# PBMR - why South Africa?

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**The replacement value of South Africa's 40 000 MWe of installed capacity is at least $40-billion. Eskom therefore needs to spend on average at least a billion dollars per year on new generation equipment to maintain the status quo. Increasing installed capacity at, say, 4% per year would raise the annual expenditure to around $2,6-billion.**

South Africa generates rather less than 2% of world electricity. World expenditure on new plant must therefore be of the order of $130-billion. By way of confirmation, last year's June IAEA Bulletin estimated $4,08-trillion for generation equipment to be installed between 2001 and 2030.

Eskom's commercial projections for the PBMR used to be based on the premise that the PBMR could pick up around 2% of the world market plus, of course, a significant slice of the domestic market. Nowadays, PBMR (Pty) Ltd. is more guarded. In a recent statement it was noted that "the business case compiled in 2002 by the international consultancy McKinsey & Company showed PBMR to be cost competitive in virtually all markets. The dramatic increase in the international cost of fossil fuels since then should make PBMR technology even more competitive today". Further "South Africa has one of the lowest power costs in the world, based on its low-cost coal. The PBMR business plan confirmed 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".

It still appears, therefore, that South Africa has either stumbled upon or has had the extraordinary vision and resolution to develop a technology potentially worth billions of dollars. What is it about the pebble bed that makes it so appealing, why did the rest of the nuclear world ignore it for so long and, more particularly, how did the idea take root in South Africa?

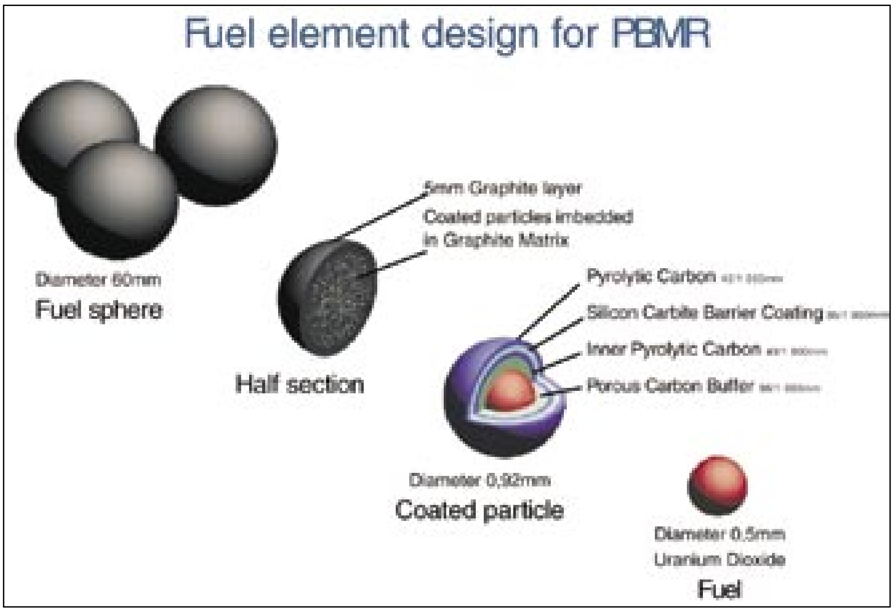
The fundamental attraction is, as ever, low cost. And the low cost claimed is tied up with claims of inherent safety. It will readily be appreciated that if there is literally no possibility of an accident capable of releasing significant quantities of radioactive material, then there is at the very least a greatly reduced need for the costly redundant safety systems that surround today's "conventional" reactors.

There are two basic types of reactor accident: loss of cooling and reactivity excursion. These are exemplified respectively by the accidents at Three Mile Island (1979) and Chernobyl (1986). Fire, which drove the radioactivity release for nine days after the initial Chernobyl explosion, must also be considered.

The ability of the PBMR system to ride through a total loss of cooling incident is attributable to the fuel design and to the relatively small module size – 165 MWe. At Three Mile Island, a not very threatening incident in the turbine hall caused the turbine to trip and, therefore, the reactor to shut down. On-going fission product heating, at several per cent of the on-load heat generation of the core, began inevitably to heat up the fuel assemblies. At the same time, a pressure release valve failed to reseat and opened a leakage path from the primary reactor coolant circuit into the containment building. The emergency core cooling systems (ECCS) started up as per design. All would have been well had the operators not intervened. Due largely to inadequate training in this type of situation, they misinterpreted the barrage of apparently conflicting information they were getting from the control room instrumentation and shut down the ECCS. The fuel temperatures continued to rise and half the core melted before the situation was correctly diagnosed and terminated.

The strength of the PBMR is that the coated uranium dioxide fuel particles within the fuel pebbles can withstand far higher temperatures (over 1600° C) without releasing significant quantities of the highly radioactive fission products accumulated within them. Moreover, thanks to the small module size and geometry of the core, the core can radiate away the accumulating fission product heat before that temperature is reached. Following complete loss of cooling, the fuel temperatures will rise to something less than 1600° C and then, with no short-term need for operator action, gradually decline. This was demonstrated long ago on a small scale at the 15MW(e) AVR prototype plant in Germany and recently at the 10 MW(t) HTR prototype in China.

In relation to the Chernobyl scenario, the PBMR core is inherently protected by the so-called Doppler effect and associated "negative temperature coefficient". The Doppler effect is the property that causes uranium-238, over 90% of uranium in the PBMR core, to absorb more neutrons as its temperature rises. Fewer neutrons are then available to participate in the chain reaction, the rate of fissions in the fissile uranium 235 dies away and the temperature increase is therefore reversed. The Doppler effect is an immutable property of uranium and therefore a factor in all reactors, including the RBMK




*Fuel element design for the PBMR*

Chernobyl-type. At very low power, however, at Chernobyl other factors not associated with the PBMR intervened to over-ride it.

Finally, fire – included here because of the frequent references to the "problem" by anti-nuclear campaigners. The Chernobyl power excursion blew the top off the reactor cavity and exposed the red hot graphite core to the atmosphere. Some twenty hours later, driven by more than 30 MW of fission product decay heat, the graphite core began to burn and went on discharging radioactivity high into the atmosphere for the next nine days. This has led opponents of the pebble bed idea to claim that the PBMR is vulnerable to fire. In fact, very pure high density reactor-grade graphite is very difficult to ignite. A strong chimney effect and a plentiful supply of air is needed. Even if the PBMR pressure vessel pipework were destroyed at both ends, i.e. above and below the pressure vessel, it appears that the 450 000 pebbles in the vessel would impede the air flow sufficiently to preclude self-sustaining combustion. This should be readily understandable in a country whose supreme cultural icon is the Weber braai.

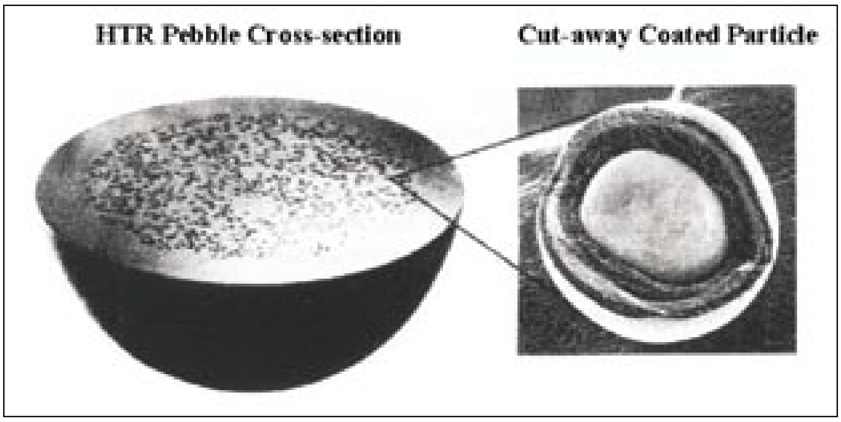
All such assertions will have to withstand the scrutiny of the National Nuclear Regulator and be substantiated during a long commissioning period, particularly at the proposed demonstration module at Koeberg.

### Early history

Accepting that the system is inherently safer and therefore cheaper than "conventional" reactor systems, and that it has been tried on a number of occasions, the obvious and frequently asked question is – why has it not been developed elsewhere? The answer requires a brief review of the history of high temperature gas-cooled reactors (variously known as HTRs or HTGRs).

The original ideas for a helium-cooled HTR and for coated particle fuel appear to have come from Britain. Physics tests were carried out in a zero power test reactor known as ZENITH at Winfrith, Dorset, in the 1950s. A UK patent for coated particle fuel was taken out in 1960. In 1959, twelve OECD countries joined forces to design and build the 20 MWt Dragon reactor, also at Winfrith.

The fuel consisted of coated particles pressed into long rods. The reactor operated successfully from 1967 to 1974. Fuel design was evolving during this period and the reactor was used, inter alia, to test fuel for the later HTRs. In particular, Dragon proved the gratifyingly good fission product retention even of un-clad uranium dioxide pellets and




*'HTR Pebble cross-section' and 'cut-away coated particle'*

the excellent retention properties of coated particles. For the PBMR, each 200g fuel sphere contains nine grams of around 9% enriched uranium.

From this point on, the form of the fuel took two different routes. Spherical fuel elements had been suggested as early as 1945 by Farrington Daniels, a senior chemist on the Manhatten project. His idea was, however, swept aside in the rush to develop a more compact water-cooled reactor for submarine propulsion. Daniels went on to become an honoured pioneer in the development of solar energy.

The Germans resurrected the spherical element idea. Coated particles were pressed into spheres 50 mm in diameter encased in a shell of high density graphite 5 mm thick. The final machined sphere, containing some 15 000 granules, thus had a diameter of 60 mm. This was the fuel for the 15 MWt AVR test reactor, the first pebble bed reactor, which operated with conspicuous success at Juelich from 1966 to 1988. It was followed by the less successful THTR (Thorium HTR, 300 MWe, 1985 to 1988).

The Americans took a different geometrical route. Peach Bottom (40 MWe, 1967 to 1974) used coated particles pressed into rods. For Fort St. Vrain (330 MWe, 1979 to 1989), the particles were pressed into upright hexagonal blocks containing holes for the helium coolant flow.

The THTR and Fort St Vrain were the first commercial HTRs. Their early closure accounts for the subsequent lack of interest in the system. Chernobyl accounts for the lack of interest in nuclear generation in general at that time. Fort St Vrain ran into a number of problems, none of them associated with the HTR reactor concept. In particular, the helium gas circulators had water-lubricated bearings which gave rise to frequent leakage of water into the reactor coolant circuit and lengthy reactor down-time. The operators eventually decided to cut their losses, swallowed hard and converted the station to burn gas.

The THTR also ran into problems, particularly vibration of reactor internals, damage to fuel spheres by control rods forced by design downward through the core, and difficulties with the equipment used to measure the 'burn-up' of pebbles discharged from the bottom of the core. These problems could have been solved but the funding, according to the contractual arrangement, had to come from the Government. In the aftermath of Chernobyl, the Government declined and the station was closed. The Minister concerned, Klaus Topfer, said in 2003 in Davos, that he now considers that decision to have been a mistake. Germany's loss was South Africa's gain, however, since the now aging engineers and scientists involved later became enthusiastic supporters of the South African programme.

### Introduction to South Africa

How did the idea take root in South Africa? It was widely known in the late 1980s that the Atomic Energy Corporation at Pelindaba was working on the design of a small indigenous PWR-based power reactor. This was supposed to be the vehicle through which PWR technology would become established in South Africa and could then be offered by the AEC to ESKOM in support of the operation of Koeberg. Investigations were also conducted jointly with ESKOM to determine the future strategy for expanding the nuclear power generation option. In this study the HTR was identified as a possible candidate and its exceptional safety characteristics became clear.

The PWR project was terminated in 1989. A number of contracts with firms in Europe had to be cancelled. During a trip to Europe for this purpose, Dr. Johan Slabber of the AEC visited Prof. Dr. Rudolf Schulten, generally regarded as the father of the HTR in Germany. The objective was to define a follow-on HTR research and development program that could be executed at Pelindaba in the

*Left to right: Dave Nicholls, chief technology officer, PBMR (Pty) Ltd. Dr Johan Slabber, senior nuclear consultant, PBMR Dieter Matzner, general manager, power plant delivery, PBMR*

wake of the cancelled PWR project. The idea of using a direct-cycle power conversion system was born during these discussions. A proposal to investigate a small inherently safe pebble bed reactor with a direct cycle power conversion system was then proposed to the AEC Board but was not accepted. The design team then dispersed. Some key members, however, among them Johan Slabber, joined IST (Pty) Ltd. in Pretoria.

In 1990, perhaps not entirely fortuitously, ARMSCOR invited IST to evaluate the suitability of the HTR for marine propulsion. Following initial sizing of the reactor, the requirement was changed from a small marine reactor to a small nuclear unit to power remote inland sites. During the execution of this work, contact was re-established with Prof. Schulten. The professor was given a contract and functioned throughout the study as a consultant. During this time he became a very good friend of South Africa and a keen supporter of the proposed design.

In a remarkable act of faith, ARMSCOR having lost interest, IST decided to pursue the small reactor project at its own expense. Mining houses were approached, there being remotely-sited mineral deposits which cannot be worked for want of economical power. Not surprisingly, none was prepared to be the first to commit to so novel a system. Eskom was approached in 1993 and also turned the idea down. The world was developing 1500 MWe nuclear units: who could get interested in the 50 MWe HTR then being offered? IST must have felt the end was nigh.

In 1992, however, IST had made a sales pitch of engineering services at Koeberg. Fortuitously, Eskom was then seeking a reliable off-site source of auxiliary power, there being a question mark over the future of the gas turbine units at Acacia. The conversation had turned to the possible use of IST's pebble bed power unit. The idea was not pursued but the seed had been sown in the mind of one Eskom engineer – that of Dave Nicholls, then Engineering Manager at Koeberg.

On his return to Megawatt Park a year or so later, Nicholls took it upon himself to promote the revolutionary concept of small modular power units to be built relatively cheaply in 24 months, more or less wherever and whenever the power is required. The timing was fortuitous. Eskom had surplus capacity and could afford time to look long and hard at alternative power sources to supplement or replace the big coal-burning units when necessary. The technologies then being studied included off-shore gas, solar and wind energy and more efficient ways of burning low-grade coal. Nicholls obtained the support of Jan de Beer, then Executive Director (Technology) and what he had by now christened the 'PBMR', the pebble bed modular reactor, was added to the list. In due course, the PBMR emerged from the studies as the front-runner, the most promising future technology. PBMR (Pty) Ltd. was established in 1999 to develop and implement the idea.

**Global perspective**

How does all this look in the global context? A power generation engineer stationed on the Moon would see a world, for the first time in its ancient history, capable of altering its own global environment – and struggling to come to terms with that fact. He would see a world contemplating the medium-term exhaustion of irreplaceable fossil fuel reserves. His antennae would pick up a babble of voices calling vigorously for the use of renewable energy, for nuclear energy and some for the development of a 'hydrogen economy' eventually to supplant fossil fuels, particularly for transport.

He might well conclude that the accelerating use of fossil fuels will increasingly be seen as unacceptable. Also that intermittent and expensive renewable energy sources will not contribute largely, at least for several decades, if then. He might therefore logically conclude that, despite certain problems, the use of nuclear energy is inevitable. His logical brain would probably distil from the babble the two real concerns, namely the possibility of a major accidental release of radioactivity and the use of nuclear generation as a smoke-screen to conceal the manufacture of nuclear weapons. He would hear much about the perceived problem of the disposal of radioactive waste but might well conclude that the problem is emotional and its solution costly rather than technically difficult. Thinking about the weapons problem, he might conclude that the solution must largely be political, and that the world will have to do better in that area than it is doing at present.

Zooming in still further, our perceptive engineer would see many organisations around the world developing different ways of wresting energy still more safely from the nucleus - to meet the anticipated resurgence. He would perceive that most are basing themselves on existing technology and are evolving and beginning to build large power stations with significantly lower potential for the feared core-melt accident, and with the capacity to withstand such an event should it ever occur. Yet other organisations would be seen to be designing smaller reactor systems with probably no potential to release significant quantities of radioactive material. One of these would be labelled 'PBMR'.

In fact, the PBMR is leading the pack, but now only just. On the basis of vast willingly-imparted German experience, Eskom took an early decision to leapfrog a prototype stage. The design would be proven by exhaustive tests in an extended commissioning process. This step, it was considered, had given the PBMR a four-year lead on the HTR competition. If further delays – and environmental court cases – can be avoided, the first module could be operating at Koeberg in 2010. Then, given the promised substantial order from Eskom, the export market could open up. Work involving also major contractors such as Mitsubishi Heavy Industries, will proceed in parallel with the further environmental representations to DEAT stemming from the recent ruling of the Cape High Court.

However, South Africa was not alone in realising the forgotten potential of the HTR. Organisations in other countries, most notably in China and Japan, also became involved. The Japanese settled on fuel consisting of coated particles pressed into hexagonal blocks rather than spheres. They took their 30 MWt "HTTR" prototype critical in 1998. It has briefly achieved the 950oC outlet gas temperature they consider necessary for hydrogen production – which they hope to demonstrate in the next few years. The Chinese, on the other hand, purchased the equipment originally used in Germany to manufacture the AVR and THTR fuel spheres. Their 10 MWt prototype pebble bed has now been operating for over three years and they talk of a 200 MWe demonstration unit also to operate in 2010. Faced with a burgeoning economy already experiencing power shortages, and with potentially massive home and export markets, they will not lightly entertain domestic delay.

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