PEBBLE FUEL ADVANTAGES

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ABSTRACT: An overview is presented of all the important issues that influenced the choice of pebble fuel for the high-temperature gas-cooled reactor (HTGR) concept developed by South Africa. Each of these issues is then discussed in detail and compared with other fuel configurations proposed for direct cycle high-temperature reactor (HTR) applications. The comparisons will be provided using objective data generated by analyses done for the design of the Pebble Bed Modular Reactor (PBMR) and data that is available in open literature for the other fuel configuration.

KEYWORDS: HTGR; HTR; Pebble Bed Modular Reactor

0. INTRODUCTION

The high-level requirements [1] for Generation IV reactors are specified in [1], which states that the reactors shall:

- Be very economical
- Have enhanced safety
- Produce minimal waste
- Be proliferation resistant

The HTGR was identified as one of the possible candidates that could fulfill these requirements.

Normally the choice of reactor defines the high-level requirements of the fuel. Gas-cooled reactors have been used practically since the inception of nuclear power, but it is the helium-cooled HTR that emerged as the dominant design focus with two fuel assembly concepts, namely:

- Fixed fuel in the form of hexagonal prismatic blocks; and
- Fuel in the form of spheres with a diameter of 60 mm.

Both concepts use the TRISO coated particle as the fundamental fuel containing component, but this is also where the similarity ends.

The Pebble Bed Modular Reactor (PBMR) chose the spherical fuel element as its fuel configuration. The PBMR design is an adaptation of pebble bed reactor technology developed in Germany in the mid-1960s and tested in AVR and later used in THTR. Instead of an indirect cycle steam plant for electricity generation, the reactor is directly coupled to a power conversion unit utilizing the Brayton thermodynamic cycle. The nominal design power is 400 MWt and 165 MWe. The design effort is focused on the early deployment of a demonstration plant that will confirm the safety, operations, construction schedule and economics suitable for global commercial deployment in the next decade.

In the following sections, an objective reasoning is presented of why the pebble fuel was chosen for the PBMR instead of block fuel. The focus of the comparison will be on design, source term, economics and nuclear material safeguards issues associated with each of the two concepts.

1. DESIGN

1.1. Core Design Flexibility

Continuous fuelling provides for flexibility to introduce fuel for a different fuel cycle on-line. Also, since each fuel element on discharge from the core is assayed for burn-up, the contents history of each fuel sphere is known. This maximizes core design flexibility and minimizes core design uncertainty.

PBMR has performed as part of the design process evaluations of various fuel cycles, and it was confirmed that the core can be used for U-Th, Pu disposition and MOX. This confirms the use of various fuel types and enrichments as demonstrated in the AVR [2]. At any specific time during the AVR operation, more than four different fuel elements with a maximum of 14 were present in the core. The fuel designs tested also contained heavy metal loadings ranging from 5 g to 20 g, and enrichments ranging from 5% to 93% U-235. All these operations were possible without any interruption to the operation of the facility. In addition, the rate of fuel cycling through the PBMR core has been analysed. The rate varies from once to 10 times through the core. No long reactor shutdowns will be required to change from one cycle to another, since the introduction of different fuel is carried out on line, and the reactivity effect monitored continuously during any such transitional period. On the question of Pu disposition, a paper was presented at the PHYSOR 2004 Conference [3]. In this paper, the standard PBMR-400 commercial reactor design was chosen. The fuel cycle variations were selected to achieve the inherently safe characteristics that are accepted as standard practice in the PBMR design philosophy.

1.2. Flux and Temperature Shaping

No flux shaping is done in PBMR. In the AVR and THTR, flux shaping was done mainly because of the relatively large core diameter.

In block fuel reactors, the so-called ‘flattening of the power map’ implies a radial and axial enrichment zoning achieved by mixing 19.9% enriched coated fuel particles with coated particles of natural uranium. In this way it is foreseen to achieve effective enrichment levels specific to fuel blocks at the top, centre, and bottom, and with varying enrichments in the radial direction as well. In certain fuel blocks, there are also control rods, and in some control blocks there is burnable poison, to suppress initial reactivity. These blocks will be shuffled during a core reload in the axial and radial directions, depending on a choice of fuel block burn-up.

A typical block fuel core could contain in the order of 1 000 fuel blocks with burnable poisons and different enrichments. Noting that the reactor physics treatment of the burn-up of strong neutron absorbers as well as control element worths is not well developed, the overall reactor physics analysis of the block fuel core could be difficult to validate.

In block fuel reactor publications, the term ‘flattening of the temperature map’ probably refers to the experience at Fort St Vrain, where the flow through blocks was throttled. The various burn-up levels of fuel blocks will each have a unique temperature effect on the coolant, and thus have to be throttled. This will add to the pressure drop over the core, and will impact on the economics of the plant. Cross-flows have caused block movement in Fort St Vrain, giving rise to outlet temperature variations with a frequency between 5 and 20 minutes [4], while indications in the HTTR in Japan, supported by experiment, are that unforeseen bypass flows have been encountered due to block movement. These occurrences cause undesirable reactivity or neutron flux noise.

For a pebble fuel core, excess reactivity can be chosen, depending on operational requirements, without shutting the reactor down. Presently, the excess reactivity in the PBMR-400 core is 1.3%Δk, which relates to a 100% to 40% power reduction Xenon override capability. In comparison, the excess reactivity required by a block fuel reactor is typically in the order of 4.5%Δk.

Since the fuelling is done on-line for a pebble-fuelled reactor, no reload analyses are required, and an approach to criticality is only required on initial core loading, or when the core is reloaded from the used fuel tank.

On the other hand, for a block fuel reactor, every reload requires complete reload analysis, and an approach to criticality loading. The fissile content of each fuel element can only be as accurate as the analysis that has been done.

1.3. Fuel Element Structural Integrity

Comprehensive stress analyses of a pebble fuel element have shown that a maximum power of 6.5 kW can be produced without exceeding the safe stress limit to which the graphite matrix material could be exposed. The stresses in a block fuel element are dependent on the specific design, and no further comment regarding its performance can be made at this stage.

1.4. Fuel Handling System Design

The fuel handling system for a block fuel reactor must be able to shuffle fuel axially and radially, and all the fuel unloading and loading operations must be carried out under shielded conditions, using remote handling equipment. The balance of the shuffling operations will require a shielded facility where access to any particular block is possible. Needless to say, these operations are all carried out with the reactor shut down. This downtime for a core change most probably will impact negatively on plant availability. Prismatic fuel blocks are exposed to different neutron fluences and temperatures that will result in distortions in different blocks of varying degrees. Remote removal and re-insertion of these blocks will undoubtedly give rise to handling problems.

The fuel handling system for pebble fuel is based on proven German design. It is designed to unload and load fuel during reactor operation. Fuel moves out of the active neutronic core region of the core in three de-fuelling chutes, and the rate at which the fuel moves provide sufficient time for the short-lived fission product activity to decay sufficiently for the burn-up measurement system to 'see' the relevant power integrating gamma spectrum peaks clearly. Each fuel sphere is assayed and routed to its destination, spent fuel tanks or core, by means of a valve system. The fuel handling system is also designed to provide for annealing of the silicon carbide coating. After annealing of a PBMR fuel sphere for 20 minutes at 650 ºC, more than 90% of the resulting radiation damage received during one core pass is recovered. The SiC properties will become practically the same as those of fresh fuel.

The pebble fuel handling system can be out of service for 20 days without affecting the reactor availability. During this period, only the load following capability is affected.

2. SOURCE TERM

2.1. Temperature Driven Release of Fission Products

Diffusion is the dominant fission product release process. Diffusion is mainly temperature driven, and for direct cycle or process heat applications, the drive is not only towards higher reactor outlet temperatures, but also towards minimizing radioactive contamination of the primary circuit to facilitate inspection and maintenance of primary circuit components. The reactor outlet temperature is one factor that determines the maximum fuel surface temperature. The fuel again determines the peak fuel temperature element power production, and the heat transfer path and properties of the element.

A factor influencing the peak fuel temperature in a block assembly is the quality of contact between the fuel compact and the graphite block. In the ideal case, the fuel compact is situated snugly in the fuel holes of the graphite block. This is not the case, since a fuel compact has typically an outer diameter of 12.5 mm, while the fuel holes in the graphite block have an internal diameter of 12.7 mm.

The most conservative case would be to assume that the compact does not touch the graphite block anywhere. This is of course physically impossible, but gives a good indication of the upper limit to the peak fuel temperature.

A CFD model was set up to aid in this calculation. A normal block fuel was set up with a power density of 6.55 MW/m^3. From the CFD analysis, the temperature on the surface of the graphite in the fuel compact holes was obtained. These results were used in an analytical analysis to calculate the peak fuel temperature.

In the first analysis, the surface temperature of the fuel compact was assumed to be equal to the graphite surface temperature. This means that perfect heat transfer takes place between the graphite and the fuel compact. The peak fuel temperature is higher than the surface as a result of the internal heat generation in the fuel compact.

For the second analysis, it was assumed that radiation and thermal conduction across the 0.1 mm gap were the only means of heat transfer between the graphite surface and the fuel compact surface. This implies that the peak fuel temperature in this case will be higher than in the previous case.

The results of the two analyses are shown in *FIGURE 1*, in which it is also indicated that the gap between the graphite and the compact does not have a large effect on the peak fuel temperatures. This accounts for an additional 20 ºC rise in the peak fuel temperature when compared to the case with perfect contact. The reason for this is because the gap between the fuel compact and the graphite block is very small (0.1 mm). This has the effect that the resistance to heat transfer from the gaseous conduction is quite low compared to the radiation resistance. The amount of heat transferred through conduction is more than 88% throughout the axial length. It will also be noted that the difference between the analysis with the gap and the analysis without the gap is larger at lower temperatures. This is caused by the reduction in radiation heat transfer resistance at elevated temperatures. Radiation becomes more efficient at elevated temperatures, regardless of the temperature difference between the surfaces.

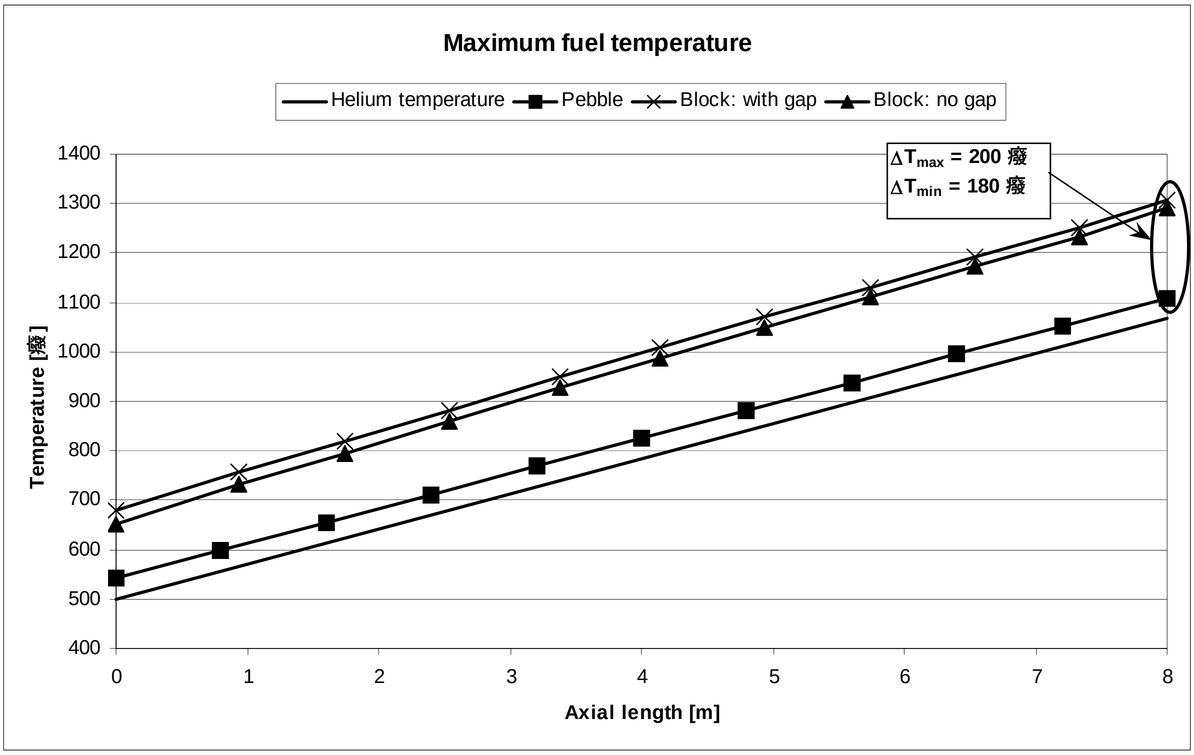

FIGURE 1. Comparison between best estimate and conservative block fuel temperatures.

2.1.1 Silver release

The silver (Ag-110m) release in the core is strongly dependent on the fuel temperature within the core. This relationship can be seen in *FIGURE 2* and *FIGURE 3*.

From the results reported in paragraph 2.1, the average mean fuel temperature can be calculated for the pebble and both block fuel designs. These temperatures can be used to calculate the silver release (Ag-110m) in the core, using the data in *FIGURE 2* and *FIGURE 3*. The results of these calculations are shown in *TABLE 1*.

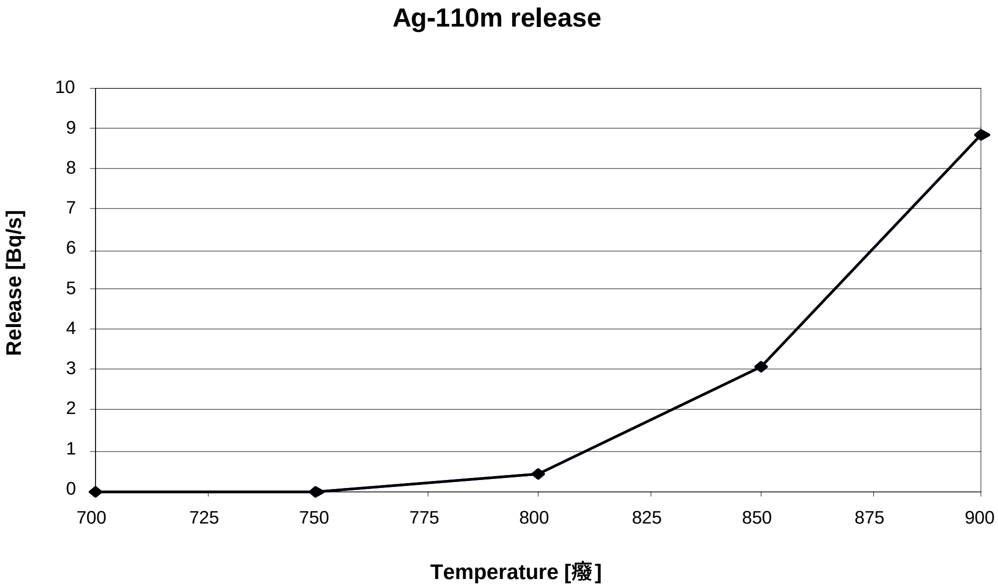

FIGURE 2. Typical silver release at lower temperatures.

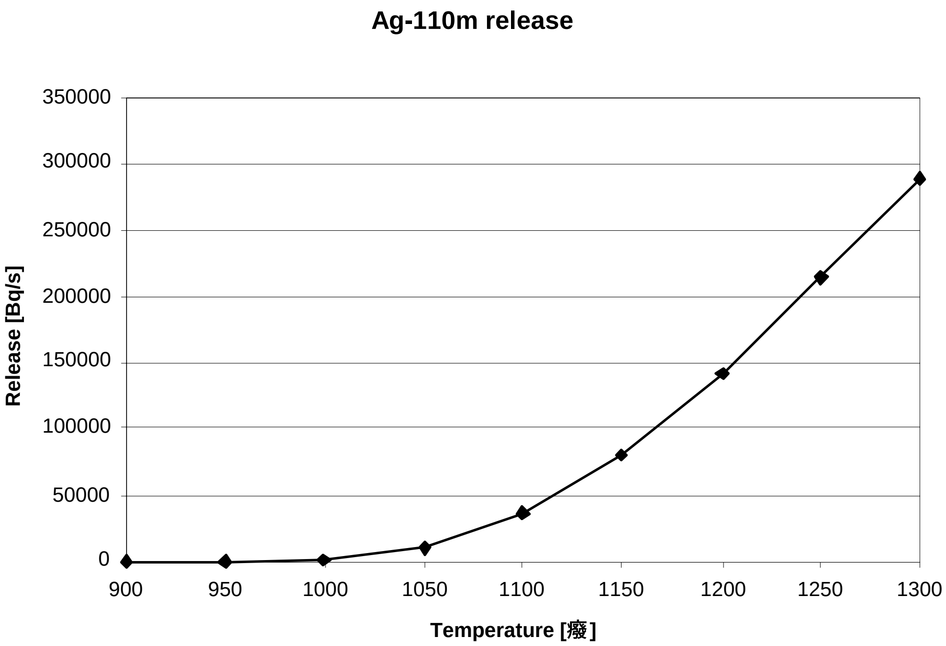

FIGURE 3. Typical silver release at elevated temperatures.

TABLE 1. Silver release comparison.

Design	**Mean peak fuel temperature °C**	**Ag-110m release Bq/s**
Pebble	826	1.78
Block with no gap	978	667
Block with gap	1 000	1 159

2.1.2 Amoeba effect

One of the phenomena occurring in coated particle fuel consists of a unidirectional movement of the fuel kernel against the temperature gradient into the coating, which may eventually result in complete destruction of the latter. During this process, the SiC coating is progressively damaged and could ultimately be destroyed. This phenomenon is called the ‘amoeba effect’. It is encountered in uranium, thorium and plutonium fuel in the oxide or carbide form. There is general agreement on the empirical dependence of the extent on such parameters as time, temperature, temperature gradient and power rating.

In [5], a comprehensive overview and theoretical discussion is presented of a number of experiments carried out to study the postulated mechanisms of mass transfer across or around the oxide kernel. There is general agreement that the phenomena involves the transfer of carbon from one side of the kernel to another in the presence of a temperature gradient, and that this is as a result of the differing equilibrium between CO and CO_2 at different temperatures. The net effect of this carbon transport is to gradually push the kernel in the direction of increasing temperature, so that the kernel moves toward the SiC layer and damage the layer. This is clearly undesirable.

The relatively high temperature gradient in the block fuel compact compared to the gradient experienced by the pebble is reason to believe that the amoeba effect in a block fuel reactor will be more of a concern than in a pebble fuel reactor. In addition, the block fuel stays in the temperature conditions for the length of the cycle, while the pebble could be considered to be in a specific orientation and temperature conditions theoretically only for an instant. Therefore even if the temperature gradient should be the same as for the block fuel, this fact virtually makes the pebble fuel immune to damage of the SiC by the amoeba effect.

The overall advantage of the pebble fuel over the block fuel is summarized as follows:
- The much lower temperature gradient in the coated particle
- The dynamic nature of a pebble fuel element in a pebble bed reactor

3. ECONOMICS

3.1. Fuel manufacturing cost

When operating with an equilibrium core, pebble fuel elements have:
- A single enrichment
- A single coated particle design
- No burnable poisons

The manufacture of pebble fuel lends itself ideally to mass production, and as a result, saving of costs.

The Ft St Vrain and HTTR reactor cores contained 27 and 13 different enrichments respectively, combined with burnable poison to compensate for excess reactivity. During manufacture of these different fuel blocks, the manufacturing lines must be separated, which implies higher costs in terms of capital investment and operations.

3.2. Fuel Utilization

In a pebble bed reactor, each fuel sphere is assayed for burn-up, and will be discharged to the spent fuel storage at the same burn-up within a small tolerance. Present indications gleaned from experiments confirm that this tolerance is acceptably small. The prismatic fuel elements, however, will be discharged as spent fuel based on analyses, and as explained earlier, such analyses still have many uncertainties which will undoubtedly influence the optimization of fuel utilization.

3.3. Power Conversion Cycle Efficiency

The reactor outlet temperature is a determinant in the efficiency of the power conversion cycle. As shown in paragraph 2.1, the maximum fuel temperature for the same reactor outlet temperature, power and coolant flow rate is 200 ºC lower for a pebble fuel element than for a block fuel element. It is therefore clear that for the same fuel temperature, the outlet temperature of a pebble-fuelled core can be 200 ºC higher than for a block-fuelled reactor. It has been calculated that a 1.5% efficiency gain in the power conversion unit could be realized per 50 ºC increase in reactor outlet temperature. A temperature of 200 ºC therefore translates to an efficiency increase of 6%.

4. NUCLEAR MATERIAL SAFEGUARDS

In a pebble fuel reactor, attempts to divert nuclear material will be detected promptly [6]. Any attempt to clandestinely introduce target material for the production of weapons material will also be detected and displayed in the operational records. It is impossible to produce weapons grade plutonium in a target of U-238, because in a single pass the Pu-240 isotope is larger than 20% of the Pu-239.

In a block fuel reactor, the remote fuel handling operations can hide the introduction of target material. Target material could be introduced as poison into relatively low flux positions, and during an operating cycle, the fluence could be chosen to produce a mix of plutonium isotopes that could be used in weapons application.

5. CONCLUSION

An objective look at the attributes of each fuel concept in relation to the performance of the reactor with reference to the specified Generation IV attributes, clearly shows the advantages of choosing to follow the pebble fuel route.

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REFERENCES

[1] U.S. Department of Energy, A Technology Roadmap for Generation IV Nuclear Energy Systems. Office of Nuclear Energy, Science and Technology http://www.nuclear.gov/.

[2] AVR – Experimental High-Temperature Reactor Association of German Engineers – (VDI) – The Society for Energy Technologies. Düsseldorf, June 1990.

[3] Plutonium Deposition in the PBMR-400 High-Temperature Gas-Cooled Reactor. Eben Mulder, Eberhard Teuchert, PHYSOR 2004, 25 to 29 April 2004.

[4] Operational Experience at Fort St Vrain. G C Bramblett, C R Fisher and F E Swart. Specialists Meeting of the International Working Group on Gas Cooled Reactors, Lausanne, Switzerland, 1 to 3 September 1980

[5] Amoeba Behaviour of UO_2 Coated Particle Fuel. M Wahne-Löffler. Institut für Chemie Forschung Zentrum. Seibersdorf A 2444. Seibersdorf, Austria.

[6] Preliminary Assessment of the Ease of Detection of Attempts at Dual Use of a Pebble Bed Reactor. A M Ougouang, H D Gougar. INEEL Presented at the ANS 2001 Writer Meeting, 11 to 15 November 2001, Reno, Nevada.

AUTHOR INTRODUCTION

The author is currently employed by the company PBMR (Pty) Ltd, in the capacity of Senior Nuclear Consultant.