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Design specification and fabrication of the temperature monitor pebbles

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Summary

In 1986 a sophisticated, multi-element "melt-wire experiment" was conducted as part of a comprehensive experimental program with and in the AVR. Melt-wire Experiment HTA-8 was carried out in the AVR with specially designed graphite matrix spheres which incorporated a set of capsules, each containing a single melt-wire. The melt-wires were fabricated of specific alloy composition that would melt if a precise temperature was exceeded. A total of 190 monitoring spheres were added into the AVR core through standard fuel loading procedures. Upon discharge, they were X-rayed to assess the momentary maximum peak temperatures experienced during their passage through the AVR. The HTA-8 experiment has provided information, from which a frequency distribution of temperature maxima at the sphere surface showing that it appears possible that the temperature distribution of fuel elements passing through the inner AVR core were normally distributed with mean surface temperature 1100°C and the temperature distribution of fuel elements passing through the outer core were also normally distributed with a mean surface temperature 1220°C. Based on the analysis of this experiment, new melt-wire test series are being proposed to be conducted in the Chinese HTR-10 representing - much better than the AVR - a small modular pebble-bed HTGR of today's design. The design of the monitor spheres is suggested to be slightly modified with regard to the melt-wire materials selected to avoid drawbacks encountered in the previous design.

Approval

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1 Introduction

The AVR high temperature gas-cooled reactor was successfully operated from 1967 to 1988. Its pebble-bed core consisted of approximately 100,000 spherical fuel elements that were circulated during reactor operation. As a test reactor and first-of-a-kind concept, the main objective of the AVR operation was to demonstrate the general principles of a pebble-bed HTGR. One of the items investigated in further detail was the fuel temperature to be expected during normal operation. For the assessment of the coolant outlet temperature, a temperature instrumentation was installed in the ceiling structure above the core, meant to monitor temperatures and temperature gradients of this structure. However, it was insufficient to determine a proper average value for the coolant and, even worse, this instrumentation broke after a few years. Therefore various alternatives have been elaborated, one of which was the special preparation of spherical elements to monitor the temperature when passing through the core.

Even though the temperature of an individual spherical fuel element in a pebble-bed HTGR cannot be determined, the 1986 melt-wire experiment at the AVR reactor in Jülich has provided valuable information. The initial analysis followed by a much more detailed theoretical evaluation about 20 years later has shown that AVR temperatures were much higher than expected.

Although the concept of monitor spheres represents a unique means to provide temperature measurements from inside a reactor core, what no other kind of reactor could ever do, still uncertainties exist regarding the temperature distribution in the pebble-bed core. With the lessons learned from the AVR melt-wire experiment and based on the experience achieved at FZJ, it is proposed to conduct congenial experiments in the only pebble-bed test reactor presently existing, the Chinese HTR-10. The experiments should be accompanied by respective model calculations, with the goal to learn about the temperature distribution in a reactor which represents the state-of-the-art design of a modular-type HTGR.

This reports describes in detail the melt-wire experiment of 1986 in the AVR and the calculation efforts to explain the test results. A final chapter will then contain the proposal for a series of similar melt-wire tests to be conducted in the HTR-10 taking account of the specific conditions in the HTR-10.

2 Melt-wire Experiments in the AVR

2.1 AVR real-time irradiation testing

The AVR was operated as an experimental helium-cooled pebble bed reactor. It had a nominal thermal power of 46 MW and generated 15 MW(el). Initial average helium gas exit temperatures were 750°C and, in 1974, were increased to 850 and 950°C, respectively. The AVR 950°C average coolant outlet temperature is a nominal value at reactor full power operation.

During its operating lifetime 1967 to 1988, the AVR was used to test the pebble bed HTR concept and its components along with spherical fuel elements. Fueling began on 14 July 1966 with 30,000 first core fuel elements, 70,000 moderator graphite spheres, and 3000 absorber spheres. Over the AVR operational lifetime, more than 290,000 spherical fuel elements of five different types and 15 variants (carbide/oxide, BISO/TRISO, HEU/LEU) were tested. In total, this represents more than 6 $x10^9$ coated fuel particles.

In February 1981, the first spherical fuel elements of high quality and high performance were inserted into the AVR. This fuel type contained $(Th,U)O_2$ LTI TRISO particles and was designated type GO-2 (AVR Reload 15). These elements were followed, since 1982, by the very high quality elements containing low-enriched (LEU) UO_2 LTI TRISO particles designated type GLE-3 (AVR Reload 19) in, and types GLE-4/1 and GLE 4/2 (AVR Reload 21). Using high enriched (HEU) mixed carbide/oxide fuel in the beginning, the AVR reactor core was, beginning in mid 1982, gradually converted to low enriched fuel. The fuel composition in the reactor core, totaling ~110,000 fuel spheres, at the end of operation was about 50% HEU and 50% LEU.

The fuel handling system includes a burnup measurement device to differentiate between pure graphite pebbles and fuel pebbles, and for the latter to decide – according to the achieved burnup – whether the fuel pebble in consideration is to be reloaded to the core or removed from the core. In the AVR, there were five feed lines, one in a central position and four in circumferential, outer positions between the graphite “noses” intruding into the core. Thereby, the inner and outer zone of the two-zone core of the AVR are created as can be seen from the horizontal core section shown in Fig. 1.

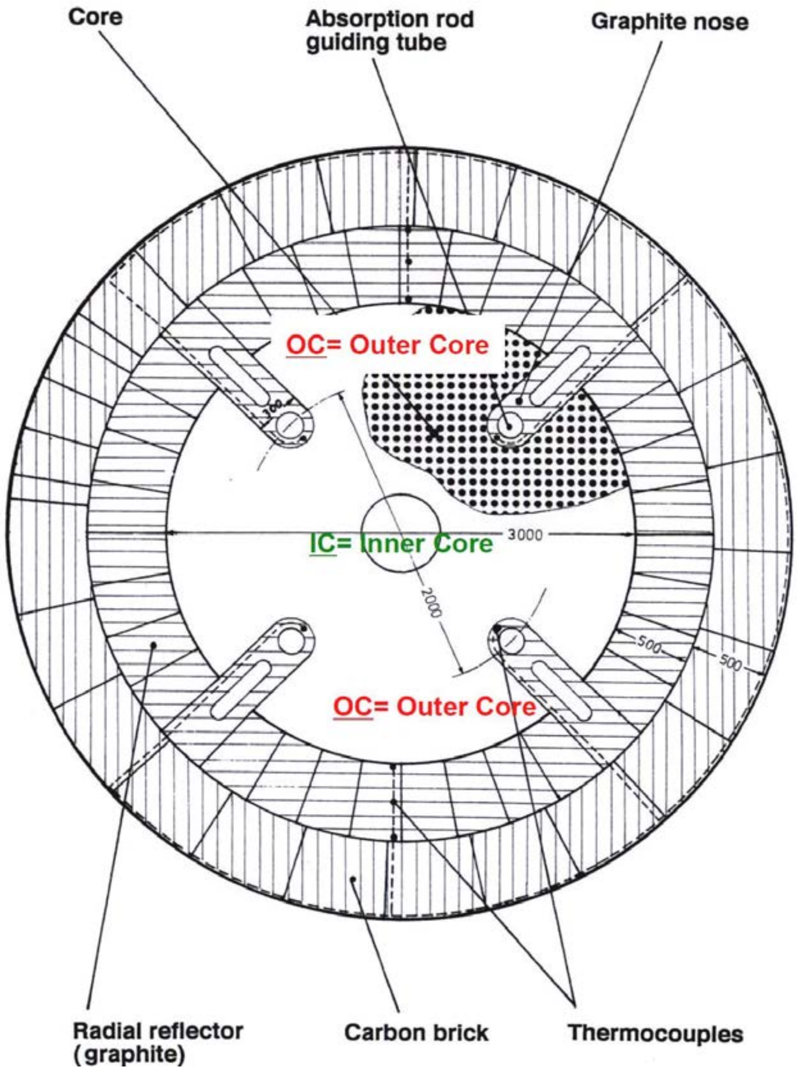


Figure 1. AVR reactor horizontal section with intruding graphite "noses" [Viljoen 2008].

2.2 Early efforts of fuel temperature measurements

Various efforts during the AVR lifetime have been made to experimentally determine maximum fuel temperatures in the AVR core. Due to the flow direction of the coolant from the core bottom upwards, the strongest temperature load on the fuel was at the beginning after insertion into the core and on the pebble bed surface. Temperature instrumentation initially implemented in the core ceiling structures to record their temperatures and temperature changes failed already within a few years. An indirect method of determining the average coolant outlet temperature was given by taking steam generator power, coolant inlet temperature and coolant flow rates, the latter derived from the coolant pressure, circulator speed, and circulator pressure difference. Direct measurements of the coolant temperature, however, were only locally possible with usual techniques.

In order to measure the temperature of the coolant as directly exiting from the pebble bed, temperature-monitoring balls were prepared and inserted into the core to flow with the pebble bed. In 1970, one fuel sphere and 16 graphite spheres were fabricated with melting bodies introduced in bore holes in both radial and tangential direction. The analysis showed surprisingly that the maximum helium temperature was at least 1000°C [AVR

1971]. In 1972, 80 additional monitoring balls were added to the core, 40 for gas and 40 for fuel temperature measurements. Drawback of these early tests was the difficulty to obtain individual core passage information for these monitor spheres and hints on where the temperatures were measured. Also, the small number of monitor spheres was statistically not satisfying. Furthermore, there was uncertainty in the identification method. The monitor spheres were flattened on two sides, with the expectation to have them retrieved via the fragment separator device [Gottaut 1990]. Compared to both results of respective AVR computer code calculations and averaged thermocouple readings, measured temperatures were found to be about 80 K higher. On the whole, results of these early tests were not well understood disagreeing with respective model predictions. Consequences from these measurements, however, were not drawn. The nominal mean coolant exit temperature was even raised from 850°C to 950°C [Pohl 2009].

2.3 HTA-8 experiment of September 1986

The experiment HTA-8 "Temperature measurement in the core by melt-wire pebbles" of September 1986 was one of quite a number of experimental scientific studies conducted in the last years of AVR operation (1985-89) that have provided reliable information on pebble bed reactor behavior under normal and off-normal conditions.

Specifically prepared A3-3 matrix spheres were fabricated in the same size of the fuel spheres for monitoring temperatures inside the core. As can be seen from the schematics in Fig. 2, these spheres contained a central cylindrical bore hole, into which a cylindrically shaped plug was screwed and sealed. The plug contained a set of 20 quartz capsules, inserted into small bore holes, each containing a single metal wire of a specific metal or metal alloy. These wires (6 mm length, 0.3 mm diameter) were welded in a protective gas (helium) atmosphere into the capsules, which were then fixed inside the bore holes by means of graphite cement. For hardening and drying of the cement, the monitor spheres were heat-treated at 100°C over 4 h and at 130°C over 16 h.

For the HTA-8 experiment, a total of 190 monitor spheres were fabricated. For easy identification, each monitor sphere received its own reference number engraved onto the surface. Photographies of the monitor sphere, the plug, and the quartz capsule are given in Fig. 3 [Derz 1988].

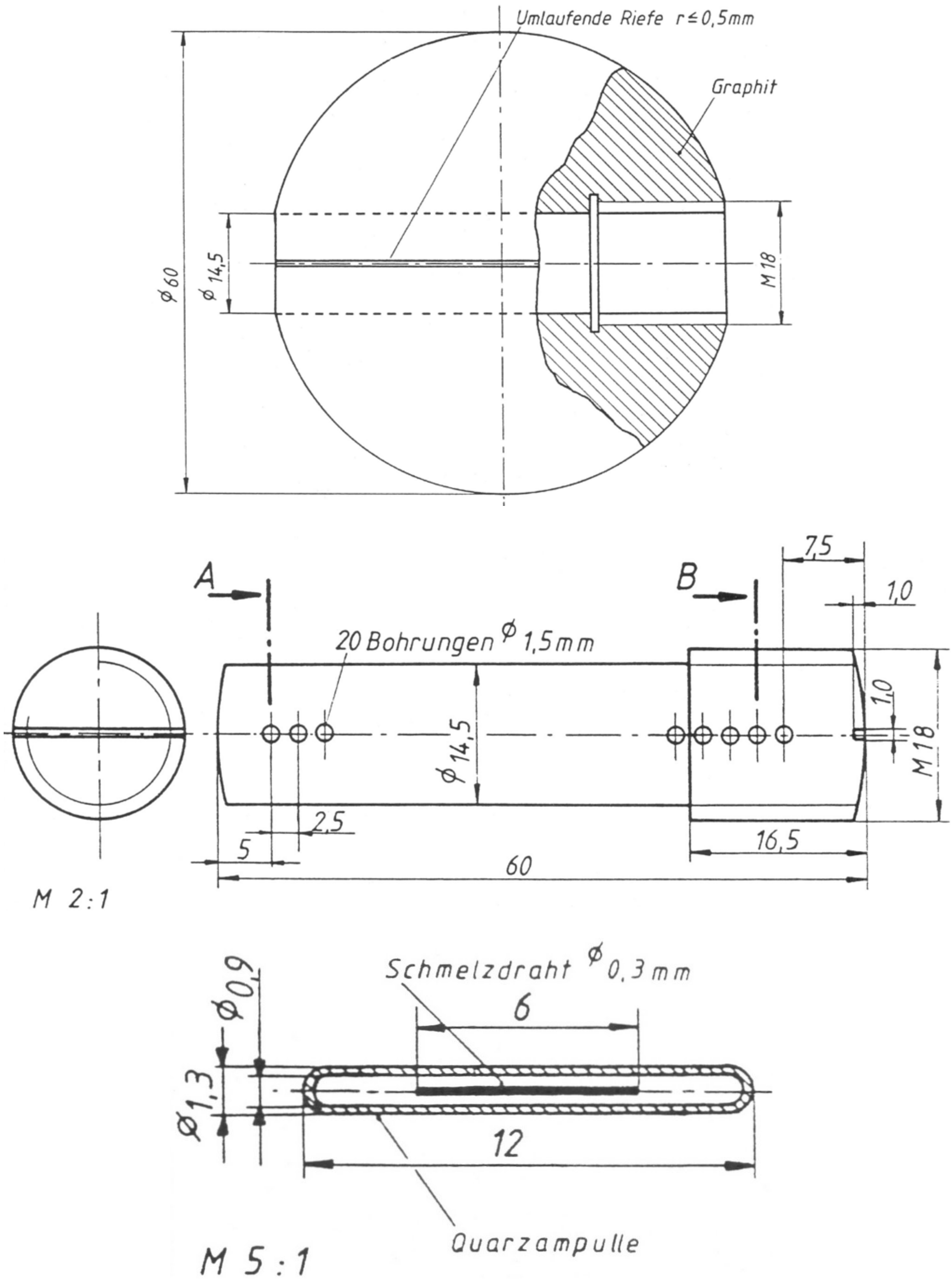


Figure 2. Dimensions of monitor sphere, plug, and quartz capsule [Gottaut 1990].

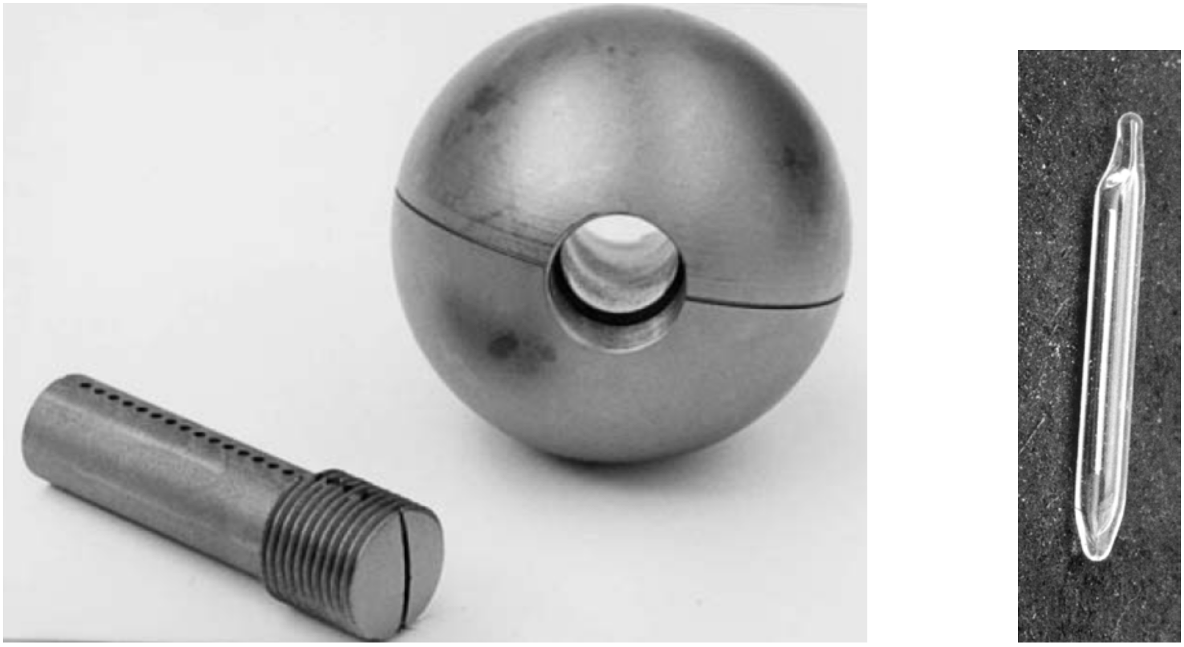


Figure 3. Temperature monitoring sphere prepared for the HTA-8 experiment [Gottaut 1990].

The metal/alloy wire was expected to melt if a certain temperature were exceeded. Table 1 provides a list of all 20 metal alloys used, their specific composition, and their liquidus temperatures[1]. Choice was made in a way to provide the stepwise coverage of the temperature range between ~650°C and ~1300°C.

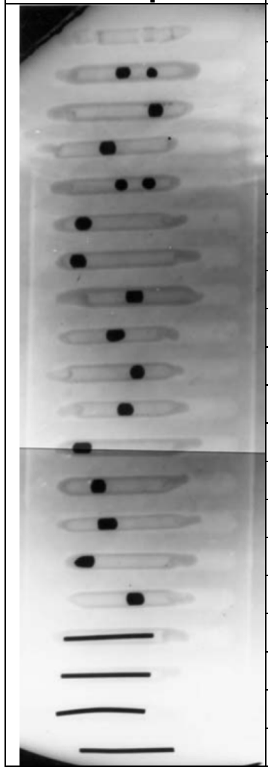
The temperature monitoring spheres were X-rayed after being discharged to obtain the momentary maximum temperature they had seen during the single pass through the AVR While passing through the core and when reaching their melting temperature, the little wires would melt assuming an almost spherical form. The presence of droplets within the quartz capsule indicated that their melting points correspond to the maximum temperature the sphere has seen on its passage through the core. Capsules with still intact metal strips indicated operating temperatures lower than the melting point of the metal alloy in consideration. An example for an X-ray radiography is shown in the left column of Table 1 with most wires molten and still four wires (at the bottom) that have remained intact.

After having passed the AVR core, the monitor spheres were identified with the help of the burnup measuring system. Activation of the melt-wire metals in the core was resulting in a certain, but low Ag-110m activity that was measurable.

From the total of 190 monitoring spheres added to the core, 102 went through the central tube and 22 through any of the four outer tubes. At the time of insertion (Sept 23, 1986), the AVR was operated at full power with a nominal average coolant outlet temperature of 950°C. About 6 weeks later, the coolant outlet temperature was lowered to 890°C and never went back to 950°C again. First appearance of a monitor sphere was about one year later on Sept. 12, 1987. Retrieval of test spheres was terminated in February 1989 after final shutdown of the AVR reactor.

[1] The liquidus temperature designates the temperature of an alloy, below which the liquid homogeneous phase begins to solidify. The temperature, at which a homogeneous solid phase is reached, is called solidus temperature. For pure metals and eutectic alloys, liquidus temperature and solidus temperature coincide.

Table 1. Melt-wire composition and melting point [Derz 1988].

Example for X-ray of melt-wire capsule	No.	Metal alloy	Alloy composition	Solidus temperature [°C] (producer)	Liquidus temperature [°C] (supplier)	Liquidus temperature [°C] (producer)
	1	Al - Fe	99.2 - 0.8	655		655
	2	Ag - Cu - In	60 - 27 - 13	605	700	710
	3	Ag - Cu	72 - 28	780	780	780
	4	Ag - Cu - Pd	68.4 - 26.6 - 5	807	810	810
	5	Ag - Au – Cu	20 - 60 - 20	835	840	845
	6	Ag – Cu	47 - 53	780	878	885
	7	Ag - Cu - Pd	52 - 28 - 20	879	900	898
	8	Ag – Cu	35 - 65	780	920	930
	9	Ag - Cu - Pd	54 - 21 - 25	901	940	950
	10	Ag	100	960	960	960
	11	Au - Cu	46 - 54	970	982	990
	12	Ag - Pd	95 - 5	970	1000	1010
	13	Au - Cu	33.5 - 66.5	1010	1020	1030
	14	Au - Cu	25 - 75	1030	1050	1050
	15	Au - Cu	10.5 - 89.5	1060	1072	1075
	16	Cu - Pd	82 - 18	1085	1088	1090
	17	Cu - Ni	90 - 10	1100	1120	1145
	18	Cu - Ni	84 - 16	1120	1150	1185
	19	Ag - Pd - Mn	64 - 33 - 3	1180		1200
	20	Pd - Cu	70 - 30	1250		1280

3 Results and evaluation of the HTA-8 experiment

3.1 Measurements

First X-ray pictures became available at the end of 1987 revealing unexpectedly high operating temperatures, considerably higher than it was ever intended. First reporting of results of the melt-wire test was made in 1989 showing that from the 144 monitoring spheres retrieved, 21 had seen unexpectedly high operating temperatures of > 1280°C (where all wires were melted). For most of the spheres added to the inner core, the maximum (coolant) temperature was around 1070°C. For spheres passing through the outer core zone, two distinct temperature levels could be identified: one at around 1100°C and another one at > 1280°C. The list in Table 2 provides the number of spheres that fall in respective temperature intervalls; Fig. 4 shows the corresponding frequency distribution [Gottaut 1990]. Since that figure was found to be flawed, a corrected histogram as shown in Fig. 5 was given.

Table 2. Operating temperature ranges experienced by graphite monitoring spheres based on post-irradiation analysis of melt-wires [Gottaut 1990].

No.	Temperature range [°C]	No. spheres
7	900 ≤ T < 920	0
8	920 ≤ T < 940	1
9	940 ≤ T < 960	1
10	960 ≤ T < 982	0
11	982 ≤ T < 1000	3
12	1000 ≤ T < 1020	0
13	1020 ≤ T < 1050	3
14	1050 ≤ T < 1072	25
15	1072 ≤ T < 1088	22
16	1088 ≤ T < 1120	29
17	1120 ≤ T < 1150	14
18	1150 ≤ T < 1200	7
19	1200 ≤ T < 1280	18
20	1280 ≤ T	21
	Σ	**144**

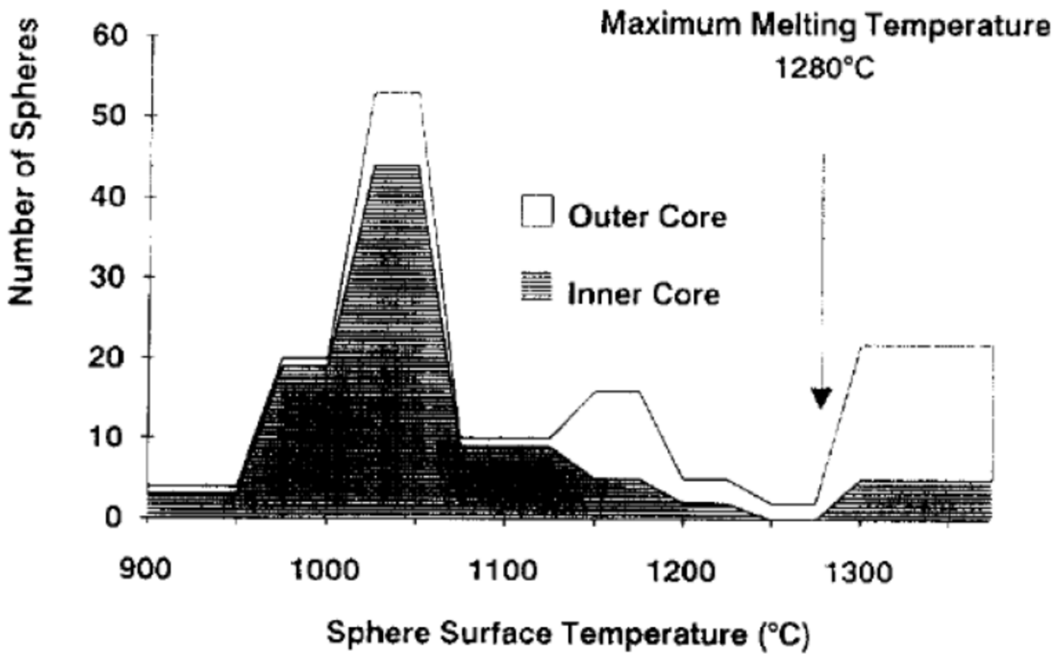


Figure 4. Frequency distribution of maximum temperatures detected by temperature monitor spheres passing the AVR core [Gottaut 1990b].

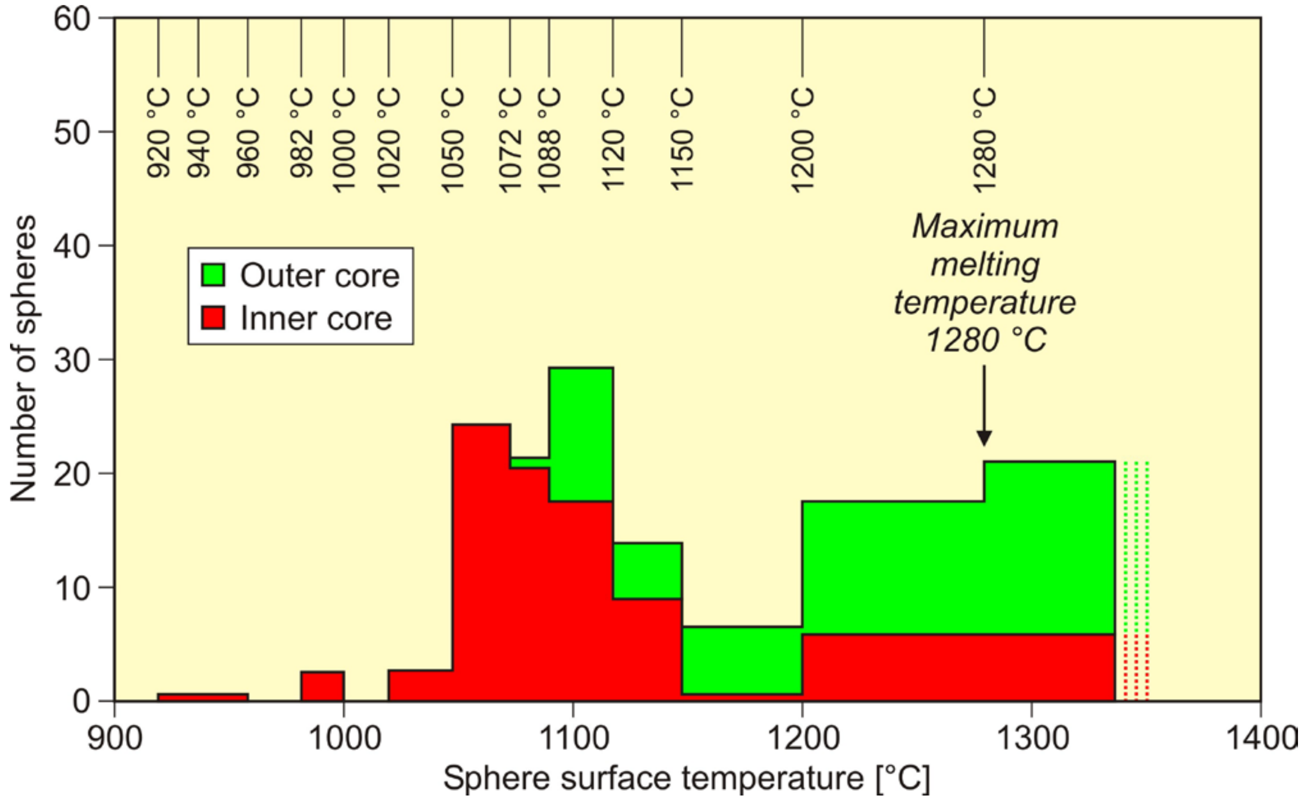


Figure 5. (Corrected) coolant temperature histogram measured with monitoring spheres in the HTA-8 experiment.

A detailed analysis of the individual core passage information for each monitor sphere has shown that 66% of the 144 melt-wire spheres passed through the inner core of AVR and 34% through the outer core (Table 3).

Table 3. Distinction of retrieved monitor spheres added to inner and outer core.

No.	Temperature range [°C]	No. spheres through	
		Inner core	Outer core
7	900 ≤ T < 920	0	0
8	920 ≤ T < 942	1	0
9	942 ≤ T < 950	1	0
10	950 ≤ T < 967	0	0
11	967 ≤ T < 991	3	0
12	991 ≤ T < 995	0	0
13	995 ≤ T < 1018	3	0
14	1018 ≤ T < 1049	25	0
15	1049 ≤ T < 1081	21	1
16	1081 ≤ T < 1119	18	11
17	1119 ≤ T < 1140	9	5
18	1140 ≤ T < 1172	1	6
19	1172 ≤ T < 1244	7	11
20	1244 ≤ T	6	15
	Σ	**95**	**49**

Specifically for the monitor spheres added through the four outer feeding lines, Table 4 lists the numbers of retrieved spheres and of those, where all wires were molten.

Table 4. Monitor spheres added to the outer core of the AVR.

Outer core feeding line #	Number of monitor spheres		
	added to core	retrieved	all wires molten
1	22	12	3
2	22	11	2
3	22	13	6
4	22	13	4
total	**88**	**49**	**15**

The table data reveal that monitor spheres with all wires molten were more or less evenly distributed over the pebble-bed surface. It means that also the highest temperatures were probably evenly distributed, making the hypothesis of the existence of so-called “hot spots” in the core fairly unlikely.

A detailed temperature analysis has given reason for certain corrections on the coolant temperatures. Gamma heating of melt-wires, quartz capsules, and the graphitic monitor sphere itself plus heat uptake from the neighboring fuel spheres resulted in a gas temperature corrections of -10 K for the melting points of all wires with number ≤ 16, while for all other wires at the higher temperature end, gas temperatures should be reduced by 20 K. Furthermore, two sets of melt-wires were taken for a re-check of the liquidus temperatures. Table 5 lists all corrections on the temperatures including the overall correction to be imposed on the gas temperature (final table column).

Table 5. Corrected melt-wire and coolant temperatures

No.	Temperature range [°C]	Liquidus temperature [°C]		Measured temperature [°C]		Assumed full melting temperature	Ambient coolant temperature at melting [°C]
		producer	supplier	sample 1	sample 2		
9	942 ≤ T < 950	950	940	952	965	952	942
10	950 ≤ T < 967	960	960	959	961	960	950
11	967 ≤ T < 991	990	982	977	976	977	967
12	991 ≤ T < 995	1010	1000	1000	1003	1001	991
13	995 ≤ T < 1018	1030	1020	1009	1001	1005	995
14	1018 ≤ T < 1049	1050	1050	1030	1026	1028	1018
15	1049 ≤ T < 1081	1075	1072	1059	1058	1059	1049
16	1081 ≤ T < 1119	1090	1088	1093	1090	1091	1081
17	1119 ≤ T < 1140	1145	1120	1140	1138	1139	1119
18	1140 ≤ T < 1172	1185	1150	1165	1155	1160	1140
19	1172 ≤ T < 1244	1200	-	1195	1188	1192	1172
20	1244 ≤ T	1280	-	1267	1260	1264	1244

Taking account of the above temperature corrections, the withdrawal times of the single monitor spheres translated into an information on the core radius, at which that sphere was likely to have passed through the core, eventually resulted in coolant temperature profiles as displayed in Fig. 6 [Pohl 2009].

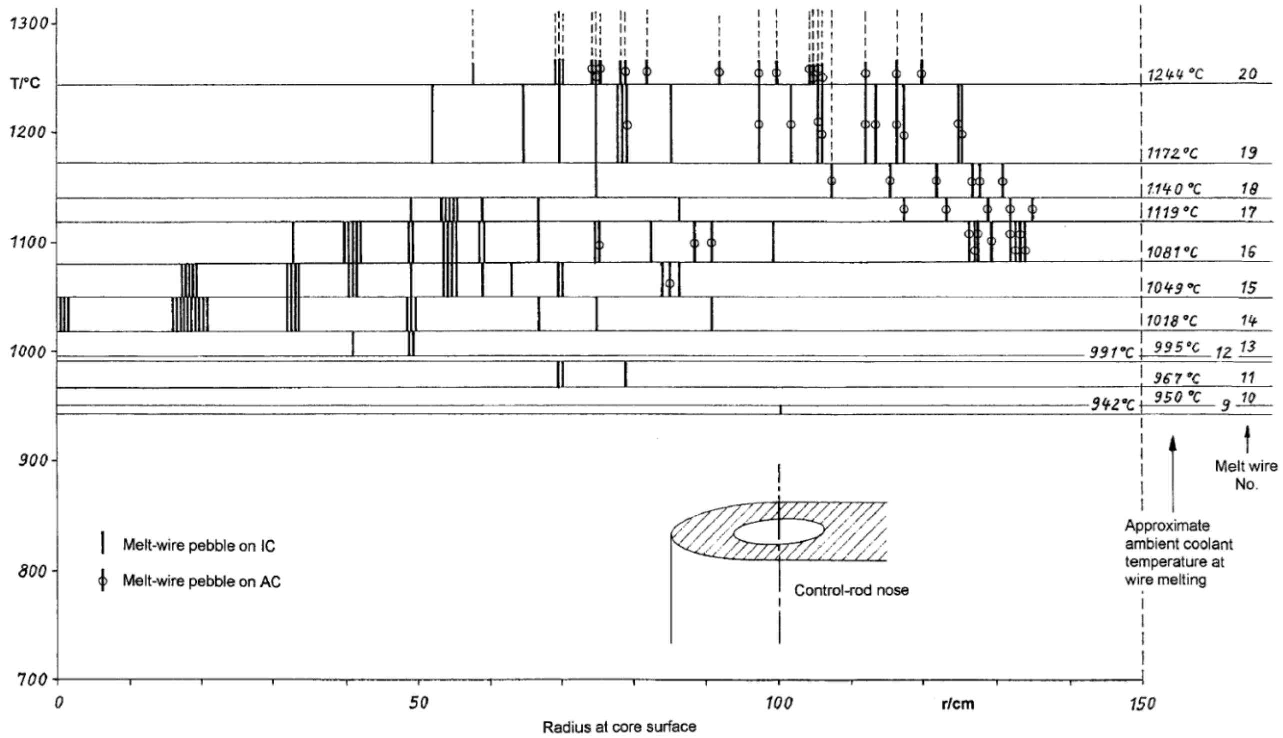


Figure 6. Corrected melt-wire data in terms of AVR core radius representing best estimate coolant temperature profiles at pebble-bed exit [Pohl 2009].

The coolant temperature profiles exhibit, as would have been expected from the uniform fuel concentration and the geometrically undisturbed core, a uniform section of around 1050°C in the inner core. Also the observed decrease at high radii, i.e. towards the vessel wall, is expected. From the transition zone between inner and outer core, temperatures were rising significantly as a result of much higher fuel concentration in the outer core (IC/OC ≈ 0.4). Furthermore, a divergence of the temperatures could be identified resulting from azimuthal differences caused by the graphite noses. While the lower temperature branch basically comprises monitor spheres that were added to the inner core, the higher temperature branch consists predominantly of outer core spheres.

3.2 Calculational Analysis

With the above results, it became obvious that the AVR reactor was operated at considerably higher temperatures than was ever intended. Various efforts were undertaken in understanding the high coolant temperature distribution using computational tools.

3.2.1 Analysis of Bypass flows in the AVR

Assuming a uniform flow (plug flow) through the reactor core, a simple correlation allows to calculate the coolant outlet temperature from the power production in the pebble-bed, the nominal coolant flow rate, and the coolant inlet temperature, often used – also in the case of the AVR – as a general approximation. At full power the helium is circulated through the core by two blowers situated below the core at a rate of 13 kg/s, a core inlet temperature of 270 ◦C, a core outlet temperature of 950 ◦C and pressure of 10.8 MPa. A more thorough analysis of the coolant flow distribution in the AVR core, however, has revealed that the flow was influenced by a number of factors, such as flow paths bypassing the pebble-bed core, the AVR core geometry, and the two-zone core.

Bypass flows are not available to cooling the pebble-bed and therefore result in an increased average exit temperature of the main coolant flow. Several main possible bypass flow paths were identified (Fig. 7) [Viljoen 2008]:

- Cooling flow through the control rod guiding boreholes in the reflector noses, exiting through three horizontal holes in the top plug in each of these nose boreholes;
- Flow between the outer carbon insulation structure and the metal shroud that was reintroduced throughout the axial dimension and also at the fuelling tubes, bypass coolant re-entry into the core or above the steam generator;
- The engineered bypass pipes (due to potential leaking valves) that reintroduce flow just below the steam generator; and
- Various other bypass flow paths dependent on i nstallation details not available, such as welds or piston ring seals

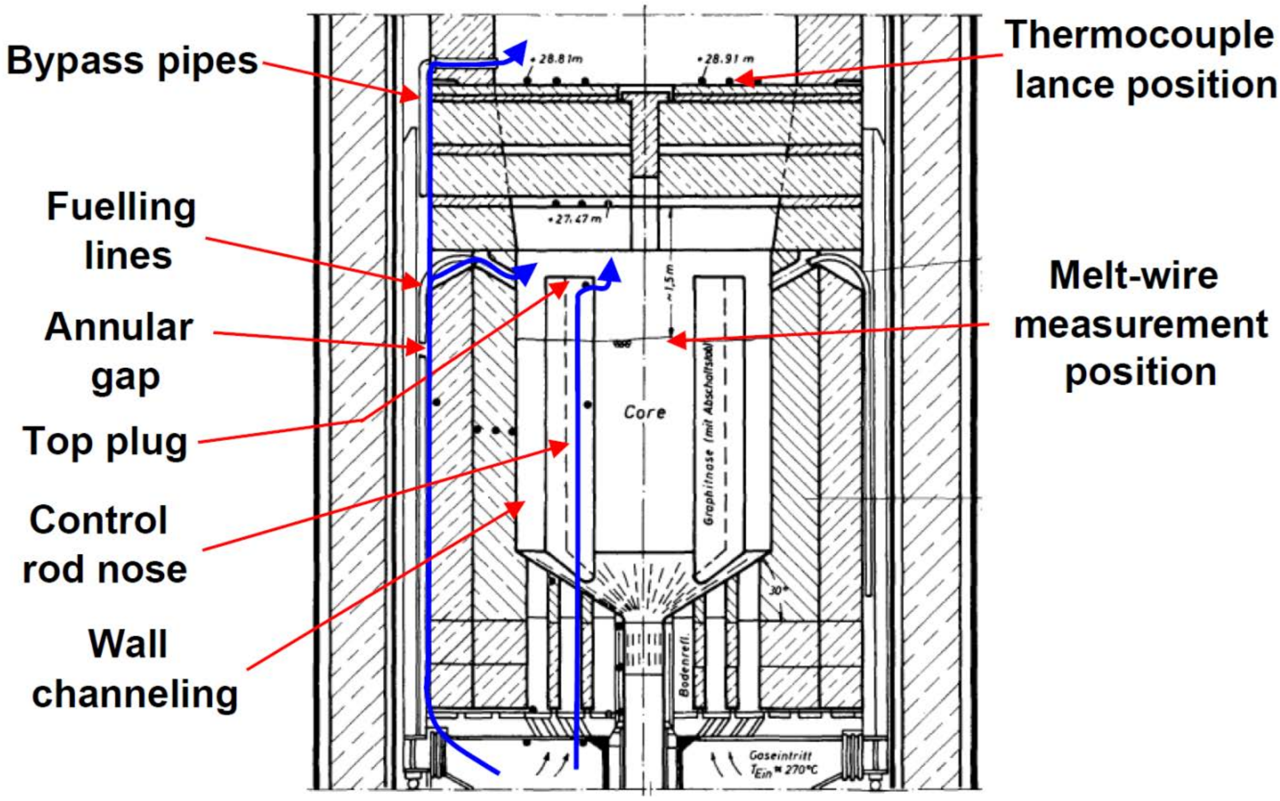


Figure 7. Locations of bypass flows in the AVR [Viljoen 2008].

PBMR conducted a first order estimation of the bypass flows (concentrating on the first two of the above list) by using existing plant data. This was accompanied by CFD calculations with the code STAR-CD modeling the flows in the AVR geometry including the main coolant flow and the bypass flows through the control rod guiding boreholes in the reflector noses and between the outer carbon structure and the metal shroud. In these calculations, the annular gap was varied (since the gap width is unknown) to determine the effect on the main flow temperature.

Results have shown that the core mass flow is very sensitive to the annular gap width. The intention with the original design was that this gap should be very close to zero for cold conditions, but became existent and significant due to differences in the thermal expansion coefficients for graphite, carbon and steel (reflector, carbon insulation, and metal shroud) under normal operating conditions.

From the results, the following conclusions could be drawn [Viljoen 2010]:

- The flow through the control rod nose holes is estimated to be in the order of 5-6% of the total flow in the reactor. The effect on the maximum gas temperature is about 44°C.
- The annulus flow was estimated at 10% based on an average outlet temperature derived from the measured temperatures of the lance in the AVR. This bypass could account for an additional increase in the maximum gas temperature of estimated 92°C. This value, however, may be overestimated if compared to the measurements with a formerly existing additional lance at a different angle.
- The effect of the power distribution, which was simulated by changing the enrichment of the fuel in the inner and outer core regions, was quantified to be almost 90°C on the maximum gas temperature. Just the change in the IC:OC volume ratio from 28:72 to 30:70 results in a difference of 35ºC. This is the uncertainty introduced by the slightly tilted central feeding tube causing different fuel concentrations in the four core sectors.
- A reduction in the mass flow through the core of 17% results in a 250ºC change in the maximum gas temperature.

Assuming a main coolant flow of 81% of the nominal mass flow, while the remainder of 19% is bypassing the pebble-bed, temperatures were estimated to reach 1136°C at the pebble-bed surface as indicated in Fig. 8. shows the results of recent CFD studies of mass and heat transport in the AVR reactor9 taking account of the massive bypass flows outside of the core.

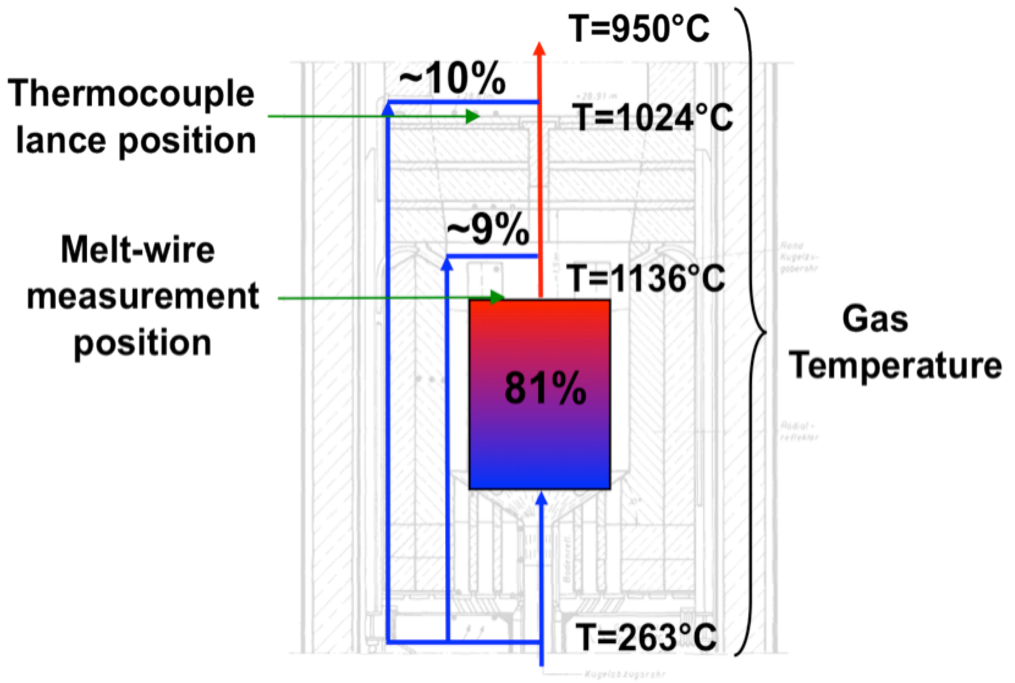


Figure 8. Estimation of AVR core bypass flows from measurements to derive maximum core temperatures based on CFD studies [Reitsma 2009].

A selection of the cases analyzed is displayed in Fig. 9 and compared to the melt-wire data. The shaded regions represent the gas temperature distribution on the top surface of the models. From this comparison it is clear how the simplification to 2D reduces the spread of the data (AVR-3b) compared to the others, especially in the region r=900mm. It can also be seen how the overall distribution is influenced by the different fueling strategies analyzed (AVR-1 vs. AVR-9).

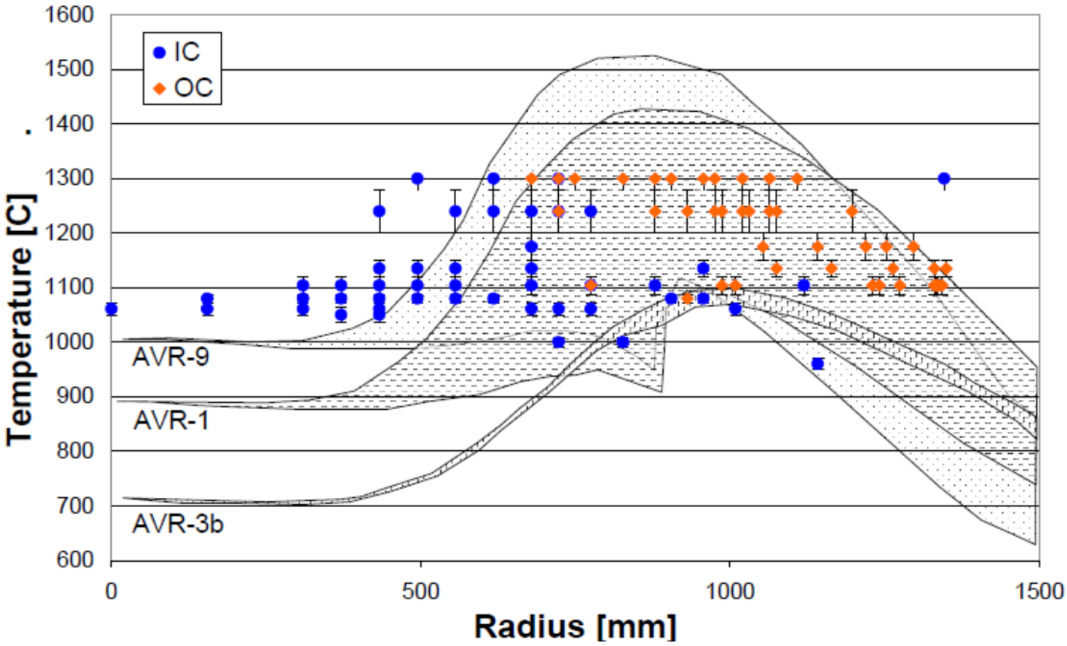


Figure 9. Comparison of PBMR calculation results for temperature profiles in the AVR core with melt-wire experimental data [Viljoen 2010]

These results – although by no means representing the final truth, but rather illustrate the uncertainties introduced with certain assumptions – show that the difference in temperature predicted between the most realistic case and historic calculations can be 300ºC or higher. Added to the historic maximum gas temperatures reported of 1010ºC, gas temperatures could indeed have possibly exceeded 1300ºC in the case of the AVR.

It can be concluded that the reason for the higher-than-expected temperatures can be essentially seen as most likely the result of undiscovered bypass flows (indicated in Fig. 8). Later analyses indeed have shown that the AVR coolant flow had large bypasses outside of the core (e.g. inside the graphite noses or near the feeding lines), and that the temperatures at the surface of the pebble bed were significantly higher than 980°C [Pohl 2009].

3.2.2 Statistical Analysis of Melt-wire Experimental Data

Based on the experimental data of the HTA-8 melt-wire test in the AVR, the possibly underlying temperature distributions were determined by constructing a so-called Quantile-Quantile (Q Q) plot [Ben 2004, Koenker 2005] based upon the probability properties of the histogram distributions [Nabielek 2012].

The analysis was done by ordering the histogram data, calculating probabilities, using these probabilities with a normal distribution to find quantiles. In the Q-Q plot of Fig. 10, it can be seen whether the quantiles and the data are linearly related: a single straight line in this type of display would represent a normal distribution of temperatures. In the case here, there are two parallel straight lines that can be interpreted as two Gaussian distributions with the same standard deviation, but different mean values for the IC and the OC melt-wire spheres. The two normal distributions define the variation of maximum fuel element surface temperatures, center temperatures of the fuel spheres would be higher by a few dozen degrees dependent on operational history, fissile loading and position in the core. The least squares fit yields the two distributions with temperatures of 1100 ± 66°C for one group and 1220 ± 100°C for the other group and their relative weights correspond to the a-priori known values of melt-wire spheres inner core/ outer core. The melt-wire results are well reproduced by normal distributions for OC spheres (red) and IC spheres (green).

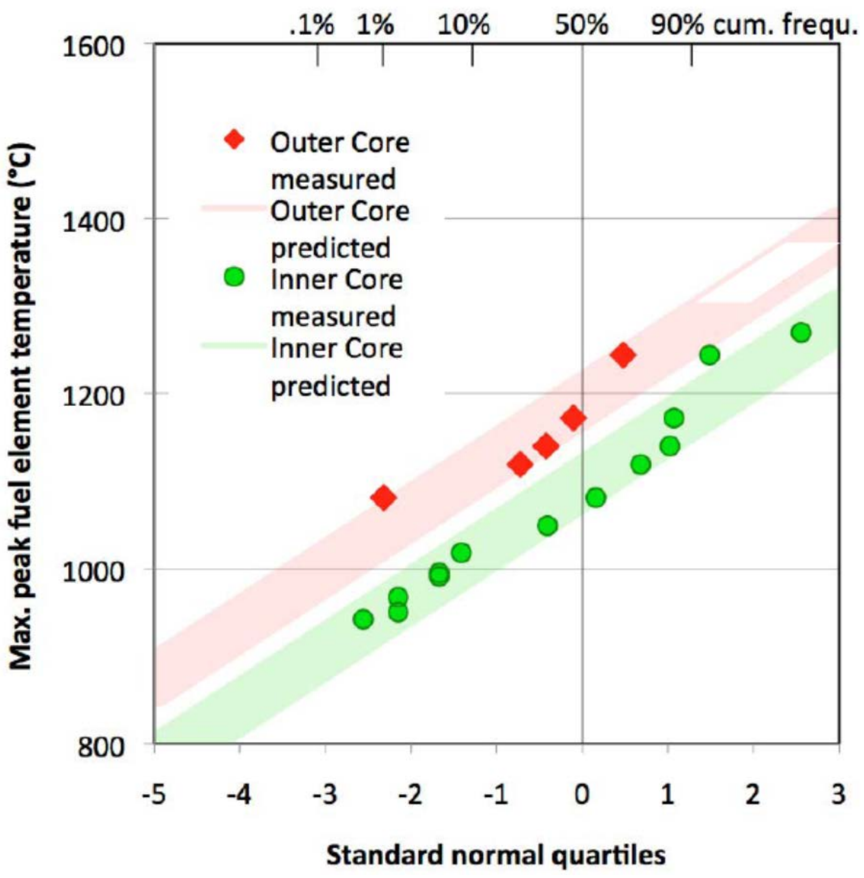


Figure 10. The melt-wire results are well reproduced by two Gaussian distributions in the Q-Q plot display [Nabielek 2012].

The Q-Q plot of simultaneous fit of outer core and inner core spheres yields the two following Gaussian distributions (Fig. 11):

TOC = 1192 ± 64°C
TIC = 1097 ± 64°C

defining the variation of maximum fuel element surface temperatures in AVR between inner core (green) and outer core (red).

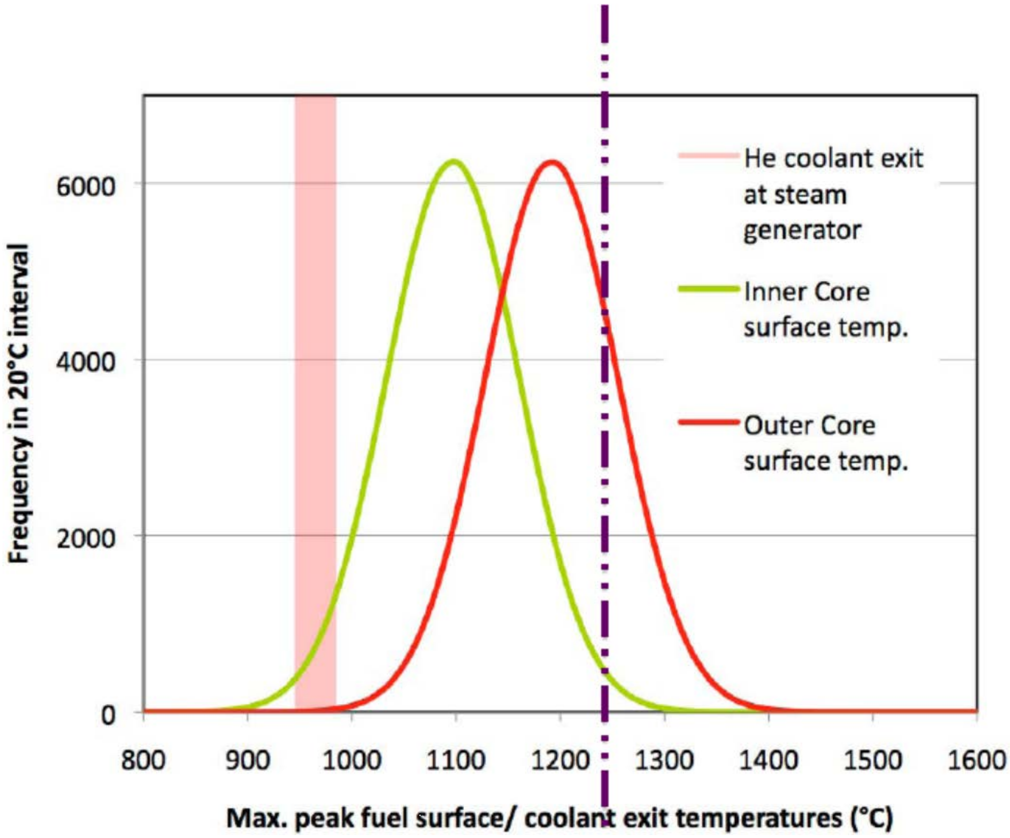


Figure 11. Two Gaussian distributions (1100±66°C and 1220±100°C) defining the variation of maximum fuel element surface temperatures in AVR between inner core and outer core [Nabielek 2012]. Vertical dash-dotted line indicates 1250°C that had been used earlier as maximum fuel temperature in AVR [Nabielek 2012].

The above distributions define the variation of momentary maximum fuel element surface temperatures in the AVR between inner and outer core locations [Nabielek 2012]. Peak central temperatures were calculated to be 37.3°C and 75.6°C higher for the inner and outer locations, respectively. The resulting distributions of the peak temperatures experienced by AVR fuel elements are shown in Figure 34. It is important to note that these very high temperatures were experienced by a limited fraction of fuel element (at the very top of the core) only for a short period on each pass through the core of the AVR. These do not represent the nominal Type GO2 fuel element operating temperatures in the AVR.

Melt-wire pebbles are A3 matrix graphite spheres that do not contain fuel and measured results are therefore characteristic of (more or less) the cooling gas temperatures. Real fuel elements containing fissile and fertile material will show higher center temperatures and a characteristic radial profile towards the sphere surface, which are depending on element power, heavy metal loading, enrichment and burnup. Assuming a typical coefficient of heat conduction of 25 W/m/K and 400 W sphere power for IC fuel, 800 W for OC fuel, sphere center temperatures will be 37.3° and 75.5°C, respectively, higher (Fig. 12) [Nabielek 2012].

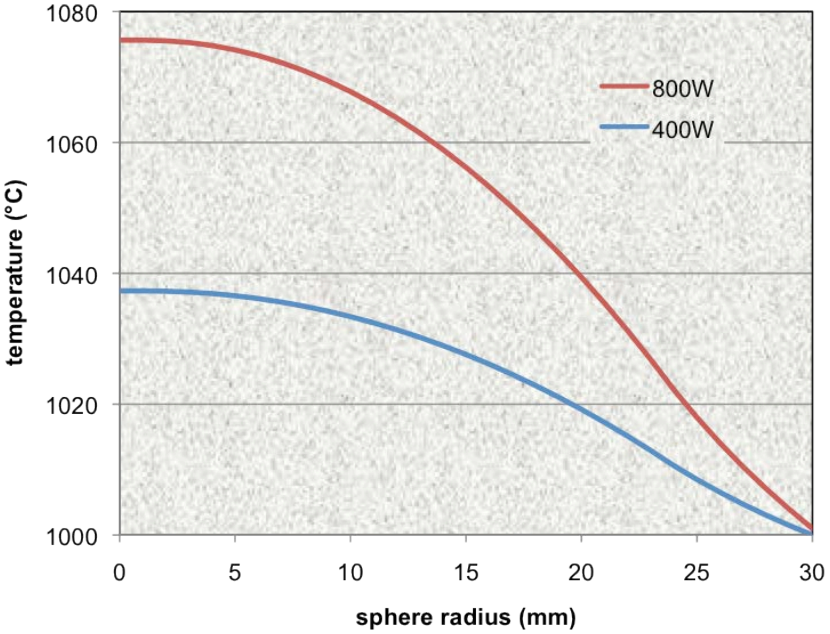


Figure 12. Temperature profiles in a spherical fuel element of the AVR inner core (blue) and the outer core (red). 1000°C has been assumed as sphere surface temperature for the calculations of the profile.

4 Proposal of New Melt-wire Experiments in the HTR-10

New melt-wire experiments are being proposed to be conducted in the Chinese HTR-10 test reactor in a close cooperation between INET and FZJ. The objectives of the tests are

- to repeat the melt-wire experiment in a pebble-bed HTGR that from the design concept is similar to the HTR-Modul, i.e., completely different from the AVR and, for the moment, the only other pebble-bed reactor in the world;
- to conservatively cover the expected temperature range, thus avoiding a major flaw of the HTA-8 experiment;
- to design the monitor sphere in a way that allows for more precise measurements of the wire melting;
- to conclusively prove the non-existence of serious hot spots in the pebble bed.

4.1 Conditions and Status of the HTR-10

The 10 MW pebble bed Helium cooled high temperature reactor, called HTR-10, has been built in the Institute of Nuclear Energy Technology of Tsinghua University. Spherical fuel elements with 60 mm in diameter with coated particles are used and the reactor contains about 27,000 fuel elements in the equilibrium core. Table 5 gives an overview of some main geometrical data, operation parameters, and some characteristic values of the fuel element design.

Table 5. Core geometry and reactor/fuel parameters.

Core diameter	150.0 cm
Average core height	197.0 cm
Number of control rods	10
Thermal power	10 MW
Helium mass flow	4.3 kg/s
Helium inlet temperature	250°C
Helium outlet temperature	700°C
Number of fuel elements	27,000
Average number of core passes	5
Average residence time	1080 d
Heavy metal content	5 g/sphere
U-235 Enrichment	17.0 wt%
Number of coated particles per sphere	8300
Average power density	2 MW/m^3
Average burn up	80,000 MWd/tHM

Different from the AVR reactor, the HTR-10 coolant flow through the pebble-bed is from top to bottom meaning that maximum helium temperatures are expected in the bottom part of the core and not at the pebble-bed surface as in the AVR. In this case, the monitor spheres will gradually increase their temperature as they pass through the core.

After the safety test with the HTR-10 in 2004, the reactor was basically operated during the winter seasons until 2005 to provide district heating to several buildings on INET site (Fig. 13). Since then operation of the HTR-10 was discontinued. Following the Fukushima nuclear accident, all nuclear power plants in China had to undergo a safety review inspection. The HTR-10 was reviewed in May 2011. The fact that the HTR-10 was still not operated until today was said to be due to lack of man power, since the INET work force was concentrated on the design of the HTR-PM. However, the reactor was recently said to resume operation in early 2015.

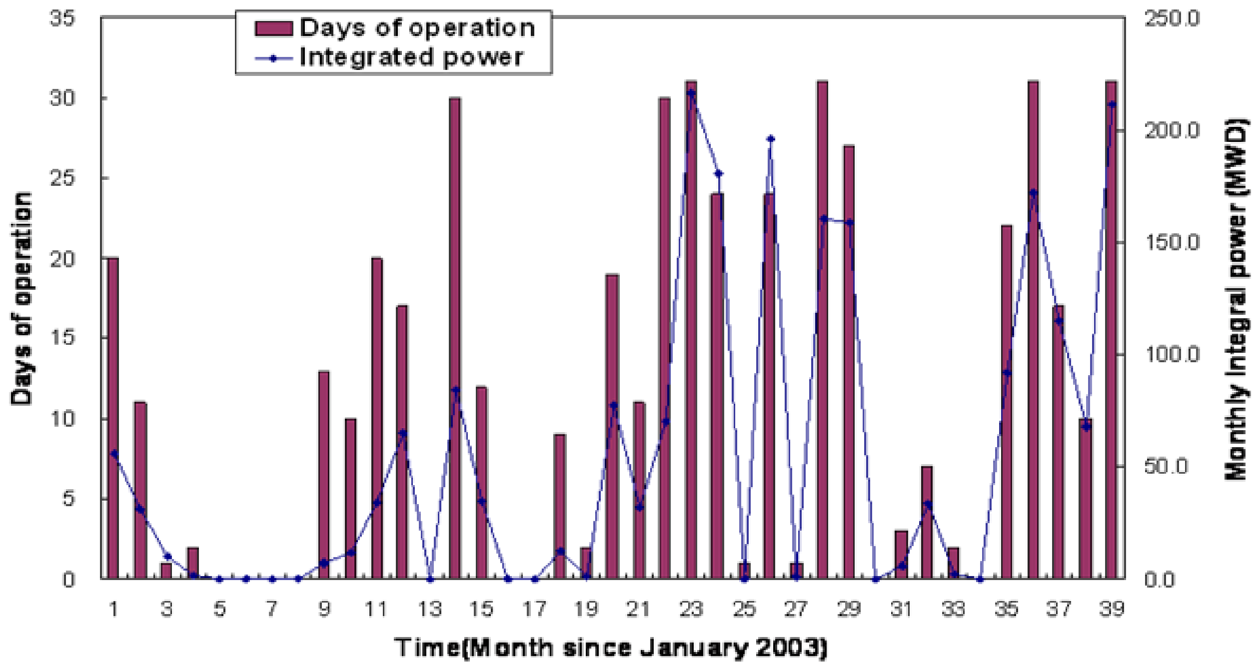


Figure 13. Days of operation and power production in the HTR-10 on a monthly base for the period 2003-2005 [INET].

The HTR-10 core is characterized by a cylindrical geometry and, thus, a pebble flow undisturbed until shortly above the cone-shaped bottom reflector eventually ending up in the discharge tube. Since there is only one (central) feeding line for the fuel elements, there will be no further way of influencing the initial position of a sphere on the pebble-bed surface once it has been added through the feeding line. Drop height of the spheres is about 4 m between top of fueling tube and pebble-bed, while the void above the pebble-bed is ~0.5 m.

The initial core of the HTR-10 was composed of 51% fuel spheres and 49% moderator spheres [Xhonneux 2014]. Up to now, the HTR-10 fuel has accumulated 200 efpd with a final lifetime foreseen to be 700 efpd. At present, the core still contains approximately 30 % of graphite spheres, which would make it difficult for the fuel handling system to distinguish the melt-wire spheres from normal moderator spheres. Here, a special technique for distinction like doping with some radioactive marker would be required.

With regard to the reshuffling times, the maximum discharge rate of the HTR-10 is 125 spheres/day. This means that reshuffling of the complete core takes a minimum of 216 days.

The HTR-10 has the license for operation at an average coolant outlet temperature of 700°C with estimated maximum temperatures not exceeding 950°C. There is, however, a plan for the future to raise the outlet temperature to 750°C (which may modify the choice for the set of melt-wires).

4.2 Design of Monitor Spheres

Based on the monitor sphere design from the HTA-8 experiment as described in the previous figures 2 and 3, and the set of melt-wires employed (see Table 1) some modifications are suggested:

- From the fact that in the HTA-8 test quite a number of monitor spheres had all wires melted, the set of melt-wires should contain one or two wires with a very high melting point (e.g. Ni with 1400 °C) to have at least one wire remaining intact;
- To further increase the precision to decide when a melt-wire is considered melted in the range between solidus and liquidus temperatures, more eutectic / pure metals for melt-wires should be chosen where the temperature interval while melting is smaller (Fig. 14). In the monitor spheres of HTA-8, only one pure metal for temperature calibration (Ag) was used (see Table 1). Optimum choice of materials, however, will finally depend on the gas outlet temperature of the reactor.
- Due to the still large amount of moderator spheres in the actual HTR-10 core, the monitor spheres should be marked/doped to allow their identification in the fuel handling system.
- The employment of activation wires inside the monitor spheres for neutron dose measurements may even allow estimating the radial position ("flow channel") of the sphere.

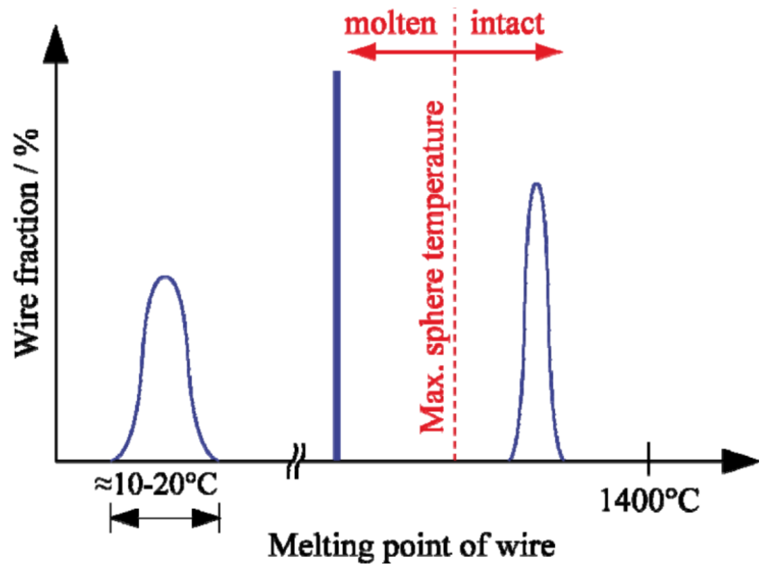


Figure 14. Different temperature intervals between solidus and liquidus depending on the material.

Prototype monitor spheres could be tested for exact temperatures of the melting wires in experimental installations like NACOK.

4.3 Assumptions for Test Conditions

Reactor operating conditions in terms of coolant temperatures are licensed for an average outlet temperature of 700°C. It is planned, however, to later raise the gas outlet temperature to averaged 750°C. Corresponding fuel temperatures are certainly depending on the degree of burnup the fuel spheres have achieved, but are expected to not exceed 950°C.

In a preceding experiment, a few monitor spheres, say 10, could be introduced into the HTR-10 core to determine maximum fuel surface temperatures with the data obtained to optimize main tests.

The main experiment is proposed to comprise 60 monitor spheres at four different core heights in the HTR-10 (Fig. 15). This could be managed by inserting during normal operation at one time 15 spheres. The next set of 15 spheres should be introduced after about a third of the average core passage time through the core, so to be done for the third and fourth set of monitor spheres. By this time, the first set introduced should have arrived at/near the discharge tube entrance. At this moment in time, reactor operation should be discontinued and the total pebble-bed be reshuffled in the shutdown state to retrieve all monitor spheres.

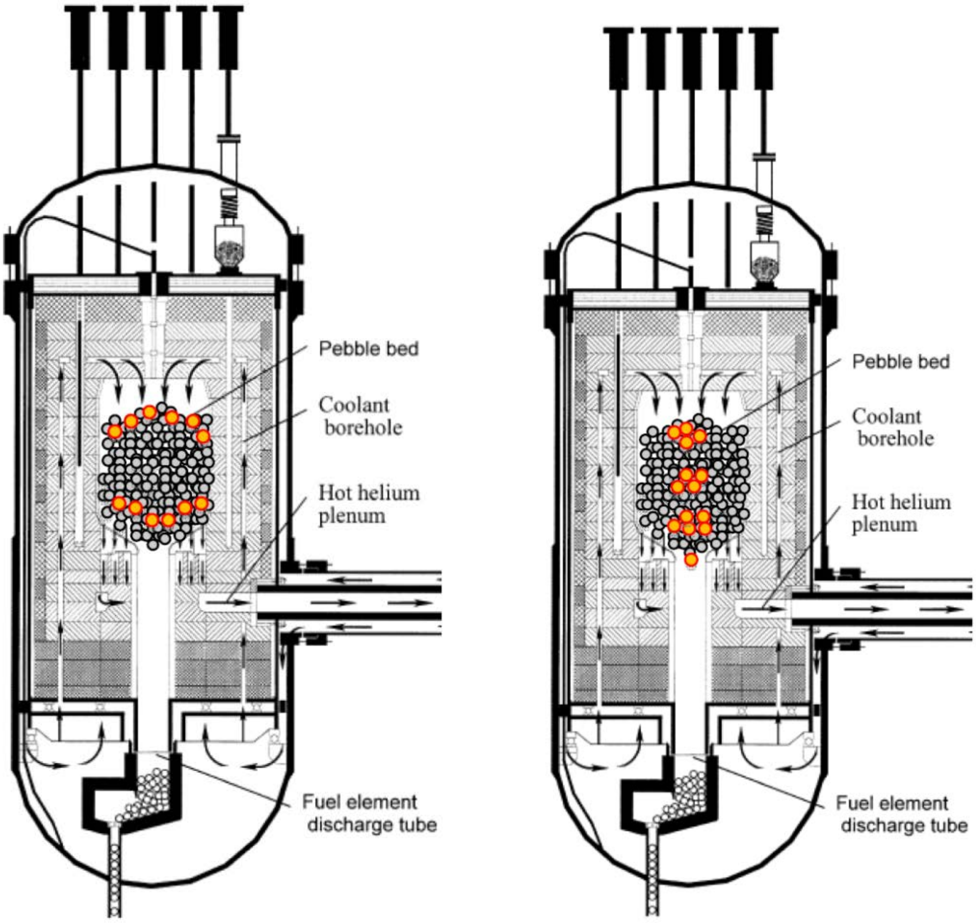


Figure 15. Monitor spheres at different core heights in the HTR-10.

Alternatively, the process could be conducted in the reverse order: create the four layers of monitor spheres (as described above) in the shutdown reactor and then start normal operation for a certain time, and then retrieve the monitor spheres in the (again) shutdown reactor.

The first of the above described procedures has the advantage that all spheres be cooled when stopping reactor operation. In particular, this will avoid an overheating of the spheres in the upper part of the defueling chute that might occur during normal reactor operation. For clarification of this issue, it could also be considered having additional monitor spheres already advanced into the defueling chute before stopping reactor operation.

Possible future experiments may include melt-wire spheres to be i ntroduced during abnormal operational states of the reactor to measure highest fuel element surface temperatures like during accident simulation testing (e.g. LOFC).

5 Summary and Conclusions

With the HTA-8 experiment in the AVR in 1986, a test was made in a real high temperature reactor to obtain information on the maximum temperatures that fuel elements would see. Due to the upwards-directed coolant flow in the AVR, the maximum temperatures are expected to occur at the pebble bed surface. The fact that the measured temperatures were higher than expected has initiated a thorough investigation of the coolant flow conditions in the reactor that might explain the results. At the same time, it is impressive, how well the all-ceramic fuel has survived these conditions.

A number of possibilities have been identified to explain these high temperatures. Of these, the peculiar geometry of the AVR design with the four buttresses (noses) protruding into the core and the strong effects of AVR core bypass flows of the coolant passing through the tips of the noses and through the outer graphite structures have been considered the potentially largest contributors to higher-than-expected fuel temperatures during normal operation. This conclusion was secured by accompanying calculations (both deterministic and statistical) that found plausible explanations for the higher temperatures in good agreement with the measurements from the monitor spheres.

Most of these uncertainties are unique to the AVR. For a present-design small modular high temperature reactor, a much more homogeneous pebble flow through the core is expected as well as the maximum temperatures to occur in the bottom part of the active core.

For the purpose of proving and demonstrating the different temperature distribution to be not affected by any assumed randomly occurring hot spots inside the core, new melt-wire experiments are being proposed to be conducted in the Chinese HTR-10 test reactor. For this purpose, the monitor sphere design as employed in the HTA-8 test should be taken with a few modifications.

Melt-wire tests to be conducted in the HTR-10 could even go beyond what was done in the AVR. Choosing a certain way of reactor operation, tests suggested would allow assessing axial and radial temperature profiles. Such tests could not have been conducted in the AVR, not to mention any other type of nuclear reactor.

All planning and design of experiments, conduction of tests, and analysis of the results should be made in close cooperation between INET and FZJ.

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