# Techno-economic analysis of the 100 $MW_{th}$ Potchefstroom Experimental Pebble Bed Reactor plant

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# ABSTRACT

**TITLE:** Techno-economic analysis of the 100 $MW_{th}$ Potchefstroom Experimental Pebble Bed Reactor (PEPER) plant
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Electricity is directly linked to the economy of a country: when electricity is limited and the price for electricity is very high, the high electricity price will have a negative influence on the economy of the country. Owing to the increasing power shortage in the world, and South Africa in particular, today, the need for reliable and economical electricity has risen drastically.

The 100 $MW_{th}$ (40 $MW_e$) PEPER power plant is a possible alternative that will help fight the lack of reliable, clean and affordable electricity in the world today. Owing to the small consumption area of the PEPER power plant, each city, mine and industry, for example, can have its own PEPER power plant in order to ensure reliable, affordable and sustainable electricity.

This dissertation presents a case study and the relevant economic model for the PEPER power plant in order to determine whether the PEPER power plant may be considered as a possible electricity source. The production costs of the PEPER are presented in US$/kWh and compared with the industrial and household electricity costs (in US$/kWh) of various countries. This is done in order to determine whether it will be economically feasible to construct a First-of-a-kind (FOAK) or *N*th-of-a-kind (NOAK) PEPER power plant in the industrial and household sectors of a selected country.

In the economic model of the PEPER plant, the fixed capital investment costs for a FOAK PEPER plant were estimated to be US$367,199,411 and the fixed capital investment costs for a NOAK (eighth) PEPER plant were estimated to be US$238,429,665. The working capital for the first two years of the PEPER plant's lifetime was estimated to be US$17,228,740. The production cost of the PEPER plant was estimated to be 0.038 US$/kWh. The sensitivity analysis conducted demonstrated that FOAK PEPER plants could be established in countries in which the electricity income is 0.145 US$/kWh or more. NOAK PEPER plants (all the PEPER plants constructed after the eighth PEPER plant is erected) could be established in countries with an electricity income of 0.10 US$/kWh or more.

The PEPER plant presented here could be used:

1. as a training tool;
2. to test fuels and materials;
3. to accumulate high temperature nuclear data; and
4. as an electricity source for the industrial and household sectors of selected countries.

**Keywords: Electricity, PEPER power plant, reliable, affordable, production**

# OPSOMMING

**TITEL:** Tegno-ekonomiese analise van die Potchefstroomse Eksperimentele Korrelbed Reaktoraanleg (PEPER)
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Elektrisiteit en Ekonomie se interaktiewe verbintenis veroorsaak dat wanneer elektrisiteit skaars en die elektrisiteitsprys buitensporig hoog is, ’n land se ekonomie verswak. Die toenemende elektrisiteitstekort wat die wêreld, en veral Suid-Afrika, vandag in die gesig staar, het gelei tot ’n drastiese toename in die aanvraag na nuwe elektrisiteitsopwekkingsmetodes.

Die 100 MW$_{th}$ (40 MW$_e$) PEPER-kragaanleg kan egter as ’n moontlike bystandsopsie oorweeg word, ten einde die tekort aan skoon en bekostigbare elektrisiteit te beveg. Die PEPER-kragaanleg beslaan slegs ’n klein area, wat dit vir elke dorp, industrie en myn moontlik maak om sy eie PEPER-kragaanleg aan te koop. Dit verseker vir elkeen van hierdie sektore betroubare, bekostigbare en volhoubare elektrisiteit.

’n Voorlopige studie van die PEPER-kragaanleg sal opgestel word, saam met ’n relevante kostemodel, om te bepaal of die PEPER-kragaanleg in die toekoms as ’n moontlike bron van elektrisiteitsvoorsienings gebruik kan word. Die produksiekoste van die PEPER-kragaanleg sal na US$/kWh afgelei word, om dit met die elektrisiteitskostes in die huishoudelike en industriële sektore van geselekteerde lande te vergelyk. Hierdie vergelykings sal gemaak word, om te bepaal of ’n PEPER-kragaanleg in ’n geselekteerde land ekonomies opgerig kan word.

In die ekonomiese model van die PEPER-kragaanleg, word die vaste kapitaalbeleggingskoste van ’n eerste prototipe PEPER-kragaanleg beraam op US$367,199,411 en die vaste kapitaalbeleggingskoste van ’n agste PEPER-kragaanleg wat opgerig word, word beraam op US$238,429,665. Die lopende kapitaalkoste vir die eerste twee jaar van die PEPER-kragaanleg se leeftyd word beraam op US$17,228,740. Die produksiekoste van die PEPER-kragaanleg word beraam op 0.038 US$/kWh. Die sensitiwiteitsanalise wat in hierdie projek gedoen is, demonstreer dat die eerste PEPER-kragaanlegte opgerig kan word in lande wat ’n elektrisiteitsinkomste van 0.145 US$/kWh of meer het. PEPER-kragaanlegte wat na die agste PEPER-kragaanleg opgerig word, kan winsgewend opgerig word in lande wat’n elektrisiteitsinkomste van 0.10 US$/kWh of meer het.

Die primêre doelwitte van die PEPER kragaanleg is om:

1. as opleidingsaanleg gebruik te word;
2. verskillende soorte kernbrandstof en -materiale te toets;
3. hoë temperatuur kerndata te versamel; en
4. as moontlike bron van elektrisiteit vir die huishoudelike en industriële sektore van geselekteerde lande te dien.

**Sleutelwoorde: Elektrisiteit, PEPER-kragaanleg, betroubaarheid, bekostigbaarheid, produksie**

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***Philippians 1:21: "For to me to live is Christ, and to die is gain."***

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| | |
|---|---|
| **4S** | Super-Safe, Small and Simple |
| **AVR** | Arbeitsgemeinschaft Versuchsreaktor |
| **CAREM** | Advanced Small Nuclear Power Plant |
| **CWS** | Cooling water system |
| **DLOFC** | Depressurised loss of forced cooling |
| **DOE** | Department of Energy |
| **EES** | Engineering Equation Solver |
| **EPCM** | Engineering, procurement, construction and management |
| **FOAK** | First of a kind |
| **GT-HTR** | Gas Turbine High Temperature Reactor |
| **GT-MHR** | Gas Turbine Modular Helium Reactor |
| **GWe** | Gigawatt electric |
| **HEU** | High-enriched uranium |
| **HPM** | Hyperion Power Module |
| **HPP** | High pressure pump |
| **HPT** | High pressure turbine |
| **HTGR** | High Temperature Gas-cooled Reactor |
| **HTR** | High Temperature Reactor |
| **HTR-10** | 10 MW High Temperature Gas-cooled Reactor Test Module |
| **HTR-10GT** | HTR-10 Direct Gas Turbine Project |
| **HTTR** | High Temperature Test Reactor |
| **HVAC** | Heating, ventilation and air conditioning |
| **I&C** | Instrumentation and control |
| **IAEA** | International Atomic Energy Agency |
| **IHX** | Intermediate heat exchanger |
| **IPH** | Intermediate pressure heater |
| **IPP** | Intermediate pressure pump |
| **IPT** | Intermediate pressure turbine |
| **IRIS** | International Reactor Innovative and Secure |
| **IRR** | Internal rate of return |
| **JAERI** | Japan Atomic Energy Research Institute |
| **LEU** | Low-enriched uranium |
| **LPH** | Low pressure heater |
| **LPP** | Low pressure pump |
| **LPT** | Low pressure turbine |
| **LWR** | Light water reactor |
| **$MW_e$** | Megawatt electric |
| **$MW_{th}$** | Megawatt thermal |
| **NOAK** | *N*th of a kind |
| **NPP** | Nuclear power plant |
| **NPV** | Net present value |

| | |
|---|---|
| **NPW** | Net present worth |
| **O&M** | Operation and maintenance |
| **OTTO** | Once-through-then-out |
| **PBMR** | Pebble Bed Modular Reactor |
| **PBMR-DPP** | Pebble Bed Modular Reactor Demonstration Power Plant |
| **PBP** | Payback period |
| **PCI** | Power control and instrumentation |
| **PCU** | Power conversion unit |
| **PEPER** | Potchefstroom Experimental Pebble Bed Modular Reactor |
| **PFD** | Process flow diagram |
| **PWR** | Pressurised water reactor |
| **r** | Real cost of money |
| **ROI** | Rate of investment |
| **RPV** | Reactor pressure vessel |
| **RS-MHR** | Remote-Site Modular Helium Reactor |
| **SCS** | Shutdown cooling system |
| **SMART** | System-integrated Modular Advanced Reactor |
| **t** | Ton |
| **TCIC** | Total capital investment cost |
| **TH** | Thermal hydraulics |
| **THTR** | Thorium High Temperature Reactor |
| **TRISO** | Tristructural isotropic |
| **$UO_2$** | Uranium dioxide |
| **WBS** | Work breakdown structure |

# Chapter 1

# Introduction

*Electric power is everywhere present in unlimited quantities and can drive the world's machinery without the need of coal, oil, gas, or any other of the common fuels.*

– *Nikola Tesla (*10 July 1856 – 7 January 1943*)*

# 1. Introduction

*Chapter 1 gives an overview of the techno-economic evaluation of the Potchefstroom Experimental Pebble Bed Modular Reactor (PEPER) power plant. The chapter also outlines the importance of the research project and its scope. Furthermore, it discusses the research objective and gives an overview of the dissertation.*

## *1.1 Background*

In South Africa, the 400 $MW_{th}$ (megawatt thermal) Pebble Bed Modular Reactor Demonstration Power Plant (PBMR-DPP) is nearing the stage at which a first-of-a-kind (FOAK) pebble bed nuclear reactor needs to be integrated with a FOAK direct cycle power conversion unit (PCU). The licensing and operation of such a system are anticipated to be extensive and time consuming. A particular goal of the PBMR-DPP is to demonstrate that it can be a successful commercial endeavour. Thus, it is foreseen that the opportunity to train nuclear engineers, scientists, and nuclear regulators might be limited. Even though instrumentation might be thorough and wide-ranging on the PBMR-DPP, it is not certain that there will be the facilities and opportunity for new instrumentation, for example instrumentation for failing sensors. The flexibility of the pebble bed reactor makes it possible to offer a test bench for fuel cycle investigations, by way of a small experimental pebble bed reactor, such as the feasibility of plutonium incineration, deploying thorium/uranium as fuel with optimised conversion rates.

As developing countries often have small electricity grids and limited turnover of capital in the energy market, small independent pebble bed reactor nuclear power plants (NPPs), with a specific thermal power rating, may offer the only affordable nuclear power option. The primary objective of this investigation is to perform a techno-economic evaluation of the PEPER plant. As part of the multi-disciplinary conceptual design of the proposed plant, this study provides the basis for the costing of a reactor and PCU.

## 1.2 Problem statement

Over two billion people worldwide do not have access to electricity in their homes [26]. Small pebble bed reactors can help overcome this electricity crisis and are a natural solution for the numerous small and/or developing countries interested in generation plants that could provide electricity for about 0.10 US$/kWh [26]. The PEPER plant could be utilised for this. A techno-economic analysis of the PEPER plant is first necessary to determine whether the plant will operate economically in countries with a determined income in the industrial and household sectors in order to assist in relieving the global electricity crisis.

In this analysis of the 100 $MW_{th}$ PEPER plant, a case study of the PEPER plant is necessary in order to select a relevant PCU for the plant. Comparative economic viabilities between the Brayton cycle, Rankine cycle and the combined cycle (discussed in Chapter 3) have to be done in order to select the best PCU for the PEPER plant. The total capital investment cost (TCIC) of the reactor pressure vessel (RPV) and the equipment of the PCU have to be calculated. An economic evaluation platform in the form of an economic model of the PEPER plant using the cost of the heavy equipment (RPV and the PCU) of the PEPER plant as input has to be developed. The number of PEPER plants constructed before the TCIC stabilises have to be determined for *N*th-of-a-kind (NOAK) calculations in the economic model. Sensitivity analysis in the economic model has to be conducted in order to determine the economic feasibility of constructing FOAK and NOAK PEPER plants in various countries with different inflation rates in the industrial and household sectors.

In the economic model of the PEPER plant, the production costs have to be determined and converted to US$/kWh, in order to compare the electricity costs in a standard currency and unit for the industrial and household sectors for the various countries. The economic model of the PEPER plant has to calculate the profit of the electricity produced in the industrial and household sectors of the countries in terms of the net present value (NPV), internal rate of return (IRR) and payback period (PBP). The economic model has to display a cash-flow diagram, showing the cumulative cash flow, cumulative discounted cash flow and the IRR cumulative cash flow over the sixty-year lifespan of the PEPER plant for the countries with different inflation rates for FOAK and NOAK PEPER plants in the industrial and household sectors.

## 1.3 Research objective

This research project conducted a case study of a 100 $MW_{th}$ PEPER plant in order to develop an economic model for the PEPER plant. The economic model is to estimate the production costs in US$/kWh, the profit that the PEPER plant will make over a particular period in a particular country and the cash-flow diagram of the PEPER plant in a particular country with a particular inflation rate in both the industrial and household sectors.

A sensitivity analysis is conducted to determine the effect on the economic feasibility of the PEPER plant when certain aspects such as fuel cost and production costs are varied. Sensitivity analysis of the following is reported on in this dissertation:

1. varying production costs versus profitability;
2. varying income versus profitability;
3. varying fuel sphere cost versus fuel sphere production cost;
4. varying cost per fuel sphere versus overall production costs;
5. varying operation and maintenance (O&M) costs versus production costs;
6. varying production costs versus profitability; and
7. cash-flow diagram.

The objectives of the techno-economic evaluation of the PEPER plant are illustrated in Figure 1.1.

**Figure 1.1:** **Objectives of the techno-economic analysis of the PEPER power plant**

Figure 1.1 shows that the equipment costs of the RPV and the heavy equipment of the PCU will be used as input for the economic model of the PEPER plant. In the economic model, the production costs (US$/kWh), working capital and fixed capital investment costs will be determined. Cash-flow diagrams showing the cumulative cash flow, cumulative discounted cash flow and the IRR cumulative cash flow of different countries with different electricity income and inflation rates will be calculated for the model. A sensitivity analysis will be conducted on the model in order to estimate the effect of increasing and decreasing income, production, fuel and O&M costs, for a NOAK and FOAK PEPER plant.

The primary goals of the PEPER plant are to:

1. function as a training facility;
2. function as a test bed for fuels and materials;
3. accumulate high temperature nuclear data; and
4. be a potential electricity source for the industrial and household sectors of selected countries.

## 1.4 Dissertation overview

This dissertation will present the techno-economic evaluation of the PEPER power plant in the six chapters that follow. Each of these is outlined below.

### *Chapter 2: Literature study*

Chapter 2 will review theoretical information and the background theory gathered through the literature review in order to formulate solutions for the defined sub-problems.

### *Chapter 3: Case study of the power conversion unit for the PEPER plant*

Three possible PCUs for the PEPER plant, namely the Brayton cycle, Rankine cycle and the combined cycle, will be discussed in this chapter. The Rankine (indirect steam cycle) is selected for the PEPER plant and the sizes of the heavy equipment are determined with the help of Engineering Equation Solver (EES). The sizes of the heavy equipment of the Rankine (indirect steam cycle) in this chapter will be used to obtain the cost of the heavy equipment of the PCU in Chapter 4.

### *Chapter 4: Equipment cost of the PEPER plant*

Chapter 4 will calculate the cost of the heavy equipment needed in the PCU of the PEPER plant using the equipment sizes of the selected PCU in Chapter 3. The cost of the RPV will also be calculated in this chapter. The Total capital investment cost (TCIC) calculated by using the costs of the selected PCU and the RPV as calculated in this chapter, will serve as input in Chapter 5 to the economic model.

### *Chapter 5: Economic model for the PEPER plant*

Chapter 5 will explain the economic model developed for the PEPER plant using the total equipment cost of the PEPER plant, calculated in Chapter 4, as input.

### *Chapter 6: Results and techno-economic evaluation*

Chapter 6 will present the results of the previous chapters and, based on these, reflect on the economic feasibility of establishing a production line for the PEPER plant.

### *Chapter 7: Conclusion and recommendations*

Chapter 7 will present a closing overview of the project. In addition, it will discuss problem areas of this research project and make recommendations for future research.

Chapter 1 has introduced the research project by way of sketching the background and the problem statement. It has presented the research objective and indicated the scope of the project. In addition, the dissertation has been outlined.

# Chapter 2

# Literature study

*To truly transform our economy, protect our security, and save our planet from the ravages of climate change, we need to ultimately make clean, renewable energy the profitable kind of energy.*

*– Barack Obama (*4 August 1961 – *)*

# 2. Literature study

*Prior to conducting the techno-economic analysis of the PEPER power plant, sufficient theoretical knowledge was gathered in order to formulate solutions for the defined sub-problems and economic models. In this chapter, the background, theoretical knowledge and 400* $MW_{th}$*, PBMR-DPP necessary for the economic analysis of the project are discussed.*

## *2.1 Introduction*

Since 1950 when nuclear power generation was established, nuclear reactors have been constructed ranging in size from 60 $MW_e$ to more than 1600 $MW_e$, with equivalent economies of scales in action [24]. Currently, there is a move to develop smaller units, owing to the need to service small electricity grids under about 4 GWe and to the high cost of large nuclear reactors generating electricity through the steam cycle [24]. Significant expertise in the small reactor engineering field has been gained through the hundreds of smaller reactors built for naval use and as neutron sources [24].

According to the World Nuclear Association, the desire to reduce costs and provide power away from large grid systems, there is a revival of interest in small and simpler units for generating electricity from nuclear power and for process heat [24]. For remote areas, there is a trend to build small nuclear reactors. The International Atomic Energy Agency (IAEA) defines *small nuclear reactors* as under 300 $MW_e$. The agency projects up to 1000 small nuclear reactors producing power by 2040. These may be built independently or as modules in series in a larger complex adding capacity incrementally as required [24].

A considerable line of development in small reactors is under 50 $MW_e$. In general, these small nuclear reactors have a greater simplicity of design, economy of mass production and reduced costs for the site used [24]. Some small nuclear reactors are constructed for regions with small loads that are far from transmission grids [24]. The electricity cost from a 50 $MW_e$ unit was estimated by the United States Department of Energy (US DOE) as 0.054 US$/kWh to 0.107 US$/kWh, compared with costs in Alaska and Hawaii that range from 0.059 US$/kWh to 0.36 US$/kWh [24].

Four small nuclear reactor units already operate in a remote corner of Siberia at the Bilibino Nuclear Cogeneration Plant. These four 62 $MW_{th}$ units produce 11 $MW_e$ electricity each and steam for district heating. The reactors are of a graphite-moderated boiling water design with water/steam channels through the moderator [24].

A well-known modular project is the PBMR-DPP of approximately 160 $MW_e$ that is being developed in South Africa. Two options were considered in parallel for the 400 $MW_{th}$ PBMR-DPP [6]:

1. The first option was a single module stand-alone power plant able to achieve fast load-following. Several modules could be placed on the same site and use a common service building but not other facilities. This option is suitable for remote locations or countries with an underdeveloped electricity generation system. However, this solution is not competitive in countries with a well-developed electricity infrastructure, or where fuel prices are low [6].
2. The second option was a multi-module power plant within a common building that shares some facilities. If the power plant is intended for base load operation only, such a plant will only need one helium inventory system for four to eight modules. Shared with previous concepts and confirmed by recent in-depth cost studies and market analysis [6], this option leads to cost savings that, together with the design changes mentioned above, make the concept competitive with almost all other forms of electricity production [6].

The PBMR-DPP is composed of a steel pressure vessel that houses about 452 000 fuel spheres. The fuel consists of low-enriched uranium (LEU) TRISO (tristructural isotropic)-coated isotropic particles contained in a moulded graphite sphere. A coated particle consists of a kernel of uranium dioxide ($UO_2$) surrounded by four coating layers. The PBMR-DPP system is cooled with helium. The heat that is transferred by the helium to the power conversion system (Brayton cycle) is converted into electricity through a helium turbine [5].

The PBMR-DPP features an annular design with a novel three-discharge chute design, while the PEPER features a cylindrical core with a single discharge layout. Furthermore, the pebbles in the PBMR-DPP pass through the reactor six times, whereas the PEPER plant features the once-through-then-out (OTTO) fuel cycle.

The PEPER plant is similar to the 10 MW High Temperature Gas-cooled Reactor Test Module (HTR-10) design by INET in China that is based on the HTR-Modul reactor design by INTERATOM (Internationale Atomreaktorbau) in Germany. These design efforts brought important factors to the forefront, one of which is considering a design that can be deployed on sound economic considerations as a starting point, even if the original design was intended for experimental purposes [7].

The main intent of the PEPER design is to provide a scaled-down version of the functional parts of the PBMR-DPP. Apart from the plant design, explicitly intended for instrumentation and measurement, an attempt was made to simplify the reactor in order to allow for the testing of novel fuel cycle investigations [7].

## 2.2 Small reactors with advanced development

The IAEA defines small NPPs as 300 $MW_e$ and less [24]. Very small NPPs are defined as 50 $MW_e$ and less [24]. Current small reactors globally with advanced development are shown in Table 2.1. A short description of these reactors follows the table.

**Table 2.1: Existing small-reactors with advanced development [25]**

| Reactor | Electric power ($MW_e$) | Reactor type | Company |
|---|---|---|---|
| CAREM | 27 | PWR | CNEA & INVAR, Argentina |
| GT-MHR | 285 | HTGR | General Atomics (US), Minatom (Russia) |
| IRIS-100 | 100 | PWR | Westinghouse LED, international |
| KLT-40S | 35 | PWR | OKBM, Russia |
| MRX | 30–100 | PWR | JAERI, Japan |
| PBMR-DPP | 165 | HTGR | Eskom, South Africa |
| SMART | 100 | PWR | Technicatome (Areva), France |
| VK-300 | 300 | PWR | Atomenergoproekt, Russia |

### *CAREM*

The CAREM (Advanced Small Nuclear Power Plant) is being developed by the CNEA (Comisión Nacional de Energía Atómica) and INVAP in Argentina. It will be a modular 100 $MW_{th}$ (27 $MW_e$) pressurised water reactor (PWR) that generates electricity through designed integral steam generators. The CAREM will be able to be used for water desalination or as a research reactor. The entire primary coolant system of CAREM is in the RPV. It is self-pressurised and relies entirely on convection. The fuel of the CAREM is 3.4% enriched standard PWR fuel with burnable poison and will be refuelled annually. The

CAREM could be deployed within a decade [24].

### *Gas Turbine Modular Helium Reactor*

The Gas Turbine Modular Helium Reactor (GT-MHR) being developed by General Atomics will be built as modules up to 600 $MW_{th}$. The GT-MHR modules will drive gas turbines at 47% thermal efficiency, yielding 280 $MW_e$. The annular core of the GT-MHR consists of 102 hexagonal fuel element columns of graphite blocks with channels for helium coolant and control rods. Graphite blocks serve as reflectors and are placed both inside and around the core. Refuelling entails replacing half of the GT-MHR core every 1.5 years. Gas Turbine Modular Helium Reactor fuel burn-up is up to 220 GWd/t with helium coolant outlet temperature of around 850°C [24].

### *IRIS-100*

The IRIS-100 is a small version of IRIS (International Reactor Innovative and Secure) being developed by Westinghouse as an advanced third generation reactor. The IRIS-100 will be a PWR with an integral primary coolant system. The fuel of the IRIS-100 is standard light water reactor (LWR) fuel enriched to 5% with burnable poison and a fuelling interval of five years. If IRIS developments continue, the IRIS-100 could be completed by 2015 [24].

### *KLT-40S*

The OKBM-designed KLT-40S reactor is well established in icebreakers. The KLT-40S is considered for remote area power, desalination and use on barges. The reactor core of the KLT-40S is generally cooled by forced circulation and relies on convection for emergency cooling. The fuel used in the core is made from uranium aluminium silicide enriched up to 20%. The KLT-40S produces 150 $MW_{th}$ (38.5 $MW_e$) and is designed to operate for three to four years between refuelling [24].

### *MRX*

The MRX is being developed by the Japan Atomic Energy Research Institute (JAERI). It will be a small 50 to 300 $MW_{th}$ PWR reactor and will be able to be used for local energy supply (30 $MW_e$) or for marine propulsion. The MRX will use conventional 4.3% enriched PWR uranium oxide fuel and have a 3.5-year refuelling interval. The MRX container will be filled with water to enhance safety. The MRX could be deployed within a decade [24].

### *Pebble Bed Modular Reactor Demonstration Power Plant*

The 400 $MW_{th}$ PBMR-DPP being developed in South Africa aims for a step-up adjustment in safety, economy and proliferation resistance. The production units of the PBMR-DPP are estimated to be around 165 $MW_e$ with a thermal efficiency of about 41% and helium coolant retaining the bottom of the core at approximately 900°C. The PBMR-DPP uses the direct Brayton cycle to generate electricity. About 452 000 fuel pebbles with a diameter of 60 mm, weighting 210 g of which 9 g consists of uranium enriched to 10% U-235, recycle six times through the reactor (one cycle takes six months) until the pebbles are expended. The PBMR-DPP has a graphite-lined reactor with a graphite central column acting as a reflector. The control rods are housed in the side reflectors and reserve shutdown units in the centre column [5].

### *System-integrated Modular Advanced Reactor (SMART)*

The System-integrated Modular Advanced Reactor (SMART) developed by Technicatome is a 330 $MW_{th}$ PWR with integral steam generators and advanced safety features. The SMART is designed to generate electricity and can generate up to 100 $MW_e$, the SMART can also be used for thermal applications like seawater desalination. The design life of the SMART is sixty years, with three-year refuelling intervals [24].

### *VK-300*

The VK-300 evolved from the VK-50 Boiled Water Reactor at Dimitrovgrad in Russia. The cooling of the VK-300 is passive by convection and all the other safety systems are convective. The fuel burn-up of the VK-300 is 41 GWd/tU and it can produce 250 $MW_e$ if it is only used to generate electricity. The VK-300 has been developed for cogeneration of electricity (150 $MW_e$) and district heating/desalination (1675 GJ/hr). The VK-300 has been developed by the N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET). Six VK-300 units will be built in Kola and Primorskaya in Russia, which will start operation between 2017 and 2020 [24].

## *2.3 High Temperature Reactors*

High temperature reactors (HTR) are very different compared to the present day introduced light water or heavy water reactors. The HTR is the latest stage of development in the gas cooled reactor line, starting from Magnox reactors and later on Advanced Gas-cooled Reactors (AGR). The use of helium as coolant and of graphite as structural material allow much higher helium temperatures compared to light water or heavy water reactors which leads to much higher efficiency. Helium is a very favourable cooling medium: it is chemically inert, has a high heat capacity and does not influence the neutron economy at all. [8]

### 2.3.1 Early High Temperature Reactors

In the 1950s, Prof. Dr. Rudolf Schulten developed the originator of the pebble bed reactor design, which compacts silicon carbide-coated uranium granules into hard, billiard ball-sized spheres to be used as fuel for a new high temperature, helium-cooled type of nuclear reactor. Following this, a 46 $MW_{th}$ experimental pebble bed reactor (the Arbeitsgemeinschaft Versuchsreaktor) was built at the Nuclear Research Centre in Jülich (Germany). It operated successfully for twenty-one years but was shut down because the pebble fuel-testing programme was ceased. Some of the last pebble fuel tested in the AVR was for a LEU fuel cycle anticipated for use in the HTR-MODUL design by Interatom/SIEMENS. [29]

#### *Arbeitsgemeinschaft Versuchsreaktor (1966–1988)*

The Arbeitsgemeinschaft Versuchsreaktor (AVR) experimental pebble bed reactor operated for over 750 weeks at 15 $MW_e$ at the Nuclear Research Centre in Jülich. The fuel was composed of approximately 100 000 billiard ball-sized fuel elements. Maximum burn-ups of 150 GWd/t were achieved. The coolant used in the AVR was helium and the fuel ranged from thorium-based fuel mixed with high-enriched uranium (HEU) to LEU [24].

#### *Thorium High Temperature Reactor (1983–1989)*

The Thorium High Temperature Reactor (THTR) of 300 $MW_e$ was developed and financed by Hochtemperatur-Kernkraftwerk GmbH (HKG) in Germany from the AVR. The fuel consisted of 674 000 pebbles, of which over half contained a mixture of thorium and HEU fuel, while the remainder of the pebbles were graphite moderators and neutron absorbers. The fuel was continuously recycled and passed the core an average of six times before the fuel was depleted. In the THTR, a steam turbine was deployed to provide electricity [24].

#### *HTR-Modul (1989)*

After the THTR, the HTR-modul of 80 $MW_e$ was designed by Siemens as a modular unit that would be constructed in pairs. It was licensed in 1989, but was never constructed.

The HTR-modul is a direct forerunner of the PBMR-DPP, as the HTR-modul design was part of the technology Eskom bought in 1996 to develop the PBMR-DPP [24].

### 2.3.2 Modern High Temperature Reactors

Modern High Temperature Gas-cooled Reactors (HTGRs) were developed using the experience gained by early High Temperature Reactors (HTRs) such as the AVR, THTR and HTR-modul. The newly developed HTRs are capable of reaching high coolant temperatures of up to 950°C to produce electricity (almost 50% efficiency) or can be used in high temperature applications.

The fuel for these HTRs is in the form of TRISO particles less than 1 mm in diameter. Each particle consists of a uranium oxide kernel of 0.5 mm in diameter, with the uranium enriched up to 20% (that is, LEU). This kernel is surrounded by layers of carbon and silicon carbide, which provides containment for fission products that are stable to 1600°C. The TRISO particles are arranged either in blocks (hexagonal prisms of graphite) or in tennis ball-sized pebbles of graphite both of which are covered in silicon carbide, each with approximately 15 000 fuel particles and 9 g uranium [24].
The reactors are inherently safe because of the strong negative temperature coefficient of reactivity and passive decay heat removal characteristics. Owing to these qualities, they do not require any containment building in the classical sense for safety reasons [24].

#### *High Temperature Test Reactor*

The High Temperature Test Reactor (HTTR) of 30 $MW_{th}$ developed by JAERI was put into operation at the end of 1998, running at 850°C. In 2004, it achieved 950°C outlet temperature. The HTTR uses prismatic fuel and is used to produce hydrogen from water [24].

#### *Gas Turbine High Temperature Reactor*

The Gas Turbine High Temperature Reactor (GT-HTR) is based on the HTTR and is being developed by JAERI. The GT-HTR will reach up to 600 $MW_{th}$ per module with exit helium reaching 850°C to drive a horizontal turbine at 47% efficiency to produce up to 300 $MW_e$. A plant consisting of four GT-HTR modules is estimated to have a cost of US$1300/kWe to US$1700/kWe and a power cost of approximately 0.034 US$/kWh [24].

#### *10 MW High Temperature Gas-cooled Reactor Test Module*

The 10 MW High Temperature Gas-cooled Reactor Test Module (HTR-10) is an experimental reactor designed by INET. It was put into operation in 2000 to reach full power in 2003. The core consists of 27 000 pebbles with an average burn-up of 80 GWd/t uranium. Each fuel pebble has 5 g of uranium enriched to 17%. The reactor operates at 700°C and drives a steam turbine [24].

#### *Pebble Bed Modular Reactor Demonstration Power Plant*

This reactor was discussed in Section 2.2.

#### *Gas Turbine Modular Helium Reactor*

This reactor was discussed in Section 2.2.

#### *Remote-Site Modular Helium Reactor*

The Remote-Site Modular Helium Reactor (RS-MHR) has been proposed by General Atomics and is a smaller version of the GT-MHR. It will be capable of producing 10 to 25 $MW_e$ [24].

#### *Hyperion Power Module*

The Hyperion Power Module (HPM) developed by Hyperion Power Generation has had preliminary discussions with the Nuclear Regulatory Commission. A US design certification application is possible in 2012, which is when the company intends to begin manufacturing in New Mexico. The HPM is a small self-regulating hydrogen-moderated and potassium-cooled reactor producing 70 $MW_{th}$ (25 $MW_e$). It is fuelled by powdered uranium hydride, operates at approximately 550°C and has a refuelling interval of five to ten years. It is estimated that the HPM will be sold for US$27 million per unit (2008) [24].

### 2.3.3 The major advantages of modern High Temperature Gas-cooled Reactors

In HTRs, the use of helium as coolant and graphite as structural material allows much higher helium temperatures compared to LWRs and heavy water reactors. In passing the core, the coolant gas helium can be heated up to such very high temperatures as 700°C to 950°C. In the PBMR-DPP, the helium is heated up from 500°C to 900°C [8]. Owing to the higher temperatures, the PCU can potentially achieve higher efficiency and there is an extended scope for the HTR, such as hydrogen production and process heat applications.

Furthermore, the higher temperatures will cause higher fuel conversion ratios, which will result into higher burn-up [8]. In addition, helium is a favourable cooling medium, as it is chemically inert, has a high heat capacity and does not influence the neutron economy.

For the pebble bed HTRs, spherical type fuel elements with a diameter of 6 cm were used (see Figure 2.1). For both the prismatic blocks and the spheres, small, coated particles (approximately 1 mm in diameter) of $UO_2$ were embedded in a graphite matrix. This configuration allowed high operation temperatures up to 1350°C under normal conditions and 1600°C in a loss of coolant accident. In this configuration, there is no release of impermissible quantities of fission products. The $UO_2$ fuel kernel was embedded in a porous buffer layer. Three layers (TRISO) of pyrolytic carbon, silicon carbide and pyrolytic carbon were used to protect the embedded fuel kernel [8].

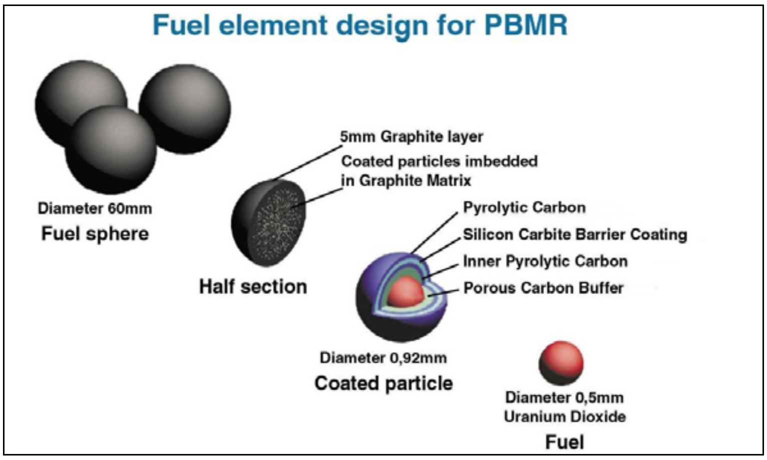

**Figure 2.1: Fuel element design for High Temperature Reactors [8]**

The main safety advantage characteristics of HTRs and the PEPER in particular are:

1. Core meltdown of the ceramic materials is physically impossible. Owing to the limited core power density, the self-acting decay heat removal sufficiently performed by conduction, convection and radiation ensures that fuel integrity is guaranteed.
2. Nuclear excursions do not cause damage to the core, owing to the strong negative temperature coefficients, continuous loading of fuel and no excess reactivity to compensate for burn-up.
3. All the fission products are contained in the coated particles provided the maximum fuel temperature $T_{fuel} < 1600°C$ during a depressurised loss of forced cooling (DLOFC) event. Less than $10^{-5}$ of the fission product inventory is released to the

environment, even in the case of severe industrial accidents [8].

## 2.4 Reactor: Potchefstroom Experimental Pebble Bed Modular Reactor

Mulder [7] designed the reactor (PEPER) that will be used as a heat source in the PEPER plant. The specifications of the PEPER are given in Table 2.2. The pebbles in the PEPER will pass through the reactor once only (OTTO cycle).

**Table 2.2: Specifications of the PEPER [7]**

| | | |
|---|---|---|
| **Power rating** | 100 | $MW_{th}$ |
| **Volume of the core** | 20 | $m^3$ |
| **Height** | 507 | cm |
| **Radius** | 115 | cm |
| **Height of conus** | 48 | cm |
| **Radius of unloading tube** | 35 | cm |
| **Flow pattern of spheres** | 9 / 9 / 10 / 12 / 15 | |
| **Number of passes through the core** | 1 | |
| **Heavy metal in fuel elements** | 9 | g/sphere |
| **Enrichment of uranium** | 9.6 | w% |
| **Number of control rods** | 16 (in 2 banks) | |
| **Thickness and materials of reflectors, barrel, vessel.** | Similar to the PBMR-DPP | |

The characteristics of the equilibrium cycles of the PEPER compared with the 400 $MW_{th}$ PBMR-DPP are shown in Table 2.3 [7].

**Table 2.3: Equilibrium cycle of the PEPER compared with the PBMR-DPP [7]**

| **Reactor** | | **PEPER** | **PBMR-DPP** |
|---|---|---|---|
| **Thermal power** | $MW_{th}$ | 100 | 400 |
| ***Core physics:*** | | | |
| **Fuel residence time** | Days | 746 | 961 |
| **Target burn-up** | $MWd/Kg_{HM}$ | | |
| **Neutron leakage** | % | 16.21 | 15.21 |
| **Neutron absorption in fission products** | % | 6.1 | 7.43 |
| **Conversion ratio** | | 0.456 | 0.447 |
| **Fast neutron dose (E>0.1 MeV)** | $10^{21/}cm^2$ | 2.33 | 2.74 |
| **Inventory of fissile nuclides** | Kg/GWth | 614 | 512 |
| **Average thermal neutron flux** | $10^{14}/(cm^2*sec)$ | 0.69 | 0.79 |
| **Fuel shuffling** | Spheres/day | 867 | 2821 |
| **Submitting of fresh fuel elements** | Spheres/day | 144 | 470 |
| ***Thermal properties:*** | | | |
| **Maximum power per sphere** | KW/sphere | 1.55 | 2.77 |

| | | | |
|---|---|---|---|
| **Maximum fuel temperature** | °C | 1608 | 1577 |
| **DLOFC maximum temperature** | °C | 1608 | 1577 |
| **Time of max. temperature after DLOFC** | H | 15 | 45 |
| **Relative decay heat at the time of maximum temperature** | % | 0.648 | 0.47 |
| ***Temperature coefficient:*** | Δkeff/°C*$10^{-5}$ | | |
| **Resonance absorber** | | -4 | -3.4 |
| **Fuel** | | -2.6 | -2.4 |
| **Reflector** | | 2 | 3.2 |
| **Total** | | -4.6 | -2.6 |
| ***Fuel cycle costs:*** | Rand/kWhe | | |
| **Fuel** | | 0.053 | 0.042 |
| **Fabrication** | | 0.026 | 0.021 |
| **Total** | | 0.079 | 0.064 |

The controlling of the load-following of the PEPER is illustrated in Table 2.4 [7].

**Table 2.4: Controlling the load-following between 100 and 40% [7]**

| | | |
|---|---|---|
| Equilibrium cycle, group 1 (8 rods) inserted to 159.5 cm below top reflector | Keff | 1 |
| 40% load, control requirement by build-up of $^{135}$Xe over 6 hours | Δkeff | -0.0096 |
| Control capability by withdrawal of group 1 | Δkeff | 0.0106 |
| Control margin at maximum $^{135}$Xe (at 6 hours) | Δkeff | 1.001 |

Table 2.5 presents the shutdown capabilities of the PEPER [7].

**Table 2.5: Shutdown capabilities [7]**

| | **Δkeff** |
|---|---|
| Group 1 (8 RCS) fully inserted to 636.5 cm below top reflector | -0.0909 |
| Decay of $^{135}$Xe and other isotopes over 4 days | 0.0261 |
| Hot shutdown by group 1 | -0.0648 |
| Cooling down to 50°C | 0.0562 |
| Cold shutdown by group 1 | -0.0086 |
| Additional insertion of group 2 (another 8 RCS) | -0.0355 |
| Cold shutdown by groups 1 & 2 | -0.0441 |

## 2.5 Fuel cycle: Potchefstroom Experimental Pebble Bed Modular Reactor

In the PEPER, a simple, inexpensive and effective fuel cycle is foreseen featuring a high level of proliferation resistance. The fuel cycle for the PEPER will be an OTTO cycle [7]. The maximum safe operating power conditions for a reactor with a cylindrical core using the OTTO cycle is 120 MW$_{th}$ to prevent DLOFC at 1600°C [9].

In the OTTO cycle, the fuel elements only move once through the core and reach their final burn-up in one pass. Using this procedure, high helium temperatures can be obtained using relatively low fuel temperatures. If the OTTO cycle is used in a core, the power production occurs mainly in the upper part of the core. The difference between the fuel and the gas temperature at the exit of the core is very small, owing to the power production in the upper part of the core. The OTTO fuel-handling system can be accepted as a proven technology based on AVR, THTR and other research in various HTR development programmes [8].

Figure 2.2 demonstrates conditions and a real core design with an OTTO fuel-handling system for HTR technology. In order to attain an average gas temperature of 950°C, the maximum fuel temperature should not be higher than 1000°C.

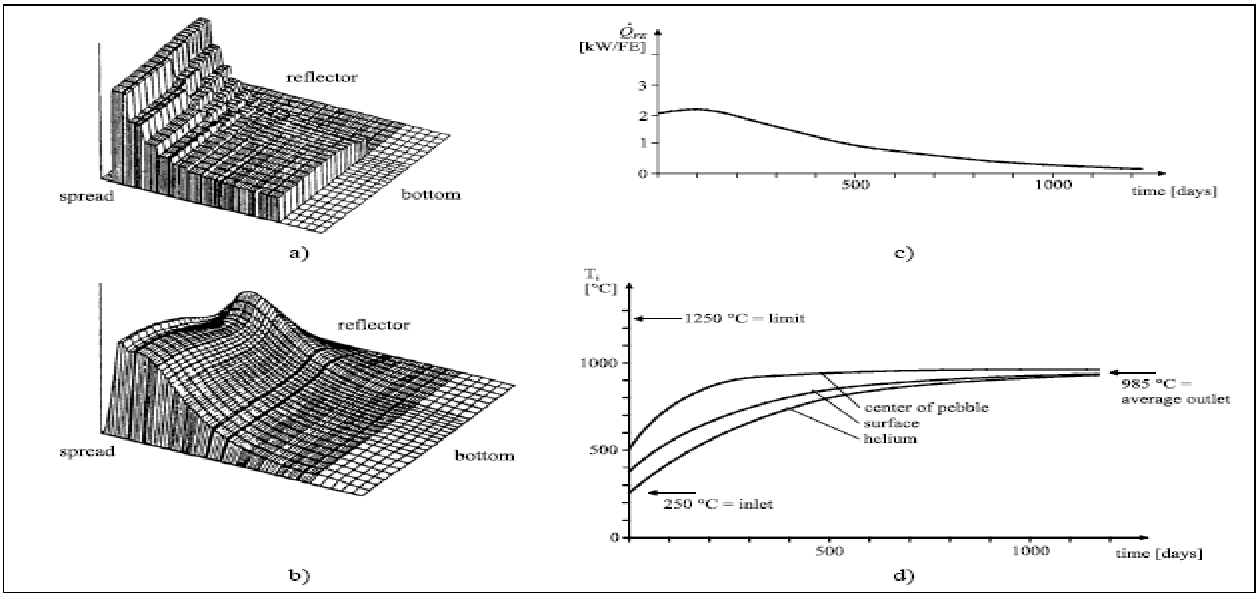

**Figure 2.2: Typical OTTO cycle power and temperature distributions [8]**

In this figure, the following is presented:

1. the density of fissile nuclides (U-235) dependant on space;
2. the spatial distribution of thermal flux;
3. a graph of thermal load of fuel elements dependent on insertion time (axial position); and
4. a graph of temperatures of gas and fuel dependent on time (axial position) [8].

## *2.6 Power conversion unit*

There are three basic options for power conversion units that can generate electricity with a modular HTR as heat source. These three PCUs are the steam cycle (Rankine cycle); closed gas turbine cycle (Brayton cycle) and the combined cycle. The process flow diagrams (PFDs) of these three PCUs are illustrated in Figure 2.3 on the next page [8].

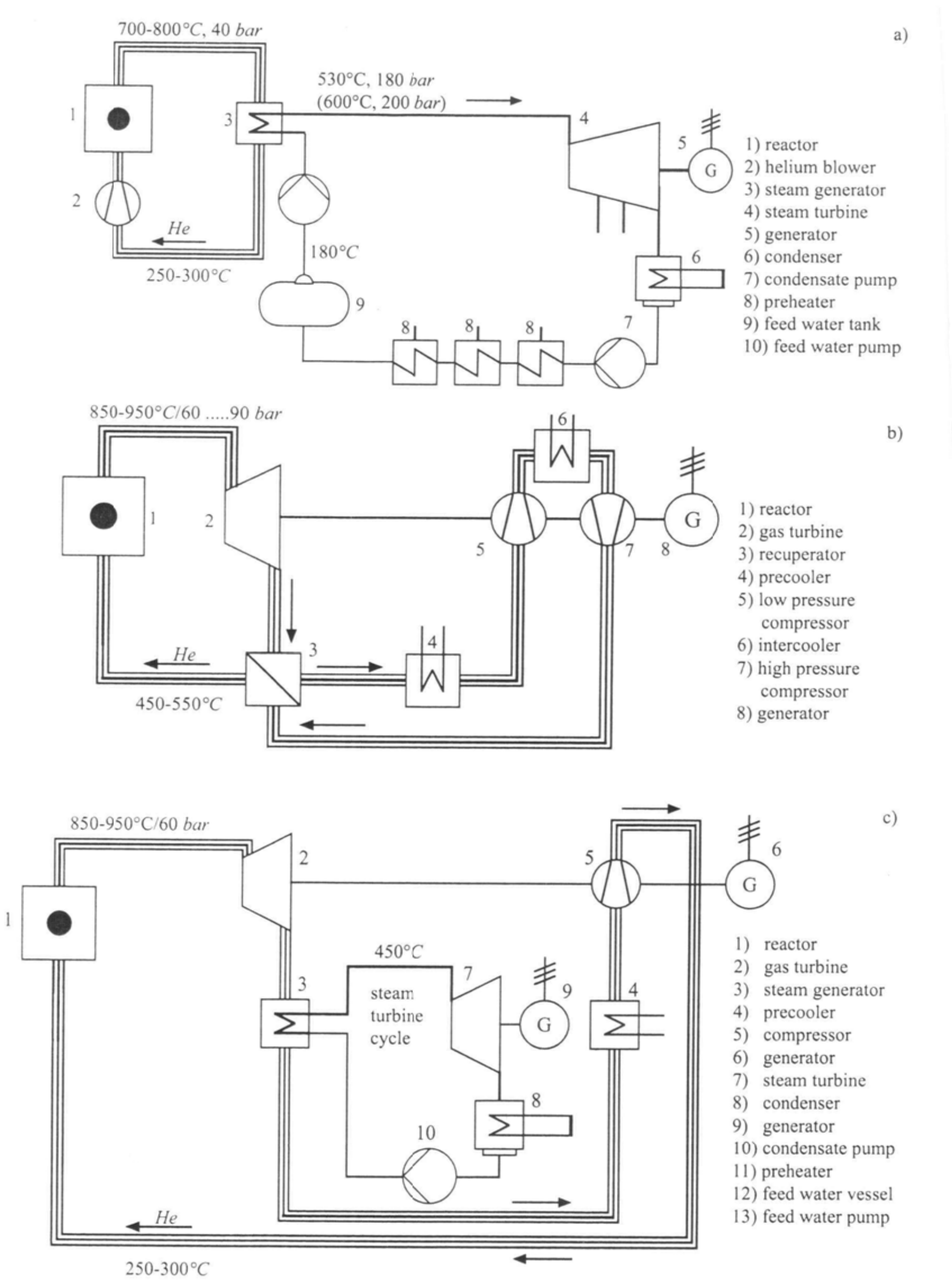

**Figure 2.3:** **Basic power conversion units producing electricity with a modular High Temperature Reactor as heat source: a) Steam cycle; b) Closed gas turbine cycle; and c) Combined cycle [8]**

### 2.6.1 400 $MW_{th}$ PBMR-DPP

The PBMR-DPP uses a single-shaft direct Brayton cycle to generate electricity with the 400 $MW_{th}$ PBMR-DPP reactor as heat source. The single-shaft direct Brayton cycle PCU is illustrated in Figure 2.4 [8].

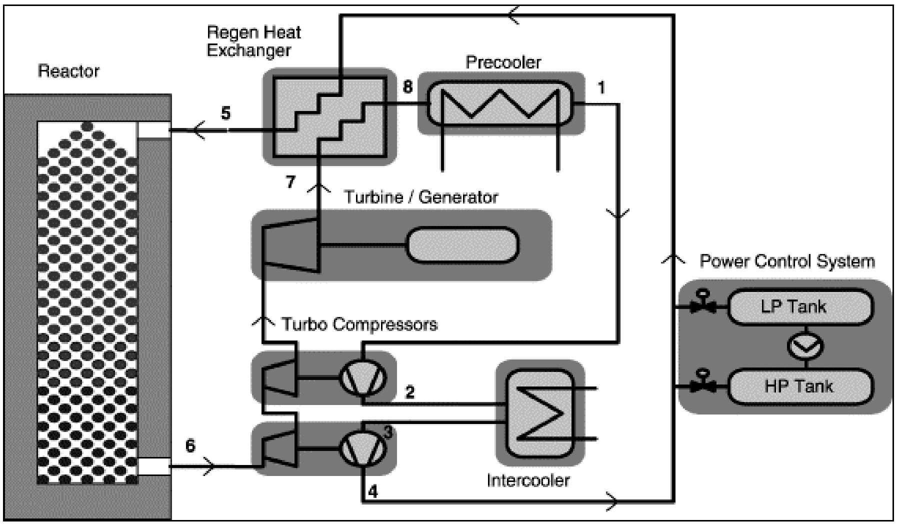

**Figure 2.4: Simplified diagram of the one-shaft direct Brayton cycle power conversion unit [8]**

The graph of temperature versus entropy for an ideal Brayton cycle is demonstrated in Figure 2.5.

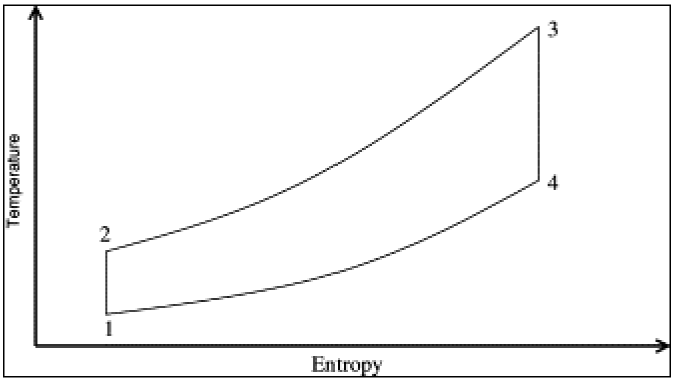

**Figure 2.5: Ideal Brayton cycle temperature versus entropy [8]**

A detailed graph of temperature versus entropy for the 400 $MW_{th}$ PBMR-DPP with a pressure of 9 MPa is shown in Figure 2.6 below.

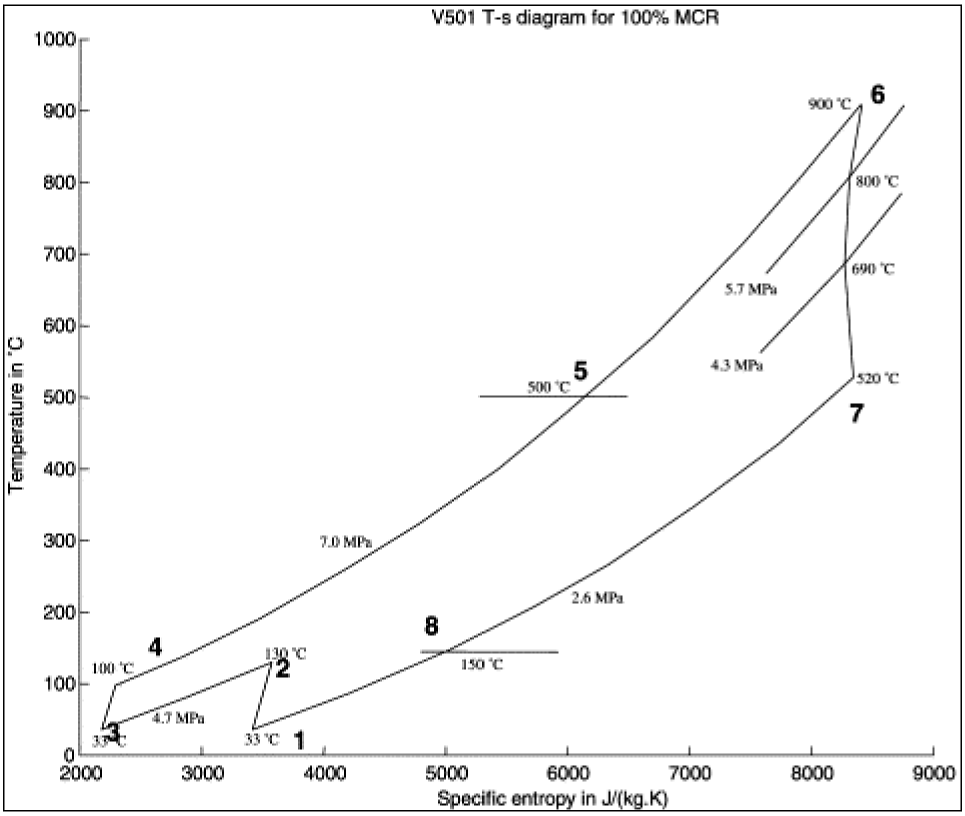

**Figure 2.6:** **400 $MW_{th}$ Pebble Bed Modular Reactor temperatures versus entropy graph for the 9 MPa main systems [8]**

### 2.6.2 HTR-10 Direct Gas Turbine Project

The HTR-10 Direct Gas Turbine Project (HTR-10GT) was approved as a demonstration project for electricity generation after the HTR-10 reached full power of 10 MW in February 2003 [27]. The HTR-10GT will generate power based on the direct gas turbine cycle, utilising the closed Brayton cycle [27].

The PCU components of the HTR-10GT are contained in the PCU vessel illustrated in Figure 2.7. The steam generator is mounted in parallel with the reactor vessel in a separate cavity with lateral supply of hot helium and removal of cold helium. The recuperator has a circular design and is located in the lower part of the vessel. The intercooler and the pre-cooler are located above the recuperator [27].

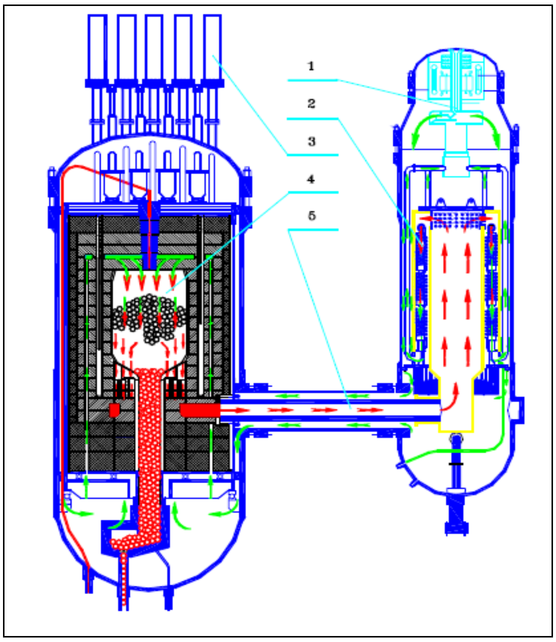

**Figure 2.7: HTR-10GT reactor with the steam generator [27]**

1: helium circulator; 2: steam generator; 3: control rod; 4: reactor; and 5: hot gas duct

The power conversion system of the HTR-10GT consists of the core, turbine, high-pressure compressor, low-pressure compressor, recuperator, pre-cooler, intercooler and connecting pipes. Helium is used as the core coolant and the working fluid for the turbine and compressors [27]. The power conversion system is illustrated in Figure 2.8.

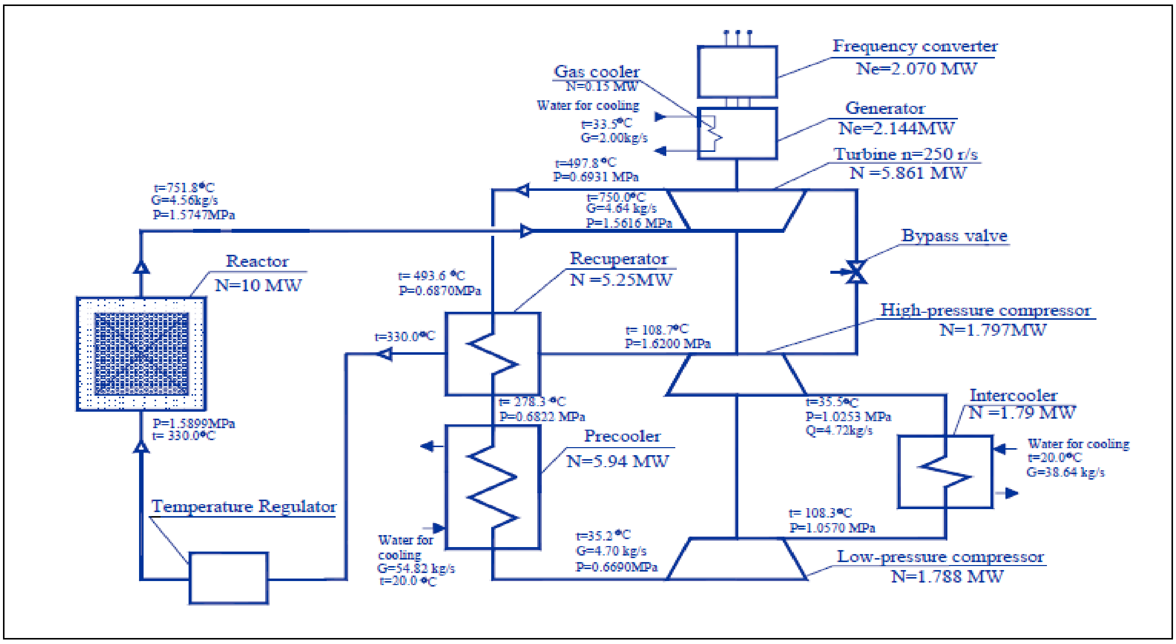

**Figure 2.8: HTR-10GT power conversion system [27]**

### 2.6.3 Gas Turbine Modular Helium Reactor Nuclear Power Plant

The Gas Turbine Modular Helium Reactor Nuclear Power Plant (GT-MHR NPP) is predicted to be commissioned as a prototype in 2010 [28]. The power conversion system is a closed gas turbine. The turbo machine consists of a generator, gas turbine and two compressor sections mounted in a single-shaft structure completely suspended on electromagnets [28]. The power conversion system is illustrated in Figure 2.9.

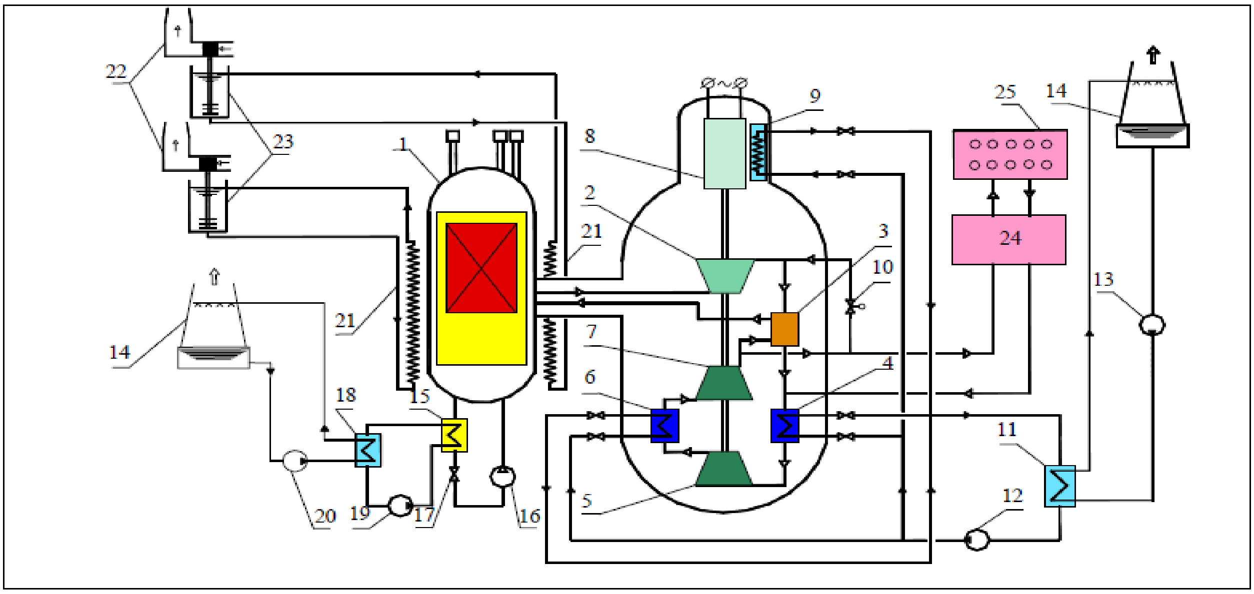

**Figure 2.9: Power conversion system of the GT-MHR NPP [28]**

1: reactor; 2: turbine; 3: recuperator; 4: pre-cooler; 5: low-pressure compressor; 6: intercooler; 7: high-pressure compressor; 8: generator; 9: generator cooler; 10: bypass valve of the turbine control and protection system; 11: heat exchanger of the PCU CWS; 12: PCU CWS pump; 13: recirculation water supply system pump; 14: cooling tower; 15: reactor SCS unit heat exchanger; 16: SCS unit gas circulator; 17: SCS unit gas circulator isolation valve; 18: SCS CWS heat exchanger; 19: SCS CWS pump; 20: reliable recirculation water supply system pump; 21: reactor SCS surface cooler; 22: air ducts; 23: heat exchanger with heat pipes; 24: primary circuit purification system; and 25: helium transportation and storage system

## 2.7 Confinement

Pebble bed HTRs are designed today such that the maximum achievable temperatures in the fuel will remain below 1600°C [8], the experimentally proven figure for retention of all fission products. Furthermore, the sublimation temperature of graphite is around 2800°C [8]. A core melt scenario is thus completely excluded in this type of reactor design [8]. Figure 2.10 illustrates this fission barrier concept.

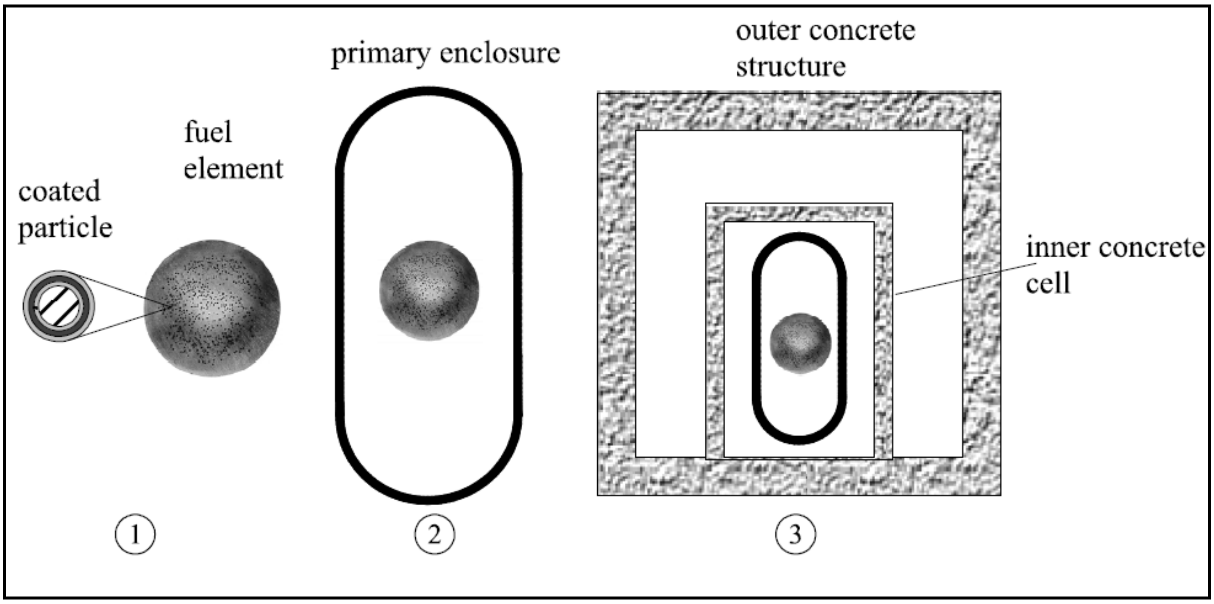

**Figure 2.10:** **Barriers to retain radioactivity within the plant in all conditions [8]**

Figure 2.11 depicts the inherent safety characteristics of the pebble bed reactor.

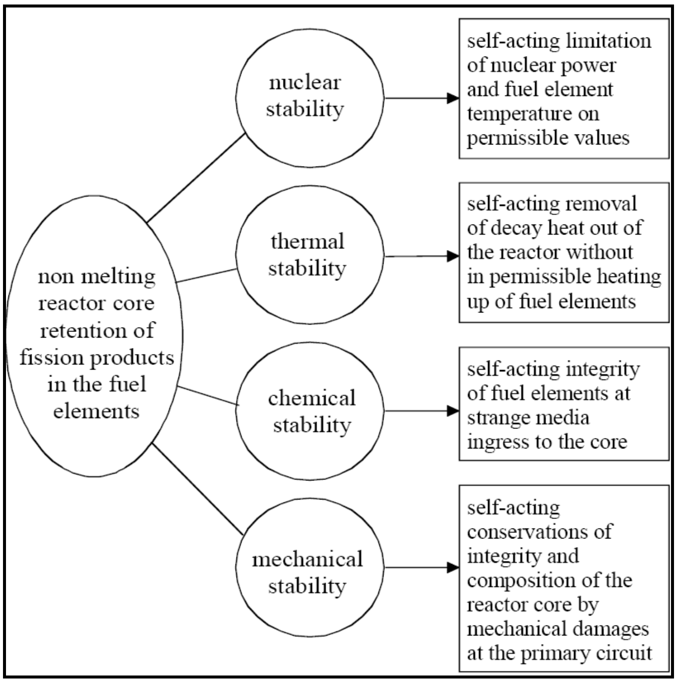

**Figure 2.11: Inherent features of a pebble bed reactor [10]**

## *2.8 Economic evaluation of the costs of generating electricity with High Temperature Reactor technology*[1]

The derivation of the economic model of the PEPER plant in terms of formulas and method will be discussed in Chapter 5 in detail. This section presents the formulas used to calculate cost estimations of past NPPs in Germany. These estimations were calculated in order to compare the values obtained with the top-down cost estimation for the economic model of the PEPER plant.

### 2.8.1 Costs incurred during the working period

The costs incurred during the working period of a power plant consist of power-dependent and work-dependent costs [8]. This is demonstrated in Figure 2.12.

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[1] The formulas presented in this section are for academic study only.

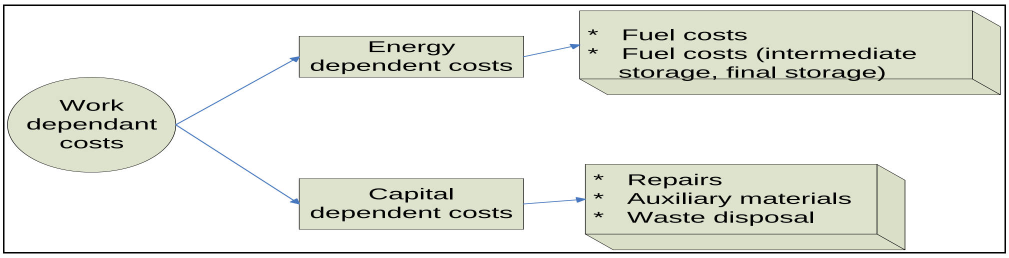

**Figure 2.12: Block diagram of work-dependant costs [8]**

Formula 2.1 was used to determine the electricity generation costs over a period of one year [8]:

$$x = \frac{Kinv}{P_{el}^0 . T} \bullet \frac{\bar{a}}{100} + \frac{C \bullet k_C}{P_{el}^0 \bullet T} + \frac{(m_{dot})_F^0 \bullet k_F}{P_{el}^0 \bullet T} + \sum_i \frac{(m_{dot})_{ai} \bullet k_{ai}}{P_{el}^0 \bullet T} + \frac{(m\_dot)_D^0 \bullet k_D}{P_{el}^0 \bullet T} \qquad 2.1$$

The parameters and their dimensions are as follows:

$x$ = power-generating cost $[ct / kWh_{el}]$;

$P_{el}^0$ = net electric power of the plant $[kW]$;

$K_{inv}$ = overall plant investment cost $[\$]$

$T$ = full-load hours per year [*h/year*];

$\bar{a}$ = capital factor (includes depreciation, interest, insurance, tax payment on capital, repairs) *[%/year*];

$(m_{dot})_F^0$ = specific amount of fuel per year [*tU/year*];

$k_F$ = specific fuel cost *[$/tU*];

$C$ = number of staff for service;

$k_c$ = annual rate of costs for staff *[$/person/year]*;

$(m\_dot)_{ai}^0$ = amount of auxiliary materials (chemicals etc.) per year $[t / year, m^3 / year ...]$;

$k_{ai}$ = specific costs for auxiliary materials $[\$ / t, \$ / m^3 ...]$;

$(m\_dot)_D^0$ = amount of waste per year $[t / year]$; and

$k_D$ = specific costs for waste disposal $[\$ / t]$.

Formula 2.1 can also be written in a slightly modified manner to yield Formula 2.2 [8]:

$$x = x_C + x_{oper} + x_F + x_{ai} + x_D \tag{2.2}$$

Formula 2.2 can be interpreted as follows:

$x$ = power-generating cost $[ct/kWh_{el}]$;

$x_C$ = capital-dependent cost;

$x_{oper}$ = operating service cost;

$x_F$ = fuel cost;

$x_{ai}$ = cost of auxiliary materials; and

$x_D$ = cost of waste disposal (including intermediate and final storage).

### 2.8.2 Investment cost of the High Temperature Reactor power plant

The overall investment cost of the HTR power plant $k_{invest}$ includes the direct investment costs $k_{direct}$ for the plant as a whole. Furthermore, material and financial contributions by the utility itself, such as ground, infrastructure, authorisations, checks and starting operation, as well as similar costs, have to be considered in calculating the direct investment cost. The sum of the direct investment cost with the additional contributions results in the total capital investment cost (TCIC) calculated by Formula 2.3 [8]:

$$k_{invest} = k_{direct} \bullet (1 + \sum_i \frac{\alpha_i}{100}) \tag{2.3}$$

The extra shares $\alpha_i$, given in per cent, are indicated below [8]:

$\alpha_1$ = payment of interest during construction time;

$\alpha_2$ = insurance during construction time;

$\alpha_3$ = taxes during construction time;

$\alpha_4$ = inflation;

$\alpha_5$ = the start-up phase;

$\alpha_6$ = builder's own material and financial contributions; and

$\alpha_7$ = plant shutdown and decommissioning.

### 2.8.3 Cost of the nuclear fuel

The fuel cost $x_F$ (ct/kWh$_{el}$) for the HTR plant consists of the various shares given in Formula 2.4:

$$x_F = x_U + x_E + x_P = \frac{k_F}{(B \bullet \bar{\eta})/100} \qquad 2.4$$

$x_U$ = cost share of natural uranium $[ct/kWh_{el}]$;

$x_E$ = cost share of uranium enrichment $[ct/kWh_{el}]$;

$x_P$ = share of manufacturing cost for the fuel elements $[ct/kWh_{el}]$;

$k_F$ = cost for the ready-to-use fuel $[ct/t\ heavy\ metal]$;

$B$ = fuel burn-up $[kWh/t\ heavy\ metal]$; and

$\bar{\eta}$ = plant's net efficiency $[\%]$.

In order to determining the cost shares of natural uranium and uranium enrichment, the exact enrichment or fuel cycle used has to be considered.

The cost of the ready-to-use fuel was calculated using Formula 2.5:

$$k_F = k_{uranium} \bullet m + k_{enrichment} \bullet a_s + k_{production} \bullet z \qquad 2.5$$

This formula can be interpreted as follows:

$k_{uranium}$ = cost of the natural uranium $[ct/tU_{nat}]$;

$m$ = quantity factor of the enriched uranium $[tU_{nat}/tU_{enrich}]$;

$k_{enrichment}$ = specific cost of enrichment $[ct/t\ separation\ work]$;

$a_s$ = separation-work-factor $[t\ separation\ work/t\,U_{enrich}]$;

$k_{production}$ = specific cost of production $[ct/\ fuel\ element]$; and

$z$ = quantity of fuel elements $[number\ of\ \ fuel\ elements/t\,U_{enrich}]$.

### 2.8.4 Costs of intermediate storage and final storage of spent fuel

The overall costs of the waste disposal $x_D$ include costs that are required for temporary storage and final storage of spent fuel elements. The cost for disposal of low and medium active waste material was also considered [8]. This is given in Formula 2.6 and Formula 2.7.

$$x_D = x_{TS} + x_{FD} + x_{AW} \tag{2.6}$$

$$x_D = \frac{k_{IS}}{(B \bullet \bar{\eta})/100} + \frac{k_{FS}}{(B \bullet \bar{\eta})/100} + \frac{k_{AW} \bullet m}{P_{el}^0 \bullet T} \tag{2.7}$$

The various parameters are explained below:

$X_{TS}$ = cost of temporary storage $[ct / kWh_{el}]$;

$X_{FS}$ = cost of final storage $[ct / kWh_{el}]$;

$X_{AW}$ = cost of waste disposal for low and medium active waste $[ct / kWh_{el}]$;

$k_{TS}$ = specific cost of temporary storage $[\$ / t]$;

$k_{FS}$ = specific cost of final storage $[\$ / t]$;

$B$ = burn-up $[kWh_{th} / t]$;

$\eta$ = average net efficiency $[\%]$;

$m$ = amount of low and medium active waste material $[m^3 / a]$;

$k_{AW}$ = specific cost of low and medium active waste $[\$ / m^3 / a]$;

$P_{el}^0$ = electrical power $[MW_e]$; and

$[T]$ = full-load hours $[h / a]$.

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*Chapter 2 has discussed the theoretical knowledge and data of the 400 $MW_{th}$ PBMR-DPP. The methods and theoretical knowledge required for the techno-economic analysis of the PEPER plant and the PCU were presented in this chapter. The formulas that were used to calculate the generating costs of electricity of other NPPs in comparison to those of the PEPER plant in comparison were also illustrated.*

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# Chapter 3

# Case study of the power conversion unit for the Potchefstroom Experimental Pebble Bed Modular Reactor plant

*Those who say it cannot be done should not interfere with those of us who are doing it.*

*– Chinese proverb*

# 3. Case study of the power conversion unit for the Potchefstroom Experimental Pebble Bed Modular Reactor plant

*In this chapter, three possible PCUs for the PEPER plant, namely the Brayton cycle, Rankine cycle and combined cycle, are discussed. One of these PCUs is selected and the sizes of the heavy equipment are determined using Engineering Equation Solver (EES).*

## *3.1 Selection of the power conversion unit for the PEPER plant*

The main goal of the PEPER plant is to demonstrate that the plant works efficiently under any circumstances. In order to achieve this goal, an effective and available PCU was chosen to produce electricity with the PEPER plant as heat source. The three types of PCU configurations considered were the Brayton cycle, Rankine cycle, and combined cycle.

The goal of the PCU is to provide a plant with high efficiency, low investment cost, modularity and low maintenance cost.

### 3.1.1 Brayton cycle

The Brayton cycle is a constant-pressure cycle named after George Brayton (1830–1892) the American engineer who developed it. The Brayton cycle is ideally suited for a gas turbine without any phase change in the coolant. Figure 3.1 illustrates the Brayton cycle in its simplest form with P-v and T-s diagrams.

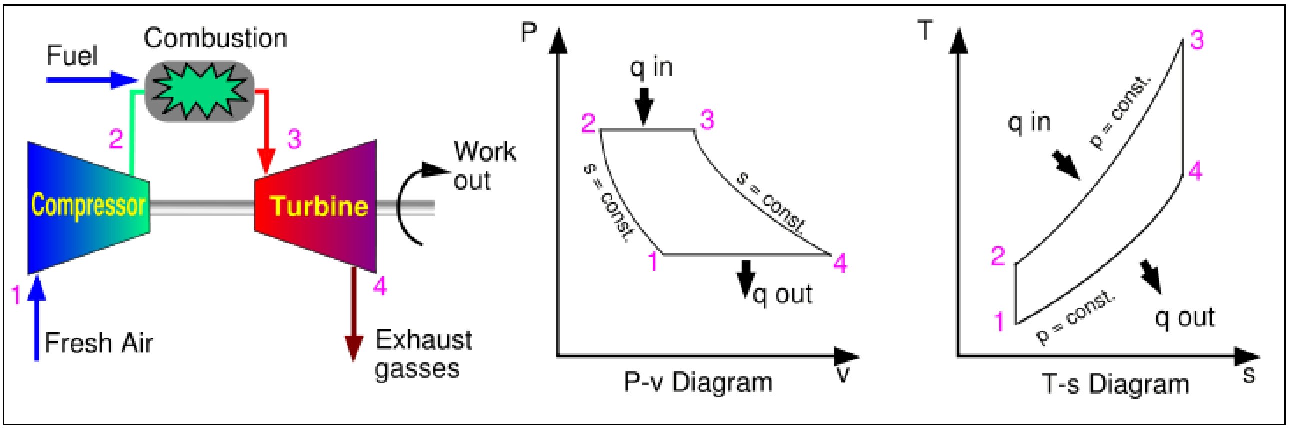

**Figure 3.1:** **Simple ideal Brayton cycle [8]**

Figure 3.2 schematically depicts the layout of the direct Brayton cycle that was anticipated for an earlier version of the PBMR-DPP.

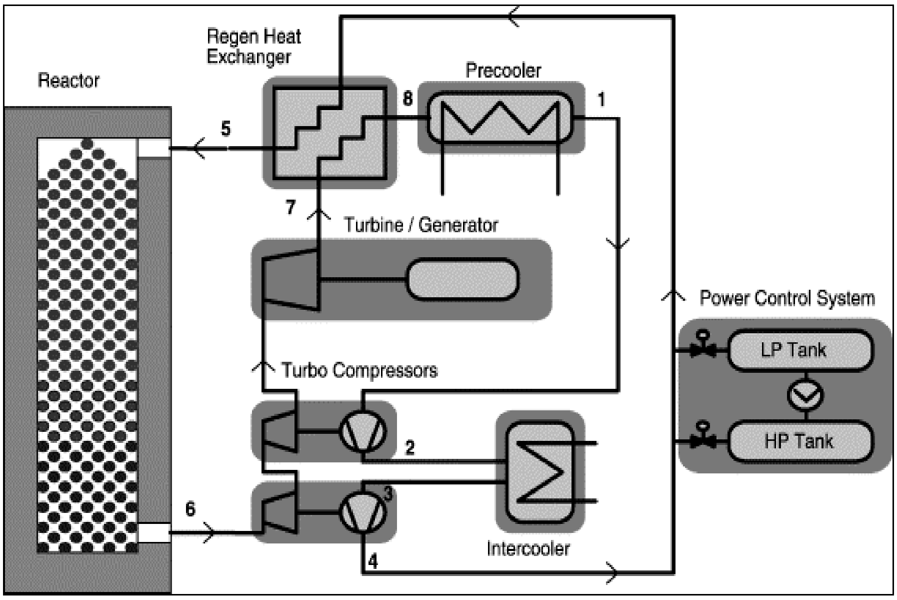

**Figure 3.2:** **Layout of a typical Pebble Bed Modular Reactor Demonstration Power Plant power conversion unit [8]**

Figure 3.3 presents the T-s diagram of the direct Brayton cycle used by PBMR-DPP.

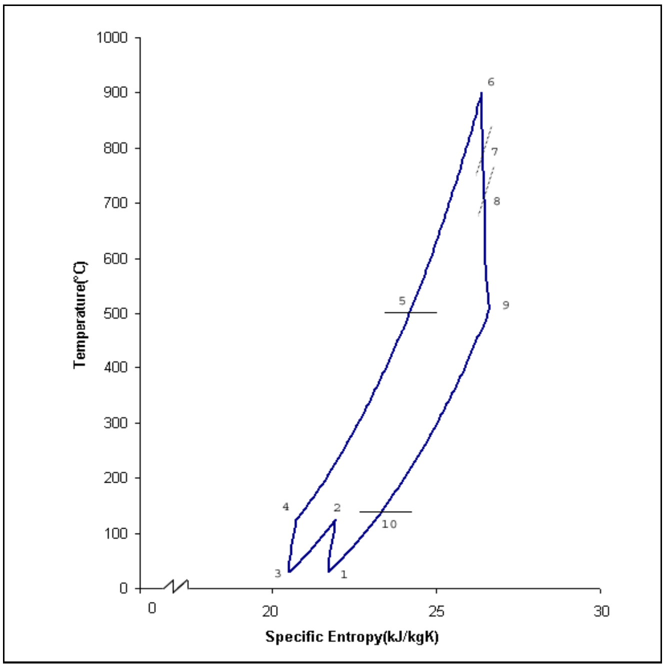

**Figure 3.3:** **Pebble Bed Modular Reactor Demonstration Power Plant T-s diagram [5]**

Materials for gas turbine power plants with maximal helium temperature of 850°C to 950°C are available. These materials are suitable for a service life of $10^5$ hours and more for the hot gas ducts and blades of turbines. Additional protection measures, well-known from conventional technology, such as internal cooling of blades and surface layers on blades, can also be used in the helium-operated machines [8].

The design and manufacturing of the heavy equipment in the Brayton cycle such as the gas turbines and compressors is likely to be time consuming and expensive, owing to the lack of knowledge and experience of this type of gas equipment. Furthermore, the maintenance cost of the gas components is anticipated to be much higher than the maintenance cost on of steam components in a Rankine (steam) cycle.

### 3.1.2 Indirect steam (Rankine) cycle

In contrast with the Brayton cycle, the Rankine cycle describes the ideal cycle in which the coolant, while circulating through the cycle, changes phase between liquid and gas [10]. The traditional coal- and gas-fired boiler steam electricity-generation plants use the Rankine (steam) cycle. In the Rankine cycle, the liquid (water) changes phase as it is heated to steam (gas) before passing through a steam turbine. Figure 3.4 depicts the layout of a regenerative Rankine cycle with its T-s diagram.

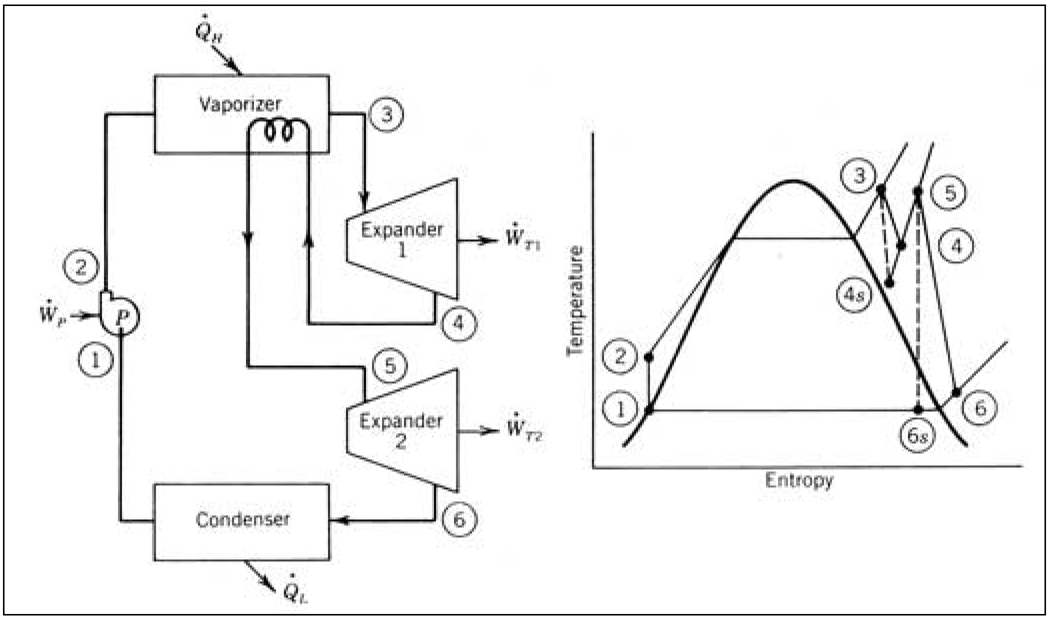

**Figure 3.4: Regenerative Rankine (steam) cycle with the corresponding T-s diagram [8](**

If the Rankine (steam) cycle is considered the PCU for the PEPER plant, the PEPER plant will have two cycles, namely the primary cycle running on helium and the secondary cycle running on steam. The primary cycle will contain the reactor and the helium blower, while the secondary cycle will be a Rankine cycle. These two cycles will be connected by an intermediate heat exchanger (steam generator), which will be used the hot helium from the reactor in the primary cycle to produce hot steam for the secondary cycle. The PFD of the indirect steam (Rankine) cycle for the PEPER plant is illustrated in Figure 3.5 on the following page.

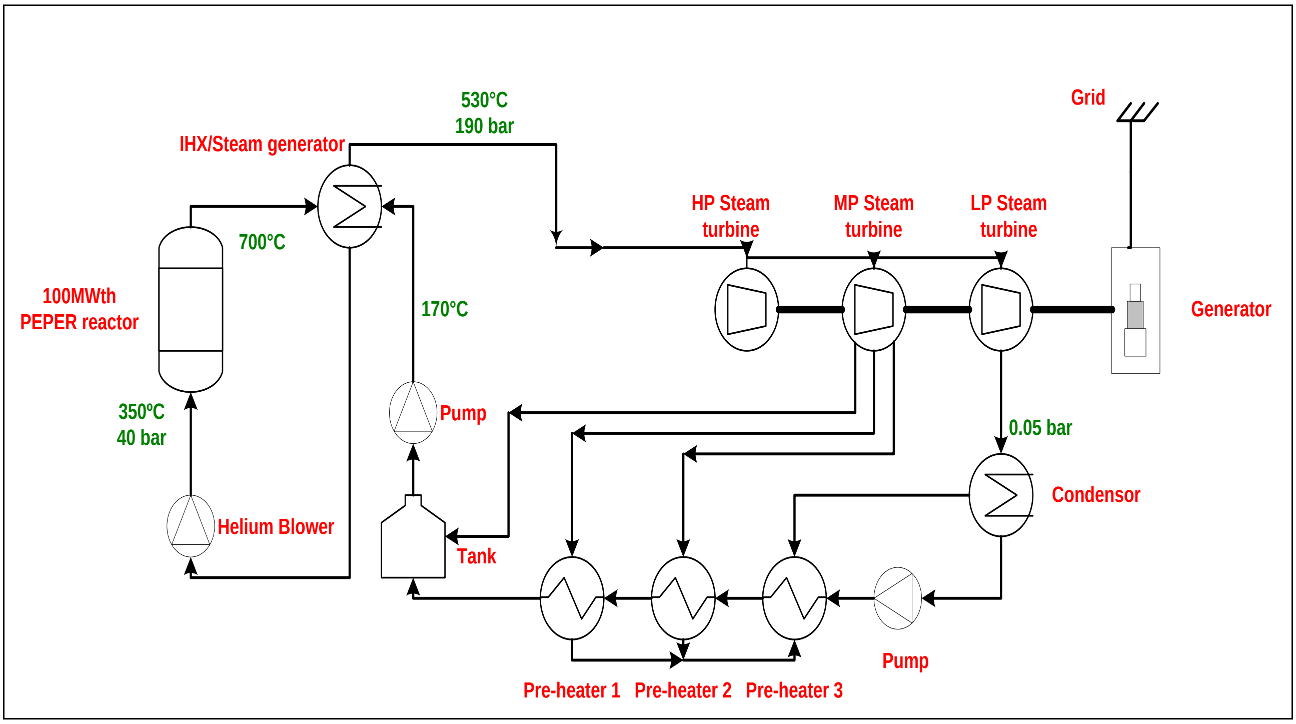

**Figure 3.5:** **Indirect steam cycle for the PEPER plant**

The Rankine cycle is used in the majority of coal- and gas-fired electricity-generating plants; therefore, all the equipment for the steam PCU has been proven and is available. In the indirect cycle, the steam generator needs to be designed and manufactured to link the primary and secondary cycles. This is an efficient and cost effective PCU for the PEPER plant to use to demonstrate that the plant is working and can be licensed.

### 3.1.3 Combined cycle

The combined cycle is a combination of the Brayton and the Rankine cycles. In the combined cycle, the boiler of the Rankine cycle replaces a steam generator (heat exchanger). The Brayton cycle, which is the primary cycle, supplies the heat. The combining of the Brayton and Rankine cycle improves overall efficiency.

In the combined cycle power plant, the gas turbine generator generates electricity and the waste heat is used to make steam to generate additional electricity through a steam turbine. This additional electricity (produced with the waste heat) enhances the efficiency of the electricity generation. If the plant produces only electricity, efficiencies of up to 60%

can be achieved. Figure 3.6 presents a basic layout of the combined cycle PCU. The Brayton cycle is on the left and the Rankine cycle on the right.

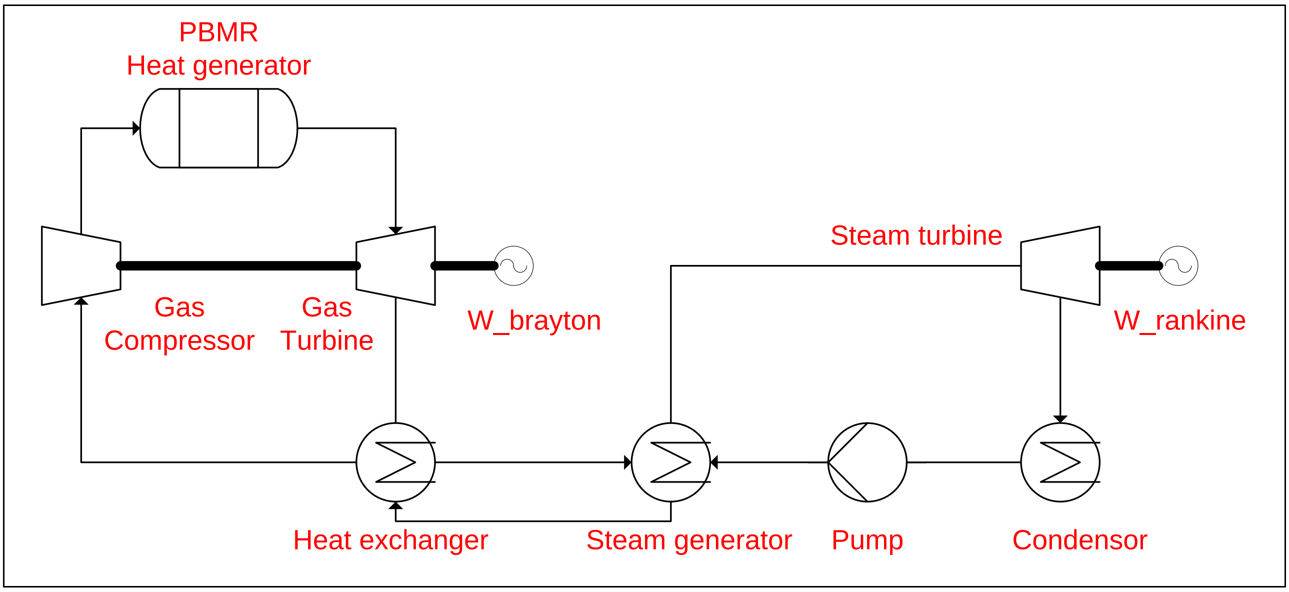

**Figure 3.6: Basic layout of the combined cycle power conversion unit**

High Temperature Reactor power generation poses the possibility of a closed loop Brayton cycle. Although high electricity efficiency can be obtained with the combined cycle, the time consumption and the expense of design and manufacturing of the gas equipment in the Brayton cycle may render it unsuitable for the first PEPER plant.

### 3.1.4 Power conversion unit selection

The indirect steam (Rankine) cycle has been proven in numerous electricity-generating power plants. Therefore, the indirect steam cycle can confidently be deployed as the PCU for the PEPER power plant. This cycle was sized with the PEPER plant as heat source in order to determine the sizes of the equipment required to construct the indirect steam cycle for the PEPER plant. Once the sizes of the equipment had been determined, the prices for the equipment were obtained, which served as input for the economic model of the PEPER plant.

## 3.2 *Sizing of the indirect steam cycle*

In this section, the process flow diagram of the indirect steam cycle is illustrated with the calculations to determine the power of the steam turbines, steam generator, condenser, reheating and the efficiency of the reactor in order to size the components of the indirect steam cycle.

### 3.2.1 Process flow diagram of the indirect steam cycle

The indirect steam (Rankine) cycle consists of a helium primary cycle and a steam secondary cycle. The primary cycle consists of a helium blower and the pebble bed reactor, and is connected to the secondary cycle through a steam generator. The helium in the primary cycle enters the steam generator at 700°C and heats the steam entering the cycle to a temperature of 530°C. The conventional steam cycle contains a high pressure turbine (HPT), intermediate pressure turbine (IPT), low pressure turbine (LPT), cooling tower (condenser), low pressure pump (LPP), low pressure heater (LPH), intermediate pressure pump (IPP), intermediate pressure heater (IPH), high pressure pump (HPP) and the reheating cycle. The three turbines are coupled by a shaft to the generator that provides electricity to the grid. The PFD of this indirect steam cycle for the PEPER plant as designed in EES is given in Figure 3.7.

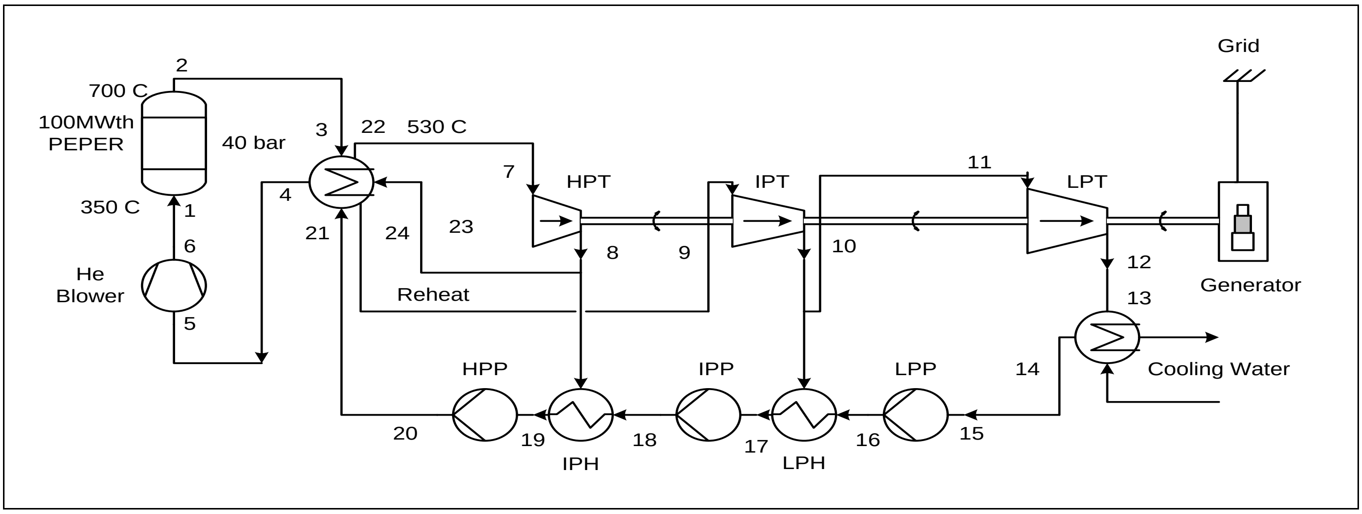

**Figure 3.7: Layout of the indirect steam cycle for the PEPER plant designed in EES**

### 3.2.2 Cycle parameters, assumptions and balance equations

The following cycle parameters and assumptions were used to size the indirect steam cycle PCU approximately in order to determine the sizes of the equipment and thus the prices of these:

1. The inlet- and outlet temperatures of the PEPER plant were taken as 350°C and 700°C, respectively, with a pressure of 40 bar over the reactor [7].
2. The KTA-pressure drop equation was used to determine the pressure drop over the PEPER plant.
3. The inlet temperature and pressure in the steam side were fixed at 530°C and 190 bar respectively [8].
4. The efficiencies of the turbines were fixed at 85% with a pressure ratio of 0.256 over the turbines [11].
5. The efficiency of the condenser was fixed at 75% and the efficiencies of the pumps at 80% [11].
6. The efficiency of steam generator was fixed at 99%, the mechanical efficiencies of the turbines were fixed at 98%, generator efficiency was fixed at 98%, and efficiency of delivery (including house load) was fixed at 95% [7].

The equations used to balance the indirect steam cycle illustrated in Figure 3.7 are set out below.

***Power of the steam turbines***

The power in the high, intermediate and low-pressure turbines was calculated using Equation 3.1 [8]:

$$\begin{aligned} Q_{HPT} &= \dot{m}_{HPT} \times (h[7] - h[8]) \\ Q_{IPT} &= \dot{m}_{IPT} \times (h[9] - h[10]) \\ Q_{LPT} &= \dot{m}_{LPT} \times (h[11] - h[12]) \end{aligned} \qquad 3.1$$

***Power of the steam generator***

The power of the steam generator was calculated using Equation 3.2 [8]:

$$Q_{SG} = \dot{m}[21] \times (h[22] - h[21]) \qquad 3.2$$

***Power of the condenser***

The power of the condenser was determined using Equation 3.3 [8]:

$$Q_{condenser} = \frac{\dot{m}_{con} \times (h[13] - h[14])}{\eta_{condenser}} \qquad 3.3$$

### *Reheating*

The power in the reheating system was calculated using Equation 3.4 [8]:

$$Q_{reheating} = \frac{\dot{m}_{reheating} \times (h[24] - h[23])}{\dot{m}_{reheating}} \qquad 3.4$$

### *Efficiency of the Potchefstroom Experimental Pebble Bed Modular Reactor plant*

The power generated in the steam cycle was determined using Equation 3.5 [8]:

$$P_{generator} = \eta_M \times (Q_{HPT} + Q_{IPT} + Q_{LPT}) \qquad 3.5$$

In Equation 3.5, $\eta_M$ represents the mechanical efficiency, and $Q_{HPT}$, $Q_{IPT}$ and $Q_{LPT}$ represent the shaft power of the high, intermediate and low pressure turbines.

Equation 3.5 was used in Equation 3.6 to determine the overall efficiency of the PEPER plant [8]:

$$\eta_{PEPER} = \frac{P_{generator}}{Q_{SG} + Q_{HPP} + Q_{IPP} + Q_{LPP}} \qquad 3.6$$

In Equation 3.6, $Q_{SG}$ represents the total heat absorbed in the steam generator, and $Q_{HPP}$, $Q_{IPP}$, $Q_{LPP}$ represent the shaft power of the high, intermediate and the low-pressure pump. The calculated efficiency of the PEPER plant with the indirect steam cycle acting as PCU is 40.33%.

### 3.2.3 Sizing of the indirect steam cycle in Engineering Equation Solver

Engineering Equation Solver was used to determine the sizes of the heavy equipment of the PCU that will be used in the PEPER plant to generate electricity from the heat produced by the PEPER plant.

The PFD with some of the calculated values is shown in Figure 3.8. The Full EES model with all the solved values will be presented in Appendix A.

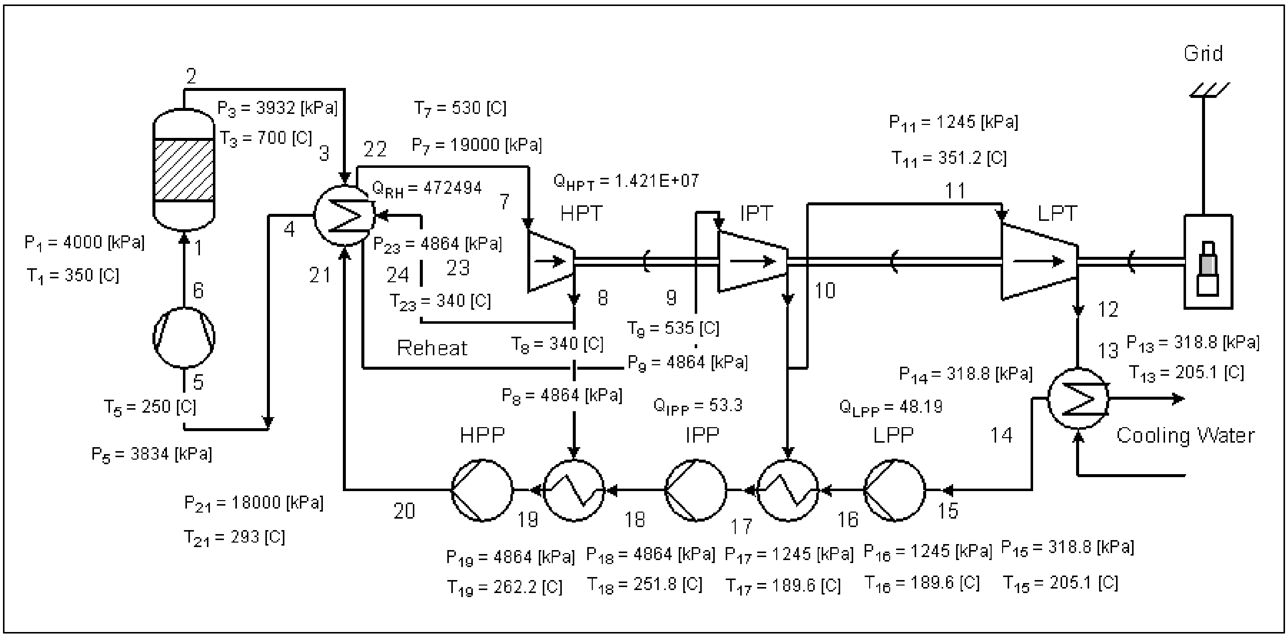

**Figure 3.8:** **Solved process flow diagram for the PEPER plant**

The equipment sizes of the indirect steam cycle for the PEPER plant were calculated using EES and are given in Table 3.1 on the next page.

**Table 3.1: Equipment sizes of the indirect steam cycle for the PEPER plant**

| **Primary cycle (Helium side)** | Mass-flow (kg/s) | Q (KW) | Efficiency (%) | Inlet pressure (kPa) | Outlet pressure (kPa) | Pressure ratio | Inlet temp (°C) | Outlet temp (°C) | Type |
|---|---|---|---|---|---|---|---|---|---|
| **Helium blower** | 55.04 | | | | | | | | |
| | | 30970 | 85 | 3932 | 3834 | 0.97508 | 700 | 250 | |
| **Secondary cycle (Steam side)** | | | | | | | | | |
| **HPT** | 46.95 | | | | | | | | |
| **IPT** | 42.25 | 13185 | 85 | 19000 | 4028 | 0.212 | 530 | 340 | Axial steam turbine |
| **LPT** | 40 | 14076 | 85 | 4028 | 604.3 | 0.15 | 530 | 366.7 | Axial steam turbine |
| **Cooling tower** | 40 | 16865 | 422.5 | 604.3 | 60.43 | 0.1 | 366.7 | 138.8 | Axial steam turbine |
| **LPP** | 42 | 41320 | 85 | 60.43 | 60.43 | | 138.8 | 86.11 | Dry or wet |
| **IPP** | 45 | 26.71 | 80 | 60.43 | 604.3 | 10 | 86.11 | 86.17 | Centrifugal |
| **HPP** | 49 | 197.7 | 80 | 604.3 | 4028 | 0.8 | 153 | 153.6 | Centrifugal |
| **LPH** | 42 | 953.2 | 80 | 4028 | 18000 | 4.468 | 208.5 | 211.9 | Centrifugal |
| **IPH** | 49 | 3400 | | 604.3 | 604.3 | | 86.17 | 153 | Centrifugal |
| **Steam generator** | | 3442 | | 4028 | 4028 | | 153.6 | 208.5 | Helical |
| **Generator** | | 43243 | | | | | | | Electrical |

This chapter has demonstrated that the indirect steam (Rankine) cycle would serve as an efficient PCU for the PEPER power plant. The sizes of the heavy equipment of the indirect steam cycle were calculated using EES and were presented in the chapter. The sizes of the heavy equipment of the plant given in this chapter will be used in Chapter 4 to obtain all the prices for the heavy equipment and thereby determine the cost of the plant.

# Chapter 4

# Equipment cost of the PEPER plant

*If I have seen further than others, it is by standing upon the shoulders of giants.*

*– Isaac Newton (4 January 1643 – 31 March 1727)*

# 4. Equipment cost of the PEPER plant

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*The equipment sizes of the selected PCU in Chapter 3 are used in this chapter to determine the cost of the heavy equipment required for the PCU of the PEPER plant. The top-down cost estimating method is used to estimate the cost of the heavy equipment used in the PEPER plant. The equipment costs determined in this chapter are overnight costs with a base date of June 2008 (all the costs are in US$).*

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## 4.1 Equipment pricing for the primary cycle of the indirect steam cycle

The equipment that will be used in the primary cycle of the indirect steam cycle for the PEPER plant is the helium blower and the RPV. The estimated prices for this equipment are given in the sections that follow.

### 4.1.1 Cost of the helium blower

Using EES, it was determined that the helium blower needed in the primary cycle of the indirect steam cycle would require a mass flow of 55 kg/s. The price of this centrifugal helium blower was estimated using the cost formulas for blowers given by Seider *et al*. [16].

***Brake horsepower***

The equipment size factor for the helium blower is the brake horsepower $P_B$ as calculated using Equation 4.1 [21]:

$$P_B = 0.00436\left(\frac{k}{k-1}\right)\frac{Q_I P_I}{\eta_B}\left[\left(\frac{P_0}{P_I}\right)^{\frac{k-1}{k}} - 1\right] \qquad 4.1$$

Equation 4.1 assumes the ideal gas law and a constant specific heat ratio k [16]. The inlet volumetric flow rate used in Equation 4.1 is $Q_I = 106.029\ ft^3/min$ (55 kg/s), the inlet pressure is $P_I = 556.075\ lbf/in^2$ (3834 kPa) and the outlet pressure is $P_O = 580.15\ lbf/in^2$ (4000 kPa). The constant specific heat ratio for helium was calculated as $k\ (cp/cv) = 1.664$. The mechanical efficiency of the centrifugal blower is taken as $\eta_B = 0.75\%$.

The equipment size factor was calculated as $P_B = 14.651$.

***Fractional efficiency of the electric motor***

The centrifugal helium blower is driven by an electric motor with a direct drive. Equation 4.2 was used to determine the fractional efficiency of the electric motor with brake horsepower [16] [21]:

$$\eta_M = 0.8 + 0.0391 \times \ln(P_B) - 0.00182 \times (\ln(P_B))^2 \qquad 4.2$$

The efficiency of the electric motor was calculated as $\eta_M = 89.2\%$.

***Power consumption of the motor for the centrifugal helium blower***

The power consumption of the motor was determined using the brake horsepower and the fractional efficiency of the motor as given in Equation 4.3 [16] [21]:

$$P_C = \frac{P_B}{\eta_M} \qquad 4.3$$

The power consumption of the motor required to drive the centrifugal helium blower was calculated as $P_C = 16.428$ horsepower.

***Base cost for the centrifugal helium blower***

The base cost of the centrifugal helium blower with the electric motor drive and the cast iron construction housing was calculated using Equation 4.4 below [16] [21]:

$$\mathrm{C_B} = \exp\{7.35356 + 0.79320[\ln(P_c)] - 0.012900[\ln(P_c)]^2\} \qquad 4.4$$

The centrifugal helium blower with the electric motor drive was estimated as $\mathrm{C_B}$ = *US$1000,000*.

### 4.1.2 Cost of the reactor pressure vessel

The reactor design determines the maximum operating temperature of the RVP. The maximum operating temperature then determines the vessel materials that will both comply with the design codes and allow an acceptable lifespan. The South African PBMR (Pty) is considering using SA-508 steel for the reactor vessel of the PBMR-DPP. This steel has been used for RVPs in LWRs and requires a relatively low operating temperature. The South African PMBR (Pty) has calculated a normal operating temperature of 280°C for the RVP. This low temperature is achieved with a pressure vessel conditioning system that uses an independent coolant stream to keep the RPV at an acceptable temperature [13].

The price of the RPV for the PEPER plant was determined by the assumption that PBMR (Pty) will make use of SA-508 steel to build the PBMR-DPP RPV and consequently SA-508 steel will be used for the RPV of the PEPER. The cost of building an RPV with SA-508 steel was indicated as US$42/kg (June 2008) [17]. The amount of SA-508 steel required to build the PEPER RPV was calculated using the EES algorithm that will be given in Appendix B. The geometry of the PEPER plant was given in Table 2.3. The total mass of SA-508 steel necessary to build the PEPER plant was calculated as 333.5 t. The total price of the 333.5 t of SA-508 steel would then be US$14,007,000.00. This price is only for the SA-508 and does not include the graphite and material for core internals. The price for the graphite and material for the core internals for the PEPER RPV was determined based on reference data for the PBMR-DPP (400 $MW_{th}$ reactor) [12], consequently the graphite and material for the core internals for the PEPER RPV was estimated as US$8,728,748.00. The total estimated price for the PEPER RPV including the graphite and core internals is thus US$22,735,748.00.

## 4.2 Equipment pricing for the secondary cycle of the indirect steam cycle

The equipment that will be used in the secondary cycle of the PEPER plant consists of turbines, pumps, heaters, the cooling tower, the helical steam generator and the generator as was illustrated in Figure 3.8. The estimated prices for this equipment are given in the sections that follow.

### 4.2.1 Costs of the turbines, pumps, heaters and cooling tower

General pricing of the equipment sizes as was presented in Table 3.1 was obtained from the PBMR-DPP in-house databank [21] for the turbines; low, intermediate and high pressure pumps; low and high pressure heaters; and cooling tower. The prices for the equipment are provided in Table 4.1.

**Table 4.1: Prices for the turbines, pumps, heaters and cooling tower [21]**

| Equipment | Rating ($m^3$/hr) | Price (US$) |
|---|---|---|
| HPT | 169 | 6,282,238.00 |
| IPT | 151 | 6,576,485.00 |
| LPT | 144 | 7,463,607.00 |
| LPP | 151 | 114,871.00 |
| IPP | 162 | 120,667.00 |
| HPP | 176 | 127,875.00 |
| LPH | 151 | 6,771,407.00 |
| IPH | 176 | 7,448,547.00 |
| Cooling tower | 144 | 100,880.00 |
| **Total equipment cost** | | **35,006,577.00** |

Table 4.1 shows that the total equipment cost for the turbines, pumps, heaters and cooling tower would be US$35,006,577 [21].

### 4.2.2 Cost of the generator

The generator was sized using the EES algorithm that will be given in Appendix A. It was determined that the generator would have to be 43.3 $MW_e$ for the PEPER plant to have an efficiency of 40.33%. The price of a 43.3 $MW_e$ generator was obtained from the school of Electrical, Electronic and Computer Engineering at the North-West University [14]. This price is US$3,739,612 (July 2008).

### 4.2.3 Cost of the helical steam generator

Basson designed the helical steam generator for the PEPER plant that will link the primary and the secondary cycle [15]. The designed parameters for the steam generator are: tube-side area for flow is 0.259 $m^2$ and the shell-side area for flow is 1.997 $m^2$. The price for this helical steam generator was obtained from PBMR-DPP in-house databank for heat exchangers [12]. This price is US$208,287.00.

## *4.3 Total equipment cost for the Potchefstroom Experimental Pebble Bed Modular Reactor plant*

The sum of the costs of the turbines, pumps, heaters, cooling tower, generator, helical steam generator, helium blower and RPV is the total equipment cost that will be used as input for the economic model for the PEPER plant. The total equipment cost of the PEPER plant is calculated in Table 4.2.

**Table 4.2: Total equipment cost of the PEPER plant**

| Equipment | Rating | Price (US$) |
|---|---|---|
| HPT (6MW) | 169 $m^3$/hr | 6,282,238.00 |
| IPT | 151 $m^3$/hr | 6,576,485.00 |
| LPT | 144 $m^3$/hr | 7,463,607.00 |
| LPP | 151 $m^3$/hr | 114,871.00 |
| IPP | 162 $m^3$/hr | 120,667.00 |
| HPP | 176 $m^3$/hr | 127,875.00 |
| LPH | 151 $m^3$/hr | 6,771,407.00 |
| IPH | 176 $m^3$/hr | 7,448,547.00 |
| Cooling tower | 144 $m^3$/hr | 100,880.00 |
| Generator | 43.3 $MW_e$ | 3,739,612.00 |
| Helical steam generator | Helical | 208,287.00 |
| Centrifugal helium blower | 55 kg/s | 1000,000.00 |
| RPV | | 22,735,748.00 |
| **Total equipment cost** | | **62,690,224.00** |

The total equipment cost of the PEPER plant that will be used for the input for the economic model for the PEPER plant is US$62,690,224.

*Chapter 4 has calculated the equipment cost of the PEPER plant that will be used as input for the economic model for the plant. The turbines, pumps, heaters, cooling tower, generator, helical steam generator and RPV were priced in this chapter. The total equipment cost for the PEPER plant was calculated as US$62,690,224. The TCIC consisting of the cost of the selected PCU and the cost of the RPV as calculated in this chapter will be used in Chapter 5 to serve as input for the economic model.*

# Chapter 5

# Economic model for the Potchefstroom Experimental Pebble Bed Modular Reactor plant

*We are more ready to try the untried when what we do is inconsequential. Many inventions had their birth as toys.*

*– Eric Hoffer (July 25, 1902 – May 21, 1983)*

# 5. Economic model for the Potchefstroom Experimental Pebble Bed Modular Reactor plant

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*The following chapter explains the economic model that was developed for the PEPER plant using the total equipment costs estimated in Chapter 4 as input.*

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## *5.1 Top-down cost estimation approach*

A top-down cost estimation approach was used to develop the economic model for the PEPER plant. The top-down approach was developed in Argentina, Canada and France [19]. The cost estimation process of the top-down model is illustrated in Figure 5.1 [19].

**Figure 5.1: Top-down cost estimation approach [19]**

The estimated cost for the PEPER plant was based on reference data from the 400 MW$_{th}$ PBMR-DPP. All the reference prices and cost ratios from the 400 MW$_{th}$ PBMR-DPP were pro-rated for output. Single module factors were used for bulk materials and installation labour was used per item delivered to site [12]. The total equipment costs of US$62,690,224.00 presented in Chapter 4 were used as input data for the economic model of the PEPER plant.

The economic model was developed for a FOAK PEPER plant with an implemented NOAK function in order to estimate the costs of a NOAK PEPER plant.

## *5.2 Production cost*

The production cost has five components, namely capital-dependent, working capital, O&M, fuel and auxiliary materials costs [18]. The capital-dependent cost and the working capital (expressed in US$) are calculated and implemented in the two years before the PEPER plants sixty-year lifetime commences (these years are noted as year minus 2 and year minus 1 in the economic model for the PEPER plant). This means that the capital-dependent and working capital must be paid in the two years prior to setting the PEPER plant into operation.

The costs for O&M, fuel and auxiliary materials were calculated in US$/kWh. The summation of these three components served as the production cost in the economic model for the PEPER plant. This production cost expressed in US$/kWh and consisting of the O&M, fuel and auxiliary materials costs serves as the production cost for the PEPER plant from year zero to year sixty.

### 5.2.1 Capital-dependent costs

The capital-dependent costs, which consist of direct and indirect costs, was applied in the first two years (construction time) of the sixty-year economic lifetime of the PEPER plant. The estimated fixed capital investment costs is the lump sum up-front cost that includes the cost to purchase and install the required machinery and equipment. It is essential that land be obtained, service facilities be made available and that the plant be erected complete with all piping, controls and services. In addition, funds are required for operational costs before sales revenue becomes available. The estimated total capital investment cost (TCIC) is the sum of the fixed capital investment costs and the working capital [20]. The fixed capital investment costs is the sum of the direct field costs, indirect field costs and the contingency costs and extends over the first two years of the economic model.

#### 5.2.1.1 Direct field cost

The direct field cost includes all the costs to construct the permanent PEPER plant. This includes the mechanical, civil structures, buildings, piping, electrical systems, structural, instrumentation, and painting and insulation costs.

The total equipment cost consisting of the high pressure turbine, intermediate pressure turbine, low pressure turbine, cooling tower, low pressure pump, intermediate pressure pump,high pressure pump, low pressure heater, intermediate pressure heater, generator, steam generator, centrifugal helium blower and the PEPER RPV is estimated in Chapter 4 to be US$62,690,224. This total equipment cost is used to derive the total direct field cost using predefined ratios. The ratios of the different components of the total direct field cost are explained below. The ratios of the total direct field cost were obtained from the 400 $MW_{th}$ PBMR-DPP for output [12] and are presented in Table 5.5.

### *Mechanical cost*

The mechanical cost includes all the costs of the major equipment as calculated in Chapter 4 with additional capital for non-process equipment, heating, ventilation and air conditioning ductwork, and insulation. The estimated mechanical cost was calculated as 118.4% of the total equipment cost [12].

### *Civil structures cost*

The civil structures cost is the cost of any civil structures in the PEPER plant. The work breakdown structure for the civil structures in Table 5.1 was obtained from *Cost estimating guidelines for Generation IV nuclear energy systems* [19]. The estimated civil structures cost was calculated as 53.2% of the total equipment cost [12].

**Table 5.1: Work breakdown structure for civil structures [19]**

| Category/commodity | Methodology |
|---|---|
| Site excavation | Developed for area of site |
| Structural excavation | Developed for all buildings |
| Structural backfill | Developed from excavation and construction scope |
| Trenching | Developed from site plan mark-up for pipe and duct bank |
| Temporary formwork | Developed from planned drawings |
| Permanent formwork | Developed from planned drawings |
| Embedded metals | Allowance-to-volume ratio of concrete by structural component |
| Reinforcing steel | Taken sample-to-volume ratio of concrete by structural component |
| Concrete | Developed from planned drawings with use of average wall/slab thickness as required |
| Structural steel | Taken or developed from planned drawings for process buildings. Non-process buildings use allowance weight/building floor areas |
| Miscellaneous steel | Ratio to weight of structural steel |
| Liner plate | Developed with engineering definition |
| Roofing | Processed buildings by take-off, other with allowances per floor area |
| Siding | Processed buildings by take-off, other with allowances per floor area |
| Painting/coating | Developed from planned drawings mark-up by engineering for type of system |
| Windows/doors | Taken from planned drawings |

| | |
|---|---|
| Interior finishes and furnishings | Developed from planned drawings marked up by engineering |
| Non-process buildings | Allowances of cost and hours per floor area, including services |

### *Building cost*

The building cost includes the costs to build the offices, storerooms, conference rooms, refreshment rooms, auditoriums, and the staff and security quarters necessary for the PEPER plant. The building cost also includes the cost of services to maintain the buildings. The estimation of the building cost was calculated as 21.6% of the total equipment cost [12].

### *Piping cost*

The cost for piping in the PEPER plant includes labour, valves, fittings, pipes and supports. [20]. The work breakdown structure (WBS) for the piping in Table 5.2 was obtained from *Cost estimating guidelines for Generation IV nuclear energy systems* [19]. The estimated cost of the piping was obtained from the PBMR-DPP for 100 $MW_{th}$ output [21] and was calculated to be 44.4% of the total equipment cost [12].

**Table 5.2: Work breakdown structure for the piping [19]**

| Category/commodity | Methodology |
|---|---|
| Process system piping | Conceptual routing of pipe from P&ID and planned drawings |
| Utility system piping | Conceptual layout of utility piping systems on planned drawings or site plans, plus system equipment interconnections |
| Facility services piping | Plumbing and drainage systems conceptual layout marked up on planned drawings |
| Process systems valves | Taken from P&IDs, including allowances for instrumentation root valves |
| Large pipe hangers | Average spacing including use of multiple pipe hangers |
| Small pipe hangers | Not quantified; included in cost of small pipe |
| Miscellaneous piping items | Not quantified; included in allowance for miscellaneous piping operations ratio to large and small pipes |
| Pipe insulation | Developed with pipe scope, based on the engineering definition for insulation requirements |

### *Electrical systems cost*

The electrical systems cost in the plant can be grouped into four major components, namely power wiring, lightning, transformation and service, and instrument and control wiring [20]. The electrical systems includes the cable tray, exposed conduits, embedded conduits, underground conduit and duct systems, and fittings, supports, covers, boxes, access holes, ducts and accessories for the scheduled cable systems. The WBS for the electrical systems in Table 5.3 was gained from *Cost estimating guidelines for Generation IV nuclear energy systems* [19]. The estimated cost of the electric systems was obtained from the PBMR-DPP with 100 $MW_{th}$ output [21] and was calculated as 15.6% of the total equipment cost [12].

**Table 5.3: Work breakdown structure for electrical systems [19]**

| Category/commodity | Methodology |
|---|---|
| Distribution equipment, direct current (DC) and emergency power | Taken from single-line diagrams |
| Cable tray | Developed from conceptual tray layout and marked up on planned drawings |
| Duct bank conduit | Developed from conceptual routing and marked up on site plans |
| Power control and instrumentation exposed conduit | Developed from historical ratio of raceway to cable |
| Scheduled power cable | Developed for single-line diagram distribution and connect loads with average length and average size distribution |
| Scheduled control cable | Developed with historical ratio to connect loads, average length and average size distribution |
| Scheduled instrumentation cable | Developed with historical ratio to quantity of field instruments, average length and average size distribution |
| Grounding | Developed from conceptual layout marked up on site plan plus route length of cable tray |
| Process buildings lighting | Reference plant ratio of commodities per floor area |
| Non-process building lighting | Not quantified; included in costs per floor area |
| Yard lighting | Developed from conceptual layout marked up on site plans |
| Communication systems | Developed from engineering mark-up of arrangement drawings |
| Cathodic protection | Developed allowance from engineering system description and marked up site plans |
| Heat tracing | Developed allowance from engineering system description and quantification of piping systems |
| Radio system | Developed from engineering system description and mark-up of planned drawings for the antenna system |
| Security system | Developed allowance for a system with engineering input and reference plant data |

### *Structural cost*

The structural cost includes the costs of the structural steel, miscellaneous steel, liners, fabricated commodities, architecture, earthwork, piles and site improvements [19]. The estimated structural cost of the PEPER plant was obtained from the PBMR-DPP with 100 $MW_{th}$ output and was calculated as 14.4% of the total equipment cost [12].

### *Instrumentation cost*

The instrumentation cost consists of the costs of the control room equipment, local control panels, field-mounted instruments, instrument racks, instrumentation bulks, packaged control systems, control and relief valves, and calibration testing. The WBS for the instrumentation presented in Table 5.4 was obtained from *Cost estimating guidelines for Generation IV nuclear energy systems* [19]. The estimated cost of the instrumentation was obtained from PBMR-DPP with 100 $MW_{th}$ output [21] and calculated as 28.6% of the total equipment cost [12].

**Table 5.4: Work breakdown structure for instrumentation [19]**

| Category/commodity | Methodology |
|---|---|
| Control room equipment | Developed from planned drawings and system data sheets |
| Local control panels | Developed from the equipment list and reference plant data |
| Field-mounted instruments | Taken from the instrument index and the P and IDs |
| Instrument racks | Taken from design allowances of the plant areas |
| Instrumentation bulks | Taken from reference plant data ratio to field-mounted instruments |
| Packaged control system | Developed costs with engineering capacity data and vendor input |
| Control and relief valves | Taken from the P&IDs |
| Calibration testing | Calibrate all instruments according to specified standards. |

### *Painting and insulation costs*

The estimated cost for the painting and insulation work on the PEPER plant was obtained from the PBMR-DPP with 100 $MW_{th}$ output [21] and was calculated as 6.6% of the total equipment cost [12].

### *Total direct field cost*

The total direct field cost was calculated from the above ratios obtained from the 400 $MW_{th}$ PBMR-DPP with 100 $MW_{th}$ output as reference [21]. The total estimated direct field cost is US$189,825,998. Table 5.5 provides a summary of this cost.

**Table 5.5: Total direct field cost**

| Direct field costs | | |
|---|---|---|
| **Project identifier** | **% of total equipment cost** | **Cost (US$)** |
| Mechanical cost | 118.4 | 74,225,225.22 |
| Civil structures cost | 53.2 | 33,351,199.17 |
| Buildings (including services) cost | 21.6 | 13,541,088.38 |
| Piping (installed) cost | 44.4 | 27,834,459.46 |
| Electrical systems (installed) cost | 15.6 | 9,779,674.94 |
| Structural cost | 14.4 | 9,027,392.26 |
| Instrumentation cost | 28.6 | 17,929,404.06 |
| Painting and insulation cost | 6.6 | 4,137,554.78 |
| **Total direct field cost** | | **189,825,998.00** |

#### 5.2.1.2 Indirect field cost

The indirect field cost, also known as the non-manufacturing fixed-capital investment, includes engineering; procurement; construction; management; temporary construction facilities; field staff subsistence and travelling; construction services, supplies and consumables; construction equipment rental; and insurance and legal services. The components of the indirect field cost were derived as a ratio of the total direct field cost. The ratios of the total indirect field cost were obtained from the 400 MW$_{th}$ PBMR-DPP for 100 MW$_{th}$ output [12].

***Engineering, procurement, construction and management costs***

Based on the PBMR-DPP with 100 MW$_{th}$ output [21], it was estimated that the engineering, procurement, construction and management (EPCM) costs for the PEPER plant would be 20% of the direct field cost [21]. Table 5.6 presents a breakdown of EPCM.

**Table 5.6: EPCM breakdown [21]**

| Description | Location |
|---|---|
| Travel costs | Local and international |
| Accommodation and subsistence | Local |
| Reprographics | Local |
| Communication | Local and international |
| Computer costs | Local |
| Third-party engineering fees | Local |
| Consultant fees | Local |
| Legal fees | Local |
| Minor consumables | Local |

### *Temporary construction facilities cost*

The cost of the temporary construction facilities includes the costs for site facility establishment and eradication, lay-down area, roads, fencing, drainage, temporary offices, ablutions, storage sheds, pre-fabrication areas, pipe shop, and similar facilities. The temporary construction facilities were estimated to be 5.76% of the total direct field cost [21].

### *Field staff subsistence and travelling costs*

The field staff subsistence and travelling costs include costs for site running (telephones, faxes, tea, coffee, stationery, sundries), site administration, supervision, disbursements and fees. The field staff subsistence and travelling costs were estimated to be 5.76% of the total direct field cost [21].

### *Construction services, supplies and consumables costs*

The costs of construction services, supplies and consumables includes costs for consumables (welding rods, gasses, slings, shackles, cleaning equipment) and small tools (drilling machines, grinders and indoor small cranes). These costs were estimated to be 5.76% of the total direct field cost [21].

### *Construction equipment rental cost*

This cost includes minor equipment (welding machines, compressors, generators) and major equipment (cranes, transport equipment, site vehicles). The rental cost for the construction equipment was estimated to be 5.76% of the total direct field cost [21].

### *Insurance and legal services costs*

Insurance and legal services costs cover accidents of all types from personnel to equipment and materials, including legal services. The insurance and legal services costs were estimated to be 5.76% of the total direct field cost [21].

### *Total indirect field cost*

The total indirect field cost was calculated from the above ratios obtained from the 400 $MW_{th}$ PBMR-DPP with 100 $MW_{th}$ output as reference [21]. The total estimated direct field cost is US$92,635,087. Table 5.7 provides a summary of this cost.

Table 5.7: Total indirect field cost

| Indirect field cost | | |
|---|---|---|
| **Project identifier** | **% of total direct field cost** | **Cost (US$)** |
| EPCM | 20.00 | 37,965,199.65 |
| Temporary construction facilities | 5.76 | 10,933,977.50 |
| Field staff subsistence and travelling | 5.76 | 10,933,977.50 |
| Construction services, supplies and consumables | 5.76 | 10,933,977.50 |
| Construction equipment rental | 5.76 | 10,933,977.50 |
| Insurance and legal services | 5.76 | 10,933,977.50 |
| **Total indirect field cost** | | **92,635,087.00** |

### 5.2.1.3 Contingency cost

The contingency of the PEPER plant consists of three components, namely contingency that covers the uncertainty of construction cost, contingency that covers the cost effect of construction schedule uncertainty, and contingency that covers uncertainty in plant performance as measured by the capacity factor. The contingencies for the PEPER plant were estimated to be 30% of the total fixed capital investment costs (total field cost) according to the PBMR-DPP with 100 $MW_{th}$ output estimation [21]. The total fixed capital investment costs as calculated by the sum of the direct and the indirect field costs. The contingency costs were estimated to be US$84,738,326.

### 5.2.1.4 Fixed capital investment costs

The fixed capital investment costs is the sum of the direct field costs, indirect field costs and the contingency costs and extends over the first two years of the economic model.
The estimated total fixed capital investment costs for the PEPER plant was estimated to be US$367,199,411 for a FOAK PEPER plant and US$238,429,665 for a NOAK PEPER plant (excluding 14% VAT; June 2008).

### 5.2.2 Working capital

The working capital of the PEPER plant consists of the total amount of money invested in construction, contingency, first fuel loading, and decommissioning costs. The costs of construction, contingency and the first fuel loading are incorporated into the first two years (before the PEPER plant is in operation) of the working capital. The decommissioning costs are subtracted from the working capital in the last year of operation with an estimated discounted rate of 6% [23] in the economic model of the PEPER plant; the discounted rate can be varied in this economic model.

### *Construction cost*

The labour cost required to erect the PEPER plant was estimated using ratios of the major equipment cost obtained from the PBMR-DPP with 100 MW$_{th}$ output [21]. These ratios are illustrated in Table 5.8 [12]. The total labour cost to erect the PEPER plant was estimated to be US$6,441,841.

**Table 5.8: Construction labour cost of the PEPER plant [12]**

| Equipment | Rating | Cost/unit (US$) | Construction labour ratio of unit cost (%) | Contractor installation/erection costs (US$) |
|---|---|---|---|---|
| HPT (6 MW) | 169 $m^3$/hr | 6,282,238.00 | 12 | 753,868.56 |
| IPT | 151 $m^3$/hr | 6,576,485.00 | 12 | 789,178.20 |
| LPT | 144 $m^3$/hr | 7,463,607.00 | 12 | 895,632.84 |
| LPP | 151 $m^3$/hr | 114,871.00 | 20 | 22,974.20 |
| IPP | 162 $m^3$/hr | 120,667.00 | 20 | 24,133.40 |
| HPP | 176 $m^3$/hr | 127,875.00 | 20 | 25,575.00 |
| LPH | 151 $m^3$/hr | 6,771,407.00 | 8 | 541,712.56 |
| IPH | 176 $m^3$/hr | 7,448,547.00 | 8 | 595,883.76 |
| Cooling tower | 144 $m^3$/hr | 100,880.00 | 40 | 40,352.00 |
| Generator | 433 MWe | 3,739,612.19 | 10 | 373,961.22 |
| Helical steam generator | Helical | 208,287.00 | 12 | 24,994.44 |
| Centrifugal helium blower | 55 kg/s | 1000,000.00 | 8 | 80,000.00 |
| RPV | | 22,735,748.00 | 10 | 2,273,574.80 |
| **Total construction cost** | | | | **6,441,841.00** |

### *First fuel-loading cost*

The fuel spheres that will be used to fill the PEPER plant for the first fuel loading were calculated as 10 7869 fuel spheres based on Equation 5.1.

Volume of the core = $20m^3$;

Porosity = $0.39$;

Void volume in core = $20m^3 \times 0.39 = 7.8m^3$;

Fuel volume in core = $20m^3 \times 0.39 = 12.2m^3$; *5.1*

Volume of pebble = $\frac{4}{3}\pi r^3 = \frac{4}{3}\pi(0.03)^3 = 0.0001131m^3$; and

Amount of pebbles = $\frac{12.2m^3}{0.0001131m^3} = 107869 \text{ fuel spheres}$.

According to the PBMR-DPP, the cost per fuel sphere is US$100 [12]. The cost of the total amount of fuel spheres for the first fuel loading would then be US$10,786,900. This is a once-off cost that would be paid in the first two years. During the following fifty-nine years, the PEPER plant will need to be filled to a third of its volume with fuel spheres annually. This annual fuel cost was implemented in the fuel cost per year fraction of the production costs.

#### *Decommissioning cost*

Decommissioning costs is the cost at the end of the PEPER plant's economic lifetime and entails that the PEPER plant be dismantled, decommissioned and decontaminated. The *Cost estimating guidelines for Generation IV nuclear energy systems* [19] claims that the decommissioning costs of a Generation IV NPP is 10% of the fixed capital investment costs. This cost was implemented in the economic model of the PEPER plant as working capital. In the last year of operation, the decommissioning cost would be subtracted in the cumulative cash-flow diagram.

#### *Total working capital*

The estimated working capital is the sum of the total construction cost and the first fuel loading cost. In the last year of operation, the decommissioning cost is added to the total working capital. The estimated working capital for the PEPER plant was calculated as US$17,228,740. This cost is split over the first two years before the PEPER plant is set into operation. The working capital in the last year of operation, thus including the decommissioning cost, was calculate as US$36,719,941 for a FOAK PEPER plant and US$23,842,966 for a NOAK PEPER plant.

### 5.2.3 Annual operation and maintenance, fuel and auxiliary material production costs

The O&M, fuel and auxiliary material costs are costs that occur annually. This production cost was taken into account for each year in the sixty-year economic lifespan of the PEPER plant. The annual O&M, fuel and auxiliary material production costs were calculated in US$/kWh.

### 5.2.3.1 Operation and maintenance costs per annum

It was estimated that hundred and forty people will be needed to operate and maintain the PEPER plant. A working factor of 80% for the operating labour was taken into account [19]. According to *Cost estimating guidelines for Generation IV nuclear energy systems* [19], a labour rate of US$34 per hour should be used in an economic model for operating a Generation IV nuclear plant. The O&M costs include the salaries for the O&M labour only, as the other non-fuel costs were calculated separately. The estimated O&M labour of the PEPER plant is given in Table 5.9.

**Table 5.9: Operation and maintenance costs**

| O&M | Quantity | Unit |
|---|---|---|
| Employees | 140 | Workers |
| Process steps | 1 | |
| Working factor | 80 | % |
| Employee hours | 280512 | per year |
| Labour rate | $34.00 | per hour |
| **Total O&M costs** | **US$9,537,408.00** | **per year** |

Equation 5.2 was used to calculate the O&M costs in US$/kWh [8]:

$$x_{\mathrm{O\&M}} = \frac{C.k_c}{P_{el}^0 \cdot T} \qquad 5.2$$

In Equation 5.2, $C.k_c$ is the operating labour cost per year (US$9,537,408.00), $P_{el}^0$ is the net electrical power of the plant (40330 kW) and T is the full-load hours per year (8766 h/year). The O&M costs were estimated to be 0.027 US$/kWh per year.

### 5.2.3.2 Fuel cost per annum

The fuel spheres needed to fill the reactor once for the first fuel loading were calculated in equation 5.1 as 10 7869 fuel spheres in the reactor. For the next fifty-nine years of the reactor's economic lifespan, fuel spheres would only fill a third of the reactor's volume in the core. Thus, the reactor would be filled with 10 7869 fuel spheres in the first year and 35 956 fuel spheres each year thereafter.

According to the PBMR-DPP, the cost per fuel sphere is US$100 [12]. The cost of the fuel spheres to be used per annum in the PEPER plant is $US\$100 \times 35956\,\text{fuel spheres} = \text{US\$3,595,600.00 per year}$ for fifty-nine years. Equation 5.3 was used to calculate the fuel cost in US$/kWh [8]:

$$x_{\text{Fuel cost}} = \frac{A_F}{P_{el}^0 \cdot T} \qquad 5.3$$

In Equation 5.3, $A_F$ is the annual fuel cost (US$3,595,600.00), $P_{el}^0$ is the net electrical power of the plant (40 330 kW) and $T$ is the full-load hours per year (8766 h/year). The estimated fuel cost is 0.01 US$/kWh per year.

#### 5.2.3.3 Auxiliary material cost per annum

The auxiliary material cost generally refers to the materials that are directly consumed in fabricating the final product. In the case of the PEPER plant, the final product is electricity. The auxiliary material in the PEPER plant that was included in the costing is the cooling water for the cooling tower in the indirect steam cycle. The amount of cooling water required in the condenser for cooling in the secondary cycle was calculated using the calculations shown below.

$$Q_{steam} = Q_{water};$$

$$\dot{m}_{steam}\, c_{p_{steam}} \Delta T_{steam} = \dot{m}_{water}\, c_{p_{water}} \Delta T_{water};$$

$$\dot{m}_{steam} = 14.8 kg/s;$$

$$c_{p_{steam}} = 1947 J/kg.^{\circ}C;$$

$$\Delta T_{steam} = 204.73^{\circ}C;$$

$$c_{p_{water}} = 4183 J/kg.^{\circ}C;$$

$$\Delta T_{water} = 10^{\circ}C;$$

$$\dot{m}_{water} = 14.8 kg/s;$$

$$\dot{m}_{water} = \frac{\dot{m}_{steam}\, c_{p_{steam}} \Delta T_{steam}}{c_{p_{water}} \Delta T_{water}};$$

$\dot{m}_{water}$ = $\frac{(14.8)(1947)(204.73)}{(4183)(10)}$;

$\dot{m}_{water}$ = $141 kg/s$;

$\rho_{water}$ = $997.1 kg/m^3$;

Volumetric flow rate = $\frac{141}{997.1} = 0.1414 m^3/s$; and

Amount of water per annum = $(0.1414 m^3/s) \times (31536000\, s) = 4459190.4 m^3 = 4459190.4 ton$

The cost of cooling water was calculated at $US\$0.08/ton$ [20]. The estimated cost for the cooling water is $US\$0.08 \times 4459190.4 ton = US\$356{,}735.23$ per year for sixty years of operation.

Equation 5.4 was used to calculate the auxiliary material cost in US$/kWh [8]:

$$x_{aix} = \frac{A_{aix}}{P_{el}^{0} \cdot T} \qquad 5.4$$

In Equation 5.5, $A_{aix}$ is the annual auxiliary material cost (US$356,735), $P_{el}^{0}$ is the net electrical power of the plant (40 330 kW) and $T$ is the full-load hours per year (8 766 h/year). The estimated auxiliary material cost is 0.001 US$/kWh per year.

#### 5.2.3.4 Total annual operation and maintenance, fuel, auxiliary material production costs

The total O&M, fuel and auxiliary material costs are 0.038 US$/kWh.

## *5.3 Installed cost of the Potchefstroom Experimental Pebble Bed Modular Reactor plant*

The installed cost of the PEPER plant is the total cost to install the PEPER plant the installed cost is given in US$/kWh. The method to estimate the cost to install the PEPER plant is explained below.

### 5.3.1 Electricity production

The product that will be fabricated from the PEPER plant is electricity, which will be sold in kWh. The total amount of electricity that would be produced by the PEPER plant in the first year was calculated as 353 532 780 kWh, as given in Table 5.10.

**Table 5.10: Electricity production of the PEPER plant**

| **Electricity production** | | | |
|---|---|---|---|
| | **Total electricity output (kW)** | **Hours per year** | **Production (kWh/year)** |
| Electricity | 40 330 | 8 766.00 | **353 532 780** |

### 5.3.2 Installed cost

The installed cost of the PEPER plant was calculated using Equation 5.5 [19]:

$$\text{Installed cost} = \frac{\text{Direct field costs} + \text{Construction labour}}{\text{Electricity produced}} \qquad 5.5$$

The direct field costs included major equipment, civil structures and buildings, piping, electrical systems, structural, instrumentation, and painting and insulation costs. The direct field costs were estimated in Section 5.2.1.1 as US$189,825,998.

The construction labour was all the labour required to construct the permanent PEPER plant. The construction labour was estimated in Section 5.2.2 as US$6,441,841.

The PEPER plant has an efficiency of 40.33% as calculated in Chapter 3. In Section 5.3.1, it was calculated that the PEPER plant could produce 353 532 780 kWh annually.

Using Equation 5.6 the installed cost per kWe of the 100 $MW_{th}$ PEPER plant was estimated to be US$4,790.03/kWe. The installed cost per kWhe was estimated to be 0.55 US$/kWh.

## 5.4 Cash-flow diagram

The cash flow, with all the costs and profits, within the economic model of the PEPER plant was determined over a lifespan of sixty years. The cash-flow diagram is illustrated in Chapter 6. Below follows concepts used in the cash-flow diagram.

### 5.4.1 Time value of money

The time value of money means that the value of the initial amount that was invested would increase over time. The time value of money is only related to the ability of money to earn money. It does not relate to inflation. This means that the money that will be invested into the PEPER plant would thus increase over time.

#### 5.4.1.1 Discounted rate

According to the *Cost estimating guidelines for Generation IV nuclear energy systems* [19], the discounted rate is the percentage rate used in calculations in which the inflation component is removed from the time value of money. Calculations that apply the discounted rate assume that the money maintains a constant value in terms of purchasing power. This means that no return on investment would be needed to cover inflation. The estimated discounted rate for a Generation IV nuclear plant is between 5% and 10% [19]. The discounted rate for the PEPER plant was selected as 6% per year [22]. Chapter 6 will discuss the sensitivity analysis in order to demonstrate the effect of the discounted rate on the cash-flow diagram on the construction and operation of the PEPER plant. The varying discounted rates will also be specified.

### 5.4.2 Inflation rate

The inflation rate is the rate of change in the general price level as measured by the Gross Domestic Product Implicit Price Deflator. The inflation rate of each country differs according to various economic factors. The cash-flow diagrams of three countries namely: Romania, France and Japan with different inflation rates will be presented in Chapter 6, in order to demonstrate the effect that the different inflation rates have on the construction and operation of the PEPER plant.

### 5.4.3 Taxes

This includes taxes associated with the permanent PEPER plant, such as property tax, that are to be capitalised with the plant. A tax rate of 28% per year was assumed for the PEPER plant; however, the tax rate can be varied in the economic model of the PEPER plant.

### 5.4.4 Construction time

It was estimated that it would take two years to construct the PEPER plant. Therefore, the fixed capital investment costs was considered over two years.

### 5.4.5 Economic lifetime

The economic lifetime of a NPP is the time that the plant would operate economically and produce electricity to sell. According to the *Cost estimating guidelines for Generation IV nuclear energy systems* [19], Generation IV systems could conceivably operate for sixty years or longer. The estimated economic lifetime of the PEPER plant was assumed as 60 years.

## 5.5 Methods for calculating profitability

The methods for calculating the profitability of the PEPER plant that were used in the economic model for the PEPER plant are grouped into the methods that do not and the methods that do take the time value of money into account. The methods that do not consider the time value of money include the rate of return on investment and PBP [19]. The methods that consider the time value of money include the NPW and discounted cash-flow rate of return [19].

### 5.5.1 Methods that do not consider the time value of money

For the methods that do not consider the time value of money, straight-line depreciation was used.

### 5.5.1.1 Rate of return on investment

The rate of return on investment is defined as the ratio of the profit to investment. For the PEPER plant, the investment would be the fixed capital investment costs. The profit would be the cumulative cash flow without the time value of money. Equation 5.6 presents the calculation of the cumulative cash-flow formula [19].

$$\begin{aligned}\text{Cumulative cash position} &= \text{net profit after taxes} + \text{depreciation} \\ &= -\ \text{total capital investment}\end{aligned} \tag{5.6}$$

In Equation 5.6, the net profit after taxes is the electricity production (Section 5.3.1) multiplied by the income, which differs per country. The industrial and household electricity income for the various countries will be listed in Appendix C. The total capital investment was the sum of the working capital and the fixed capital. Chapter 6 will present the rate of investment (ROI) for various countries.

#### 5.5.1.2 Payback period

The PBP is a profitability measure and is the period necessary for the total return of the capital investment. The PBP was calculated in years using Equation 5.7 [20]:

$$\mathrm{PBP} = \frac{\mathrm{V}+\mathrm{A}_{\mathrm{x}}}{(\mathrm{A}_{\mathrm{j}})_{average}} \qquad 5.7$$

For the PEPER plant, $V+A_x$ is the fixed capital investment costs (Section 5.2.1.4), $(A_j)_{average}$ is the average value of the profit that the PEPER plant makes after taxes over the economic lifetime of sixty years.

### 5.5.2 Methods that consider the time value of money

The NPW and discounted cash-flow rate of return account for the earning power of invested money by discounting techniques. These methods of economic analysis demonstrate the profitability of the PEPER plant best.

#### 5.5.2.1 Net present worth

The NPW is the total of the present worth of all cash flows minus the present worth of all capital investment [19]. The NPW was calculated using Equation 5.8 [19]:

$$\mathrm{NPW} = \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{PWF}_{\mathrm{cf,j}}[(s_j - c_{oj} - d_j)(1-\Phi) + rec_j + d_j] - \sum_{j=-b}^{N} PWF_{v,j}\Gamma_j] \qquad 5.8$$

In Equation 5.8, $PWF_{cf,j}$ is the selected present worth factor for the cash flows in year $j$, $S_j$ is the value of the sales of the electricity in year $j$, $C_{oj}$ is the total product cost not including depreciation in year $j$, $PWF_{v,j}$ is the appropriate present worth factor for investments occurring in year $j$, and $\Gamma_j$ is the total investment in year $j$.

The discounted rate of 6% was used to incorporate an earning into the present worth factors [19]. Taking this into account, the NPW is the amount of money earned over the repayment of all the investment costs and earnings on the investment costs at the discounted rate of 6% used in the present worth factor calculations. The PEPER plant would provide a return greater than the discounted rate if the NPW were positive. The investment in the PEPER plant would be more favourable if the NPW is higher [19]. Chapter 6 will provide the NPV of the various countries.

#### 5.5.2.2 Internal rate of return

The internal rate of return (IRR) also known as the discounted cash-flow rate of return, refers to the return on investment in which all investments and cash flows are discounted. The IRR was determined by setting the NPW in Equation 5.9 to zero and then solving for the discounted rate that satisfies this relation. The MS Excel function goal seek was used to find the discounted rate in Equation 5.9. The IRR was only calculated when the NPW was positive. If the NPW was positive, the calculated IRR showed the actual earning rate of the investment [19].

## *5.6 FOAK and NOAK*

The above calculations and costs are for a FOAK PEPER plant. The NOAK calculation was done in order to demonstrate that the fixed capital investment costs (direct, indirect and contingency costs) decrease, until the NOAK (eighth) PEPER plant is reached at which the fixed capital investment costs will no longer decrease [19].

Using the *Cost estimating guidelines for Generation IV nuclear energy systems* [19], it was assumed that the NOAK PEPER plant (where the fixed capital investment costs will be stabilised) would be the eighth PEPER plant constructed. A cost factor of 0.94 (6% decrease in cost [19]) is applicable to the fixed capital investment costs for each PEPER plant constructed, from the FOAK PEPER plant until the eighth NOAK PEPER plant is reached [19]. This means that the fixed capital investment costs of the second PEPER plant constructed would be the fixed capital investment costs of the FOAK PEPER plant multiplied by 0.94, the fixed capital investment costs of the third PEPER plant would be the fixed capital investment costs of the second PEPER plant multiplied by 0.94, and thus the fixed capital investment costs would continue decreasing by 0.94 until the eighth PEPER plant is constructed. After the eighth NOAK PEPER plant has been constructed, the fixed capital investment costs would no longer decrease.

The NOAK plant cost echoes the valuable cost experience of prior plants that were built. The fixed capital investment costs was estimated to be US$367,199,411 for the FOAK

PEPER plant. The fixed capital investment costs of the FOAK PEPER plant would decrease by 0.94, until the cost stabilises at the eighth PEPER plant which is defined as the NOAK PEPER plant at US$238,429,665. The list with PEPER plants from one to eight, with the corresponding fixed capital investment costs, will be given in Appendix D.

The following assumptions were made and apply to the costing of the NOAK plant [19]:

1. The design would be identical (or nearly identical) to the first commercial PEPER plant with little or none improvements.
2. Equipment manufacture and plant construction would be performed by the same contractors as used for the first commercial PEPER plant.
3. There would be no changes to regulations or major codes and standards subsequent to the first plant.
4. All project services; procurement and construction would be based on competitive bids for a series of identical plants.
5. The plant costs that were repetitive would be incurred in building an identical plant.
6. The non-recurring engineering and home-office services costs of the reactor manufacturer or other major process equipment manufacturing would be zero for the NOAK plant.

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*Chapter 5 has explained the economic model developed in this research project for the PEPER plant. The production cost, including the O&M, fuel and auxiliary materials costs, were estimated to be 0.038 US$/kWh. The installed cost of the PEPER plant, consisting of the direct field and construction labour costs was estimated to be US$4,760.03/kWe or 0.55 US$/kWhe. The results of the economic model derived here will be presented in Chapter 6.*

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# Chapter 6

# Results of techno-economic evaluation

*Almighty God, Who has created man in Thine own image, and made him a living soul that he might seek after Thee, and have dominion over Thy creatures, teach us to study the works of Thy hands, that we may subdue the earth to our use, and strengthen the reason for Thy service; so to receive Thy blessed Word, that we may believe on Him Who Thou has sent, to give us the knowledge of salvation and the remission of our sins. All of which we ask in the name of the same Jesus Christ, our Lord.*

*– James Clerk Maxwell (13 June 1831 – 5 November 1879)*

# 6. Results of techno-economic evaluation

This chapter presents the results obtained using the economic model of the PEPER plant. The results of the different measurements, namely the methods that do not consider the time value of money and those that do, are used to determine the profitability of the PEPER plant, with varying costs. It also discusses the economic feasibility of producing such a PEPER power plant. The results of a sensitivity analysis of the varying fuel sphere cost, varying O&M costs, NOAK and the varying income costs. Cash-flow diagrams illustrating the cumulative cash flow; cumulative discounted cash flow, IRR cumulative cash flow of the various countries with different electricity income costs and inflation rates are given. In addition, the production cost of the PEPER plant is compared with the estimated production costs of the US DOE, 4S (Super-Safe, Small and Simple) and HPM.

## *6.1 Sensitivity analysis*

In the sensitivity analysis, the fixed capital investment costs of the NOAK plants (one to eight) was first varied against the IRR, in order to demonstrate the increase in profitability when more PEPER plants are produced. The income costs were varied against IRR, PBP and NPV in order to determine the minimum profitable income price with a production cost of US$0.038 and working capital of US$17,149,307 for a FOAK and NOAK PEPER plant, respectively. The elements that play a major role in the production cost were varied in order to demonstrate the impact on the production cost. The varying production costs were then compared to IRR, PBP and the NPV in order to demonstrate the profitability of the PEPER plant with two income costs, namely US$0.10 and US$0.15.

## *6.2 NOAK*

In Section 5.6, it was noted that the NOAK PEPER plant would be the eighth PEPER plant constructed. The fixed capital investment costs would begin decreasing by a rate of 6% from the FOAK PEPER plant until the eighth PEPER plant is constructed.

The decreasing fixed capital investment costs from the FOAK to the NOAK PEPER plant is illustrated in Table 6.1. In this table, the IRR is given alongside the associated fixed capital investment costs in order to demonstrate the increasing IRR with the decreasing fixed capital investment costs. The household electricity income of Hungary (0.167 US$/kWh) was used as input for the economic model of the PEPER plant for illustration purposes. After the eighth (NOAK) PEPER plant has been constructed, the fixed capital investment costs will no longer decrease.

**Table 6.1: Fixed capital investment costs with the corresponding IRR**

| 100 $MW_{th}$ PEPER plant number | Fixed capital investment costs (US$) | IRR (%) |
|---|---|---|
| 1 | 367,199,411.06 | 8.332 |
| 2 | 345,231,413.45 | 8.849 |
| 3 | 324,577,668.82 | 9.394 |
| 4 | 305,159,550.94 | 9.967 |
| 5 | 286,903,137.44 | 10.570 |
| 6 | 269,738,928.44 | 11.205 |
| 7 | 253,601,581.93 | 11.874 |
| 8 | 238,429,665.05 | 12.579 |

Figure 6.1 shows the graph of the decreasing fixed capital investment costs against the IRR as more PEPER plants are built.

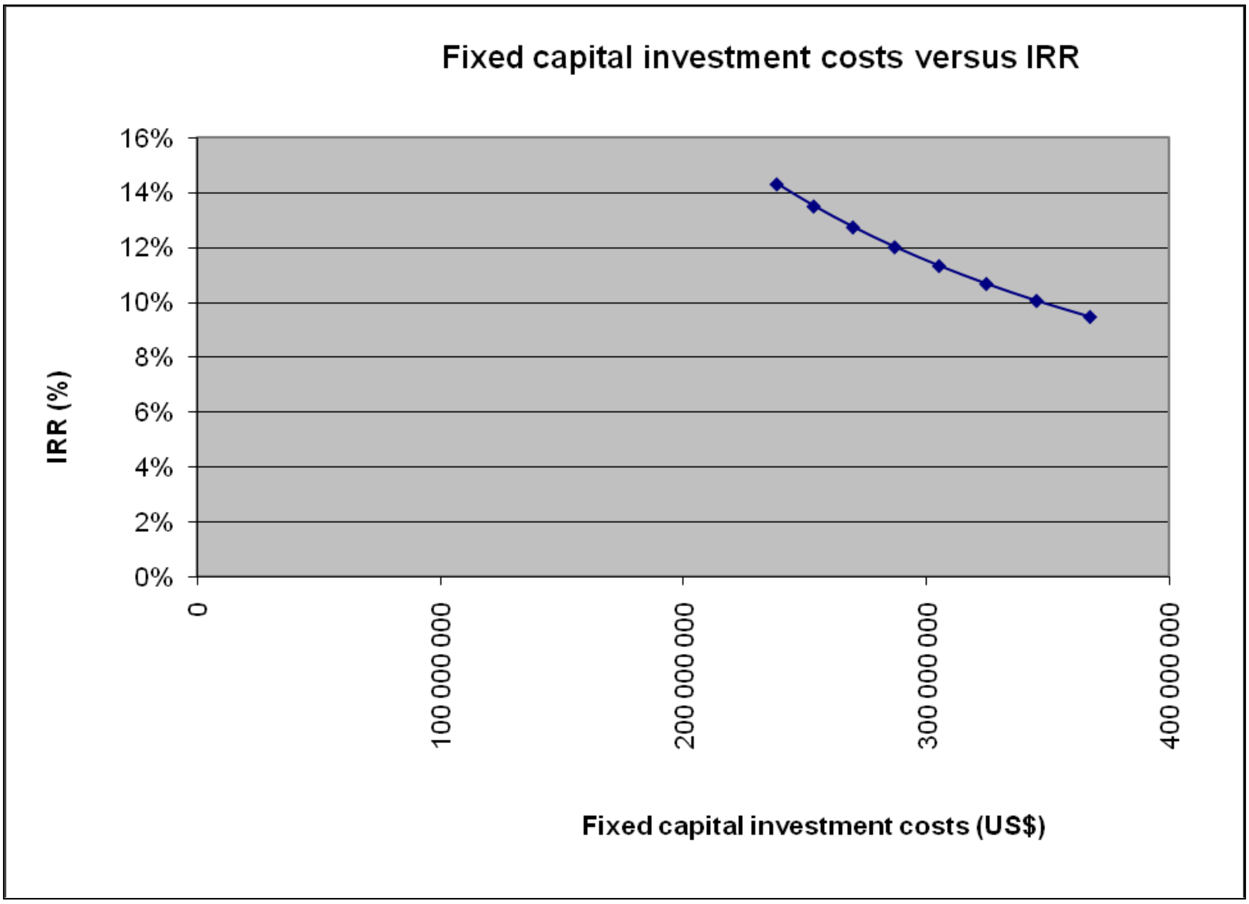

**Figure 6.1: Graph of the varying fixed capital investment costs versus the IRR**

In Figure 6.1, the effect of the decreasing fixed capital investment costs with the increase in IRR is illustrated. The fixed capital investment costs of the first (FOAK) PEPER plant is estimated to be US$367,199,411 with an IRR of 8.332%. The fixed capital investment costs of the eighth (NOAK) PEPER plant is estimated to be US$238,429,665 with an IRR of 12.579%.

## *6.3 Varying electricity income costs*

The electricity income costs were compared with profitability measurements in order to determine the minimum electricity income cost for a profit with a production cost of 0.038 US$/kWh and a working capital of US$17,228,740 for a FOAK and NOAK PEPER plant, respectively. The income costs were varied from 0.045 US$/kWh to 0.25 US$/kWh.

### 6.3.1 Net present value

For a FOAK PEPER plant with a fixed capital investment costs of US$367,199,411, Figure 6.2 demonstrates that the minimum electricity income required in order to equalise costs would be approximately 0.145 US$/kWh. With an income of 0.145 US$/kWh, the NPV would be US$19,298,446. With an income of 0.20 US$/kWh, the NPV would be US$336,767,717.

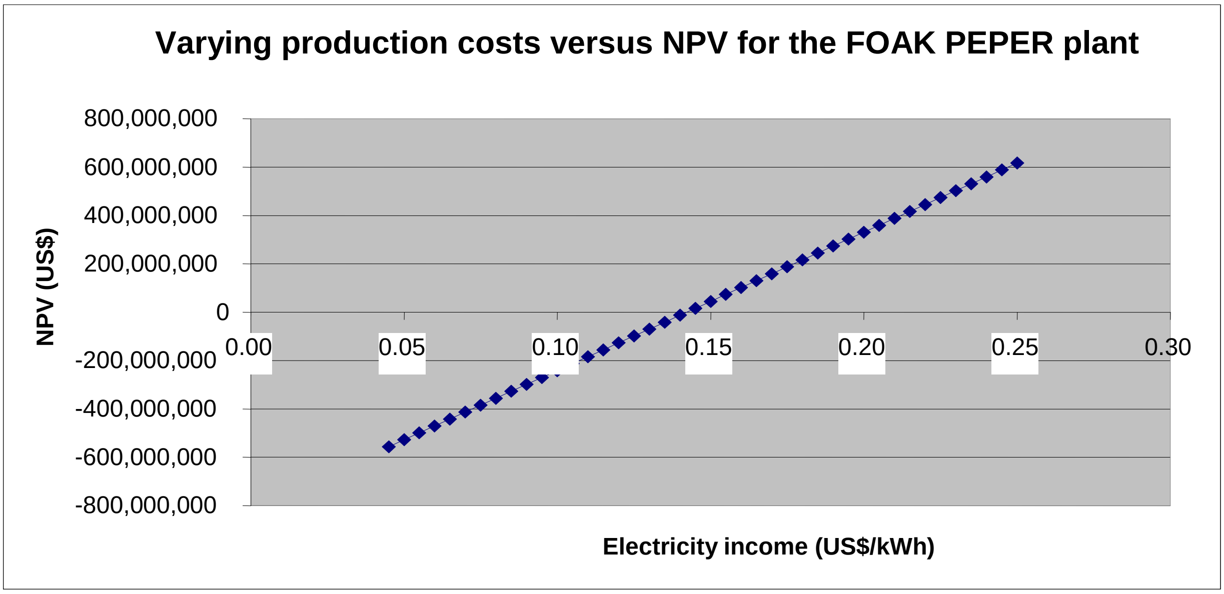

**Figure 6.2: Graph of the varying production costs versus net present value for a FOAK PEPER plant**

The varying production costs versus NPV for the NOAK PEPER plant is illustrated in Figure 6.3. For the eighth (NOAK) PEPER plant with a fixed capital investment costs of US$238,429,665, Figure 6.3 indicates that the minimum income required in order to equalise costs would be approximately 0.10 US$/kWh. With an income of 0.10 US$/kWh, the NPV would be US$118,299,954. With an income of 0.15 US$/kWh, the NPV would be US$169,757,809. With an income of 0.20 US$/kWh, the NPV would be US$457,815,573.

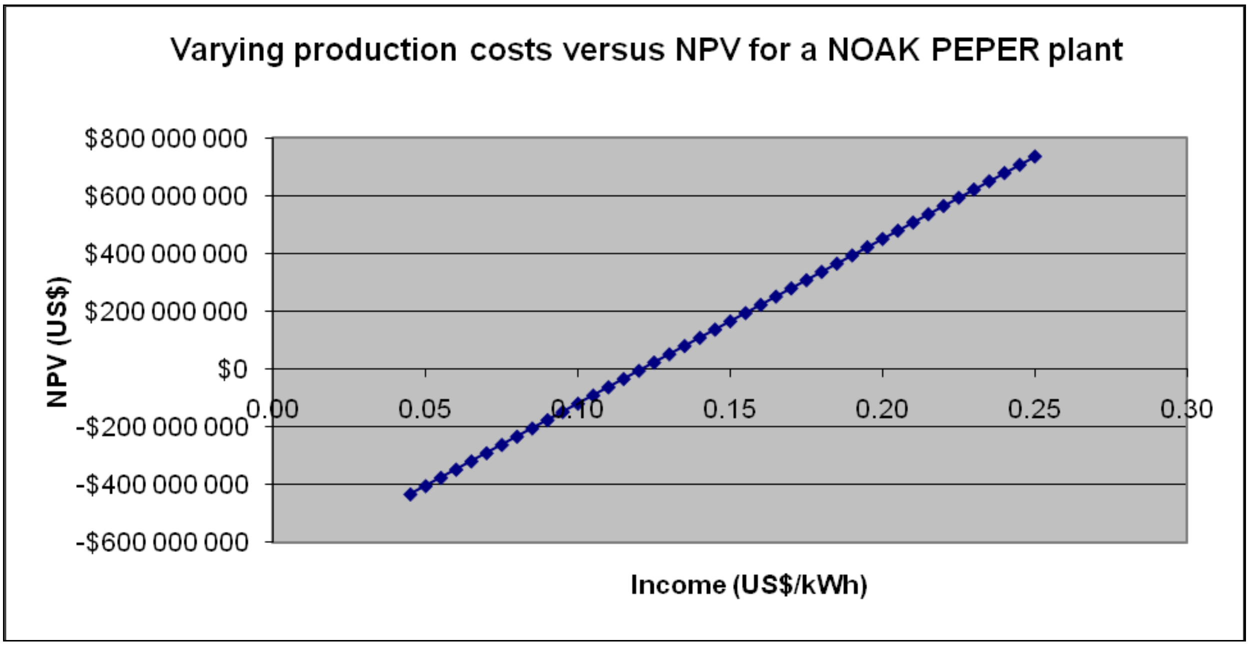

**Figure 6.3: Graph of the varying production costs versus net present value for a NOAK PEPER plant**

### 6.3.2 Internal rate of return

In Section 6.3.1, it was demonstrated that the first positive NPV for a FOAK PEPER plant would be evident in a country with an income of 0.145 US$/kWh. The effects of varying income costs with the IRR in the sensitivity analysis of the economic model for the PEPER plant are illustrated in Figure 6.4. The IRR for a FOAK PEPER plant with an income of 0.145 US$/kWh would be 6.33%. The IRR for a FOAK PEPER plant with an income of 0.20 US$/kWh would be 11.6%. The IRR for a FOAK PEPER plant with an income of 0.25 US$/kWh would be 16.27%.

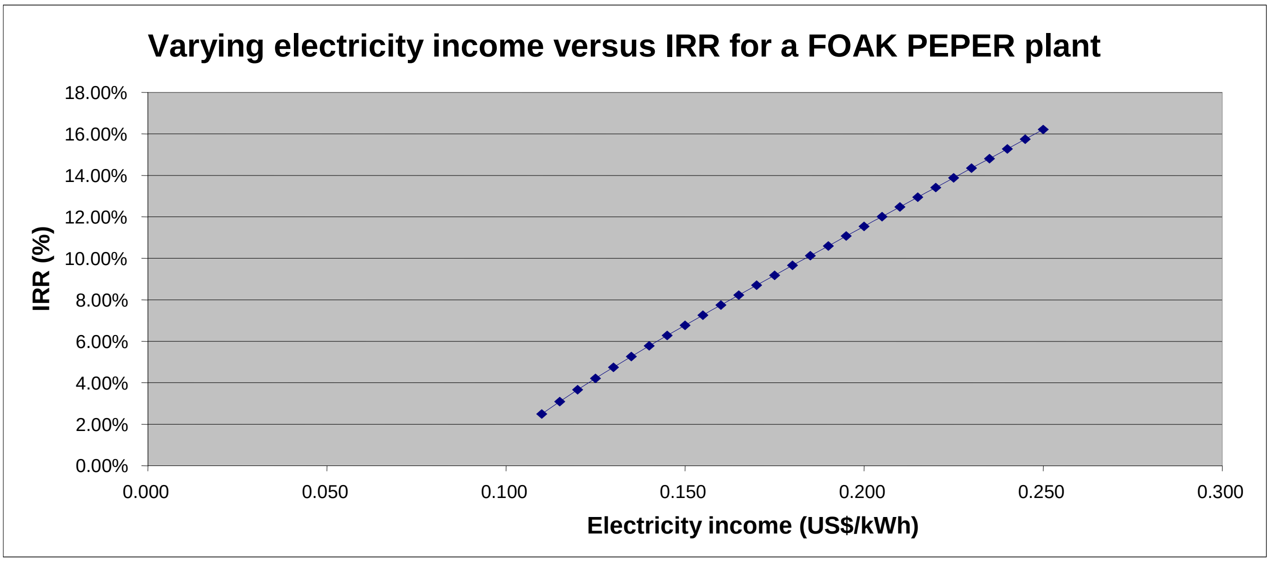

**Figure 6.4:** **Graph of the varying electricity income versus IRR for a FOAK PEPER plant**

Figure 6.5 illustrates the different IRRs for a NOAK PEPER plant with an income that varies from 0.10 US$/kWh to 0.25 US$/kWh.

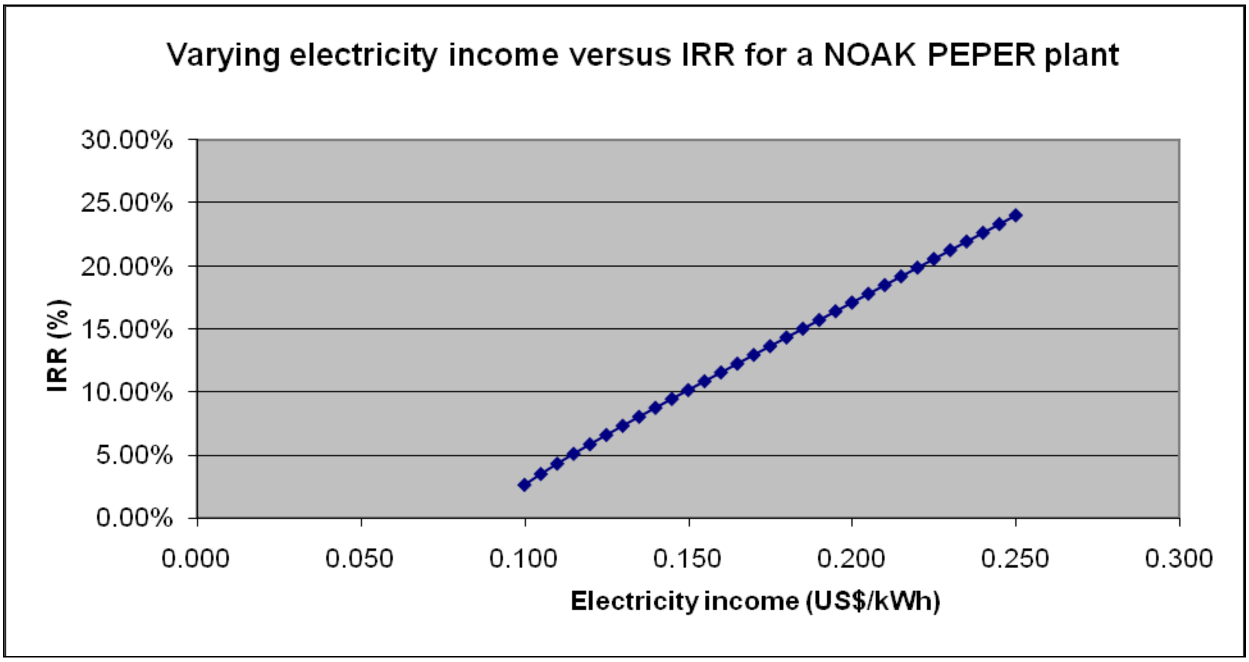

**Figure 6.5:** **Graph of the varying electricity income versus IRR for a NOAK PEPER plant**

### 6.3.3 Payback period

Figure 6.6 represents the PBP (in years) for a FOAK PEPER plant with a minimum income of 0.145 US$/kWh.

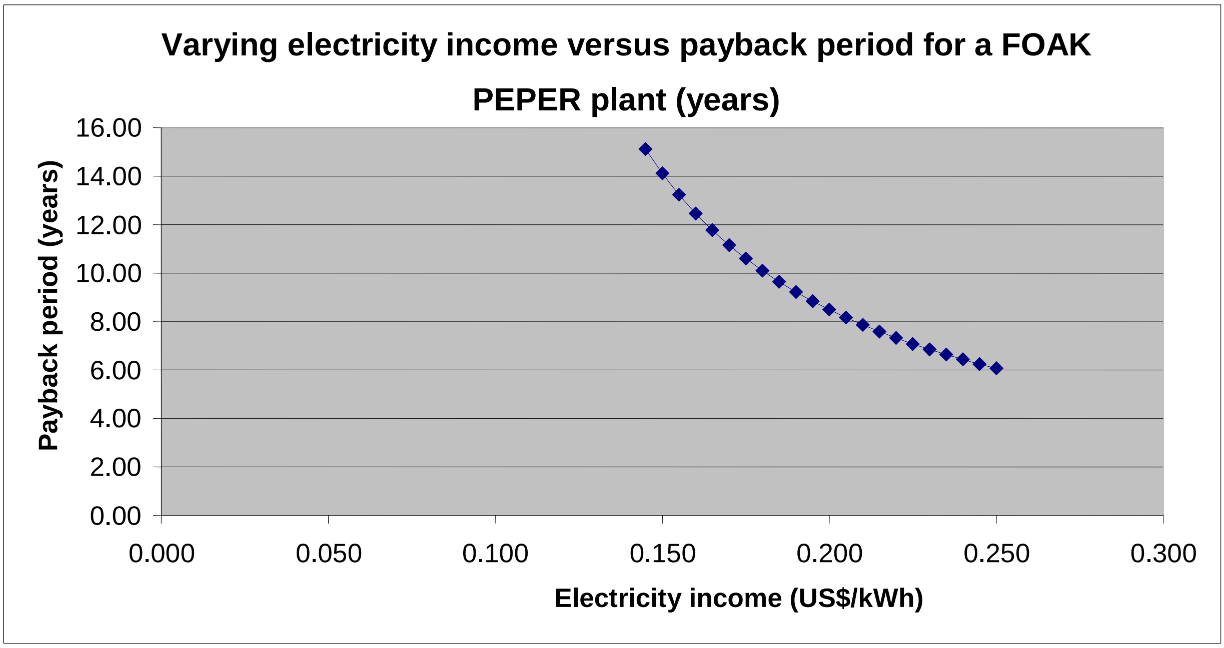

**Figure 6.6:** **Graph of the varying electricity income versus payback period for a FOAK PEPER plant**

Figure 6.7 illustrates the PBP (in years) for a NOAK PEPER plant with a minimum income of 0.10 US$/kWh.

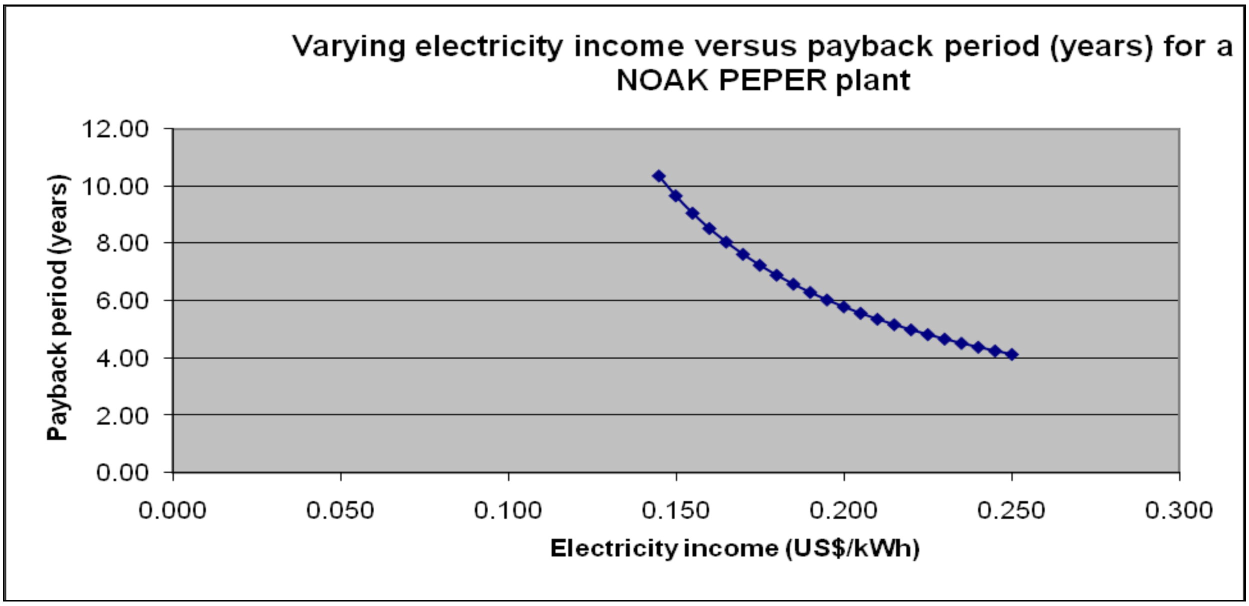

**Figure 6.7:** **Graph of the varying electricity income versus payback period for a NOAK PEPER**

**plant**

### 6.3.4 Conclusion

It was determined that if a country wished to earn a profit with a FOAK PEPER plant, the electricity income would need to be at least 0.145 US$/kWh. If the PEPER plants were in production and the eighth (NOAK) PEPER plant was built, the PEPER plant could be installed in a country that has a minimum electricity income of 0.10 US$/kWh and still earn a profit.

## *6.4 Varying production costs*

The major elements in the production cost are the cost of the fuel spheres and O&M. The fuel sphere cost and O&M costs were therefore compared with the production cost.

### 6.4.1 Varying fuel sphere cost

The cost per fuel sphere was varied from US$50 to US$300. Figure 6.8 demonstrates the increase in fuel sphere production cost as the cost per fuel sphere increases.

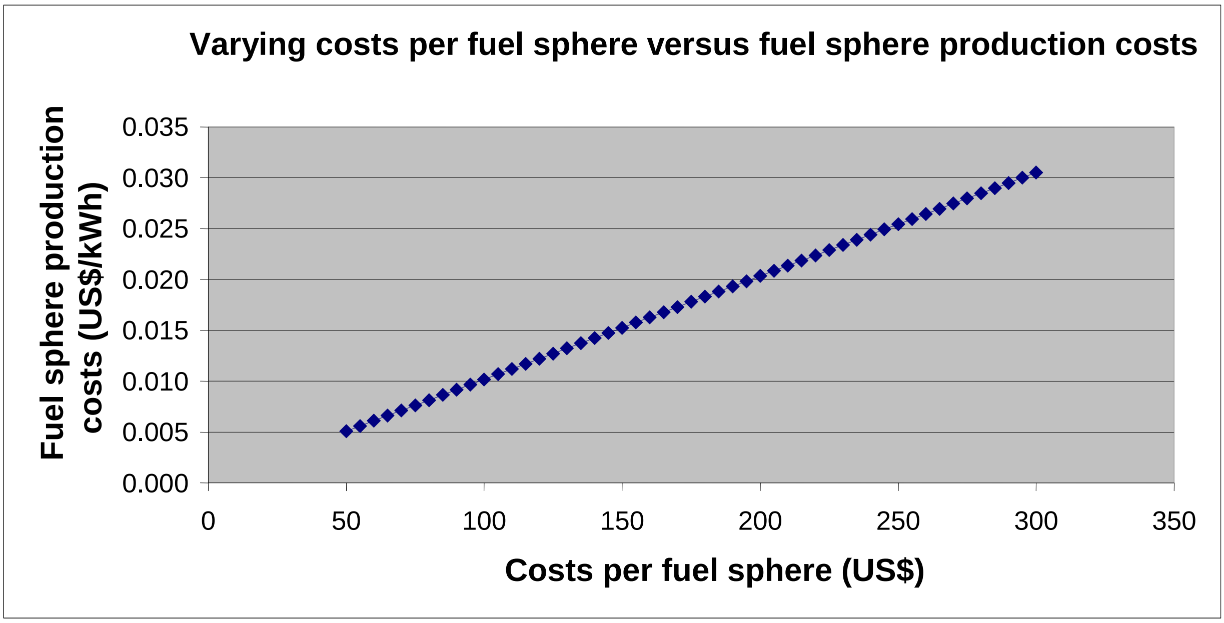

**Figure 6.8: Graph of the varying costs per fuel sphere versus fuel production costs**

Figure 6.8 indicates that if the cost per fuel sphere is US$50, the fuel sphere production cost would be 0.0051 US$/kWh. If the cost per fuel sphere were US$100, the fuel sphere production cost would be 0.0102 US$/kWh. If the cost per fuel sphere were US$200, the fuel production cost would be 0.0203 US$/kWh. If the cost per fuel sphere were US$300, the fuel sphere production cost would be 0.0305 US$/kWh.

Figure 6.9 specifies the effect of the increasing cost per fuel sphere on the overall production cost. The total production cost would be 0.0331 US$/kWh if the cost per fuel sphere were US$50. The overall production cost would be 0.0382 US$/kWh if the cost per fuel sphere were US$100. The overall production cost would be 0.0483 US$/kWh if the cost per fuel sphere were US$200. The overall production cost would be 0.0585 US$/kWh if the cost per fuel sphere were US$300 per fuel sphere.

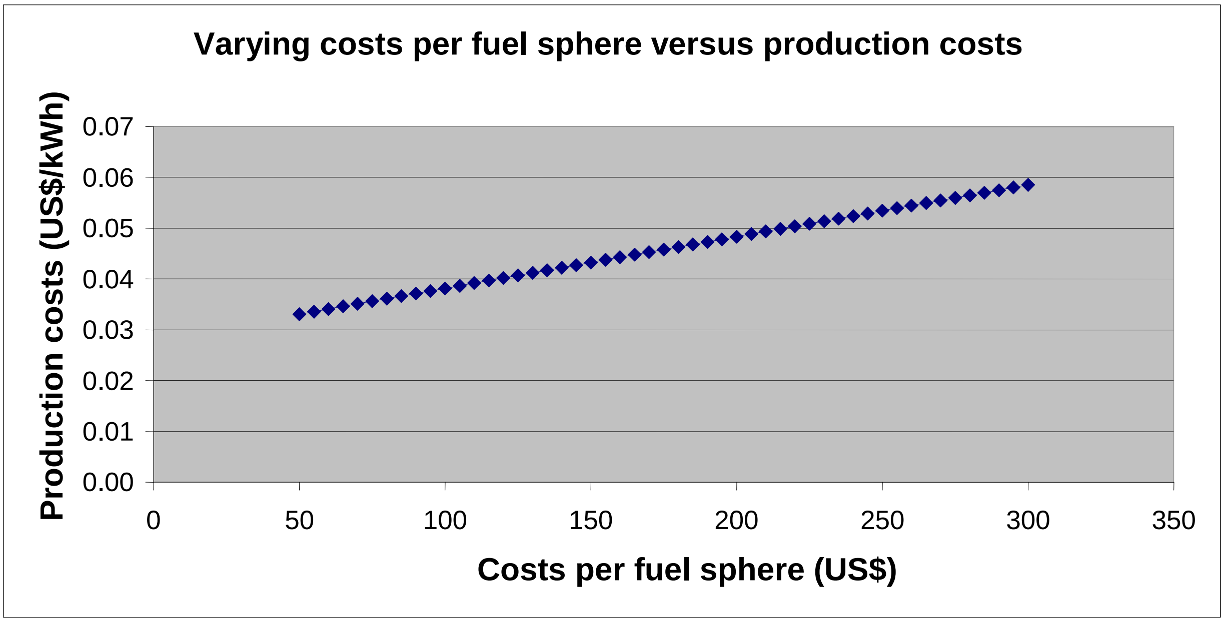

**Figure 6.9:** **Varying costs per fuel sphere versus production costs**

### 6.4.2 Varying operation and maintenance costs

The O&M costs were varied from 0.01 US$/kWh to 0.057 US$/kWh and plotted against the overall production cost. The effect of the varied O&M costs with the overall production cost is shown in Figure 6.10 on the next page.

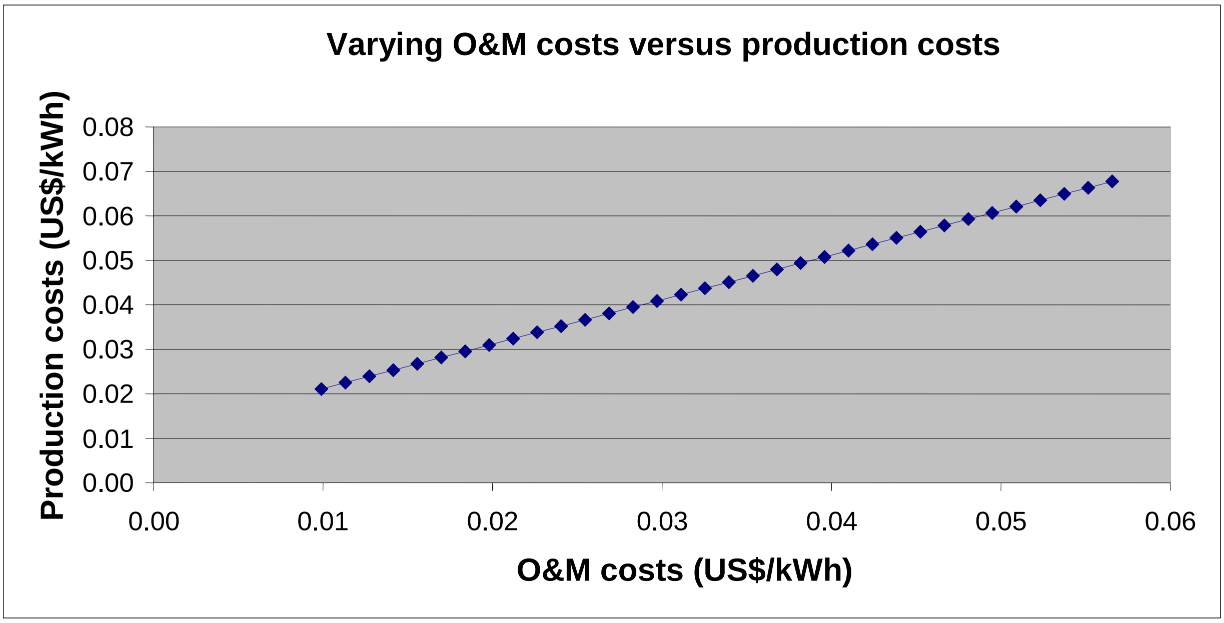

**Figure 6.10:** Varying operation and maintenance costs versus production costs

Figure 6.10 demonstrates that if the O&M costs were 0.01 US$/kWh, the production cost would be 0.021 US$/kWh. If the O&M costs were 0.03 US$/kWh, the production cost would be 0.041 US$/kWh.

### 6.4.3 Varying production costs versus profitability

The production costs were varied between 0.025 US$/kWh and 0.05 US$/kWh and the income costs were kept constant at 0.10 US$/kWh and 0.15 US$/kWh to determine what the effect would be on a FOAK or a NOAK PEPER plant in countries with similar income costs. Both these costs were plotted against IRR.

#### 6.4.3.1 Production costs versus internal rate of return with an electricity income of 0.10 US$/kWh

***FOAK***

Figure 6.11 demonstrates the varying production costs versus IRR for an income of 0.10 US$/kWh for a FOAK PEPER plant. In the figure, it is evident that the minimum production cost would need to be 0.03 US$/kWh in order for the FOAK PEPER plant to equalise costs.

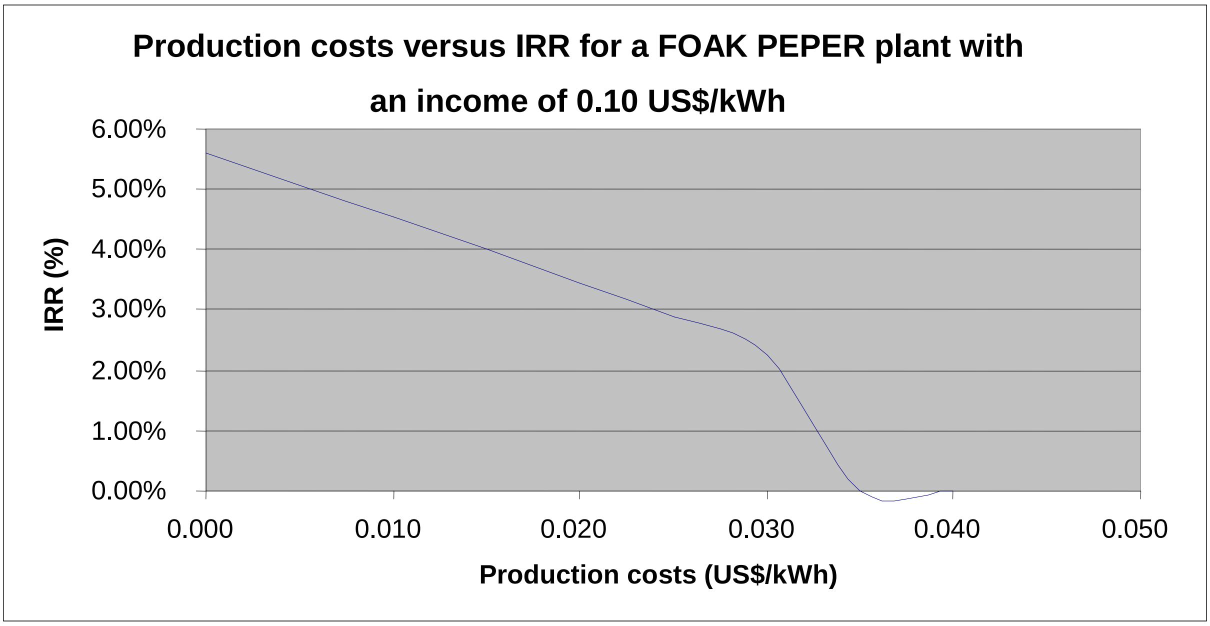

**Figure 6.11:** Varying production costs versus IRR for a FOAK PEPER plant with an electricity income of 0.10 US$/kWh

### *NOAK*

Figure 6.12 demonstrates that the production cost would need to be at least 0.04 US$/kWh for a NOAK PEPER plant with an income of 0.10 US$/kWh to equalise costs.

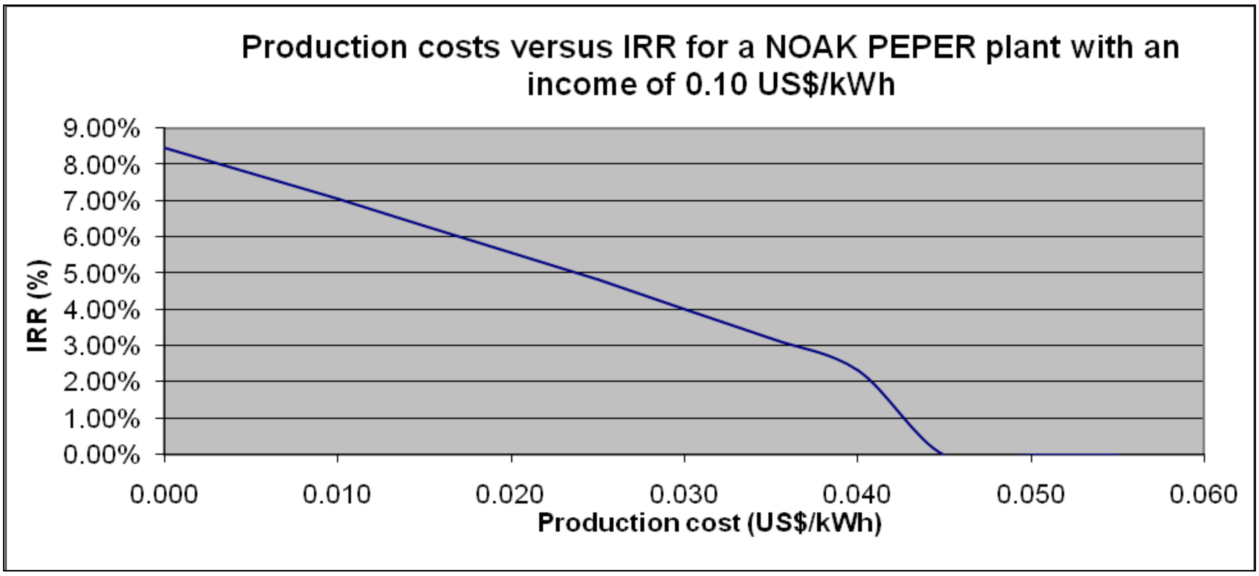

**Figure 6.12:** Varying production costs versus IRR for a NOAK PEPER plant with an electricity income of 0.10 US$/kWh

#### 6.4.3.2 Production costs versus internal rate of return with an electricity income of 0.15 US$/kWh

***FOAK***

Figure 6.13 demonstrates that a production cost of at least 0.08 US$/kWh is necessary for a FOAK PEPER plant with an income of 0.15 US$/kWh to equalise costs.

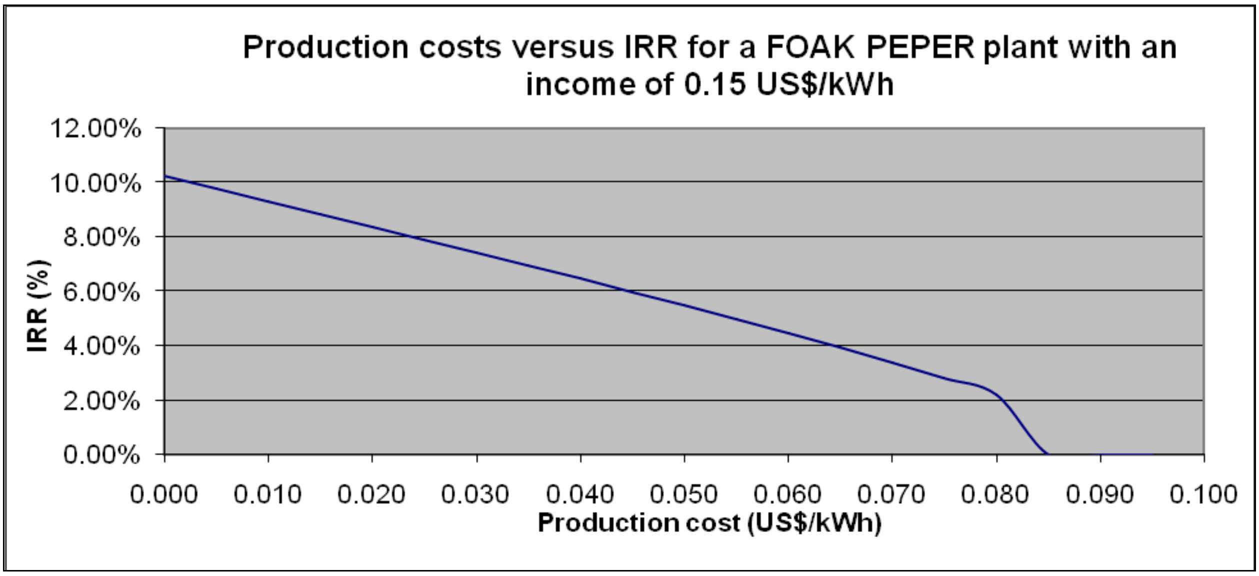

**Figure 6.13: Varying production costs versus IRR for a FOAK PEPER plant with an electricity income of 0.15 US$/kWh**

***NOAK***

Figure 6.14 indicates that in order for a NOAK PEPER plant with an income of 0.15 US$/kWh to equalise costs, a minimum production cost of 0.09 US$/kWh is necessary.

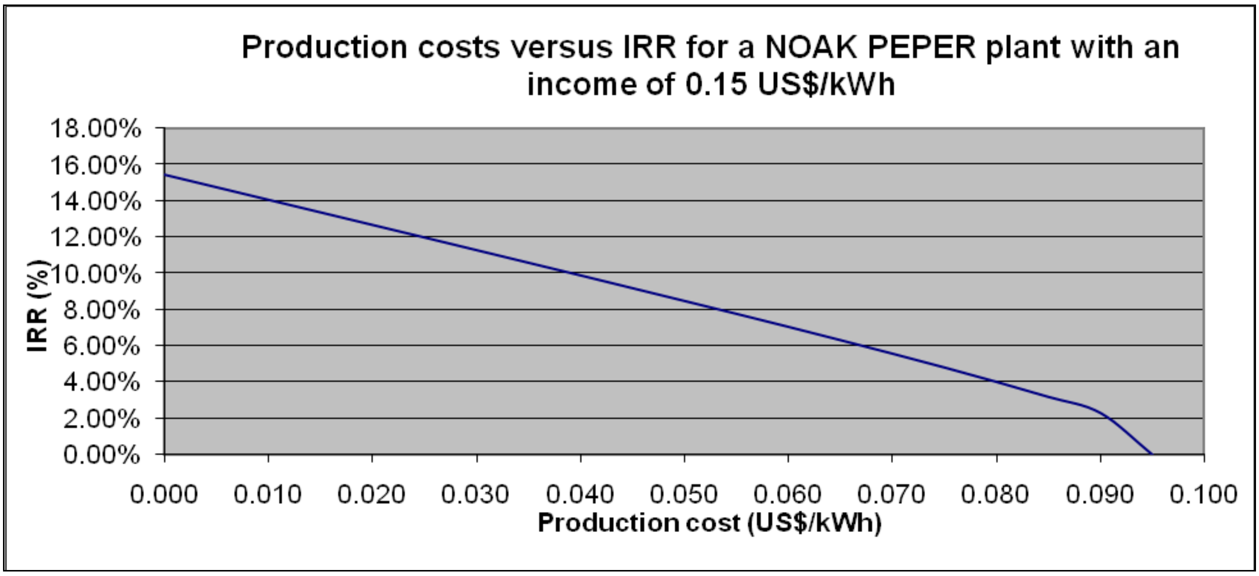

**Figure 6.14: Varying production costs versus IRR for a NOAK PEPER plant with an electricity income of 0.15 US$/kWh**

## 6.5 *Cash-flow diagrams of various countries*

Cash-flow diagrams for Romania, France and Japan with their different electricity income and inflation rates were plotted for FOAK and NOAK PEPER plants. The cash-flow diagrams demonstrate the effects of the different income costs and inflation rates in the cumulative cash flow, cumulative discounted cash flow and the IRR cumulative cash flow. The cash-flow diagrams of other countries could also be plotted using the economic model developed for the PEPER plant.

For all the PEPER plants in all the countries, the production cost was 0.038 US$/kWh, the working capital was US$17,149,307.88, the discounted rate was 6% and the taxes were 28%.

### 6.5.1 Romania

In Romania, the inflation rate was 8.46% [23] and the household electricity income was 0.135 US$/kWh.

*FOAK*

Figure 6.15 demonstrates that the cumulative discounted cash flow and the IRR cumulative cash flow are negative. This means that it would not be profitable to build a

FOAK PEPER plant in Romania to provide household electricity. As shown in Section 6.3, a minimum income of 0.145 US$/kWh would be needed to build and operate a profitable FOAK PEPER plant.

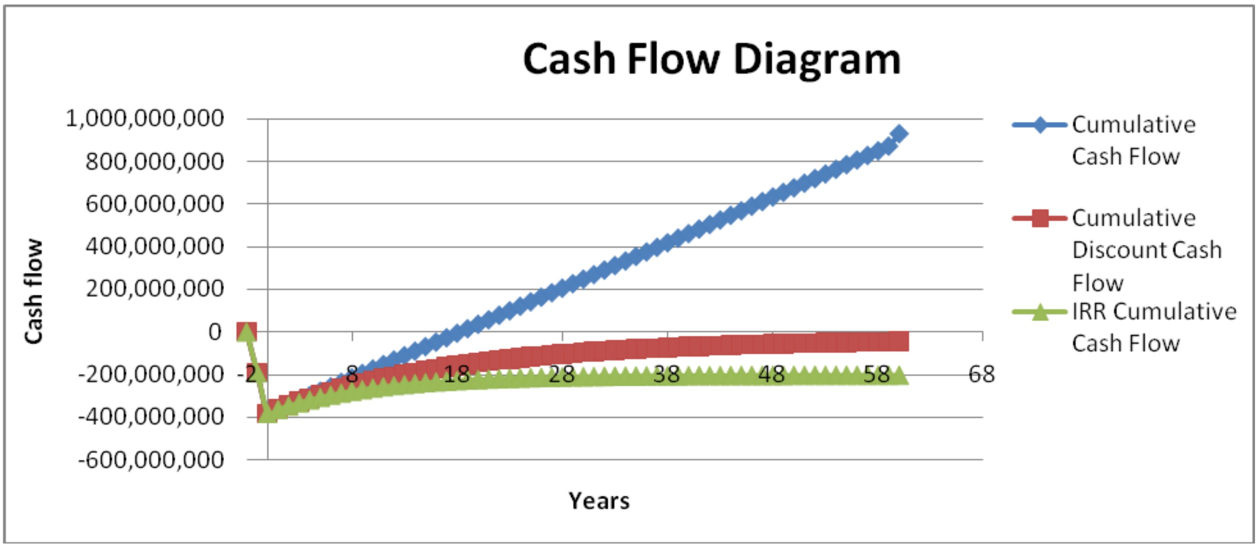

**Figure 6.15:** **Cash-flow diagram for a FOAK PEPER plant in Romania**

***NOAK***

Figure 6.16 illustrates that it would be profitable to construct a NOAK PEPER in Romania. If a NOAK PEPER plant were constructed in Romania, provided the inflation rate and electricity income as used here remain constant, the IRR would be 8.116% and the NPV would be US$84,127,108.63 during its economic lifespan of sixty years.

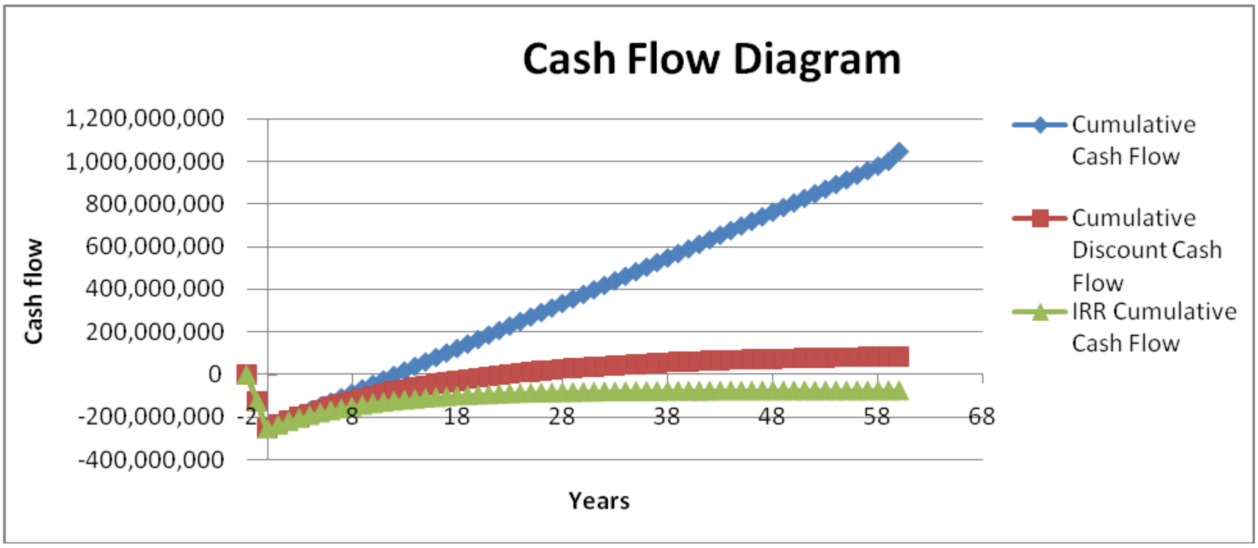

**Figure 6.16:** **Cash-flow diagram for a NOAK PEPER plant in Romania**

### 6.5.2 France

In France, the inflation rate was 3.3 % [23] and the household electricity income was 0.146 US$/kWh.

#### *FOAK*

Figure 6.17 demonstrates that it would be profitable to construct a FOAK PEPER plant in France. If a FOAK PEPER plant were constructed in France, provided the inflation rate and electricity income as used here remain constant, the IRR would be 6.276% and the NPV would be US$16,078,598 during its economic lifespan.

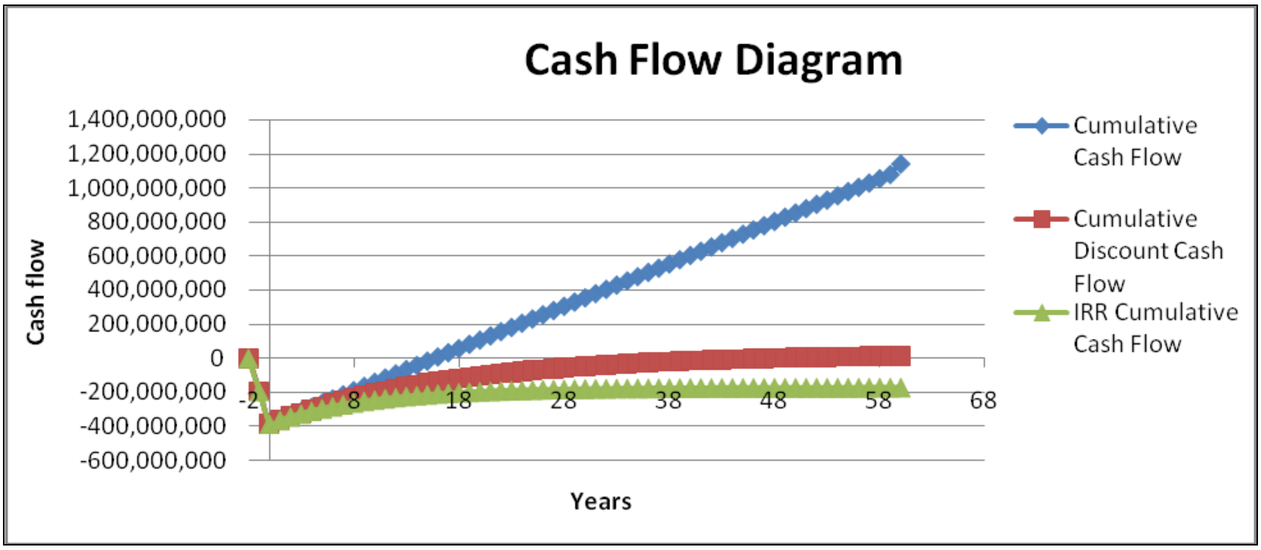

**Figure 6.17: Cash-flow diagram for a FOAK PEPER plant in France**

#### *NOAK*

Figure 6.18 demonstrates it would be very profitable to construct a NOAK PEPER plant in France. If a NOAK PEPER plant were constructed in France, provided the inflation rate and electricity income as used here remain constant, the IRR would be 9.614% and the NPV would be US$144,361,962.02 during its economic lifespan.

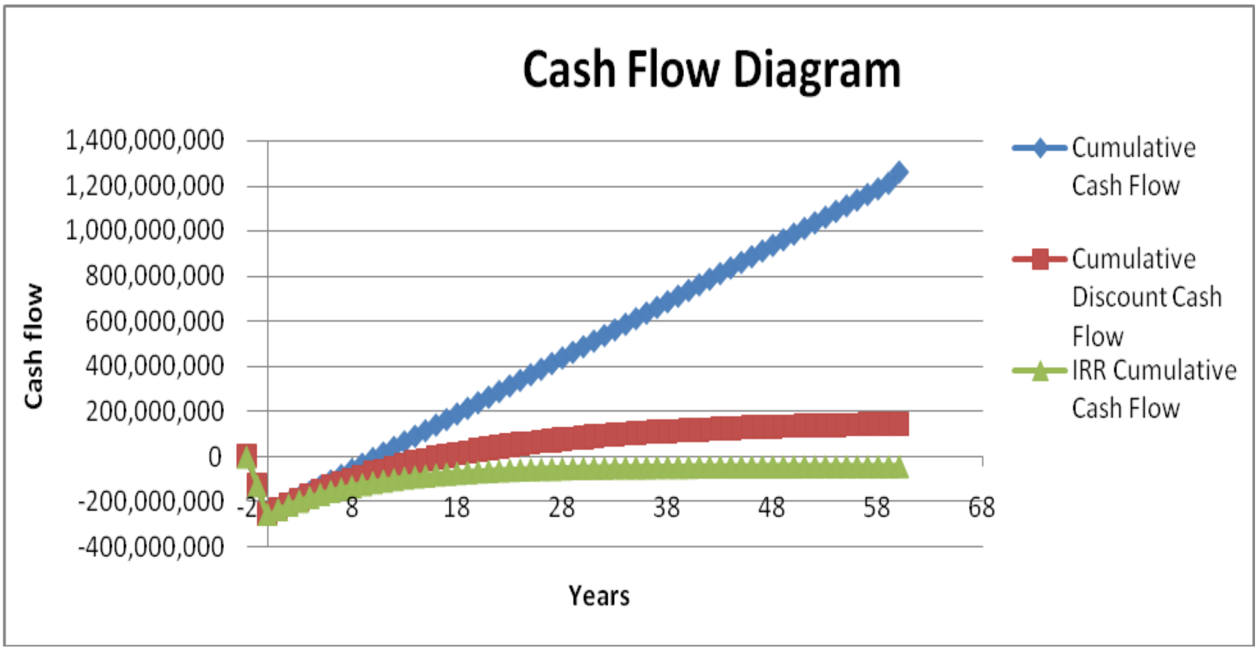

**Figure 6.18:** **Cash-flow diagram for a NOAK PEPER plant in France**

### 6.5.3 Japan

In Japan, the inflation rate was 0.8% [23] and the household electricity income was 0.18 US$/kWh.

***FOAK***

Figure 6.19 demonstrates that it would be profitable to construct a FOAK PEPER plant in Japan. If a FOAK PEPER plant were constructed in Japan, the IRR would be 9.484% and the NPV would be US$208,466,019.36 during its economic lifespan.

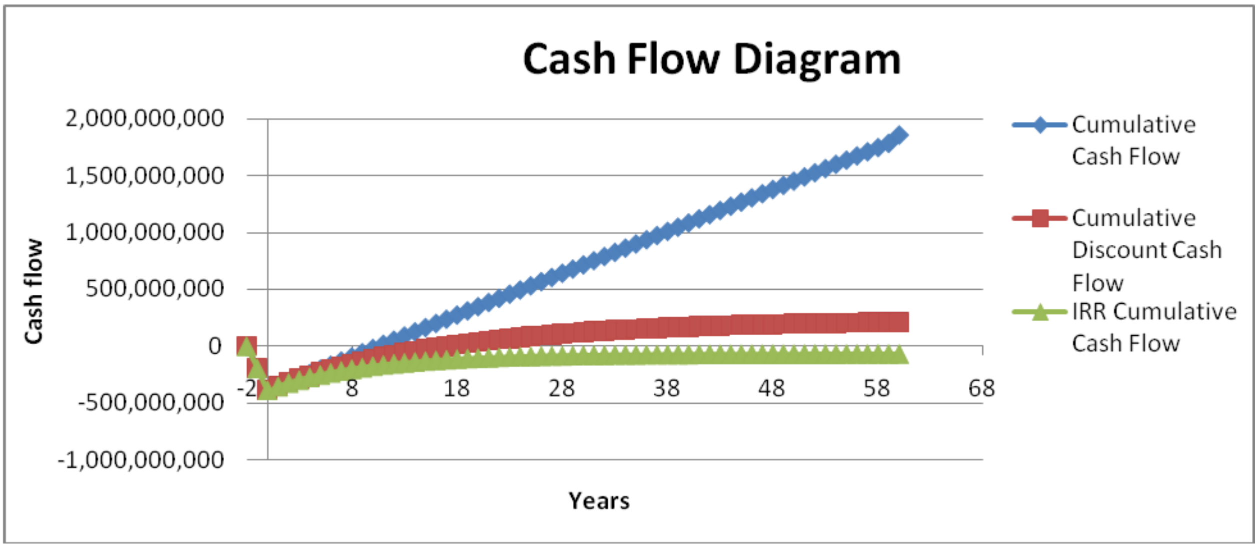

**Figure 6.19:** **Cash-flow diagram of a FOAK PEPER plant in Japan**

***NOAK***

Figure 6.20 shows that it would be very profitable to construct a NOAK PEPER plant in Japan. If a NOAK PEPER plant were constructed in Japan, the IRR would be 14.307% and the NPV would be US$336,749,383.28 during its economic lifespan.

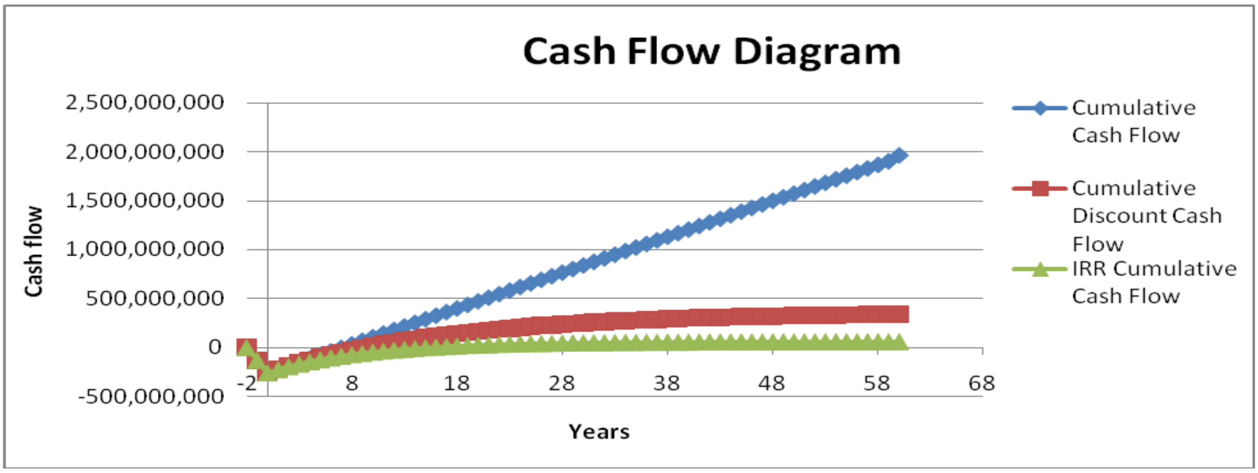

**Figure 6.20:** **Cash-flow diagram for a NOAK PEPER plant in Japan**

## *6.6 Production cost comparisons of the Potchefstroom Experimental Pebble Bed Modular Reactor plant with other very small nuclear power plants*

The IAEA defines small NPPs as 300 $MW_e$ and less [24]. Very small NPPs are defined as 50 $MW_e$ and less [24]. The PEPER plant with an electrical output of 40.33 $MW_e$ was thus compared to other very small NPPs of 50 $MW_e$ and less. The reactors are compared at the levelised energy cost unit of US$/kWh and are compared in terms of their production costs.

Very small NPPs are still in the planning and design phase. Owing to this, data on the costs of very small NPPs is very scarce and the available costs are estimated costs. In this section, the estimated production cost of the PEPER power plant (0.038 US$/kWh) will be compared to the estimated production costs of other very small power plants.

### 6.6.1 Small nuclear power plant cost estimations by the United States Department of Energy

According to the US DOE, the electricity production cost of a 50 $MW_e$ NPP is 0.054 US$/kWh to 0.107 US$/kWh [25]. The production cost comparison between the PEPER plant and the US DOE estimations is shown in Figure 6.21.

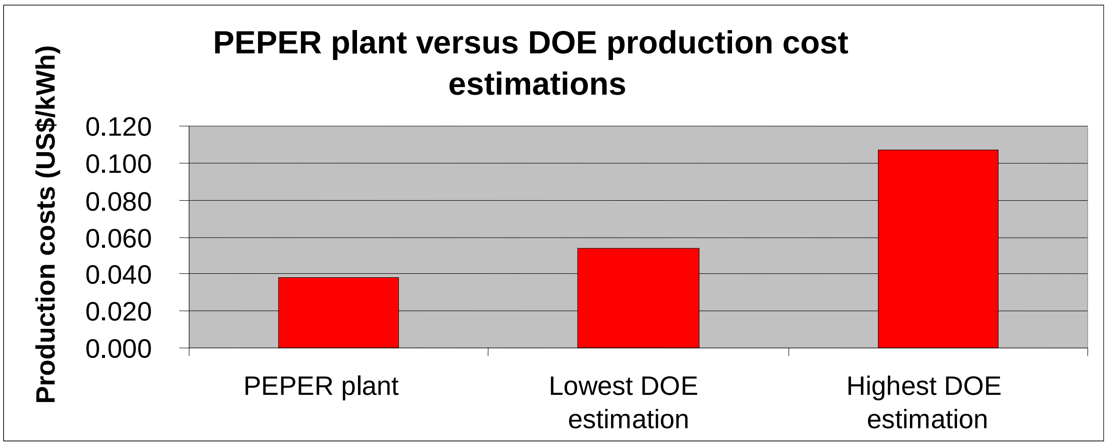

**Figure 6.21: Production cost comparison between the PEPER plant and US DOE**

In Figure 6.21, the production cost of the PEPER plant compares very favourably with the production cost estimations by the US DOE. The production cost estimations of the US DOE are likely for worst-case scenarios and range between US$0.054 and 0.107 US$/kWh.

### 6.6.2 Estimated production cost of the 50 $MW_e$ nuclear power plant 4S

Toshiba (Japan) is designing a 50 $MW_e$ liquid sodium-cooled NPP called the 4S. The design approval of the 4S is estimated to be completed at the end of 2013. The production cost of the 4S is estimated to range between 0.05 US$/kWh and 0.07 US$/kWh [24].

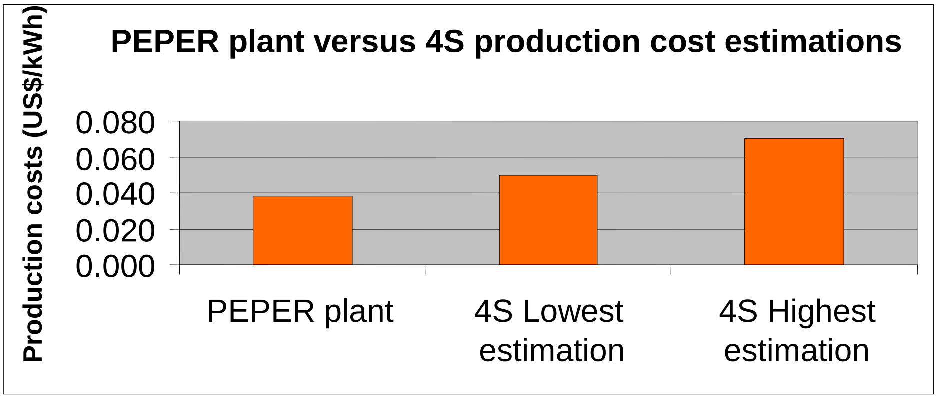

**Figure 6.22: Production cost comparison between the PEPER plant and the 4S**

In Figure 6.22, it can be seen that the PEPER power plant would produce electricity at 0.012 US$/kWh less than the 4S power plant's lowest production cost estimation. The PEPER plant production cost estimation is in the range of the 4S estimated production cost and even lower.

### 6.6.3 Estimated production cost of the Hyperion Power Module

Hyperion (US) is using technology developed and licensed by Los Alamos National Laboratory to commercialise HPM, a NPP (70 $MW_{th}$) that is designed to produce 25 MW electrical power [26]. According to Hyperion, HPM is approximately the size of an average bathtub and would provide enough energy for approximately 25 000 homes [26]. Hyperion will submit an application for a manufacturing license to the Nuclear Regulatory Commission in September 2009 [26].The production cost of HPM is estimated to be 0.08 US$/kWh and less "anywhere on the planet" [26].

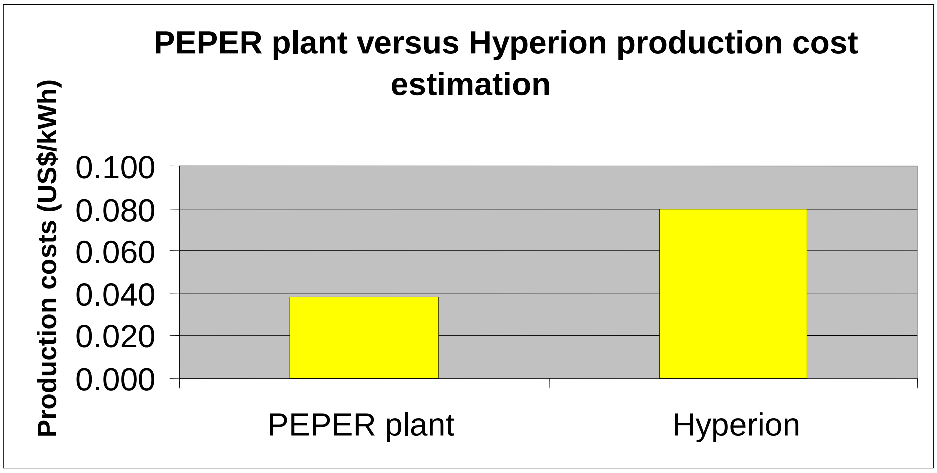

**Figure 6.23:** **Production cost comparison between the PEPER plant and HPM**

Figure 6.23 demonstrates that the estimated production cost of the PEPER plant is much lower than the roughly estimated production cost of the 25 MW$_e$ HPM.

### 6.6.4 Conclusion

In the above estimated production cost comparisons the PEPER plant compares very favourably with the production cost estimations of the US DOE, 4S and HPM. The estimated production cost estimations are in the same range and in all three cases the estimated production cost of the PEPER plant is less than the other production cost estimations.

The slightly lower estimated production cost of the PEPER plant is likely a reflection of a more accurate estimation, as the components of the PEPER plant have already been selected and priced in this techno-economic analysis. The estimated production costs by the US DOE, 4S and HPM were generally calculated on projected prices for PCUs that would produce electricity from the various NPPs.

The estimated production costs of the PEPER, US DOE, 4S and HPM are given in Figure 6.24. The average production cost estimations of 0.083 US$/kWh from the US DOE and 0.06 US$/kWh from the 4S are used in this figure to compare single estimated production costs with one another.

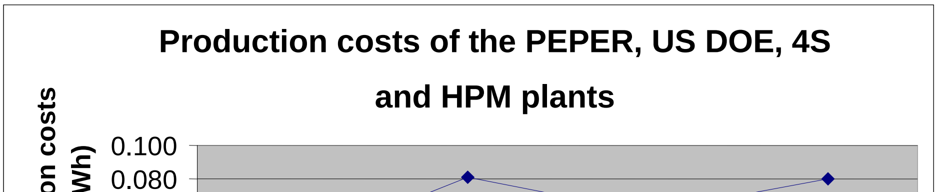

**Figure 6.24: The estimated production costs of the PEPER, US DOE, 4S and HPM nuclear power plants**

Figure 6.24 demonstrates that the estimated production cost of the PEPER plant compares very favourably with the estimated production costs of the US DOE, 4S and HPM NPPs. The production cost of the PEPER is in range and even a bit lower than the estimated production costs of the DOE, 4S and HPM NPPs.

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*Chapter 6 has presented the results and sensitivity analysis of the economic model explained in Chapter 5. In Chapter 6, it was determined that if a country wished to earn a profit with a FOAK PEPER plant, the electricity income would need to be at least 0.145 US$/kWh. If the PEPER plants were in production and the eighth (NOAK) PEPER plant was built, the PEPER plant could be installed in a country with a minimum electricity income of 0.10 US$/kWh and still earn a profit. The estimated production cost of the PEPER plant compares favourably with the production cost estimations of the US DOE, 4S and HPM NPPs.*

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# Chapter 7

# Conclusion and recommendations

*Speculations? I have none. I am resting on certainties. 'I know whom I have believed and am persuaded that He is able to keep that which I have committed unto Him against that day'. A Christian finds his guide in the Word of God, and commits the keeping of his soul into the hands of God. He looks for no assurance beyond what the Word can give him, and if his mind is troubled by the cares and fears which assail him, he can go nowhere but in prayer to the throne of grace and to Scripture.*

**–** Michael Faraday (22 September 1791 – 25 August 1867)

# 7. Conclusion and recommendations

This chapter provides an overview of the research project. It also discusses problems identified during the execution of the project. It concludes with recommendations for future research in this area of study.

## *7.1 Summary of the dissertation*

Chapters 1 and 2 gave an introduction and background to the techno-economic evaluation of the PEPER plant as presented in this dissertation. Chapter 3 discussed the possible PCUs for the PEPER plant. The indirect steam (Rankine) cycle was selected as the PCU to be used for the PEPER plant. Chapter 3 also discussed the sizing of the indirect steam cycle for the PEPER plant, which was accomplished using EES. The sizes of the major equipment (RPV and the equipment of the PCU) were as derived and examined in Chapter 3. These were used in Chapter 4 to price the major equipment for the PEPER plant. The prices for the major equipment of the PEPER plant in Chapter 4 were used as input for the economic model of the PEPER plant that was explained in Chapter 5. Chapter 5 gave an overview of the direct and indirect costs, fixed capital investment costs, working capital and production cost as determined by the economic model. Chapter 6 discussed the most pertinent results of the economic model. Sensitivity analysis was conducted in order to demonstrate the impact of various factors on the production cost and profitability of the PEPER plant. The sensitivity analysis was used to determine the minimum income a country would require in order to establish a profitable FOAK or NOAK PEPER plant for the industrial and/or household electricity sectors.

In the economic model of the PEPER plant discussed in Chapters 5 and 6, the fixed capital investment costs for a FOAK PEPER plant was estimated to be US$367,199,411 and the fixed capital investment costs for a NOAK (eighth) PEPER plant was estimated to be US$238,429,665. A working capital of US$17,228,740 was estimated for the first two years of the PEPER plant's lifetime. Finally, the production cost of the PEPER plant was estimated to be 0.038 US$/kWh.

## 7.2 Conclusion

The sensitivity analysis (Chapter 6) demonstrated that FOAK PEPER plants could be established in countries in which the electricity income is 0.145 US$/kWh or more. NOAK PEPER plants (all the PEPER plants constructed after the eighth PEPER plant is erected) could be established in countries with an electricity income of 0.10 US$/kWh or more.

Of the thirty-one countries listed in the economic model for the PEPER plant, FOAK PEPER plants for the household sector could be established for the countries listed in Table 7.1. Table 7.2 lists the countries in which the electricity income in the industrial sector was 0.145 US$/kWh or more and which would thus be suitable for FOAK PEPER plants for the industrial sector.

Table 7.3 lists the countries in which NOAK PEPER plants would be economically feasible in the household sector. Table 7.4 lists the countries in which NOAK PEPER plants would earn a profit in the industrial sector.

### *Profitable FOAK PEPER plants for household electricity*

This prices and inflation rates were valid for June 2008 [23].

**Table 7.1: Profitable FOAK PEPER plants for household electricity**

| Household electricity prices | | |
|---|---|---|
| **Country** | **Household (US$/kWh)** | **Inflation rate (%)** |
| France | 0.146 | 3.30 |
| Germany | 0.220 | 3.00 |
| Hungary | 0.167 | 7.00 |
| Ireland | 0.214 | 4.70 |
| Italy | 0.215 | 3.60 |
| Japan | 0.180 | 0.80 |
| Netherlands | 0.284 | 2.30 |
| New Zealand | 0.153 | 3.40 |
| Slovak Republic (Slovakia) | 0.190 | 4.60 |
| Spain | 0.156 | 4.60 |
| United Kingdom | 0.170 | 3.30 |

### *Profitable FOAK PEPER plants for industrial electricity*

The prices and inflation rates were valid for June 2008 [23].

**Table 7.2: Profitable FOAK PEPER plants for industrial electricity**

| Industrial electricity prices | | |
|---|---|---|
| **Country** | **Industrial (US$/kWh)** | **Inflation rate (%)** |
| Italy | 0.208 | 3.60% |

### *Profitable NOAK PEPER plants for household electricity*

The prices and inflation rates were valid for June 2008 [23].

**Table 7.3: Profitable NOAK PEPER plants for household electricity**

| Household electricity prices | | |
|---|---|---|
| **Country** | **Household (US$/kWh)** | **Inflation rate (%)** |
| Australia | 0.103 | 4.20 |
| Czech Republic | 0.134 | 6.80 |
| Finland | 0.135 | 4.20 |
| France | 0.146 | 3.30 |
| Germany | 0.220 | 3.00 |
| Greece | 0.110 | 4.90 |
| Hungary | 0.167 | 7.00 |
| Ireland | 0.214 | 4.70 |
| Italy | 0.215 | 3.60 |
| Japan | 0.180 | 0.80 |
| Mexico | 0.117 | 4.95 |
| Netherlands | 0.284 | 2.30 |
| New Zealand | 0.153 | 3.40 |
| Romania | 0.135 | 8.46 |
| Slovak Republic (Slovakia) | 0.190 | 4.60 |
| South Africa | 0.100 | 11.10 |
| Spain | 0.156 | 4.60 |
| Switzerland | 0.138 | 2.90 |
| Turkey | 0.128 | 10.74 |
| United Kingdom | 0.170 | 3.30 |
| United States | 0.102 | 4.20 |

### *Profitable NOAK PEPER plants for industrial electricity*

The prices and inflation rates were valid for June 2008 [23].

**Table 7.4: Profitable NOAK PEPER plants for industrial electricity**

| Industrial electricity prices | | |
|---|---|---|
| **Country** | **Industrial (US$/kWh)** | **Inflation rate (%)** |
| Denmark | 0.109 | 3.40 |
| Hungary | 0.114 | 7.00 |
| Indonesia | 0.099 | 10.38 |
| Ireland | 0.129 | 4.70 |
| Italy | 0.208 | 3.60 |
| Japan | 0.112 | 0.80 |
| Mexico | 0.107 | 4.95 |
| Portugal | 0.105 | 2.80 |
| Romania | 0.104 | 8.46 |
| Slovak Republic (Slovakia) | 0.106 | 4.60 |
| Turkey | 0.114 | 10.74 |

## *7.3 Recommendations*

A detailed design is required for the indirect steam cycle. Once the major component sizes from the detail design of the indirect steam cycle have been obtained, these will need to be priced and compared with the prices in Chapter 4. Should the prices differ, this could be used as input in the economic model for the PEPER plant, in order to determine the new profitability of the PEPER plant.

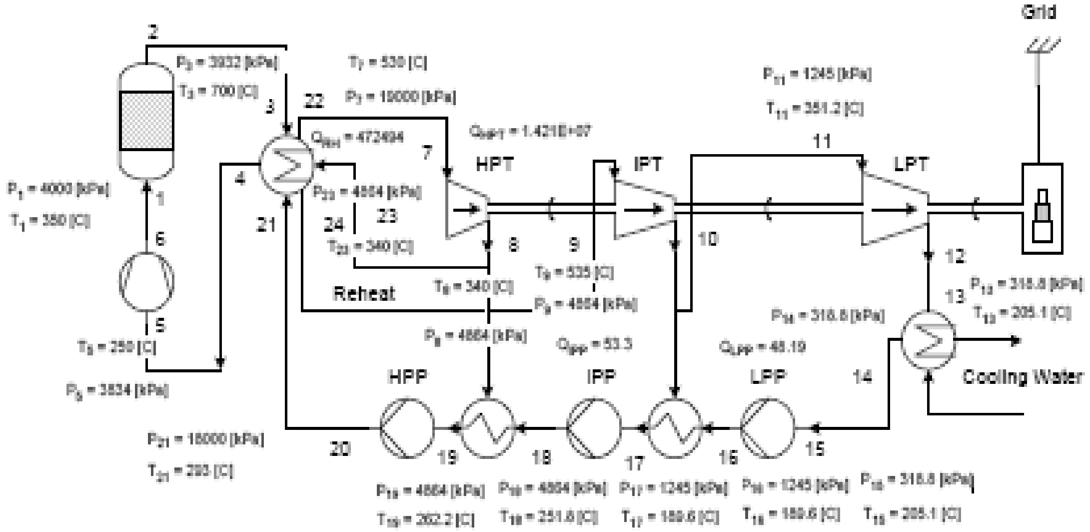
In this document, the direct and indirect costs were determined using a top-down cost estimation approach: the costs were determined based on ratios from the total equipment cost. The ratios were obtained from the PBMR-DPP. A bottom-up cost estimation approach could be used in which all the details of the direct and indirect costs are obtained from manufacturers, construction companies, insurance companies and so on. These direct and indirect costs of the bottom-up cost estimation could then be compared with the direct and indirect costs of the PEPER plant as determined in the economic model using top-down cost estimation. Should there be a significant difference in cost, the new cost could be replaced with the previous direct and indirect costs in the economic model in order to determine the new profitability of the PEPER plant.

Based on the *Cost estimating guidelines for Generation IV nuclear energy systems* [19], it was assumed that for the PEPER plant, the NOAK PEPER plant would be reached when the eighth PEPER plant was constructed. The FOAK PEPER plant is defined as the first PEPER plant constructed and operational. Thereafter, the fixed capital investment costs would decrease by 6% until the fixed capital investment costs stabilises at the eighth (NOAK) PEPER plant.

An investigation could be conducted to determine the number of PEPER plants that would need to be constructed and operational before the fixed capital investment costs would stabilise (the exact *n* of the NOAK PEPER plant). Such an investigation could determine the amount by which the fixed capital investment costs would decrease with each new PEPER plant constructed. The NOAK PEPER plant and the decrease in the fixed capital investment costs obtained in this investigation could be incorporated into the economic model of the PEPER plant in this study in order to determine the new profitability of the NOAK PEPER plant.

*Chapter 7 has outlined the final conclusions and recommendations of this research project. The fixed capital investment costs of a FOAK PEPER plant were estimated in the economic model for the PEPER plant to be US$367,199,411. The fixed capital investment costs of the NOAK PEPER plant were estimated in the economic model for the PEPER plant to be US$238,429,665. The working capital for both FOAK and NOAK PEPER plants was estimated to be US$17,228,740 for the first two years of the PEPER plant's economic lifetime. The production cost of the PEPER plant was estimated in the economic model for the PEPER plant to be 0.038 US$/kWh. FOAK PEPER plants could be established in countries in which the electricity income is 0.145 US$/kWh or more. NOAK PEPER plants could be established in countries in which the electricity income is 0.10 US$/kWh or more.*

# Appendix A: Engineering Equation Solver program for the indirect steam cycle of the Potchefstroom Experimental Pebble Bed Modular Reactor plant



*100 MWth PEPER - Power Conversion Unit*

*Indirect steam cycle*

*Yvotte Brits 12807443*

*Helium side*

$H := 5.07$ *length of reactor*

$R := 1.15$ *radius of reactor*

$D := 2 \cdot R$ *Diameter*

$\varepsilon := 0.39$ *porosity*

$dp := 0.06$ *fuel diameter*

$Dh_{peb} := dp$

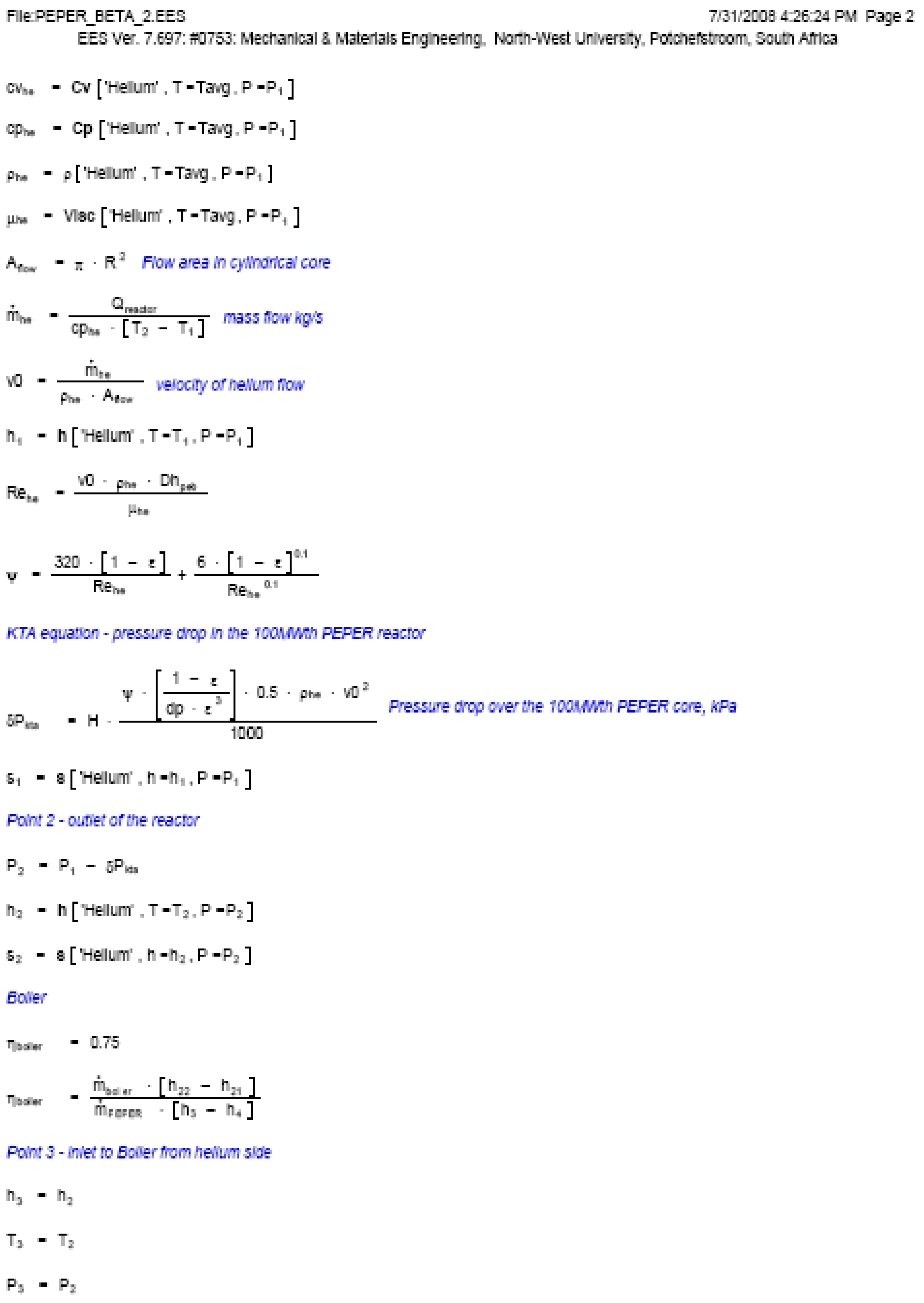
$T_1 := 350$ *Inlet temperature*

$T_2 := 700$ *Outlet temperature*

$P_1 := 4000$ *Reactor pressure, kPa*

$Q_{reactor} := 1 \times 10^8$ *Reactor heat generation, Watt*

$Tavg := \frac{T_1 + T_2}{2}$ *Average temperature in reactor*



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$$cv_{he} = Cv\left['Helium', T=Tavg, P=P_1\right]$$

$$cp_{he} = Cp\left['Helium', T=Tavg, P=P_1\right]$$

$$\rho_{he} = \rho\left['Helium', T=Tavg, P=P_1\right]$$

$$\mu_{he} = Visc\left['Helium', T=Tavg, P=P_1\right]$$

$$A_{flow} = \pi \cdot R^2$$ *Flow area in cylindrical core*

$$\dot{m}_{he} = \frac{Q_{reactor}}{cp_{he} \cdot \left[T_2 - T_1\right]}$$ *mass flow kg/s*

$$v0 = \frac{\dot{m}_{he}}{\rho_{he} \cdot A_{flow}}$$ *velocity of helium flow*

$$h_1 = h\left['Helium', T=T_1, P=P_1\right]$$

$$Re_{he} = \frac{v0 \cdot \rho_{he} \cdot Dh_{peb}}{\mu_{he}}$$

$$\psi = \frac{320 \cdot \left[1 - \varepsilon\right]}{Re_{he}} + \frac{6 \cdot \left[1 - \varepsilon\right]^{0.1}}{Re_{he}^{\ 0.1}}$$

*KTA equation - pressure drop in the 100MWth PEPER reactor*

$$\delta P_{kta} = H \cdot \frac{\psi \cdot \left[\frac{1 - \varepsilon}{dp \cdot \varepsilon^3}\right] \cdot 0.5 \cdot \rho_{he} \cdot v0^2}{1000}$$ *Pressure drop over the 100MWth PEPER core, kPa*

$$s_1 = s\left['Helium', h=h_1, P=P_1\right]$$

*Point 2 - outlet of the reactor*

$$P_2 = P_1 - \delta P_{kta}$$

$$h_2 = h\left['Helium', T=T_2, P=P_2\right]$$

$$s_2 = s\left['Helium', h=h_2, P=P_2\right]$$

*Boiler*

$$\eta_{boiler} = 0.75$$

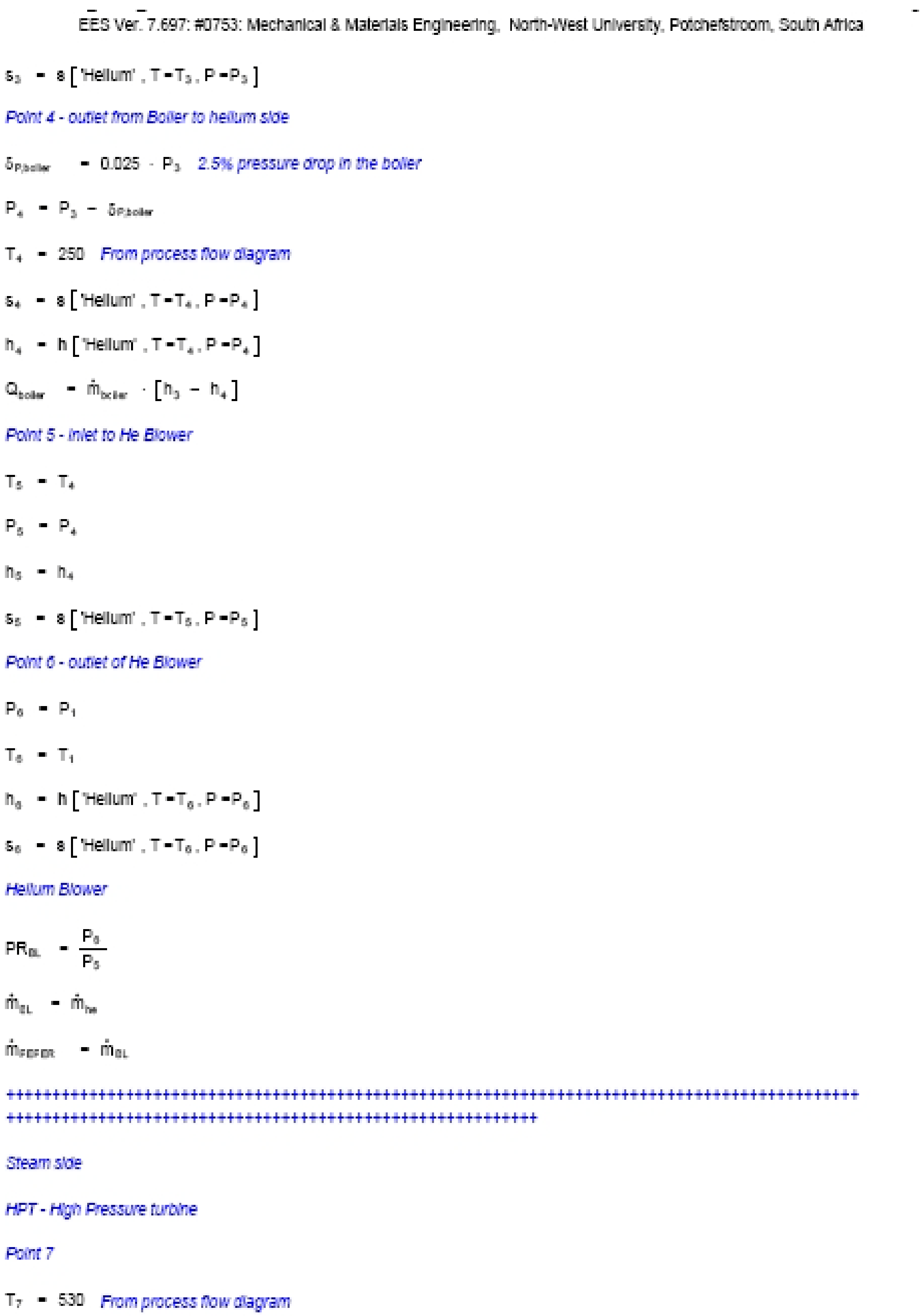
$$\eta_{boiler} = \frac{\dot{m}_{boiler} \cdot \left[h_{22} - h_{21}\right]}{\dot{m}_{PEPER} \cdot \left[h_3 - h_4\right]}$$

*Point 3 - inlet to Boiler from helium side*

$$h_3 = h_2$$

$$T_3 = T_2$$

$$P_3 = P_2$$



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$s_3 = s['Helium', T=T_3, P=P_3]$

*Point 4 - outlet from Boiler to helium side*

$\delta_{P,boiler} = 0.025 \cdot P_3$ *2.5% pressure drop in the boiler*

$P_4 = P_3 - \delta_{P,boiler}$

$T_4 = 250$ *From process flow diagram*

$s_4 = s['Helium', T=T_4, P=P_4]$

$h_4 = h['Helium', T=T_4, P=P_4]$

$Q_{boiler} = \dot{m}_{boiler} \cdot [h_3 - h_4]$

*Point 5 - inlet to He Blower*

$T_5 = T_4$

$P_5 = P_4$

$h_5 = h_4$

$s_5 = s['Helium', T=T_5, P=P_5]$

*Point 6 - outlet of He Blower*

$P_6 = P_1$

$T_6 = T_1$

$h_6 = h['Helium', T=T_6, P=P_6]$

$s_6 = s['Helium', T=T_6, P=P_6]$

*Helium Blower*

$$PR_{BL} = \frac{P_6}{P_5}$$

$\dot{m}_{BL} = \dot{m}_{he}$

$\dot{m}_{PEPER} = \dot{m}_{BL}$

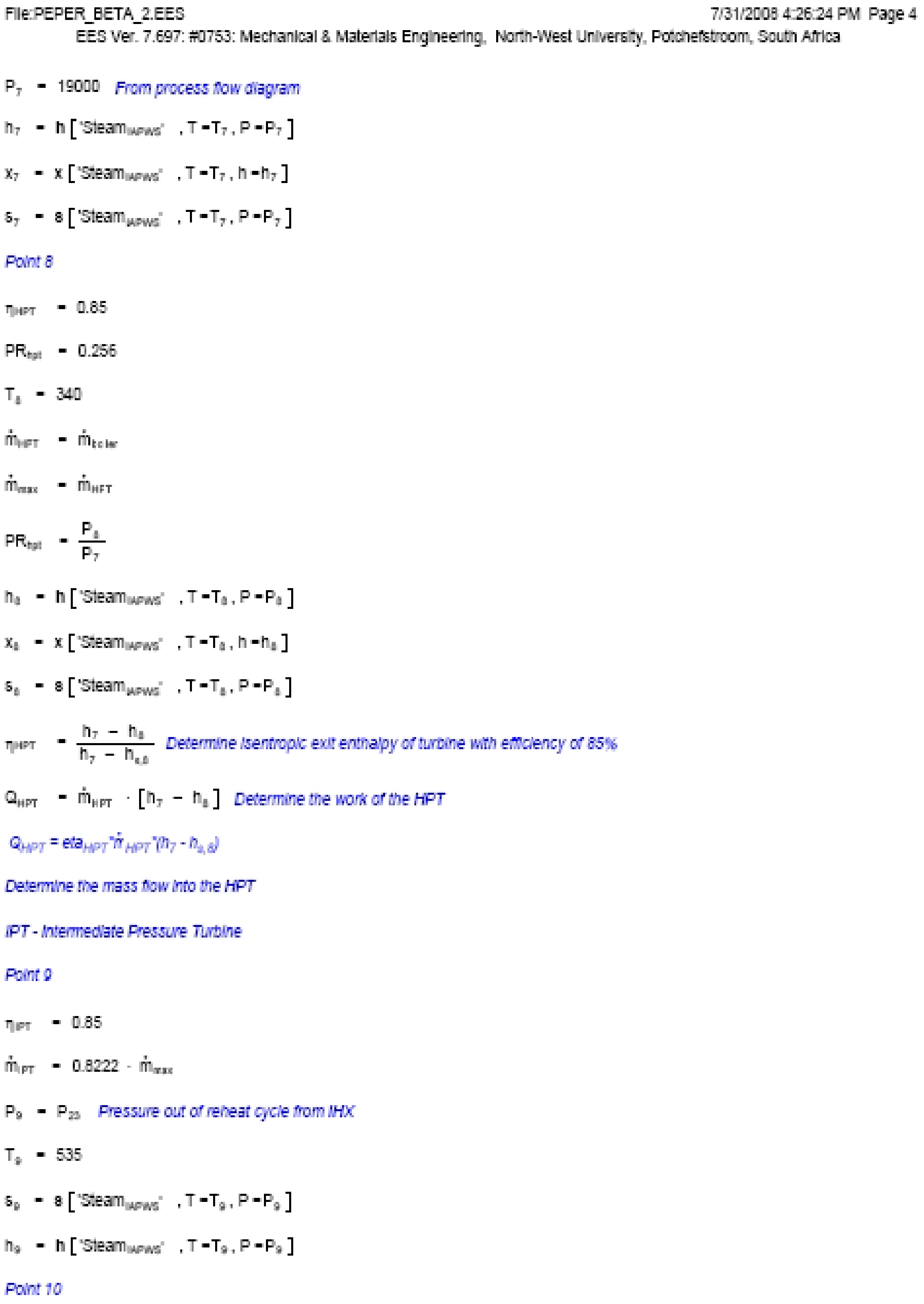
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

*Steam side*

*HPT - High Pressure turbine*

*Point 7*

$T_7 = 530$ *From process flow diagram*



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$P_7 = 19000$ *From process flow diagram*

$h_7 = h\left[\text{'Steam}_{IAPWS}\text{'}, T = T_7, P = P_7\right]$

$x_7 = x\left[\text{'Steam}_{IAPWS}\text{'}, T = T_7, h = h_7\right]$

$s_7 = s\left[\text{'Steam}_{IAPWS}\text{'}, T = T_7, P = P_7\right]$

*Point 8*

$\eta_{HPT} = 0.85$

$PR_{hpt} = 0.256$

$T_8 = 340$

$\dot{m}_{HPT} = \dot{m}_{tc\ ler}$

$\dot{m}_{max} = \dot{m}_{HPT}$

$$PR_{hpt} = \frac{P_8}{P_7}$$

$h_8 = h\left[\text{'Steam}_{IAPWS}\text{'}, T = T_8, P = P_8\right]$

$x_8 = x\left[\text{'Steam}_{IAPWS}\text{'}, T = T_8, h = h_8\right]$

$s_8 = s\left[\text{'Steam}_{IAPWS}\text{'}, T = T_8, P = P_8\right]$

$\eta_{HPT} = \dfrac{h_7 - h_8}{h_7 - h_{s,8}}$ *Determine isentropic exit enthalpy of turbine with efficiency of 85%*

$Q_{HPT} = \dot{m}_{HPT} \cdot \left[h_7 - h_8\right]$ *Determine the work of the HPT*

*$Q_{HPT} = eta_{HPT} * \dot{m}_{HPT} * (h_7 - h_{s,8})$*

*Determine the mass flow into the HPT*

*IPT - Intermediate Pressure Turbine*

*Point 9*

$\eta_{IPT} = 0.85$

$\dot{m}_{IPT} = 0.8222 \cdot \dot{m}_{max}$

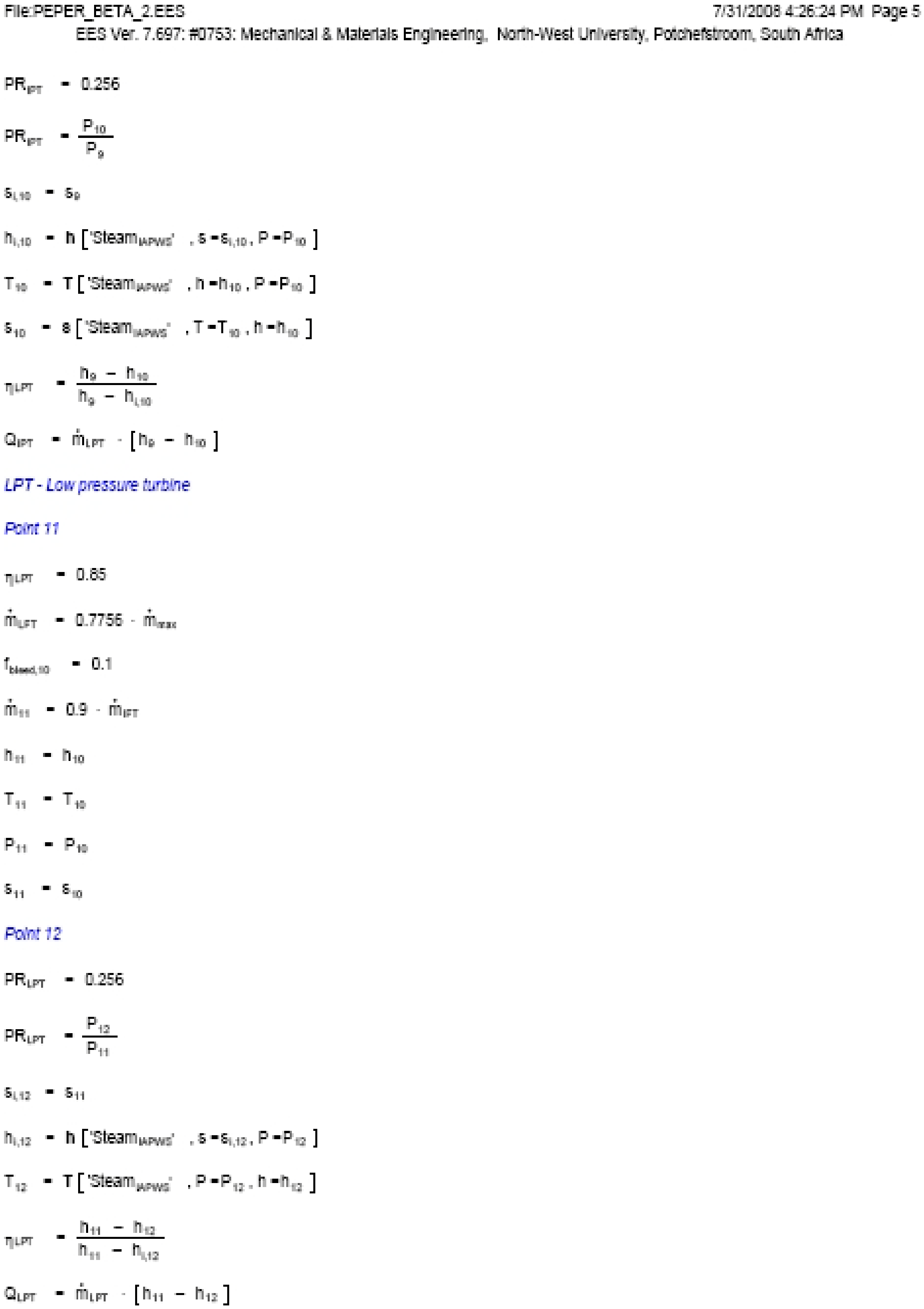
$P_9 = P_{23}$ *Pressure out of reheat cycle from IHX*

$T_9 = 535$

$s_9 = s\left[\text{'Steam}_{IAPWS}\text{'}, T = T_9, P = P_9\right]$

$h_9 = h\left[\text{'Steam}_{IAPWS}\text{'}, T = T_9, P = P_9\right]$

*Point 10*



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$PR_{IPT} = 0.256$

$PR_{IPT} = \frac{P_{10}}{P_9}$

$s_{i,10} = s_9$

$h_{i,10} = h\left['Steam_{IAPWS}', s = s_{i,10}, P = P_{10}\right]$

$T_{10} = T\left['Steam_{IAPWS}', h = h_{10}, P = P_{10}\right]$

$s_{10} = s\left['Steam_{IAPWS}', T = T_{10}, h = h_{10}\right]$

$\eta_{LPT} = \frac{h_9 - h_{10}}{h_9 - h_{i,10}}$

$Q_{IPT} = \dot{m}_{LPT} \cdot \left[h_9 - h_{10}\right]$

*LPT - Low pressure turbine*

*Point 11*

$\eta_{LPT} = 0.85$

$\dot{m}_{LPT} = 0.7756 \cdot \dot{m}_{max}$

$f_{bleed,10} = 0.1$

$\dot{m}_{11} = 0.9 \cdot \dot{m}_{IPT}$

$h_{11} = h_{10}$

$T_{11} = T_{10}$

$P_{11} = P_{10}$

$s_{11} = s_{10}$

*Point 12*

$PR_{LPT} = 0.256$

$PR_{LPT} = \frac{P_{12}}{P_{11}}$

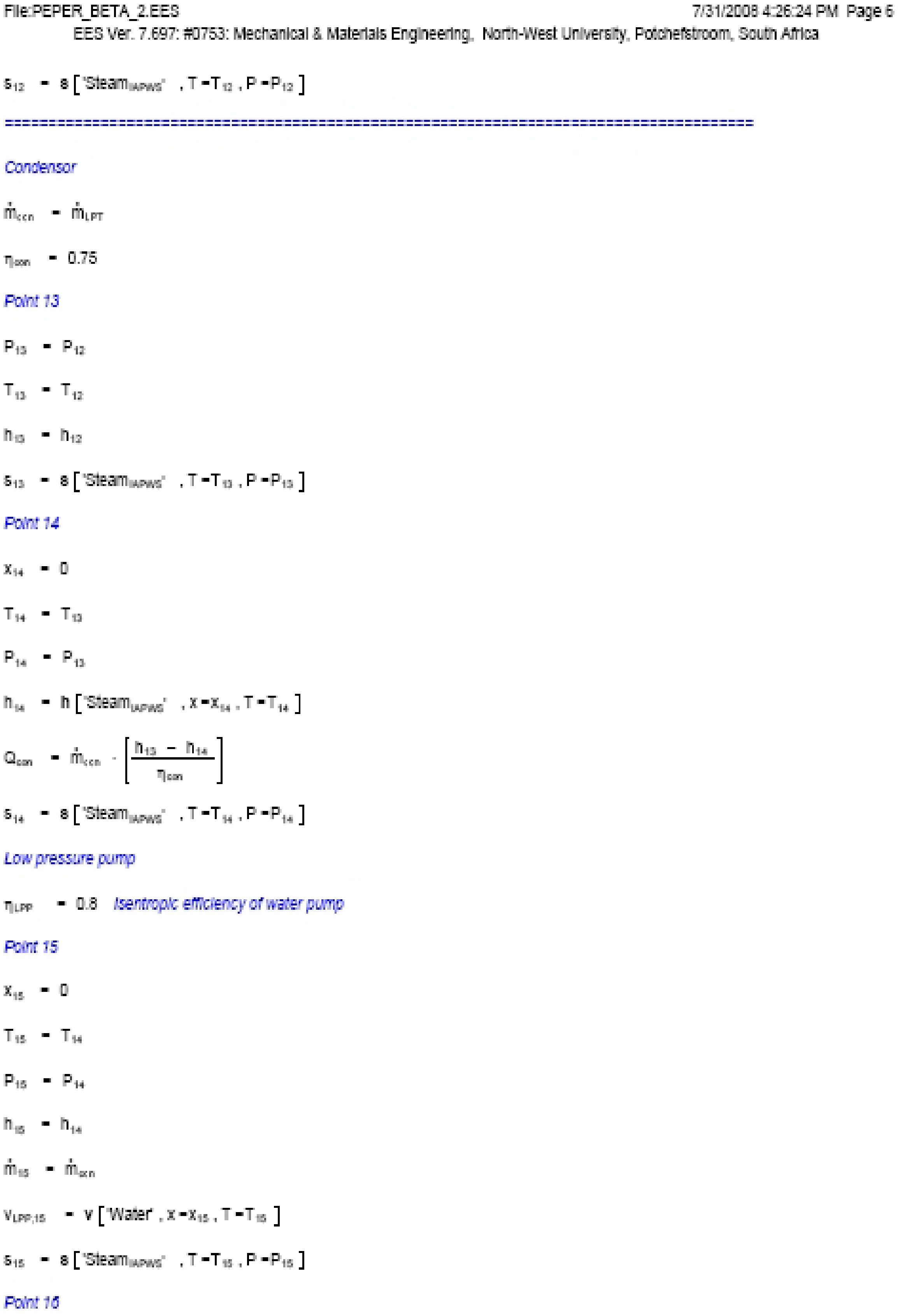
$s_{i,12} = s_{11}$

$h_{i,12} = h\left['Steam_{IAPWS}', s = s_{i,12}, P = P_{12}\right]$

$T_{12} = T\left['Steam_{IAPWS}', P = P_{12}, h = h_{12}\right]$

$\eta_{LPT} = \frac{h_{11} - h_{12}}{h_{11} - h_{i,12}}$

$Q_{LPT} = \dot{m}_{LPT} \cdot \left[h_{11} - h_{12}\right]$



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$s_{12} = s\left[\text{'Steam}_{\text{IAPWS}}\text{'}, T=T_{12}, P=P_{12}\right]$

==================================================================================

*Condensor*

$\dot{m}_{con} = \dot{m}_{LPT}$

$\eta_{con} = 0.75$

*Point 13*

$P_{13} = P_{12}$

$T_{13} = T_{12}$

$h_{13} = h_{12}$

$s_{13} = s\left[\text{'Steam}_{\text{IAPWS}}\text{'}, T=T_{13}, P=P_{13}\right]$

*Point 14*

$x_{14} = 0$

$T_{14} = T_{13}$

$P_{14} = P_{13}$

$h_{14} = h\left[\text{'Steam}_{\text{IAPWS}}\text{'}, x=x_{14}, T=T_{14}\right]$

$$Q_{con} = \dot{m}_{con} \cdot \left[\frac{h_{13} - h_{14}}{\eta_{con}}\right]$$

$s_{14} = s\left[\text{'Steam}_{\text{IAPWS}}\text{'}, T=T_{14}, P=P_{14}\right]$

*Low pressure pump*

$\eta_{LPP} = 0.8$ *Isentropic efficiency of water pump*

*Point 15*

$x_{15} = 0$

$T_{15} = T_{14}$

$P_{15} = P_{14}$

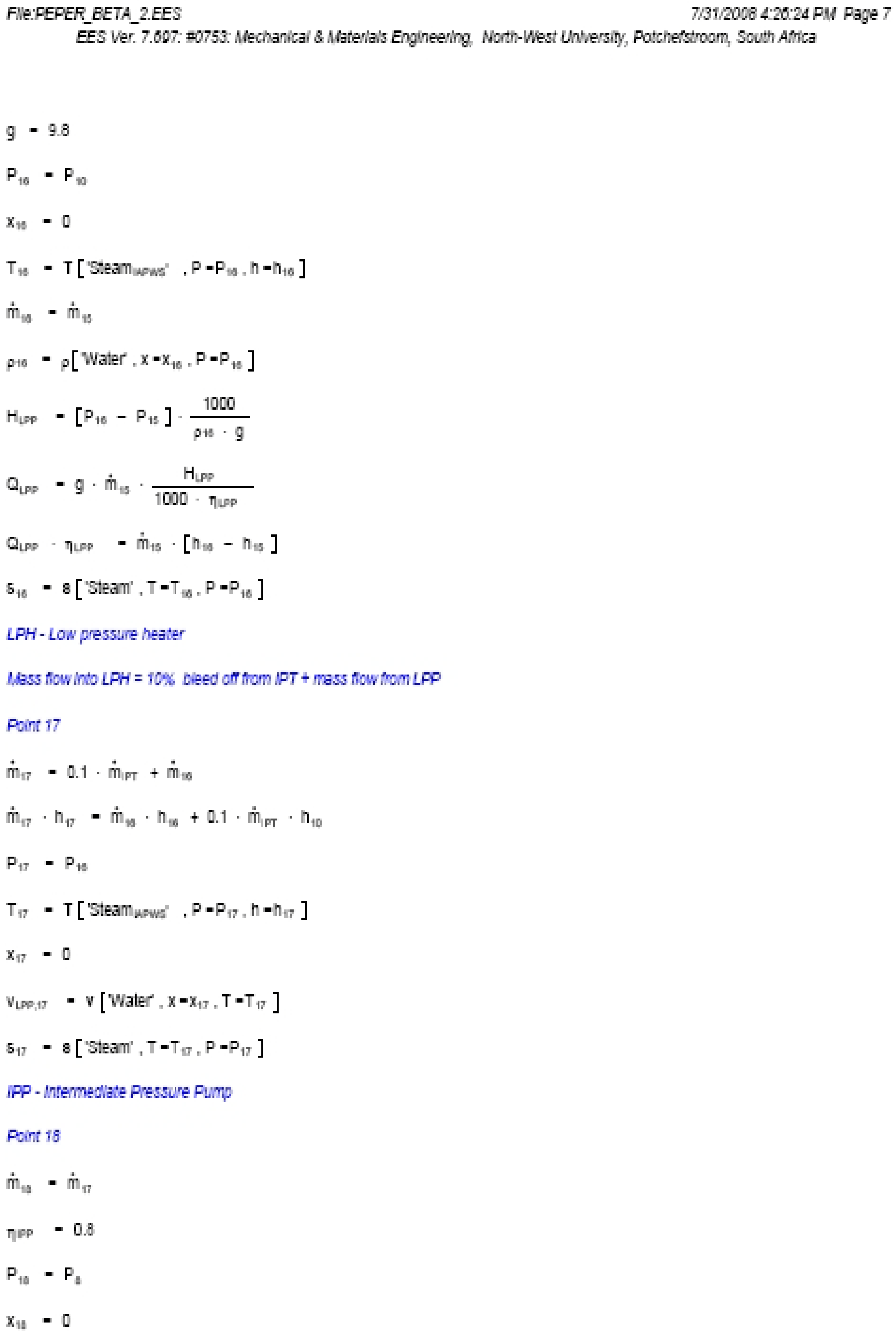
$h_{15} = h_{14}$

$\dot{m}_{15} = \dot{m}_{con}$

$v_{LPP,15} = v\left[\text{'Water'}, x=x_{15}, T=T_{15}\right]$

$s_{15} = s\left[\text{'Steam}_{\text{IAPWS}}\text{'}, T=T_{15}, P=P_{15}\right]$

*Point 16*



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$g = 9.8$

$P_{16} = P_{10}$

$x_{16} = 0$

$T_{16} = T\left['Steam_{IAPWS}', P = P_{16}, h = h_{16}\right]$

$\dot{m}_{16} = \dot{m}_{15}$

$\rho_{16} = \rho\left['Water', x = x_{16}, P = P_{16}\right]$

$H_{LPP} = [P_{16} - P_{15}] \cdot \frac{1000}{\rho_{16} \cdot g}$

$Q_{LPP} = g \cdot \dot{m}_{15} \cdot \frac{H_{LPP}}{1000 \cdot \eta_{LPP}}$

$Q_{LPP} \cdot \eta_{LPP} = \dot{m}_{15} \cdot [h_{16} - h_{15}]$

$s_{16} = s\left['Steam', T = T_{16}, P = P_{16}\right]$

*LPH - Low pressure heater*

*Mass flow into LPH = 10% bleed off from IPT + mass flow from LPP*

*Point 17*

$\dot{m}_{17} = 0.1 \cdot \dot{m}_{IPT} + \dot{m}_{16}$

$\dot{m}_{17} \cdot h_{17} = \dot{m}_{16} \cdot h_{16} + 0.1 \cdot \dot{m}_{IPT} \cdot h_{10}$

$P_{17} = P_{16}$

$T_{17} = T\left['Steam_{IAPWS}', P = P_{17}, h = h_{17}\right]$

$x_{17} = 0$

$v_{LPP,17} = v\left['Water', x = x_{17}, T = T_{17}\right]$

$s_{17} = s\left['Steam', T = T_{17}, P = P_{17}\right]$

*IPP - Intermediate Pressure Pump*

*Point 18*

$\dot{m}_{18} = \dot{m}_{17}$

$\eta_{IPP} = 0.8$

$P_{18} = P_{8}$

$x_{18} = 0$

$\rho_{18} = \rho[\text{'Water'}, x = x_{18}, P = P_{18}]$

$T_{18} = T[\text{'Water'}, P = P_{18}, h = h_{18}]$

$H_{LPP} = [P_{18} - P_{17}] \cdot \frac{1000}{\rho_{18} \cdot g}$

$Q_{LPP} = g \cdot \dot{m}_{17} \cdot \frac{H_{LPP}}{1000 \cdot \eta_{LPP}}$

$Q_{LPP} \cdot \eta_{LPP} = \dot{m}_{17} \cdot [h_{18} - h_{17}]$

$s_{18} = s[\text{'Steam}_{IAPWS}\text{'}, T = T_{18}, P = P_{18}]$

*IPH - Intermediate Pressure Heater*

$\dot{m}_{19} = \dot{m}_{18} + 0.1 \cdot \dot{m}_{IPFT}$

$\dot{m}_{19} \cdot h_{19} = \dot{m}_{18} \cdot h_{18} + 0.1 \cdot \dot{m}_{IPFT} \cdot h_{8}$

$P_{19} = P_{18}$

$T_{19} = T[\text{'Steam}_{IAPWS}\text{'}, P = P_{19}, h = h_{19}]$

$x_{19} = 0$

$v_{LPP,19} = v[\text{'Water'}, x = x_{19}, T = T_{19}]$

$s_{19} = s[\text{'Steam'}, T = T_{19}, P = P_{19}]$

*HPP - high pressure pump*

*Point 20*

$\dot{m}_{19} = \dot{m}_{20}$

$\eta_{HPP} = 0.8$

$P_{20} = P_{21}$

$x_{20} = 0$

$\rho_{20} = \rho[\text{'Water'}, x = x_{20}, P = P_{20}]$

$T_{20} = T[\text{'Water'}, P = P_{20}, h = h_{20}]$

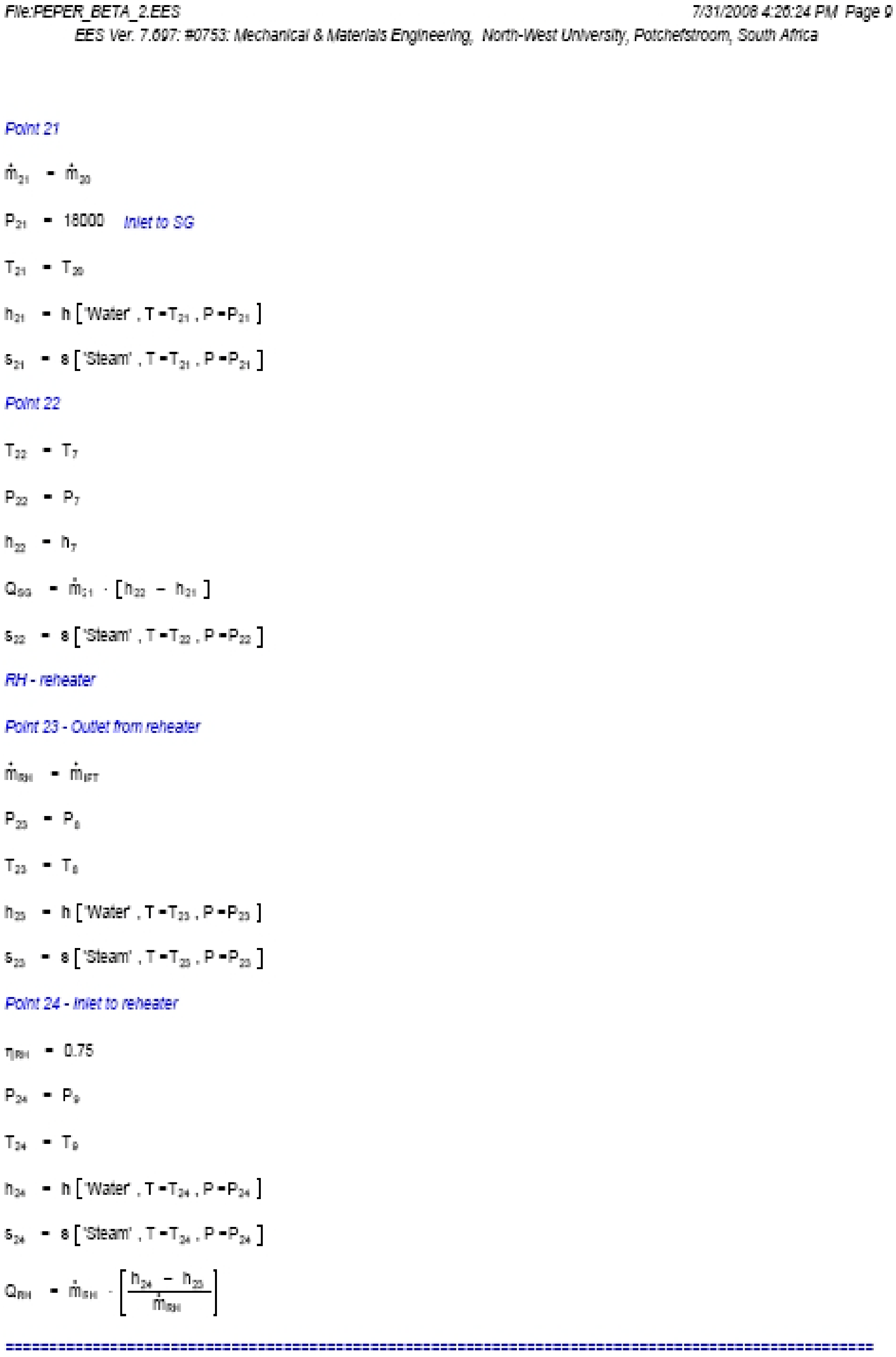
$H_{HPP} = [P_{20} - P_{19}] \cdot \frac{1000}{\rho_{20} \cdot g}$

$Q_{HPP} = g \cdot \dot{m}_{19} \cdot \frac{H_{HPP}}{1000 \cdot \eta_{HPP}}$

$Q_{HPP} \cdot \eta_{HPP} = \dot{m}_{19} \cdot [h_{20} - h_{19}]$

$s_{20} = s[\text{'Steam'}, T = T_{20}, P = P_{20}]$

*Steam Generator*



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*Point 21*

$\dot{m}_{21} = \dot{m}_{20}$

$P_{21} = 18000$ *Inlet to SG*

$T_{21} = T_{20}$

$h_{21} = h\left[\text{'Water'}, T=T_{21}, P=P_{21}\right]$

$s_{21} = s\left[\text{'Steam'}, T=T_{21}, P=P_{21}\right]$

*Point 22*

$T_{22} = T_7$

$P_{22} = P_7$

$h_{22} = h_7$

$Q_{SG} = \dot{m}_{21} \cdot \left[h_{22} - h_{21}\right]$

$s_{22} = s\left[\text{'Steam'}, T=T_{22}, P=P_{22}\right]$

*RH - reheater*

*Point 23 - Outlet from reheater*

$\dot{m}_{RH} = \dot{m}_{IPT}$

$P_{23} = P_8$

$T_{23} = T_8$

$h_{23} = h\left[\text{'Water'}, T=T_{23}, P=P_{23}\right]$

$s_{23} = s\left[\text{'Steam'}, T=T_{23}, P=P_{23}\right]$

*Point 24 - Inlet to reheater*

$\eta_{RH} = 0.75$

$P_{24} = P_9$

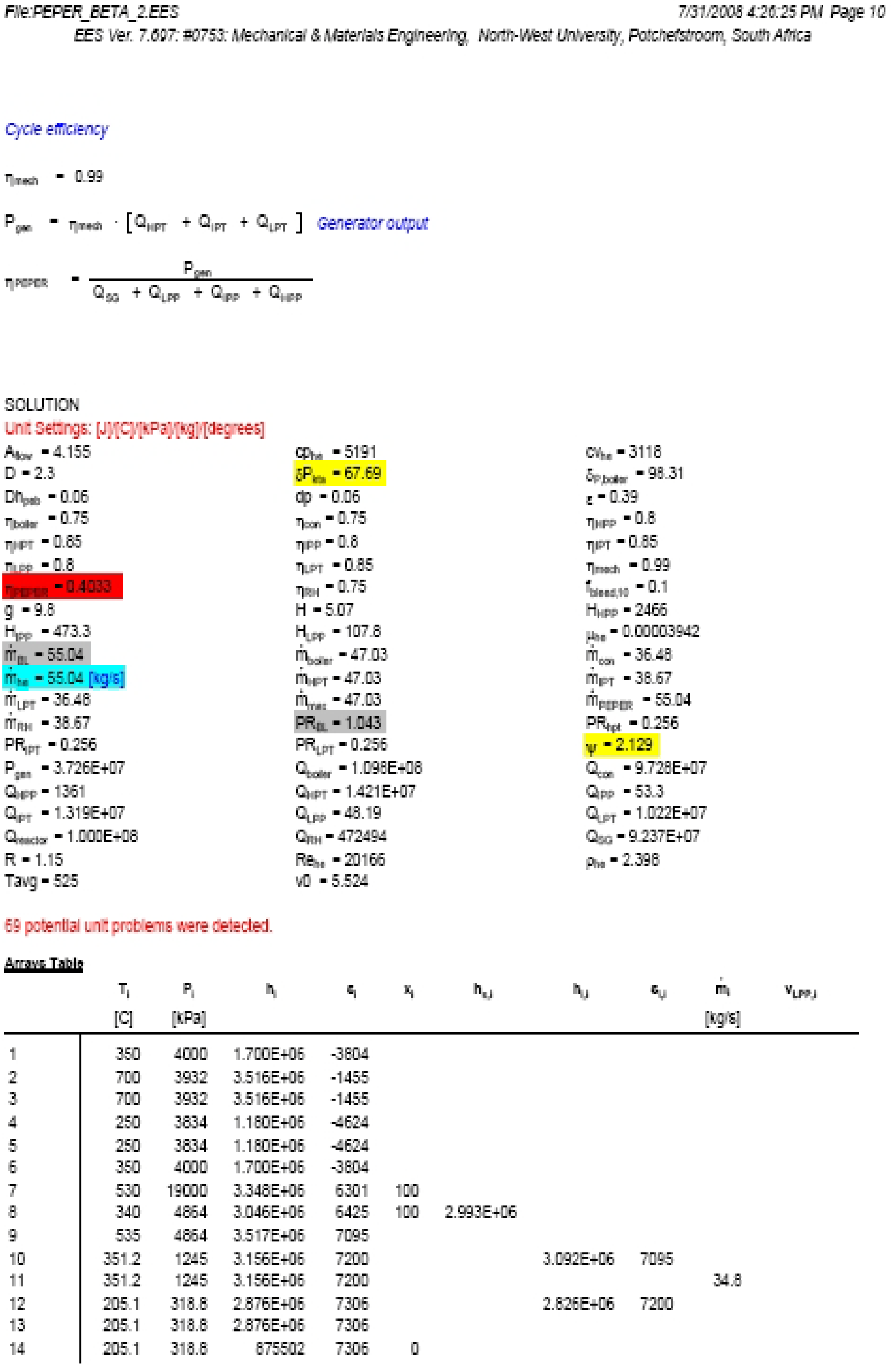
$T_{24} = T_9$

$h_{24} = h\left[\text{'Water'}, T=T_{24}, P=P_{24}\right]$

$s_{24} = s\left[\text{'Steam'}, T=T_{24}, P=P_{24}\right]$

$Q_{RH} = \dot{m}_{RH} \cdot \left[\frac{h_{24} - h_{23}}{\dot{m}_{RH}}\right]$

==========================================================================================



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*Cycle efficiency*

$\eta_{mech} = 0.99$

$P_{gen} = \eta_{mech} \cdot [Q_{HPT} + Q_{IPT} + Q_{LPT}]$ *Generator output*

$$\eta_{PEPER} = \frac{P_{gen}}{Q_{SG} + Q_{LPP} + Q_{IPP} + Q_{HPP}}$$

SOLUTION

Unit Settings: [J]/[C]/[kPa]/[kg]/[degrees]

$A_{flow} = 4.155$
$D = 2.3$
$Dh_{peb} = 0.06$
$\eta_{boiler} = 0.75$
$\eta_{HPT} = 0.85$
$\eta_{LPP} = 0.8$
$\eta_{PEPER} = 0.4033$
$g = 9.8$
$H_{IPP} = 473.3$
$\dot{m}_{BL} = 55.04$
$\dot{m}_{he} = 55.04$ [kg/s]
$\dot{m}_{LPT} = 36.48$
$\dot{m}_{RH} = 38.67$
$PR_{IPT} = 0.256$
$P_{gen} = 3.726E+07$
$Q_{HPP} = 1361$
$Q_{IPT} = 1.319E+07$
$Q_{reactor} = 1.000E+08$
$R = 1.15$
$Tavg = 525$

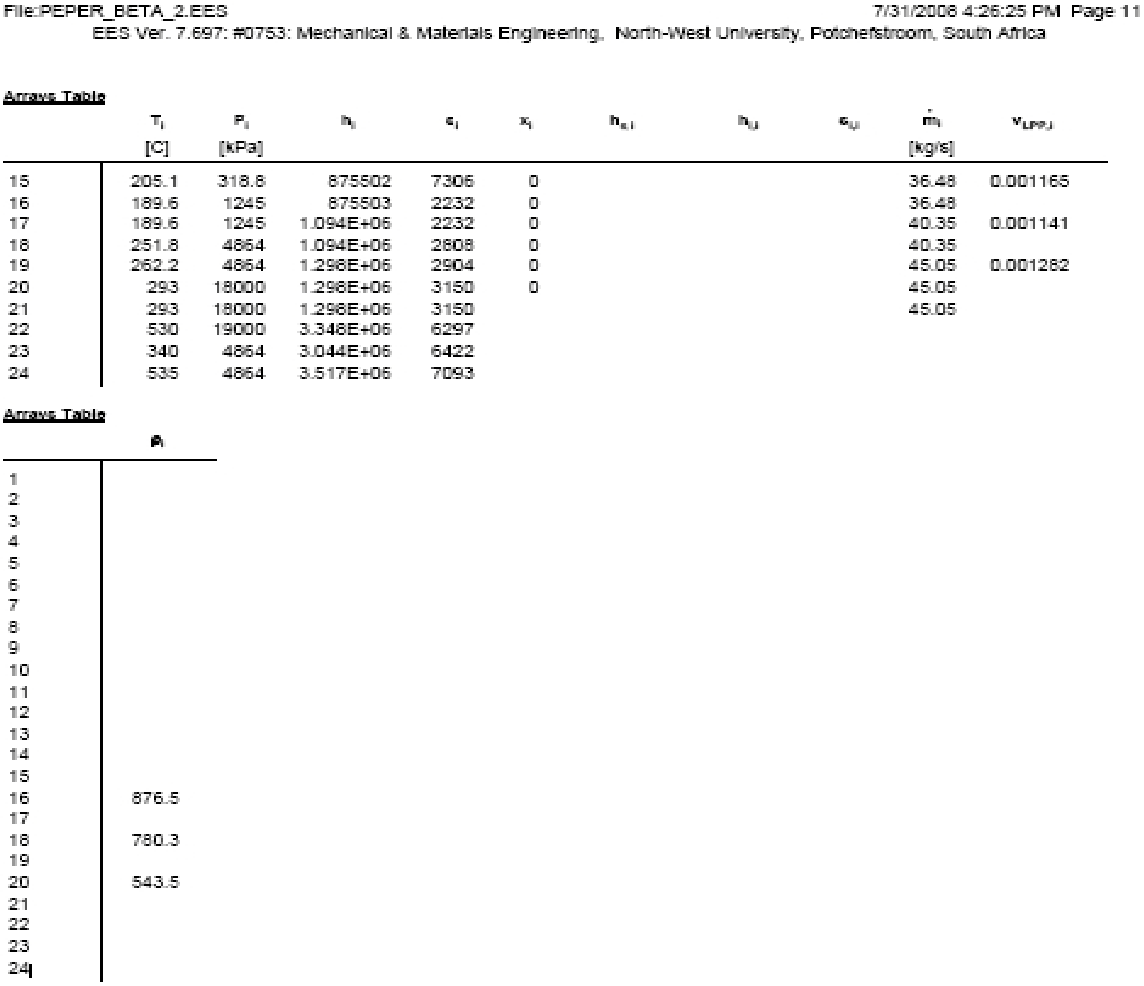
$cp_{he} = 5191$
$\delta P_{bts} = 67.69$
$dp = 0.06$
$\eta_{con} = 0.75$
$\eta_{IPP} = 0.8$
$\eta_{LPT} = 0.85$
$\eta_{RH} = 0.75$
$H = 5.07$
$H_{LPP} = 107.8$
$\dot{m}_{boiler} = 47.03$
$\dot{m}_{HPT} = 47.03$
$\dot{m}_{mes} = 47.03$
$PR_{BL} = 1.043$
$PR_{LPT} = 0.256$
$Q_{boiler} = 1.098E+08$
$Q_{HPT} = 1.421E+07$
$Q_{LPP} = 48.19$
$Q_{RH} = 472494$
$Re_{he} = 20166$
$v0 = 5.524$

$cv_{he} = 3118$
$\delta_{P,boiler} = 98.31$
$\varepsilon = 0.39$
$\eta_{HPP} = 0.8$
$\eta_{IPT} = 0.85$
$\eta_{mech} = 0.99$
$f_{bleed,10} = 0.1$
$H_{HPP} = 2466$
$\mu_{he} = 0.00003942$
$\dot{m}_{con} = 36.48$
$\dot{m}_{IPT} = 38.67$
$\dot{m}_{PEPER} = 55.04$
$PR_{hpt} = 0.256$
$\psi = 2.129$
$Q_{con} = 9.728E+07$
$Q_{IPP} = 53.3$
$Q_{LPT} = 1.022E+07$
$Q_{SG} = 9.237E+07$
$\rho_{he} = 2.398$

69 potential unit problems were detected.

**Arrays Table**

| | $T_i$<br>[C] | $P_i$<br>[kPa] | $h_i$ | $s_i$ | $x_i$ | $h_{s,i}$ | $h_{t,i}$ | $s_{t,i}$ | $\dot{m}_i$<br>[kg/s] | $v_{LPP,i}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 4000 | 1.700E+06 | -3804 | | | | | | |
| 2 | 700 | 3932 | 3.516E+06 | -1455 | | | | | | |
| 3 | 700 | 3932 | 3.516E+06 | -1455 | | | | | | |
| 4 | 250 | 3834 | 1.180E+06 | -4624 | | | | | | |
| 5 | 250 | 3834 | 1.180E+06 | -4624 | | | | | | |
| 6 | 350 | 4000 | 1.700E+06 | -3804 | | | | | | |
| 7 | 530 | 19000 | 3.348E+06 | 6301 | 100 | | | | | |
| 8 | 340 | 4864 | 3.046E+06 | 6425 | 100 | 2.993E+06 | | | | |
| 9 | 535 | 4864 | 3.517E+06 | 7095 | | | | | | |
| 10 | 351.2 | 1245 | 3.156E+06 | 7200 | | | 3.092E+06 | 7095 | | |
| 11 | 351.2 | 1245 | 3.156E+06 | 7200 | | | | | 34.8 | |
| 12 | 205.1 | 318.8 | 2.876E+06 | 7306 | | | 2.826E+06 | 7200 | | |
| 13 | 205.1 | 318.8 | 2.876E+06 | 7306 | | | | | | |
| 14 | 205.1 | 318.8 | 875502 | 7306 | 0 | | | | | |



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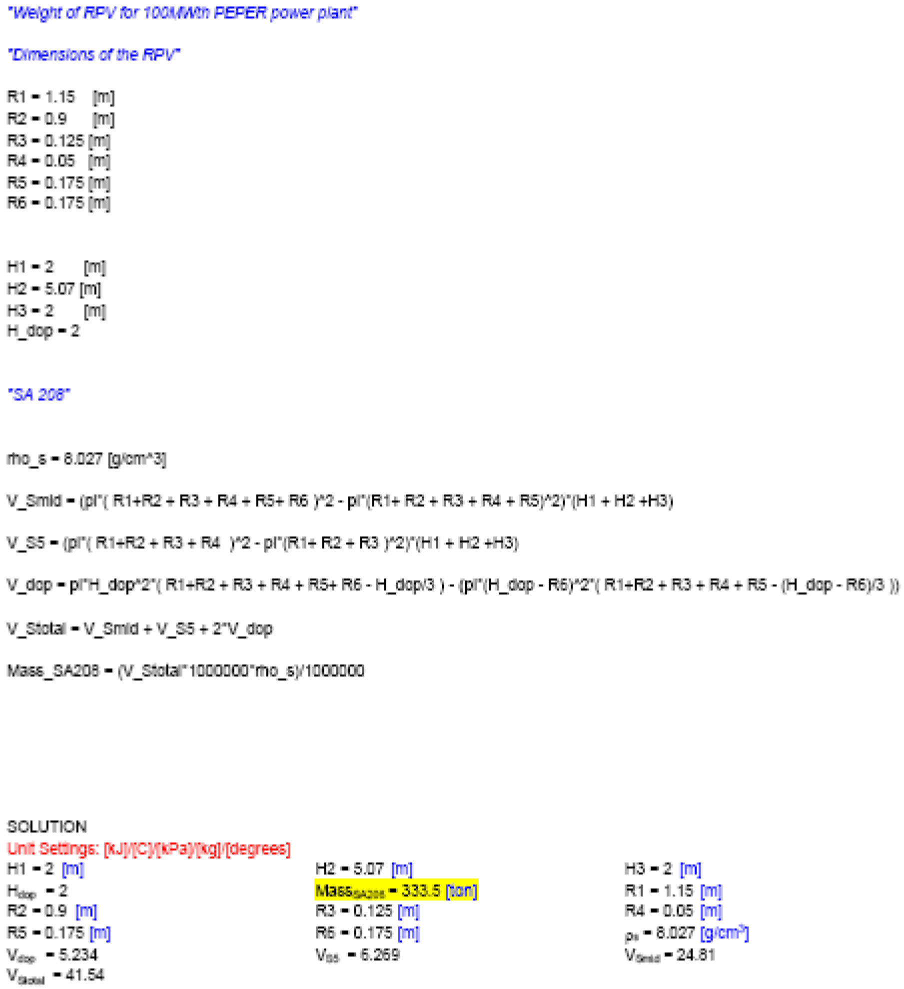
**Arrays Table**

| | $T_i$ [C] | $P_i$ [kPa] | $h_i$ | $s_i$ | $x_i$ | $h_{s,i}$ | $h_{l,i}$ | $s_{l,i}$ | $\dot{m}_i$ [kg/s] | $v_{LPP,i}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 205.1 | 318.8 | 875502 | 7306 | 0 | | | | 36.48 | 0.001165 |
| 16 | 189.6 | 1245 | 875503 | 2232 | 0 | | | | 36.48 | |
| 17 | 189.6 | 1245 | 1.094E+06 | 2232 | 0 | | | | 40.35 | 0.001141 |
| 18 | 251.8 | 4864 | 1.094E+06 | 2808 | 0 | | | | 40.35 | |
| 19 | 262.2 | 4864 | 1.298E+06 | 2904 | 0 | | | | 45.05 | 0.001282 |
| 20 | 293 | 18000 | 1.298E+06 | 3150 | 0 | | | | 45.05 | |
| 21 | 293 | 18000 | 1.298E+06 | 3150 | | | | | 45.05 | |
| 22 | 530 | 19000 | 3.348E+06 | 6297 | | | | | | |
| 23 | 340 | 4864 | 3.044E+06 | 6422 | | | | | | |
| 24 | 535 | 4864 | 3.517E+06 | 7093 | | | | | | |

**Arrays Table**

| | $\rho_i$ |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |
| 7 | |
| 8 | |
| 9 | |
| 10 | |
| 11 | |
| 12 | |
| 13 | |
| 14 | |
| 15 | |
| 16 | 876.5 |
| 17 | |
| 18 | 780.3 |
| 19 | |
| 20 | 543.5 |
| 21 | |
| 22 | |
| 23 | |
| 24 | |

# Appendix B: Calculation of the mass of SA-508 steel used in the reactor pressure vessel of the Potchefstroom Experimental Pebble Bed Modular Reactor plant



```
"Weight of RPV for 100MWth PEPER power plant"

"Dimensions of the RPV"

R1 = 1.15    [m]
R2 = 0.9     [m]
R3 = 0.125 [m]
R4 = 0.05   [m]
R5 = 0.175 [m]
R6 = 0.175 [m]


H1 = 2      [m]
H2 = 5.07 [m]
H3 = 2      [m]
H_dop = 2


"SA 208"


rho_s = 8.027 [g/cm^3]

V_Smid = (pi*( R1+R2 + R3 + R4 + R5+ R6 )^2 - pi*(R1+ R2 + R3 + R4 + R5)^2)*(H1 + H2 +H3)

V_S5 = (pi*( R1+R2 + R3 + R4  )^2 - pi*(R1+ R2 + R3 )^2)*(H1 + H2 +H3)

V_dop = pi*H_dop^2*( R1+R2 + R3 + R4 + R5+ R6 - H_dop/3 ) - (pi*(H_dop - R6)^2*( R1+R2 + R3 + R4 + R5 - (H_dop - R6)/3 ))

V_Stotal = V_Smid + V_S5 + 2*V_dop

Mass_SA208 = (V_Stotal*1000000*rho_s)/1000000
```

```
SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
H1 = 2  [m]                   H2 = 5.07  [m]                H3 = 2  [m]
H_dop  = 2                    Mass_SA208 = 333.5 [ton]      R1 = 1.15  [m]
R2 = 0.9  [m]                 R3 = 0.125 [m]                R4 = 0.05  [m]
R5 = 0.175 [m]                R6 = 0.175 [m]                ρs = 8.027 [g/cm^3]
V_dop  = 5.234                V_S5  = 6.269                 V_Smid = 24.81
V_Stotal  = 41.54
```

# Appendix C: Household and Industrial electricity prices for the various countries

## *Household electricity prices*

| Household electricity prices | |
|---|---|
| **Country** | **Household (US $/kWh)** |
| Australia | 0.103 |
| Canada | 0.070 |
| Chinese Taipei (Taiwan) | 0.075 |
| Czech Republic | 0.134 |
| Denmark | 0.320 |
| Finland | 0.135 |
| France | 0.146 |
| Germany | 0.220 |
| Greece | 0.110 |
| Hungary | 0.167 |
| India | 0.050 |
| Indonesia | 0.053 |
| Ireland | 0.214 |
| Italy | 0.215 |
| Japan | 0.180 |
| Kazakhstan | 0.027 |
| Korea, South | 0.093 |
| Mexico | 0.117 |
| Netherlands | 0.284 |
| New Zealand | 0.153 |
| Poland | 0.142 |
| Portugal | 0.189 |
| Romania | 0.135 |
| Slovak Republic (Slovakia) | 0.190 |
| South Africa | 0.040 |
| Spain | 0.156 |
| Switzerland | 0.138 |
| Thailand | 0.076 |
| Turkey | 0.128 |
| United Kingdom | 0.170 |
| United States | 0.102 |

## *Industrial electricity prices*

| Industrial electricity prices | |
|---|---|
| **Country** | **Industrial (US$/kWh)** |
| Australia | 0.063 |
| Canada | 0.055 |
| Chinese Taipei (Taiwan) | 0.054 |
| Czech Republic | 0.092 |
| Denmark | 0.109 |
| Finland | 0.081 |
| France | 0.051 |
| Germany | 0.083 |
| Greece | 0.07 |
| Hungary | 0.114 |
| India | 0.073 |
| Indonesia | 0.099 |
| Ireland | 0.129 |
| Italy | 0.208 |
| Japan | 0.112 |
| Kazakhstan | 0.017 |
| Korea, South | 0.066 |
| Mexico | 0.107 |
| Netherlands | 0.047 |
| New Zealand | 0.059 |
| Poland | 0.082 |
| Portugal | 0.105 |
| Romania | 0.104 |
| Slovak Republic (Slovakia) | 0.106 |
| South Africa | 0.011 |
| Spain | 0.087 |
| Switzerland | 0.075 |
| Thailand | 0.069 |
| Turkey | 0.114 |
| United Kingdom | 0.075 |
| United States | 0.062 |

# Appendix D: Decreasing fixed capital investment costs with increasing construction of Potchefstroom Experimental Pebble Bed Modular Reactor plants

| ***FOAK and NOAK, 6% decrease with each new PEPER plant constructed, until the eighth (NOAK) PEPER plant is reached*** | |
|---|---|
| ***Module number*** | ***Direct, indirect and contingency costs (US$)*** |
| *PEPER plant number 1* ***FOAK PEPER plant*** | $367,199,411.06 |
| *PEPER plant number 2* | $345,231,413.45 |
| *PEPER plant number 3* | $324,577,668.82 |
| *PEPER plant number 4* | $305,159,550.94 |
| *PEPER plant number 5* | $286,903,137.44 |
| *PEPER plant number 6* | $269,738,928.44 |
| *PEPER plant number 7* | $253,601,581.93 |
| *PEPER plant number 8* ***NOAK PEPER plant*** | $238,429,665.05 |

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19 November 2009

Tel: 079 697 5047

Dear Sir/Madam,

**Letter of confirmation**

This letter serves to confirm that the following document has been language edited at the request of the author, Mr Yvotte Brits:

*Techno-economic analysis of the 100MWth Potchefstroom Experimental Pebble Bed Reactor (PEPER) plant*

Yours faithfully,

Sabrina Raaff

**Qualifications:**

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Bachelor of Arts Honours in Linguistics and Applied Language Studies

Bachelor of Arts in English Language and Linguistics

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