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CHANGING THE FACE OF NUCLEAR POWER VIA THE INNOVATIVE PEBBLE BED MODULAR REACTOR

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Abstract

It is estimated that electricity demand in South Africa could outstrip supply by current power stations between 2005 and 2010. Furthermore, the emphasis on export has lead to more and more large industrial plants being erected near the coast resulting in load growth in coastal areas, away from the traditional Gauteng industrial hart land. This, in turn, increased the burden on the Eskom power transmission network and gave rise to a growing need for smaller, distributed power generation units.

The Pebble Bed Modular Reactor (PBMR) offers a unique combination of advantages to address this need, namely:

- Inherent safety characteristics.
- Low environmental impact.
- Small unit size conducive to distributed generation.
- Short construction periods.
- Excellent load following capability.
- High load factor.
- Competitive economics.

Besides these factors, it is also envisaged that the project will offer substantial potential for export, job creation and expansion of the local technology base.

The aim of this paper is to provide an overview of nuclear power and specific PBMR related issues and to show why the PBMR offers such an attractive solution to future power supply needs.

1 Introduction

As shown in Figure 1, it is estimated that electricity demand in South Africa could outstrip supply by current power stations between 2005 and 2010 [1]. Furthermore, the emphasis on export has lead to more and more large industrial plants being erected near the coast resulting in load growth in coastal areas, away from the traditional Gauteng industrial hart land. This, in turn, increased the burden on the Eskom power transmission network and gave rise to a growing need for smaller, more widely distributed power generation units.

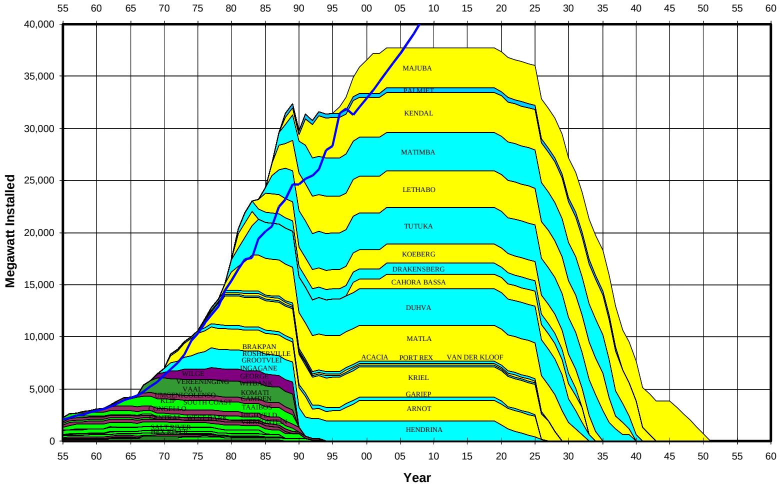
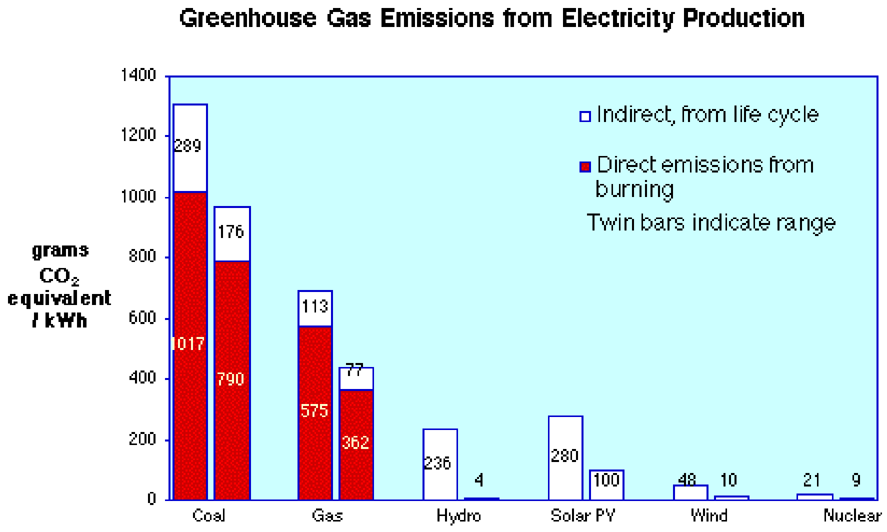


Figure 1 Summary of estimated South African electrical power demand and supply offered by existing power stations until 2060 [1].

As part of its Integrated Electricity Planning (IEP) process, Eskom has looked at various supply side options [2]. Besides the need for smaller, more widely distributed generation, the evaluation criteria also included the following:

- The capital and operation and maintenance (O&M) cost must be comparable or better than that of large coal fired power stations at approximately US$ 1,000 per kW and 2.0 US¢/kWh respectively in 1996.
- The construction lead times must be as short as possible to minimise the risks associated with over- or under supply resulting from inherent demand forecast inaccuracies. The lead-time for conventional coal-fired power stations is approximately 42 months.
- Good load following capability is required to improve flexibility of supply compared to the current situation, which favours base load production.
- The availability/load factor must be comparable with or better than the current Eskom target of 90 %.

In addition to this, it would be beneficial to expand Eskom's diversity of fuel supply, of which coal currently contributes approximately 90 %, and it is vital that any new technology must not unduly increase the burden on the environment. Rather, it should reduce the negative impact associated with existing coal-fired plants including carbon dioxide emissions, high demand on highveld water resources and other external costs. As illustrated in Figure 2, nuclear power generation produces no direct CO_2 emissions and only very limited quantities through indirect means. It is therefore not surprising that the requirements set out above prompted renewed consideration of the nuclear option.


Greenhouse Gas Emissions from Electricity Production

Source: IAEA 2000

Figure 2 Greenhouse gas emissions from electricity production [3].

However, two major problem areas related to nuclear technology was identified, namely cost and public acceptance. This resulted in the rejection of conventional Light Water Reactor (LWR) technology. Nonetheless, the innovative modular High Temperature Gas-cooled Reactor (HTGR) using coated fuel particles, coupled with a closed cycle gas turbine Power Conversion Unit (PCU) was identified as a prospect to overcome these problems. Hence the Pebble Bed Modular Reactor (PBMR) project was born in 1993 with the potential to meet Eskom's requirements.

The PBMR offers the following unique combination of advantages:

- Inherent safety characteristics.
- Low environmental impact.
- Small unit size conducive to distributed generation.
- Short construction periods.
- Excellent load following capability.
- High load factor.
- Competitive economics.

2 Current status of nuclear power

2.1 Conventional nuclear power plants

Of the nuclear reactors currently in operation worldwide, roughly 60 % are of the pressurised water reactor (PWR) type and 20 % are of boiling water reactor (BWR) type. Both of these use enriched uranium dioxide (UO_2) pellets as fuel arranged in tubular form fuel rods. Both can also be classified as light water reactors (LWR) that use ordinary water as coolant and moderator. Whereas the coolant is circulated through the reactor core to transfer heat from it, the moderator is required to slow neutrons from fission down so that they can initiate further fission reactions [4]. Most of these reactors are refuelled in a batch-processing mode, i.e. the reactor needs to be shut down and opened up at intervals of between one and two years to replace a quarter to one third of the fuel rods.

The PWR (Figure 3) has a primary coolant circuit with water flowing through the reactor under high pressure. Heat is transferred to a secondary circuit via a steam generator heat exchanger where water is heated and evaporated to produce steam that drives an ordinary steam turbine cycle.

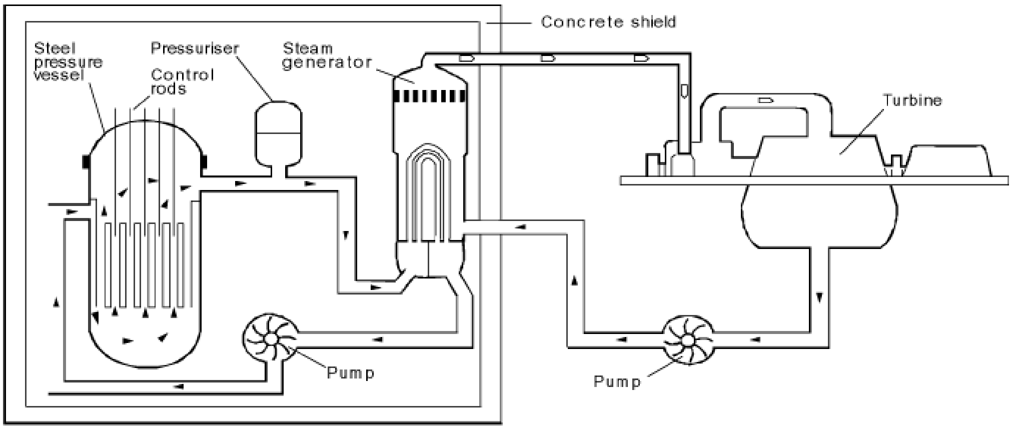


Figure 3 Schematic of a typical pressurised water reactor (PWR) power plant courtesy of World Nuclear Association [4].

The BWR (Figure 4) has only one coolant circuit operating under lower pressure. The water covering the reactor core is continually boiled off from where it passes through the steam turbines.

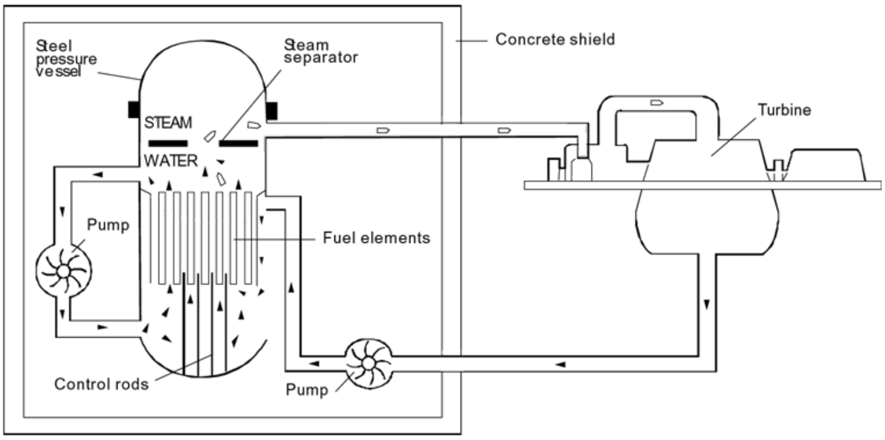


Figure 4 Schematic of a typical boiling water reactor (BWR) power plant courtesy of World Nuclear Association [4].

A disadvantage of the LWR concept is that the batch-processing refuelling scheme requires some excess reactivity directly after refuelling to ensure longer continuous operation. Furthermore, the presence of water in the high-density liquid phase means that a very large volume of radioactive steam may be discharged to the atmosphere in the unlikely case of a severe incident.

Besides these conventional LWR reactors, a further 15 % of existing reactors are either of the pressurised heavy water reactor (PHWR, also known as CANDU) type or of the advanced gas-cooled reactor (AGR or Magnox) type.

The PHWR employs natural UO_2 fuel and therefore requires heavy water (D_2O), which is a more efficient moderator. The coolant is also heavy water and the operating principle is similar to that of the PWR, except that the pressure tube design is such that the reactor can be refuelled progressively instead of in batch-processing mode.

In the AGR carbon dioxide (CO_2) coolant gas is circulated through a graphite-moderated core. The heat is then transferred to a secondary cycle via a steam generator where, similar to the PWR, water is heated and evaporated and the steam drives an ordinary steam turbine cycle.

2.2 World electricity generation

As shown in Figure 5, nuclear power plants currently supply 16 % of the total electricity generated worldwide [4]. Figure 6 shows that the USA is the largest single contributor, at nearly one third of the total. Other large contributors are France, Japan, Germany and Russia. There are currently 440 commercial reactors operating in 31 countries with a total installed capacity of approximately 360,000 MWe, and another 30 reactors are under construction. In 17 countries nuclear reactors provide at least a quarter of all electricity and in 10 countries nuclear power contributes at least one third of the total.

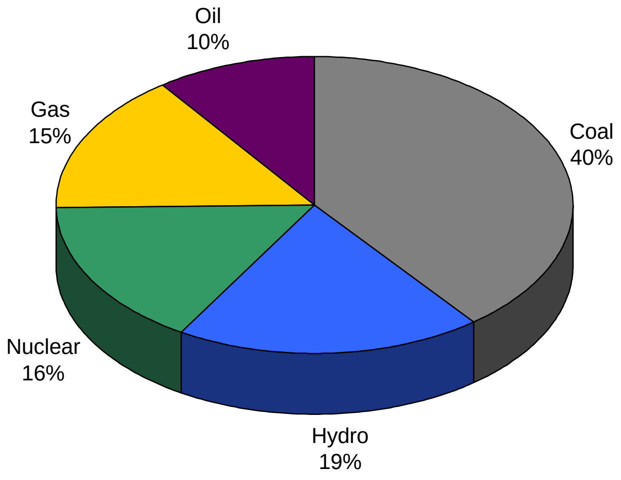


Figure 5 Distribution of world electricity generation [4].

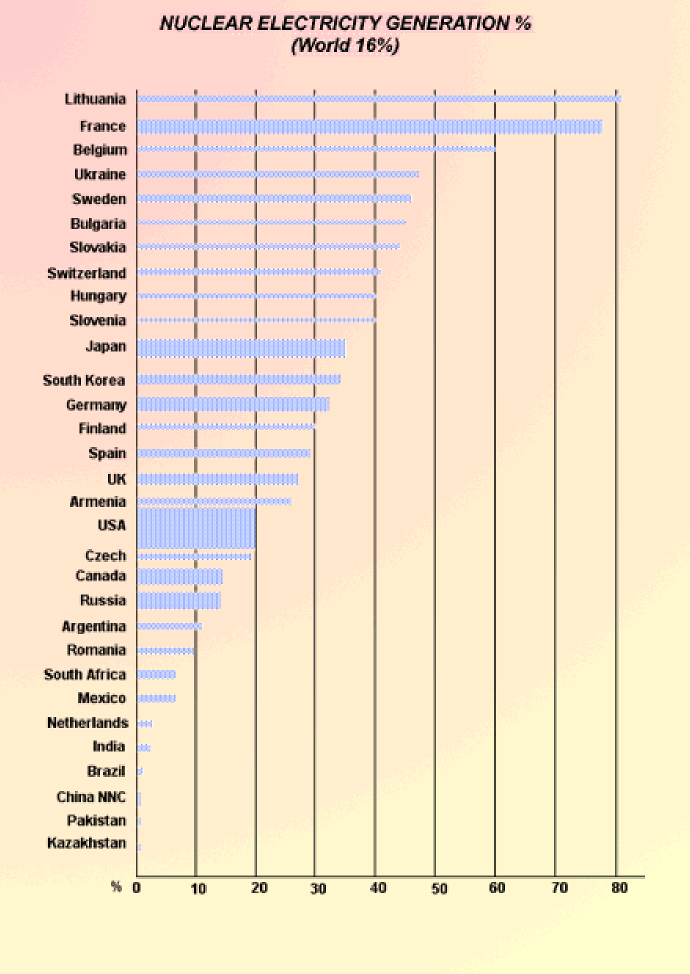
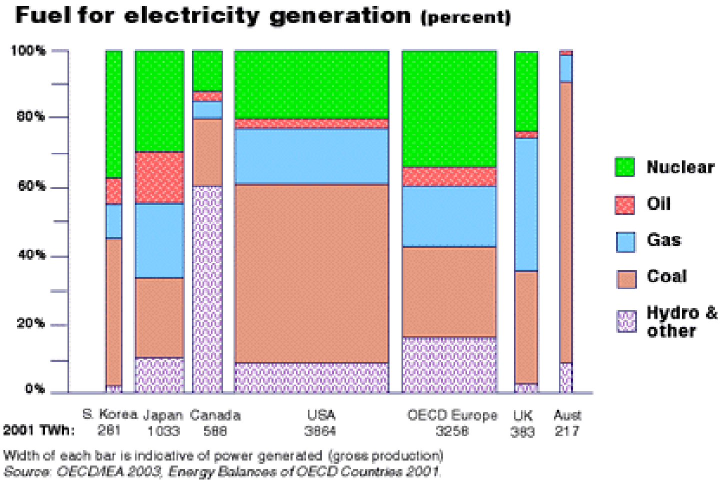


Figure 6 Percentage contribution of nuclear power to electricity generation in different countries courtesy of World Nuclear Association [4].

As far as the diversity of fuel supply for electricity generation is concerned, nuclear power is the second most important source in the United States and as shown in Figure 7, it is also the single most important source in European OECD countries.



Width of each bar is indicative of power generated (gross production)
Source: OECD/IEA 2003, Energy Balances of OECD Countries 2001.

Figure 7 Percentage contribution of fuel types for electricity generation in selected regions [8].

From the data provided above it should be clear that nuclear power has gained substantial acceptance worldwide and currently plays and important role in the global energy supply mix. Despite this, arguments against nuclear power regarding safety and economics persist. However, as illustrated by the remarks of pre-eminent environmental leader James Lovelock, many of these are unfortunately based on disinformation and fear and not on sound scientific or economic arguments [10].

2.3 Nuclear safety

Civil nuclear power generation has until now seen only two major accidents namely Three Mile Island (TMI) in the USA during 1979 and Chernobyl in the Ukraine during 1986. The TMI accident was caused by a cooling malfunction, which caused a reactor core melt and some radioactive gas was released to the atmosphere. However, the total incident caused no injuries or adverse health effects.

In the case of Chernobyl, the accident was much more severe. It resulted from a sequence of events that was initiated when operators conducted a series of tests after disabling many of the safety systems. The ultimate causes of the accident were a flawed reactor design, inadequately trained personnel and lack of a culture of safety. Thirty people were killed in the period directly after the accident and approximately ten more have died later of thyroid cancer. Fortunately, since then safety of all Soviet-designed reactors have improved immensely [4].

Despite these accidents, nuclear power is still the safest form of energy generation in terms of human fatalities. This is clearly illustrated by the results of one of the best studies on comparative safety of energy systems, namely the GaBE project conducted in 1998 by the Paul Scherrer Institute in Switzerland [7]. Figure 8 provides a summary of their results based on worldwide records for the period 1969 to 1996. It shows that natural gas has ten times more fatalities per TW.year than nuclear and hydro has one hundred times more than nuclear.

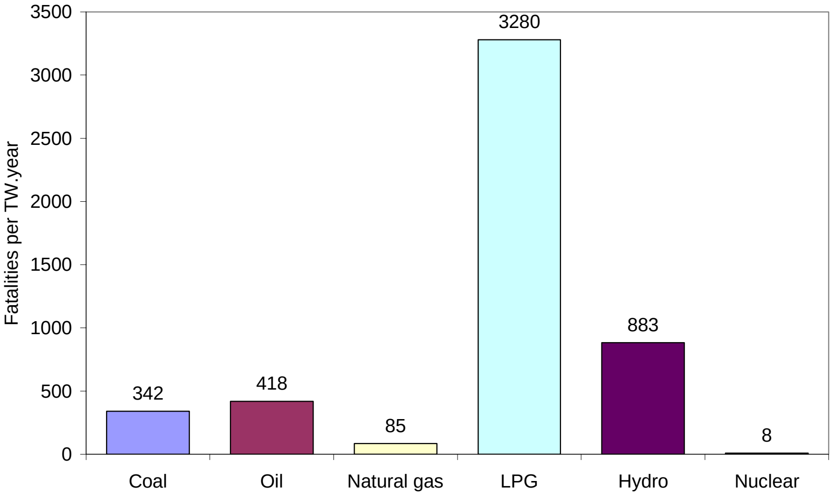


Figure 8 Deaths per TW.year associated with different energy sources based on worldwide records for the period 1969-1996 [7].

2.4 Economics of nuclear power generation

In many regions nuclear energy is competitive with fossil fuels despite the high capital cost penalties incurred due to extensive safety requirements. In the US, it is currently the most operationally economic source of electricity generation. This was confirmed by energy secretary Spencer Abraham in his speech to the senate energy and natural resources committee in February 2004 [9]. The US indeed fares well in this department since it boasts 13 of the world's 23 top performing reactors achieving load factors of more than 98 %. In 2002 five of the top 23 plants were Japanese. However, efficient operation is not restricted to the USA and Japan. Almost two-thirds of the world's reactors achieve 80 % while the average load factor worldwide has improved from 65 % in 1990 to the current value of around 90 % [4].

As shown in Figure 9, there is very little difference between coal and nuclear when comparing the total fuel and O&M costs, which was approximately 2.0 US¢/kWh in 2001. Although it is very difficult to estimate capital costs since it varies greatly between locations and plants, OECD estimations of total costs in the US put nuclear at 3.73 US¢/kWh, coal at 3.27 US¢/kWh and gas at 5.87 US¢/kWh [4].

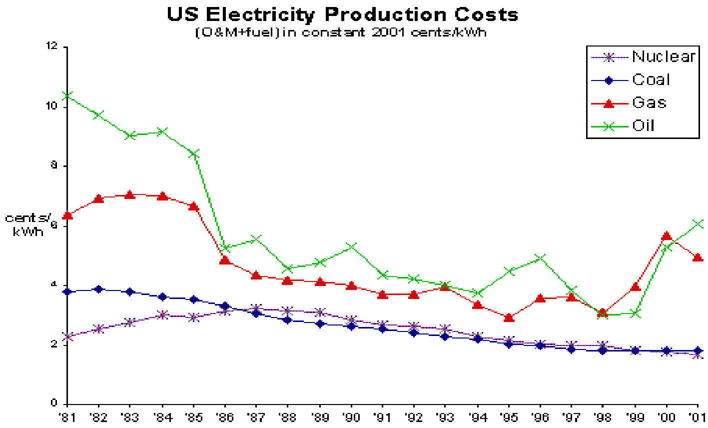


Figure 9 Comparison of US electricity production costs courtesy of World Nuclear Association [4]

Another interesting fact is that when all external costs, including social, health and environmental, are taken into account for complete fuel chains, nuclear power fares very well indeed. This should not be surprising since it produces relatively small amounts of waste that are tightly controlled, monitored and regulated. This fact has been illustrated in various comprehensive studies of energy systems. Summary results from two such studies ([5],[6]) are shown in Figure 10 and Figure 11.

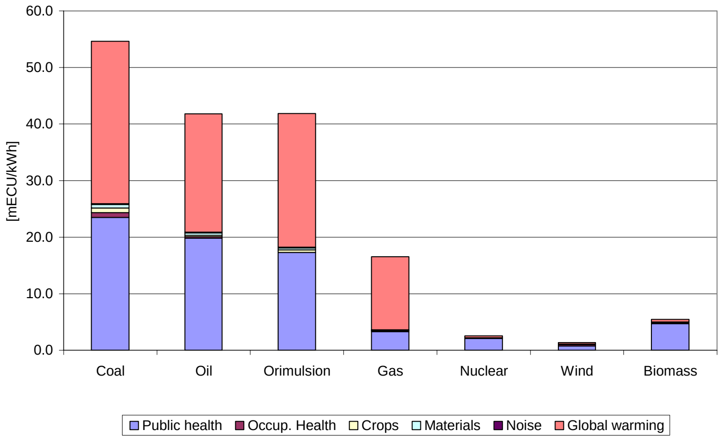


Figure 10 External costs for reference UK power generation cycles from the European Commission's ExternE study [5].

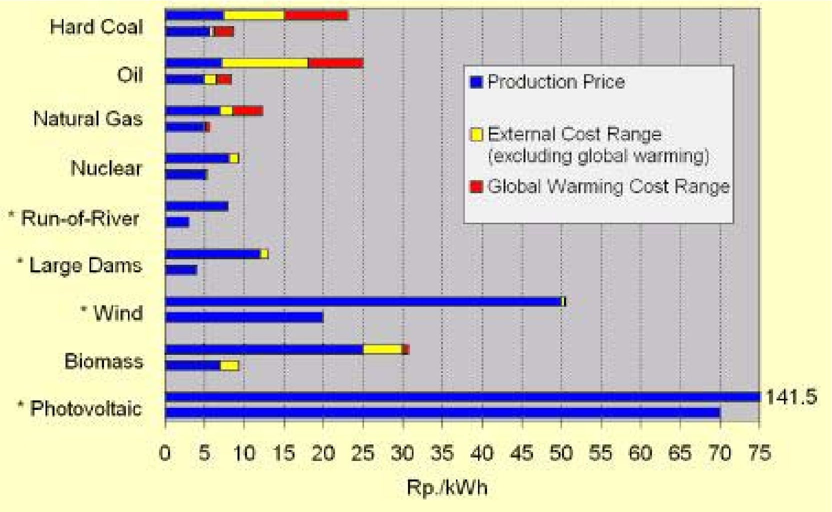


Figure 11 Production and external costs for power generation in Switzerland [6]. The two bars represent the lower and upper ranges of values.

2.5 Advanced nuclear power plants

Despite the already good record, more advanced nuclear power plants are continually being conceptualised and developed in a quest to further improve both safety and economics. The majority of reactors currently in operation are collectively known as Generation II while very few so-called Generation I reactors are still in operation [4]. Various Generation III advanced reactors are in development while two are already in operation in Japan and others are under construction. Generation III reactors are in many cases further developments of PWR, BWR and CANDU. The so-called Generation IV reactors are all still in the conceptual design phases. The PBMR is probably one of the best-known new designs.

3 The Pebble Bed Modular Reactor

3.1 The PBMR concept

The PBMR reactor is a helium cooled, graphite moderated High Temperature Gas-cooled Reactor (HTGR) reactor that uses enriched UO_2 as fuel. The fuel kernel, shown in Figure 12, has a diameter of approximately 0.5 mm and is contained in a coated particle made up of several different layers. The coated particles are embedded in a graphite matrix with 50 mm diameter and covered with a 5 mm thick graphite layer. This then forms the fuel sphere or so-called ‘pebble’. The reactor has an annular core configuration similar to the one shown in Figure 13.

The core is 3.7 m in diameter and 9 m in height and contains approximately 450,000 pebbles. From the inlet manifold the coolant gas flows up the riser channels, through the horizontal inlet slots and into the top end of the core. From there it flows down through the gaps between the pebbles while it picks up the heat generated by the fission process, and out through a series of channels into the outlet manifold situated below the core. The core is situated inside a steel pressure vessel that is lined with graphite bricks acting as a neutron reflector. The reactor is refuelled in a continuous manner with pebbles circulating through the core several times before they are depleted and replaced. This of course increases the availability since the reactor need not be shut down for refuelling.

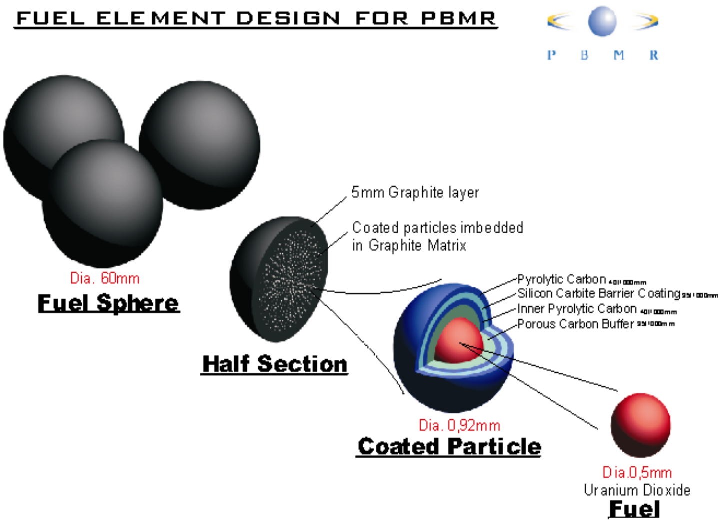


Figure 12 Schematic of the fuel element design courtesy of PBMR (Pty) Ltd.

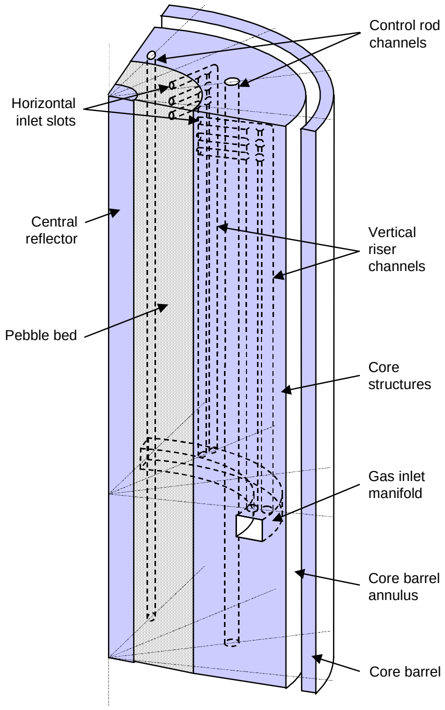


Figure 13 Section through typical annular reactor core layout.

From the outlet of the reactor the hot gas is fed into a gas turbine cycle where it drives the turbines. It is therefore classified as a direct cycle as opposed to an indirect cycle where heat is transferred to a secondary cycle through an intermediate heat exchanger. The layout of the PBMR gas turbine cycle or PCU is shown schematically in Figure 14. The cycle consists of a pre-cooler (PC), low pressure compressor (LPC), inter-cooler (IC), high pressure compressor (HPC), recuperator heat exchanger (RX), pebble bed nuclear reactor (PBR), high pressure turbine (HPT), low pressure turbine (LPT) and power turbine (PT). The HPT drives the HPC while the LPT drives the LPC. The power turbine drives the electrical generator that supplies power to the electricity grid. The power output of a single PBMR plant will be 170 MWe.

The layout shown in Figure 14 is formally categorized as a three-shaft, closed loop, recuperated and inter-cooled Brayton cycle.

The maximum pressure in the PCU manifold is 9 MPa or approximately 90 times atmospheric pressure. The maximum gas temperature at the outlet of the reactor is 900 °C and the reactor inlet temperature is approximately 500 °C. The high gas temperature as well as the fact that no intermediate heat exchanger is required in the direct cycle, increases the efficiency of the plant. Another very important contributing factor is the presence of the recuperator heat exchanger. In this heat exchanger the gas flowing to the reactor is pre-heated with energy that would normally have been wasted, thereby reducing the energy that has to be added in the reactor.

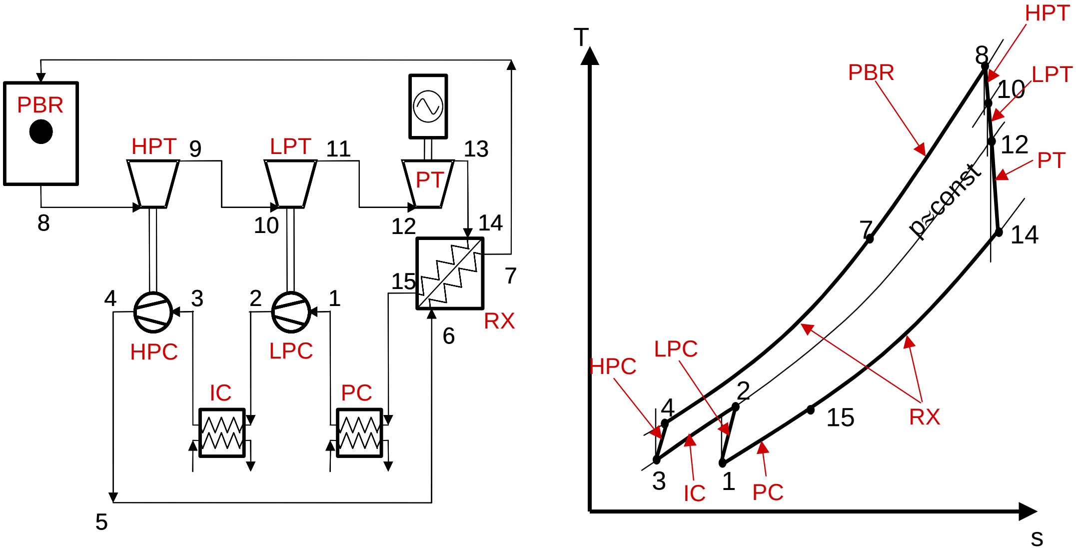


Figure 14 Schematic of the PBMR PCU concept together with the Temperature-entropy diagram showing the processes taking place in each of the major components.

The gas flow path through the power plant is shown schematically in Figure 15. The physical height of the complete reactor is approximately 20 m and the diameter is 6 m.

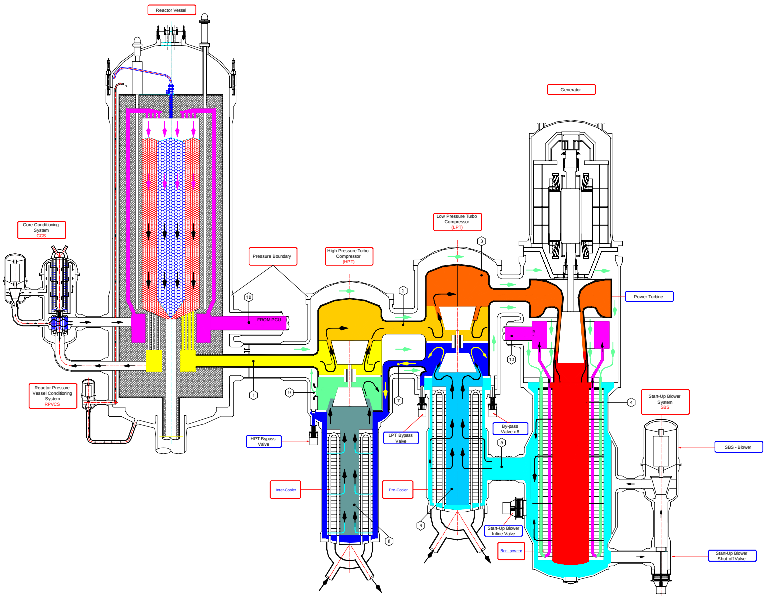


Figure 15 Schematic of the gas flow path through the reactor and PCU courtesy of PBMR (Pty) Ltd.

3.2 Safety

Several factors work hand-in-hand in the PBMR concept to eventually obtain a so-called 'inherently safe' reactor. Inherent safety means that the design of the plant is such that there is no physical process capable of causing a radiation hazard outside of the site boundary. This is significantly different from traditional approaches where enough safety systems are simple added to the plant to actively guard against radiation release.

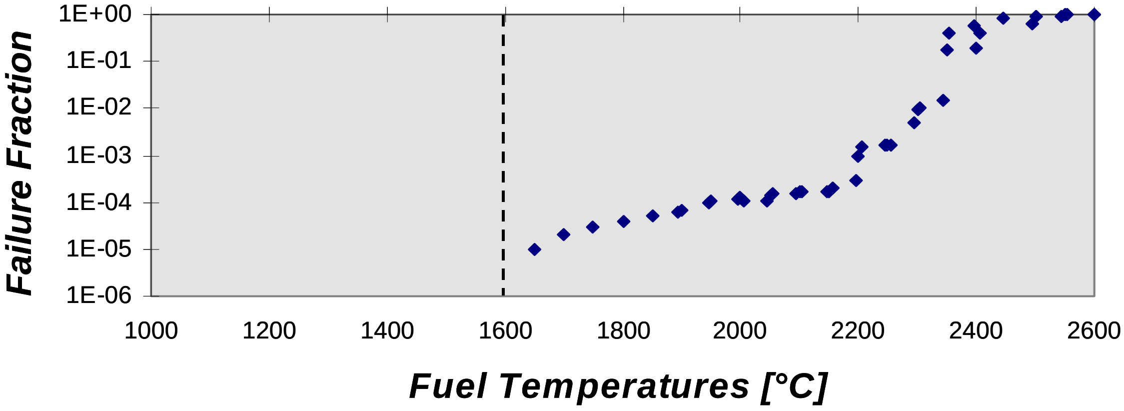


Figure 16 Results of fuel integrity tests courtesy of PBMR (Pty) Ltd.

The most important design features with regard to safety are:

- The coated fuel particles: The Silicon Carbide coatings around the fuel kernels act as a miniature pressure vessel that contains all the fission products. Figure 16 shows the results of extensive tests conducted in Germany on the coated fuel particles to determine its ability to contain fission products at different temperatures. The results have shown that as long as the fuel temperature is maintained below 1,600 °C, the coated particles will remain completely intact and no fission products will be released into the primary circuit.
- The use of graphite as moderator and reactor structural material: The graphite used in the fuel remains stable up to a temperature of approximately 2,800 °C. Therefore, it means that if the maximum temperature in the reactor is maintained below 1,600 °C under all circumstances, the structure of the fuel and core cannot change and radiation release or a core melt scenario will be impossible.
- The low core power density: The power density in the PBMR core is low compared to other reactors. This means that the temperature gradients within the core are lower than that of conventional reactors.
- The continuous refuelling scheme: This means that there is never a need for a large amount of excess reactivity as is the case in batch-processing schemes directly after refuelling. It is therefore easier to control the amount of power generated at all times.
- The so-called 'negative temperature coefficient' of the fuel design: This implies that the reactivity or ability of the fuel to produce power becomes smaller as the fuel gets hotter. Therefore, a chain reaction cannot occur where

hot fuel produces more power and therefore becomes even hotter and produces even more power.

- The high thermal inertia of the core: Due to the high mass of graphite in the core its thermal inertia is also very high. This means that even if a lot of heat is added to the spheres, the temperature changes are very slow. It is therefore easier to control the fuel temperature.
- The slender geometry of the reactor: The tall slender geometry of the reactor design implies that any heat generated within the core can easily be rejected to the outside through simple heat conduction. This means that even in the worst case Depressurised Loss of Forced Cooling (DLOFC) event where there is no cooling done by the helium gas, the decay heat produced in the reactor can be rejected to the outside via passive means. This characteristic, combined with the low power density, low excess reactivity, negative temperature coefficient and high thermal inertia, means that it is physically impossible for the temperature in the reactor to ever exceed 1,600 °C.
- The use of helium as coolant: The helium will never change phase as opposed to water in a LWR reactor. Its thermo-physical characteristics are therefore always predictable. Helium is also chemically inert which means that it will not react with the graphite or other core components. Furthermore, the neutron absorption cross-section of helium is very small which means that it will never influence the reactivity in the core and the gas itself will not become radioactive. All of these characteristics combine to ensure that even if helium is released to the atmosphere, it will be in significantly smaller volumes than steam boiling of from a LWR core and it will not be radioactive.

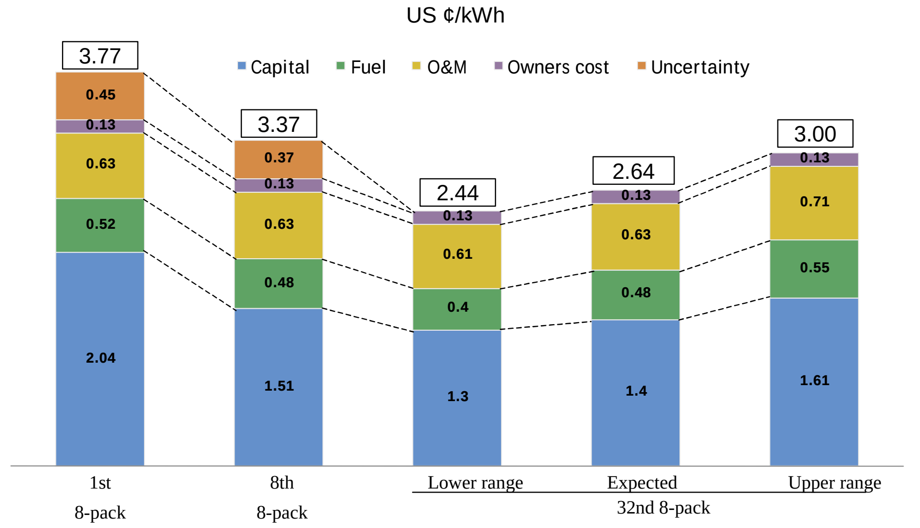
3.3 Waste generation and disposal

Whereas a large coal-fired plant uses approximately six trainloads of coal per day with an ash content of up to 40%, an equivalent nuclear plant would use only on large truckload of fuel per year [12]. This means that a nuclear power station generates much less waste than a conventional fossil fuel power station. In the PBMR design provision is made to store all of the spent fuel that is generated during the 40-year life span on site, where it can safely be stored for another 40 years after which it can be moved to a final repository.

The storage of the PBMR spent fuel is safeguarded by the fact that the fission products are encapsulated by the silicon carbide particle coating which can keep it isolated for approximately one million years. The graphite matrix in which the particles are packed is inherently stable and therefore it will not disintegrate.

3.4 Economics

Figure 17 shows the projected capital, fuel, O&M and other costs associated with the PBMR power plant. It shows that the expected cost price of the plants will be between 1.3 and 1.61 US¢/kWh. Although this is only cost price that does not include mark-up, it compares favourably with the numbers quoted in Section 2.4. With regard to fuel and O&M costs, the expected cost of 1.11 US¢/kWh also compares very well with the value of 2.0 US¢/kWh stated earlier for South African coal fired plants as well as existing US coal fired and nuclear plants.



[1] PBMR plants sold at cost, fuel business discount rate = 9.71% pre-tax, O&M are customer costs, Generator discount rate = 8% pre-tax. Standard generator costs (i.e., land), initial owners (i.e., initial licensing, initial He and fuel fill), not included
Source: McKinsey

Figure 17 Projected capital, fuel, O&M and other costs for the PBMR plant courtesy of PBMR (Pty) Ltd.

3.5 Other advantages

Besides the inherent safety properties and competitive economics, the PBMR plant has the following additional advantages:

- The small unit size of less than 200 MW and small fuel volume requirements make it ideal for distributed power generation.
- The construction period will be approximately 24 months as opposed to more than 42 months for conventional power plants.
- The emergency planning zone or area that must be evacuated around the plant in case of a serious incident is only 400 m while in a conventional LWR plant it is approximately 16 km.
- The plant will have excellent load following capability in that it will be able to change the power output at a rate of 10 % of nominal full power per min.
- The plant will be able to manage a 100% loss of load without having to trip, which means it can be restarted much quicker than would otherwise be the case.
- The outage rate is estimated at 2.5% planned and 2.5% forced which means that it will have a high load factor of greater than 90 %.

3.6 Non-electrical capabilities

Of all nuclear reactors, High Temperature Gas Reactors can supply the widest range of process temperatures for industrial applications [2]. The most important of these is hydrogen production via sulphur iodine thermo chemical water splitting as well as steam and CO_2 reforming of methane. Other important applications are the desalination of seawater, heavy oil recovery, district heating and coal gasification and liquefaction.

Lately there has been considerable interest in the US in hydrogen production as part of President Bush's new hydrogen fuel for transportation initiative. This has led to the announcement of a project that will provide a total investment of approximately 1,000 million US dollars to develop high temperature nuclear reactors for clean hydrogen production [9]. This poses exciting opportunities for the PBMR since prominent US experts believe that the PBMR is uniquely suited for providing the energy needed for this process [13].

In view of this, negotiations are taking place between Eskom, PBMR and Areva, the French nuclear giant who owns Framatome, who built the Koeberg power plant. It is reported that Framatome is interested in acquiring a share in the PBMR company which could improve the PBMR's chances when bidding for the US project [14].

4 PBMR plant systems

The PBMR power plant consists of many advanced plant systems including the reactor, the PCU, the helium services, auxiliary cooling systems, fuel handling plant and control systems.

Figure 18 shows a schematic of the reactor together with simulated core and reflector temperatures. It shows how the gas temperature is increased as the gas moves through the reactor from top to bottom.

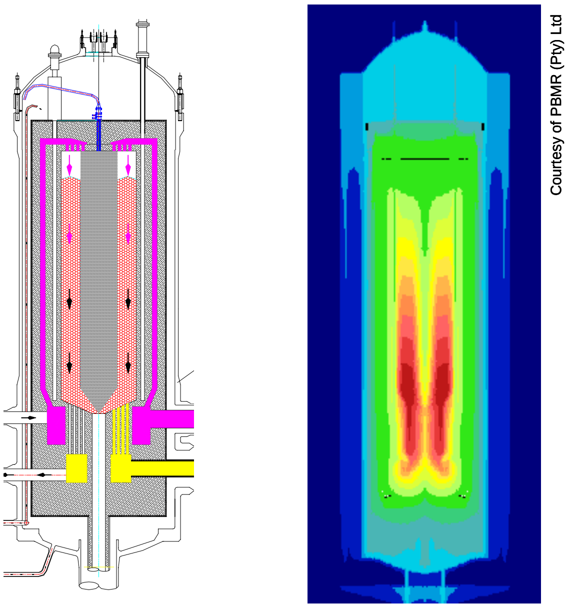


Figure 18 Schematic of the PBMR reactor layout together with simulated fuel temperatures courtesy of PBMR (Pty) Ltd.

Figure 19 shows a three dimensional solid model drawing of the plant including the reactor and PCU. The inlet manifold of the reactor is connected to the two feed pipes around the HPT and LPT units while the hot gas from the reactor outlet is fed back to the turbines through the single thick pipe attached to the HPT unit.

The unit designated SBS is the Start-up Blower system while the CCS is the Core Conditioning System. The purpose of the SBS is twofold namely to aid in the initial start-up of the plant and to provide secondary cooling of the reactor. The purpose of the CCS is to remove core decay heat when the normal core heat removal, provided by the Brayton cycle or the Start-up Blower System (SBS), is not available. Figure 20 shows close-ups of the SBS and CCS.

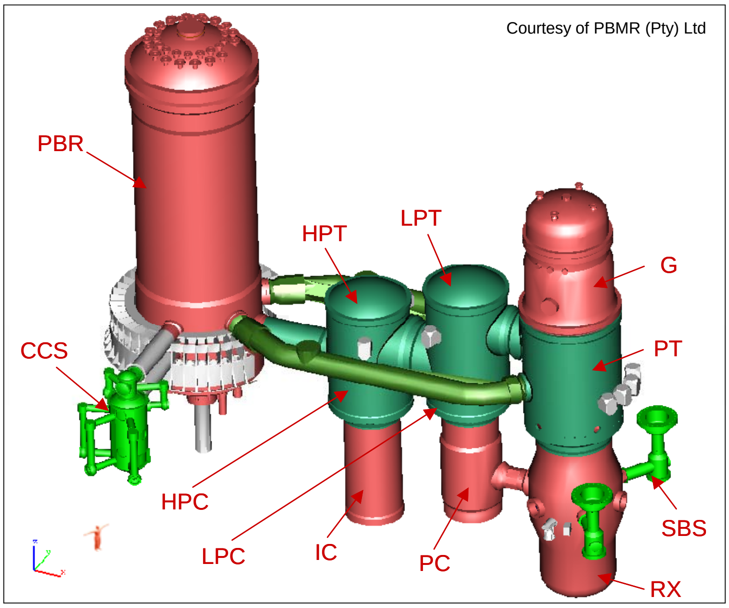
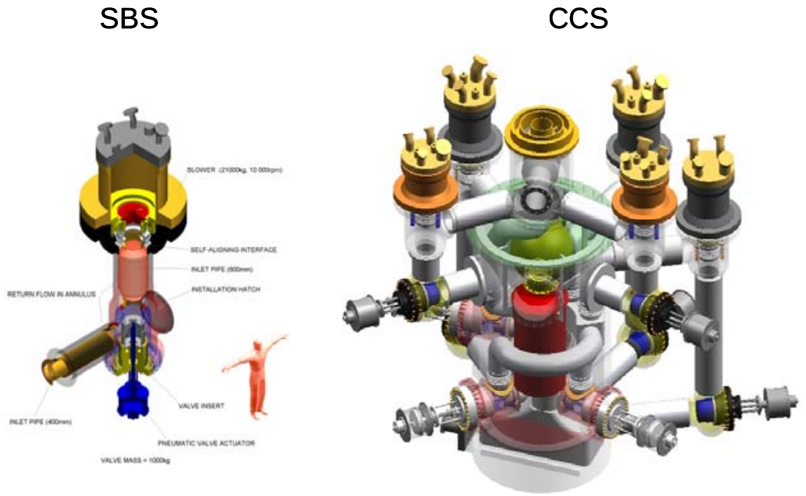


Figure 19 Three dimensional representation of the PBMR reactor and PCU courtesy of PBMR (Pty) Ltd.



Courtesy of PBMR (Pty) Ltd

Figure 20 Solid models of the SBS and CCS courtesy of PBMR (Pty) Ltd.

Another important auxiliary cooling system is the Reactor Cavity Cooling System or RCCS, shown in Figure 21. The purpose of the RCCS is to cool the concrete containment around the reactor pressure vessel. This is a completely passive system that requires no pumps but rather makes use of natural convection within the co-axial tubes that surround the reactor.

The fuel handling and storage system is an intricate system of pipes and tanks that continuously circulates the fuel spheres through the reactor. It also transports fresh fuel from the storage bays and takes spent fuel to the spent fuel tanks.

Figure 22 shows a solid model of the integrated plant. The top floor next to the reactor also houses the helium storage tanks that form part of the helium inventory and control system or HICS.

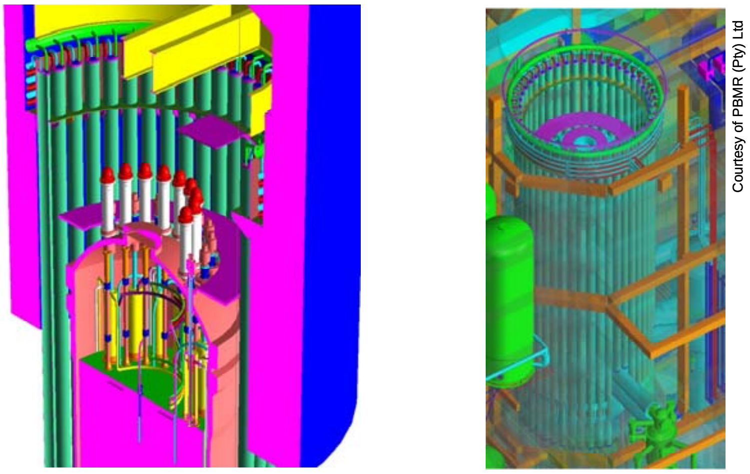
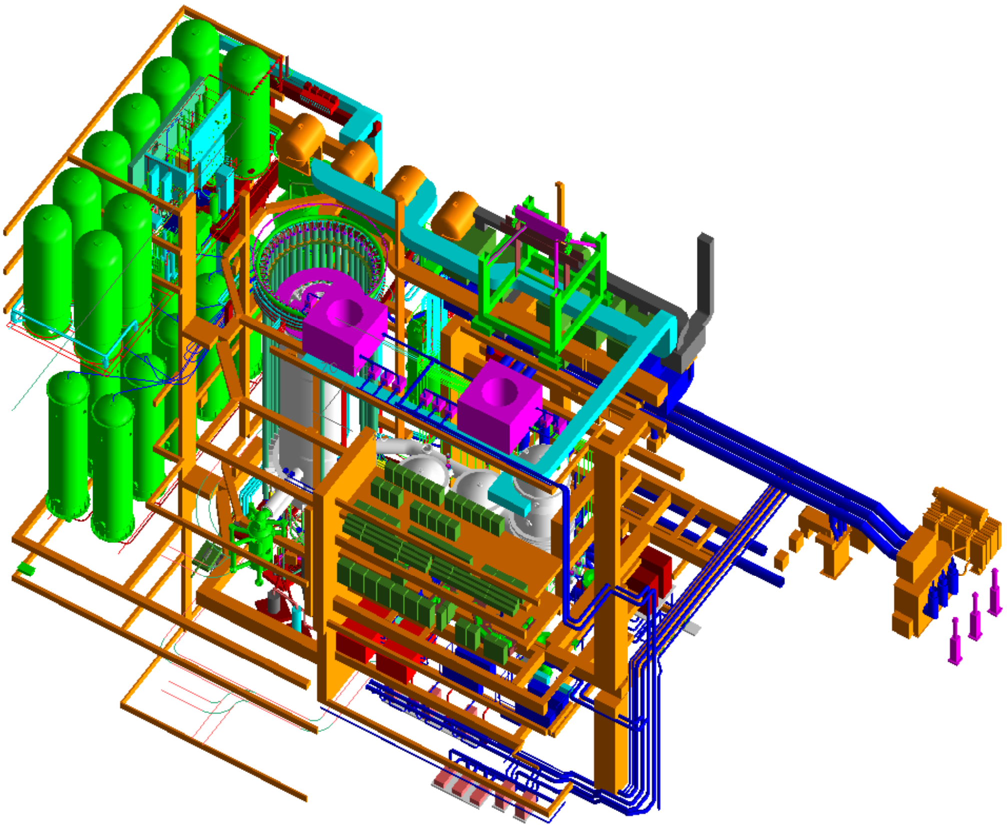


Figure 21 Solid model of the RCCS courtesy of PBMR (Pty) Ltd.



Courtesy of PBMR (Pty) Ltd

Figure 22 Solid model of the integrated plant courtesy of PBMR (Pty) Ltd.

The PBMR employs various novel control systems for start-up, load following and load rejection. Figure 23 shows some of the components namely the SBS, the HICS, and the Gas Cycle By-Pass or GCBP valve. The SBS is used to start the plant when there is initially no flow through the turbines that can drive the compressors.

The HICS is used to add additional helium gas to the closed cycle or to extract gas from the cycle. When gas is added it results in an increase of the system pressure, which in turn results in an increase in the gas density. This increases the gas mass flow rates in all of the components and therefore also increases the power output.

When gas is extracted, the opposite happens and the power output is decreased. Load following is therefore achieved by simply adding or extracting gas from the system.

In the case of a load rejection, the braking effect of the electrical generator on the power turbine is lost instantaneously. The power turbine will then tend to over speed, unless the power output of the plant is quickly reduced. This very rapid reduction in power output is achieved by opening the GCBP valve which connects the highest pressure point in the plant with the lowest pressure point. This then very quickly reduces the pressure ratios across the turbine resulting in a rapid reduction of power output.

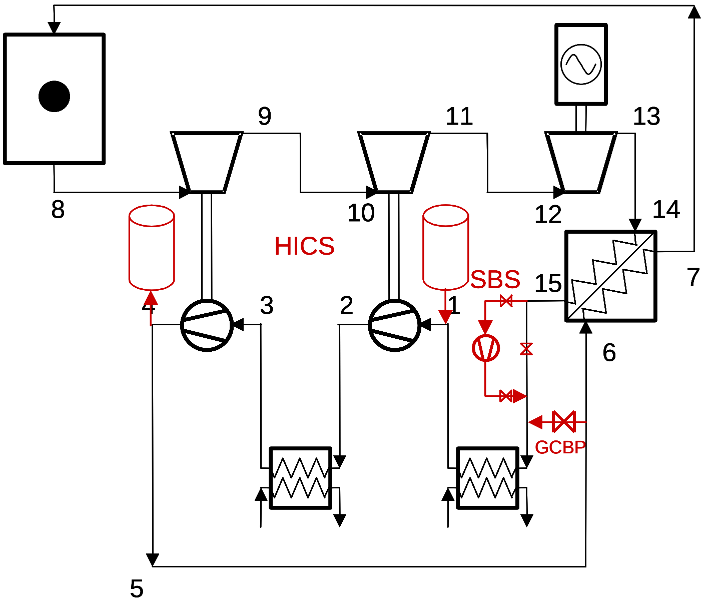


Figure 23 Components of the PBMR plant control system.

As shown above, the PBMR is at the forefront of HTGR power plant development. Although the reactor concept has been subjected to extensive testing when it was initially developed in Germany, some of the technologies within the PCU has not been used or tested before. Although the concept of a three-shaft, closed loop, recuperated and inter-cooled Brayton cycle is nothing new in theory, such a plant has never been built elsewhere. It has therefore never before been proven in practice that it can be started up and controlled. This fact gave rise to the need for a prototype plant of the PCU in which these issues could be addressed in order to mitigate the development risk.

5 The PBMM prototype

In order to demonstrate the operation of this particular closed-loop configuration, as well as to illustrate the envisaged PBMR control methodologies for start-up, load following, steady state full load and load rejection, the so-called Pebble Bed Micro Model or PBMM prototype plant was designed, constructed and commissioned at the Engineering Faculty of North West University in Potchefstroom South Africa (previously Potchefstroom University) between January and September 2002.

The plant was not intended to be an exact scaled-down version of the actual PBMR plant, but the plant layout has the same topology and representative major components. Also, the control system has the same topology and degrees of freedom as that of the PBMR plant.

Some of the differences between the model and the actual PBMR plant are as follows:

- The turbo machines are off-the-shelf single-stage centrifugal turbochargers rather than purpose designed multi-stage axial flow machines. The plant was designed around these turbochargers because of obvious time and budgetary constraints. Although there are many differences in the detail design of axial and centrifugal flow machines, their overall performance characteristics within a system are essentially the same with regard to pressure ratio and isentropic efficiency versus non-dimensional mass flow rate. Therefore, it is sufficient to illustrate the overall operation of the cycle.
- The heat source is a high temperature electrical resistance heater of 420kW instead of the pebble bed nuclear reactor. The maximum design outlet temperature of the heater is 700°C.
- The working fluid of the model is nitrogen rather than helium. The main reason for this is to allow the use of off-the-shelf turbochargers that were developed for use in large internal combustion engines with air as working fluid. Nitrogen was chosen instead of air because it has essentially the same thermo-physical properties but contains no oxygen. This is desirable since the presence of oxygen in the cycle may cause corrosion and flammability problems.
- The load on the power turbine shaft is an external load compressor rather than an electrical generator as is the case in the PBMR plant. The energy imparted to the fluid by the compressor is dissipated via an external load cooler.

Figure 24 shows a solid model of the PBMM plant indicating the positions of the electrical heater, the turbo machinery and the heat exchangers. The total length of the pressure vessel in 17 m and the maximum diameter is 1.5 m.

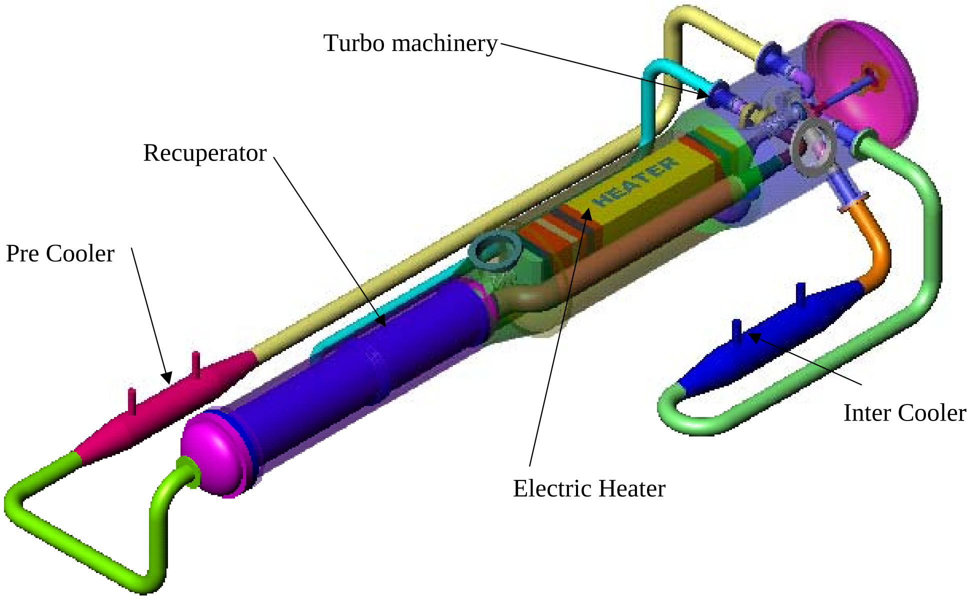


Figure 24 Solid model of the PBMM plant.

The design of the turbo machinery for the PBMM plant posed very special challenges. Under normal circumstances, turbo machines are specifically designed for a particular power plant, once the plant specifications are known. In this case the process was reversed and the plant had to be designed around three independent existing off-the-shelf turbo chargers. The correct matching of the speeds and power outputs of the compressor and turbine pairs was therefore essential. This process was complicated by the fact that there are three free-running shafts.

In order to overcome these difficulties the design of the plant was done with the aid of Flownex ([15],[16],[17]), a locally developed thermal-fluid simulation software package that has the ability to simulate the steady-state and transient operation of the integrated system, making use of the performance characteristics of the individual components. By making use of Flownex, all the operating conditions of the plant could be simulated before it was built. Figure 25 shows a solid model of the three turbo chargers affixed to the hot plate inside the PBMM pressure vessel.

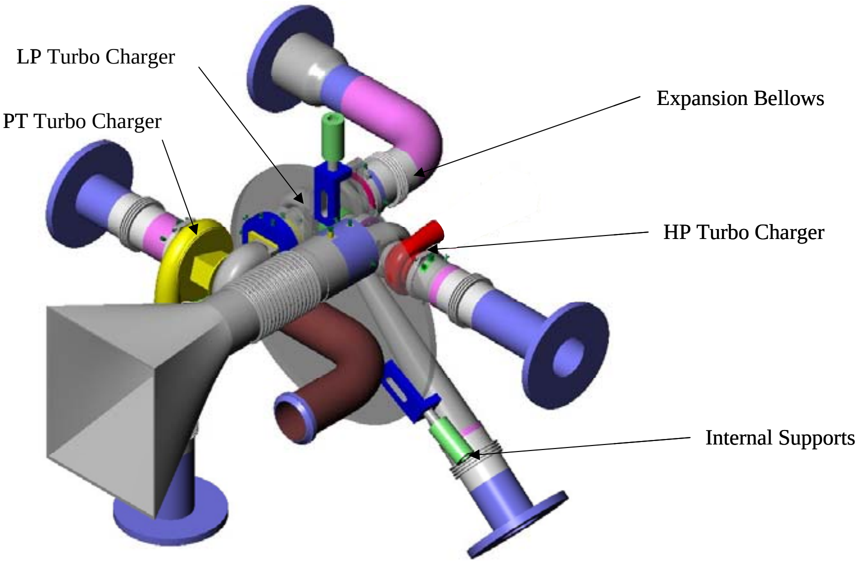


Figure 25 Solid model of the three turbo chargers affixed to the hot plate inside the PBMM pressure vessel.

The design and construction of the plant was completed within a record nine months and it was successfully started up in September 2002. Figure 26 shows the predicted start-up procedure compared with the values that were measured during the actual start-up. It is clear that good comparison was obtained and that the simulation capability played a major role in the success of the project.

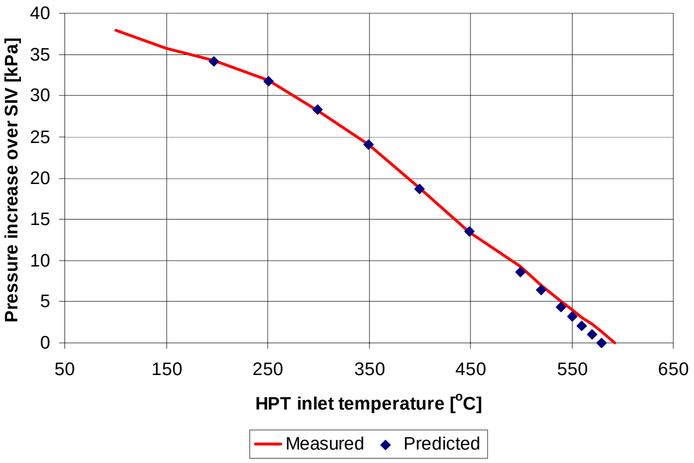


Figure 26 Comparison of the measured and predicted start-up procedure.

Subsequently all of the important control actions including load following and load rejection was successfully demonstrated. The PBMM plant has attracted attention from all over the world and more than twenty international delegations from inter alia the USA, UK, Japan, Germany, Russia, France and Sweden have since visited the plant.

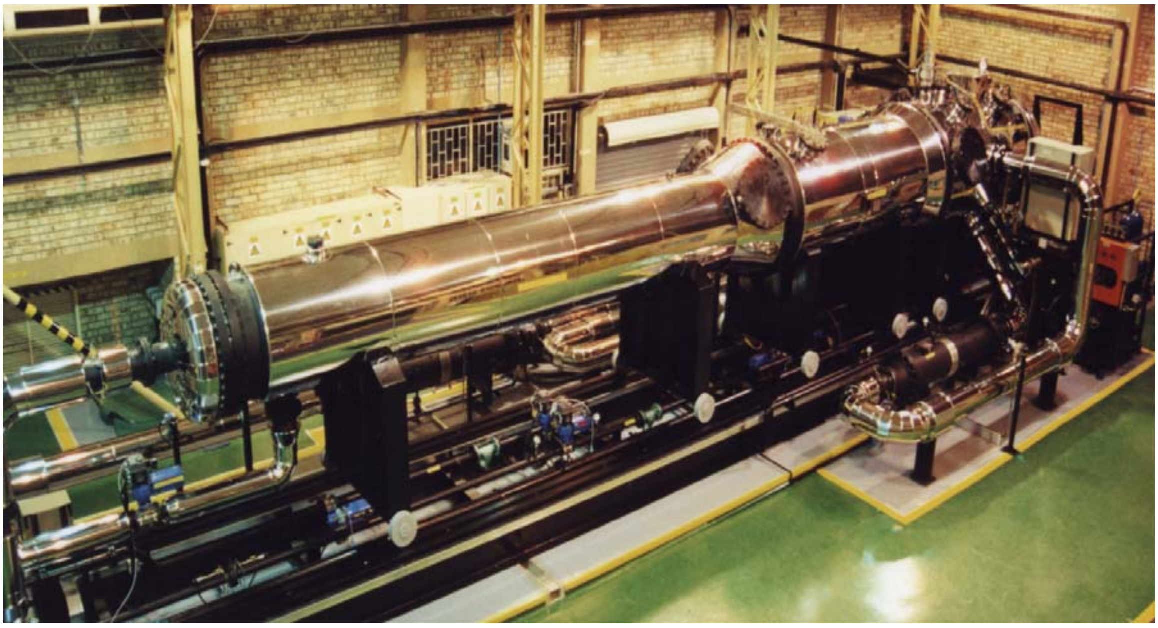


Figure 27 Photograph of the completed PBMM prototype plant.

6 Conclusions

The Pebble Bed Modular Reactor (PBMR) offers a unique combination of advantages to address future power supply needs, namely:

- Inherent safety characteristics.
- Low environmental impact.
- Small unit size conducive to distributed generation.
- Short construction periods.
- Excellent load following capability.
- High load factor.
- Competitive economics.

It also has great potential for hydrogen production, desalination of seawater, heavy oil recovery, district heating and coal gasification and liquefaction.

Having proved the technical feasibility of this unique power plant concept with the aid of inter alia the PBMM prototype plant, the project now offers substantial potential for export, job creation and expansion of the local technology base.

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