The Importance of the AVR Pebble-Bed Reactor For the Future of Nuclear Power

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Abstract

The AVR pebble-bed high temperature gas-cooled reactor (HTGR) at Juelich, Germany operated from 1967 to 1988 and was certainly the most important HTGR project of the past. The reactor was the mass test bed for all development steps of HTGR pebble fuel. Some early fuel charges failed under high temperature conditions and contaminated the reactor. An accurate pebble measurement (Cs 137) allowed to clean the core from unwanted pebbles after 1981. The coolant activity went down and remained very low for the remaining reactor operation. A melt-wire experiment in 1986 revealed max. coolant temperatures of >1280°C and fuel temperatures of >1350°C, explained by un-derestimated bypasses. The fuel still in the core achieved high burn-ups and showed under the extreme temperature conditions excellent fission product retention. Thus, the AVR operation qualified the HTGR fuel, and an average discharge burn-up of 112% fifa revealed an excellent fuel economy of the pebble-bed reactor.

Furthermore, the AVR operation offers many meaningful data for code-to-experiment comparisons.

KEYWORDS: *HTGR, high temperatures, high burn-ups, fission product retention*

1. Introduction

The AVR pebble-bed high-temperature gas-cooled reactor (HTGR) at Juelich, Germany operated from 1967 to 1988 and was certainly the most important HTGR project of the past.

Since 1994, the plant is being decommissioned. The spent fuel pebbles have been put to interim storage in CASTOR casks at the neighbouring Juelich Research Centre. Many auxiliary systems have already been dismantled. At present, the reactor vessel is prepared for being grouted. The vessel with all its internals will be removed from the plant as a whole unit and put to interim storage at the Centre while green field conditions will be restored on site.

From the operational and experimental history of the plant there are, of course, no new results. They have, however, newly been weighted to present an orientation pole in the present search for better reactor concepts for the future, and for the many newcomers to the HTGR.

AVR data are plenty. This paper concentrates on the overall qualification of the pebble bed system and its fuel. It should be mentioned in this introduction, however, that in the field of dust and activity behaviour in the primary system fresh concerns have arisen that some of the AVR experimental data in that field could have been wrongly interpreted and that some chapters in the old reports, including the ones mentioned below, might need some review. The subject is not further deepened here.

Attached to this paper is a recommendation paper on future nuclear power.

2. Short reminder on AVR design and operation

The AVR was a simple design (Fig. 1) with the pebble bed core of about 92,000 fuel pebbles, the steam generator and the 2 coolant circulators integrated in the reactor vessel. The coolant flow was upward. The 4 control rods moved in from below and were guided in 4 graphite “noses” that protruded 65 cm into the pebble bed. The reflector graphite is surrounded by carbon material for thermal insulation. At the time, a second reactor vessel had been provided for safety purposes and the interspace used to position a first biological shield. During reactor operation, the pebbles were circulated via the discharge tube. Per full power day about 500 pebbles were circulated, about 50 fresh fuel pebbles loaded and about 50 spent fuel pebbles removed from the system. The main technical data are listed in Table 1.

Figure 1: AVR pebble-bed HTGR

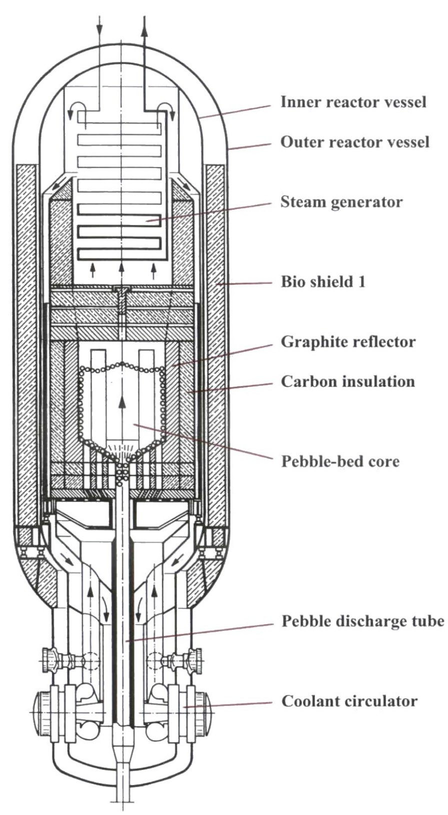

Table 1: Technical Data of AVR

Thermal power rating	(MW)	46
Electric power	(MW)	15
Average core power density	(MW/m^3)	2.6
Coolant inlet temperature	(°C)	275
Coolant outlet temperature (nominal)	(°C)	950
Primary system pressure	(bars)	10.8
Core diameter	(m)	3.0
Average core height	(m)	2.8
Steam temperature	(°C)	505

3. Major operational achievements

The AVR, in its 21 years of operation, was the mass test bed for all development steps of HTGR pebble fuel. On the whole, the operation of the reactor was a success story. Nevertheless, fission product releases from various earlier types of fuel after the adoption of very high temperatures in the AVR in 1974 and a rather inaccurate pebble measurement impeded for many years to demonstrate in full scope what the multi-passage pebble-bed reactor in terms of fuel efficiency and modern state-of-the-art coated-particle fuel in terms of fission product retention can really perform.

It was the increase of the coolant outlet temp. from a nominal 850°C to 950°C in early 1974 that led to the very high temperatures in the core (reasons below). (U/Th) C_2 fuel in BISO coatings showed then a higher release of Sr-90 and various other solid fission products that went by diffusion, as PIE in the Centre revealed, through intact coatings. At about that time a first small charge of LEU fuel pebbles had been loaded, and after they had acquired some burn-up a higher rate of particle failures occurred, also revealed in PIE. This is attributed to their higher load with fissile material (40% more), that led to even higher temperatures in these pebbles compared to the rest, and a buffer layer density that was not small enough to provide a suitable buffer function. The contamination of the reactor was massive by both releases and still greatly affects decommissioning.

A new accurate pebble measurement (Cs 137) came in use end of 1981 and allowed to clear the core from unwanted pebbles within about a year. Together with a melt-wire experiment at stationary high-temperature operation in 1986 to investigate the temperatures in the reactor, the unique performance of both reactor and fuel became obvious.

3.1 Fission product retention

Within 1983 the coolant activity attained a final low level and remained at that for the rest of the AVR operation until the final shut-down end of 1988. The release of fission products into the coolant was then only in the order of what could be expected from the - as manufactured - uranium contamination of the pebbles then still in the reactor. Table 2 gives typical values measured at high temperature (950°C nominal) stationary operation.

Table 2: Coolant activity concentrations in Bq/m³ (standard cond.) at stationary high-temperature operation

Total fission gases	4.6 E 08
Tritium	3.7 E 07
C 14	1,9 E 07
Co 60	1.0 E 01
I 131	5.2 E 02
Cs 137	3.0 E 02
Sr 90	2.0 E 02
Ag 110m	4.9 E 01

3.2 Temperatures

During such operation the melt-wire experiment was carried out in Sept. 1986. It revealed coolant temperatures as directly exiting from the pebble bed of > 1280°C in the outer core and about 1070°C in the central part of the core. (Unfortunately, 1280°C was the highest melting temperature in use.) The large difference to the nominal 950°C is today attributed to stronger than expected coolant bypasses through the control-rod guiding boreholes in the 4 noses. The according maximum fuel temperature was certainly > 1350°C, also for high burn-up pebbles, and it is likely that in certain parts of the core values clearly beyond 1400°C were present. Thus, the AVR was indeed the first "Very high temperature reactor".

3.3 Burn-ups

The types of fuel still present in the core at the time of the melt-wire experiment and their achievements in burn-up are summarized in Table 3. Compared to present pebble bed designs the AVR burn-ups were very high. This is partly also true for the LEU fuel whose massive loading did not start until 1982. At final shut-down, about half of the core consisted of LEU.

Table 3: AVR fuel performance at very high temperatures and low fission product release.

Fuel	**Coating**	**Burn-up**
HEU/Thorium $(U/Th)O_2$	BISO	Discharge average 112 % fifa (18.2 % fima, 166 GWd/to)
HEU/Thorium	TRISO	~ 16 % fima, ~ 150 GWd/to
HEU (Feed particles) UCO, UC_2	TRISO	Feed particles : 77 % fima, 690 GWd/to
LEU (10 %) UO_2	TRISO	Max. 10 % fima, 89 GWd/to Average 8.5 % fima, 76 GWd/to
LEU (17%) UO_2	TRISO	Max. 14 % fima, 125 GWd/to Average 11 % fima, 98 GWd/to

Because of the variety of fuel used in the AVR, the reactor never obtained a real equilibrium core. In the last 4 operational years, however, the average discharge burn-up of the old oxide HEU/Thorium pebbles with BISO coating remained about constant at 18.2 % fima which means 112 % fifa and is in comparison to other thermal reactors an outstanding achievement in terms of fuel economy. Also the 10 % enriched LEU fuel had acquired at final shut-down up to 100 % fifa and would have come to considerably higher values if AVR operation had been continued.

The high fuel economy of the multi-passage pebble-bed HTGR is indeed a central feature in this new "weighing" of AVR results, and also in the attached "Manifesto".

Burn-up expressed in fima or GWd/to is a measure for the stress that fission products cause in a fuel element. Here, extreme values were achieved in the HEU/Thorium pebbles with separated fissile and fertile particles (named GFB 3 to 5). While the pebble burn-up attained the already mentioned average of 18.2 % fima the fissile particles, that contained only HEU (93 %), achieved an average of 77 % fima. Theoretically, more than 100 % fima is not possible. These particles too, showed excellent fission product retention under the extreme temperatures in the AVR. The results indicate that there seems to be no need to put a limit on fima.

4. Recommendations for future plants

Drawing from their long experiences the AVR company put up a manifesto (attached to this paper) stressing the importance of the modular pebble bed reactor for the future of nuclear power in terms of simplicity, safety and fuel economy. Major items are the mass employment of this reactor type because of its safety and particular fuel economy, the plead for cylindrical cores as the simplest possible design, the abolishment of unnecessarily stringent shut-down requirements in the licensing, the stronger backing of future HTGR fuel licences on the above mentioned performance data of the AVR, and the adoption of simple, cheap disposal techniques for typical HTGR wastes.

5. Importance for V & V activities

So far, there has been no really satisfactory computer model representation of the AVR. A major reason for this is the existence of the noses. To represent the noses in a 3-dimensional model is of course not a big problem as such. The difficulties lie in the influences of the noses on the pebble flow, and the question was if the effort of an AVR benchmark is worthwhile when all future pebble-bed reactors, as is foreseeable, will not have any noses.

From a present point of view, and this is here another item of the new "weighing", the effort is to recommend. The reason is that at the AVR by far the most meaningful experimental results for code-to-experiment comparisons were obtained. The major experiments here are the pebble flow experiments that, although the nose influence could not be separated, differed in an inner and an outer core fuelling, and of course the melt-wire experiment. For instance, the measured average pebble circulation number needed to bring a test pebble through the inner core (central feeding pipe) and the size of the inner core in terms of pebble number are genuine results that strongly depend on the real flow behaviour. A reactor with only one pebble feeding position like the HTR-10 can experimentally be investigated only as a whole core. A measured average circulation number is meaningless for comparison, because that number is equal to the pebble contents of the core and thus trivial.

6. Conclusions

The AVR qualified both the reactor concept and its fuel. It was demonstrated that under extreme temperatures and up to high burn-ups excellent fission product retention can be achieved. Any modern HTGR layout like PBMR stays within the experience margins of AVR. In a way, pebble-bed fuel has been “pre-licensed” in the AVR.

It is known that in other HTGR projects and tests HTGR fuel did not always behave well and that the fuel behaviour in the AVR is theoretically not really understood. Yet, arguments that the results in AVR were just chance, exotic, due to some lucky circumstances, that could maybe not be repeated are vividly rejected here. The fuel development concerning the core contents from the time of the AVR core cleaning by the improved pebble measurement comprises some 15 years of fuel fabrication at Nukem, some 200,000 produced pebbles[1], HEU and LEU applications, HEU and Thorium in mixed and in separated particles, fuel mainly as oxide but also UCO and UC_2 , BISO and TRISO coatings, and different graphites.

Furthermore, the AVR demonstrated that the multi-passage pebble-bed system is among the best in fuel economy, an aspect that will gain more and more importance in the future.

References

On design:

- atomwirtschaft-atomtechnik (atw), special print from Heft 5, 1966 (special edition on AVR)

On performance:

- Ziermann/Ivens, AVR-Abschlussbericht, FZJ 3448, Oct. 1997
- AVR-Experimental High-Temp. Reactor, 21 Years of successful operation for a future energy technology, Association of German Engineers (VDI), VDI-Verlag Duesseldorf, 1990

A compact library on AVR, including the above contributions, was made available by NEA as a CD-ROM. IRPhE/AVR, NEA-1739/01.

[1] About one million if the production for THTR is included.

Attachment

Peter Pohl **AVR: Our HTGR Manifesto**

Motivation

In a world of new nuclear concepts, a profusion of ideas, and many newcomers to the HTGR, the author, having been chiefly involved in operation and experiments of the Juelich AVR pebble bed reactor for many years, feels compelled to shortly put down (in the following 11 points) what from our AVR experience and reflections is important, desirable, and obsolete in the future.

1. The global challenge

The green-house effect is a real threat. The only remedy is to reduce drastically the use of fossil fuel, and as soon as possible. A replacement by renewable energies is in principal possible, yet with consequences that are hardly bearable. Since nuclear fusion is not available yet, it must be the new role of nuclear fission energy to be the major replacement for fossil fuel; to embark on anything less does not make much sense. In addition to a high safety of new reactor systems, a stringent economy on the limited natural fuel resources is therefore of utmost importance.

2. The reactor choice

In the search for new reactor types the modular HTGR is holding a prominent position. Moreover, for us it has to be the pebble bed. The simplicity of this reactor concept, the unique re-fuelling during reactor operation, and the non-requirement of excess fuel loading are well known advantages. But there is one more, and, in the new situation of stringent fuel economy, probably the most important of all:

The achievable burn-up in a multi-passage pebble bed is considerably higher than can usually been obtained in other thermal reactor types (except maybe Candu type).

According to AVR experience (see below), average burn-ups of 110 to 120 % fifa (or more) can be expected at optimum enrichment. Thus, whenever fuel is used that is not, or no longer, intended to be reprocessed it ought to be used in a pebble bed reactor!

3. Keep it simple!

Choose the simple cylindrical core! The economy of size is well matched by the economy of large production numbers and pre-fabrication at the factory to the highest possible degree. (Germany alone would need some 1000 to 2000 modular units, depending on size.) The according power conversion unit is already a large and technologically ambitious machine. It is certainly not “too small” to be effective!

4. The overall efficiency

A high thermal efficiency in electricity generation is certainly desirable. However, co-generation is more effective, some 70 to 80 % of the heat should be used. But this is still not the whole story. At Judgement Day the question will be: How much useful energy did you extract from the given unit of natural fuel? That is the overall efficiency. Let us maximize this!

5. Peu-a-peu

The Dutch concept of using small peu-a-peu fuelled pebble beds for ship propulsion and other industrial purposes is very appealing. It is the simplest possible design, yet the fuel usage is rather insufficient. This major disadvantage can, however, be compensated when the peu-a-peu spent fuel is further used in the stationary multi-passage pebble beds. Combining both systems is the answer.

6. Accurate pebble measurement

The desired high fuel economy is directly related to the accuracy of the individual pebble measurement. At AVR, by gamma spectrometric measurement of Cs 137 an accuracy of about ± 2 % for high-burn-up pebbles was obtained. At very short pebble cooling times, however, the accuracy of the Cs method declines. The author worked out a different method for which the Juelich Research Centre applied for a patent. With this, a similar accuracy as at AVR can be expected, independent of the pebble cooling time.

7. Weapon-grade plutonium

Because of the unique fuelling of the multi-passage pebble-bed, weapon-grade Pu can be used up to almost 100 % in that reactor. Why content one-self with almost 90 % as claimed for the prismatic HTGR, and which, besides, seems very optimistic.

8. Licensing: AVR base for fuel performance

The tests in large numbers of HTGR fuel in the AVR satisfy the requirements for future HTGR plants in both achieved burn-up and fuel temperature. The fuel performance in the AVR must therefore be the basis in the licensing procedure of new fuel.

After the introduction of the precise pebble measurement in the AVR end of 1981 the release of fission products went down to very low levels. In the following years, at maximum fuel temperatures of > 1350 °C (based on the melt-wire experiment), the major fuel achievements, under the high temperatures and with the low release, can be summarised as follows:

Fuel	Coating	Burn-up	
HEU/Thorium	BISO	Discharge average	**112 % fifa**
$(U/Th)O_2$		(18.2 % fima, 166 GWd/to)	
HEU/Thorium	TRISO	~ 16 % fima, ~ 150 GWd/to	
$(U/Th)O_2$			
HEU (Feed particles)	TRISO	Feed particles: 77 % fima, 690 GWd/to	
UCO, UC_2			
LEU (10 %)	TRISO	Max.	10 % fima, 89 GWd/to
UO_2		Average	8.5 % fima, 76 GWd/to
LEU (17 %)	TRISO	Max.	14 % fima, 125 GWd/to
UO_2		Average	11 % fima, 98 GWd/to

9. Licensing: Abolish cold-shutdown requirement with rods!

In contrast to reactors with fixed cores the pebble bed can always be made sub-critical to cold conditions by removing pebbles from the core. The requirement of achieving cold shut-down conditions with shut-down rods is therefore obsolete. The design of sufficient rod worth can be left to the operator just to serve the practical needs of a shut-down period.

In the AVR, the 4 rods in the graphite "noses" were not sufficient for cold shut-down. Yet this never represented a problem. During outings, the reactor was sub-critical by the inserted rods and by using the decay heat to keep the core at some temperature. And in the unexceptionally long outing of 15 months in 1978/79 in connection with the steam generator leak repair several thousand pebbles were removed from the core.

A back-up shutdown system is also obsolete because there cannot be a dangerous situation. If a pebble bed gets critical with the rods inserted its power and temperature remain so low that it is "as good as shut-down". Any repair work can be conducted, e.g. the repair of the pebble circulation system. And besides, there is always the possibility to fill N_2 into the reactor to make it sub-critical. At AVR, the cold reactor was held sub-critical by N_2 even with all rods withdrawn.

Thus, do not provide more than 12 rods in the side reflector. Limit the hollow spaces in the reflector in the interest of a good fuel economy. Do not turn the reflector into a "Swiss cheese"!

For the same reason, do not provide extra rods for short-term load following. In view of a lot of vehicle fuel that will have to be produced that load following had better be done on the load side rather than the generation side.

10. Reduced operational air ingress

Some inactive impurities in the coolant like N_2 or Ar are difficult to remove in the helium purification plant. A major source for a regular intake of such impurities are the fresh fuel pebbles that contain air in their pores. Make sure, therefore, to fill the pores of fresh pebbles with helium before they are locked into the primary system.

11. Simple waste disposal

Keep it simple, also in waste management! The main HTGR waste – the spent fuel, but also graphite (and carbon) from decommissioning – is entirely ceramic and needs no further treatment. Embedding this waste in concrete blocks is simple and safe. Concentration methods for waste are obsolete; there is storage space in abundance. And a dilution of the material to a certain degree even furthers safety. In Germany, all given-up underground mines easily offer disposal space for several hundred years of nuclear power. In most other countries the situation is similar.