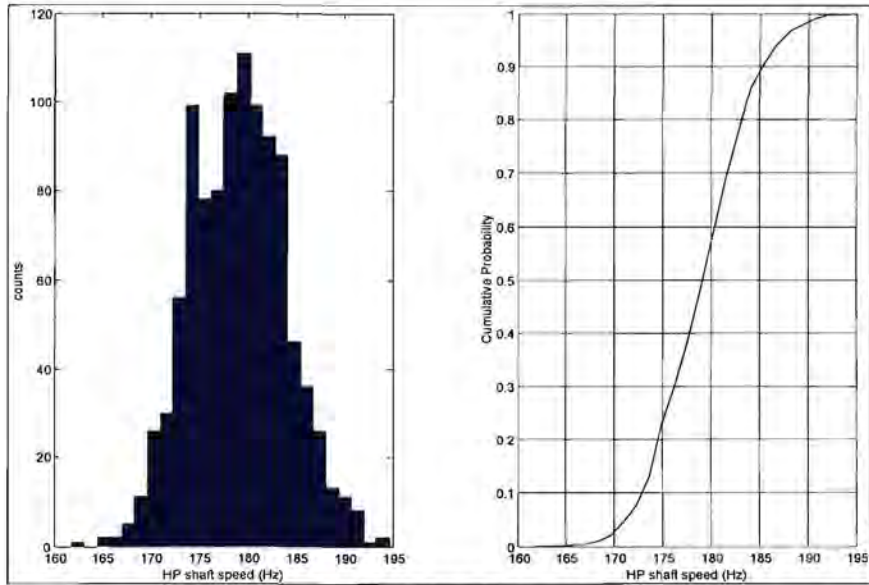


Figure 31: HPTU Shaft Speed Results

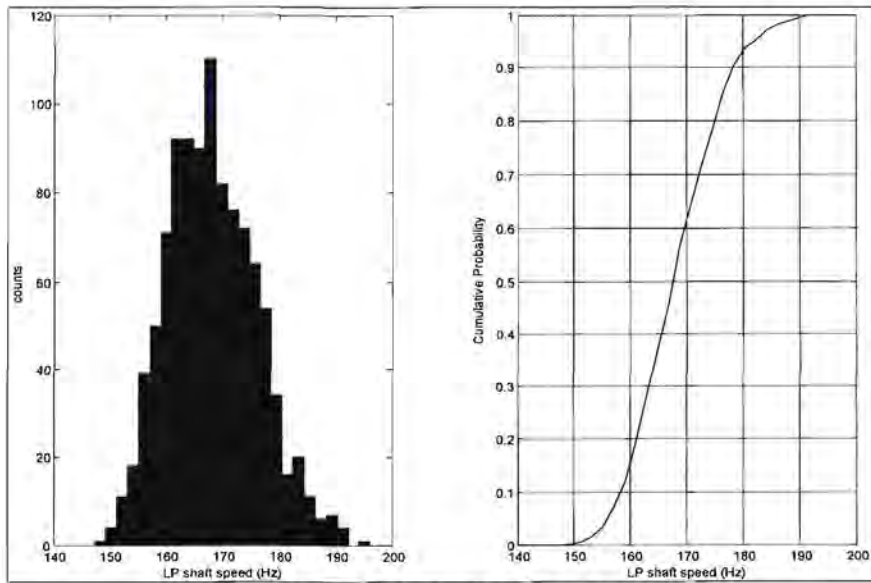


Figure 32: LPTU Shaft Speed Results

From the above comparison, it can be seen that the nominal speed of both the HPTU and LPTU differ substantially in the two studies. However, it is noted that the HPTU has in both cases the smaller speed range variation when compared to the LPTU. These values indicate a good correlation between the two studies, considering the substantial differences between the two turbo machine models, the largest difference being 14.3% for the lower limit of the LPTU speed.

5.3.2 Compressor Surge Margins

The compressor surge margin results are compared in Table 20 and Table 21, while the May 2002 results are graphically illustrated in Figure 33 and Figure 34.

Table 20: HPC Surge Margin Results Comparison

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
May 2002	12.6%	11.8%	7.7%	14.7%	10.1%	13.2%
Case A	11.7%	11.2%	7.7%	14.2%	9.7%	12.6%
Difference	-0.9	-0.6	0.0	-0.5	-0.4	-0.6

Although the HPC run at quite different speeds in the two studies, the results obtained for the HPC surge margin compare almost exactly. The compressors have the same surge margin and are found to behave the same in both Monte Carlo studies. The variation found from the 10% to the 90% values in Case A is smaller than the variation found in the May 2002 study (Compare $13.2\% - 10.1\% = 3.1\%$ to $12.6\% - 9.7\% = 2.9\%$). This can be attributed to a slight difference in angle of the speed lines of the compressor map, as well as the shape of the surge line near the operating region.

Table 21: LPC Surge Margin Results Comparison

	Nominal Value	Mean	Lower Limit	Upper Limit	10% value	90% value
May 2002	8.6%	2.9%	-4.4%	12.5%	-0.5%	6.6%
Case A	11.2%	10.9%	5.6%	15.2%	8.9%	12.8%
Difference	2.6%	8.0%	10.0%	2.7%	9.4%	6.2%

Again, there is a difference in the running speeds of the LPC in both studies. Larger differences were found for the LPC than the HPC. The negative values found in the previous study indicate that the LPC is surging, which is not a valid operating point for a compressor.

The surge margin of the LPC in the previous study was too small. The supplier of the Case A LPC, took notice of this and increased the surge margin on the LPC. The Case A

study indicates that the LPC is not surging, although the lower limit is still below the surge margin limit set by the supplier.

The May 2002 study also found the variation in the LPC surge margin to be larger when compared to the HPC. The LPC is therefore more prone to surging than the HPC in both studies, which indicates a good correlation. The variation between the 10% and 90% values also got smaller in the Case A study (compare $12.8\% - 8.9\% = 3.1\%$ to $6.6\% - (-0.5\%) = 7.1\%$). Again this can be attributed to different angles in speed lines, as well as a change in surge line shape near the operating region.

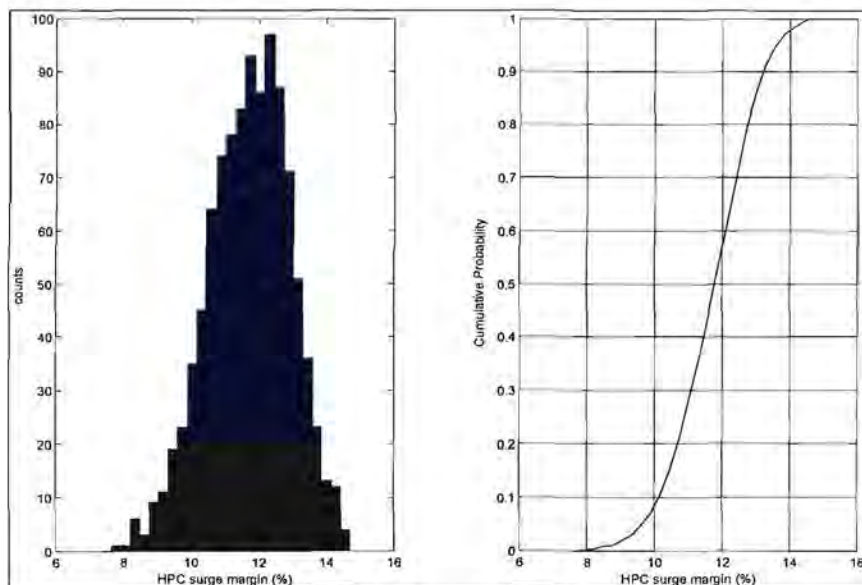


Figure 33: HPC Surge Margin Results

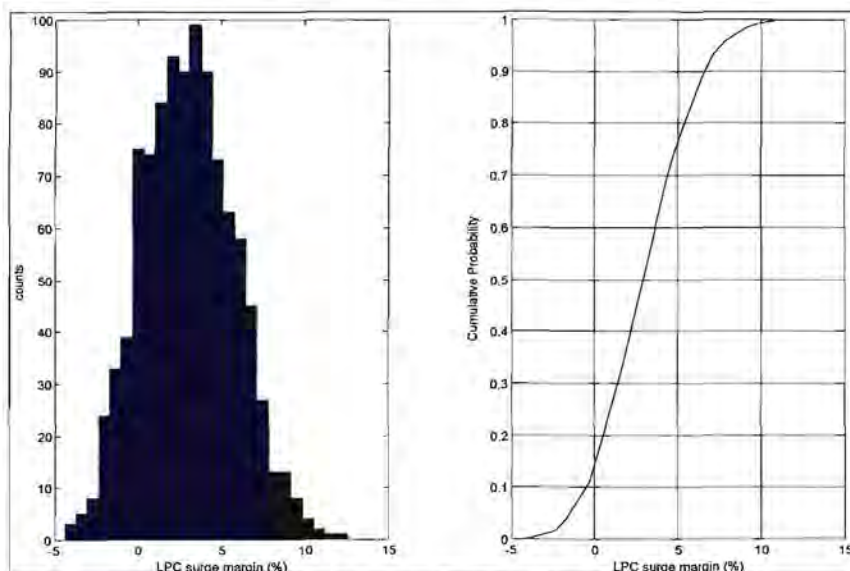


Figure 34: LPC Surge Margin Results

5.4 CONCLUSION

This chapter compares the results of this study to the May 2002 study done on the PBMR plant. The differences and similarities between the two studies with regards to absolute values (300MW maximum reactor power versus 400MW maximum reactor power) and model detail were pointed out.

Considering the differences, the HPTU and LPTU shaft speed results were found to be fairly similar and the same tendencies were found. The HPTU speed variation is less than the LPTU speed variation in both cases. Although the allowable speed range limitation was not imposed on the Alstom machines, it also ran close to the 80% - 105% of nominal speed range.

The surge margins of the HPC and LPC also indicate the same tendencies in both studies. The variation in the LPC surge margin is larger than the HPC surge margin. The LPC would therefore be more prone to surging and this should be taken into account when designing these machines.

The grid power and cycle efficiency was not part of the May 2002 study and the results could thus not be compared. However, the good correlations between the studies found for the shaft speed and surge margin results, provide sufficient confidence that the results of the present study is acceptable.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This study looked at the uncertainty of the rotational speed of the turbo units, compressor surge margins, grid power and cycle efficiency as a means to gaining an understanding of the variation that can be expected in these parameters. Engineering judgement was used in selecting the input parameters. The nominal values of these input parameters will change as the design of the PBMR plant matures. The input variations chosen around these input parameters were mostly larger than would be realistically expected, attempting to force the results outside the allowed operating limits.

The shaft speed results revealed that both the HPTU and LPTU operated within the specified operating range of 80% to 105% of nominal design speed for steady state operation for all the cases analysed.

The surge margin results indicate that the LPC is more prone to surging than the HPC, since it has a larger variation. The 10% probability value of the LPC surge margin was found to be below the minimum surge margin value specified by the supplier. Therefore, the surge margin of the LPC has to be increased to move the operating point to the allowable operating region.

The grid power and cycle efficiency results indicate variations that where the mean value coincide very closely with the nominal value for all the cases analysed. This gives confidence in the nominal results. It also demonstrates the robustness of the plant design, since the fairly large input variations could not significantly shift the mean value from the nominal value.

In conclusion it can be said that the problem stated at the outset of the study was addressed sufficiently. An understanding of the expected operating ranges was gained and a deficiency in the LPC surge margin could be pointed out. The PBMR plant design has been proven to be a fairly robust design and the confidence in the thermo-hydraulic modelling has been enhanced a great deal.

Abbreviated results obtained from this study were included in the proceedings of the HTR 2004 conference in Beijing, China. It is contained in paper D09 and was presented by the author, a privilege made possible by PBMR [50].

It should be noted that PBMR recently changed the three-shaft turbo machine layout to a single shaft layout. In doing so, the uncertainty regarding the shaft speeds of the turbo machines is greatly reduced, since the single shaft machine will run at a constant speed, only deviating in transient operation. The uncertainty regarding the surge margin, grid power and cycle efficiency found in this study, would still apply.

6.2 RECOMMENDATIONS FOR FURTHER WORK

The study can be refined by introducing the physical limits of the reactor power output (never more than 400MW_{th}). This will require modifications to the Matlab code to check the reactor power output of each run and adjust the inputs for that run accordingly.

This study should be repeated on the expected plant transients, like the start-up, PCU trip and loss of load. The variations obtained in this fashion should be checked against existing limits for acceptability.

It should be possible to introduce a weighing scheme to the results so that "time" could be included in the Monte Carlo simulations. This will make it possible to produce distributions to encapsulate the six-year lifetime of the turbines. The weighing scheme will thus be based on an equivalent number of runs for the time spent in a particular mode or state during the six-year period. Physical properties such as the deterioration in the efficiency of the turbo machines over time can also be included.

No distinction between design uncertainty and manufacturing uncertainty was made during these simulations. Also, some of the variations, like the variation in loss factor for the intakes and diffusers, were chosen wide because of the amount of uncertainty in the value itself. These variations should be narrowed down in future simulations. Consultation with the suppliers on variation should be done in order to do a realistic refinement.

In the analyses described in this document, the nominal value for cooling water temperature was taken the same as the design value, which is 18°C. In future simulations, the actual nominal value at the plant location should be used. At Koeberg, this would then imply approximately 16°C.

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APPENDICES

A. MONTE ANALYSIS RESULTS GRAPHS

A.1 SHAFT SPEED RESULTS

The shaft speed results are indicated as a percentage of nominal speed. The first set of figures display the HPTU results and is followed by the results of the LPTU.

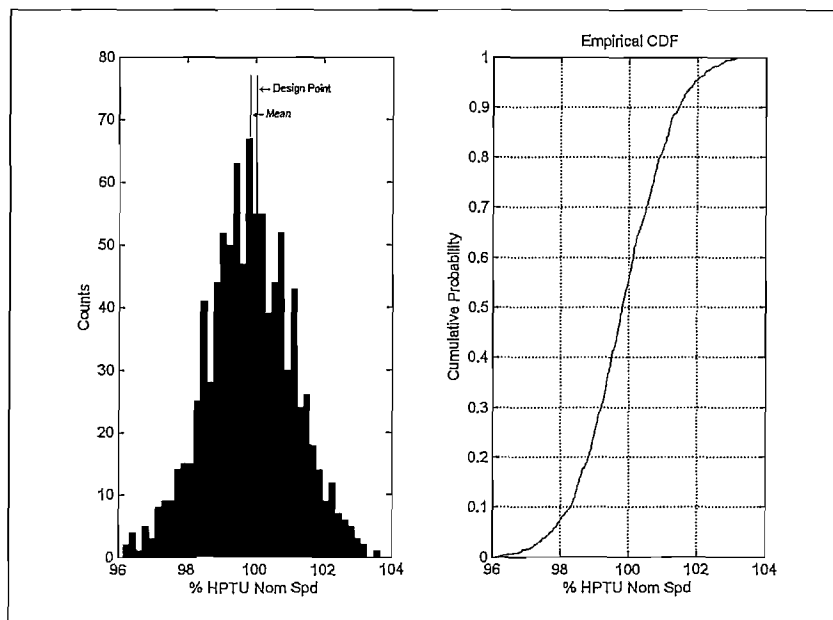


Figure 35: HPTU % of Nominal Design Speed (Case B)

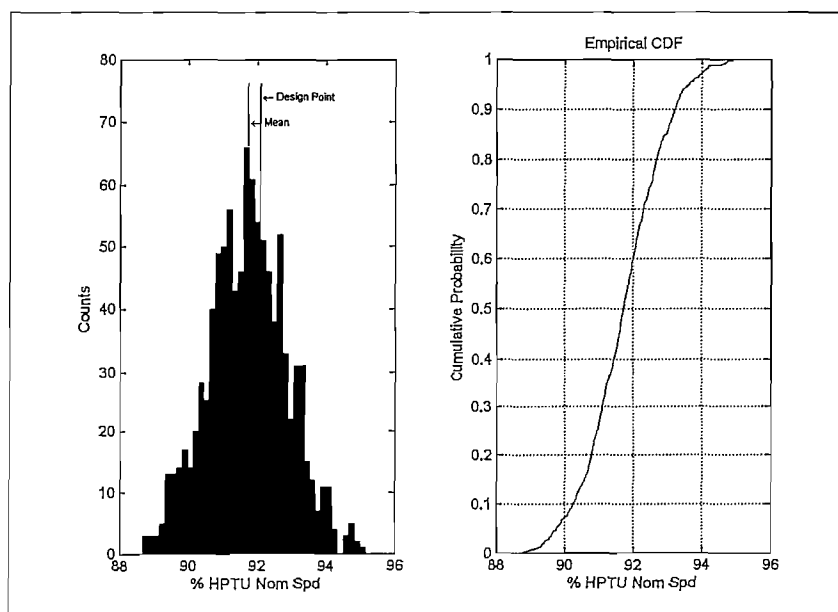


Figure 36: HPTU % of Nominal Design Speed (Case C)

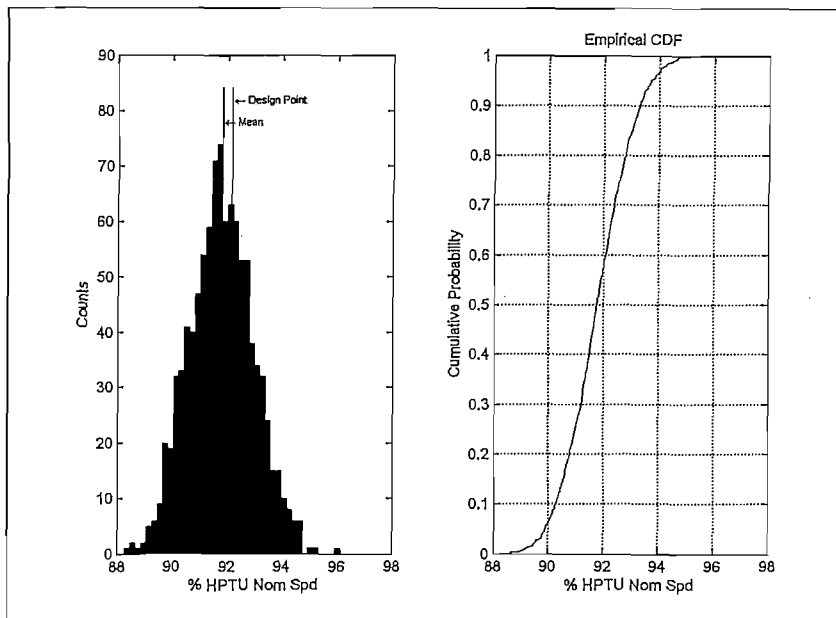


Figure 37: HPTU % of Nominal Design Speed (Case D)

The next set of figures displays the values for the LPTU:

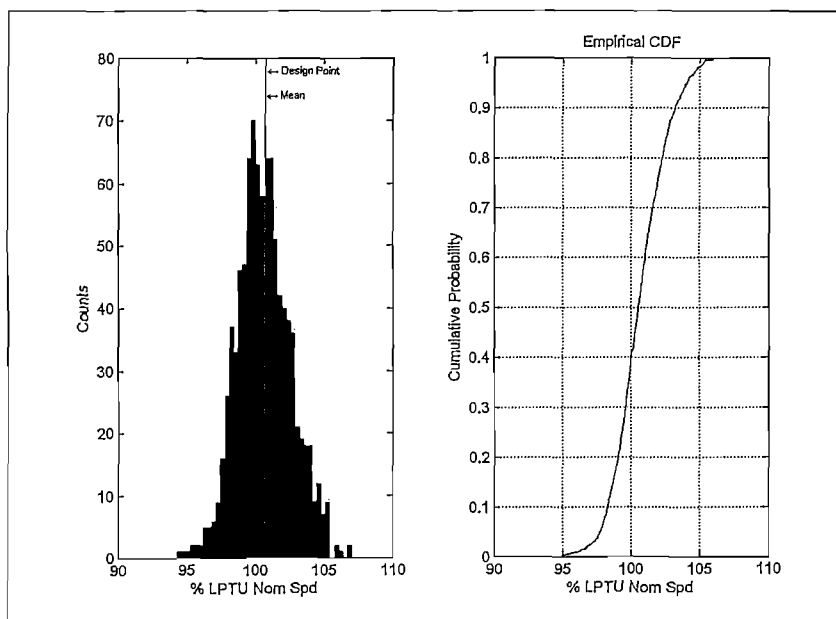


Figure 38: LPTU % of Nominal Design Speed (Case B)

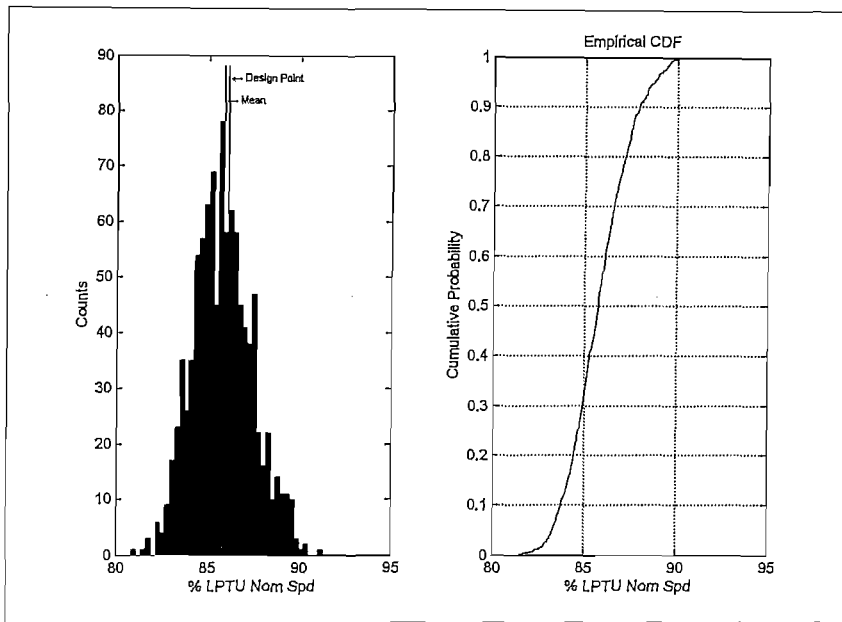


Figure 39: LPTU % of Nominal Design Speed (Case C)

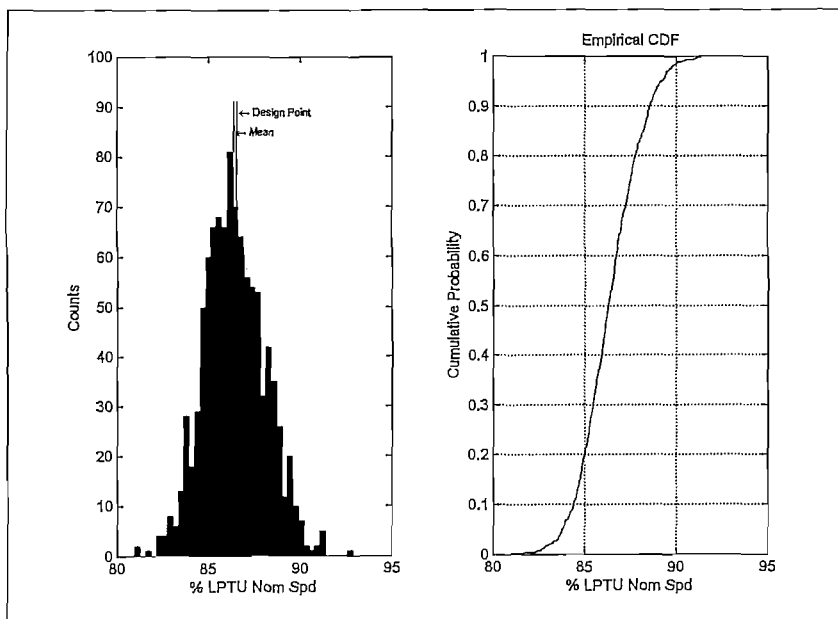


Figure 40: LPTU % of Nominal Design Speed (Case D)

A.2 COMPRESSOR SURGE MARGINS

The compressor surge margin results are indicated in the figures below. The first set displays the results for the HPC and is followed by the results of the LPC.

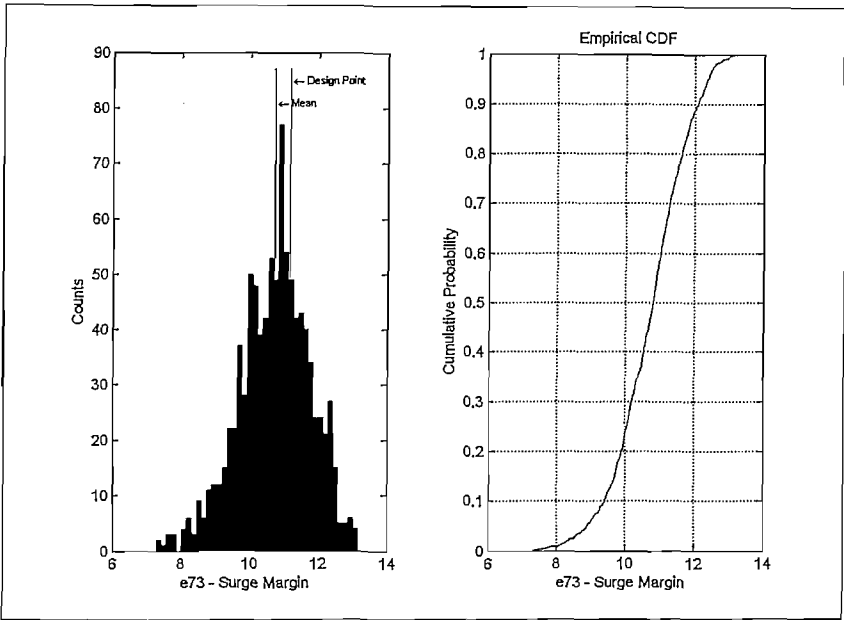


Figure 41: HPC Surge Margin (Case B)

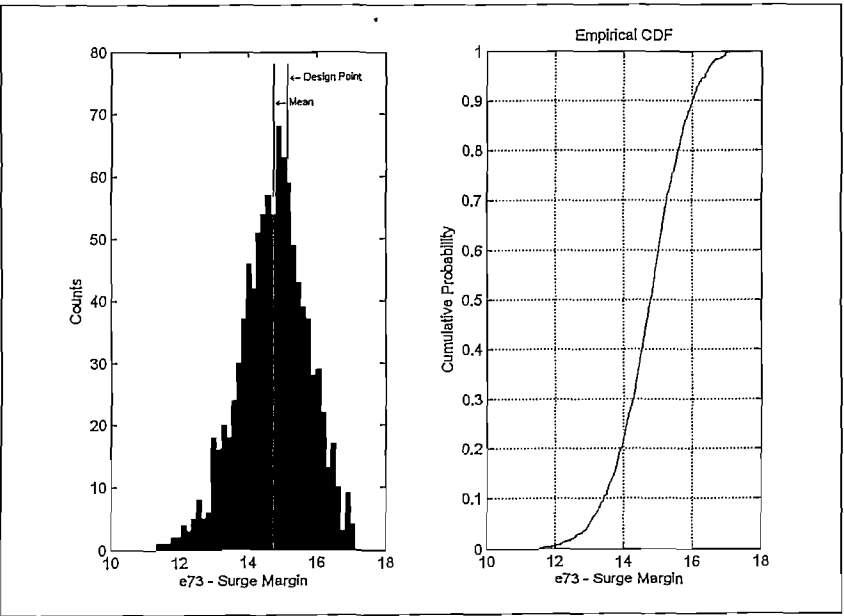


Figure 42: HPC Surge Margin (Case C)

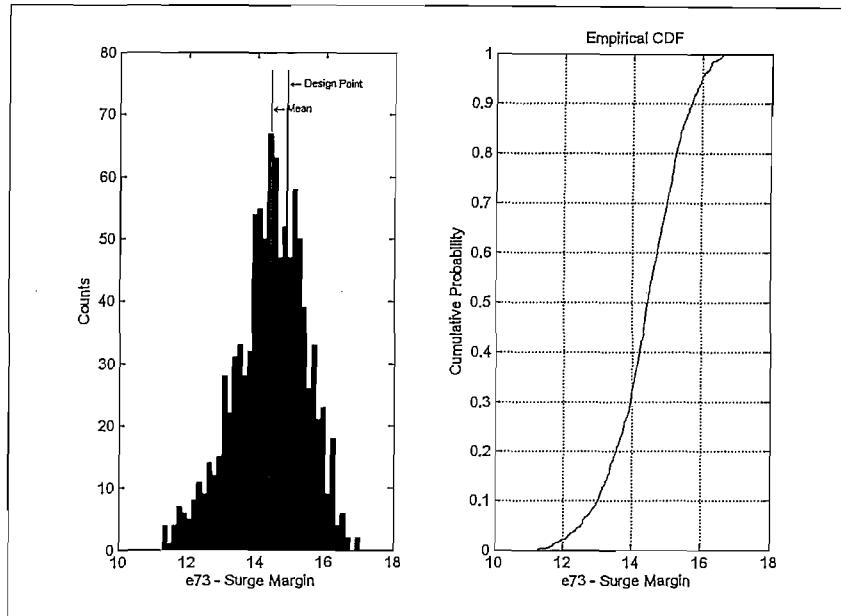


Figure 43: HPC Surge Margin (Case D)

The following set of figures indicates the LPC Surge Margin results:

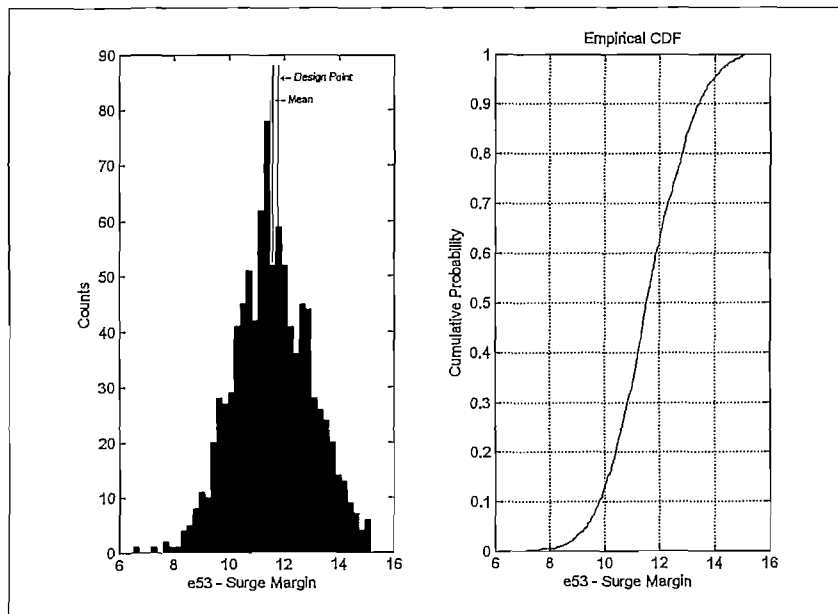


Figure 44: LPC Surge Margin (Case B)

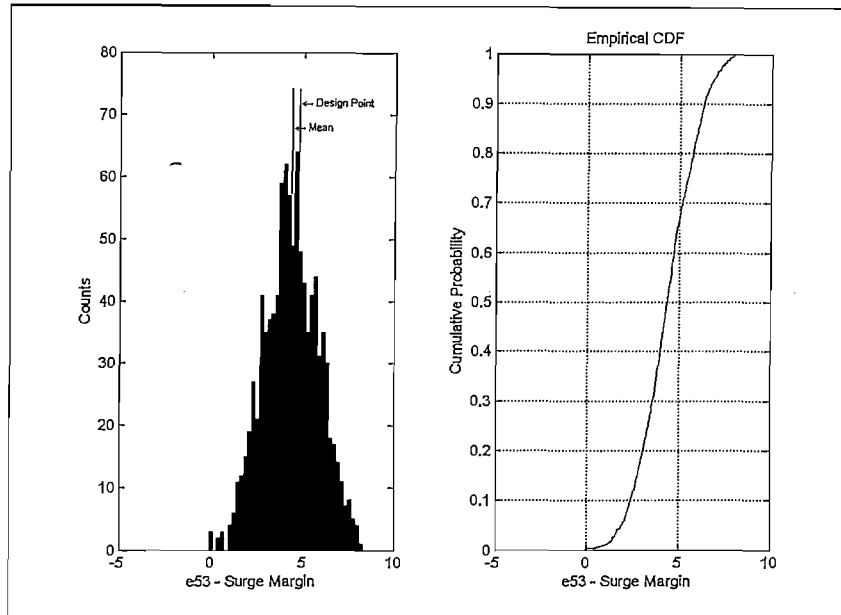


Figure 45: LPC Surge Margin (Case C)

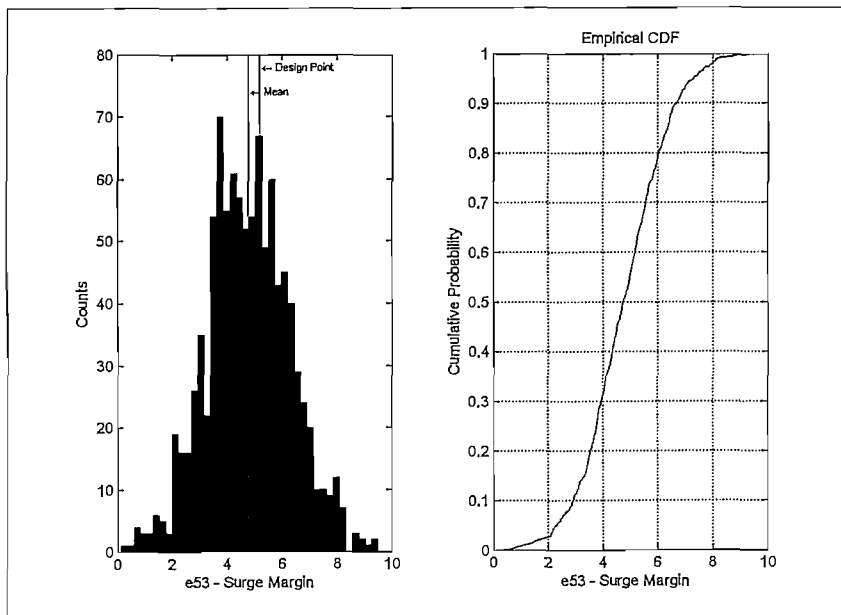


Figure 46: LPC Surge Margin (Case D)

A.3 GRID POWER RESULTS

The grid power is calculated using equation (4.1). The results for Case B to Case D are shown below.

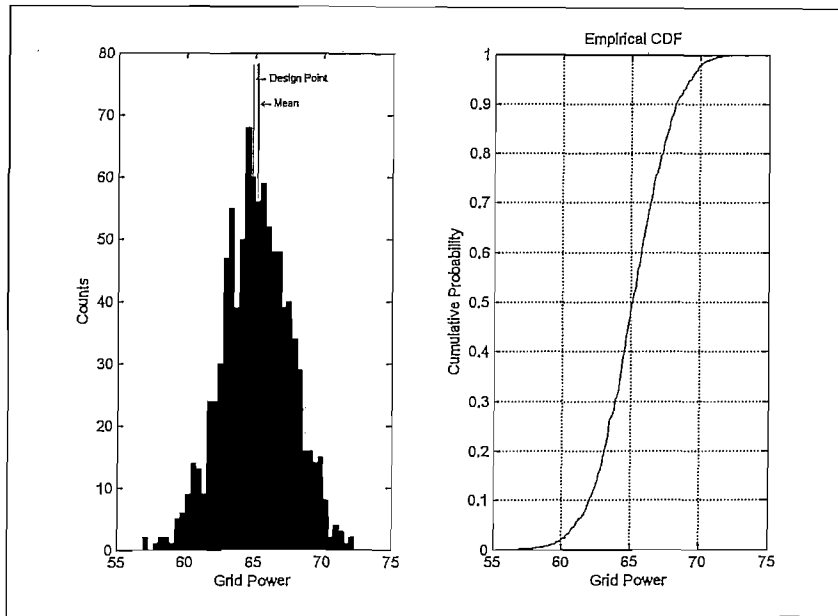


Figure 47: Grid Power (Case B)

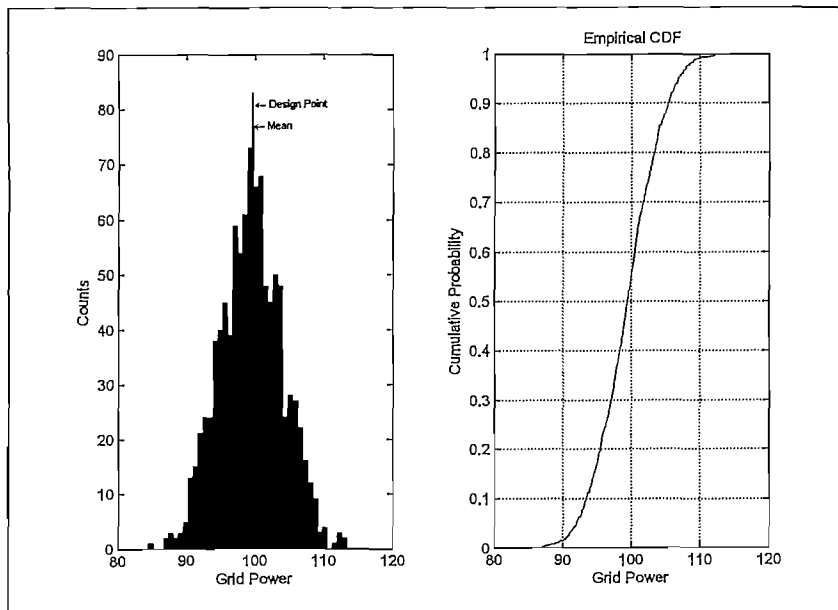


Figure 48: Grid Power (Case C)

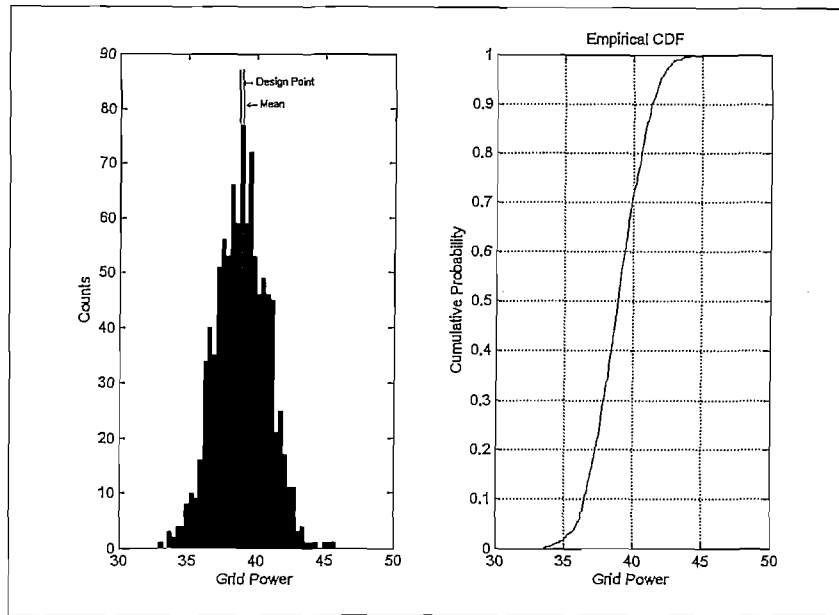


Figure 49: Grid Power (Case D)

A.4 CYCLE EFFICIENCY RESULTS

The grid power is calculated using equation (4.2). The results for Case B to Case D are shown below.

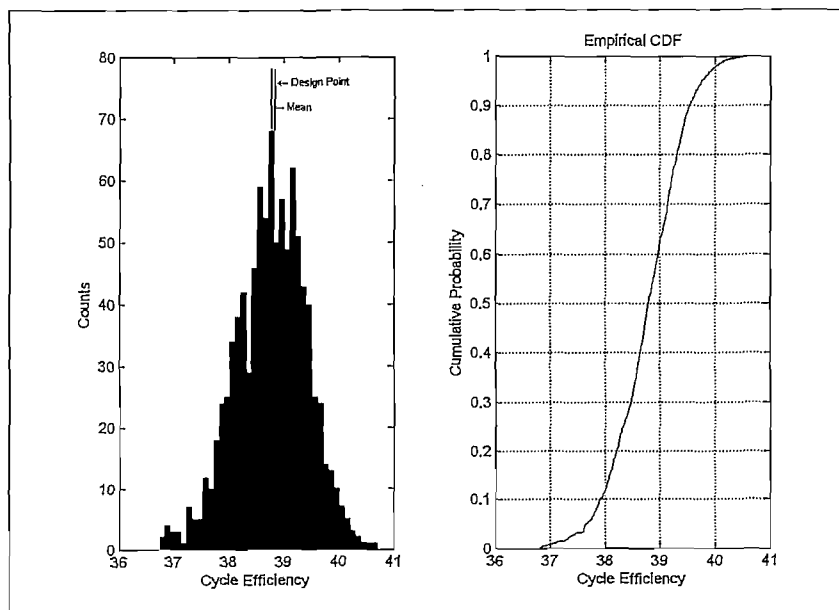


Figure 50: Cycle Efficiency (Case B)

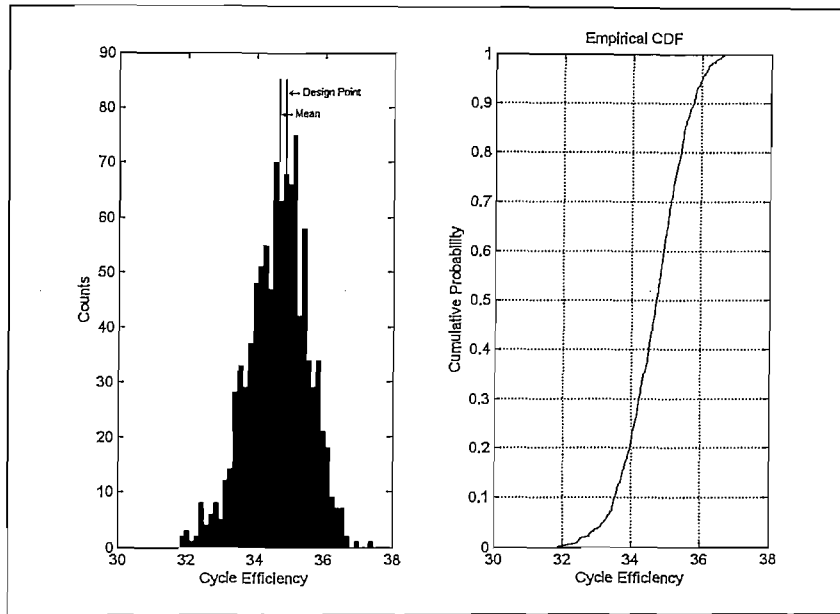


Figure 51: Cycle Efficiency (Case C)

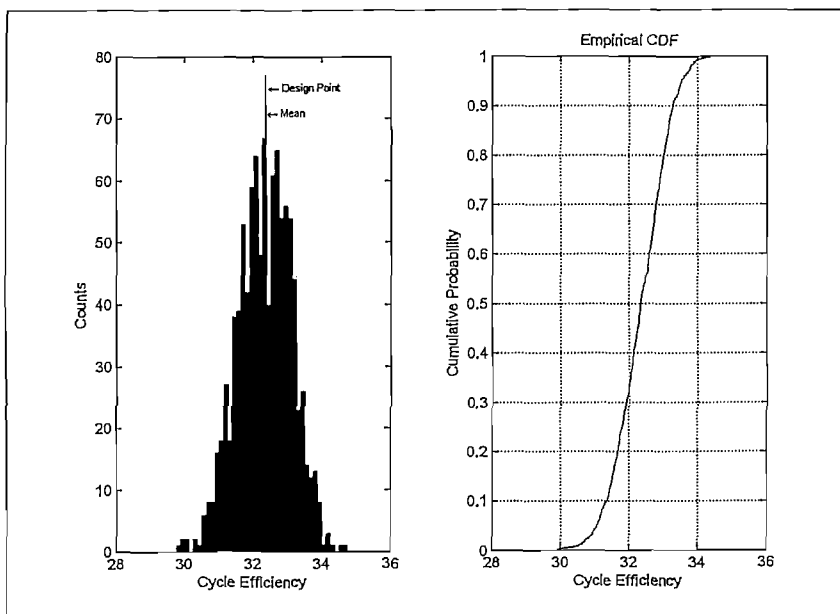


Figure 52: Cycle Efficiency (Case D)

B. DOUBLE TRI-ANGULAR DISTRIBUTIONS

The PDF and CDF for a double triangular distribution is described in Figure 53:

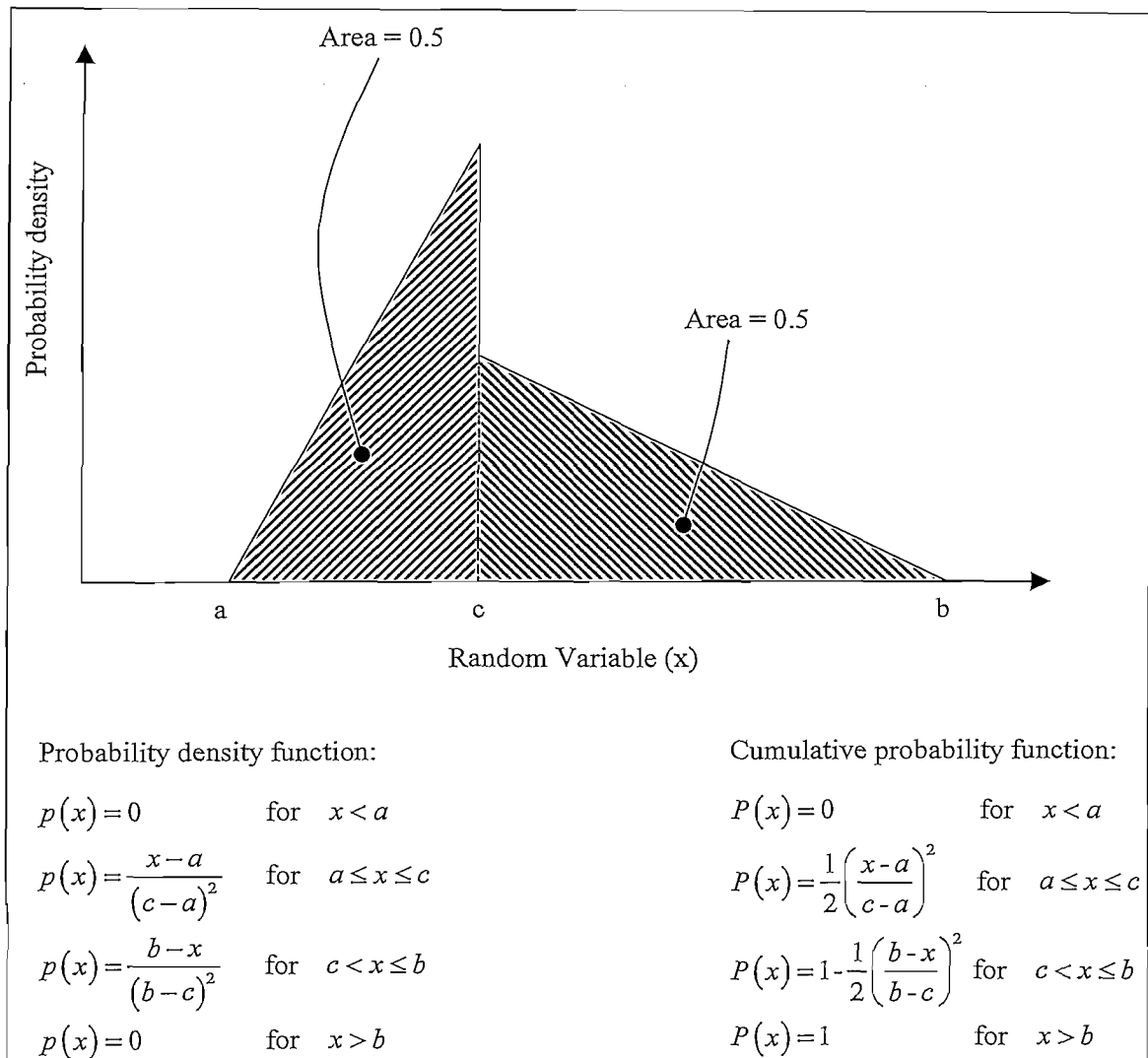


Figure 53: The definition of the triangular probability density function.

C. FLOWNEX ANALYSER INPUT SPREADSHEETS

C.1 INPUT FOR CASE A

The inputs for Case A were as follows:

LOOKUP TABLE											
Parameter	Node(0)/Element(1)	Number	Field Number	Sensitivity			MonteCarlo				
				Low Value	Nom Value	High Value	Low Value	Mid Value	High Value	Distribution	Runs
1	1	150	9				0.4839084	0.537676	0.806514	1	1000
2	1	11	9				0.2752362	0.305818	0.458727	1	
3	1	133	2				0.025011249	0.025661	0.028110217	1	
4	1	113	2				0.031070831	0.031878	0.034920599	1	
5	1	9	104				0.978951	0.989773	1.000602	1	
6	1	9	106				0.97	1	1.01	1	
7	1	152	9				0.412155	0.45795	0.686925	1	
8	1	19	9				0.2443338	0.271482	0.407223	1	
9	1	182	2				0.018054962	0.018524	0.020292025	1	
10	1	116	2				0.028446019	0.029185	0.031970566	1	
11	1	17	104				0.981456	0.992773	1.004089	1	
12	1	17	106				0.97	1	1.01	1	
13	1	27	9				1.4785938	1.642882	2.464323	1	
14	1	33	9				0.1650168	0.183352	0.275028	1	
15	1	3874	2				0.013472994	0.013823	0.015142338	1	
16	1	3875	2				0.017438964	0.017892	0.019599704	1	
17	1	29	104				0.977482	0.988296	0.999112	1	
18	1	29	106				0.97	1	1.01	1	
19	1	39	7				14267.105	28534.21	42801.315	1	
20	1	39	13				10.6911	11.879	13.0669	1	
21	1	39	14				10.6911	11.879	13.0669	1	
22	1	39	21				3.2058	3.562	3.9182	1	
23	1	39	22				3.2058	3.562	3.9182	1	
24	1	158	9				1.512	1.68	1.848	1	
25	1	3899	2				0.00036	0.0004	0.00044	2	
26	1	41	6				2660.41	5320.82	7981.23	1	
27	1	41	11				29.7981	33.109	36.4199	1	
28	1	43	6				2304.605	4609.21	6913.815	1	
29	1	43	11				17.289	19.21	21.131	1	
30	1	51	9				0.258849	0.28761	0.431415	1	
31	1	55	9				2.2409784	2.489976	3.734964	1	
32	1	183	2				0.021457568	0.022015	0.024116224	1	
33	1	53	104				0.968203	0.984714	1.00135	1	
34	1	53	106				0.97	1	1.01	1	
35	1	61	6				2660.41	5320.82	7981.23	1	
36	1	61	11				29.7981	33.109	36.4199	1	
37	1	63	6				2304.605	4609.21	6913.815	1	
38	1	63	11				17.289	19.21	21.131	1	
39	1	71	9				0.3112164	0.345796	0.518694	1	
40	1	75	9				1.6272396	1.808044	2.712066	1	
41	1	181	2				0.018501365	0.018982	0.020793739	1	
42	1	73	104				0.96813	0.984777	1.001299	1	
43	1	73	106				0.97	1	1.01	1	
44	1	1	13				9.141	11	12.925	2	
45	1	1826	2				0.10218	0.1474	0.184367	3	
46	1	3828	9				1.7	2	2.3	3	
47	1	1	19				1218.450197	1234.6454	1250.836404	3	
48	0	78	2				8991000	9000000	9009000	3	
49	0	99	4				287.25	291.15	291.35	3	

C.2 INPUT FOR CASE B

The inputs for Case B were as follows:

LOOKUP TABLE										
Parameter	Node(0)/Element(1)	Number	Field Number	Sensitivity			MonteCarlo			Runs
				Low Value	Nom Value	High Value	Low Value	Mid Value	High Value	
1	1	150	9				0.4839084	0.537676	0.806514	1000
2	1	11	9				0.2752362	0.305818	0.458727	1
3	1	133	2				0.025011249	0.025661	0.028110217	1
4	1	113	2				0.031070831	0.031878	0.034920599	1
5	1	9	104				0.978951	0.989773	1.000602	1
6	1	9	106				0.97	1	1.01	1
7	1	152	9				0.412155	0.45795	0.688925	1
8	1	19	9				0.2443338	0.271482	0.407223	1
9	1	182	2				0.018054962	0.018524	0.020292025	1
10	1	116	2				0.028446019	0.029185	0.031970566	1
11	1	17	104				0.981456	0.992773	1.004089	1
12	1	17	106				0.97	1	1.01	1
13	1	27	9				1.4785938	1.642882	2.464323	1
14	1	33	9				0.1650168	0.183352	0.275028	1
15	1	3874	2				0.013472994	0.013823	0.015142338	1
16	1	3875	2				0.017438964	0.017892	0.019599704	1
17	1	29	104				0.977482	0.988296	0.999112	1
18	1	29	106				0.97	1	1.01	1
19	1	39	7				14267.105	28534.21	42801.315	1
20	1	39	13				10.6911	11.879	13.0669	1
21	1	39	14				10.6911	11.879	13.0669	1
22	1	39	21				3.2058	3.562	3.9182	1
23	1	39	22				3.2058	3.562	3.9182	1
24	1	158	9				1.512	1.68	1.848	1
25	1	3899	2				0.00036	0.0004	0.00044	2
26	1	41	6				2660.41	5320.82	7981.23	1
27	1	41	11				29.7981	33.109	36.4199	1
28	1	43	6				2304.605	4609.21	6913.815	1
29	1	43	11				17.289	19.21	21.131	1
30	1	51	9				0.258849	0.28761	0.431415	1
31	1	55	9				2.2409784	2.489976	3.734964	1
32	1	183	2				0.021457568	0.022015	0.024116224	1
33	1	53	104				0.968203	0.984714	1.00135	1
34	1	53	106				0.97	1	1.01	1
35	1	61	6				2660.41	5320.82	7981.23	1
36	1	61	11				29.7981	33.109	36.4199	1
37	1	63	6				2304.605	4609.21	6913.815	1
38	1	63	11				17.289	19.21	21.131	1
39	1	71	9				0.3112164	0.345796	0.518694	1
40	1	75	9				1.6272396	1.808044	2.712066	1
41	1	181	2				0.018501365	0.018982	0.020793739	1
42	1	73	104				0.96813	0.984777	1.001299	1
43	1	73	106				0.97	1	1.01	1
44	1	1	13				9.141	11	12.925	2
45	1	1826	2				0.10218	0.1474	0.184367	3
46	1	3828	9				1.7	2	2.3	3
47	1	1	19				1221.162752	1238.1484	1255.179237	3
48	0	79	2				3615693.356	3652215.5	3688737.666	3
49	0	99	4				287.25	291.15	291.35	3

C.3 INPUT FOR CASE C

The inputs for Case C were as follows:

LOOKUP TABLE										
Parameter	Node(0)/Element(1)	Number	Field Number	Sensitivity			MonteCarlo			
				Low Value	Nom Value	High Value	Low Value	Mid Value	High Value	Runs
1	1	150	9				0.4839084	0.537676	0.806514	1000
2	1	11	9				0.2752362	0.305818	0.458727	1
3	1	133	2				0.025011249	0.025661	0.028110217	1
4	1	113	2				0.031070831	0.031878	0.034920599	1
5	1	9	104				0.978951	0.989773	1.000602	1
6	1	9	106				0.97	1	1.01	1
7	1	152	9				0.412155	0.45795	0.686925	1
8	1	19	9				0.2443338	0.271482	0.407223	1
9	1	182	2				0.018054962	0.018524	0.020292025	1
10	1	116	2				0.028446019	0.029185	0.031970566	1
11	1	17	104				0.981456	0.992773	1.004089	1
12	1	17	106				0.97	1	1.01	1
13	1	27	9				1.4785938	1.642882	2.464323	1
14	1	33	9				0.1650168	0.183352	0.275028	1
15	1	3874	2				0.013472994	0.013823	0.015142338	1
16	1	3875	2				0.017438964	0.017892	0.019599704	1
17	1	29	104				0.977482	0.988296	0.999112	1
18	1	29	106				0.97	1	1.01	1
19	1	39	7				14267.105	28534.21	42801.315	1
20	1	39	13				10.6911	11.879	13.0669	1
21	1	39	14				10.6911	11.879	13.0669	1
22	1	39	21				3.2058	3.562	3.9182	1
23	1	39	22				3.2058	3.562	3.9182	1
24	1	158	9				1.512	1.68	1.848	1
25	1	3899	2				0.00036	0.0004	0.00044	2
26	1	41	6				2660.41	5320.82	7981.23	1
27	1	41	11				29.7981	33.109	36.4199	1
28	1	43	6				2304.605	4609.21	6913.815	1
29	1	43	11				17.289	19.21	21.131	1
30	1	51	9				0.258849	0.28761	0.431415	1
31	1	55	9				2.2409784	2.489976	3.734964	1
32	1	183	2				0.021457568	0.022015	0.024116224	1
33	1	53	104				0.968203	0.984714	1.00135	1
34	1	53	106				0.97	1	1.01	1
35	1	61	6				2660.41	5320.82	7981.23	1
36	1	61	11				29.7981	33.109	36.4199	1
37	1	63	6				2304.605	4609.21	6913.815	1
38	1	63	11				17.289	19.21	21.131	1
39	1	71	9				0.3112164	0.345796	0.518694	1
40	1	75	9				1.6272396	1.808044	2.712066	1
41	1	181	2				0.018501365	0.018982	0.020793739	1
42	1	73	104				0.96813	0.984777	1.001299	1
43	1	73	106				0.97	1	1.01	1
44	1	1	13				9.141	11	12.925	2
45	1	1826	2				0.10218	0.1474	0.184367	3
46	1	3828	9				1.7	2	2.3	3
47	1	1	19				1050.497256	1067.1	1083.753095	3
48	0	78	2				8336826.694	8421037.1	8505247.436	3
49	0	99	4				287.25	291.15	291.35	3

C.4 INPUT FOR CASE D

The inputs for Case D were as follows:

LOOKUP TABLE										
Parameter	Node(0)/Element(1)	Number	Field Number	Sensitivity			MonteCarlo			Runs
				Low Value	Nom Value	High Value	Low Value	Mid Value	High Value	
1	1	150	9				0.4839084	0.537676	0.806514	1000
2	1	11	9				0.2752362	0.305818	0.458727	1
3	1	133	2				0.025011249	0.025661	0.028110217	1
4	1	113	2				0.031070831	0.031878	0.034920599	1
5	1	9	104				0.978951	0.989773	1.000602	1
6	1	9	106				0.97	1	1.01	1
7	1	152	9				0.412155	0.45795	0.686925	1
8	1	19	9				0.2443338	0.271482	0.407223	1
9	1	182	2				0.018054962	0.018524	0.020292025	1
10	1	116	2				0.028446019	0.029185	0.031970566	1
11	1	17	104				0.981456	0.992773	1.004089	1
12	1	17	106				0.97	1	1.01	1
13	1	27	9				1.4785938	1.642882	2.464323	1
14	1	33	9				0.1650168	0.183352	0.275028	1
15	1	3874	2				0.013472994	0.013823	0.015142338	1
16	1	3875	2				0.017438964	0.017892	0.019599704	1
17	1	29	104				0.977482	0.988296	0.999112	1
18	1	29	106				0.97	1	1.01	1
19	1	39	7				14267.105	28534.21	42801.315	1
20	1	39	13				10.6911	11.879	13.0669	1
21	1	39	14				10.6911	11.879	13.0669	1
22	1	39	21				3.2058	3.562	3.9182	1
23	1	39	22				3.2058	3.562	3.9182	1
24	1	158	9				1.512	1.68	1.848	1
25	1	3899	2				0.00036	0.0004	0.00044	2
26	1	41	6				2660.41	5320.82	7981.23	1
27	1	41	11				29.7981	33.109	36.4199	1
28	1	43	6				2304.605	4609.21	6913.815	1
29	1	43	11				17.289	19.21	21.131	1
30	1	51	9				0.258849	0.28761	0.431415	1
31	1	55	9				2.2409784	2.489976	3.734964	1
32	1	183	2				0.021467568	0.022015	0.024116224	1
33	1	53	104				0.968203	0.984714	1.00135	1
34	1	53	106				0.97	1	1.01	1
35	1	61	6				2660.41	5320.82	7981.23	1
36	1	61	11				29.7981	33.109	36.4199	1
37	1	63	6				2304.605	4609.21	6913.815	1
38	1	63	11				17.289	19.21	21.131	1
39	1	71	9				0.3112164	0.345796	0.518694	1
40	1	75	9				1.6272396	1.808044	2.712066	1
41	1	181	2				0.018501365	0.018982	0.020793739	1
42	1	73	104				0.96813	0.984777	1.001299	1
43	1	73	106				0.97	1	1.01	1
44	1	1	13				9.141	11	12.925	2
45	1	1826	2				0.10218	0.1474	0.184367	3
46	1	3828	9				1.7	2	2.3	3
47	1	1	19				1052.625324	1069.3386	1086.132092	3
48	0	78	2				3385199.231	3419393.2	3453587.095	3
49	0	99	4				287.25	291.15	291.35	3

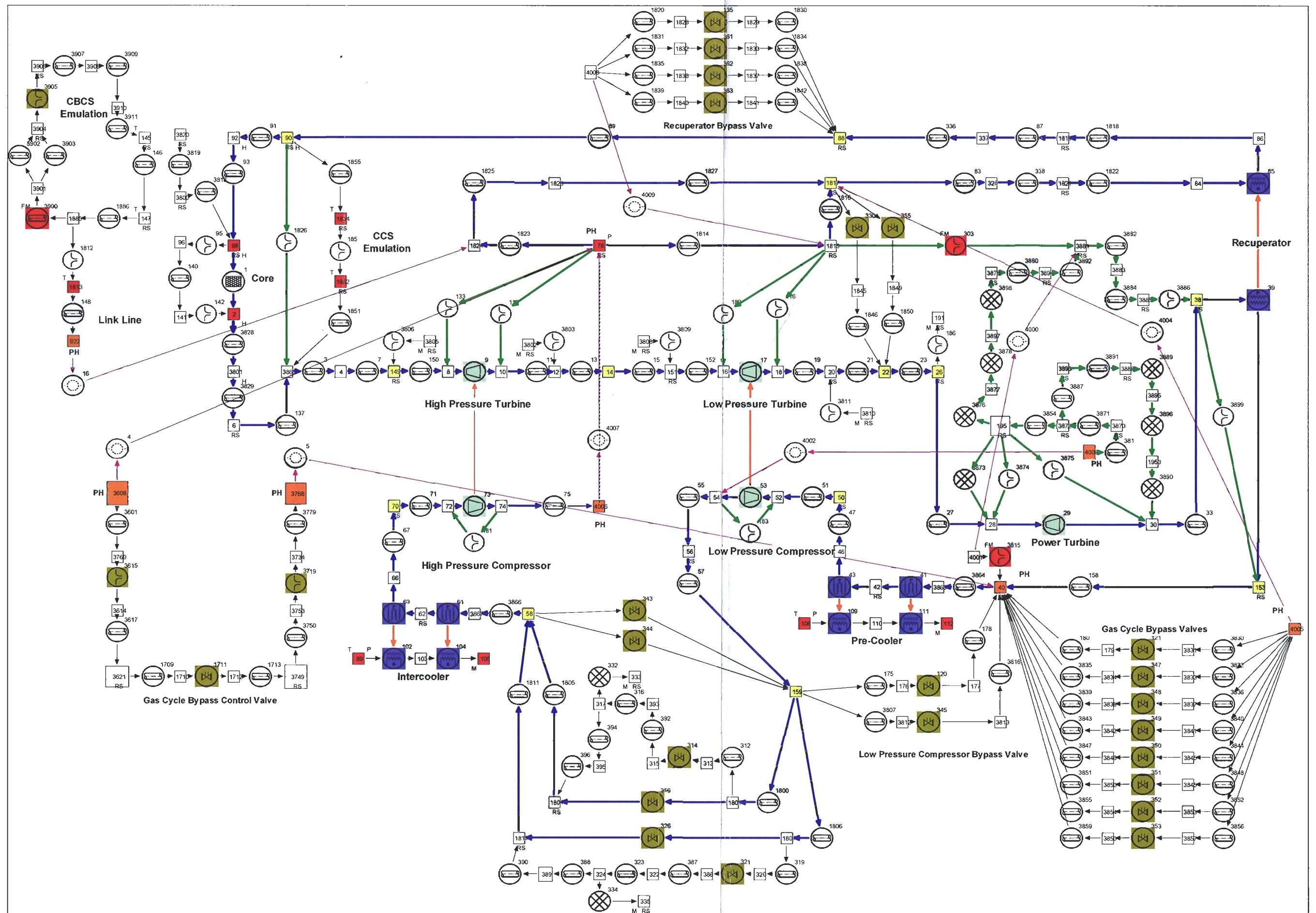


Figure 5: PBMR MPS Flownex model