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Core-Adjacent Instrumentation Systems for Pebble Bed Reactors for Process Heat Application - State of Planning

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Zusammenfassung

In den vergangenen Jahren wurden die Planungsarbeiten sowie theoretische und experimentelle Entwicklungsarbeiten für die corenahen Instrumentierungssysteme großer HTR weiter vorangetrieben. Die laufenden Arbeiten und die hierbei erzielten Ergebnisse für Neutronenflußsysteme und die betriebliche Messung von Heliumtemperaturen von 1253 °K werden vorgestellt und diskutiert.

Abstract

Planning and theoretical / experimental development work for core surveillance instrumentation systems is being performed to meet requirements of pebble bed reactors for process heat application. Detailed and proved instrumentation concepts are now available for the core-adjacent instrumentation systems. The current work and the results of neutron flux measurements at high temperatures are described. Operation devices for long-term accurate gas outlet temperature measurements up to approximately 1423 °K will also be discussed.

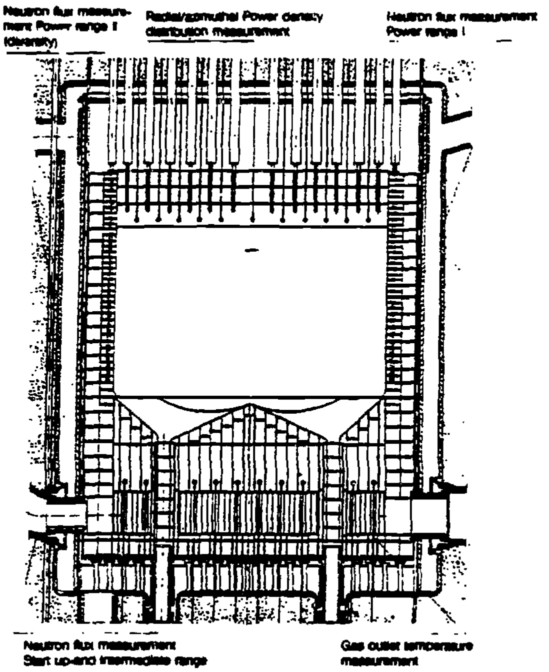
1. Introduction

More sophisticated instrumentation has to be considered for large HTR's for process heat generation in comparison to HTR's for electricity generation.

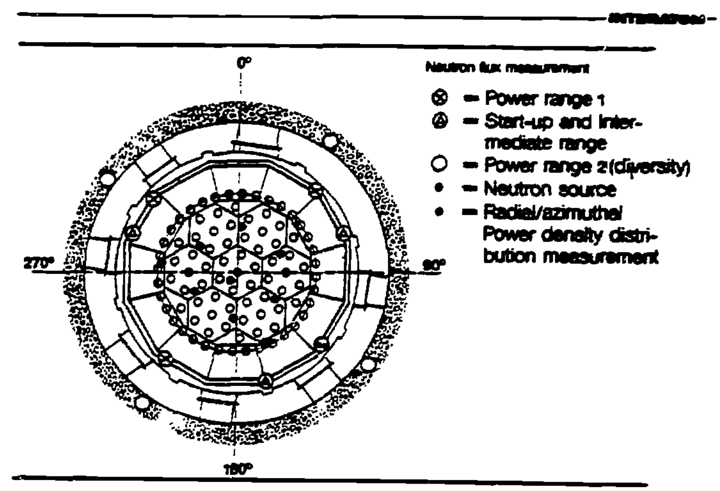
In the Federal Republic of Germany current activities are aimed at the development and construction of a plant for the gasification of brown coal and mineral coal to synthetic natural gas (SNG). This plant, which is called the Prototype Nuclear Process Heat (PNP), is designed for 500 MW_{th}, the core outlet temperature amounts to 1253 °K.
As in large LWR's, the most important nuclear and thermodynamic properties of the core during operation are of major concern; i. e. mainly the power density and gas outlet temperature distribution. This is especially the case in the PNP, as the high gas outlet temperature of 1253 °K necessitates the avoidance of unbalanced loads in the core in order to preclude additional heat exchanger loading.

Different works / 1,2 / have been able to show that it is possible to detect disturbances in the power density distribution with sufficient accuracy using the following three core-adjacent instrumentation systems (Fig. 1):

- Neutron flux measurement
- Gas outlet temperature measurement
- Radial/azimuthal power density distribution measurement



Core-adjacent Instrumentation Systems for a large Pebble Bed HTR Fig. 1a



Core-adjacent Instrumentation Systems (PNP 500)

Fig. 1b

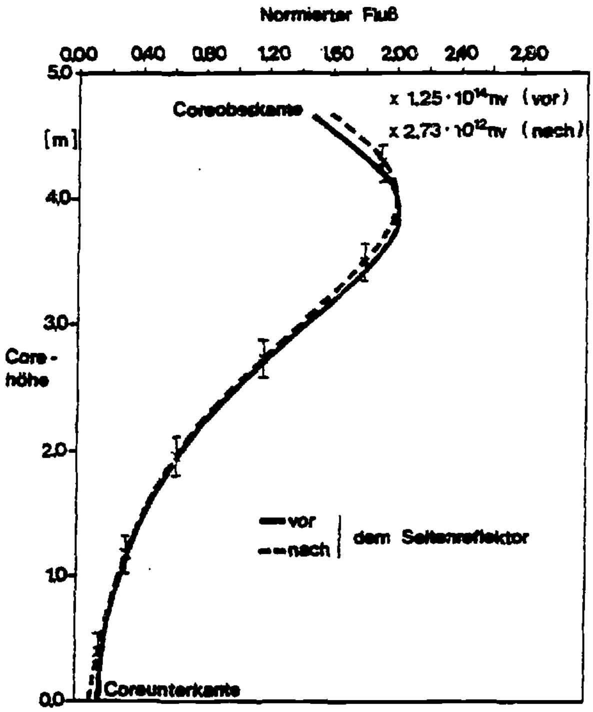
The concepts, the state of planning and some R + D results are explained below.

2. Neutron Flux Instrumentation

- The neutron flux instrumentation provides the reactor protection system signals which serve to detect reactivity disturbances and to give information on the axial power distribution.
  In the case of reactivity accidents, the neutron flux is the only process variable which detects the accident quickly enough. In accordance with the German Safety Regulations / 3 /, the neutron flux in the power range must therefore be recorded by diverse instruments, i. e. 2 completely separate measuring systems are installed. These operate with different measuring methods.

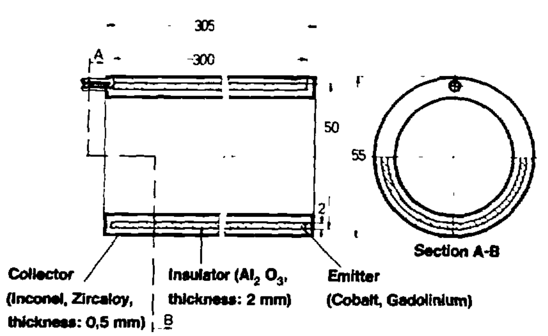
The first system is installed between the side reflector and the thermal shield (in the cold gas gap). With reference to the power range, four measuring positions are azimuthally distributed at approx. 90 ° . Six equally spaced neutron detectors (Large Area Self-Powered Detectors / 4,5 /) are axially distributed in each of these four measuring positions (Fig. 1). It was possible to demonstrate that these six detectors reproduce the axial neutron flux distribution in front of the side reflector well. As a result, axial flux mapping is possible (Fig. 2).

Fig. 2



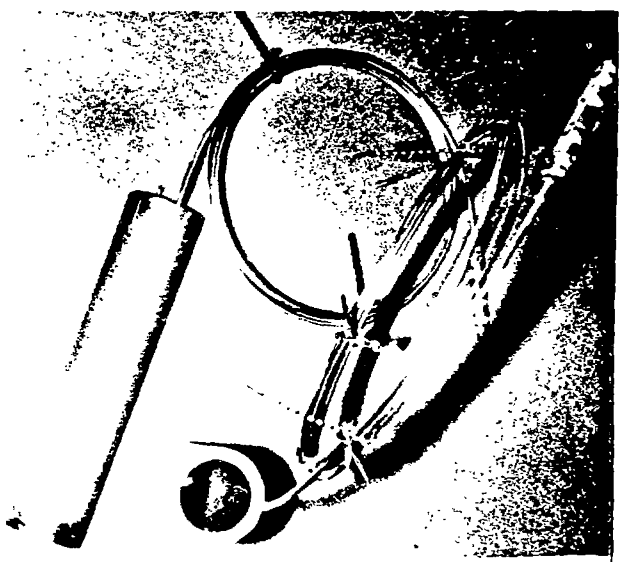
Axialer Neutronenflußverlauf,
vor – und nach dem Seitenreflektor

At an early stage of component development it became evident that the ionisation chambers coated with B-10 or U-235 cannot be used for this measuring system because of the high temperature loading (723 °K - 773 °K, gamma heating included). It therefore seemed appropriate to employ high temperature reactor self-powered detectors which had so far only been used for incore measuring systems for the out-of-core neutron flux instrumentation of the PNP. In contrast to the conventionally designed detectors, large area SPND will be provided and developed (Figs. 3, 4) to guarantee a measuring signal which is considered sufficient over the whole measuring range (10^{-8} - 2×10^{-6}A) at a prevailing thermal neutron flux of about 6×10^{12}nv (axial averaged). Prototypes of these large area SPND (Fig. 4) are being manufactured by Hartmann + Braun, Munich and the Nuclear Research Centre, Jülich.



Large-Area Self-Powered Neutron Detector

Fig. 3



Prototyp eines großflächigen SPN-Detektors

Fig. 4

The six neutron flux detectors of each measuring position are installed in a guide tube. It reaches from the upper edge of the bottom reflector to the terminal box in the control rod drive room (or halfway up the prestressed concrete vessel). Cold gas (573 °K) flows through the guide tubes and cools the SPND detectors. The detector signals are conveyed out via mineral insulated cables, which, however, are replaced by flexible cables insulated with glass-fibre in the upper part of the guide tube to facilitate assembly and disassembly of the detector.

As regards the start-up and intermediate range of the neutron flux measurement, 3 measuring positions are also provided in the gap between the thermal shield and the side reflector. Each measuring position consists of a thimble which is externally cooled by cold gas. As a result, the detectors for the start-up and intermediate range do not come into direct contact with the reactor atmosphere. Each measuring position accomodates two detectors for the start-up range (pulse fission chambers) and one detector for the intermediate range (AC-fission chamber), the maximum temperature loading of which amounts to approximately 723 °K. In order to protect the detectors from too high radiation and temperature loadings at full reactor power, they are retracted by about 7.5 m from the measuring position into a standby position once a reacor power of $\gtrsim$ 10 % has been attained.
The three measuring ranges of the neutron flux instrumentation (start-up range, intermediate range, power range) cover a range of approx. 5×10^{1}nv to approx. 7.5×10^{12}nv.

The second diverse neutron flux instrumentation is installed in the prestressed concrete vessel directly below the liner (Fig. 1). Four neutron flux detectors, which are axially equally spaced over the core height, are installed in each of the four measuring positions displaced from each other by 90°. The low temperature permits the use of boron-lined ionisation chambers with a neutron sensitivity of 10^{-13} A/nv. Reproduction of the axial neutron flux distribution at the core edge is not longer possible with this instrumentation or can only be achieved with a large error.

The concept of diverse neutron flux measurement does not require any development because it has been tested many times in PWR's.

3. Measurement of the Gas Outlet Temperature Distribution

In particular high temperature reactors for process heat with He-outlet temperatures of 980 °C require the gas outlet temperature profile to be as constant as possible in order to guarantee the necessary lifetime of the heat decoupling components (He/He heat exchangers, steam reformer).

For this purpose, about 20 exchangeable NiCr-Ni and PtRh-Pt thermocouples (i. e. 1 thermocouple per m^2 core section) will be equally spaced on the core bottom section. The thermocouples (TC) located in the graphite structures of the core bottom will be designed for a graphite-helium ambient temperature of 1150 °C. The robust design (6 mm Ø, about 0.8 - 1 mm thickness of the outer sheath's protective ceramic tube to avoid direct contact of the thermocouple sheaths with graphite structures) will ensure that the failure rate during the lifetime of $\gtrsim$ 4 years is as low as possible. The TC response time is $\approx$10 sec. in helium at 40 bar, which is admissible. With regard the sheath alloys resistant to carbonization and He-impurities, tests carried out under HTR conditions showed that Incoloy 800 and DIN 1.4981 are suitable for these purposes. Long-term tests ($>$ 1 a) have been carried out under realistic HTR conditions to verify the suitability of the above sheath alloys for thermocouples / 6 /.

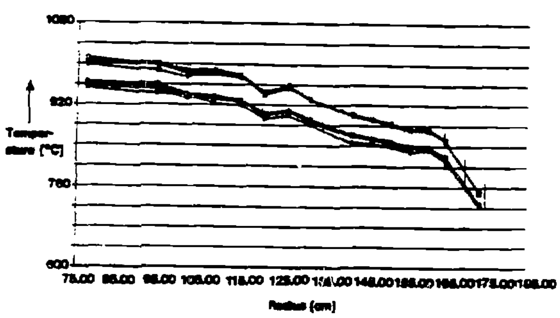
For calibration purposes, all the TC for measuring the gas outlet temperature distribution will be equipped with an integrated noise thermometer / 6, 7 / so that a calibration accuracy of $\pm$ 0.5 % is guaranteed. Let me give some details about the constructive design (exchangeable TC):

The axial measuring position of all TC's is approx. 10 - 15 cm above the lower edge of the core bottom in boreholes conveying hot gas. The TC's run axially in straight lines from the measuring position through boreholes in the columns of the hot gas plenum and through brick-stones into the prestressed concrete vessel (PCV). Here each TC runs through a corresponding shutter tube to the outlet from the PVC where it ends in a terminal box or changes into a compensating lead.

The non-exchangeable TC's are distributed among 3 shutter tubes, jointly conveyed through the PCV and guided to the individual measuring positions after entering the brick-stones.

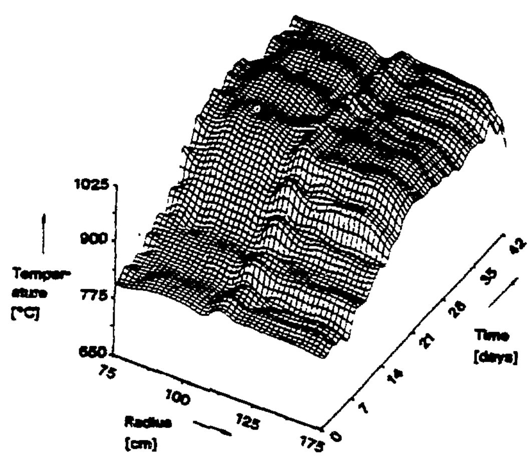
The length of the thermocouples between measuring point and exit from the PCV is approx. 12 m. About 1.2 m of this length is within the hot gas area, i. e. the thermocouple including cable is exposed to a nominal temperature of 1253 °K along this stretch.

The informative contents of the hot gas temperature profile measurement in a pebble bed HTR required for operational purposes and the understanding of the high temperature behaviour are described by WISCHNEWSKI et al. in / 8 /.
Measurement results are given in Figs. 5 and 6. Fig. 6 demonstrates the behaviour of the hot gas profile during a period of 42 days, whereby the average gas outlet temperature has increased from about 1133 °K to about 1243 °K. Fig. 5 shows a detail from this period of time during which the average gas temperature outlet was increased by about 40 °K.



Radial Temperature Profile in the Top-Reflector of AVR

Fig. 5



Temperature Profile during 42 days of AVR

Fig. 6

4. Measurement of the Radial/Azimuthal Power Density Distribution

The task of the instrumentation installed in the top reflector of the PNP 500 is to detect the radial / azimuthal power density distribution of the upper core zones - up to approx. 0.5 m into the pebble bed. The signals received serve for:

- Optimization of the reactor operating mode
- Experimental verification of the core design
- Detection of accidents (e. g. unbalanced loads, false loads)

It is not planned to use the measuring system for reactor protection or reactor closed loop control tasks.
The fission chamber signals are conveyed to the process computer for evaluation and are displayed in the control room.

The radial / azimuthal power distribution is detected by measuring the fast neutron fluxes in the top reflector, because the thermal neutron flux no longer reflects the power distribution in the upper core zones due to the cavity between pebble bed and top reflector. Miniature fission chambers with U-238 or Np-237 coatings are planned as sensors. The detectors are provided with a 4 mm thick shielding of B_4C to preclude a slowly developing thermal neutron sensitivity (Cause: breeder effect in the fissile material).

The detectors are continuously located at their measuring point approx. 10 cm above the lower edge of the top reflector. A fast neutron flux ϕ_f of approx. 1×10^{13}m, a thermal neutron flux ϕ_{th} of approx. 6×10^{13}nv and a γ-dose rate of approx. 5×10^{7} R/h prevail at this measuring position. The detector temperature is approx. 703 °K. The fast neutron sensitivity of an Np-fission chamber amounts to approx. 5×10^{-19} A/nv. The dimensions are as follows:

Detector length:	without B_4C shielding	103 mm
	with B_4C shielding	124 mm
Detector outer diameter:	without B_4C shielding	9 mm
	with B_4C shielding	18.5 mm

The detectors can be retracted if necessary. For this purpose, each measuring position is equipped with a drive unit which permits a hub of 3.5 m.

A gas outlet bypass stream (approx. 573 °K) cools the fission chambers. In the case of the PNP 500 reactor seven measuring positions are planned. These are equally spaced over the core cross-section. Each of the detectors is located in a vertical shutter tube (outer diameter: 120 mm) and they therefore have sufficient space between the control rods. The detector linear drives are integrated into these shutter tubes.

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