P B M R

Pebble Bed Modular Reactor

In the 1950's, Dr. Rudolf Schulten (later Prof. Dr. Schulten, "father" of the pebble bed reactor) had an idea. The idea was to compact silicon carbide coated uranium granules into hard billiard-ball-like spheres to be used as fuel for a new high temperature, helium cooled type of reactor. The idea took root and in due course the AVR, a 15MW (megawatt) demonstration pebble bed reactor, was built in Germany. It operated successfully for 21 years. Then, in the intense wave of post-Chernobyl anti-nuclear sentiment that swept Europe, particularly Germany, the idea almost submerged. It is resurfacing in South Africa ...

FF/9

THE KEY TO CLEAN, SAFE AND AFFORDABLE ENERGY

It is small, safe, clean, cost efficient, inexpensive and adaptable. Those, in a nutshell, are the features of the Pebble Bed Modular Reactor (PBMR).

The PBMR is currently being investigated by Eskom, South Africa's power utility giant, to establish whether it could be included as an option in South Africa's future energy generation mix. Design and costing studies indicate that the PBMR has a number of advantages over other potential power sources. Locally, it has the potential to provide South Africa with competitive power generation in coastal areas. Internationally, it will be highly competitive with virtually all other forms of energy generation.

Most of South Africa's coal-fired electricity is generated by large-scale plants built near the pit-heads of two extensive coal-producing areas, both of them far inland on the eastern side of the country.

This requires long power lines from the coal-rich areas to load centres away from the pit-heads, which in turn implies high capital costs and transmission losses. Transporting coal to distant power stations is prohibitively expensive. The opportunities for producing hydro-electric power or power from natural gas in South Africa are severely limited.

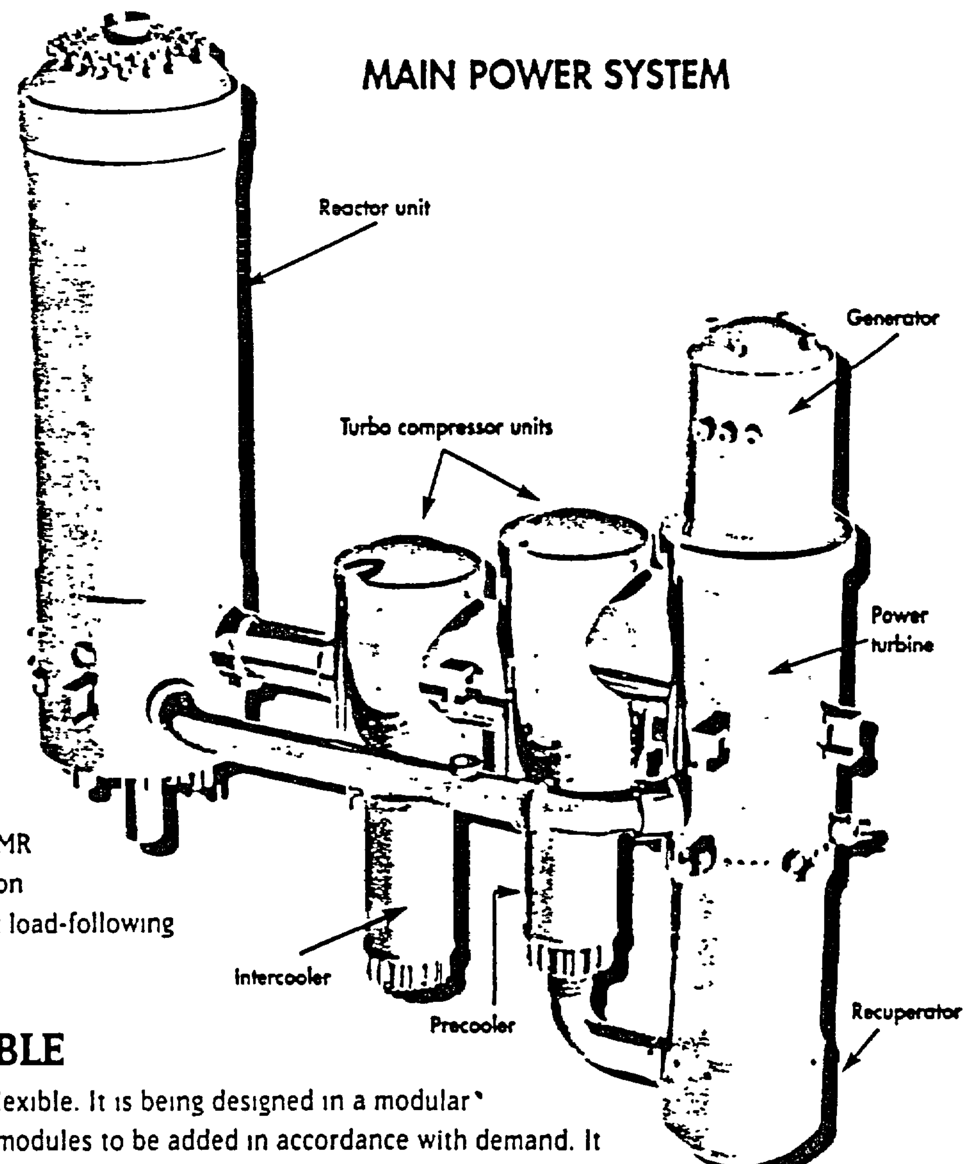
Although the demand in South Africa is currently lower than the capacity, it is anticipated that new capacity will have to be commissioned by about 2007. Even moderate growth of 2,5 percent will result in peak electricity demand exceeding capacity between 2005 and 2010. In addition, Eskom's older power 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 000MW of electricity that will be needed by 2025 (over and above the currently installed 40 000MW)

Large thermal, nuclear or hydro-electric 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.

Eskom also experiences short, sharp demand peaks in winter that are difficult to accommodate with the slow ramping characteristics of the existing large power stations.

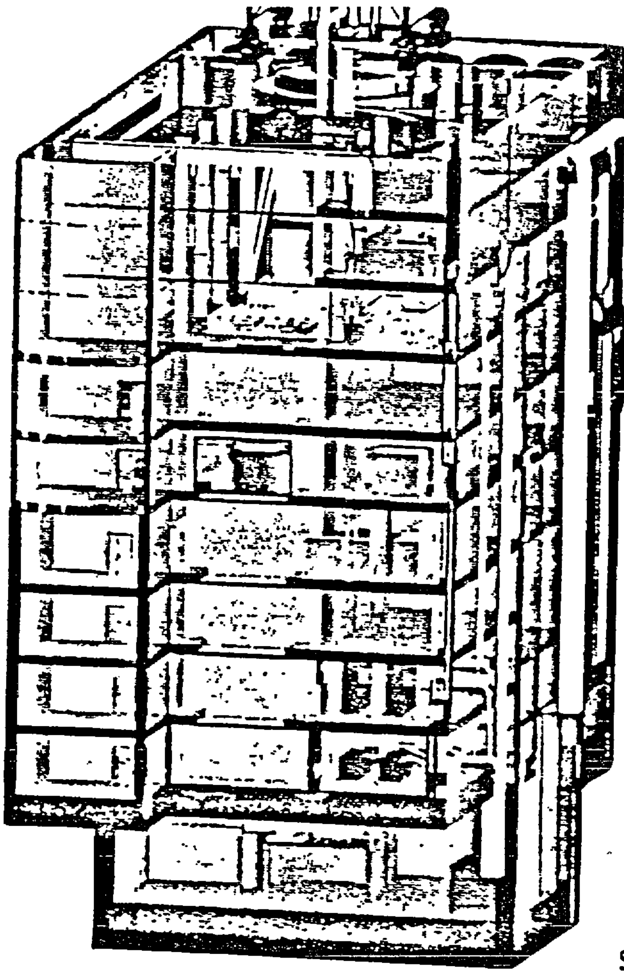
These factors prompted the investigation into small electricity generation plants that can be placed near to the points of demand. The PBMR concept, which has a short construction lead-time, low operating cost and fast load-following characteristics, is such an option.



THE PBMR IS ADAPTABLE

The PBMR reactor is adaptable and flexible. It 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. An added attraction is that they are extremely well suited for



A cross-section of the PBMR module building, four of which will fit on a soccer field.

THE PBMR IS SMALL

The PBMR is based on the philosophy that the new generation of nuclear reactors should be small A single PBMR module would be sized to produce about 110MW, which is about 10 percent of the output of a conventional nuclear or fossil fuel-driven power station. The modular approach makes it possible to build smaller nuclear power plants to serve local needs and expand them as demand grows.

The main building of a module will cover an area of about 1 600m² (54m x 30m), which means that about four modules would fit on a soccer field. The height of the building will be 47,5m, half of which will be below ground level.

THE PBMR IS COST EFFICIENT

South Africa has one of the lowest power costs in the world, based on its abundant low-cost coal. Current indications are that the PBMR's output cost would be in the same order as the cost of electricity produced by a new South African coal-fired plant situated at the pit-head The cost per unit of electricity produced would, however, be much lower than a coal-fired plant at the South African coast or the world average cost of US3.4c/kWh The costs of decommissioning, long-term storage of radioactive waste and insurance are included in these estimates. Unlike Eskom's other low cost options such as coal and imported hydro, the PBMR costs are virtually independent of location.

The PBMR is relatively inexpensive to build compared with other energy generators. The estimated cost is about US$1 million per MW of installed capacity, compared to US$900 000 per MW for a new coal-fired power station in South Africa. This more than compensates for the cost of coal away from the the pithead.

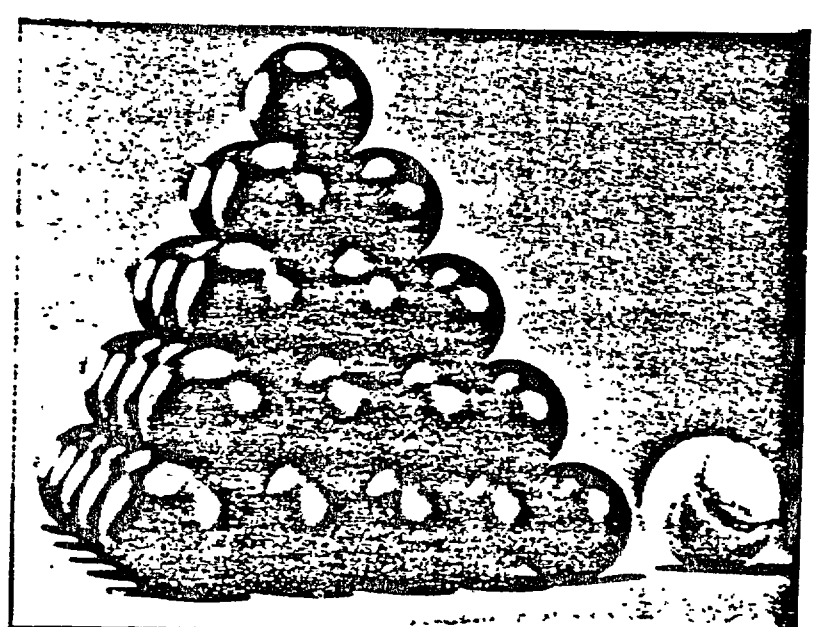
THE PBMR'S SAFETY FEATURES

The PBMR has a simple design basis, with passive safety features that require no human intervention and that cannot be by-passed or rendered ineffective in any way.

If a fault occurs during reactor operations, the system, at worst, will come to a standstill and merely dissipate heat on a decreasing curve without any core failure or release of radioactivity to the environment.

Its inherent safety is a result of the design, the materials used, the fuel and the natural physics involved, rather than the engineered active safety systems in a Pressure Water Reactor (PWR).

The helium, which is used to transfer



The pebbles, which are 60mm in diameter, are slightly smaller than a tennis ball.

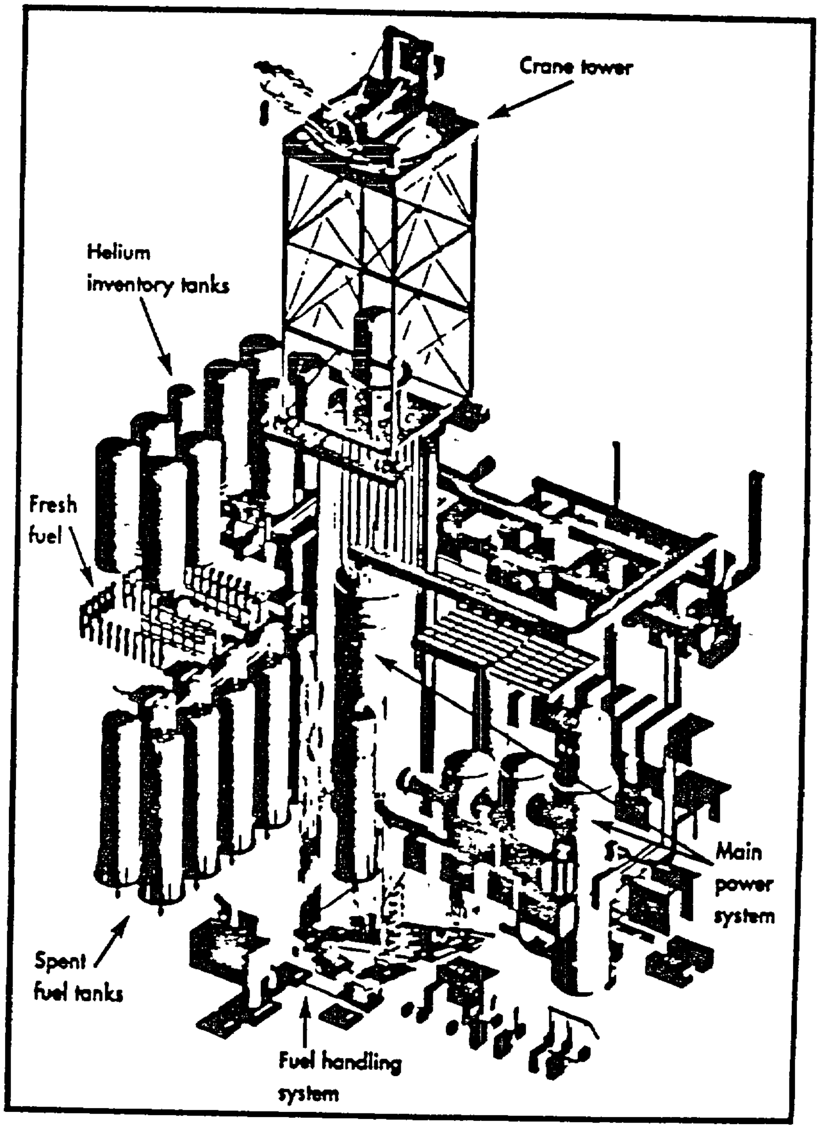
heat from the core to the power-generating gas turbines, is chemically and radiologically inert. It cannot combine with other chemicals, it is non-combustible and it cannot become radioactive when passed through the core.

The inherently safe design of a PBMR, which renders the need for safety grade backup systems and off-site emergency plans obsolete, is fundamental to the cost reduction achieved over other nuclear designs. One of the fundamental design differences between current generation reactors and High Temperature Gas-cooled Reactors (HTGRs) with coated particle fuel is the individual "containment" function of each fuel particle. The inherent design of these fuel particles, coupled with the advanced design of the reactor, prevents a major or severe loss of containment.

NO GREENHOUSE GASES

The PBMR will provide an economic mitigation strategy for greenhouse gas reductions, since nuclear power generation produces no carbon dioxide emissions, smoke or any other gases. France's carbon dioxide emissions from electricity generation fell by 80 percent between 1980 and 1987 as its nuclear capacity increased, and Germany's nuclear power programme has saved the emission of over two billion tons of carbon dioxide from fossil fuels since it began in 1961.

Emissions of sulfur dioxide in the US would have been three million tons higher and emissions of nitrogen oxides more than two million tons higher if utilities had built fossil plants instead of nuclear plants. If, by some misfortune, all of America's 103 nuclear plants were shutdown and replaced by fossil plants, it would be necessary to remove 90 million automobiles from the nation's highways just to keep the level of emissions at the current levels.



WASTE GENERATION AND DISPOSAL

A major advantage of radioactive waste is that it is so small in volume compared to the equivalent waste from, for example, a coal-fired power station. One kilogram of natural uranium has the same energy output as 17 tons of coal with an ash content of up to 40 percent. A large coal-fired power station uses about six trainloads of coal a day, while a nuclear power station of equivalent capacity uses only one large truckload of fuel per year.

The PBMR will generate about 19 tons of spent fuel pebbles per annum, of which less than one ton is depleted uranium. The spent fuel is much easier to store than fuel rods from conventional nuclear reactors, as the silicon carbide coating on the fuel particles will keep the radioactive decay particles isolated for approximately a million years. This is longer than the activity of any of the radioactive products, including plutonium.

The PBMR system has been designed to deal with nuclear waste efficiently and safely. There will be enough room for the spent fuel to be stored in dry storage tanks at the PBMR plant for the power station's expected 40-year life, during which time no spent fuel will have to be removed from the site.

After the plant has been shut down, the spent fuel can be safely stored on site for another 40 years before being sent to a final repository No decision has yet been made on the location of such a site.

AND EXPORT POTENTIAL

If the promise of the PBMR pans out, it could dramatically boost the prospects of nuclear energy on a global scale, fulfilling at last the dream of a non-polluting power source that's safe, cheap and even popular.

The recent flare-up of oil prices is a sobering reminder of the volatility in this market, the exhaustibility of fossil fuels and the urgent need for stable, reliable, non-polluting sources of electrical power that are indispensable to a modern industrial economy.

As the world economy continues to expand due to the increased use of new technologies, so will demand for electricity. International electricity demand is expected to increase by a massive 91 percent by 2020. As electricity demand increases, new plants will be needed both to accommodate the new demand and to replace plants built 40 to 50 years ago. However, the public will not accept new plants that cause harm to the environment.

Throughout the world people are demanding a cleaner environment. Global warming is a serious concern. Building more generating plants powered by solar and wind energy is one way to reduce greenhouse gases More wind and solar generating facilities will be constructed over the next two decades But solar and wind power will not be sufficient to meet the growth in electricity demand over the next several decades, let alone replace outmoded plants. Other technologies such as fuel cells will make a contribution, but will not supersede the existing systems

The most environmentally responsible way to meet demand will be through nuclear power. The PBMR therefore offers a unique opportunity for South Africa to develop an advanced industrial base in a globalised world economy. Significant export opportunities exist to First World countries as well as Third World and Developing World countries.

As the dominant economic power in Sub-Saharan Africa, South Africa is seen as instrumental to the economic upliftment of the region In fact, South Africa feels a moral obligation in this regard, as articulated by President Thabo Mbeki in his African Renaissance plan

The confidence in the PBMR's export potential is underscored by an independent assessment of the world market, which showed that up to 20 modules per year (which represent less than two percent of the world market's annual capacity requirements), could be exported once the technology has been fully demonstrated.

Similar to an aircraft manufacturer introducing a new type of plane, a project of this magnitude requires a "launch customer". To this end, Eskom has conditionally agreed to buy ten modules if the demonstration plant proves to meet financial expectations.

THE PEBBLE BED EVOLUTION

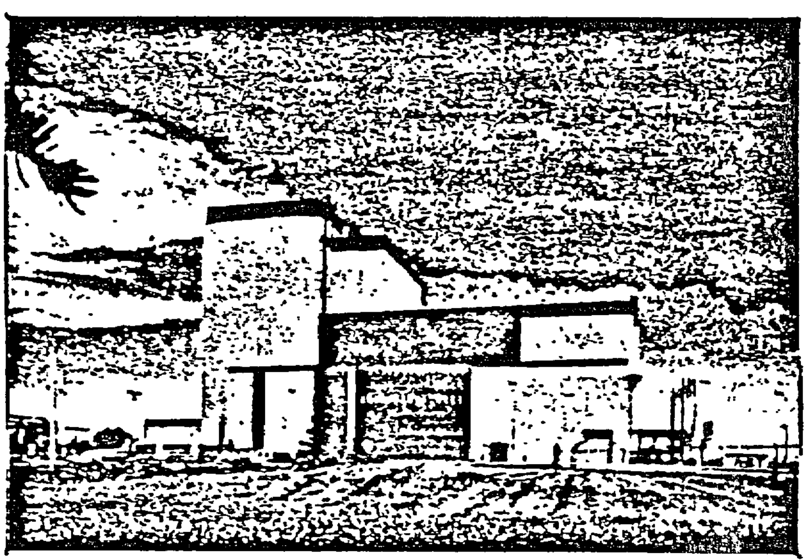
High-Temperature Reactor (HTR) technology had been successfully developed by the mid-1980s in Germany with the building of the AVR research reactor and the Thorium High-Temperature Reactor (THTR) power reactor The PBMR is a follow-on plant based on the fundamental research and development results gained on these plants, as well as the UK, USA and Japanese experience

The 15MW AVR was a research reactor built to demonstrate the characteristics of the HTR reactor type based on the pebble bed concept. Different types of fuel design, fuel loading configurations and HTR safety characteristics were tested and demonstrated Despite being the first prototype, the AVR achieved a utilisation factor of approximately 70 percent over its 21-year operating life The value of the inherent safety features of this type of small HTR was only fully recognised after the Three Mile Island accident in the USA.

The 300MW THTR (Thorium High-temperature Reactor) was built as a first-of-its-kind production plant, which was intended to demonstrate the viability of the different subsystem hardware designs, with specific emphasis on plant availability and maintainability The design, therefore, concentrated on building a plant with a life span of 40 years and an availability of 80 to 90 percent The THTR-300 was going to be the front-runner of a commercial machine, namely the HTR-500

Following the Chernobyl accident in 1986, the West German government came under severe pressure to start closing down nuclear plants It was easier to close down the HTR research reactors which had no impact on the electricity supply to Germany, than commercial nuclear power stations

Although both were pebble bed reactors, there were fundamental differences between the AVR and THTR-300 plants The key engineering differences resulted from the size of the reactor. The change in size from AVR (40MWth) to the THTR (800MWth) resulted in major engineering differences in the THTR such as a much larger core diameter (2.5m to 5m), a concrete pressure vessel, in-core control rods and active safety-grade systems.



The 330MW Fort St Vrain High-Temperature Gas Reactor which operated for 14 years in the US.

These changes were largely driven by the presumed need for larger reactor power levels and resulted in the vast majority of the commissioning problems with the THTR. The concrete pressure vessel led to difficulties in insulation of the low temperature concrete (limit 60°C) from the high temperature gases (650°C) Due to the need to insert the control rods into the pebble bed by force, the in-core control rods resulted in damage to fuel elements The resulting high scrap level in the fuel system led to low availability of the fuel handling system.

In 1996, Eskom purchased the PBMR license from HTR, a joint venture of Siemens and ABB

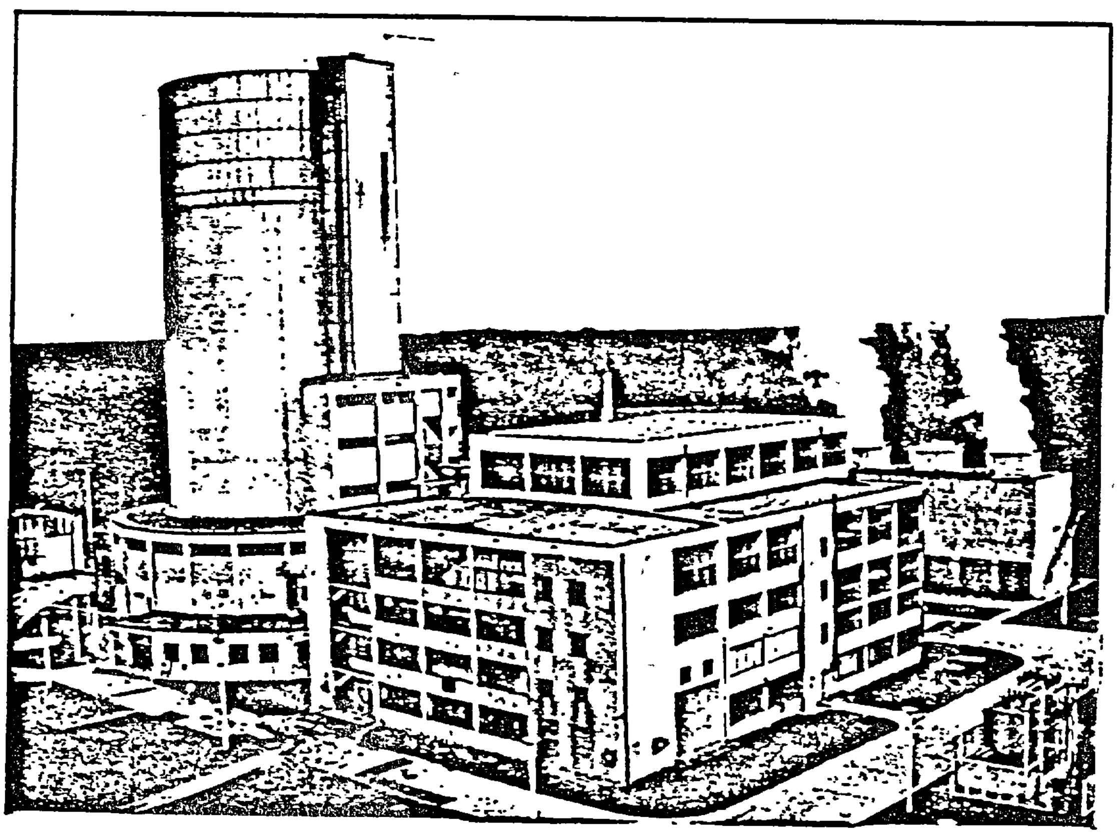
The PBMR project team believes that it has improved upon the design concepts of the THTR-300 plant Some technical design concepts which were not successful, have specifically been addressed by the PBMR, such as a steel pressure vessel instead of a concrete pressure vessel and control rods in the reflector instead of in the core.

The PBMR concept also includes the technological advances made in gas turbine technology since the 1980s and provides a plant configuration with the most robust safety case of any HTR yet designed The small plant size and the elimination of a steam cycle, allows the achievement of the robust safety case of the PBMR.

Despite its technical deficiencies, the THTR-300 achieved the following milestones:

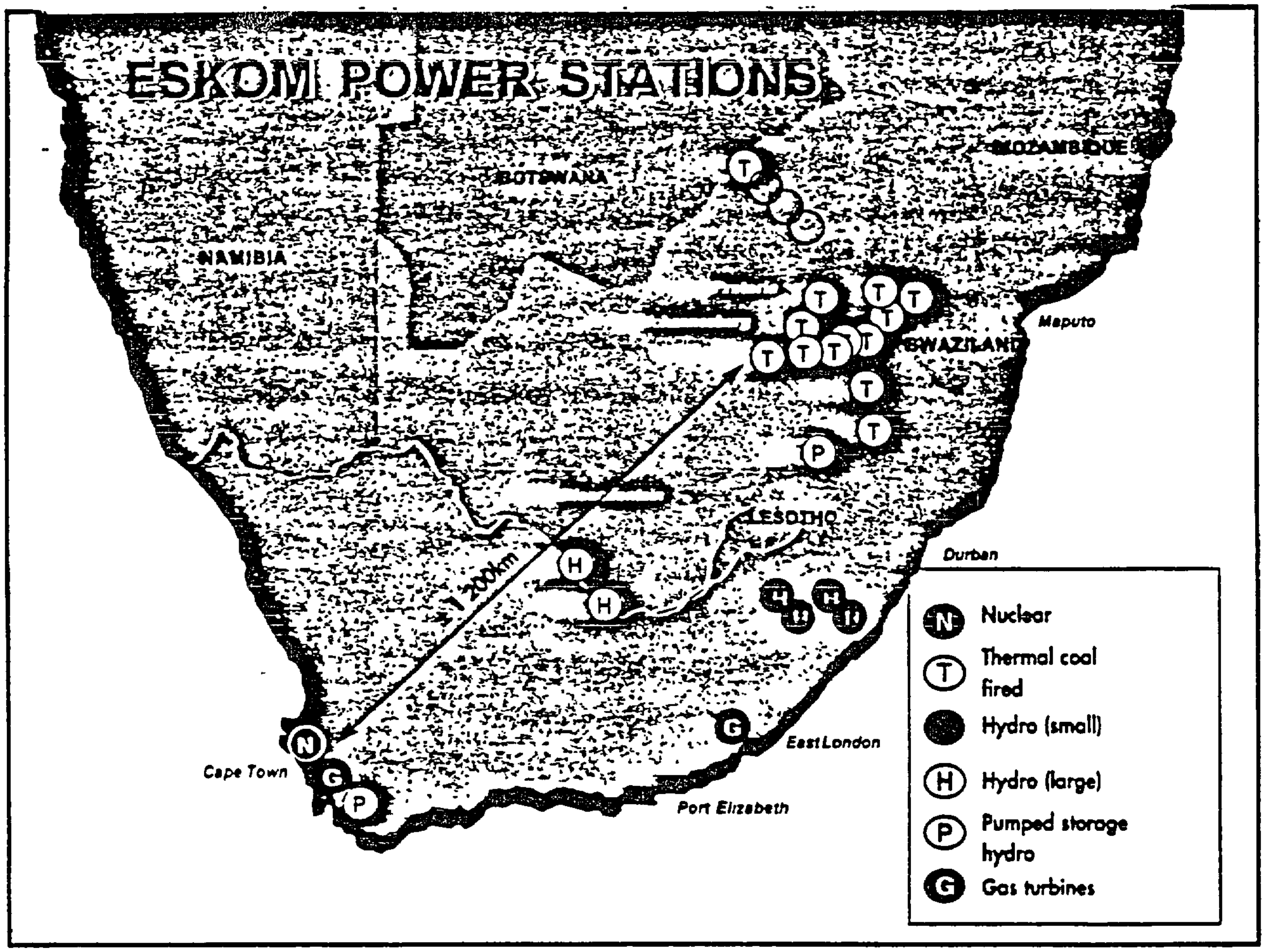
- first nuclear power on 6 September 1985;
- first power into the grid on 16 November 1985;
- 100 percent power performance on 23 September 1986, and
- handover to the utilities' consortium (HKG) on 1 June 1987

The fuel design of the PBMR falls within the qualified fuel design parameters of the German fuel programme The actual fuel design is that specified for the Interatom Modul reactor design, which was qualified and certified in Germany There was a large range of specific fuel designs (in terms of coatings and kernel dimensions) used on the THTR and AVR



The 15MW experimental pebble bed reactor which operated in Germany for 21 years.

HOW THE PBMR PROJECT CAME ABOUT



About 93.5 percent of South Africa's electricity is generated in coal-fired power stations, with one large nuclear station (Koeberg, near Cape Town) providing an additional 4.5 percent. A further 1.5 percent is hydro-electric. There are no more economic hydro sites in South Africa that could be developed to deliver significant amounts of power. The country's natural gas resources are also too limited to qualify as a viable option for power generation

In view of this, the South African power utility giant Eskom has been investigating the PBMR since 1993 as part of its Integrated Electricity Planning process. The overall objectives of these investigations were to establish whether such a system could form part of Eskom's expansion planning, and what specific advantages it would bring over other options. These included an evaluation of the technical performance and economic merits of the project.

These investigations confirmed that the PBMR should be considered as a possible option for future South African electricity supply. It is clear that it has major potential advantages, both to the electricity supply industry and to the overall South African economy

Since the technology had not previously been commercialised, the need exists to demonstrate the techno-economic viability on a full-scale demonstration plant. Indications are that this technology offers a cost-effective option with short construction lead-times that would enable power utilities to drastically shorten their decision-making horizon for the addition of new capacity and to add capacity in smaller increments.

Conventional power stations are expanded in increments of between 600 and 1 000MW. A typical coal-fired power station would consist of 6 x 600MW units and require a lead time of about eight years PBMRs can be added in increments of 114MW (or even smaller), with construction lead times of only two years.

In 1995, Eskom commissioned a Pre-feasibility Study by Integrated System Technologies (IST), 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.

A comprehensive evaluation was also performed to determine the international interest existing within this field of technology, including the availability of this technology. These results show that the design has been established in enough detail to support safety studies, confirm operating limits and estimate costing The costing includes construction costs for a single module of 110MW capacity and a power plant consisting of 10 modules; operating and maintenance costs, fuel plant costs; and design and development costs

A PBMR company has been formed between Eskom, the Industrial Development Corporation, British Nuclear Fuel and the US utility Exelon, to build and market PBMR-based power plants. The intention is to build and operate a single module to serve as a demonstration plant and a launch platform for local and international sales. Successful completion of the demonstration phase will be followed by commercialisation, with Eskom likely to be the first customer.

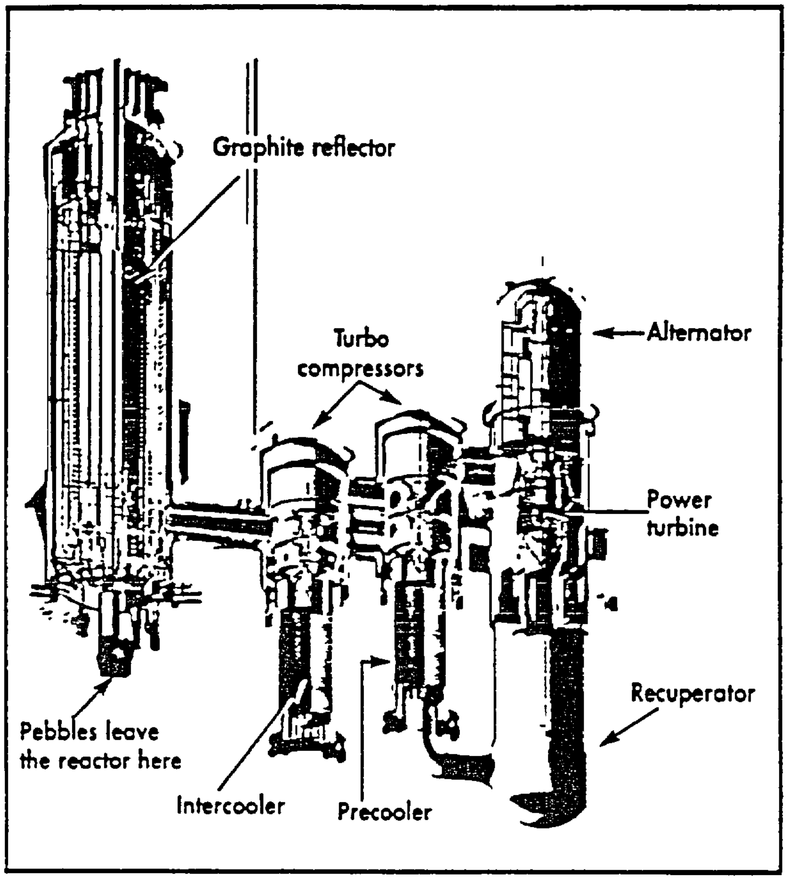
The first phase of the project, which was given the go-ahead by the South African Government in April 2000, involves undertaking a detailed feasibility study, an environmental impact assessment (EIA) and a public participation process

Approval to continue is also subject to a series of milestone reviews by the South African Government, the successful completion of the EIA process, as well as the issuing of a construction license by the South African National Nuclear Regulator. Assuming a favourable outcome of the EIA, the issuing of a construction license by the National Nuclear Regulator, shareholder approval and Government consent, preliminary construction activities could commence in the first half of 2002 Commercial operation is forecasted about four years later.

Target dates

June 2000	Environmental Impact Assessment application
June 2000	National Nuclear Regulator (NNR) application
October 2000	Safety Analyses Review issued to NNR
April 2001	Detailed feasibility study completed
End 2001	Construction approval
2004	Start hot non-nuclear testing
2005	Synchronisation

HOW THE PBMR WORKS



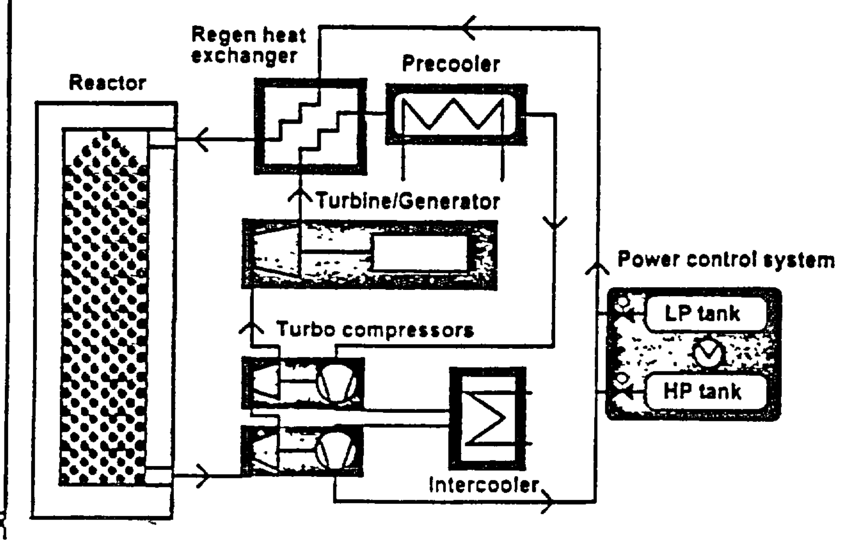
The PBMR is a helium-cooled, graphite-moderated High-Temperature Reactor (HTR).

The PBMR consists of a vertical steel pressure vessel, 6m in diameter and about 20m high. It is lined with a 10cm 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 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 310 000 fuel spheres The balance are pure graphite spheres which serve the function of an additional nuclear moderator.

To remove the heat generated by the nuclear reaction, helium coolant enters the reactor vessel at a temperature of about 500°C and a pressure of 70 bar. 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 900°C

The hot gas then enters the first of three gas turbines in 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 bar, 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 intercooler and 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 three times as high.

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

On-line refueling 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.

The aim is to operate uninterrupted for six years before scheduled maintenance. However, for the first demonstration module a certain amount of interim shut-downs will be required for planned evaluation of component/system performance. During a shut-down there are a variety of options to consider, namely system shut-down in a thermally hot condition or in a cold condition

Shut-down will be done by inserting the control rods Start-up is affected by making the reactor critical and using nuclear heat-up of the core and removing this heat in the core conditioning system. At a specified temperature, the Brayton cycle is initiated by means of an external blower system, whereafter the core conditioning system is shut down and the heat removed by the coolers in the power conversion unit.

Plant Specifications

Maximum sent-out power	100-115MW
Continuous stable power range	0-100%
Ramp rate (0-100%)	10%/min
Load rejection without trip	100%
Cost	US$1000/kWe
Construction lead-time	24 months
General overhauls	30 days per 6 years
Outage rate	2% planned and 3% forced
O&M and fuel costs	US$4-5/MWh
Emergency planning zone	<400 meters
Plant operating life time	40 years

P B M R

THE PBMR'S PARTICIPATING COMPANIES

Participation in the PBMR project by two major international companies, British Nuclear Fuel (BNFL) and the US utility Exelon, is a clear indication of the confidence in the PBMR's technical, commercial and export potential.

BNFL and Exelon jointly have a 35 percent stake in the project. The South African power utility giant Eskom is the main shareholder with 30 percent, while the Industrial Development Corporation of South Africa (IDC) holds a 25 percent stake. The remaining 10 percent is reserved for black empowerment investment.

Exelon Corporation, created by the merger in October 2000 of PECO Energy and Unicom Corporation, is one of the US's largest electric utilities, with approximately five million customers and more than $12-billion in annual revenues It comprises three business segments – energy generation, energy delivery and unregulated enterprises – and has one of the US's largest portfolios of generation capacity.

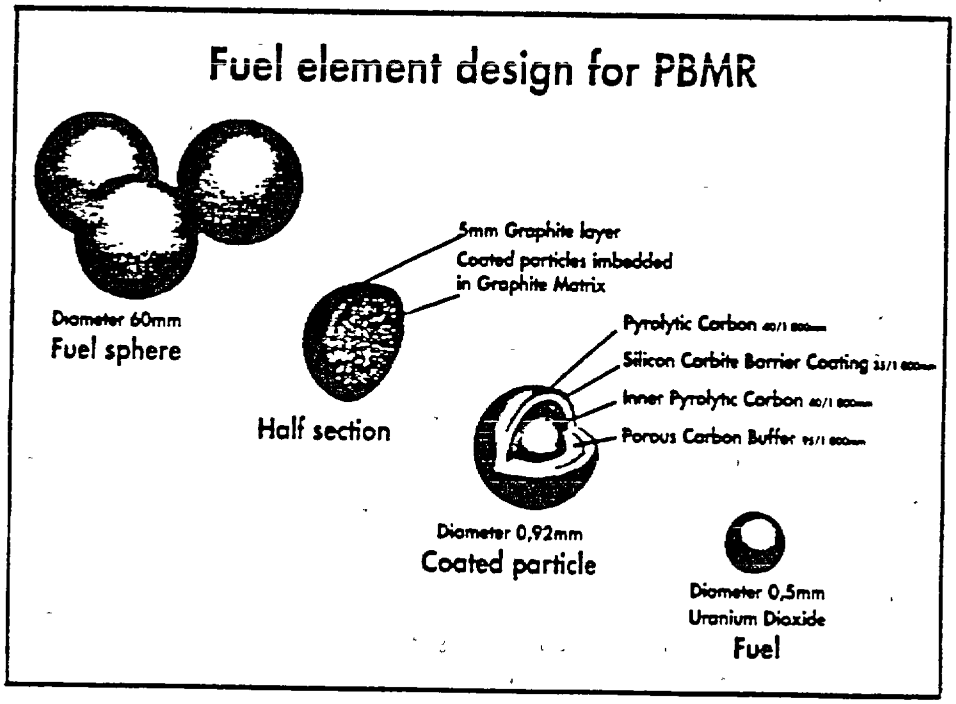
The combined portfolio of nuclear, coal-fired, gas-fired, oil/gas-fired, pumped storage and run-of-the-river hydro units provides more than 22 500MW of generation. Exelon distributes electricity to customers in Illinois and Pennsylvania and gas to customers in Pennsylvania

BNFL provides products and expertise to the nuclear industry worldwide. The company's business covers fuel manufacture and reactor services, electricity generation, spent fuel management and nuclear decommissioning and clean-up In just two years, BNFL has grown from a UK-based business into a global company with the acquisition of the Westinghouse and ABB nuclear businesses Today, BNFL operates in 15 countries worldwide, employing more than 23 000 people.

Eskom covers generation, transmission and distribution Its large pit-head, coal-fired power stations comprise about 85 percent of its installed capacity of over 35 000MW. Its one nuclear station, Koeberg (2 x 965MW PWRs near Cape Town) provides 6 percent of Eskom's power and supports the Western Cape region which is 1 400km from the nearest coal-fired power station. Eskom prides itself on being one of the lowest-cost generators in the world with an overall busbar cost of about one US cent per kWh

The IDC is a state-owned, registered public company which provides loan and equity financing for a variety of enterprises. It has been profitable almost from its inception in 1940 and is, therefore, fully self-funding Its mandate is to promote economic growth in the South African Development Community (SADC) region by financing sustainable, competitive industries and other enterprises (such as tourism and agricultural projects) in accordance with sound business principles. All the IDC's investments are subjected to comprehensive risk-benefit analyses, in which environmental risk analysis is included as a matter of course, not only to protect the IDC's investment interests, but also to contribute to the achievement of national environmental objectives.

HOW THE PBMR FUEL WORKS



The PBMR fuel is based on proven high quality German moulded graphite sphere and triple coated particles (TRISO). Essentially, the fuel elements are multi-layer spheres consisting of enriched uranium and various forms of carbon.

In the fabrication process, tiny beads of enriched UO_2 are dropped to form microspheres, which are then gelled and calcined (baked at high temperature) to produce uranium fuel "kernels". The kernels are then run through a Chemical Vapor Deposition (CVD) machine – typically using an argon environment at a temperature of 1 000°C – in which layers of specific chemicals can be added with extreme precision.

For the PBMR fuel, the first layer deposited on the kernels is porous carbon, which allows fission products to collect without over-pressurising the coated fuel particle. This is followed by a thin coating of pyrolitic carbon (a very dense form of heat-treated carbon), followed by a layer of silicon carbide (a strong refractory material), followed by another layer of pyrolitic carbon.

The porous carbon accommodates any mechanical deformation that the uranium oxide particle may undergo during the lifetime of the fuel. The pyrolytic carbon and silicon carbide layers provide an impenetrable barrier designed to contain the fuel and the radioactive decay products resulting from the nuclear reactions.

Some 15 000 of these fuel particles, now about a millimeter in diameter, are then mixed with a graphite phenol powder and pressed into the shape of 50mm diameter balls. A 5mm thick layer of highly pure carbon is then added to form a "non-fuel" zone, and the resulting spheres are then pressed, sintered and annealed to make them hard and durable.

Finally, the fuel elements are machined to a uniform thickness of 60mm, about the size of a tennis ball.

Each fuel sphere contains 9g of uranium, which means that the total uranium in one fuel load is 2.79 tons The total mass of a fuel sphere is 210g.

During normal operation, the PBMR core contains a load of 440 000 spheres, 310 000 of which are fuel spheres. The balance are solid nuclear grade graphite and serve the function of an additional nuclear moderator. Graphite is used in nuclear applications because of its structural characteristics and its ability to slow down neutrons to the speed required for the nuclear reaction to take place.

The graphite spheres are located in the centre of the core and the fuel spheres in the annulus around it. This geometry limits the peak temperature in the fuel following a loss of cooling.

In order to have a self-sustaining or "chain" reaction, the uranium in the PBMR pebbles is enriched, on average to 8 percent. This is the isotope of uranium which undergoes the fission reaction in the core. U-235 occurs in natural uranium in a concentration of 0.7 percent.

The reactor will be continuously replenished with fresh or re-useable fuel from the top, while used fuel is removed from the bottom The fuel pebbles are measured to determine the amount of fissionable material left If the pebble still contains a usable amount of the fissile material, it is returned to the rector at the top for a further cycle. Each cycle is about three months

When a fuel sphere has reached a burn-up of 80 000MWd/T of uranium metal, it is removed and sent to the spent fuel storage facility Each fuel pebble passes through the reactor about 10 times and a reactor will use 10 to 15 total fuel loads in its design lifetime. A fuel sphere will last about three years and a graphite sphere about 12 years.

The extent to which the enriched uranium is used to depletion (called the extent of "burn-up") is much greater in the PBMR than in conventional power reactors There is therefore minimal fissile material that could be extracted from depleted PBMR fuel This, coupled with the level of technology and cost required to break down the barriers surrounding the spent fuel particles, protects the PBMR fuel against the possibility of nuclear proliferation or other covert use.

The spent fuel storage facility in a PBMR is situated in the reactor building. The fuel is transported to the spent fuel storage by means of a pneumatic fuel handling system The spent fuel storage consists of 10 tanks, each with a diameter of 3.2m and a height of 14m. One tank can store 330 000 spheres.

The South African Nuclear Energy Corporation (NECSA), where fuel rods for Eskom's Koeberg nuclear reactor near Cape Town were manufactured in the past, is currently under contract from the PBMR project team to develop the fuel manufacturing capability using the technology established in Germany.

THE PBMR'S SAFETY FEATURES

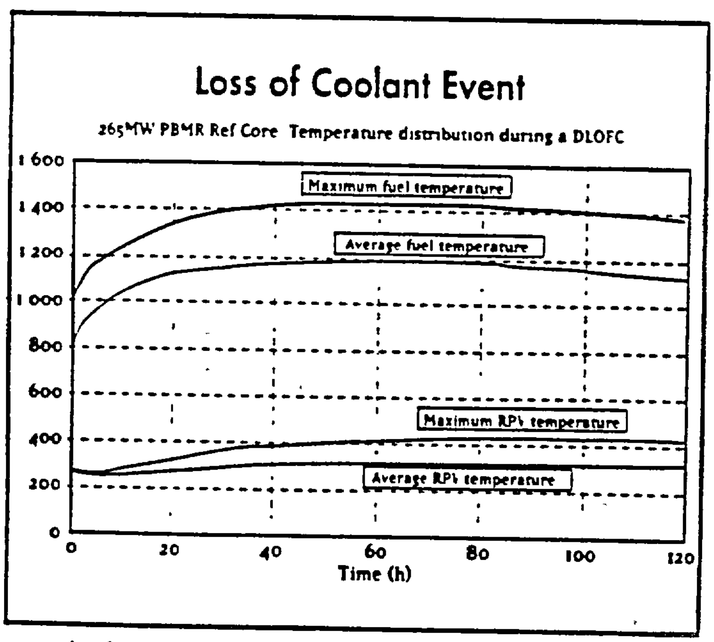
In all existing power reactors, safety objectives are achieved by means of custom-engineered, active safety systems. In contrast, the Pebble Bed Modular Reactor (PBMR) is inherently safe as a result of the design, the materials used, the fuel and the natural physics involved. This means that, should 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 it loses its integrity and therefore releases its radioactivity.

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 decay is such that the removal of the decay heat is achieved by radiation, conduction and convection, independent of the reactor coolant. The combination of the very low power density of the core (1/20th of the power density of a Pressure Water Reactor), and temperature resistance of fuel in billions of independent particles, 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. Because oxygen cannot penetrate the helium, oxygen in the air cannot get into the high temperature core to corrode the graphite used in the reaction



The figure shows the performance of the fuel under extended periods at high temperatures.

Why a core melt-down is not possible

The peak temperature that can be reached in the core of the reactor (1 600°C under the most severe conditions) is below any sustained temperature that may cause damage to the fuel. This is because the fuel is made partly from ceramic materials like graphite and silicone carbide, which makes it extremely robust.

Even if a reaction in the core cannot be stopped by the small absorbent spheres (that perform the same function as control rods) or cooled by the helium, the reactor will stop any nuclear fission and cool down naturally and in a very short time.

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

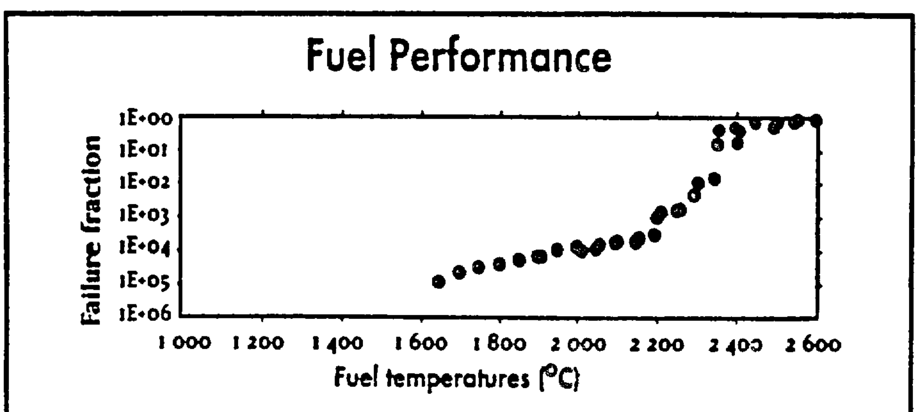
If, through some accident, both the inlet and the outlet gas pipes were ruptured, it would take some nine hours for natural air to circulate through the core. Even if this could happen, it would only lead to less than 10^{6} (one millionth) of the radioactivity in the core being released per day. That means that the amount of activity released in 24 hours under this very severe (and recoverable) situation would be some 10 000 times less than that requiring any off-site emergency actions.

To avoid such a double failure of the main gas ducting, the piping is designed to leak before it breaks, so that the depressurisation will be gradual and cannot lead to such a rupture. The physical construction of the building is such that no external missile can cause a common failure of both pipes. The helium pressure inside the closed cycle gas turbine is higher than the air pressure outside it, so nothing can get inside the nuclear circuit to contaminate it.

This inherently safe design of a PBMR renders obsolete the need for safety grade backup systems and most aspects of the off-site emergency plans required for conventional nuclear reactors and is fundamental to the cost reduction achieved over other nuclear designs. Emergency 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.

The concept is based on the well-tried and proven German AVR power plant that ran for 21 years. This safe design was proven during a public and filmed plant safety test, when the flow of coolant through all cooling to the reactor core was stopped and the control rods were left withdrawn just as if the plant was in normal power generation mode.

It was demonstrated that the nuclear reactor core shut itself down within a few minutes. It was subsequently proven that there was no deterioration of the nuclear fuel. This proved that a reactor core meltdown was impossible and that an inherently safe nuclear reactor design had been achieved.



The figure shows the temperature of the hottest part of the fuel and overall average after a total loss of coolant.