Pebble bed reactor – safety in perspective

Dr Albert Koster, PBMR (Pty) senior consultant, nuclear safety, replies directly to criticisms of the PBMR reactor in NEI's March 2009 issue.

POWER PLANT DESIGN

PBR safety revisited

The safety behaviour of pebble bed reactors (PBRs) may be less benign than earlier assumed. A new study from Forschungszentrum Jülich analysing experience with the AVR reactor suggests that future PBRs require additional safety measures, and that major R&D effort is still necessary. By Rainer Moormann

On 5 February 2009 PBMR issued a news bulletin stating that the company will be focusing on the design of a plant to service both the electricity and process heat markets. In the March issue of this magazine [pp22-3] Prof. Stephen Thomas insinuates that the change was motivated not by commercial considerations but because PBMR was aware of problems with pebble bed performance at high temperatures, as alleged by Dr. Rainer Moormann in a second article [pp16-20]. In order to set the record straight it is necessary to chart a short history of the development of HTRs and PBMR in particular.

The backbone of the High Temperature Reactor (HTR) is the coated particle fuel that was initially developed in the 1950s for the DRAGON reactor in the UK as part of a European/USA project. The original particle had a high-density pyrolytic carbon layer and a porous buffer layer and was called the BISO particle. This was used in the early HTRs in either pebbles or prismatic graphite blocks (AVR, THTR, Peach Bottom). Later fuel development included an interlayer of SiC within the high-density pyrocarbon layer. All these layers effectively block gaseous fission products and most, but not all, metallic fission products. This fuel, which was developed mainly in the USA and Germany, was exhaustively tested in both material test reactors and in the latter half of the AVR operation. This fuel was also used for the fissile particles in the Fort St Vrain plant in the USA and forms the basis for all new HTR projects since then.

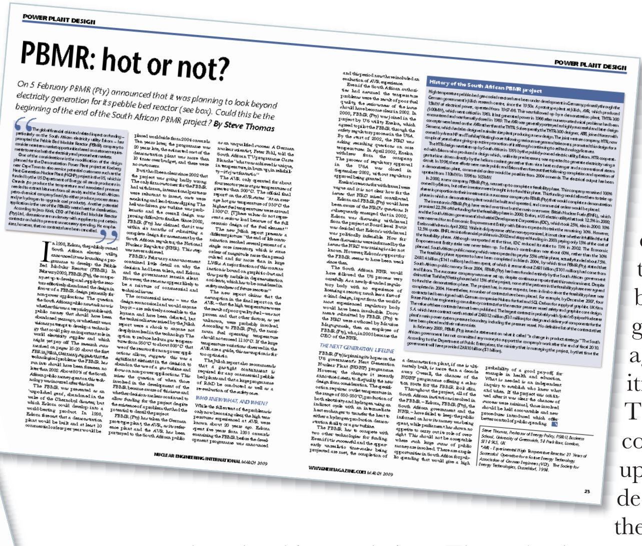
Initially, the HTR was conceived for electricity production, as were all other reactors. However, the first oil shock of 1973 which *inter alia* gave a temporary boost to the development of synfuels from coal, also stimulated designers to look at HTRs for the production of process heat for a variety of uses. But politics (reunification of Germany in 1989 scuppered a project to replace coal in East Germany) and the collapse of the oil price kept such plans on the drawing board.

In 1988, Eskom was considering future expansion of the nuclear option and together with the South African Atomic Energy Corporation looked at various options, one of which was an HTR for which the AEC took the lead. When some money was made available from a different source in 1989, a new study led to the selection of a direct cycle HTR electricity plant as a possible alternative or supplement to future LWRs for the Eskom grid. The selection was made for the HTR, which is designed to eliminate or withstand catastrophic nuclear accidents like a core melt accident. The direct cycle promised higher efficiencies, but requires high temperatures. Again, this project only had electricity production in mind. In 1999, when PBMR (Pty) Ltd. was finally established with a staff of around 30 people, the oil price was still close to the lowest level since WWII and, hence, process heat applications were still in the future. But times have changed drastically since then. The sharp rise in oil price (which peaked at almost $150 a barrel in July 2008) made such ventures as the Canadian oil sands viable. The global warming issue, barely visible in 1998, has become a major concern.

Whereas the business case for PBMR (Pty) Ltd. in 2002 was still firmly focused on electricity, changes in global energy supply security, cost and environmental impacts have made the process heat market very promising once again. At the same time, the global energy community was exploring other uses of nuclear energy under the umbrella of the Generation IV International Forum. The US Department of Energy identified the VHTR, a version of a high temperature gas reactor as their primary selection for the USA NGNP programme that is based on process heat applications with the ultimate goal of hydrogen production. PBMR (Pty) Ltd. has been actively involved in this programme since 2002.

This brings us to the allegations of hiding facts and supposed safety problems in pebble bed reactors as so stridently described in the March issue of *NEI*. To this end, only the safety concerns raised by Moormann need to be addressed as Thomas based his argument on the premise that Moormann is correct: that PBMR knew about safety problems all the time and opted to keep quiet about it.

In his articles, Moormann presents a number of different arguments but by some analysis, these can be boiled down to two major issues. The first is that both the AVR and THTR were shut down because of safety concerns. The second is that the AVR was highly contaminated and this was due to high fuel temperatures that caused excessive release of caesium and strontium from the fuel. He then advances reasons why the fuel temperatures might have been high and draws conclusions about the safety of future pebble bed


POWER PLANT DESIGN

PBMR: hot or not?

On 5 February PBMR (Pty) announced that it was planning to look beyond electricity generation for its pebble bed reactor (see box). Could this be the beginning of the end of the South African PBMR project? By Steve Thomas

reactors based on his speculations. The major contentions are addressed below; others have been covered at the *HTR 2008* conference or in prior published articles.

WHY THE AVR WAS SHUT DOWN

Moormann makes a few statements on the closure of both the AVR and THTR that are not supported by the literature and personal recollections of the people involved. In effect, the AVR had come to a natural end of life for a research reactor. Further research required a new project called the AVR II, which was not approved by the German government. As a result, in 1985 the AVR researchers defined 21 final experiments that they still considered worthwhile [1]. Of these, all were performed but one. A blowdown experiment to investigate the mobility of the dust in the primary circuit was not done, even though it was approved by the regulator. If safety problems existed at the AVR, continued operation would not have been allowed, nor would significant experiments be approved by a regulator. There is no known document that cites safety reasons for the shutdown, but there are statements on the AVR closure of which we quote, the first by Prof. Theenhaus, a member of the FZJ board and published in [2]. The translated quotation reads:

> *"In more than 20 years of operation the advantages and positive characteristics of this type of reactor have convincingly been demonstrated. Many experiments have been performed, with particular emphasis on safety research…This demonstration reactor and in a certain sense research reactor completely fulfilled its mission."*

Dr. Marnett, technical director of the AVR GmbH, stated: "The AVR-Experimental Power Station has operated for 21 years...and was taken out of operation in 1988 for reasons unrelated to the plant itself."[3]

Moormann also claims that the THTR was shut down because of technical problems, but the technical problems experienced by the THTR were teething troubles that had been anticipated and budgeted for in the risk-sharing agreement between the utilities and the government. The unplanned increased cost in 1989 was due to the updated estimates of the decommissioning costs and the potential delays caused by having to re-license the fuel plant or have no fuel for more than two years. Although the government agreed to the increased share in the risk, the state of Nord-Rhein Westphalen did not. The utility threatened to stop operations and in the dispute that followed the decision was taken that enough had been learned and the State did not want any further expenditure. This is substantiated by a citation (translated) from a paper by Prof. Knizia, the then chairman of the board of VEW (whose subsidiary HKG operated the THTR) and Dr. Baumer, who at the time was station manager for the THTR:

> *"…It was not technical and especially not safety related technical problems in the plant, but external economical factors that caused risks that were outside the influence of the operator, together with a lack of commitment from the political sides to further support the project that caused the eventual early closure of the project THTR..."[4]*

Moormann also states "a study on the operational safety of the PBR prototype, the AVR reactor, was performed at FZJ and published in June 2008." The author therewith implies that this was a study initiated by the research centre. However it is entirely his own initiative and the references are to his own report and not independent corroboration of his opinions.

He also states "the same fuel type that in the AVR (BISO coating, UC_2-kernel) has released a major fraction of Sr-90 was also used in core 2 of the US Peach Bottom block-type HTR without any significant Sr-90 release"…. "there was almost no correlation between the release of metallic fission products and noble gas release that indicates inadequate fuel quality."

The fuel that failed in the AVR and led to caesium releases had a much higher fuel density than the other fuel pebbles. The buffer layer that is porous to absorb gaseous fission products, was much denser than prescribed. This fuel batch is generally accepted to have caused excess failed particles with resultant release of metallic fission products [6]. The release of strontium followed the introduction of a specific UC fuel in 1974. It is thus stretching the argument to compare this to fuel used in Peach Bottom. The detection of caesium and strontium in the gas stream was preceded by the detection of noble gases, which was the main reason the particular fuel was identified as being the culprit.

It is unfortunate that Moormann has chosen to include so many unsubstantiated (by references) statements such as "however, in THTR300, pebble flow was virtually restricted to the core axis, and hardly occurred at all in the outer core zones." PBMR staff consulted extensively with engineers and scientists involved in the design and operation of the THTR. PBMR also has access to all design and test documents from the THTR and no reference to non-existent pebble flow can be traced. However, based on the removal rate of spheres broken in the initial testing of the in-core control rods, it was deduced that the flow velocity of pebbles against the side reflector was about a factor of six lower than those in the middle. This was partly due to the large core diameter (5.6m) but also due a to high temperature difference between the side and the centre of the core, which was later adjusted. For modular pebble bed reactors like PBMR the long and narrow core causes less of a radial gas temperature difference and also, due to the geometry, less variation in pebble flow. In any case, the pebble flow at most causes a shift in power density, but has no effect on fission product release and only a second-order effect on the maximum expected accumulated burn up. Note that cycling the fuel is a means to reduce the maximum to average flux distribution, but whether a pebble is cycled 3 times or 10 times makes no difference to the integrity of the fuel.

Moormann states correctly that at the end of life of the AVR, it was found that the gas temperatures in the core were much higher than anticipated or derived. He advances many reasons why this could be the case. He states *inter alia*: "If external flows reduce the core cooling, it is reasonable to expect a homogeneous core temperature increase. This was not found, so external bypass flows cannot explain the high AVR temperatures."

At the *HTR-2008* conference, there was a contribution by PBMR (Pty) Ltd. analysts who did a complete review of the AVR design and operation [5] using modern analytical tools. One of the challenges are that there were no fixed in-core and only limited ex-core (above the core top ceiling structure) gas temperature measurements, thus the statement by Moormann based only on these measurements quite far from the top of the pebble bed is puzzling. The analysis shows clearly that the main contributor to the increased average temperature was the neglect of core bypass flows. Final 3D analysis now being processed that uses the actual fuel load history and therefore the correct spatial power profile shows very good agreement with the AVR measured data and the resultant high gas temperatures. The so-called 'unpredictable hot gas currents' can be explained by detailed analysis taking the specific design features of the AVR (upward gas flow, fuel load and pebble flow, noses protruding the core, bypass streams in the control borings, *etc*) into account, and these are not relevant for other pebble bed designs. It therefore shows that the other reasons advanced by Moormann are at the most secondary, or do not fit at all. He then uses these high gas temperatures to postulate that this gave rise to unacceptably high caesium and strontium release from modern fuel and he rejects the accepted explanation given in [6]. From this again, he calculates that a potential existed for high doses if all the contaminated dust were released to the environment and that the same will occur in newer pebble bed reactors. Using the German dose criteria on advanced PBMRs leads him to the conclusion that PBMRs need a gastight containment.

Moormann apparently assumes a complete lack of mitigating defence-in-depth design solutions. Design solutions are tailored to cover all possible accident progression scenarios. The initial release of fission products for HTRs is small, despite what he maintains, but delayed releases may occur if active cooling in depressurized conditions fails. If the reactor were in a containment, this would lead to an increase in containment activity that cannot be filtered due to excessively high temperatures and pressures. By first relieving the initial pressure burst and then closing the containment, this problem is solved. This solution can variously be called a confinement or a low-pressure containment and has been the preferred solution for all modular HTRs and is also as such described in an IAEA report [7]. The initial release can, as is foreseen for the PBMR, be filtered to remove the dust.

Moormann proposes areas where he feels more research is needed, some of which are addressed below.

Full evaluation of the operational experience and problems of AVR and THTR300.

PBMR (Pty) Ltd. has been in the process of evaluating the AVR for the last two years. The starting point was to collect all the design drawings and descriptions to (for the first time) enable the AVR to be modelled in detail. The latest results were presented at *HTR-2008* [5]. Additional results explaining the fuel temperatures will appear soon in print.

Components from the AVR continue to be examined, at the request of PBMR (Pty) Ltd., for dust characterization, concentration and dust adherence to better understand the mobility of agglomerated dust, or the lack of it.

Experiments on iodine release from fuel elements in core heat-up accidents.

This is part of the planned PBMR fuel qualification tests where fuel will be placed in test reactors and subjected to expected operating temperature conditions. Afterwards the irradiated fuel will be subjected to post-irradiation heat-up testing to simulate design-based accident events where measurements of all significant nuclides will be made.

Full understanding and reliable modelling of core temperature behaviour, and of pebble bed mechanics, including pebble rupture.

The publications presented at *HTR-2008* and the final model results show that this is already achieved. The terminology 'pebble rupture' is misleading; pebbles do not rupture. A very small percentage may fail due to mechanical handling and movement and the faulty pebbles are automatically removed from the core when they exit at the bottom of the core.

CONCLUSION

Re-interpreting old data always presents a problem, as it is impossible to go back and perform more experiments. It thus requires a concerted analytical effort that PBMR has undertaken with promising results. Moormann, without the benefit of such analysis, has very recently decided that the previous interpretation of the reason for spikes in fission product release in the AVR is wrong and advanced his own view. This view is not shared by anyone else directly involved with the operation of the AVR and the analysis provided in [6] is considered a valid interpretation of the data, especially when combined with the many irradiation experiments performed over the years. It is faulty reasoning to conclude that pebble bed reactors are unsafe, based on this one-sided conclusion and a flawed understanding of what mitigating design solutions have been included in the PBMR design for a considerable number of years.

PBMR is not about to ignore any valid safety concern or new opinions about earlier experiments. But Moormann's views are old news and not supported by new, advanced work or the preponderance of contemporary evidence, analysis and expert opinion established during the AVR and THTR operating periods and more recently. Further, modern tools and techniques are highly reliable tools only conceived of just a short time ago that make the ability to accurately predict system and component performance in ways unimagined when earlier designs were developed.

References

[1] KIRCH-IVENS-1990, in AVR-High-Temperature Experimental Reactor, 21 Years of Successful Operation, VDI-1990*; page 95.*

[2] R Theenhaus, Final Report on AVR Operation, 1997, Introduction, page 4.

[3] Marnet, Chrysanth; Wimmers, Manfred; Ziermann, Egon: Das Versuchskernkraftwerk der AVR – wichtige Ergebnisse eines anderen Reaktorkonzepts, (The Experimental Nuclear Power Station of the AVR GmbH - Important Results of a Different Reactor Concept), Schulten-70-1993*, pages 275-284.*

[4] Klaus Knizia, Ruediger Baeumer: Bau, Betrieb und Stillegung des THTR 300, Erfahrungen und ihre Bedeutung für die weitere kerntechnische Entwicklung; Schulten-70-1993*, pages 285-292.*

[5] Viljoen C, Sen S, Ubbink O , Reitsma F, Pohl P, Barnert H; The re-evaluation of the AVR Melt-wire Experiments using Modern Methods with Specific Focus on Bounding the Bypass Flow Effects. HTR-2008-58115.

[6] Nabielek H, Verfondern K, Kania; Fuel and Fission Products in the Julich AVR Pebble Bed Reactor, paper HTR-2008-58337.

[7] Considerations in the development of safety requirements for innovative reactors: Application to modular high temperature gas cooled reactors. IAEA TecDoc *1366, August 2003.*