Energy Policy 39 (2011) 2431–2440

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The Pebble Bed Modular Reactor: An obituary

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ARTICLE INFO

Article history:
Received 1 October 2010
Accepted 26 January 2011

Keywords:
Nuclear power
Pebble Bed Modular Reactor
South Africa

ABSTRACT

The High Temperature Gas-cooled Reactor (HTGR) has exerted a peculiar attraction over nuclear engineers. Despite many unsuccessful attempts over half a century to develop it as a commercial power reactor, there is still a strong belief amongst many nuclear advocates that a highly successful HTGR technology will emerge. The most recent attempt to commercialize an HTGR design, the Pebble Bed Modular Reactor (PBMR), was abandoned in 2010 after 12 years of effort and the expenditure of a large amount of South African public money. This article reviews this latest attempt to commercialize an HTGR design and attempts to identify which issues have led to its failure and what lessons can be learnt from this experience. It concludes that any further attempts to develop HTGRs using Pebble Bed technology should only be undertaken if there is a clear understanding of why earlier attempts have failed and a high level of confidence that earlier problems have been overcome. It argues that the PBMR project has exposed serious weaknesses in accountability mechanisms for the expenditure of South African public money.

1. Introduction

Like the fast reactor, the High Temperature Gas-cooled Reactor (HTGR), using helium as the coolant and graphite as the moderator, has exerted a peculiar attraction over nuclear engineers. Despite many unsuccessful attempts over half a century to develop it as a commercial power reactor, there is still a strong belief that a highly successful HTGR technology will emerge. Indeed, the Very High Temperature Reactor (VHTR), which would be developed from existing HTGR designs, is one of six reactor designs that was designated in 2001 by ten leading nuclear power nations as one of the six most promising reactor designs to form a fourth generation of nuclear designs (existing designs are designated Generation III or earlier).[1]

The most determined recent attempt to commercialize this technology came with South Africa's programme, started in earnest in 1998, to develop a type of HTGR known as the Pebble Bed Modular Reactor (PBMR). The decision in March 2010 by the South African government, foreshadowed a year previously by the Treasury Minister, not to provide further funds seemed to be the death knell for this latest attempt. In June 2010, all bar a skeleton staff to protect intellectual property were offered redundancy.[2] Finally, in September 2010, the South Africa Minister at the Department of Public Enterprises announced to the South African Parliament the abandonment of the programme (Department of Public Enterprises, 2010). By 2010, the programme was running decades late and the costs were many times over the original budget. No customers had been won, no foreign investors were contributing and Eskom, the owner of the company developing the technology (PBMR Ltd.) estimated it would be at least a further 20 years before the technology could be offered as a commercial product (McKune, 2010). The decision to stop public funding relegates the PBMR to the status of one of a long list of reactor technologies that have theoretical attractions but which are still decades away from commercial application. This article reviews this latest attempt to commercialize an HTGR identifying what issues have led to its failure and what lessons can be learnt from this experience.

1.1. What is the attraction of the HTGR

The High Temperature Gas-cooled Reactors that have been built and developed to any great extent are cooled by helium gas[3] and moderated by graphite.[4] This is technically a much more efficient combination than the most commonly used reactors, which are cooled and moderated by water, so-called Light Water Reactors (LWRs). HTGRs are more economical with uranium and the high temperatures mean a greater proportion of the reactor

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[1] See for example: 〈http://www.gen-4.org/Technology/systems/vhtr.htm〉.

[2] Business Day. Nuclear expertise lost to SA as PBMR cuts back staff, June 22, 2010.

[3] The coolant is the medium that transfers the heat from the reactor to the electricity generation circuits.

[4] The moderator maximises the probability that the neutrons emitted by the uranium fuel will collide with another uranium atom before they escape the reactor core.

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doi:10.1016/j.enpol.2011.01.066

heat is converted to electricity than LWRs.[5] LWRs can only operate at about 315 °C, well below the level that fossil fuel fired plants can reach. HTGRs operate at up to 900 °C. VHTRs are expected to operate in excess of 1000 °C, opening the way for use of the heat for processes such as hydrogen generation, processing of tar-sands and conversion of coal into synthetic petroleum.

1.2. History of the HTGR

Up to 1990, four major nuclear design countries had had major programmes to commercialize HTGR technology: Germany, USA, UK and France. All of these programmes came to nothing. Subsequently Japan, China and Russia, as well as South Africa, have shown an interest in the HTGR. It was the German technology that was taken up by South Africa and China.

1.2.1. Germany

Germany has a long history of HTGR development using Pebble Bed technology. In 1959, Germany ordered the AVR plant (Arbeitsgemeinschaft Versuchsreaktor) built at the Jülich government nuclear research centre. This 15 MW (e) plant, financed by the government, was supplied by a group led by the Brown Boveri and Krupp companies. It went critical in 1966, generating electricity a year later and continuing in service until 1989. It was based on the pebble bed concept under which the fuel and graphite moderator are in the form of tennis-ball size 'pebbles'. These are continuously fed into the top of the reactor column and are continuously removed from the bottom. A pebble is expected to be used up to ten times before it would be too depleted to use. The design and dimensions of the fuel pebbles were the essentially the same for all successor Pebble Bed designs.

AVR had a good reputation as a prototype, although, as argued later, this reputation is now in question. Its successor, THTR-300 (300 MW (e)) also used the pebble bed concept and was ordered in 1970. This too was subsidised by the government but also involved utility funding. The industrial grouping behind it, HRB, again centred on Brown Boveri but with support from General Atomic a US company that had built high temperature reactors but not of the Pebble Bed design in the USA. Subsequently, Siemens produced a modular design of HTGR using the pebble bed concept, but none were built.

THTR-300 went critical in September 1983, but was only connected to the grid in November 1985 and was declared commercial[6] in June 1987. From June until October of that year, it operated at about two-thirds full-power, suffering a range of problems including difficulties with the fuel circulation system. It restarted in January 1988 for a couple of months, running at about two-thirds of its full power rating, until more repairs were necessary to the fuel circulation and collection system. It ran for another five months but was shut down due to damage in the gas ducts. Repairs were completed in February 1989. However, the plant remained closed on the orders of the safety regulator because of concerns about safety and the unwillingness of the various owners of the plant, including the federal government, to continue to provide subsidies to operate the plant.[7] THTR-300 suffered from a substantial number of other technical problems, some of which were specific to the pebble bed design (e.g. 18,000 damaged fuel pebbles, graphite dust formation, thermal insulation failure in the core bottom by overheating). In September 1989, the plant was permanently closed and, since 1997, has been in a state of 'safe enclosure', at least until 2027. Decommissioning is intended to be finished by 2080.[8]

Siemens and ABB (the successor company to Brown Boveri after it merged with ASEA) pooled their expertise on HTGRs in 1988 at the instigation of the German government to form a new company called HTR GmbH, which developed the 200 MW (th) HTR-Modul reactor which was expected to produce about 80 MW (e). With little realistic prospect of sales in Europe, their strategy appears to have been to license the technology to countries such as the then Soviet Union, China, Japan and South Africa.

1.2.2. USA

US development of HTGRs has been based on designs in which the fuel is prismatic, rather than in the form of pebbles. The USA was the first country to generate electricity using an HTGR power plant, Peach Bottom 1, completed in 1967, which produced about 40 MW of electricity and operated until 1974. By the time it was complete, a demonstration plant had already been ordered, Fort St. Vrain, which produced 330 MW of power and went critical in 1974. Again the next phase got ahead of completion of the previous phase and orders for eight full-size plants of the HTGR design, for the first time without any government subsidy, were placed from 1971 to 1974. Four of these were for units of 770 MW and four for units of 1160 MW, but little progress on these plants was made and all were cancelled in 1974–1975. General Atomic, the vendor, withdrew the design from the market because the orders would not have been profitable and it had to compensate the customers. For example, General Atomic agreed to pay Delmarva Power & Light US$125 million to terminate contracts for the construction of two 770 MW reactors.[9]

Experience with Fort St. Vrain was poor. Although it went critical in 1974, it did not produce power till 1976 and was not declared commercial until 1979. Over its ten years of commercial service till 1989, its average load factor (power produced as a percentage of theoretical output had the plant operated uninterrupted at full power) was 15 per cent, almost the lowest lifetime load factor ever achieved by a commercial nuclear power plant.[10] It was then retired, the site decommissioned and the plant replaced by a conventional gas-fired generation plant.

Work continues on the HTGR in the USA, for example, through part of the US government's Generation IV research effort, the Next Generation Nuclear Plant (NGNP) programme,[11] which, optimistically, has an objective to have a prototype plant in operation by 2021. The main US private company throughout most of this period has been, and continues to be, General Atomic. In May 2010, Westinghouse, one of the partners in PBMR Ltd., which had won contracts under the NGNP programme, withdrew from the programme.

1.2.3. UK

The UK was a pioneer of gas-cooled nuclear technology using graphite as moderator, but carbon dioxide gas as the coolant. This technology was used in the 11 commercial 'Magnox' power plants[12] and the seven commercial Advanced Gas-cooled Reactor power plants. Carbon dioxide is cheaper than helium but is not as efficient and is corrosive. A working reactor using helium as

[5] There are two variants of LWR, the Pressurised Water Reactor (PWR) and the Boiling Water Reactor (BWR).

[6] Power plants are declared commercial when they complete an acceptance test and control of them is handed over from the vendor to the customer.

[7] Nucleonics Week (1989). Bonn rejects more funding and approves closing THTR, April 27, 1989, pp. 1, 10–11.

[8] Nucleonics Week (1989). Bonn rejects more funding and approves closing THTR, April 27, 1989, pp. 1, 10–11.

[9] Chemical Week (1975). Atomic deal cancelled, November 5, 1975, p. 24.

[10] For a review of the history of Fort St Vrain, see a website authored by past and present workers at the site 〈http://www.fsvfolks.org/FSVHistory_2.html〉.

[11] See for example 〈http://www.nextgenerationnuclearplant.com/〉.

[12] Two of these stations, both comprising four small reactors, were dual purpose plutonium and power producers, while the other nine, each comprising twin reactors, were optimised to produce power.

coolant, the Dragon HTGR research reactor, was ordered in 1957, completed in 1964, and operated until 1974. It produced 20 MW of heat but did not have an electricity generation circuit. However, since 1964, HTGRs have not been the subject of serious consideration for orders in Britain.

1.2.4. France

France's initial commercial orders were also for carbon dioxide cooled, graphite moderated reactors. Five commercial-size units were built, with the expectation that helium would replace carbon dioxide in future orders. However, in 1968 American PWR technology was chosen to replace the existing designs as a result of strong pressure from the utility, and HTGR technology has not been seriously considered as an option for commercial orders since then.

1.2.5. Japan

HTGR development of Japanese design has been underway at a slow pace since about 1990. A prototype reactor (HTTR) producing 30 MW thermal power but no electricity was completed in 1998, three years later than scheduled. There are no specific plans to build further HTGRs.

1.2.6. China

In 1989, China signed a licensing deal with HTR GmbH to develop HTGRs in China using the pebble bed design and links with South Africa have been forged (see below). While there are plans to build a demonstration plant based on the PBMR design, these have continually slipped. In 2005, it was expected that a demonstration plant would be in service by 2010[13] but by 2009, the expected completion date was 2013.[14] Breeder reactors now seem the priority for reactor design development.[15] An experimental reactor, HTR-10 (10 MW of heat), based on the HTR-Modul concept, has been in operation since 2003.

1.3. The PBMR in South Africa

Auf der Heyde and Thomas (2002) stated the main differences between the PBMR proposed by Eskom and the pressurised water reactor, PWR (the most commonly used design and the design used in South Africa's only nuclear power plant at Koeberg) were as follows:

- The unit size of a PBMR has a power output of about 110 MW, while a typical PWR produces about 900–1200 MW.
- The primary coolant is helium, rather than ordinary water.
- The coolant drives a gas turbine in the proposed South African PBMR while in a PWR, the coolant passes through a heat exchanger where steam is generated, which drives a steam turbine.
- The moderator is graphite rather than ordinary water.
- The reactor is refuelled while the plant is operating, while in a PWR, it is necessary to shut the plant down annually for refuelling.
- Uranium enriched to about 10 per cent is used compared to 3 per cent for a PWR.

The major innovation compared to earlier Pebble Bed designs was that the helium coolant would be fed directly to a gas turbine rather than passing through a steam generator powering a conventional steam turbine. This was expected to increase the efficiency with which the energy from the reactor would be utilised, reducing the capital cost per installed kW (e).[16]

The South African PBMR was designed to be modular and built in clusters of up to eight interdependent units on the same site. The ability to add units incrementally was expected to make the design more suitable for small national electricity systems and systems where demand was dispersed.

South Africa has been pursuing civil nuclear power since the 1970s. The motives then were tangled up with the South African weapons programme and the decisions are not well-documented (Fig. 2005). The results of this period were:

- Two PWRs bought from the French company, Framatome were built at the Koeberg site in the Cape region and operated by the state-owned electric utility, Eskom, and
- The state-owned South African Atomic Energy Corporation (AEC), renamed the South African Nuclear Energy Corporation (NECSA) in 1999, was set up as a broad ranging R&D, fuel cycle and waste disposal company.

Eskom and NECSA have been the main industrial forces behind the PBMR. Although the development of the PBMR in South Africa was announced in 1998, the history of the project goes back a decade earlier. PBMR Ltd., the South African company set up in 1999 to develop the technology, states the first contact with the German programme was in 1988 through the South African AEC.[17] The political changes of the time led to the abandonment of the nuclear weapons programme in 1990 and AEC was in limbo while a new role was found for it. The PBMR was taken up by Eskom in 1993. The Mandela government was ambivalent about the role it saw for nuclear power and it was not till 1998 that Eskom made public its development work on the PBMR. However, it is likely that the government as 100 per cent owner of Eskom knew of and approved the work carried out before 1998.

In June 1999, Eskom concluded an agreement with HTR GmbH for non-exclusive rights to the technology. The HTR GmbH was owned by ABB Reaktor and Siemens.[18] ABB Reaktor was taken over by the British nationally owned fuel cycle company, British Nuclear Fuels Limited (BNFL) in 1999. BNFL had also taken over the reactor design and supply division of Westinghouse in 1998. BNFL merged the ABB Reaktor and Westinghouse nuclear divisions into their Westinghouse division. This was sold to Toshiba in 2006. As discussed later, in June 2000, BNFL took a 20 per cent stake in PBMR Ltd. with an expectation that it would increase its stake to 35 per cent. BNFL/Westinghouse thus had a dual role in the project of being technology licensor and commercial partner. Siemens subsequently combined its reactor division with that of the French company, Framatome, to form the joint venture, Areva NP, in which Siemens holds 34 per cent and Areva the rest of the shares. In 2009, Siemens announced its intention to withdraw from the joint venture, although by January 2011, this had not been completed. So, despite its German origins, the intellectual property of the Pebble Bed is now held by a French company, Areva NP and a Japanese/American company, Toshiba-Westinghouse.

The South African government started funding the project directly from 2004 onwards and from 2005 onwards contributed 95 per cent of the funding for PBMR Ltd. However, in 2009, it

[13] Nucleonics Week (2005). China to complete design in 2006 for high-temperature pebble bed, June 23, 2005, p. 8.

[14] Nucleonics Week (2009). China's HTR site may also host large Westing-house-based units, May 28, 2009, p. 6.

[15] See for example: 〈http://www.chinadaily.com.cn/china/2010-07/21/content_11032957.htm〉.

[16] See for example, Modern Power Systems, Eskom takes a cool look at high temperature reactors, October 1998, p. 35.

[17] 〈http://data.energynpsconsultation.decc.gov.uk/documents/npss/EN-6.pdf〉.

[18] Nuclear News, Agreement calls for German HTR technology, June 1999.

announced that 2009/10 would be the last year it would fund the PBMR. As a result PBMR Ltd. announced the abandonment of the programme to build the demonstration plant of 400 MW (th) (165 MW (e)) that would have led to commercial sales of plants of this size.[19] PBMR Ltd. cited the inability of Eskom, its only realistic customer, to finance nuclear orders as the reason for this announcement. This financial issue had become clear in December 2008 when Eskom had had to abandon a call for tenders for about 3.5 GW of large nuclear power plants because it could not finance the orders. The fact that Eskom had begun to pursue what it called 'conventional' nuclear power plants in 2006 suggested that, at best, it was not optimistic about the timescale for deployment of the PBMR and at worst, it had lost all confidence in the design.

The new strategy (PBMR, 2009, p. 16) was to pursue the process heat market, for example, desalination and processing tar sands. The thermal output of the reactor would be halved, the helium-driven gas turbine would be replaced by a conventional steam circuit. This seemed no more than a way to use the last year's funding on the small chance that a market for such a design would emerge. As expected, the year contained many highly optimistic statements from PBMR Ltd. about the possibility of new investors (e.g. Mitsubishi), new investment from existing partners (Westinghouse), new markets and new partnerships (agreements with China and Algeria), but none of these prospects materialised. A small amount of funding, about US$10 million, was won in March 2010 under the US Next Generation Nuclear Plant programme, but far too little to sustain the company for long.[20] In May 2010, Westinghouse, one of the partners in PBMR Ltd., withdrew the PBMR from the NGNP. In February 2010, the company announced it was looking to reduce the number of employees by 75 per cent,[21] in March 2010, the Chief Executive, Jaco Kriek announced his resignation,[22] and in June 2010, the trade union, Solidarity, announced that only 25 employees of the 800 employed in February 2010 would remain, mainly to look after the intellectual property.[23] The Department of Public Enterprises announced the final closure of the programme in September 2010 (Department of Public Enterprises, 2010).

2. Assessment of the programme

When Eskom announced the programme, the PBMR was promoted primarily as an export technology. Eskom forecast that by 2004, PBMRs would be available to order commercially and that it would export more than 1000 units over the following two decades. By 2009, the first commercial orders were not expected to be possible before 2030 and no customers existed (McKune, 2010). A design for the demonstration plant had still not been submitted to the South African safety regulator to start to carry out a detailed assessment of the design despite the fact that PBMR Ltd. had been saying since 2002 that the design was only about 6 months away from being submitted.

[19] PBMR Ltd (2009). PBMR Considering Change In Product Strategy, News Release, February 5, 2009, PBMR Ltd. 〈http://www.pbmr.co.za/index.asp?Content=218&Article=105&Year=2009〉.

[20] The Times (South Africa). Nuclear firm's bailout will not stop retrenchments, March 24, 2010.

[21] PBMR Ltd (2010). Pebble Bed Modular Reactor Company is Contemplating Restructuring, News Release, February 18, 2010, PBMR Ltd. 〈http://www.pbmr.co.za/index.asp?Content=218&Article=110&Year=2010〉.

[22] PBMR Ltd (2010). PBMR's Chief Executive Resign, News Release, March 8, 2010, PBMR Ltd. 〈http://www.pbmr.co.za/index.asp?Content=218&Article=111&Year=2010〉.

[23] Business Day, Nuclear expertise lost to SA as PBMR cuts back staff, June 22, 2010.

At the time the PBMR was first announced, Thomas (1999) published a paper on the prospects for the PBMR. He posed three questions about the PBMR:

- Will it operate reliably?
- Will it be economic? and
- Will anyone buy it?

He argued that there was significant risk that the PBMR project would fail on at least one criterion and, as a result, the PBMR project had to be seen as a high-risk project. He questioned whether it was appropriate for such a risky project to be funded by public money, especially in a country like South Africa with so many demands for public money many of which were high return and low risk.

These questions – technological viability, economics and markets – remain the fundamental ones against which the project must be evaluated. In the light of the concerns about public funding, this paper also asks how much the development costs were, who paid them and whether the scrutiny of this public expenditure appears to have been inadequate.

2.1. Technological viability

Thomas suggested that the track record of HTGR development was poor. As shown above, all the major countries with nuclear power design capability had tried to develop a commercial HTGR design, but none had been successful. He identified in particular the failure of the PBMR's apparent predecessor in Germany, the THTR300 and also the risk of using a helium-driven gas turbine, a technology that was unproven, as issues of particular concern.[24]

It is difficult to know what technical issues have actually been encountered as PBMR Ltd. has released no information about the factors causing delay. One possible explanation for these delays is that PBMR Ltd. experienced significant problems in producing a design that would be economic, reliable and would satisfy the safety regulator.

The failure of the THTR300 was dismissed as irrelevant by PBMR Ltd. who claimed that its predecessor, the AVR, was the real reference design for the PBMR. The AVR, it was claimed, had been highly successful. A German nuclear scientist, Peter Pohl, told the South African Carte Blanche television programme: 'what was achieved is unique, in temperature, in burn up, in reliability – it's just fantastic.'[25] As argued later, the claim that the AVR was a success is now hard to justify.

2.1.1. The gas turbine

There was negligible experience with a helium-driven gas turbine, which in the promotional material was described as the 'standard Brayton cycle' implying a well proven technology. A contract to develop this was initially given to the French company Alstom, but in 2001 or 2002, it appears a new contract with MHI (Japan) was signed and Alstom exited the project.[26] In 2009, when PBMR Ltd. announced that they were making radical revisions to the design, the helium gas turbine was abandoned in favour of a conventional steam cycle in which the helium coolant produces steam in a heat exchanger, which then powers a normal steam turbine. The only specific evidence that developing the

[24] The programme to develop a helium-driven gas turbine, HHV, at Jülich was terminated in 1982. 〈http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/28008800.pdf〉. The test facility only ran for 325 h at 850 °C 〈http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/gtpcs.pdf〉.

[25] 〈http://www.mnet.co.za/Mnet/Shows/carteblanche/story.asp?Id=3516〉.

[26] Japanese Business Digest. Japan NFI, MHI To Participate in PBMR Project in South Africa, July 16, 2002.

gas turbine was a major problem is the replacement of Alstom and the fact that, in 2002, the critical path activity to the timetable of the day to complete the demonstration plant by 2007 was the delivery of the gas turbine. In some respects, the gas turbine was not central to the project. China is developing Pebble Bed technology using the same technology as South Africa but using a conventional steam cycle. The use of a gas turbine could therefore have been abandoned at any point or delayed with the demonstration plant being built using a steam cycle.

2.1.2. Unit size

Another potentially important design issue has been the size of the plant. When it was originally announced, the design was very closely based on the HTR-Modul-200 but had already been scaled up to 267 MW (th) producing about 110 MW (e). This has been further scaled up successively to 125 MW (e), 137 MW (e) and finally 165 MW (e) or 400 MW (th), without changing the physical dimensions of the plant (Thomas, 2005). PBMR Ltd. has never specified why these output increases were adopted. Increasing the output of the plant without increasing its physical size should have resulted in scale economies. The detailed design changes necessary to increase the output by 50 per cent have also never been identified, although they would have required changes to the control rods. By moving away from the Modul-200, which had been produced by designers with a large amount of experience of the PBMR concept, it is possible that significant new problems were created.

2.1.3. Fuel temperature

The most conspicuous potential problem was only made explicit in 2008 when a report reviewing experience with the AVR was published by the Jülich Center (Moormann, 2008). It was the Jülich AVR design, which South Africa had taken as the basis for its PBMR and the issue identified, if valid, would be generic to Pebble Bed designs.

Moormann (2008) found that the AVR's fuel had reached dangerously high temperatures during operation. Although the exact temperature reached inside the reactor is unknown, melt strips placed within dummy fuel pebbles, which are designed to withstand heat of up to 1400 °C, melted, meaning the reactor was being operated beyond the design limits for the fuel. The report disagreed with an Association of German Engineers (1990) report that stated that high temperatures within the AVR were solely the result of poor-quality fuel and that AVR experience indicated that pebble bed reactors could be operated at higher temperature than at AVR. The Jülich report concluded that factors, as yet unknown, but other than poor-quality fuel were probably involved. The result of these high temperatures was that the reactor vessel had become massively contaminated and had to be filled with concrete to immobilise the radioactive dust. AVR decommissioning was found to be extremely complicated and costly and is not expected to be completed before 2080. Significantly, the US Nuclear Regulatory Commission very quickly picked up on the high temperatures when they began to evaluate the PBMR in 2001.[27]

According to PBMR Ltd., the maximum fuel operating temperature within the reactor should not exceed 1130 °C[28] although they have always claimed the fuel would not be damaged by temperatures up to 1600 °C.[29] This assumption is not valid if the fuel damage at the AVR was not due to poor-quality fuel. The Jülich study was intended to establish whether there was a link between the high temperatures observed in the AVR and the extreme contamination of the AVR. The Jülich report found that such fuel failure would contaminate reactor components on orders of magnitude higher than similar contamination in traditional Light Water Reactors, and would thus increase decommissioning costs. The report concludes that contaminated graphite dust created by the rubbing of fuel pebbles within the AVR as they worked themselves through the reactor could become a major safety issue in the case of an accident.

The Jülich report further recommended that gas-tight containment structures be built for any commercial pebble bed plant deployed and that further research and development was necessary to evaluate the safety of the design and to understand why such high temperatures were experienced at the AVR. The need for such containments for PBMR-based plants has been the subject of disagreement for some time. PBMR Ltd. claimed the pebble bed is 'intrinsically safe' and 'melt-down proof'. It argued that no pressure containment was needed and that the emergency evacuation zone need be no larger than the plant site itself. If a containment structure was required, the additional cost would add significantly to the cost of the plant. The Jülich report is bitterly contested by PBMR advocates who dispute his interpretation of the high temperatures and the need for a gas-tight containment (Koster, 2009).

While this report only became public in 2008, the problems that it exposed had long been known about and Thomas (2008) identifies when policy-makers in South Africa should have been aware of the problems. He concluded:

> "There seems strong *a priori* evidence that those involved in the project should have been aware of the issues at least from the point when NRC began to raise serious questions in 2002, if not earlier."
>
> For example, in 2002, the Nuclear Fuel newsletter reported[30]:
>
> "NRC, in its draft research plan, said the integrity of the fuel was key because it would act as a primary fission product barrier during normal operation and under accident conditions. "These fuel temperatures are predicted by reactor system calculations using a combination of codes and models for core neutronics, decay heat power, and system thermal hydraulics," the report said. But experiments in German's AVR reactor "showed the unexpected presence of in-core hot spots," and the staff was concerned about the ability to predict maximum fuel temperatures for the PBMR and other HTGRs."

2.2. Economic issues

Eskom's publicity on the PBMR claimed: "By 1993 it had become clear that building a new traditional Pressurised Water Reactor (PWR) such as Koeberg would be prohibitively expensive."[31] The clear implication was that Eskom expected the PBMR to be significantly cheaper than existing commercial nuclear power plant designs. By 1998, when the South African PBMR programme was made public, the world nuclear industry was confidently claiming new nuclear power plants could be built for

[27] Nuclear Regulatory Commission (2005). Attachment 5-b-Staff's Comments on Fuel Performance, June 12–13 2001, Summary-Meeting PBMR. ADAMS accession number ML012040398.

[28] Matzner, D. (2005). Update: Nuclear energy: PBMR moves forward, with higher power and horizontal turbine. Modern Power Systems, February 2005, p. 11.

[29] 〈http://www.pbmr.com/contenthtml/files/File/WhynoChernobyl.pdf〉.

[30] Nuclear Fuel. Questions remain on PBMR fuel: NRC research looks at HTGRs, August 5, 2002, p. 11.

[31] 〈http://www.eskom.co.za/nuclear_energy/pebble_bed/pebble_bed.html〉.

Table 1
Funding to PBMR Ltd. (R '000,000).
Source: PBMR annual report and accounts (various).

	2005/06	2006/07	2007/08	2008/09	2009/10	To 2009/10[1]/%
South African govt.	509	1056	2195	1009	1700	7595/81
Eskom	0	0	0	0	0	817/9
IDC	193	0	0	0	0	450/5
Exelon	0	0	0	0	0	102/1
Westinghouse	146	0	0	0	0	457/5
Total	848	1056	2195	1009	1700	9422/100

Notes:

1. Contributions to 2009/10 represent the total contribution from the founding of PBMR Ltd.
2. For 2009/10 we assume the government contribution was R1.7 billion. Financial Mail 'Nuclear Power Station Funding crunch' August 28, 2009.
3. Annual contributions prior to 2005/06 are not available.

an 'overnight' cost of US$1000/kW.[32] This is a claim that has come back to haunt the nuclear industry as forecast costs continue to rise. For example, in 2010, Standard & Poors found that the average forecast cost of building new nuclear plants in the USA was US$6500.[33] While this cost includes finance, it is clear that estimated construction costs have gone up several-fold in only a decade. The US$1000/kW claim was one enthusiastically taken up by the PBMR proponents and early estimates (Nicholls, 2001) for the PBMR were even more optimistic at US$870/kW. In October 2003, a senior official with PBMR Ltd. was still claiming a construction cost of US$1000/kW. This was at a time when the Olkiluoto order for an advanced Pressurised Water Reactor was being placed at a contract price of about US$2500/kW.[34] PBMR Ltd. has not claimed the PBMR would be cheaper than conventional, larger nuclear designs in recent years, but there was an implication it would, at worst, be no more expensive.

PBMR Ltd.'s plan was to build a demonstration unit with a small associated fuel manufacturing plant, completion of which would be followed quickly by sale of commercial units. In November 1998, Nicholls, then Eskom's PBMR Project Manager and subsequently the first CEO of PBMR Ltd., forecast the demonstration plant would cost US$200 million to design and construct (then about R1.1 billion), double the price of commercial plants but this cost included the cost of the fuel fabrication plant.[35] Within a year, this timetable was a year late and since then, the timetable has slipped and the costs escalated at an alarming rate. Excluding the unknown amount of money spent by Eskom prior to the setting up of PBMR Ltd., a total of R9.2 billion was spent on the PBMR (see Table 1) long before any construction on the demonstration plant and the associated fuel plant was due to take place. Hogan's statement (Department of Public Enterprises, 2010) said the final total for investment in the PBMR was R9.214 billion and the government contribution was R7.419 billion and that a further R30 billion would be needed to bring the project to commercial status.

According to PBMR Ltd.'s 2007/08 annual report, the demonstration plant would not have been complete before 2014 and further expenditure of R22.8 billion would be required, made up of R14.5 billion for the demonstration plant, R2.3 billion for the fuel plant and R6 billion for other investments. However, in September 2009, the CEO of PBMR Ltd., Jaco Kriek, was quoted as saying the latest estimate for the demonstration plant was R31 billion and the commissioning date 2018 at the earliest.[36] Steve Lennon (Eskom) suggested in 2010 that commercial PBMR units might not be available to order before 2030.[37] PBMR Ltd. had been reluctant to publish price estimates for commercial units after the initial optimism that a price less than US$1000/kW could be achieved, but given that the cost of the demonstration plant alone appears to have increased more than 10-fold in about a decade, it is clear that the projected cost of commercial orders had also increased at a high rate. Whether this rate is higher or lower than the increase experienced by conventional nuclear designs is impossible to determine.

2.3. Markets

In November 1998, when the PBMR project was first publicised, Eskom was working on the basis of annual sales of 30 units per year, of which 20 would be exports.[38] A minimum of five units a year would be needed to maintain scale economies. However, this was derived by a crude calculation based on an estimate of the world market for power plants of all types and an assumption that the PBMR would win 2 per cent of this market. There was vague talk about markets such as Chile, Cyprus and Egypt but no specific market analysis and, beyond Eskom, no customer was identified.

This all changed with the recruitment of PECO/Exelon to PBMR Ltd. PECO had a history of development of the HTGR and was host to the Peach Bottom prototype. The CEO, Corbin McNeil, was seen as a particular enthusiast for HTGR technology. The most valuable element PECO brought to the project was a promise to pilot the design through the US safety assessment procedures. Having generic safety approval from the US authorities, the Nuclear Regulatory Commission (NRC), would not only open up the US market, it would also be an essential element to sales into other international markets. All but the most experienced nuclear buyer countries would want the re-assurance of safety approval from a high-prestige country, such as USA, Germany, France, UK or Japan, before they would buy a new design.

[32] 'Overnight' costs include the cost of the first fuel load but do not include the cost of finance. They are the standard way to compare capital costs of different nuclear technologies on a fair basis.

[33] 〈http://www.standardandpoors.com/prot/ratings/articles/en/us/?assetID=1245219894605#ID92〉.

[34] Slabber, J. (2003). ASME Workshop on PBMR Needs in RSA. Powerpoint presentation to ASME Workshop on PBMR Needs in RSA, 28 October 2003. 〈http://webcache.googleusercontent.com/search?q=cache:uAFIxbO7SgoJ:cstools.asme.org/csconnect/FileUpload.cfm%3FView%3Dyes%26ID%3D12253+ASME+Workshop+on+PBMR+Needs+in+RSA&cd=1&hl=en&ct=clnk&gl=uk&client=firefox-a〉.

[35] Nucleonics Week. Old technology may hold promise for future of nuclear power, November 19, 1998 & Nucleonics Week. Eskom hopes to have PBMR pilot ready for decision in late 2000, October 14, 1999.

[36] Nucleonics Week. South Africa's pebble-bed demo plant postponed indefinitely, official says, September 17, 2009.

[37] McKune, I. (2010). Pebble bed modular reactor demonstration plant is funded but not constructed. South African Journal of Science 106(5/6), Art. 287.

[38] Nucleonics Week. Old technology may hold promise for future of nuclear power, November 19, 1998.

The Detailed Feasibility Report (DFR) (PBMR, 2002a) published after the recruitment of Exelon and the Final Environmental Impact Report (FEIR) (PBMR, 2002b) published after Exelon's exit were based on little more analysis. The DFR (PBMR, 2002a, p. 50) assumption was that in the first decade after commercial sales started, Exelon would buy up to 40 units and Eskom, up to 10 units. Exelon had signed a letter of intent to buy at least 10 units, while Eskom only promised to buy up to 10 units if the PBMR was the cheapest option available. Letters of intent do not represent a binding commitment and when Exelon exited the project, it paid no penalties for not taking up the option. The commitment from Eskom was even more meaningless. If the PBMR was not the cheapest option, Eskom did not have to buy it and if it was the cheapest option, why would Eskom buy anything else? Overall, the DFR was seriously over-optimistic, given the absence of anything remotely close to a firm order, suggesting that: "the sale of PBMR plants and fuel is more likely to be constrained by supply capacity limitations than by demand." It backs this up saying:

> "The market analysis shows that the potential exists for the market to conservatively absorb up to 235 five-pack plants (1,175 modules) over the two decades following the start-up of the demonstration plant. This represents only 3.3 per cent of the world demand for new generation capacity. Notwithstanding this excellent potential, the base-case sales scenario adopted in the enterprise business plan forecasts the sale of only 258 modules over the evaluation period of 25 years, and is therefore conservative."

Despite the fact that Exelon had withdrawn from the project when the FEIR (PBMR, 2002b) was published, it still anticipated commercial sales beginning in 2006 with 15 units going to Exelon in the period 2006–2008 and a total of 44 units by 2017. Eskom sales were expected to be at a much slower rate, starting in 2007, completing the 10-unit order by 2012 and ordering a total of 20 units by 2017. Other customers were expected to buy 76 units by 2017. So, in the first 12 years of the commercial phase, the FEIR forecast sales of 140 units, a slightly faster rate of sales than the DFR. The DFR represented a significant downgrading of sales forecasts to about 10 units a year from earlier when Nicholls (Nicholls, 2000) forecast 30 units per year.

The lack of a substantial base for these forecasts was acknowledged by the new CEO, Jaco Kriek, of PBMR Ltd. in September 2004 when he replaced Nicholls. He said there was a need for 'a "much more detailed marketing strategy" with "a strong focus on customers" needs. He said marketing strategies would be tailored to a given country or customer, versus a more generic strategy followed in the past.'[39] Since then, as costs have escalated and time-scales slipped, there has been frequent speculation about possible markets, but it is clear these prospects were never more than vague expressions of interest.

2.4. Development costs and funding

In 1999, Eskom set up a subsidiary, PBMR Ltd., to carry out the next phase of work on the PBMR. This company would remain 100 per cent owned by Eskom, through its then legally separate company, Eskom Enterprises. PBMR Ltd. would be responsible for carrying out the 'feasibility' phase. One of PBMR Ltd.'s first priorities was to enlist new investors to the project, to bring in private finance or skills or strategic advantages. It was planned that 30 per cent of the project would be retained by Eskom with 10 per cent reserved for a Black Economic Empowerment Entity (as required under South African law) leaving 60 per cent for other new investors. When the feasibility phase was complete, investors would have the option to take a stake, proportionate to their contribution to the feasibility phase, in a new company, which would carry out the demonstration phase and sell commercial units.

In July 1999, South Africa's Industrial Development Corporation (IDC) took a 25 per cent interest in PBMR Ltd. In June 2000, BNFL took a 20 per cent stake in PBMR Ltd. with an expectation that it would increase its stake to 35 per cent.[40] At that time it was reported that negotiations were underway with PECO, a Philadelphia-based utility that merged with a Chicago based utility (Unicom) in October 2000 to become Exelon and in September 2000, PECO took a 10 per cent stake.[41] Subsequently, BNFL increased its stake to 22.5 per cent and PECO to 12.5 per cent. This arrangement appeared largely to fulfil the objective of bringing in new investors to take 60 per cent of the project. However, a Black Economic Empowerment Entity had not been found and IDC did not bring private capital, skills or strategic advantages to the project.

It has never been announced when (or if) the feasibility phase ended but contributions from the four partners largely ended in 2004 or earlier. It is clear that none of the partners brought in met the investment levels they were committed to (see Table 1). Up to 2004 Eskom made up the shortfall and from then on, the government provided almost all the funding. Exelon withdrew from the project in April 2002. BNFL effectively collapsed financially in 2002 and reduced its stake to 15 per cent, stopping contributions entirely from 2003, exception for a single payment in 2005. Westinghouse made no payments whatsoever after its sale to Toshiba in 2006. IDC, unreported at the time, reduced its stake to 13 per cent in 2002. No Economic Empowerment Entity was brought in.

The ownership of, and investment in PBMR Ltd. have been consistently misstated in the South African media. For example, in February 2010, the CEO of PBMR Ltd., Jaco Kriek, told a South African news paper that global investors had invested R2 billion in the PBMR. Table 1 shows that the total investment by sources other than South African public money (the government, Eskom and IDC) amounted to about R500 million.[42] It was frequently stated in the media that investors own stakes in PBMR Ltd. PBMR Ltd. has always been 100 per cent owned by Eskom, although the Annual Report makes it clear the governance of the company is determined by a co-operation agreement between Eskom and the other investors (PBMR, 2009, p. 72). Details of this co-operation agreement have not been made public. The 2008/09 PBMR Ltd. Annual Report (PBMR, 2009, p. 72) states:

> "Effective control is not excercised [sic] by Eskom Holdings Limited, but in terms of a co-operation agreement between Eskom Holdings Limited ("Eskom"), the Industrial Development Corporation of South Africa Limited, Westinghouse Electric Company LLC and PBMR. Eskom has the right to appoint directors to PBMR, including the Chairman of the Board, and shall appoint directors nominated by the Industrial Development Corporation of South Africa Limited and Westinghouse Electric Company LLC."

[39] Nucleonics Week. PBMR awaiting new lease on life as Cabinet decision approaches, September 2, 2004, p. 5.

[40] Nucleonics Week. BNFL signs on to Eskom's Pebble-bed Reactor project, June 15, 2000.

[41] Nucleonics Week. PECO Energy signs on to become partner in Eskom's PBMR project, September 7, 2000.

[42] Sunday Times (South Africa). More nuclear power 'a no-brainer' for future, February 14, 2010.

The original agreement foresaw that the funders would be: Eskom (40 per cent); IDC (25 per cent); BNFL (22.5 per cent); and Exelon (12.5 per cent). In September 2005, it was reported that a new shareholder agreement had been drafted in which the government would initially take a 30 per cent share, IDC share would take 14 per cent, BNFL 15 per cent with Eskom initially taking the remaining 41 per cent but with an expectation that this share would dilute to 5 per cent, implicitly because it stopped contributing.[43] It was implied that BNFL and IDC would continue to invest. However, despite statements in subsequent annual reports suggesting the signing of a new shareholder agreement was imminent this was never signed.

By 2009, of the 14 Board members, three were from IDC, two from Westinghouse, and one from Eskom. There were three independent directors and the other members of the Board were employees of PBMR Ltd. For 2009/10 it was reported that government had allocated a further R1.7 billion.[44]

Exelon stopped contributing in 2002 and BNFL stopped contributing in 2003, except for a small contribution in 2005/06. IDC made no contributions after 2005/06 and Eskom stopped contributing after 2004. PBMR Ltd. was funded entirely by the South African government from 2006 onwards. This means that South African public money (government, Eskom and IDC) accounted for 95 per cent of the income of PBMR Ltd. from its incorporation. The South African government contributed over 80 per cent of its income even though it was not represented on the Board.

Eskom was widely seen by the South African public as being the driving force behind the programme. However, the ending of its funding in 2004 and evidence from 2002 of the Board's strong reservations about the technology[45] suggest that this was far from the case. From at least 2004 onwards, the impetus was solely from within government itself. The stated reasons for Eskom stopping its contributions were that 'the government is "not eager for Eskom to continue as an investor and a potential customer".'[46] This is very similar to Exelon's stated reasons for leaving the project: 'it had re-evaluated its role as a "reactor supplier" and concluded that was inconsistent with the company's business strategy.'[47] Neither explanation seems convincing. Both Eskom and Exelon willingly entered the project as utilities so the apparent contradiction was always apparent. It is impossible to determine from the outside what the real factors were. How far were these decisions influenced by cost escalation? The CEO of Exelon stated: 'the project was three years behind schedule and was "too speculative."'[48] Subsequently, the Chief Executive Officer of Exelon suggested that part of the reason for their exit from the project was the absence of a containment.[49] Eskom's concerns had led it appoint PriceWaterhouseCoopers in 2002 to carry out an economic assessment, an assessment that concluded the reactor was 'not competitive in South Africa'.[50] Westinghouse has contributed minimally since 2003 so it seems clear that the impetus for the project has come solely from the South African government since 2004 or perhaps earlier.

[43] Nucleonics Week. PBMR shareholders' accord sees state taking 30% direct stake, September 1, 2005, p. 1.

[44] Financial Mail. Nuclear Power Station Funding crunch, August 28, 2009.

[45] Nucleonics Week. Eskom tries to protect documents showing misgivings about PBMR, October 6, 2005, p. 1.

[46] Nucleonics Week. PBMR awaiting new lease on life as Cabinet decision approaches, September 2, 2004, p. 5.

[47] Nucleonics Week. Exelon abandons PBMR project, rejects role as rector vendor, April 18, 2002, p. 1.

[48] Energy daily. Pebble Bed Reactor "Too Speculative"–Exelon CEO, April 24, 2002.

[49] 〈http://cenvironment.blogspot.com/2010/05/norris-mcdonald-meets-john-rowe-ceo-of.html〉.

[50] Nucleonics Week. Eskom tries to protect documents showing misgivings about PBMR, October 6, 2005, p. 1.

2.5. Checks and balances

What remains unexplained is why the South African government should have had such total faith in a project that even before its contributions started was, so blatantly, going badly wrong. Equally important, why were there no 'checks and balances' to question why such large sums of public money were being spent to so little effect. PBMR Ltd. was allowed to continue to sign contracts with suppliers up to 2008 despite the constant slippages in the schedule.

The South African media, with a few honourable exceptions,[51] has been happy to print, uncritically, material provided by the PBMR's proponents. Cost escalations have passed with little critical reporting, promises by PBMR Ltd. that new investors and new customers would soon be signed up and that the design was nearly complete were also repeated continually. A high proportion of the important material for evaluation of the programme was released by PBMR Ltd. to the international trade press, such as Nucleonics Week, a source that is essentially unavailable to the South African public.

Amongst the NGOs and other civil society organisations, the record is better. An environmental group, Earthlife Africa and a public interest law firm, the Legal Resources Centre have consistently and resolutely argued against the PBMR, although PBMR Ltd. and the government have consistently tried to marginalise them, never addressing the real issues they raised.

The Parliamentary committees that monitor the Departments of Minerals & Energy, Public Enterprises and Finance have exercised little scrutiny over the project. The Parliamentary Portfolio Committee for Environmental Affairs did schedule a major 'Summit' to examine the Pebble Bed, but this was cancelled by the government only a day before it was due to take place on dubious grounds when several foreign speakers had already been flown in.[52]

Fig (2010) is highly critical of the Parliamentary mechanisms for accountability for public expenditure on projects of the scale of the PBMR. He makes a number of wide-ranging recommendations, including:

- Since 2009 there has been a presidentially-appointed inter-ministerial committee on energy chaired by the public enterprises minister. This committee needs to have a website for listing its participants and publicising its discussions. The committee should also lay out a clear division of its own and departmental mandates. Scrutiny over the work of the inter-ministerial committee should be undertaken by the appropriate parliamentary portfolio committee.
- All past, current and future grants, loans and investments to the PBMR company should be publicised.
- The Department of Energy should release into the public domain past feasibility reports on the PBMR, including those issued by (i) the International Review Panel and (ii) PriceWaterhouse Cooper.
- Minutes of Eskom board meetings reflecting the debates on the viability of the PBMR should be released into the public domain.

Other organisations that should have had the courage to ask hard questions include: the South African Auditor General whose job it is to enable 'oversight, accountability and governance in the

[51] Melanie Gosling of the Cape Times has consistently asked pertinent questions, while the South African satirical magazine, Noseweek, has published in-depth analyses of the failings of the programme.

[52] Nucleonics Week. Environmentalists, union leaders fume over South African 'summit', February 26, 2004, p. 9.

public sector', and the National Energy Regulator of South Africa, which asked no questions about Eskom's expenditure on the PBMR.

The National Nuclear Regulator has said little about the status of its work on the PBMR and has never mentioned the issue of pebbles overheating. This was a problem very quickly picked up in 2001 by the US NRC when it began its review of the PBMR design and aired in public hearings. It has also been equivocal about issues such as the need for a containment.

3. Lessons

The lessons from this experience can be divided into three areas: development of HTGR technology, accountability for public money, and the opportunity cost of pursuing nuclear power.

However, prior to discussing this, it is worth dismissing two 'myths' that have acquired currency since the abandonment of the project. There have been attempts to present the abandonment of the Pebble Bed project partly as the consequence of the 'credit crunch' and partly as the result of naive management by the Directors of PBMR Ltd. However, at most, it seems likely the credit crunch did no more than hasten the end of the project and poor management allowed the project to continue long after it should have been abandoned. Well before 2008, costs and time-scales were escalating at an alarming rate, there was no interest from any customers and international investors showed no interest in providing new funds. There was also the unexplained failure to complete a design for the demonstration plant sufficiently for the safety regulator to review it.

3.1. *HTGR technology*

HTGR technology clearly has a powerful attraction to nuclear scientists and engineers because of its intrinsic properties. Any criticism of the technology is met with vitriolic criticism by its proponents.[53] However, the failure of yet another attempt to produce a commercially viable design suggests any further attempts to commercialise HTGRs must be based on a clear understanding of why earlier attempts have failed and with a high level of confidence that the earlier problems have been fully overcome. South Africa was all to credulous to the belief that it had uncovered an 'uncut diamond' that just needed polishing and a large world market open up to it. The new democratic South African government was keen to have an opportunity to show how strong South Africa's technological capability was.

Problems with German prototypes and demonstration plants were ignored and the abandonment of the German programme written off as a hysterical reaction to the Chernobyl disaster. Real technical issues, for example, the problem of high temperatures in the fuel, which the US Nuclear Regulatory Commission uncovered very quickly when it began to review the design, were swept under the carpet. Indeed, the South African nuclear safety regulator, the National Nuclear Regulator (NNR) gave approval in 2003 for the design in principle with no mention whatsoever of the fuel temperature problems. A senior official at the NNR merely stated: "we see no reason why the reactor would not meet our requirements."[54]

The VHTR was portrayed as the most credible and closest to commercial deployment of the Generation IV designs. The failure of the PBMR project and its withdrawal from the US NGNP programme damages the reputation of the VHTR and the time when Generation IV designs can be deployed is likely to have been pushed back significantly.

3.2. *Accountability for public money*

From the start, this was clearly a high-risk project and it is questionable whether public money, especially in a country like South Africa with such a high demand for capital for high-return, low-risk investment, for example, in health and education should have been risked on such a project. Eskom, the instigator of the project, clearly began to show concern by 2002, four years into the project, but felt unable to confront the government with these concerns. Had Eskom been able to get the project abandoned then 90 per cent of the total funds spent on the project would have been saved. Eskom should not escape from blame. They switched their support for nuclear reactors from the PBMR to 'conventional' nuclear power plants such as the Areva EPR or the Westinghouse AP1000, but the assumptions behind this switch on cost and time-scales were little more realistic than those they made for the PBMR originally. As a result, an expensive and time-consuming call for tenders was carried in 2008 for plants it had no hope of being able to afford. Eskom seems not to have learnt that it must subject the claims of the nuclear industry to much greater critical scrutiny before adopting them.

It is unclear why the government had such unshakeable faith in the project pouring large amounts of taxpayers' money into the project long after it was clear it was going badly wrong. How far this was down to the 'Concorde Syndrome' under which it becomes politically harder to abandon high-prestige public projects the longer they go on because of the political embarrassment of having to admit public money had been wasted is hard to tell. A more robust system of scrutiny of public expenditure, through Parliamentary Committees and national public expenditure audit bodies should have been able to expose the problems of the project much sooner. Organisations such as the NNR and the economic regulator for the energy sector, the National Energy Regulator for South Africa are culpable for their silence.

3.3. *The opportunity cost of pursuing nuclear power*

South Africa spent 12 years pursuing the PBMR during which time R&D on the PBMR has dominated budgets. As a result of the neglect of other options, the electricity supply system, previously very reliable and cheap, has become expensive and unreliable with frequent power cuts and shortages. Had the resources poured into the PBMR gone into lower risk, more prosaic options such as energy efficiency, renewable and gas-fired generation, it is hard to imagine supplies would not have been cheaper, more reliable and 'greener'.

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[53] For example, the US Larouche Foundation has published vitriolic (and inaccurate) criticism of the author for asking questions about the technology. See for example, G. Murphy (2008). Who's Trying to Strangle the PBMR?. 21st Century Science & Technology, Fall/Winter 2008, pp. 62–67. One of the pioneers of the pebble bed technology wrote to the author: 'Clear, the enemies of the pebble bed reactor will jump on this 'report from a British Professor' with greatest pleasure. And these enemies are everywhere'.

[54] Inside NRC. South African regulator treading cautiously on PBMR licensing, September 22, 2003, p. 8.

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