THE AVR HIGH-TEMPERATURE REACTOR - OPERATING EXPERIENCE, STORAGE AND FINAL DISPOSAL OF SPENT FUEL ELEMENTS

R. Theenhaus and S. Storch
Research Centre Jülich GmbH
Federal Republic of Germany

ABSTRACT

The AVR is the first power plant with helium-cooled HTR to use spherical fuel elements. The experimental reactor was in successful operation for 21 years. In the first years of operation the main aim was the demonstration of the technical feasibility of high-temperature reactors. Special importance was attached to the testing and behavior of the fuel elements. The AVR was decommissioned in late 1988 and approx. 170,000 spent fuel elements of various designs and compositions have been discharged. HTR fuel element reprocessing is not economically viable. Final disposal of the fuel elements is therefore envisaged after several years of intermediate storage.

DESIGN OF THE AVR

The principle of an HTR is the generation of high coolant temperatures to achieve high efficiencies. Moreover, chemical engineering processes can be operated using HTR heat at a high temperature level.

The required coolant temperature of about 1000°C can only be reached in nuclear reactors with ceramic materials. Graphite has been selected as a material for spherical fuel elements to satisfy nuclear physical, economic and technical requirements.

At the beginning of AVR design in 1957, it was also decided to transfer the heat from the reactor core to the steam generator by means of non-corrosive helium.

The graphite-moderated AVR core consists of a pebble bed of about 100,000 fuel elements in a cylindrical vessel made of graphite. The vessel has a diameter of 3 m and a fuel element packing height of 2.8 m. It furthermore serves as a neutron reflector.

The helium heated in the pebble bed (pressure 10 bar) is delivered by two cooling gas blowers through channels in the reflector head to the steam generator installed above the reactor core.

The fuel elements produce a thermal power of 46 MW in the reactor core. The helium cooled down to 150°C in the steam generator flows back to the blowers in a gap on the inner reactor vessel. The helium is blown into the reactor core from below at a temperature of 275°C.

The steam generator consists of four parallel systems. The feedwater enters at a temperature of 115°C and leaves the superheater as steam at 550°C and a pressure of 73 bar. The turbine of the power plant produces an electrical output power of 15 MW.

OPERATING EXPERIENCE

The AVR experimental power plant was initially designed and operated to demonstrate the technical feasibility of a high-temperature reactor with ceramic spherical fuel elements. During its 21 years of power operation, the operational goals have repeatedly changed. The tolerant operating behavior of the experimental facility with respect to technical disturbances, repairs and experimental setups made it possible to gradually gain valuable insights into HTR technology. In addition to feasibility, high availability was demonstrated.

From the beginning of electricity production in late 1967 until decommissioning in late 1988, a total of 1.67×10^9 kWh was supplied to the public grid. The average time utilization was 70 %. During this period, the AVR core was loaded with 300,000 different fuel elements. 180,000 spent fuel elements were discharged and conveyed to KFA storage facilities.

The good properties of the fuel elements and of the improved coated particles as well as their high retention capability for fission products were not known at the beginning of AVR design and construction. A high contamination of the primary coolant loop had been expected. The AVR was therefore equipped with two pressure vessels.

However, the contamination of the helium coolant gas was unexpectedly low, so that only small quantities of radioactive substances were released into the environment. Airborne releases comprised

nobel gases totalling	20 - 30 Ci/a
tritium totalling	< 100 Ci/a
C-14 totalling	< 2 Ci/a.

The radiation exposure of the operating staff was consequently very low.

During the long period of operation, the upper graphite reflectors of the reactor were exposed to high neutron dose rates. Damage to the reflector due to stresses and graphite abrasion was not observed, as expected, after an inspection with very small TV cameras.

An essential experience made was the positive repair behavior of the entire reactor. A leakage occurred at the steam generator after 72,000 hours of operation, causing 27 t of water to flow into the reactor core and collect in the reactor vessel. The water/steam was removed after disconnecting the defective tube segment. Operation was then continued without discharging the fuel elements. The cause of this leakage has not yet been clarified.

RESULTS OF THE EXPERIMENTS

During the first years of AVR operation, it was important to demonstrate the feasibility of the HTR with its fuel elements and components. Operation under full load was given top priority. Excellent operating behavior, the availability of the experimental facility and valuable information concerning the structural design of follow-on HTRs rank among the most important results.

Experiments relating to the special HTR characteristics were also intended to demonstrate the safety of the reactor principle. Of particular significance in this connection is an experiment already carried out in 1970. During thermal power operation at 44,000 kW, the coolant gas blowers were stopped, i.e. heat transport from the reactor core was interrupted. If this process had occurred as an accident, the shutdown rods had been automatically inserted into the core to shut the reactor down. During this experiment, however, the shutdown rods were not moved. Nevertheless, a pronounced power reduction was observed within a short time. The temperatures in the reactor core decreased correspondingly. The residual heat of 1800 kW was dissipated to the steam generator by natural convection. The reactor stabilized automatically, which demonstrated a rather outstanding property of the HTR reactor.

In the last two years of AVR operation, 21 further experiments were planned, installed and except for one experiment, carried out successfully. In addition to AVR GmbH and KFA Julich GmbH as the operators, and HRB and Interatom as the reactor manufacturers on the German side, the Japanese research institute JAERI, as well as General Atomic and ORNL on the American side participated in the experiments.

On the whole, extremely successful experiments were carried out in the fields of

- HTR safety
- reactor physics
- measuring technology for temperatures, neutron flux and fuel burn-up
  as well as
- fuel element testing.

The results provided fundamental insights into HTR technology.

The AVR experimental power plant has demonstrated a high availability and cumulated in two extraordinary results:

1. a maximum coolant gas temperature of 1000°C,
2. a maximum average fuel burn-up of > 100,000 MWd/t HM.

AVR FUEL ELEMENTS

The development, irradiation and long-time testing of graphite fuel elements was a major task to be performed with the experimental reactor until its last year of operation (1988). During the first phases of development, concepts were still pursued involving the use of pellets in a graphite matrix. The most important requirement with respect to the fuel element was a continuous improvement of the retention capability for fission gases under extreme reactor conditions.

Decisive progress began with the almost simultaneous invention of the so-called "coated particle" in the USA and Great Britain.

It took several years to further develop this fuel particle. The first particles made of U-Th dicarbide with a pyrocarbon layer (PyC) were not suited for the high burnup (> 14 % fima) involved.

Kernel swelling with increasing burn-up ultimately led to the development of a first layer as the "buffer layer" and a second gastight coating. These particles were named "BISO particles" in the USA. In Germany, sphere fabrication concentrated on the further development of the "pressed element" which was tested in the AVR.

A new particle was developed in the seventies to enclose the initially high-enriched U 235 in four coatings. This TRISO particle was tested on a priority basis in the AVR, beginning in 1981. It was finally fabricated with low-enriched UO_2. The TRISO-LEU particle in a pressed fuel element has to date successfully completed the development of HTR fuel elements.

The various AVR fuel elements contain 30,000 - 40,000 coated particles of UO_2 or (U,Th)-O_2/-C_2. The particles have several coating layers. The very resistant SiC layer together with the dense and pressure-stable PyC coating are the main fission product barriers. The release of gaseous fission products is also of significance for spent fuel element storage. Fission gases capable of being released are produced by U, Th contamination of the graphite matrix.

Table I contains reference data of a spent fuel element.

TABLE I
Data of Spent Fuel Element

mass, total		200 g
diameter		60 mm
burn-up fima, max.		20 %
U 235 (93 %)		0.65 g
U 233 Pu 239, 241		0.10 g
cooling time	200 d	4 years
activity	1.8 TBq	560 GBq
thermal power	0.2 W	0.04 W

SPENT AVR FUEL TREATMENT

The AVR was decommissioned in late 1988. 110,000 fuel elements are still loaded in the reactor core. Approximately 180,000 spent fuel elements of various designs and compositions have been discharged.

Generally, in terms of electricity generation, uranium consumption in HTRs without fuel reprocessing is similar to LWRs with fuel reprocessing. The isotopic composition of the bred plutonium in spent HTR fuel represents a low neutron value, i.e. is less economic than in the spent LWR fuel elements.

INTERMEDIATE STORAGE

During its operating time the AVR reactor discharged 50 - 100 spent fuel elements per day. They are packaged in sealed stainless steel canisters. Since 1973 the small canisters have been temporarily stored in a water pool facility at the Research Centre Jülich.

After a storage time of about two years, the fuel elements are filled into large canisters with a capacity of 950 fuel elements. They are stored in a natural-convection-type dry storage facility. This hot cell has storage racks in which two canisters are placed on top of each other. The total capacity amounts to 106,000 elements, which is the total load of the AVR core.

The decay heat of all the fuel elements is some kilowatts. The fuel element temperature in the centre of the canister is less than 60°C. The exhaust air activity of the storage facility is controlled. Fission gas release is so low that it cannot be measured.

After decommissioning of the AVR reactor, 300,000 spent fuel elements, filled in canisters, will be accommodated in transport-storage casks for intermediate storage. These casks will be stacked on two levels in a storage hall. The hall dimensions are 25/18/13 m.

Casks of nodular cast iron, e.g. of the CASTOR type, have proved suitable for the transport and storage of LWR fuel elements over a period of years. Closure is effected by two lid systems, generally making use of metallic gaskets. The leak test is carried out consecutively after mounting each lid. The sealing function is checked by a pressure pick-up (manometric switch) which triggers an electric display if a seal should fail. The space between the two lid seals is filled with helium at a pressure of 6 bar.

The AVR cask version follows a more economic design. The cask functions are reduced to mechanical protection and radiation shielding.

Research results show that the coatings remain intact at > 1000°C during reactor operation thus completely retaining the fission products. Temperatures are considerably lower (max. 100°C) during intermediate storage so that the HTR fuel elements already have an effective and reliable fission product barrier.

Furthermore, since the spheres have to be packaged before handling, the idea arose of sealing the required canisters by remote-controlled automatic welding equipment. Arc welding seals the canister except for an extremely narrow annular gap. The leak rates achieved are at least 1×10^{-9} mbar l/s. The canisters are filled with helium before welding. The weld is tested for helium leakage in the cell and is permanently stable with respect to corrosion.

FINAL DISPOSAL

HTR fuel element reprocessing is not economically viable. Final disposal of the fuel elements is therefore envisaged after several years of intermediate storage.

In the FRG it was decided to dispose of radioactive waste in a salt dome formation, as a very good option for thorough separation from the biosphere.

The properties of spent AVR pebble bed fuel offer flexibility in the choice of packaging design and emplacement technique. The reference concept is the insertion of 400-litre steel drums with a capacity of 1800 spheres into vertical 300 m deep boreholes. The disposal technique for heat-generating "intermediate level wastes" arising from LWR fuel element reprocessing and for spent AVR fuel elements is under development in the Asse salt mine R + D project (2).

At present, two package variants are being explored: a thin-walled drum with backfill option and a cast iron container.

Both container concepts are not HTR-specific. The spent AVR fuel elements must be transferred from intermediate storage containers or canisters.

The waste packages to be disposed of in deep salt rock formation must resist external pressure and corrosion. In the future, it should be possible to use the intermediate storage AVR canisters or the low-priced transport-storage containers directly for final disposal. A proposed concept considers the placing of the sealed container in a horizontal position in the mine drift (3).

The necessary proofs and techniques are being demonstrated by experiments at the KFA Jülich and field tests in the Asse salt mine. These experiments will in particular demonstrate that the good properties of the AVR fuel elements with regard to fission product retention can also be taken into account for final disposal.

REFERENCES

1. N. Kirch, G. Ivens Ergebnisse der Versuche mit dem AVR VDI Reports 729, 1989, pp. 87-101 VDI Verlag Düsseldorf
2. D. Niephaus, E. Barnert, P.H. Brücher, K. Kroth, KFA Jülich GmbHIntern. Waste Conf. 1989, Kyoto, Japan, Oct. 23-25, 1989
3. E. Merz, S. Storch, Technical Concept of Interim Storage and Direct Disposal of Spent HTR Fuel Elements, ENC 1986, Geneva, Switzerland, June 1-6, 1986.