2011 International Congress on Advances in Nuclear Power Plants
ICAPP 2011 May 2-5, 2011. Nice, France
Paper Nr. 11076

The Technology of High-Temperature-Reactors

Design, Commissioning, and Operational Results of AVR-15-MWel Experimental Reactor Jülich, Germany and THTR-300-MWel Demonstration Reactor Schmehausen, Germany and Their Impact on Future Designs

Dr.- Ing. Urban Cleve
HohenfriedbergerStr 4
D-44141 Dortmund, Germany
Tel: +49-231-432321, Fax: +49-231-432321, Email: uicleve@t-online.de

Prof. Dr.-Ing. Dr.-Ing.E.h. Klaus Knizia
Blumenweg 17
D-58313 Herdecke
Tel: +49-2330-974947, Fax:+49-2330-974949, Email: klaus.knizia@gmx.net

Prof. Dr.-Ing. Kurt Kugeler
Nordstr.25
D-52428 Jülich
Tel: +49-2461-7889, Fax: +49-2461-6214831, Email: k.kugeler@fz-juelich.de

Abstract – *This paper recalls the main design features of new large HTR-Power-Plants and shows that all goals of Professor Schulten's initial ideas were realized. Today, European and in particular German industry has had very good experience, knowledge and technology foundations for the design and safe nuclear operation of large HTR power plants up to the highest of capacities. Electrical power with very high thermodynamic efficiency can be produced as well as high temperature gases for operation of chemical processes; e.g. to synthesize hydrocarbon fuel from abundant feedstocks such as coal, biomass or recycled CO2.*

1. The Basic Design Features of Pebble Bed Reactors in Germany

The German development of HTR-Reactors was mainly initiated by Prof. Dr. Rudolf Schulten`s ideas. He started this technology early in the 1950's and 1960's while employed by Brown Boveri, in cooperation with Krupp by "BBC/Krupp Reaktorbau GmbH".

Main Basis of his ideas and main design features are:

- Spherical graphite fuel elements, called pebbles, which contain the fission material.
- Graphite as main construction material for the core.
- A safe integrated reactor concept with helium as cooling gas.

The first experimental reactor was the AVR-46-MW_{th}-Experimental reactor Jülich, Germany, Fig. 1, Jülich, Germany.

Figure 1. The AVR-46 MWth Experimental Power Station.

As early as in 1966 the basic design of the THTR-300, Fig.9, was initiated as demonstration reactor.

The goal at all the time and still today is the construction of an inherently safe nuclear power station with outstanding safety. The basic nuclear physical design should not permit an uncontrolled intensification of the nuclear fission process. No graphite dust is allowed, to leave the integrated inner reactor system uncontrolled.

2. The Pebbles as Fuel Elements

The most important components of a nuclear power station are the fuel elements. They contain the fissile material for generating the energy. The more robust the fuel elements are, the safer the nuclear power plant. The main material of the pebble fuel element is graphite. The spherical pebbles have a diameter of 6 cm while the diameter of the inner fuel is 5 cm.

Embedded in the graphite matrix are approximately 15,000 coated particles (CP) in one pebble. The CP's were developed over a long period of time with international cooperation from companies in the United States, Great Britain, The Netherlands, Australia, France, and Germany. They have a diameter of 0.9 mm. The fuel kernel is gastight and is encapsulated by three layers of hard and pressure-resistant PyC-SiC-PyC, the so called "TRISO Elements", Fig. 2.

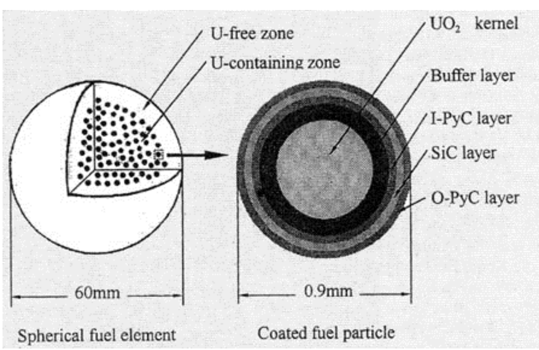

Figure 2. TRISO-Fuel Elements and coated particles.

The TRISO Elements avoid fission and decay products (radioactive waste) which are the sources of dangerous radioactivity. The coating prevents the fission materials from hazardous substances and keeps them safely contained. In addition the coatings do not deteriorate, even under high pressure and they do not corrode. In every kind of final storage, gamma radiation is generally insignificant in long term. It decays very quickly. The basic concept of a fuel element of the HTR reactor is to eliminate risk and minimize sources of dangerous material through multiple layers of containment.

The output of the power plant depends on the number of pebbles. The pebbles form a "pebble bed", in the core, and they are loaded from above and withdrawn from below. The reactor is thus operated by means of continuous charging with fuel elements. The continuous operation of a pebble bed reactor makes it possible to achieve a very high utilization of the fuel elements, uses the fissile material very efficiently, and allows continuous operation for a long period of time without shutting down for fuel element changing.

The pebbles have proved in long time operation as excellent fuel elements. They have many advantages in comparison with other designs. Continuous operation over 8760 hours/ year is possible for several years. No shut down for exchange of fuel elements is necessary.

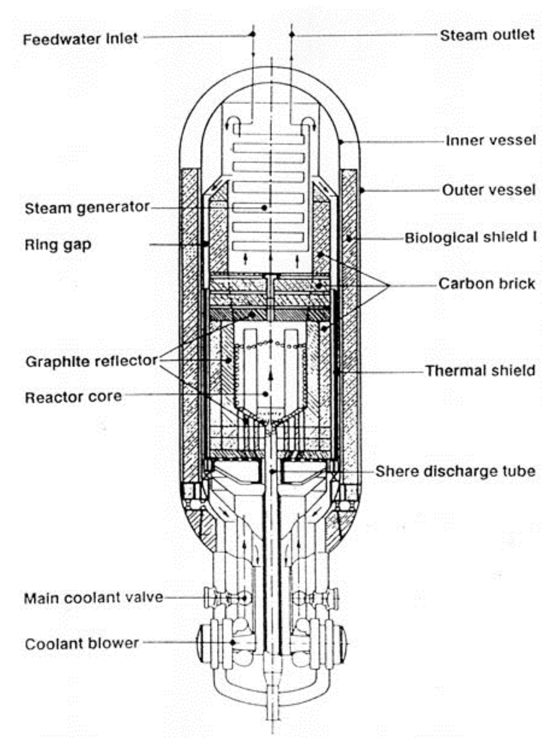

Figure 3. Section through the AVR primary circuit.

Modern HTR TRISO fuel particles have been shown to retain fission products during normal operation and under accident conditions.[1]

The quality level of the German fuel produced in the 1980s set a world-wide standard, which was later followed by other countries active in HTR fuel development.[2]

3. Operational Results of the AVR

The design of the AVR started in the early 1960s and attained its first criticality on August 28, 1966. First electric power was produced on December 18, 1966. A cross-section of the AVR reactor is shown in Fig. 3.

The inner graphite core structure of the AVR is shown in Fig. 4. The core diameter is 3 m and is surrounded by the graphite reflector, the thermal shield, the inner pressure vessel, the first bio shield and the outer pressure vessel. The main components are the steam generator, the cooling gas blowers, Fig. 5, the shutdown rods, the fuel feed system shown in Fig. 6 -extraction system of the pebbles-, and the fuel cycle, Fig.7 and the helium gas cleaning circuit.

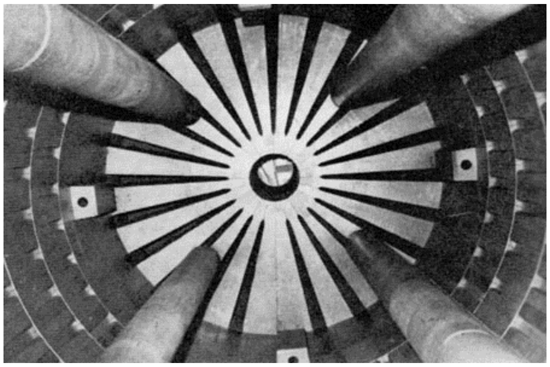

Figure 4. Section through the AVR primary circuit.

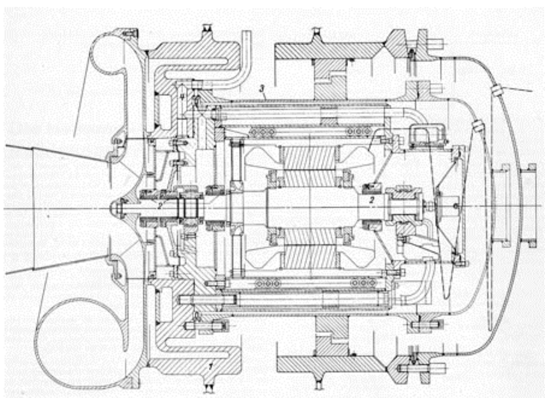

Figure 5. Gas cooling blowers.

The AVR was in operation for more than 22 years. The main operational results are:

- The simulation of a loss-of-coolant accident. The blowers were stopped, the shutdown rods were blocked, and the electrical supply was placed out of operation. This was the simulation of a worst case scenario. First experiment was done in 1967. Gas temperature was 850°C with a power output of 46 MW_{the}. This can cause the most severe type accident for a nuclear power station as occurred in Chernobyl. The core and graphite temperatures had been measured and the experiment showed that in the case of a loss-of-coolant accident, decay heat can be removed from the core without forced cooling and without causing unacceptably high temperatures in the surrounding components. Thesecond tests in 1976 supplied extensive data material for the testing of computer program simulations. Cooling gas temperature was 950^{o}C. These experiments demonstrated that

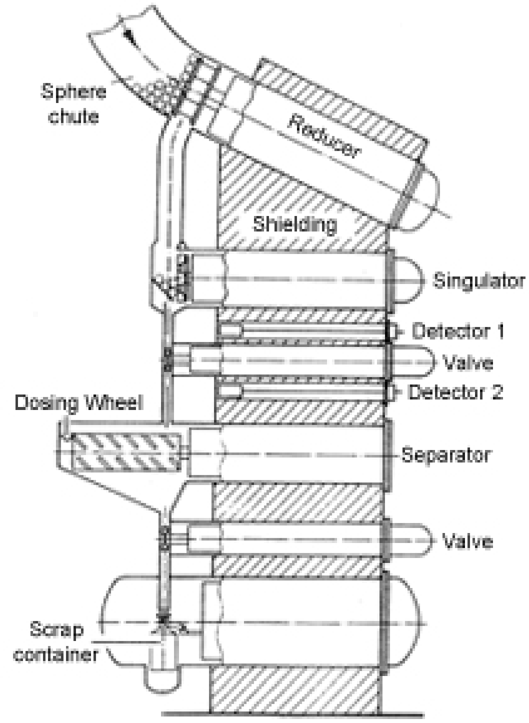

Figure 6. The fuel extraction system.

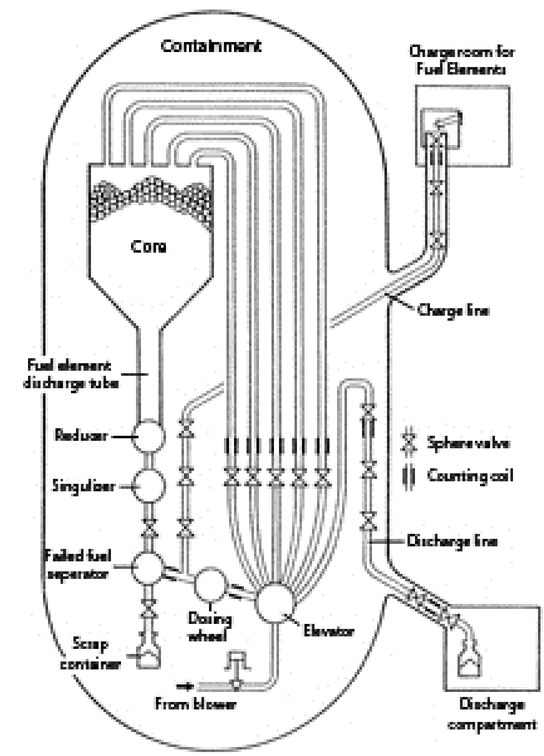

Figure 7. Basic diagram of the fuel cycle.

the reactor was “inherently safe”. Fig.8.

- A similar test was done and proved with the HTR-10 in China, with the same success.
- One major incident happened with the steam generator. The steam generator was designed with four separate circuits, to provide the ability to shut down one circuit in case of leakage. In this situation, high pressure hot water or steam leaked into the helium gas. This only occurred on time. The problem was identified in a short time and the reactor was shut down. The control concept for water ingress accidents worked well. This was the only serious incident which occurred in all the years of operation. The reactor was out of operation for many months and after repair the steam generator worked without problems and at its full capacity of 15 MW_{el}.

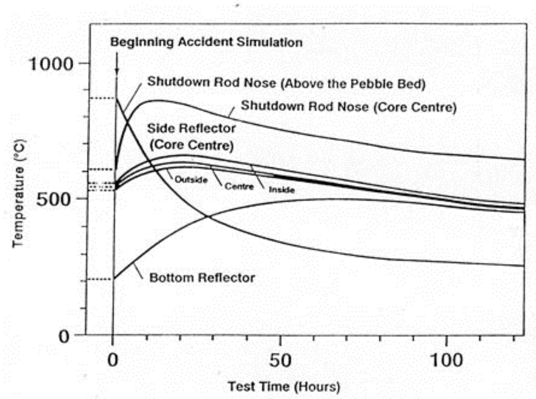

Figure 8. Loss-of-Coolant Accident Test results.

- All other components worked safely and were tested under normal conditions in the laboratory. Primary and final testing was performed under helium conditions in the reactor. All these tests indicated a lot of problems and difficulties that could only be solved after quite expensive and extensive testing. However, a lot of experience in the field of helium technology was gained. During operation, all components could be repaired by use of special, newly designed devices to help to protect operational personnel from radioactivity. These devices worked very well and many repairs could be performed during operation of the reactor.
- The radioactivity of the helium gas in the primary circuit was as low as 360 Curie.
- The fuel feed and discharge system showed excellent availability. 2,400,000 fuel elements were transported during the time of operation. Only 220 fuel elements were destroyed resulting in only 0.0092% of the handled elements being ruptured.
- During the operation in 22 years no accidents with radioactivity exposure occurred with personnel nor with the environment.
- The AVR was an excellent test reactor for a variety of different fuel elements with different kinds and compositions of U and Th. A complete survey of all fuel element types, inserted and tested in the AVR is given in /5,10/.
- The operational time of the AVR in spite of experiments, was 66.4%. The highest availability was 92% in 1976, an outstanding result for a very new design.

AVR was shut down for political reasons on December 31, 1988. All current and planned tests with fuel elements were stopped, which was a very poor decision for future development of HTR-reactors.

4. The THTR-300 in Hamm-Uentrop / Schmehausen

The basic design of the $THTR\text{-}300_{el}$ demonstration reactor was started in 1965, Fig. 9. When the decision was made to construct the THTR, no prior experience from the AVR could be brought forward since the AVR was not yet in production. Even so, it was a bold decision to construct a new reactor with such a high capacity as follow-on concept to the AVR and up to now it was the right decision.

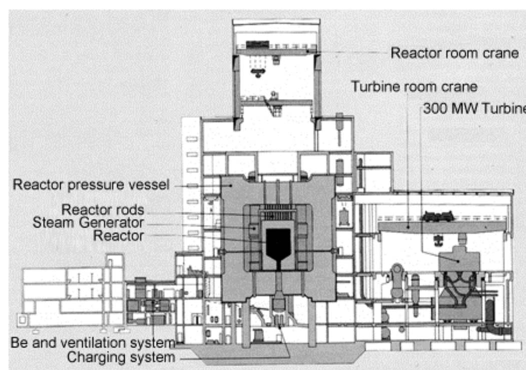

Figure 9. The THTR-300 MWel Demonstration Power. Station in Schmehausen, Germany.

The main design differences of the THTR to the AVR were:

- Pre-stressed concrete pressure vessel instead of steel. The dimension was 16 m in diameter and 18 m high and was designed this way mainly for safety reasons. A model with a scale of 1:20 was designed and tested by water pressure. First very small cracks occurred at a pressure between 90-120 bar. The main crack was reached at 190 bar. After pressure drop to 40 bar the vessel was nearly gastight again.

- A closed inner circuit for the He cooling gas to avoid the release of fission products and graphitic dust which for example could be partially contaminated with Sr-90, Cs-137, and/or Ag.
- No containment.
- Helium gas flow from top to bottom.
- TRISO pebble fuel elements.
- All other components such as blowers, fuel element feeding, helium gas circuits, steam generator, graphite structures, etc. were designed very similar to the components in the AVR.

Later calculations of the reactor core showed that the diameter of the core was too large and the shutdown rods in the surrounding graphite structure could not cool down the fuel bed to the necessary low temperature in case of a shutdown of the reactor. Up to this time no experience was available with the behavior of the graphite core structure in long time operation. Therefore, a decision was made to insert the shutdown rods into the fuel bed with the danger that fuel elements could be crushed. Also, a decision was made to design a new extraction device for the pebbles which was very different from the extraction device used by the AVR. Both of these decisions were made without any prior experience of similar designs. These both decisions were discovered to be mistakes after the power plant was put into operation. There was no nuclear risk at all, but the operation led to difficulties. The rupture of pebbles was 0.6%, very high compared to the results of the AVR at 0.0092%.

The positive results of the operation of THTR-300$_{el}$ are as follows:

- HTR power stations can be operated and connected to the network in the same way as conventional plants.
- Rupture of fuel elements does not increase the radioactivity of the helium cooling gas.
- Thermodynamic efficiency can be as high as in the best conventional power plants, two times intermediate reheating of the steam is possible.
- The nuclear and radiological safety of personnel and the environment is excellent.
- No radiation injuries, neither in the AVR nor in the THTR-300, occurred.

5. New Design of large HTR-Reactors with Ring-Cores

The longtime operational experience of the AVR and despite the relatively short period of 3 years operation of the THTR, many important discoveries were generated from these two plants which are necessary for the design and construction of new and future commercial HTR power plants. It is possible to design plants with higher capacity up to 4,000 MW$_{the}$, and it will be possible to operate them with very high efficiency and reliability. So new HTR power plants can be designed with the same high capacity as the most modern PWR-Gen.IV power stations.

The experiences with graphite structures in the AVR and THTR-300 were excellent. Therefore this core design may not produce any problems. The designs in AVR and THTR had been constructed without any experience as first time solutions. Now we have a lot of long time experience and additional design possibilities to construct graphite cores with very high stability. An internal inspection of the graphite structure of the AVR after more than 22 operational years showed not the smallest shift of graphite blocks. Furthermore the development of graphite as suitable material in HTR-Reactors has made good progress in the meantime.

.

The main design features for this very new concept must be:

- TRISO pebbles as fuel elements.[1,2]
- Use of U-235 together with Th-232 to breed U-233.
- Pre-stressed concrete pressure vessel;

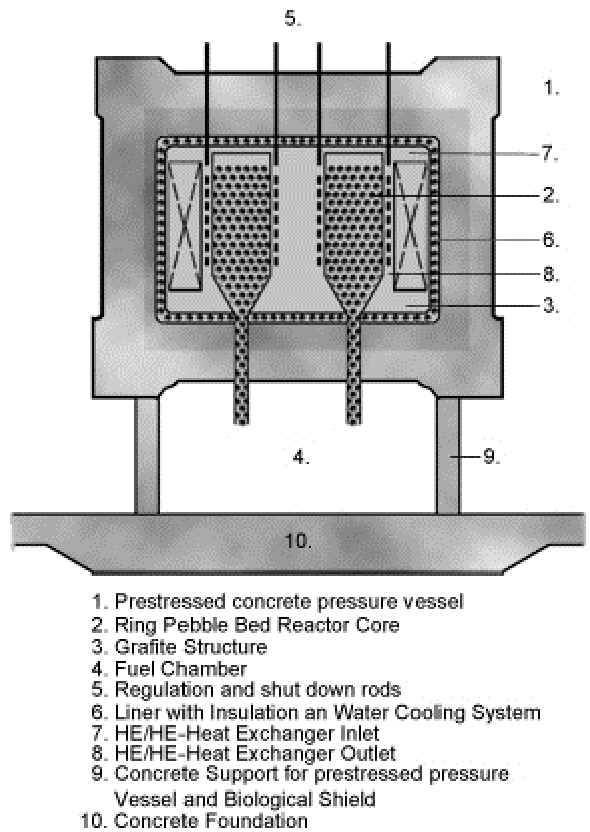

Figure 10. New Design of a Ring Core Pebble Bed Reactor.

- New design of a Pebble-Bed-Ring-Core /PBRC/ with several extraction devices for the pebbles, Fig. 10.
- An additional advantage of a Ring Core is the better and more regular/symmetrical flow of pebbles through the core. This leads to higher burn down of the pebbles and better cooling of the complete pebble bed.
- Shut down rods, only inserted in the graphite structures.
- He/He-heat exchangers in the interior of the pressure vessel.
- Outside steam generators, He/H_2O for use in power plants to produce electrical energy in steam turbine generators as well as high temperature gases for operation of chemical processes, e.g. to synthesize hydrocarbon fuel from abundant feedstocks, such as coal or biomass, to produce, for example, liquid fuel or for high temperature heat in a variety of chemical plants.
- All other components are similar to the components used in the AVR and THTR power plants. So they may not produce difficult technical problems.
- Inherent safety features of the reactor are paramount. As twice tested in the AVR and in the HTR-10. A major accident is not possible for nuclear physics reasons.

- In case of an accident the rest-heat of the core can be removed by the heat exchangers and by the water cooling system of the liner.

At the end of operational life of the reactor, all radioactive components can be stored in the concrete pressure vessel. This is one of the main experiences to store the radioactive components very safely in the concrete pressure vessel of the THTR, now for more than 22 Years. All of the burned out pebbles used in the AVR and THTR power plants are currently stored in cast iron "castor" containers in Ahaus, Germany. The measured radioactivity outside the containers is as low as 0,001mS. Temperatures in the interior of the containers lower than 50° C are measured.

All experiences and the design shows, that all safety re-evaluations for HTR-concepts[3], proposed by R. Moormann,-FZ Jülich-, in 2008, which caused large political trouble in Germany in 2009, were already considered and solved in the design of THTR-300. He did not refer in his paper to the design of the THTR-300 with a single argument. So there is not a single new proposal or understanding in this report with regards to the existing knowledge in 1966. (Moormann refused several demands to discuss his paper. The management of Fz-Jülich had been recommended by writing to withdraw this paper, as it is a disgrace. No answer, no comment up to now.)

Remains the question of possible problems with the Non-proliferation Treaty –NPT- , as PU may be produced by burning U238. The experience is, that PU is only produced as long as the pebbles are not nearly fully burnt-up. Extensive calculations and test were done in ZA [4] showing, that combinations of PU 238/239/240/241/242, U235, Fissile PU i.e.PU 239 and PU 241 and Th can be burnt together in coated particles. So a Pebble Bed HTR can be used to burn-up PU. The design of the pebbles fuel cycle –Fig.7- shows, that every single pebble can and will be measured to the degree of burn-up. So with a HTR Pebble Bed Reactor the disposal of PU can be very extensively controlled, as each pebble can be treated individually. So very detailed and full control of PU disposal is guaranteed and possible by inspection.

Further this experience proves that all problems of safe long-term final storage of burned fuel elements, components and other waste can be solved by this integrated concept of a new HTR power plant. No external storage or transportation of fuel elements or other radioactive material is necessary.

The engineering design of this concept is still completely available with the basic know how of all parts, circuits and components of AVR and THTR, as well as all fundamental documents for approval of all authorities for erection and operation. [5,6,7]

6. Summary and Conclusions.

Future designs of HTR-Reactors should/must have the following important design elements, mainly for safety reasons:

- Inherently safe design.
- No melting of the core is possible.[8]
- Gastight integrated helium circuit.
- Smaller reactors with one central core can be designed with steel vessels, -example AVR-,
- Larger reactors up to highest capacities should be designed with pre-stressed concrete pressure vessels, example THTR-300.
- Pebble-Bed-Ring-Core /PBRC/ for higher capacities. No shut down rods into the pebble bed.
- Pebbles as fuel elements with TRISO coated particles.
- Small room is necessary to store the fuel elements.
- Safe against heavy earthquakes.
- Safe against terrorism and other greater/heavier accidents.
- Very good and simple control of nuclear material e.g. PU.

This design will have the following main economical advantages:

- High primary helium gas temperatures up to 1100^o C;
- High He-primary and secondary gas/steam temperatures make it possible to reach high efficiency in secondary processes.
- High gas temperatures are the basic to install on secondary site l chemical processes to produce e.g. hydrogen and/or liquid fuels.
- No shut down of the power plant for exchanging of fuel elements.
- Combination of producing electric power and heat for heat supply for different kinds of following processes.
- Thermodynamic water/steam circuit up to two times intermediate reheating of the steam.
- Thermodynamic efficiency as high as in conventional power plants
- Very high burn up of nuclear material.
- Use of Th 232 in combination with U 235 to produce U 233.
- Breeding of new nuclear material.
- Very good possibility to handle and store radioactive material, the pebbles included, in the power station.
- Long time storage of radioactive material is possible.
- No transportation of radioactive material outside the power station is necessary.
- Burn-.up and "disposal" of PU included Weapons-PU.

This concept of an HTR makes it possible to build a nuclear power station without any danger of a major accident and promises high efficiency and longtime operational periods. The integrated design makes it possible to avoid any radioactivity outside the power station. After final shut down all radioactive waste, including the pebbles can be stored inside the concrete parts of the station. No radioactivity can or should be detected outside the plant. So this design will have the highest possible safety standard.[8,9]

References

1. H. NABIELEK, K. VERFONDERN, M. J. KANIA, HTR Fuel Testing in AVR and MTRs. HTR Conference, Prague (2010).
2. H. NABIELEK, C. TANG, A. MÜLLER, "Recent Advances in HTR Fuel Manufacture". HTR Conference, Prague (2010).
3. R. MOORMANN, A Safety Re-evaluation of the AVR Pebble Bed Reactor Operation and its Consequences for Future HTR Concepts, FZ-Jülich Report 4274 (2008).
4. E.MULDER, D.SERFONTEIN, W.VAN DER MERVE; E.TEUCHERT: Thorium and uranium fuel cycle symbiosis in a Pebble Bed High Temperature Reactor. Proceedings of HTR 2010 Prague 2010.
5. U. CLEVE, The Design of High Temperature Reactors (Die Technik der Hochtemperatur-reaktoren), Atomwirtschaft atw (12/2009 with 35 lit.refers.).
6. U. CLEVE, Nuclear High Temperature Technology to Produce Liquid Fuel of Hydrocarbon and Electrical Power (Nukleare Hochtemperaturreaktor-technik zur Erzeugung flüssiger Brennstoffe, von Wasserstoff und elektrischer Energie), atw (4/2011 with 23 lit.refers.) .
7. K. KNIZIA, Der THTR-300- eine vertane Chance? Atomwirtschaft-atw(7/2002)
8. K.Kugeler, Gibt es einen katastrophenfreien Kernreaktor? Physikalische Blätter 37(2001),Nr.11.
9. H.Bonnenberg: High Temperature Gas-Cooled Reactor with Spherical Fuel Elements – A German Development Implemented Abroad. DGAP-2007.