The pebble bed modular reactor, desalination challenges and options

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Abstract: The Pebble Bed Modular Reactor (PBMR) is a development lead by Eskom, the South African state power utility. The technology used is based on the previous German HTGR work linked to a direct cycle gas turbine (or Breyton Cycle) being developed in conjunction with Mitsubishi Heavy Industry. The initial commercial plant design has a thermal output of 400 MW with an electrical output (nett) of over 165 MW. The interesting feature of desalination is that the nature of the inter-cooled closed cycle is the rejection of waste heat (about 200 MW) at temperatures of up to 120°C to cooling water circuits.

The options that could be considered include a reverse osmosis plant using a sea water inlet temp of 25°C with an outlet from the reactor's coolers of 40°C. This would result in a power consumption of some 14 MW from the reactor with a water production of 78,000 m^3/day per reactor. If the evaporative approach is to be used, the current design can yield 400kg/s of water @ 102°C, or (with minor modifications to the coolers and some increased limits on the operating flexibility of the reactor) 342 kg/s @ 115°C. In both these last two cases, there would be no reduction in the electrical power dispatched to the grid.

The advantages of such a system to desalination applications are several. The size of the reactor means that even in reasonably small electrical grids (as small as 1000 MW total) a number of PBMRs could be grouped together. This would avoid the problem of backing up the desalination system with a fossil fuel source when the reactor is in maintenance. An effective installation could be four PBMRs linked through a common cooling water system to two desalination plants (each to be supported by one reactor). Since the PBMR uses on-load fuelling systems, the plant does not have the problem of short operating cycles (12–18 months) but can operate for six years between 30-day maintenance periods. It is also designed, due to the inherent safety features of small HTGRs, to be operated with a far smaller nuclear infrastructure, using extensive turn key vendor support (as with current gas fired power stations). These features make the PBMR far more suitable for developing countries, where the application of existing nuclear designs (e.g. a. 1000 MW PWR) would be problematic.

Keywords: nuclear desalination; HTGR breyton cycle; Eskom; PBMR; helium.

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Biographical notes: David Nicholls joined the UK Royal Navy at the age of 17, in 1971. While serving there, he obtained a Degree in Mechanical Engineering and a Post Graduate Diploma in Nuclear Reactor Technology. He served as an engineer officer in the nuclear submarine program. David left the RN in 1982, spending two years as the manager of a small engineering company in the UK before joining Eskom in 1984 in the Nuclear Engineering Division, and has remained there since then, mainly in the head office technical area but with a period as Technical Support Manager at the Koeberg Nuclear Power Station. He has led the PBMR programme since its inception in 1993, becoming the full time CEO of PBMR Company (an Eskom subsidiary) in 1999. In 2004, he returned to Eskom head office as the PBMR Program Manager.

1 Introduction

The PBMR project should be seen against the background of the particular economic circumstances of Eskom, the project's dominant investor. On one hand, Eskom is one of the world's largest utilities by generation, with total capacity of almost 40,000 MWe, of which about 90% is coal-fired. South Africa's single nuclear plant, Koeberg (2 × 922 MWe, PWR), supplies about 7% of the nation's power. On the other hand, Eskom is one of the world's lowest-priced power suppliers, with retail tariffs of only about 2 cents (US) per kWh.

Complicating this picture further is the fact that the coal-fired plants are located near the inland coal seams, while much of the future industrial development is expected to be at the coast. The bulk of the Eastern Cape's power, for example, is transmitted 1000 km from its point of generation, and very long transmission lines present complications of their own.

Although, the demand in South Africa is currently lower than the capacity, it is anticipated that new capacity will have to be commissioned by about 2008. Even a moderate growth of 2.5% will result in peak electricity demand exceeding capacity between 2005 and 2010. In addition, Eskom's older power stations reach the end of their design life after 2025. South Africa will, therefore, need to access and use all natural resources to produce the additional 20,000 MW of electricity that will be needed by 2025.

For grid stability purposes, it would be preferable to have power plants located closer to the load centres. Transporting coal to distant power stations is, however, prohibitively expensive. The opportunities for producing hydroelectric power or power from natural gas in South Africa, are severely limited. Large thermal, nuclear or hydroelectric power stations require lead times of up to eight years, and could result in the installation of surplus capacity if economic growth is not as expected.

In view of this, Eskom has been investigating the PBMR since 1993 as part of its Integrated Electricity Planning process. These investigations confirmed that the PBMR should be considered as a possible option for future South African electricity supply.

In 1995, Eskom commissioned a pre-feasibility study followed by a techno-economic study in 1997. By mid-1998, the project had progressed to the point at which it had entered the full-scale engineering design phase.

In 1999, Eskom obtained the right to access the German HTR engineering database that includes details of the Siemens/Interatom HTR-Modul design. This design can be regarded as the forerunner of the PBMR as an inherently safe reactor.

Since reactor design is not a core business for Eskom, a separate entity, PBMR (Pty) Ltd., was established in 1999, initially to work up the design and then to establish beyond doubt the technical and commercial feasibility of the project. The technical staff, which now numbers over 400 engineers and scientists based in Centurion near Pretoria, was drawn from organisations such as Eskom, IST, Denel and Necsa.

One of the conditions imposed by Eskom to assure itself of the international viability of the PBMR concept was that, the project should proceed only if credible overseas nuclear organisations saw sufficient potential in it to bear part of the development cost. The required interest was quickly manifest.

In 1999, the Industrial Development Corporation (IDC) of South Africa took up a 25% shareholding, followed in 2000 by British Nuclear Fuels (22.5%) and Exelon (12.5%). Eskom (40%) is still the main investor. Exelon, however, indicated in April 2002 that it would not be participating in the project beyond the current (detailed feasibility) phase. The decision came after a broad-based review of Exelon's investments to ensure a disciplined strategy focused on the fundamentals of generation, power marketing and distribution.

Structurally, PBMR is now an independent, unincorporated R&D company with a dedicated staff of over 400.

Since the technology had not previously been commercialised, PBMR (Pty) Ltd. intends building a demonstration module at Koeberg, and an associated fuel plant at Pelindaba. Current focus is on the completion of a comprehensive evaluation of the economics of a commercial PBMR plant and the associated business case, which considers its competitiveness against alternative energy sources. At the same time, design enhancements are being incorporated into the basic PBMR design, to improve both its economics and operability.

2 Technology

The PBMR is a helium-cooled, graphite-moderated High Temperature Reactor (HTR). As such, the design is not new. A number of small reactors of this type were built in the 1950s and 1960s and a 300 MWe pebble bed type was built in Germany in the early 1980s. While the initial experimental units showed great promise, engineering and operating problems emerged as the units were scaled up. The German pebble bed unit (Schmehausen) ran commercially for just two years before it was shut down permanently.

Thus, while the PBMR draws heavily on the German experience, the PBMR project seeks to avoid the principal operating problems that the Germans encountered, by strictly limiting unit size and simplifying other systems.

The PBMR consists of a vertical steel pressure vessel, 6m (19.7 ft) in diameter and about 20 m (65 ft) high. It is lined with a 100 cm (39 inch) thick layer of graphite bricks, which serves as a reflector and a passive heat transfer medium. The graphite brick lining is drilled with vertical holes to house the control rods.

The PBMR uses silicon carbide and pyrolitic carbon coated particles of enriched uranium oxide encased in graphite, to form a fuel sphere or pebble about the size of a tennis ball. Helium is used as the coolant and energy transfer medium to a closed cycle gas turbine and generator system.

When fully loaded, the core would contain about 400,000 fuel spheres. The initial design, which also specified 110,000 pure graphite balls to serve as an additional moderator, has subsequently been changed (see section on Design Changes).

To remove the heat generated by the nuclear reaction, helium coolant enters the reactor vessel at a temperature of about 500ºC and a pressure of 90 bars. It then moves down between the hot fuel spheres, after which it leaves the bottom of the vessel having been heated to a temperature of about 900ºC.

The hot gas then enters the first of three gas turbines in a series, the first two of which drive compressors and the third of which drives the electrical generator. The coolant leaves the last turbine at about 530°C and 26 bars, after which it is cooled, recompressed, reheated and returned to the reactor vessel.

The process cycle used is a standard Brayton cycle with a closed circuit water-cooled inter-cooler and pre-cooler. A high efficiency recuperator is used after the power turbine generator to recuperate the thermal energy. Lower energy helium is passed through the pre-cooler and inter-cooler as well as the low and high pressure compressors before it is returned through the recuperator to the reactor core.

The significance of the high pressure and high temperature of the helium coolant lies in its superior thermal efficiency. By comparison, the steam turbines for Light Water Reactors (LWRs) operate at such low temperatures and pressures that they are more costly to build and less productive than the turbines for a fossil-fired plant, where temperatures and pressures may be several times higher.

While a typical LWR has a thermal efficiency of 33%, a heat efficiency of about 42% is anticipated in the basic PBMR design. Increases in fuel performances leading to higher operating temperatures, offer the prospect of up to 50% efficiency.

Online re-fuelling is another key feature of the PBMR. While the unit remains at full power and the reactivity of the initial core subsides, fresh fuel elements are added at the top of the reactor.

Scheduled maintenance shutdowns, to meet regulatory requirements, should not number more than two per year, and should last no more than a single weekend each. If something like a turbo-compressor fails, the expectation would be that the vendor would appear promptly, switch it for a spare, and leave – obviating the need for a permanent on-site staff of compressor maintenance experts.

Overall, each unit should be off-line (for overhaul) no more than a week each year, for perhaps a two-week stretch every three years, and for no more than thirty days for major maintenance, every six years. The overall capacity factor target is 95%, an aggressive target, but not an unreasonable one given the premise of design simplicity.

3 Triso fuel

The starting material for the manufacture of the fuel is, uranyl nitrate solution, enriched to contain 8% uranium-235. Falling droplets of the solution are transformed by chemical engineering techniques into 'kernels' of enriched uranium oxide (UO_2) approximately 0.5 mm in diameter. These kernels are coated successively with porous graphite, dense pyrolytic graphite, silicon carbide, and finally a further shell of pyrolytic graphite. The shells so formed are respectively 90, 40, 35 and 40 microns thick, in order to give a final coated particle diameter of just less than a millimetre.

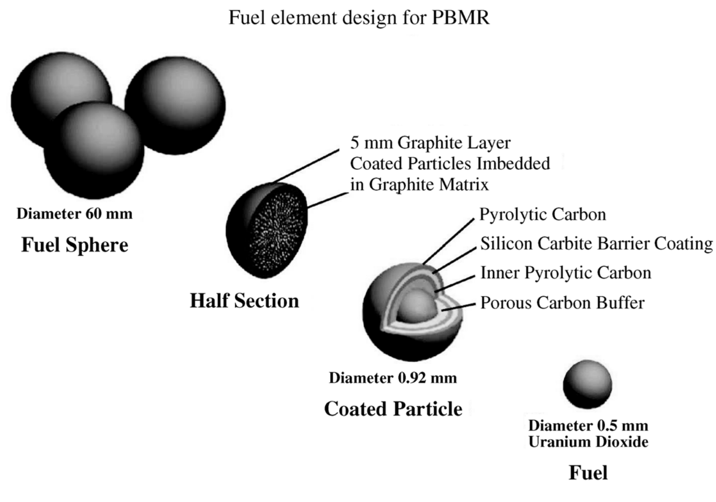
The coating technique is to float the UO_2 kernels on a stream of argon, in a small fluidised bed furnace. Appropriate organic gases are then introduced to the argon stream. The important silicon carbide shell, for example, is formed in a three hour process by decomposing gaseous CH_3SiCl_3 into HCl and the required SiC which deposits on the floating kernels. The process is relatively straightforward.

The innermost shell of porous carbon accommodates both the swelling of the uranium oxide kernel under irradiation and fission product gases (isotopes of xenon and krypton) which diffuse from or recoil out of the kernel during operation. A build-up of pressure, which might otherwise rupture the outer containment shells, is thereby avoided. The first pyrolytic graphite shell protects the kernel from chemical attack during the formation of the silicon carbide shell. The highly stable and mechanically strong silicon carbide shell forms a miniature pressure boundary, which retains essentially all fission products formed during operation. Its stability is the key to PBMR safety. Finally, the outer pyrolytic carbon layer protects the silicon carbide shell from physical damage during the subsequent manufacturing processes, which form the spherical fuel element.

These processes consist of compacting a mixture of some 15,000 coated particles together with resin-coated graphite dust into a sphere 50 mm in diameter, pressing this sphere into 5 mm thick hemispherical shells of pure graphite, and heating the sphere so formed to 900°C under vacuum, to decompose the resin binder and to degas the final product. The 'pebble' is finally machined to produce a near-perfect sphere with a diameter of 60 mm.

The final product is a smooth, tough sphere, which handles very much like a large black billiard ball. Each 200-gram 'billiard-ball' contains nine grams of enriched uranium. During operation, the graphite acts as the moderator, slowing fission neutrons born in the uranium kernels with energies around 2 MeV down to the 'thermal' energies around 0.02 eV at which energy further uranium-235 fission will take place. The pebbles are thus both fuel and moderator. Figure 1 is a schematic representation of the fuel. Inset is a photograph of an actual coated particle.

Figure 1 Fuel element design for PBMR



The fuel will be made at Pelindaba by NECSA using German technology. Extensive testing of irradiated fuel made in Germany showed that fewer than two granules in 100,000 have damaged or defective silicone carbide shells.

The ability to retain fission products within the coated particles at high temperature, is the key to the safety of high temperature gas reactors. The increasing release-rate of fission product Krypton 85 from the coated particles with temperature, and with annealing time at high temperature, signals progressive failure of the silicon carbide shell. The fuel suffers progressive degradation with temperature, but only at temperatures above 1600°C. There can be no significant release of fission products at temperatures below 1600°C. As discussed below, even under accident conditions, the fuel temperature can never reach that level.

4 Design status

The fundamental elements of the PBMR design have been established since the present phase started in 1996. These are the 'pebble bed' core with on-load fuelling, and the three shaft layout with two turbine driven compressors and power turbine driving the generator, with all the shafts being vertical. The initial design specified that all components (except RPV and core barrel) could be replaced during the plant life if required, and that space and layout permitted changes to component geometry if there were design deficiencies in the initial plant. This philosophy has been retained and as an implication, the majority of the decommissioning plan of the reactor is very close to standard maintenance practices.

As the team has developed, the design, along with the input from the key suppliers (such as MHI, SGL etc.) has evolved. The initial plant was a 268MWth design, operating at 7 MP(a). By late 2000, it was realised that the capacity could be increased with minor changes to 302 MWth, which changed the operating pressure to 8.5 MP(a).

In line with the desire to improve the economics of the project, a complete review was undertaken in 2002 of any changes that could assist in this. The other issues which arose came from the increasingly detailed design and analysis reviews taking place, based on the knowledge gained in the design process to date (over 1,000,000 man hours at that time).

The principle design changes that occurred as a result of this review are as follows:

- Changing the central reflector from a dynamic column made up of graphite spheres to a fixed graphite column. This was possible due to the increased understanding of the manufacturability of such a column and allowed for an increase in reactor power to 400 MWth, a reduction in the complexity of the fuel handling system, and significant reduction of peak operating fuel temperature to below the revised limit of 1130°C. This revised fuel limit came from detailed calculations of Ag and Cs diffusion from the fuel and the related maintenance problems. The increase to 400 MWth was not the limit of potential power increases, but analysis showed little cost-benefit from going any higher.
- Changing the turbine system pressure ratio from 2.7 to 3.2, while increasing the system peak pressure from 8.5 MP (a) to 9.0 MP(a). This allowed the optimum balance of pressure boundary cost vs. turbine costs while absorbing the increased thermal output. The electrical power sent out (with 25°C sea/river water) is 165 MW, rising to some 170 MW if the heat sink is 15°C.

- Changing the generator from helium submerged to an air-cooled one. This removed concerns about contamination of the generator, design of the auxiliary bearings and overload conditions on the electro-magnetic thrust bearings. It required a dry gas seal and this is being supplied by Crane Seals (a test rig will be running by year end). The extra helium leakage this causes is about one third of the specified allowance for the overall plant.
- configuring the overall PBMR into an eight-pack configuration to maximise the sharing of support systems. This is the most cost-effective layout and allows the plants to be brought on-line as they are completed.

5 Safety features

Although, improved thermal efficiency is a benefit of any HTR, the driving force for this particular design is safety, because once the safety issue goes away all the economics fall nicely into place.

In all existing power reactors, safety objectives are achieved by means of custom-engineered, active safety systems. In contrast, the Pebble Modular Reactor (PBMR) is inherently safe as a result of the design, the materials used, the fuel and the physics involved. This means that, should a worst-case scenario occur, no human intervention is required in the short or medium term.

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

In ‘conventional’ reactors, the heat removal is achieved by active cooling systems (such as pumps) and relies on the presence of the heat transfer fluid (e.g., water). Because of the potential for failure in these systems, they are duplicated to provide redundancy. Other systems, such as a containment building, are provided to mitigate the consequences of failure and provide a further barrier to radioactive release.

In the PBMR, the removal of the decay heat is achieved by radiation, conduction and convection, independent of the reactor coolant conditions. The combination of the very low power density of the core (1/30th of the power density of a Pressurised Water Reactor), and the temperature resistance of fuel in billions of independent particles to high temperature, underpins the superior safety characteristics of this type of reactor.

The helium, which is used to transfer heat from the core to the power-generating gas turbines, is chemically and radiologically inert. It cannot combine with other chemicals, it is non-combustible and it cannot become radioactive when passed through the core. Since air cannot enter the primary circuit, oxygen cannot get into the high temperature core to corrode the graphite used in the reactor.

The peak temperature that can be reached in the core of the reactor (1600ºC under the most severe conditions) is below the temperature that may cause damage to the fuel. This is because the radio nuclides, which are the potentially harmful products of the nuclear reaction, are contained by a layer of silicon carbide, which is extremely good at withstanding high temperatures.

Even if there is a failure of the active systems designed to shut down the nuclear reaction and remove core decay heat, the reactor will stop any nuclear fission and cool down naturally. This is because of a strong negative temperature coefficient of reactivity and the inherent heat-removal mechanisms of convection and conduction.

The size of the PBMR core is such that it has a high surface area to volume ratio. The reactor therefore never reaches a temperature at which significant degradation of the fuel can occur. The plant can never be hot enough for long enough to cause damage to the fuel.

This inherently safe design of the PBMR renders the need for safety grade backup systems and most aspects of the off-site emergency plans required for conventional nuclear reactors obsolete, and is fundamental to the cost reduction achieved over other nuclear designs. Plans related to aspects such as the transport of fuel will still be required, albeit modified to suit the specific characteristics of the fuel and the transport mode.

In the worst accident scenario that can be devised, the maximum extra dose of radiation to a person outside the plant – assuming that the person remained in place for the entire duration of the accident – would be the equivalent of one day's extra exposure to natural background radiation. Not only is that dose trivial, there would be no added exposure whatever beyond 400 meters from the plant. Consequently, there would be no need for an emergency planning zone beyond the plant site boundary, which makes locating these units more proximate to the load a realistic proposition.

6 Desalination properties

The PBMR project was launched by Eskom with the objective of meeting its electrical generation requirements away from the abundant South African coalfields. To this end, all the specifications were aimed at achieving safe, low cost and flexible power generation. Desalination has therefore always been a secondary consideration. Discussions with other potential customers have, however, led to an evaluation of the merit of the PBMR for desalination.

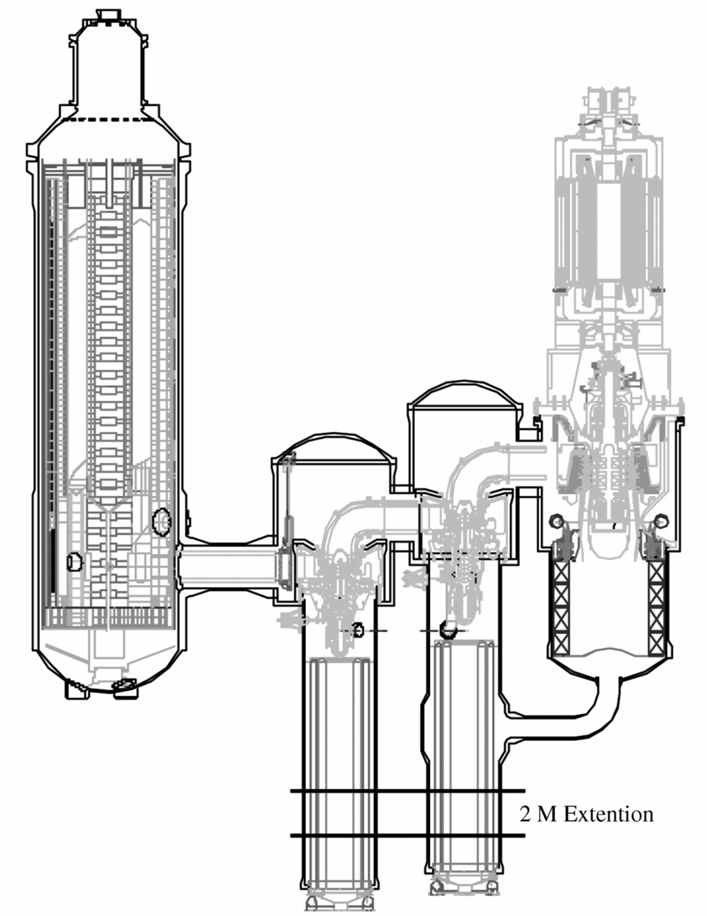
This evaluation has been very positive. The PBMR size (400 MW thermal & 165+ MW electrical) linked to its Brayton cycle, leads to a good desalination product.

There are two desalination routes: by evaporation or, secondly, by reverse osmosis. The only notable specific consideration for the evaporation route, is the need to have an additional loop isolating the secondary circuit of the power plant from the desalination circuit. Figure 2 illustrates the adjustment that is required for the evaporation route.

The cycle has two major water-cooled heat exchangers (the pre-cooler and inter-cooler), which have gas inlet temperatures of 159°C and 119°C respectively. Therefore, by changing the heat exchanger size and water flow rates, a water outlet of 220 MW with a temperature of 80–90°C is possible with minor impact on the electrical output. Without impacting the internal design of the system at all, a temperature of 45°C is achieved at the main sea water outlet.

The advantage of a Reverse Osmosis (RO) plant is that it does not require an additional circuit.

Figure 2 Extension of pre-cooler and inter-cooler to increase discharge water temperature



The following is applicable to the RO route:

- assuming that all of the Cooling Water (CW) discharged from a 165 MWe PBMR, were used as feed stock for a desalination plant, and assuming a raw water temperature of 25°C and a 40°C feed temperature to the desalination plant, the CW feed flow would be approximately 2.27 m^3/sec
- of this 2.27 m^3/second feed flow, some 0.9 m^3/sec would emerge as desalinated water and the balance as brine waste
- 0.9 m^3/sec product = 3 240 m^3/hr or 77 760 m^3/day (77.76 Megalitres/day). Visualise a dam 100 m × 100 m; we would fill it to a depth of 7.8 metres in 24 hours
- power consumption in the desalination process would be approximately 13,800 KW or 13.8 MW. This would leave a balance of ± 150 MW available for sale into a grid
- the physical area occupied by the RO section of the desalination plant would be approximately 1,630 m² (roughly 40 metres square). Total plant building area might be roughly twice this figure, i.e., 3200 m² or 55 metres square (but square is not mandatory, nor would all of the stuff necessarily have to be inside the building).

For the above calculations, the following was assumed:

- that RO desalination consumes 4.25 KWH per cubic metre of product
- that the membrane life would be three to five years
- that the total maintenance cost (including membrane replacements) would be 2.25% of capital cost per annum
- that 132 RO elements, each 8″ diameter x 1 metre long, would be required to treat 1 megalitre/day. This would occupy a floor space of roughly 7 metres x 3 metres (which would be roughly 40% of the total floor space required in the plant; more than 40% as the plant capacity increases)
- that, for every volume of sea water entering the plant, roughly 40 % emerges as treated water and 60% leaves as concentrated brine waste
- that pumping pressure to the RO plant is ideally in the range of 1000 psi, i.e., 68 bars. A portion of this energy can be economically recovered via the use of hydraulic turbines (linked mechanically to the HP feed pumps) in the brine waste discharge stream
- that pre-warming of the feed to the RO plant is process-wise advantageous. The ideal feed temperature is roughly 40°C
- that pre-filtration (with activated carbon) before the RO plant is essential, to remove any residual chlorine and all organic matter from the feed stock. Both chlorine and organics tend to quickly destroy the RO membranes.

This brief review therefore indicates that the PBMR is very well suited to combined desalination and electrical production, without impacting the fundamental design.

7 The modular concept

The PBMR reactor is being designed in a modular fashion, which allows for additional modules to be added in accordance with demand. It is much less location-dependent than hydro-electric or fossil-fuelled power stations.

Dry cooling, although more expensive, is an option that would provide even more freedom of location. They can be used as base-load stations or load-following stations and can be configured to the size required by the communities they serve.

8 Fitting power to load

A feature of both modular design – and the design of each module – is a remarkable degree of flexibility in matching power output to both grid requirements generically and to daily load patterns more specifically. Unlike LWRs, which are made to run flat out as baseload units, load following is a distinct possibility with the PBMR.

On the level of the individual module, pitch adjustments to the turbine blades will be able to alter power output moderately, but very quickly. More significantly, increasing or decreasing the amount of helium added to the cooling loop would change the mass flow crossing the turbines (as well as the temperature), making it feasible to change power levels more dramatically without changing core reactivity. Longer-term reactivity can be altered by changing the rate at which fresh fuel is added.

The flexible output design criteria calls for each unit being able to move from half power to full power to half power in a matter of minutes. When the possible variations for a single module are combined into a multi-unit plant, it is easy to see how the PBMR could more closely emulate a gas-fired unit for purposes of meeting demand ‘peaks’ and ‘shoulders’.

Plant modularity also has great significance in terms of possible market penetration. Even in ‘big grid’ places like Japan, North America and northern Europe, there are always pockets where transmission assets are slim. (In the US, for instance, the relative weakness of the transmission links between regions is one of the major causes of huge regional power price disparities, as well as the chief reason for a building boom for new gas-fired units.) While it may not be feasible to build smaller-scale LWRs near these under-served load pockets, PBMRs could fit these local load requirements very well.

9 Cost efficiency

Among the most pivotal economic requirements for the PBMR project is a realistic construction cost that is comparable to that of other South African base load generation, principally coal. In this respect, the design target for a commercial scale plant of an eight-pack, with a total output of about 1 320 MWe, is about $1,000 per KWe installed. If this target is achieved, PBMR’s output cost should be below US 3c/kWh.

10 Schedule

In addition to shareholder approval, approval to continue with the construction of a demonstration module is subject to a series of milestone reviews by the South African Government, the successful completion of the EIA process, and the issuing of a construction license by the National Nuclear Regulator. Assuming a favourable outcome of all these approval processes by early 2003, preliminary construction activities could commence by late 2004.

In the development phase, which extends through 2010, there are five projects that make up the Project Management Plan, namely, the Pilot Fuel Plant; the Demonstration Power Plant; development of PBMR Company infrastructure; the Generic Multi-module Power Plant Design and US Licensing Certification; and the Development and Engineering of the Commercial Fuel Plant. As client orders emerge, the transition to commercialisation will take place with the subsequent commitment to build the Commercial Fuel Plant and establish the remainder of the company to market, sell, deliver and service a growing fleet of PBMRs worldwide.