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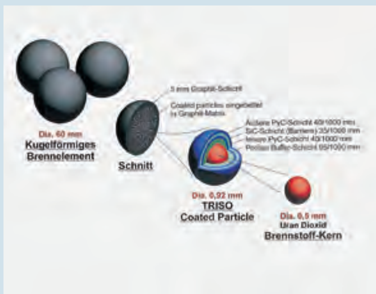
Urban Cleve

The Technology of TVHTR-Nuclear-Power Stations With Pebble Fuel Elements



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The Technology of TVHTR-Nuclear-Power Stations With Pebble Fuel Elements

Power and Heat for the Production of Drinking Water Out of Sea-wastewater and/or Hydrogen in Combination with Solar Plants

Urban Cleve

Basic design features and operational experiences

Design principals of TVHT reactors

The German development of TVHTR Power Stations *[4, 5, 6]* was primarily initiated through the ideas of *Prof. Dr. R. Schulten*. He developed this technology in the 1950`s while employed by *Brown Boveri*. *Dr. Schulten* became CTO at the new *BBC/Krupp Reaktorbau GmbH* in Mannheim and later as Professor and Director of *KFA-Jülich Nuclear Research* Department *[6]*. *Dr Schulten* stated:

"In the field of Nuclear Energy, the AVR Reactor occupies a specific unique position. Helium gas cooled, graphite moderated, inherently safe and the hottest reactor worldwide. It is the story of the only pure German development of nuclear power plant technology."

Main design features of the AVR Reactor are:

- Spherical graphite fuel elements which contain the fission material.
- Graphite as main core construction material and as reflector and moderator.
- A safe integrated reactor concept with helium used for the cooling gas.
- Enclosed primary helium gas circuit in one reactor vessel.

These are the most important basics for safe operation. The goal until now has been the construction of an inherently safe nuclear power station with out-standing nuclear and design safety *[6, 19]*.

AVR power station

The technology of the AVR was set up from "zero", **Figure 1**, as there was no prior experience with engineering and design of components operating in a helium environment *[1, 2]*.

The complete new development of all components was a huge challenge and consequently routine delays and cost increases were experienced. Additionally, the TÜV, a regulatory oversight business, underwent phases of learning and had to develop better testing methods for the nuclear power stations. During cold tests under normal environmental temperature and pressure all components were extensively and successfully tested.

Fig. 1.
The AVR 46 MWth/15 MWel Experimental HTR Power plant.

- The steam generator, **Figure 2**, was constructed several times and during production new test procedures had to be developed. After completion it underwent a helium pressure test, the first of its kind worldwide.

Fig. 2.
The AVR steam generator during manufacturing.

- The absorbing rods functioned hundreds of times without showing any problems. After installing into the reactor and tested in a helium atmosphere they failed completely. It needed extensive design improvements, after which functioned perfectly.
- All components of the pebble charging system were tested over years of operation. They showed only some problems during operation and improvements could be performed under radioactive conditions using specially designed equipment.
- Nearly 600 helium valves manufactured by suppliers failed completely and had to be newly designed and tested under helium conditions. The new design (by BBK) was a great success. No further problems were identified after testing in a helium atmosphere.

All problems had been solved and an average yearly availability of 66.4 % with a maximum of 92 % per year was achieved during 23 years of operation including the periods for which numerous experiments were performed.

This probably established a world record for a completely new reactor design.

The section through the AVR with inner core, the graphite reflector, thermal shield, inner reactor pressure vessel, biological shield 1 and the outer pressure vessel is shown in **Figure 3**.

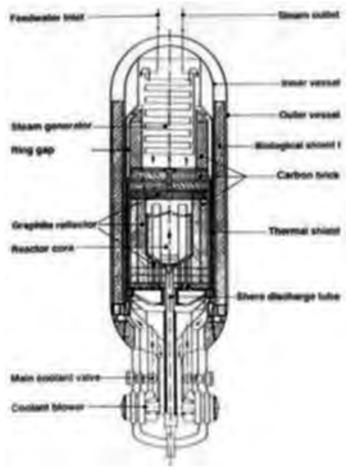

Fig. 3.
Section through the AVR reactor.

Fig. 4.
View into the core of the AVR.

- We had only one major problem, an incident of INES 1. Only one of the some thousand weldings of the steam generator leaked. After several months of repair the steam generator functioned very good again with full capacity. *[6, 7]*.
- The inner core structure, **Figure 4**, has a diameter of 3 m and 4.5 m high.
- The fuel charging unit, *[7, 8]* **Figure 5**, designed and developed by BBK, with all its numerous components functioned sensationally well. In 23 Years of operation only 220 pebbles were discharged. This was a figure of 0.0092 % of the 2,400,000 moved pebbles. A basic diagram of the fuel cycle shows **Figure 6** *[7, 8, 9]*.

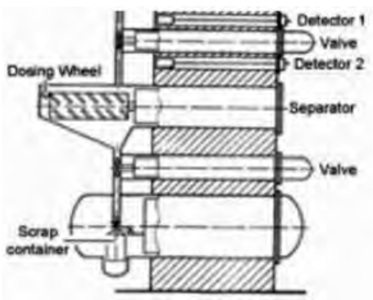

Fig. 5.
View into the core of the AVR.

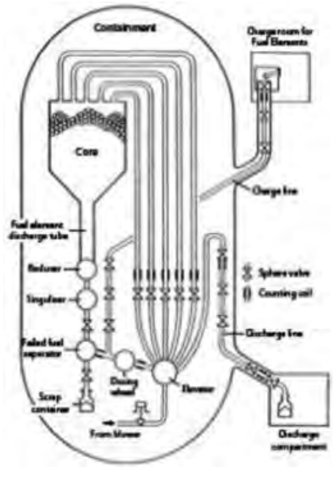

Fig. 6.
Fuel cycle of pebble bed transportation system.

- After decommissioning in 1989 it was ascertained, that the complete graphite interior had not moved by one millimeter. It looked as newly installed. Only some very small accumulations of graphite dust in some corners could be detected.
- According to the INES scale only one incident occurred with "1", all other events had an INES level of "zero" during 23 years of operation *[6, 7]*.
- Because of the excellent functioning of all de- and remounting equipment for the components, repairs could be done during operating of the reactor. No personal had been injured by radiation.
- The AVR had to be shut down only by political reasons in 1988. It was an excellent test reactor for a variety of different fuel elements with different kinds of compositions of Uranium, Thorium and Plutonium. All these international experiments must be stopped, a very poor decision for future development of HTR-Power-Stations worldwide.

As a result, it can be confirmed, that the operation of the AVR Reactor was a unique success story.

The AVR modul reactor

An AVR design, modified with an integrated He_{prim}/He_{sec} heat exchanger and only one steel pressure vessel, is the far best developed and operational completely tested.

Fig. 7.
THTR-300 MWel/750MWth Demonstration Power Station.

Modul concept of a Small Model HTR (SMHTR) up to 100 MWth/40 MWel

The design of the THTR-300el-Demonstration Nuclear Power Station

The basic design of the THTR-300 Power Station started in 1965, **Figure 7**. No prior experience from the AVR could be brought into the new design (**Figure 8**).

The main design differences of the THTR-300 to the AVR are:

- Pre-stressed concrete pressure vessel (PCPV) instead of two steel-vessels (**Figure 9**). The dimension was 25 meters in diameter and 28 meters high. The PCPV was chosen primarily for safety reasons. A model with a scale of 1:20 was tested with water pressure. Very small cracks occurred at a pressure between 90-120 bar. The main crack was Occurred at 190 bar. After a pressure drop to 40 bar the vessel was nearly gastight again. This test was the baseline for the calculation of the THTR-300 PCPV *[28]*.
- A closed inner circuit of helium cooling gas to avoid the release of fission products and graphite dust. This was the most important design factor to avoid release of contaminated primary helium gas or contaminated particles of graphite dust.
- Helium gas flow from top to bottom.
- TRISO-Pebbles as fuel elements.
- All other components such as blowers, fuel element feeding and handling components, graphite structures, etc. were designed and improved very similar to the components of the AVR and showed no problems.

New nuclear calculations of the reactor physics showed, that the diameter

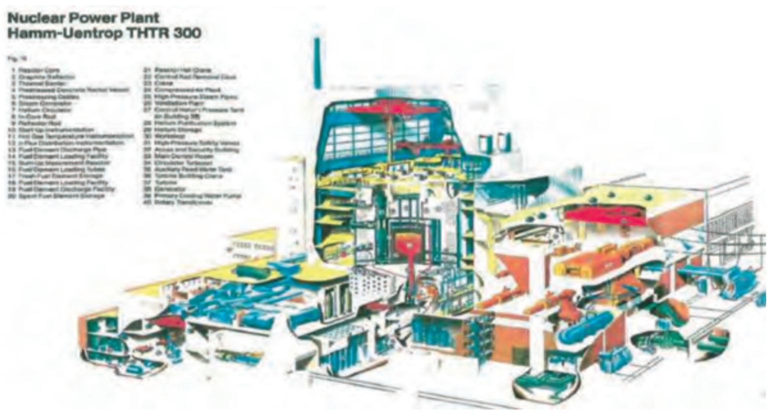

Fig. 8.
Survey of the THTR-300.

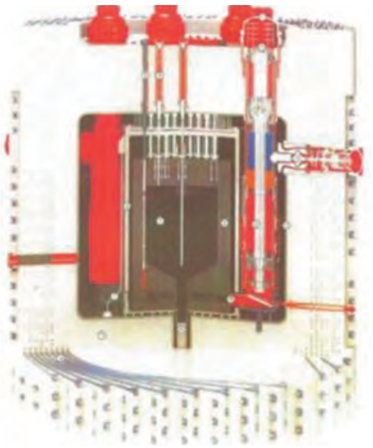

Fig. 9.
Pre-stressed concrete pressure vessel and THRT-300 core.

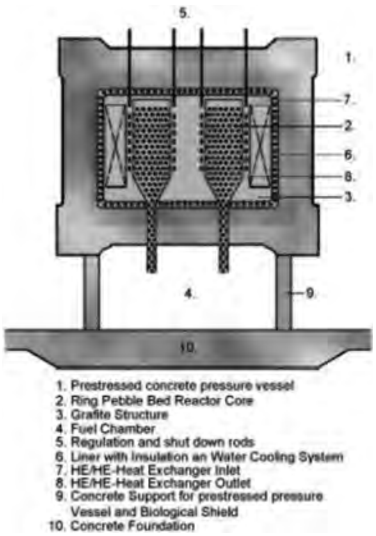

Fig. 10.
Concept of pebble bed ring core.

of the core with 5.6 m was too large, so the shutdown rods in the surrounding graphite reflector could not cool the pebbles to the low temperatures necessary in case of shutdown of the reactor. Until this time no prior experience was available with the behavior of the graphite core structure during extended operation. Therefore, the decision was made to insert the shutdown rods directly into the pebble bed with the potential danger of crushing the fuel elements. An alternative design with a pebble bed ring core PBRC (**Figure 10**) *[4]* could not be chosen, as no prior experience existed with the behavior of the graphite structure in the AVR. Testing of the insertion of rods into the pebble bed could not be performed under operational conditions. This decision was discovered later when operating the THTR-300 during commissioning of the power station which was a terrible mistake. There was no nuclear risk, but 0.6 % of the pebbles ruptured which was substantially higher when compared to the results of the AVR at 0.0092 %.

All operational difficulties with the THTR-300-Reactor based on this unique problem.

Table 1 *[14]* shows the differences between calculated design parameters and the parameters in operation. Smaller differences cannot be calculated and it was determined that without the problems of a high percentage of crushed pebbles, the THTR-300 would have been operated with the same high operational times as obtained with the AVR.

Plant parameter	Units	Calculated values	Measured values
Reactor thermal power	MW	761.65	763.5
Circulated speed	rpm	5,369	5,361
Helium flow	kg/s	297	293.9
SG inlet He temperature	°C	750	750.4
SG outlet He temperature	°C	247	245.9
Feedwater flow	kg/s	254	253.9
Main steam temperature	°C	545	544.3
Main steam pressure	bar	186	184.9
Reheat flow	kg/s	247.3	237.9
Reheat temperature	°C	535	532.3
Reheat pressure	bar	46.3	47.5
Generator output	MWe	305.9	306
Net electric output	MWe	295.5	295.6
Net heat rate	kcal/kWh	2,145	2,134

Tab. 1.
THTR-300, Comparison of key plant parameters.

Today, it can be determined that the PBRC would have avoided all of these difficulties. The stability of the graphite structure of the AVR ascertained after the shutdown of the AVR, proved this design could be the basis for a new PBRC which was patented in 1965 *[4]*.

The positive results of the operation of the THTR-300 include *[11, 12, 13]*:

- HTR power stations can be operated and connected to the power grid in the same manner as conventional power plants.
- Rupture of fuel elements does not increase the radioactivity of primary helium cooling gas.
- Thermodynamic efficiency is as high as in conventional power plants.
- The nuclear and radiological safety of personal and environment is excellent.
- No radiation injuries, neither in the AVR nor in the THTR-300 occurred.
- The contaminated primary helium gas and graphite dust are safely surrounded and contained in the PCPV.
- The pre-stressed concrete pressure vessel PCPV showed it was an excellent safety barrier against radiation, plane crashes, terrorist attacks, and earthquakes up to the highest magnitudes, etc.

The pebble fuel elements

Design and operational experiences with pebble fuel elements

The most important components of a nuclear power station are the fuel elements. They contain the fissile material for generating the energy and the more robust the fuel elements the safer the nuclear plant. The main material of a pebble fuel element is graphite and they have a diameter of

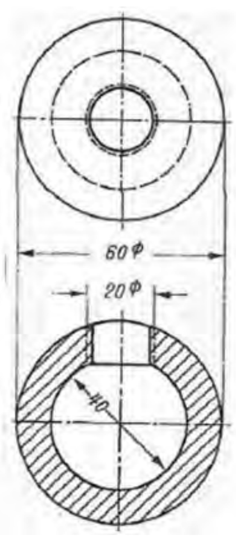

Fig. 11.
Original concept of a pebble and later installed TRISO pebble.

Fig. 12.
Arrangement of a TRISO-pebble.

60 mm while the diameter of the inner fuel containing matrix is 50 mm *[14]*.

Figure 11 shows the difference between the first idea of a pebble with non-coated fuel and the current type. The inner diameter of the coated fuel particles is 0.5 mm. Embedded in the inner graphite matrix are approximately 15,000 coated particles (cp) in one pebble and contain the fuel material (**Figure 12**). The fuel kernel is encapsulated by three layers of very hard and pressure resistant PyC-/-SiC-/-PyC and is gas tight (**Figure 13**). These are the "TRISO" Fuel Elements and each coated particle has a diameter of 0.9 mm.

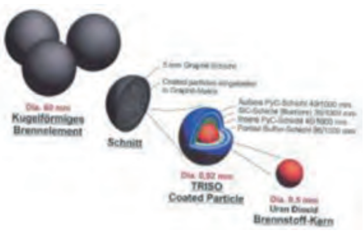

Fig. 13.
Composition of a TRISO-pebble.

Without coating the radioactivity of the primary helium gas in the AVR was calculated initially to be 10^7 Curie. Therefore, the AVR was designed with two pressure vessels. All piping and helium operated components were surrounded with clean helium gas, to prevent primary contaminated Helium gas from entering the reactor vessel. These fuel elements were not initially used.

The newly developed TRISO elements avoid fission and decay products, which are the sources of dangerous radioactivity. Three layers form a containment for every CP and keep all fission products safely enclosed. The layers remain gas tight from 1,620 °C to 1,800 °C and do not deteriorate or corrode even under high pressure.

As previously mentioned, AVR was initially designed with a helium primary gas activity of 10^7 Curie. After the development of the pebbles with coated particles the primary helium gas activity was measured at only 360 Curie *[3]*, a factor of 0.000036 lower. They were proven in long term operation in the AVR as reliable fuel elements and have very excellent advantages in comparison with all fuel elements in other nuclear power stations.

Fresh pebbles can be stored and handled without any risk of radiation (**Figure 14**). Radiated, burnt down pebbles or graphite balls will be stored

Fig. 14.
Treatment of pebbes by hand, first pebble loading into the core of the AVR-HTR.

Fig. 15.
Storage of burnt-down pebbles in casks.

(**Figure 15**). primarily in specially designed containers or stockrooms inside the basement of the reactor building. No cooling is necessary and they can be stored over a longtime without risk of contamination or radiation of the surrounding area or personnel *[15, 16, 17]*.

Breeding of fissile Uranium-233 by using Thorium-232

Sufficient Thorium can be found in the surface of the earth to generate electricity and heat by nuclear power stations for a very long time. *[20, 21, 22]* However, fissile fuel needs to be produced from the Thorium. This is possible by breeding ^{232}Th up to ^{233}Th using slow neutrons initially resulting in Protactinium (^{233}Pa) which decays to fissionable ^{233}Uranium. This process is a very good possibility in a THTR power station.

The coated fuel kernels can contain Uranium 235/238, Plutonium 238-242, or Thorium 232 [15, 17, 18]. These fuel materials can be combined in a pebble matrix and burned together. After extracting the core, every single pebble can be measured to its degree of burn-up. In HTR-Pebble Bed reactors the disposal of Pu can be extensively controlled and each pebble is treated individually. A very detailed and full control of Pu disposal is guaranteed and possible through inspection to meet the NPT.

Decommissioning and Reprocessing of Fuel Elements and Coated particles

The paper by the Netherlands European Joint Research Centre JRC describes results of an experiment: "A High Voltage Head-End Process for Waste Minimization and Reprocessing of Coated Particle Fuel for High Temperature Reactors." *[10]* This process is proposed for the separation of coated kernels from the fuel matrix and makes it possible to reprocess the burnt down fuel by separation of the coatings and the fuel kernel. The fuel kernels remain intact and has been successfully demonstrated in experiments as shown in **Figure 16, 17,** and **18**. The characteristics of the coated fuel kernels and the complete pebbles, manufactured by NUKEM, is shown in **Table 2**.

This process, proposed and studied with experiments by EU-JRC-Petten, envisages the complete removal of the coating-layers to make the fuel accessible for further reprocessing and manufacturing of new fuel kernels.

Pebble Bed Ring-Core Design for very large TVHT-Reactors

Important discoveries were generated from the long-term operation of the AVR and relatively short period of three years operation of the THTR-300, The information obtained from these two power plants is

Coated particle	
Particle batch	HT 354-383
Kernel composition	UO_2
Kernel diameter in micro-meter	501
Enrichment [U-235 wt. %]	16.75
Thickness of coatings in micro-meter	
Buffer	92
Inner PyC	38
SiC	33
Outer PyC	41
Particle diameter	909
Pebble	
Heavy metal loading [g/pebble]	6.0
U-235 contents [g/pebble]	1.00 +/-1%
Number of coated particles per pebble	9,560
Volume packaging fracture [%]	6.2
Defective SiC layers [U/U_{tot}]	7.8×10^{-6}
Matrix graphite grade	A3-3
Matrix density [kg/m^3]	1,750
Temp. at final heat treatment [°C]	1,900

Tab. 2.
Typical chracteristics of coated particles and pebbles produced by NUKEM.

Fig. 16.
Reprocessing of pebbles before separaing coating.

Fig. 17.
Reprocessing of pebbles, separated coating shells.

Fig. 18.
Reprocessing of pebbes, fuel kernels separated from coating.

necessary for the design and construction of future large commercial V/HTR power plants. The experience gained with the graphite structures are excellent and new PBRC design based on the experiences may not produce any problems. The PCPV *[4]* of the THTR-300 was designed without any prior experience and was a first-time solution.

Together with the improved manufacturing of the graphite by suppliers and extensive knowledge from previous designs it is possible to construct graphite cores and reflectors with high long term stability (**Figure 4**). The internal inspection of the AVR core showed no shift of graphite blocks after more than 23 years in operation and development of graphite as a suitable material in HTR-Reactors made good advancements with improved development.

Unlike the THTR-300 the absorber rods are installed in the surrounding graphite moderator to prevent damage to the graphite pebbles. This was a major problem with the THTR-300 (**Figure 19**).

The core parameters shall be small and not too high. This is important for lower decay heat temperatures in case of a loss of coolant accident (**Figure 20**).

The dimensions of a ring-core can be optimized by:

- difference between inner and outer diameter,
- height of fuel zone,
- core volume,
- power density of fuel zone,
- maximum helium gas temperature,
- optimal flow of pebbles through the core.

These six factors can be optimised with regard to maximum decay heat temperature, which must not exceed 1,600 °C in case of cooling loss (loca) and/or pressure drop (lopa), which would indicate an MC Accident.

The possible main design features for this new concept may include:

- TRISO pebbles as fuel elements.
- Use of U-235 together with Th-232 to breed U-233, PU *[20, 21]*.

Fig. 19.
Pebble bed of the THTR-300 with shot down rods in the pebble bed.

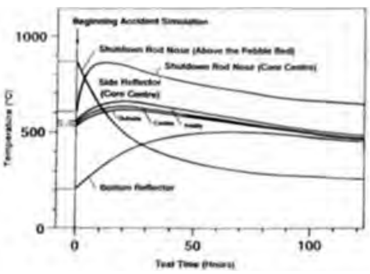

Fig. 20.
Results of loss of coolant LOCA/MCA accident of AVR.

- A pre-stressed concrete pressure vessel to surround the primary helium completely with extreme safeguarding against all types of potential critical events, terrorrist attacks, and disturbances inside and outside of the powerplant, and absolutely safe against cyber-attacks *[26]*.
- The new design of a pebble bed core in a ring form, (**Figure 10**) *[4]* with several extraction devices for the pebbles below the core. An advantage of this design is an improved and more regular or symmetrical flow of pebbles through the core with higher possible burn up of the fuel and improved symmetrical cooling of the complete pebble bed *[7]*.
- Shut down and regulation rods only in the graphite reflector,
- $He_{primary}/He_{Secondary}$ heat exchangers in the primary helium circuit of the PCPV to avoid water ingression *[4]*.
- Only one heat transport system to supply the different secondary plants with high temperature heat will reduce costs and simplify design of the pressure vessel.
- The secondary pure helium is inside the pipes and will have a slightly higher pressure against the primary integrated helium circuit. In case of a leak, the ingressing pure helium will be contaminated and can be cleaned up by the helium cleaning plant and refilled into the clean helium circuit.
- This design makes it possible, to install the He/He-heat exchanger tightly into the pressure vessel. Several different exchanger systems were constructed without the ability to extract them from the vessel as practiced in the THTR-300.
- This design makes it impossible to contaminate anything outside of the reactor vessel and all possible industrial processes can be designed without danger of radioactive contamination in a quite normal conventional construction.
- This nuclear power facility makes it possible to construct every secondary industrial production plants close to the HTR Power Station.
- Helium gas flow upstream from bottom to ceiling. The experience from the AVR shows this solution has some advantages compared with downstream design in the THTR-300.

One of the most important feature of this design is the small core, very similar to the core of the AVR. The results of the MCA tests with heat rise by decay heat (**Figure 20**) can be put into consideration. So, we are able to increase the primary maximum helium heat temperature to the highest possible temperatures, possibly to 1,100 °C, limited only by the maximum allowable metallic tube temperature of the He/He heat exchanger inside the PCPV.

Design of important components for a new 600 MW_{el}/1.500 MW_{th} Pebble Bed Reactor and potential risks

The Pre-stressed concrete pressure vessel. (PCPV)

The reactor vessel is, for safety reasons, the most important component of every nuclear power station. The calculation for larger cores for pebble bed reactors showed that the diameter of the core is too great for construction using steel pressure vessels and therefore cannot be manufactured using metallic materials. It was decided to look for other construction materials for a large HTR pebble bed design with high volume and high pressure.

Two solutions had been taken into consideration, a pre-stressed cast iron vessel and a pre-stressed concrete pressure vessel. The PCPV had been chosen due to its excellent safety advantages versus the cast iron vessel. Several safety conditions could not be reached with a pre-stressed cast iron vessel and the construction would have some fundamental problems.

This HTR design was a completely new construction without any prior experience and the operational helium gas pressure was calculated at 40 bar. It was decided to perform experiments with a 1:20 scale model. The model was pressurized with warm water. Very small cracks began to form at a pressure between 90-120 bar. The main crack was reached at 190 bar.

After the pressure dropped to 40 bar, the vessel was nearly gastight again. After the pressure drop the cables pulled the concrete together *[4]*. These results were deemed very important since this test proved that oxygen could not enter into the vessel in event of a crash. Throughout the testing, all necessary factors were measured and used as a baseline for new calculation programs to calculate the PCPV for the THTR-300.

Fig. 21.
Arrangement of stressing cables of the THRT-PCPV.

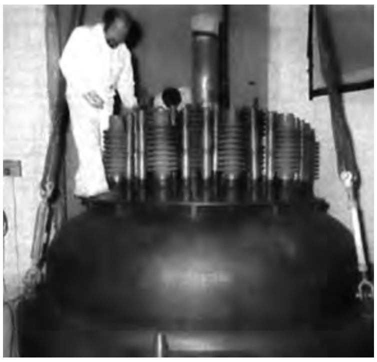

Fig. 22.
Top of the steam generator of THTR-300.

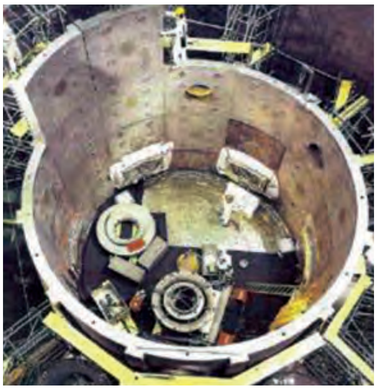

Fig. 23.
Installation of the thermal shield.

Development, design and erection of the THTR-300 pre-stressed concrete pressure vessel

Figure 21 shows the cross section of the reactor *[26]*. Located Inside are the core, graphite and carbon brick structures, thermal shield, six steam generators, blowers, shut down rods, measuring devices, and isolation with liner and liner cooling system further the penetrations for the steam generators, the holes in the concrete are reinforced by steel layers with steel tops (**Figure 22**). There are 135 penetrations in total, the largest of which are for extracting the steam generators at 2.25 m. All of the penetrations are surrounded by cables and have encountered no design problems. The construction phase is demonstrated in **Figures 23, 24** and **25**.

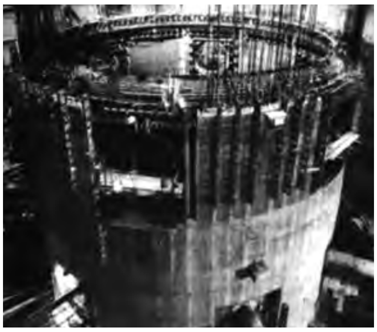

Fig. 24.
PCPV during manufacturing.

Fig. 25.
Model of bottom of THTR-300 core.

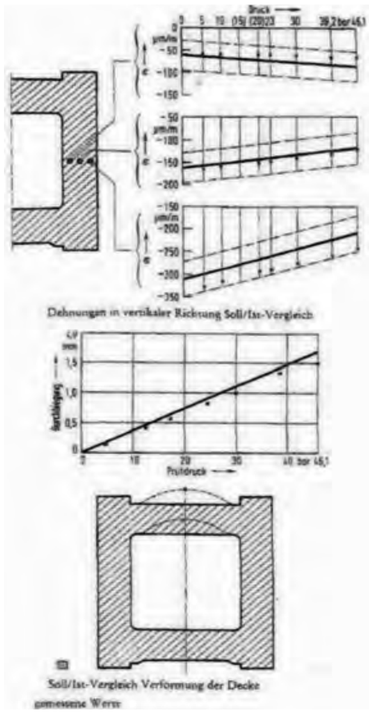

Fig. 26.
Results of pressure test of the THTR-PCPV.

The results of the pressure test

Figure 26 shows the accuracy between the measured and calculated factors. The pressure tests were performed using nitrogen and helium to ensure accurate measuring. The design pressure was 39.2 bar and the highest possible pressure in case of an accident was calculated at 46.1 bar. The test reached the calculated and highest possible pressure (as required by the TÜV) without any problems arising *[14]*. As a result, it can be assured that existing design knowledge and calculation program are sufficient to calculate larger PCPV up to the highest possible capacities, potentially reaching 4.000 MWth.

Safety criterions

The main safety criterion *[19]* of a PCPV are:

- Safety against plane crashes, terrorist attacks, political disturbances.
- Safety against air ingress.
- Safety against loss of contaminated graphite dust.
- Safety against all kind of crashes or cracks.
- Safety against earthquakes up to highest degrees.

Within the inner He/He heat exchanger:

- Safety against water ingress.
- Safety against tritium ingress.

Graphite reflector and ceramic structure

The large numbers of design experiences with both reactors will lead to the best technical solutions. SGL Group is a very important supplier for both graphite and carbon bricks production and is capable of designing very reliable structures, **Figure 4**.

Core and Helium gas flow

The experience of the AVR proves that the flow from bottom up has some advantages. The helium gas temperature range is 230 °Cto 280 °C and entrance temperature from 750 °C to 950 °C possible reach 1,100 °C at the highest. This is dependent on the metallic material stresses and strength of the tube material.

The design of the wall of the graphite reflector is very important for good and symmetrical pebble flow through the pebble bed. The best test results obtained from the wall designed for the AVR was thoroughly tested in advance at the test laboratory of BBC/Krupp. *[1]* **Figure 27**. This design leads to a very symmetrical gas flow across the pebble bed from bottom up and consequently leads to very good symmetrical cooling of all pebbles across the bed. The calculation factors for this design had been developed in the BBC/Krupp laboratory and showed excellent results *[6, 7]*.

The pebble flow in the AVR was much better than in the THTR-300 due to the larger diameter of the THTR bed. Diameters that are too large lead to very different pebble flow velocities, up to a factor of 10 times, between the wall and center of the bed *[7, 14]*. Very high burnt-up results of the fuel can be achieved with good symmetrical pebble flow.

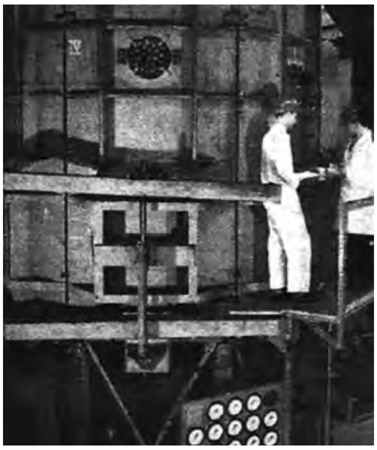

Fig. 27.
Pebble bed flow experiments in the laboratory of BBC/Krupp with 1:1 scale.

Helium-pr/Hes-ec heat exchangers

- The calculations can be based on the results of the tests performed by FZ-Jülich with the test devices (**Figure 28**) *[36]*.

Fig. 28.
Test facility of He-He heat exchangers in FZ-Jülich laboratory.

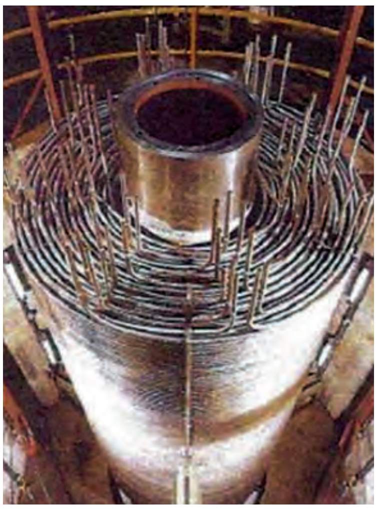

Fig. 29.
Manufacturing of the THTR steam generator.

- The results of the very high temperature steam boiler tests, with steam temperatures of 600 °C, done in the GKM Mannheim, Germany Power Station, can be put into consideration.
- The secondary helium shall have a higher pressure than the primary helium circuit. No radioactivity can pollute the secondary part of the power station.
- Manufacturing is done same with the design, proved in the THTR-300 with the steam generators (**Figure 29**).

The Helium blowers

The blowers in the AVR and in the THTR-300 showed no problems at all. An increase to higher capacities may be possible without problems. They should be still oil lubricated (**Figure 30**).

The shut down and regulation rods

- An identical design of the THTR-300 regulation rods can be used, only more pieces will be necessary (**Figure 31**).

The fuel element circuit

- The experience with the AVR-installation during 23 years of operation is excellent *[5, 6, 8]*.

Fig. 30.
Helium blower of THTR-300.

Fig. 31.
Shut down and regulation rod of THTR-300.

No changing or enlarging of components is necessary. Several charging units shall operate parallel. These components, previously designed by BBC/Krupp, can be used without changing the construction, **Figure 5**.

The Helium Cleaning Plant

- The task of the Helium cleaning plant is to clean in a bypass the helium gas of the primary circuit from impurities such as solid graphite dust and the radioactive chemical elements Krypton, Xenon, Argon and Tritium. A detailed description is published in ATW 5/1966 *[23]*.

Safety systems and MCA tests

The AVR was the worldwide only nuclear power station with two times MCA test-simulations *[4, 5, 19]*.

The first was done in spring 1967 during the commissioning period. As mentioned, we had a lot of undecided problems with the unknown behavior of important components, so mainly with the absorber rods. We had an agreement with the TÜV that a MCA-test-simulation should prove the inherent nuclear safety and the good behavior of all these components.

At highest helium gas temperature of 850 °C and full power of 46 MW_{th} the blowers were stopped by quick stop. The complete power plant was without electricity, also the reserve-diesel-engines were out of operation and the absorber rods were blocked. Only the core temperature measuring was in function. After stop, by the temperature moved by decay heat slowly up to about 1.000 °C. *[3]* Then the temperature falls down during the next days to normal degrees. Some days later we re-started the complete power station without any problem *[4]*.

After this test, full licensing was granted by the TÜV for the completed power station.

A second the test was done in 1976. *[6]* This time all instruments could be considered and all data were taken to measure the temperature course by the simulation of a loss of coolant accident to develop a calculation program for such a future case (**Figure 20**).

These two worldwide first experiments had been the simulation of a worst-case scenario, an MCA, the only tests in nuclear power stations up to now.

We knew exactly, that there was no nuclear risk at all, as the radioactivity of the primary helium gas was very low. The coated particles made a very good job.

A similar experiment was done in 1986 in Chernobyl. There the fuel was not coated and the reactor not inherent safe. The result is well-known.

Also, loss of coolant was the reason for the MCA in Fukushima, again the fuel was not coated.

This shows the difference and advantages of the reliability of pebble fuel elements with coating of the fuel particles in case of accidents versus other Nuclear Power Station designs.

Compared with the originally calculated radioactive contamination for the AVR power plant of 10^7 Curie the measured radioactivity of the AVR in operation with coated particles was 360 Curie. The resultant calculation factor is 0.000036.

With the Chinese Experimental HTR-10 MW_{th} reactor a further successful loss of coolant test was done with TRISO pebble fuel elements.

Further we will install the following additional installations to safe the reactor in every case of heavy danger *[19]*:

- Diesel motor driven generators for electrical reserve power.
- Quick extraction of all pebbles from the core to a special safe store.
- Shut down rods in the graphite reflector.
- Gastight design of the Reactor building as containment.
- Water tight basement.

Summary and Safety Conclusions:

- Inherently safe design.
- No melting of the core is possible.
- Gastight integrated helium circuit.
- Safe against water ingress.
- Safe against air ingress.
- Safe against heavy earth quakes.
- The PCPV is safe against terrorism and other severe attacks and has proved as an excellent containment.
- The PCPV has proved after decommissioning as an excellent bunker for longtime storage of all contaminated components, up to now for more than 25 years.
- No graphite burning possible.
- Continuous cooling of the pebbles is not necessary for the new elements, pebbles in the core, or in the castors and store.

"The safest Nuclear Power Station is the most economical Power Station."

The Secondary electric and/or heat producing parts of a HTR-Power Station

Nuclear safety regulations

No nuclear safety regulations are necessary for every secondary industrial plant in connection with nearby HTR-Power station *[24, 25, 26, 27]*.

In 23 Years of operation there was not the smallest radioactive contamination measured in the turbine part of the AVR. After the shutdown of the THTR-300 the complete secondary part had been sold and is still in operation in another conventional power station connected to a normal steam boiler plant.

The Helium$_{secondary}$/water-steam generator

The secondary helium, coming from the He/He-heat exchanger in the primary helium circuit, is lead to a new design of Helium/water-steam generator. This generator produces the steam for the steam turbine-generator set to produce the electricity. The steam data are conventional with a steam pressure of may be 220 bar and 525 °C and intermediate, if required two times, reheating to 525 °C.

The temperature of the secondary helium will be calculated in accordance with the he/he- heat exchanger in the primary helium circuit. These temperatures depend on the cube-material, the higher the temperature, the smaller the heat-exchanger. This is only an economical question.

The steam turbine generator set and auxiliary components

No design changes or modifications are necessary *[29]*. The same construction as in conventional power stations can be designed and installed.

That means a conventional turbine with temperature entrance of 525 °C, 220 bar steam pressure, intermediate heating one or two times up to 525 °C,

Fig. 32.
Precleaning installation for sea/wastewater.

the water-cooled condenser and the generator. The water leaving the condenser is pumped through several heat exchangers, which are fed by extracted steam from the turbine. Everything as conventional as in all conventional Power Stations. All components and installations of the secondary part can be designed as in normal conventional power stations. There is not a difference in design.

The sea/wastewater desalination plant

Overview

The sea/wastewater desalination plant can be installed with experienced components *[30, 31, 32]*. These will consist of the seawater pre-cleaning installation, **Figure 32**, and the following different heat exchangers for heating up the water until evaporation. The distilled water is free of solid particles, and can be used as drinking water or for many other purposes. The residual salt, brine and further solids can be sold or deposited.

A solar plant can be used to reduce the necessary heat from the steam turbine during sunshine. The produced heat in the nuclear part can be nearly completely used with highest thermodynamic efficiency. The Seawater is extracted from the sea and pre-cleaned.

Turbine condenser

The condenser of the turbine, **Figure 33**, is the first stage to heat up the seawater. Seawater resistant tubes are necessary in the condenser. The quantity of cooling seawater, the temperature rise and condenser pressure must be economically optimized. The efficiency of the thermodynamic process must be calculated. Normally the temperature rise in the condenser is calculated with 5°-10 °C. Also the quantity of cooling water can vary, for a 600 MWel unit between 20.000 – 40.000 m^3 / hour. If the required cooling water quantity is too high for the desalination plant, the water can be released back into the Sea (**Figure 33**).

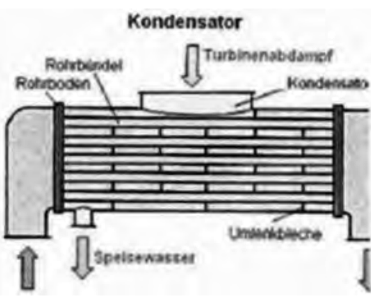

Fig. 33.
chematic of a turbine condenser.

Solar plant

A conventional solar plant, **Figure 34**, can be installed. The solar energy depends on sunshine intensity, which depends mainly the daily time and seasonal periods of the year and environmental conditions (**Figure 35**). The heat from the solar plant must be transported to the heat exchanger as second heating stage. This circuit makes it possible, to reduce the extracted steam from the turbine. The safe steam can be used for additional production of electric energy in the low pressure part of the turbine by expension the steam down to condenser pressure. The solar plant is able to produce electricity indirectly.

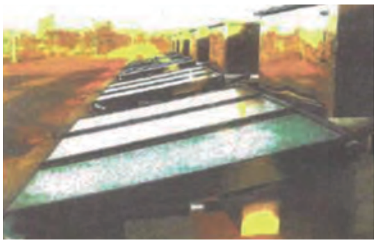

Fig. 34.
Solar plant.

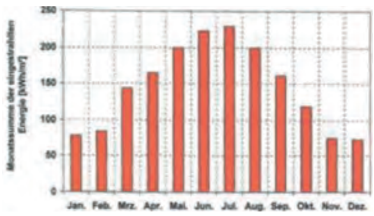

Fig. 35.
Average solar energy in Tunis CIty, 1997.

Desalination plant

Well know seawater desalination plants can be installed, working as distillation process so as MSF (multi-stage-flash)-plant (**Figure 36**). The preheated sea-water will be brought with the steam extracted from the turbine to a temperature of 90 °C to 135 °C, (1.0-1.5 bar). Then the seawater streams to the evaporating chambers with economically optimized number of stages. The distillate then can be used as drinking water. With nearly the same technic works the MED (multi-effect-distillation) process (**Figure 37**). Chemicals must be added as far as necessary, this is depending from the quality of the seawater.

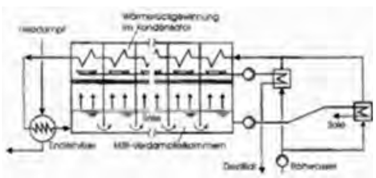

Fig. 36.
Multi-stage-flash desalination plant.

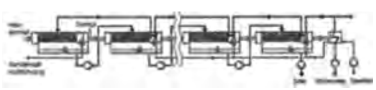

Fig. 37.
Multi effect distillation plant.

An economically plant optimization is to be carried out to choose the best process.

The brine, consisting of the chemicals, salt and other solid components of the seawater will be evaporated. To evaporate the solid particles several possibilities are applicable, evaporating by the sun directly, by solar heat or by low pressure steam from the turbine. The solid parts will be dried and stabilized. Then they may be sold or stored.

An analysis should be carried out, which demonstrates the influence of different plant designs, operating parameters and environmental conditions on the efficiency and the costs of the plant and their thermodynamic efficiency.

Advantages of co-generation of electric power and water

- The use of pre-cleaned seawater as cooling water for the turbine condenser makes it possible to operate this process without cooling towers or smaller ones if necessary. All residual heat from the thermodynamic process to generate electric power, which otherwise is dissipated in the cooling towers, is used for pre-heating the sea-water during the first stage.
- The extracted low pressure steam from the turbine feeds the high-pressure line of the turbine to produce electricity and the residual heat of the steam is then used in the evaporating process for the desalinization plant.
- The thermodynamic efficiency of the combined processes can reach nearly 100 %.
- The combined feeding of the evaporators by steam from the turbine and with heat from the solar plant makes it possible to operate the evaporators of the desalination plant up to 8,760 hours per year. This provides nearly 100 % operational time for this high investment costs.
- The solar plant replaces the extracted steam from the turbine. More electricity can be indirectly produced.

- The final evaporation and drying of the brine can be completed using solar heat, a very economical process.
- The water produced can be collected and stored. Both processes can be produced separately and alternatively, according to operational demands as a main or by-product.

Summary and conclusions

Main Design Principals of large VHTR-Power Plants:

Future designs of VHT- Reactors must have the following design elements *[38]*, mostly by safety reasons:

- Pebbles with TRISO coated particles.
- inherent safe design, no melting of the core is possible.
- Gastight closed primary helium circuit in one pressure vessel.
- Pre-stressed concrete pressure vessel.
- $Helium_{primary}/Helium_{secondary}$ heat exchangers in the primary circuit.
- Pebble bed ring core (PBRC).
- Small core dimensions.
- Several extractions for pebbles.
- Safe against all possible dangerous events, extern and intern.
- Safe against all types of terroristic attacks, cyber-attacks, plane crashes and similar attacks.
- High magnitude earthquakes.
- Highest possible safety standard.

Economical advantages:

- Very high primary helium gas temperatures.
- No shut down for fuel elements changing and transportation.
- Thermodynamic efficiency as high as in fossil power stations.
- One/two times intermediate reheating possible.
- Very high burn up of nuclear material.
- Use of ^{232}thorium in combination with ^{235}Uranium to breed ^{233}Uranium.
- Burn up of Plutonium, weapons plutonium included.
- Reaching the non-proliferation-treaty agreement (NPT).
- Safe storage of all nuclear material.
- Safe and easy storing of radioactive material.

(V)HTR to Co-Generate Electricity and high- plus low-temperature heat for several Industrial Processes (23, 24, 33):

Production of electricity by gas turbines *[37]*:

- Hydrogen production *[34, 35]*.
- Chemicals.
- Industrial Gases.
- Steel making.
- Nuclear Preheating.
- Town Heating.

and so on.

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