IAEA TM on the Management of Spent Fuel (Pebbles and Compacts) from High Temperature Reactors, July 7-11, 2025, Vienna

SPENT FUEL MANAGEMENT IN THE DECOMMISSIONING PROCESS FOR THE GERMAN HIGH TEMPERATURE REACTORS AVR AND THTR-300

Karl Verfondern

Retired from Research Center Jülich, Germany
Email: charlie@karlverfondern.de

Abstract

Two pebble bed High-Temperature Gas-Cooled Reactors (HTR) were operated in Germany, the AVR in Jülich from 1967–1988 and the THTR-300 in Hamm-Uentrop from 1983–1988. Both reactors were shut down in the meantime with all fuel removed from the cores. A description will be given on the characteristic features of the spherical fuel element and the management of the spent fuel spheres of these reactors. The operation of the AVR was accompanied by a comprehensive fuel development and qualification program where the reactor served as test bed for mass fuel qualification. It was completed by extensive postirradiation examination (PIE) work. In contrast, the fuel spheres of the THTR demonstration plant were never subjected to routine PIE. The total spent fuel from the two German HTRs amounts to approximately 910,000 spheres with 32% being from the AVR and 68% from the THTR-300.

1. INTRODUCTION

Since the general change of the HTR fuel cycle from high enriched uranium (HEU) to low enriched uranium (LEU) at the beginning of the 1980s, the HTR fuel strategy in Germany was guided by the need to meet non-proliferation aspects and to find a convincing publically accepted spent fuel concept. The German reference spherical fuel element with its safety related properties has many positive features, which are effective not only during normal operation and during accidents, but also under conditions of intermediate storage and final disposal:

- Efficient use of uranium and in-situ generated plutonium in LEU fuel due to high burnup;
- Isotopic composition of the spent fuel which is non-proliferation friendly;
- TRISO coating of the fuel particles as an effective long-term barrier against fission product transport reducing the need for additional barriers;
- Passive air cooling systems sufficient from the beginning of intermediate storage due to the low power density of the fuel (< 1 kW/m^3 after 1 yr of cooling);
- Disposal techniques developed for medium active waste applicable to spent HTR fuel;
- Minimal spent fuel conditioning effort due to homogeneous graphite matrix;
- Corrosion resistance of both matrix graphite and particle coatings against repository relevant atmospheres allowing for a simple fuel disposal packaging concept;

- Use of small and easy-to-handle equipment in intermediate and final storage due to the small fuel sphere dimensions.

For these reasons, the concept for HTR spent fuel treatment, which was selected in January 1985, is presently the only accepted method of spent fuel management in Germany involving the two steps of

1. intermediate dry storage in appropriate containers and facilities, and

2. transfer to a deep-mined repository for final disposal utilizing techniques of treatment similar to heat generating medium active waste.

2. SPENT FUEL MANAGEMENT FOR THE AVR TEST REACTOR

2.1. Characterization of AVR Fuel

The 46 MWt (15 MWe) AVR reactor in Jülich obtained first criticality in August 1966 and began operation at the end of 1967. During its 21 years of operation with a time utilization factor average of 67.2%, a thermal power production of 5117 GWh, and a delivery of 1670 GWh of electricity were achieved. In the 1970s, the focus was on demonstrating reactor operation and proving HTR principles. In the 1980s, the focus turned to more experiments designed and conducted by AVR and FZJ in cooperation with the German nuclear industry and various foreign partners. At the end of 1988, the reactor was permanently shut down.

The AVR was primarily used to test the HTR concept, the components, and the fuel. Fueling of the first core loading started in July 1966 with about 30,000 first core fuel elements, 70,000 moderator (graphite) balls, and 3000 absorber balls. In sum, more than 290,000 spherical fuel elements of 15 variants (carbide/oxide, BISO/TRISO, HEU/LEU, one/two-particle systems, different heavy metal (HM) loadings) (Fig. 1, Tables 1 and 2) with more than 6 billion coated fuel particles were inserted into the core. Fuel element design also changed soon with reload charge 3 (GK, yellow) from machined graphite shells to pressed matrix materials.

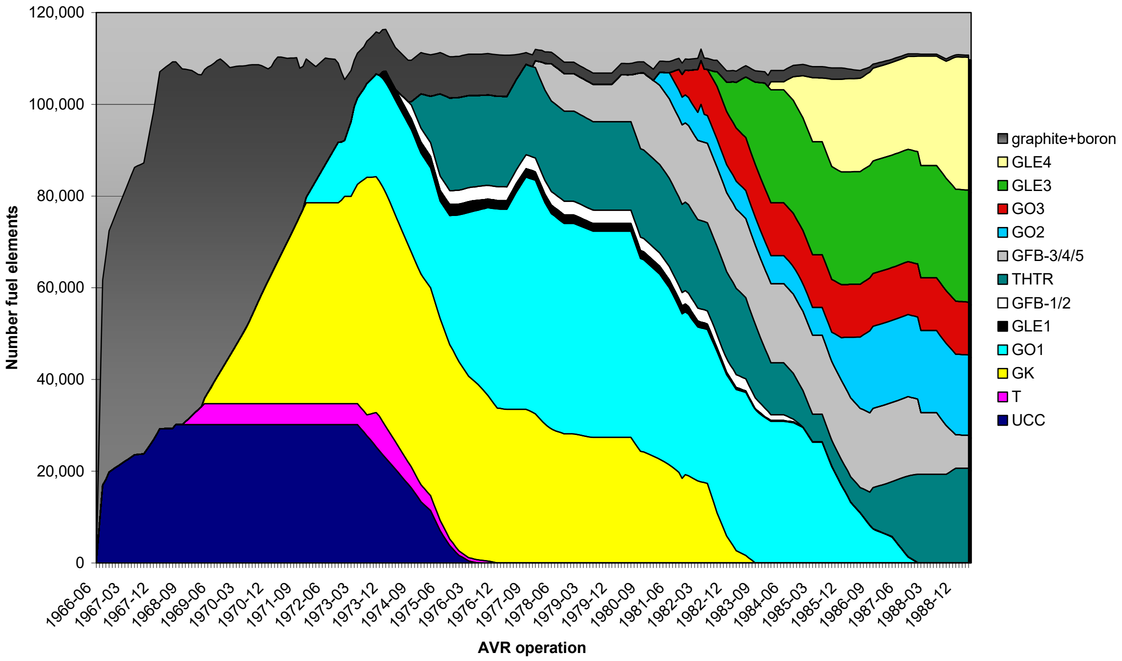

FIG. 1. Operational life history of different fuel element types in the AVR.

Using high enriched mixed carbide/oxide fuel at the beginning, the reactor core was, since mid 1982, gradually converted to a low enriched fuel cycle. By the end of operation, a total of 2.4 million spheres were recycled in the core, some 180,400 fuel elements were removed from the core. Operating elements inserted to the core were distinguished between fuel elements, graphite moderator spheres, and boron spheres. From October 1971, absorber and graphite spheres were no longer distinguished. The composition of the reactor inventory of totally ~110,000 fuel spheres remaining in the reactor at the end of operation was about 50% of HEU and 50% LEU fuel [Pohl 2001].

The first core (UCC) and the first reload (T) fuel consisted of a hollow sphere (shell) made of electrographite with 10 mm wall thickness. Through an opening, the coated particles and a "matrix" called mixture of graphite powder, binder, and a graphite, which expands irreversibly at high temperatures (1450°C), were pressed in to fill the void. In T spheres, the coated particles were made to stick on the inside wall like a wall paper (3–4 particle layers), with the remaining void filled with a binder containing graphite powder. The opening was closed by a threading plug.

All following AVR reload charges (since 1969) consisted of NUKEM manufactured semi-isostatically pressed mixtures of particles with so-called "A3 standard" matrix material in a 50 mm diameter sphere plus a fuel-free A3 matrix zone of 5 mm thickness on the outside. Two types of A3 matrix material were employed: A3-3 consisting of natural graphite powder (72.0%), electro graphite powder (18.0%) and non-graphitized phenol resin binder coke (10.0%); A3-27 is like A3-3 with slightly deviating component shares (71.2%, 17.8%, and 11.0%, respectively), and with the resin binder being synthesized during matrix manufacture. A3-27 was used starting with AVR reload charge 14 from November 1976.

While all shell-type spheres and the first moulded-type variant (GK) contained HEU mixed carbide coated particles, it was soon started with the insertion of HEU mixed oxide fuel variants. These included the THTR fuel particles with BISO coating and the (same) $(Th,U)O_2$ particle with TRISO coating which became the reference fuel for THTR follow-on plants. Testing of LEU fuel began in the middle of the 1970s with GLE variants, the last production charges being GLE-3 and GLE-4 known as the high-quality German HTR fuel spheres and reference for the HTR-Module concept.

Table 1 provides fuel statistics where the totally 290,700 fuel spheres inserted in the AVR core are distinguished in terms of particle kernel composition, coatings, and type of fuel element/matrix [Pohl 2001].

TABLE 1. AVR AS TEST BED FOR DIFFERENT TYPES OF FUEL

Type of fuel	**# fuel spheres**
Fuel kernel design	
HEU mixed carbide	87,600
HEU mixed oxide	129,400
HEU fissile/fertile	20,300
LEU oxide	53,400
Coating design:	
BISO	202,900
TRISO	74,300
Mixed (fissile TRISO, fertile BISO	13,500
Fuel element design:	
Shell type	37,700
Moulded type	253,000
A3-3 matrix material	135,300
A3-27 matrix material	117,700

Table 2 describes the fuel composition of the AVR classified into five groups relevant for the decommissioning process, two groups of HEU fuel with different Th loadings and three groups of LEU fuel with different enrichments. The table also provides the respective number of fuel spheres that have gone into the core compared with those that were left after terminating reactor operation at the end of 1988 [Pohl 2002].

TABLE 2. FUEL INVENTORY OF AVR AT THE END OF OPERATION

AVR Fuel		**Number of FE gone into core**	**Number of FE end of operation**
Type	**Variant**		
1. HEU, 5g Th	UCC, T, GK, GO, GFB-3/4/5	196,139	36,255
2. HEU, 10g Th	GFB-1/2, THTR	38,465	20,255
	All HEU	**234,604**	**56,510**
3. LEU, 20gU (15% enr+U_{nat})	GLE-1	2,400	73
4. LEU, 10g U (10% enr)	GLE-3	24,611	24,450
5. LEU, 6g U (16.7% enr)	GLE-4	29,090	28,947
	All LEU	**56,101**	**53,470**
	Total:	**290,705**	**109,980**

2.2. Management of Spent Fuel during Reactor Operation

The discharge chute of the reactor core with 500 mm diameter contained approximately 13,000 spheres. It was closed at the bottom by a slotted disc. On turning the disk, several spheres passed on into a buffer space for the singulizer which separated a single sphere from the buffer and conveyed it to a scrap separator diverting all spheres with < 56 mm diameter.

In equilibrium operation, during each equivalent full power day (efpd), on the average 625 spheres were circulated. Of these, about 50–60 fuel spheres per efpd identified as spent fuel were discharged, while the remaining spheres were reshuffled to the core. The discharged fuel was replaced with the same amount of fresh fuel given to the outer core region. Fuel spheres having achieved final burnup were guided through a sixth tube for discharge and channeled out to a spent fuel shipping flask with a capacity of 50 spheres. These stainless steel flasks were moved through a circular conveyor and stored in a ring channel for a certain cooling period. The flasks were then sealed and transported outside the reactor by means of a shielded bottle to the water pools of the Hot Cells with a total capacity of 65,000 spheres (13 storage racks, each consisting of 20 tubes, each tube taking up a stack of five AVR flasks filled with 50 fuel spheres each), or of the DIDO MTR with a capacity of 28,500 spheres [Brinkmann 1980]. The wet buffer storage, typically for 2–4 yrs, was successfully conducted since 1973 [Duwe 1985, Storch 1985].

The next step was the opening of the flasks in the Hot Cells and repackaging of the spheres into larger, dry storage canisters made of stainless steel and with a capacity of 950 spheres (Fig. 2, top) filled with helium at atmospheric pressure, their specified leak tightness was guaranteed to be $< 10^{-2}$ Pa·ℓ/s [Krumbach 2004]. Fuel elements which were found wet due to leaky sealings of the steel flasks, were separated and also given into dry storage canisters, but then sealed with a particular leak-tight welding.

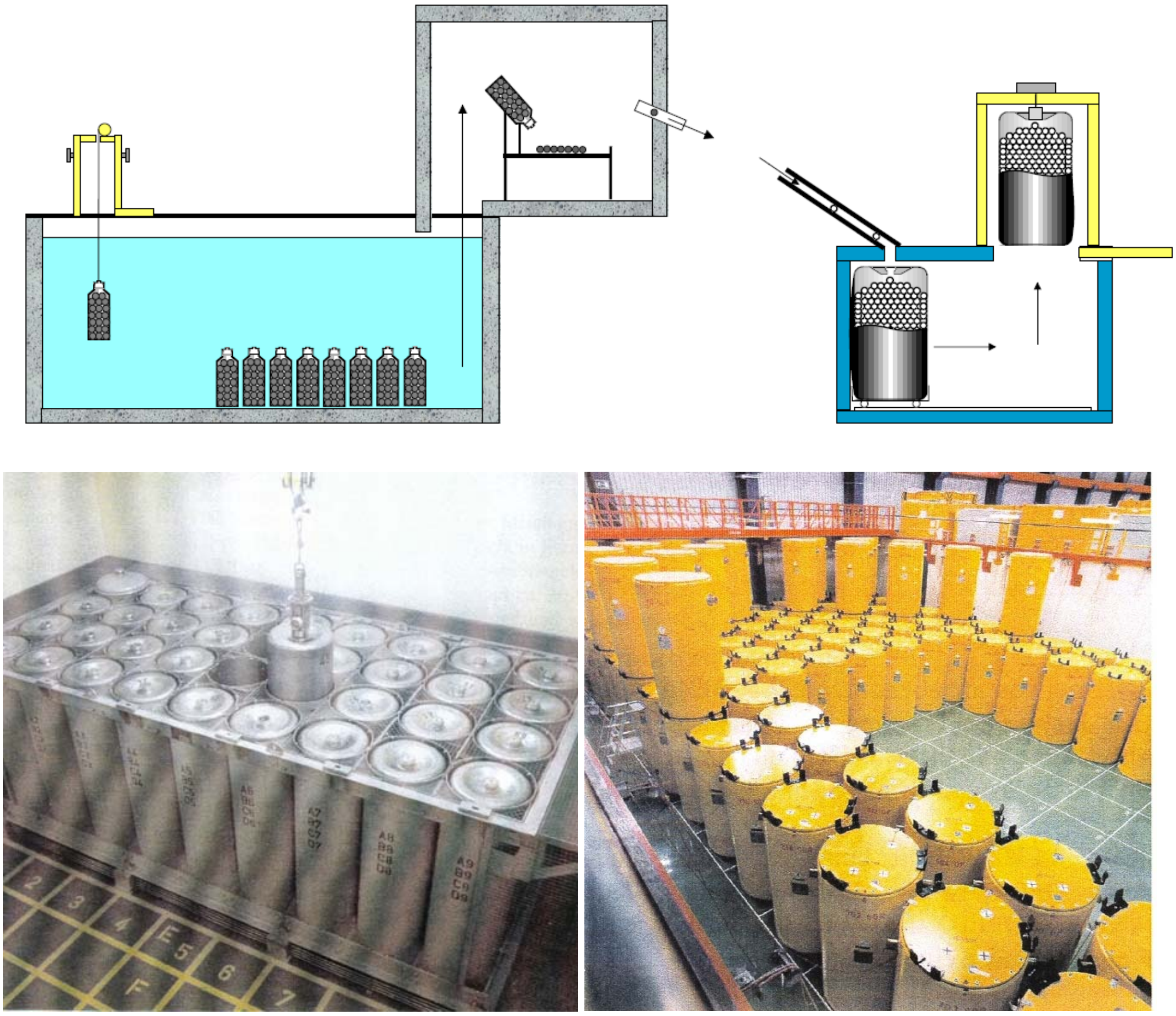

FIG. 2. AVR spent fuel management in the Hot Cells at FZJ (top)
AVR canister storage (bottom left), storage in CASTOR casks (bottom right).

The dry storage canisters were transported from the hot cells to the AVR dry store (AVR-TL) for intermediate storage of canisters in two layers on 36 positions. It was designed to remove a maximum of 7.2 kW by natural circulation and supported by a ventilation system of 2000 m^3/h of air exchange. Basis of design were spent fuel spheres with a cooling time of minimum 2 yrs, a burnup of 5–15% FIMA, a decay heat production of 0.1 W/FE, and an activity of 480–630 GBq/FE (13–17 Ci/FE). Correspondingly, the concrete shielding walls had a thickness of 1.3 m [Brinkmann 1980]. The AVR-TL was filled by 1984 with 72 canisters containing about 68,000 spheres [Storch 1985]. A measurement program on the filled dry store revealed a temperature increase of 0.6°C between air inlet and outlet, a maximum temperature of 32°C of a canister, and an annual release rate from the fuel contents (950 spheres, > 4 yrs cooling time) into the canister atmosphere of 11 MBq (3×10^{-4} Ci) of tritium and 5.6 MBq (1.5×10^{-4} Ci) of Kr-85 [Storch 1985]. The employment of the 950-sphere canisters was considered to ease the future repackaging step to the reference 400 l final disposal drums. The dry storage facility was operated since 1981 without any disturbance and took up 72 of the dry storage canisters in 36 positions (Fig. 2, bottom left).

In accordance with the decommissioning strategy of the German Federal Government for safe storage, a further spent fuel store was erected on-site FZJ with space to hold the transport and storage casks for the spent fuel spheres from AVR. This cask store (AVR-BL) provided 158 positions (Fig. 2, bottom right), meaning that all AVR fuel of about 290,000 spherical elements could be kept for the time being. Reference data for designing the transport and storage casks were a fuel burnup of 15% FIMA, a cooling time of 4 yrs, a decay heat power of 0.06 W, and a total activity of 555 GBq (15 Ci) [Storch

1985, Röllig 1987, KFA 1988]. Since 2014, the AVR-BL received protection against airplane crash and terrorist attack.

The CASTOR THTR/AVR was chosen as transport and storage cask, to guarantee the requirements of safety against criticality, assured removal of decay heat, gas-tight and long-term enclosure of all radioactive substances, and sufficient shielding against ionizing radiation [KFA 1988]. The cask, a thick-walled (370 mm) body made of spherulitic graphite cast iron with 2.78 m height and 1.38 m diameter and an overall weight of 32 t was to receive two of the 950-sphere canisters. The cask is closed by a double-lid system with a primary lid of 250 mm thickness and below a secondary lid of 70 mm thickness, both firmly screwed to the cask body and sealed by special metal gaskets. The void between primary and secondary lid is filled with helium at some overpressure. In addition, a steel sheet is fixed above the double-lid system to protect against mechanical impacts and humidity ingress. Safety testing of the CASTOR THTR/AVR cask included a drop from 9 m height, a bonfire test at > 800°C over 30 min, and an airplane crash simulation by shooting an ~1 t weight with nearly speed of sound onto the cask [KFA 1988].

The AVR-BL was licensed in 1993 and received its first cask loading the same year [JEN 2024]. It is, for the time being, store of 288.161 fuel spheres and 124 moderator spheres in 152 CASTOR casks of type THTR/AVR with a total of 1.9 t of heavy metal material, of which 75 kg is fissile material [Mank 2015].

2.3. Decommissioning of AVR

The first application for a decommissioning license for the AVR experimental reactor was submitted already back in 1986 and it was granted in March 1994 [Pohl 1998]. The initially chosen decommissioning strategy for the AVR was "safe enclosure". It was split into two phases [Marnet 1998]:

(1) Defueling of the reactor, dismantling of plant systems outside the reactor building;

(2) Dismantling of components, alteration of components, installation and operation of new facilities for the state of safe enclosure as well as operation in the state of safe enclosure.

The composition of the reactor inventory of totally ~110,000 fuel spheres remaining in the reactor at the end of operation was about one half each of HEU and LEU fuel. Defueling started in April 1994 with HEU fuel only. Due to the fact that a particular license was required for LEU fuel handling in the Hot Cells of FZJ, all LEU fuel identified was reshuffled back into the core. Selection was made by measurement of the U-232 isotope which is practically present in the thorium containing HEU fuel only. During operation, a perfect distinction by Pa-233 in the gamma scan was possible. The defueling process was interrupted after having discharged 35,000 HEU fuel elements with a HEU share in the circulated elements reduced to 17%. After the LEU license was finally granted, defueling was resumed in March 1996. A restriction was given at the beginning in that upper limits for heavy metal and Pu-239 contents in the CASTOR casks had to be obeyed, which was met by "selective defueling". After obtaining the permission for considerably higher limits, unselective defueling could begin with still 63,000 spheres in the core [Pohl 1998]. The defueling process was accompanied by regular criticality measurements to ensure in-time countermeasures in case of too high a fuel concentration in the core center conceivably resulting from the fresher fuel of the outer zone displaced to the inside during defueling. The defueling was completed by middle of 1998 [Pohl 1998].

Table 3 provides the important characteristics of the AVR spent fuel spheres including also a distinction between three groups of CASTOR casks, containing either BISO fuel only, or TRISO fuel only, or a mixture of these types [Delley 2014].

TABLE 3. FUEL CHARACTERISTICS OF AVR SPENT FUEL SPHERES

	AVR-1	AVR-2	AVR-3	Total AVR
# Casks	55	47	50	152
# Fuel spheres	97,200	90,000	101,000	288,200
Fuel type	TRISO	BISO	BISO/TRISO	BISO and TRISO
Total Uranium (g)	458,603	45,078	44,138	547,819
U-235 (g)	35,005	15,228	9,210	59,443
U-233 (g)	3,738	9,093	12,341	25,173
Fraction U-235+U-233 (%)	8.4	54.0	48.8	15.4
Thorium (g)	284,355	428,232	575,922	1,288,508
Plutonium (g)	4,769	454	824	6,047

As a result of an inspection for residual fuel in the core, the equivalent of 197 fuel elements was said to be unretrievable [Pohl 2002]. It was a conservatively estimated upper limit of fuel loss in the core, but was considered by the regulator to be sufficiently low and safely enclosed to remain inside the reactor vessel. Total heavy metal contents of the fuel left in the core was calculated to be 486 g of uranium (including 71 g of U-235 and 24 g of U-233), 7.2 g of plutonium, and 1180 g of Th-232 [Pohl 2002].

In 2003, the AVR GmbH was taken over by the "Energiewerke Nord" (EWN) in Lubmin, Germany, and the decommissioning strategy was changed. In an agreement between the Federal Government and the State of Northrhine Westfalia (NRW), it was decided to not only have a safe enclosure of the AVR reactor, but to have the site returned to the so-called "green-field" status with complete dismantling of all facilities and site clean-up. The plan was to lift the defueled and grouted reactor pressure vessel including all internals as a whole out of the reactor building and store it in a separate building. In March 2015, the 26 m long, 8 m diameter, and 2200 t heavy reactor vessel was finally removed in one piece to an off-site (on-site FZJ) interim storage building (Fig. 3), designed for storage over 30–60 yrs [BASE 2024]. Dismantling work of other components of the primary circuit was continued and has been completed. The dismantling of other sections like demolition of concrete started in 2020 and is being carried out by radio remote control using a demolition robot [BASE 2024].

On September 1st, 2015, the company JEN (Jülicher Entsorgungsgesellschaft für Nuklear-anlagen) was founded by a fusion of the AVR GmbH and the nuclear services of the Research Center Jülich responsible for the decommissioning, dismantling, and waste management of the nuclear facilities at FZJ including the AVR and return them back to green field.

The operational license of the cask store (AVR-BL)was limited to June 2013. A prolongation of the license was not granted, as in the meantime the proof of safety against earthquakes could no longer be given with the standardized procedure. The Research Center Jülich was then obliged by directive of the NRW State Government to elaborate a concept for the immediate removal of the AVR fuel from the store. The concept presented in 2014 intensively considered three independent, equally weighed options:

- Relocation of AVR (and THTR) fuel to the USA;
- Transport of AVR fuel to the central interim store Ahaus (TBL-A);
- Construction of a new interim store for AVR fuel at Jülich.

FIG. 3. Transport of AVR reactor vessel to interim store.

(1) The US option envisaged the return of all AVR fuel to the USA, the country of origin of the HEU material. The plan was a digestion of the HEU and LEU fuel with a retrieval of the fissile material and its downblending to LEU at the Savannah River National Laboratory [Delley 2014, Mank 2015, Mank 2019]. This option was eventually abandoned in 2022 in consultation with the relevant German federal and state ministries, as it turned out to be too cost extensive and the processing technologies of the fuel to be applied not sufficiently mature [JEN 2024].

(2) The transport of the 152 CASTOR casks from Jülich to the central interim store in Ahaus (BZA) appears to be the easiest and quickest solution for the required removal of the fuel spheres from the AVR-BL store, as it is already the storage place for 305 CASTOR casks filled with the THTR fuel spheres. The license for storage at the BZA was granted in 2016, the one for transport is still pending. Once the transport license is granted, the transports could begin and are expected to take about 2 years. Responsible Federal Ministries judge the transport option as “principally preferable” [JEN 2024].

(3) The construction of a new interim store at Jülich must be based on latest safety requirements (e.g. new reference earthquake, once per 100,000 yrs, owner must prove that ground does not liquefy in such an earthquake, or if liquid, dose will be below allowed limits) will be by far the most expensive solution and would most probably take the longest time to meet the directive of removal of the AVR fuel. A site for the new building has been agreed upon in the meantime. Also the required environmental assessment was successfully conducted. This option, however, would be dropped as soon as transports to Ahaus had started [JEN 2024].

3. SPENT FUEL MANAGEMENT FOR THE THTR-300 DEMONSTRATION REACTOR

3.1. Characterization of THTR Fuel

The concept of the “Thorium Hochtemperatur-Reaktor”, THTR-300, in Hamm-Uentrop dates back to the end of the 1960s. Construction (1971–1983) and operation (1983–1988) of the THTR-300 with a thermal power of 750 MW were characterized by various licensing-technical and political obstacles. The shutdown of the reactor in September 1988 was done for a scheduled annual revision and was loaded with fresh fuel, but continued discussions eventually ended up in the decision by the operator in September 1989 for decommissioning the plant [Bäumer 1991b]. The THTR was operated for not more than 16,410 hours or an equivalent time of 423 days of operation at full load.

The THTR fuel concept was based on a high-enriched uranium-thorium fuel cycle and licensed in 1973. The fuel particle consisted of a homogeneous U-Th mixed oxide kernel surrounded by a BISO coating. Total particle diameter is about 760 µm. Each THTR sphere contains approx. 34,100 of those BISO particles. The heavy metal content amounted to 1.032 g of 93% enriched uranium plus 10.2 g of thorium per fuel sphere. Fuel fabrication took place from 1973 to 1980 for the initial core (380,000 spheres) and from 1980 to 1988 for reload (600,000 spheres). Unlike the AVR reactor, the THTR-300 was fueled with this one type of fuel element and coated particle design only. Also fuel temperatures were lower than in the AVR under normal operating conditions with an average coolant outlet temperature of 750°C.

Apart from the experience gained from THTR operation, the investigation of the irradiation behavior of THTR fuel elements was done as part of the qualification program in respective experiments in MTRs and, as a mass test, in the AVR reactor. The THTR reactor itself was not designed for an intentional discharge of fuel elements for testing purposes. Correspondingly, PIE work was conducted on those spheres tested in the MTRs and on random samples of THTR-type fuel taken from the AVR. There were never fuel elements discharged from the THTR taken for further PIE.

The calculated contents of heavy metal contained in 617,606 fuel elements removed from the THTR core are given in Table 4 [Niephaus 2000].

TABLE 4. CALCULATED HM CONTENTS OF THTR SPENT FUEL ELEMENTS

Contents in total THTR fuel (kg)				
U-233	**U-235**	**U-238**	**Th-232**	**Pu total**
104	239	–	6110	2.2

The initial THTR core contained a total of 674,200 spherical elements, of which 358,200 (or 35%) were fuel elements, 272,500 (40%) were graphite elements, and 43,500 (7%) were boron and hafnium doped absorber elements. During reactor operation, 1.3 million spheres were circulated, 235,000 of which were permanently removed and replaced with fresh fuel [Bäumer 1991a]. At the time of termination of operation on September 1, 1989, a total of 704,426 operating elements were in the core and the loading facility [Knizia 2002]. From the core itself, approximately 670,000 operating elements (see Table 5) [Niephaus 2000]had to be finally removed from the core, 84% of which were fuel elements with an average burnup of 5.3% FIMA [Niephaus 2000]. The at-reactor canister store for spent THTR fuel was licensed in 1982. It received its first regular spent fuel in 1988.

TABLE 5. COMPOSITION OF THTR CORE

Type	**Number of operating elements**	
	First core	**Before unloading**
Fuel elements	358,221	562,929
Moderator elements	299,794	76,130
Absorber elements	43,445	30,779
Total operating elements		**669,838**
Fuel elements discharged as spent fuel	–	250,690

3.2. Management of Spent Fuel during Reactor Operation

All fuel canisters were stored for 1–2 yrs in a reactor spent fuel store with 72 storing positions for three canisters each plus 9 more positions for high active waste (Fig. 4). Shielding is given by concrete walls of 1.9 m thickness. The store is designed for a heat removal of 232 kW which was realized by a forced convection cooling system [Röllig 1987].

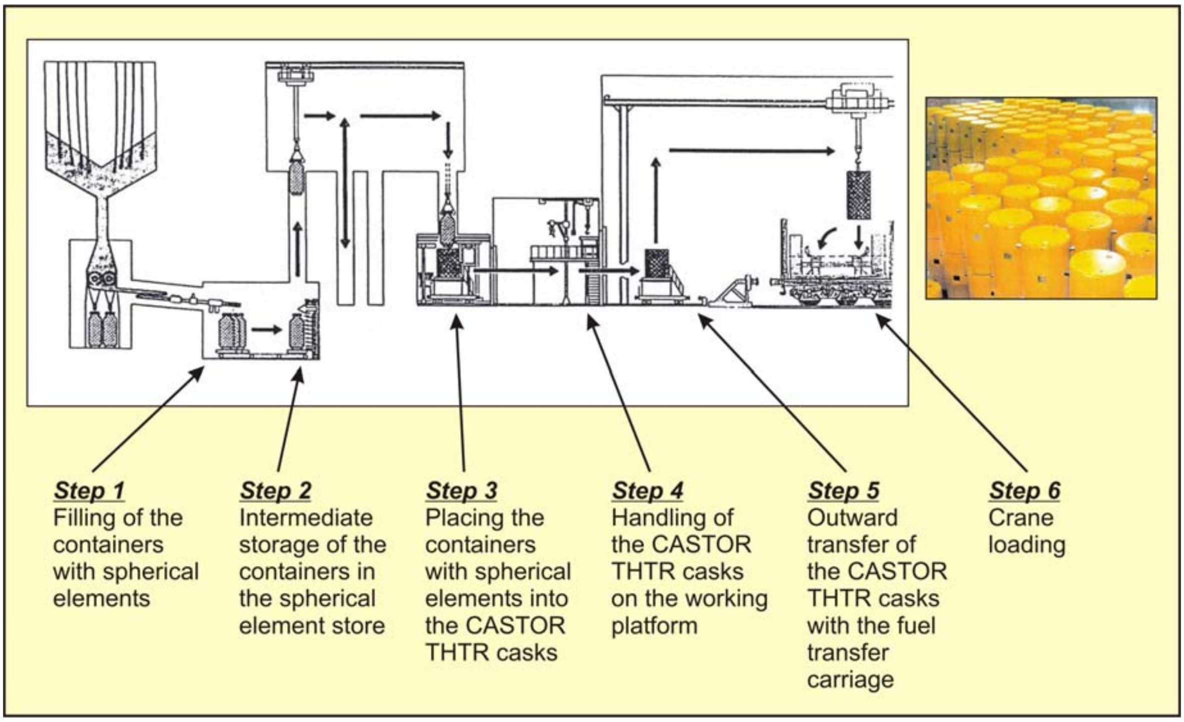

FIG. 4. THTR-300 spent fuel management [Schröder 1993].

Special crap containers in the fuel handling system were used to take up damaged fuel spheres. Between start and end of plant operation, ten containers were filled with about 17,000 damaged operating elements mainly resulting from control rod operation, four more were filled until the end of fuel unloading.

3.3. Decommissioning of THTR-300

Decommissioning strategy for the THTR-300 was predetermined to be "safe enclosure" as there was no alternative concept readily available. The decommissioning procedure was conducted in four consecutive steps [Bäumer 1991b, Schröder 1993]:

1. Transition of the plant from power operation into shut-down state operation; primary circuit depressurized; nitrogen substituted for helium; shutdown rods fully inserted and locked; removal of decay heat by natural convection and radiation;

2. Unloading the reactor and spent fuel storage as a prerequisite for safe enclosure; transport to the Ahaus central interim store (BZA); core inspection device for visual control of fuel-free state;

3. Establishment of safe enclosure; assurance that all residual radioactivity be sealed from environment and controlled; effective dose from release into environment < 0.1 mSv/yr; all buildings except for reactor hall, reactor building, and auxiliary building to be released from the validity of the Atomic Energy Act;

4. Maintaining the state of safe enclosure for 30 yrs by passive measures; largely no maintenance; monitoring the few remaining systems.

Steps 2, 3, and 4 required a license according to the German Atomic Energy Act.

During the shut-down state operation of the THTR, the removal of decay heat was done using the steam generators, then liner cooling only, and finally by the passive mechanisms of radiation and natural circulation with no active components. The temporal sequence is shown in Fig. 5. The operational data as of June 1992 were a reactor pressure of 1 kPa (10 mbar), temperatures of the cooling gas nitrogen between 50°C and 72°C, and a power production by the decay heat of ~20 kW [Bäumer 1992].

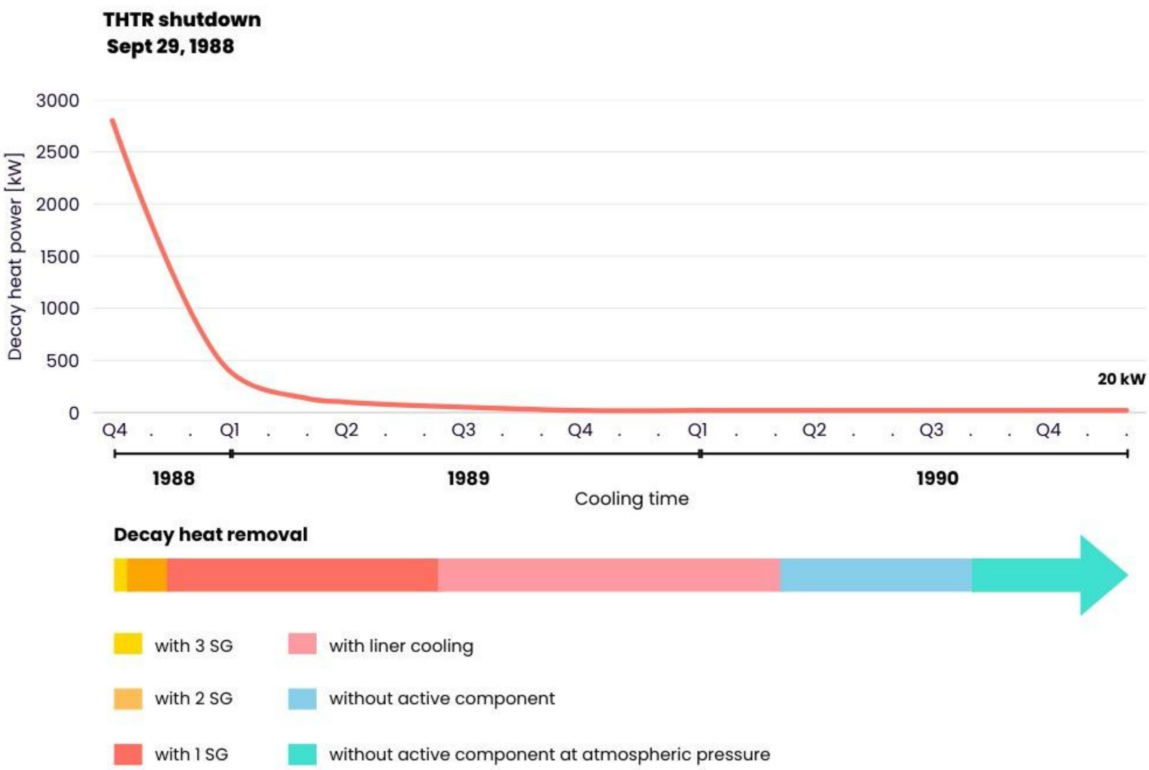

FIG. 5. Decay heat removal from the THTR core since shut-down on Sept 29, 1988 [modified from Bäumer 1991b and 1992].

The still required recurring inspections on the plant amounted to almost 3000 per year, most related to measurement, control and regulation technology, and mechanical process engineering. Compared to the about 4000 inspections per year during normal reactor operation, it does not really represent a significant reduction in the number of inspections [Bäumer 1991b].

Unloading of the THTR pebble bed core was an operational procedure, which never ever permission was applied for. Therefore, it required a separate operational license [Bäumer 1992]. The issues to be considered were the assurance of undercriticality at all times of unloading and the potential bending of the core control rods through the radial flow of the spheres. The unloading process is, in principle, similar to the discharging process during normal operation except for some process engineering modifications concerning the replacement of the helium gas by nitrogen and air as well as the reduced temperatures in the depressurized reactor. Absolutely subcritical conditions during the unloading process (target: 0.95) were guaranteed by insertion of both reflector and in-core control rods and by the addition of 4200 absorber elements.

The flow pattern of the spheres during the unloading procedure was studied in experiments using a 1:2 core model showing that a central funnel is formed which leads to a mixture of fuel elements with different burnups (Fig. 6). While the central section formed an area with medium burnup fuel, high burnup fuel was located in the outer bottom region. The outer top region mainly contained low burnup and fresh fuel that was inserted into the core just prior the decision of final shut-down [Bäumer 1991b, Dietrich 1995, Plätzer 1998]. Bending tests were conducted with a core model and an original-sized control rod.

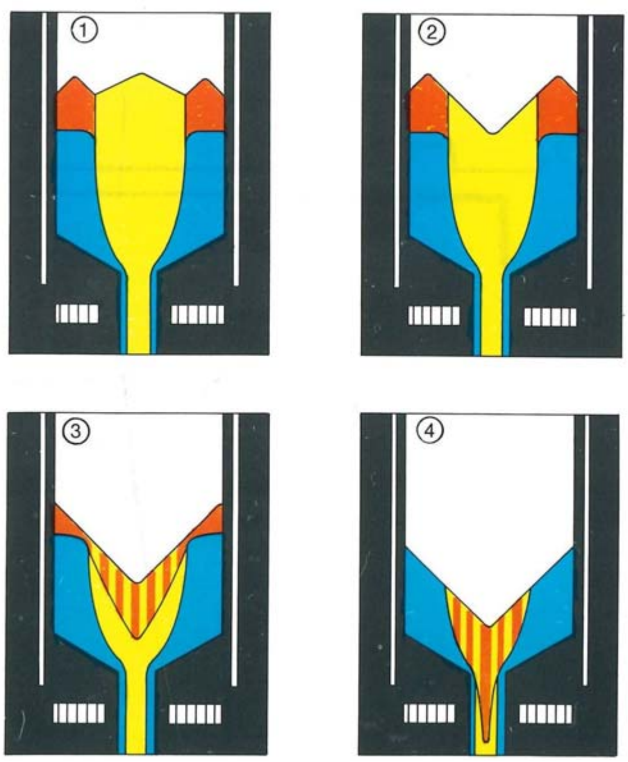

FIG. 6. Assumed pebble flow during core unloading [Bäumer 1991b].
(top outside, orange = low burnup; bottom outside, blue = high burnup; central, yellow = medium burnup)

The unloading of the THTR pebble bed was conducted from Dec 1993 to Oct 1994. It was monitored by means of the burnup measuring system where a reactivity effect was created when a fuel element was passing. Operating elements were sorted by this way and transferred to steel canisters each containing 2100 elements. The efficiency of the selection process was about 97%, meaning that from the total of about 300,000 graphite elements and 43,500 absorber spheres, approximately 3% have gone with the fuel elements into the fuel canisters [Niephaus 2000].

The unloading process was completed in October 1994 achieving the state of a “nuclear fuel free” reactor. The inventory of fissile material remaining in the core after completion of the unloading process was estimated by the operator to be 1.31 kg (by an external reviewer in a very conservative way: 1.64 kg), both values lower than the required upper limit of 2.5 kg [Dietrich 1995]. All still unused fresh fuel elements, at the time of final shutdown a total of 362,348 spheres, was returned to the manufacturing company NUKEM, which then shipped the fuel to UKAEA in Dounreay for reprocessing [Dietrich 2006].

For the next step of transport and storage of the fuel elements to an external interim store, respective casks of the CASTOR THTR/AVR type have been used with one CASTOR to contain one fuel canister with approximately 2100 fuel elements. Maximum burnup per fuel element container was about 8.8% FIMA, maximum decay heat per fuel element container was about 100 W, both values significantly lower than the design values. Neutron dose rates at the loaded transport and storage cask were shown to be less than 1 μSv/h.

The storage license for the casks in the interim storage site Ahaus (BZA) was issued in 1992. Special six-axle railway wagons were available to carry three casks each. By April 1995, a total number of approximately 620,000 spent fuel elements had been transported in 305 CASTOR casks in 57 shipments from the THTR site to the BZA. They include the 14 scrap canisters and two more CASTOR casks filled with the graphite moderated 500 W “Solid Moderated Reactor” fuel consisting of 767 HEU U-Al fuel foils containing a total of 3.6 kg of U-235. Table 6 provides the important characteristics of the THTR spent fuel spheres [Delley 2014].

TABLE 6. FUEL CHARACTERISTICS OF THTR SPENT FUEL SPHERES

	THTR
# Casks	303[(a)]
# Fuel spheres	628,053
Fuel type	BISO
Total Uranium (g)	420317
U-235 (g)	233,706
U-233 (g)	78,886
Fraction U-235+U-233 (%)	74.4
Thorium (g)	6,172,679
Plutonium (g)	1,034

(a) Excluding the two CASTOR casks that contain the burnup measurement reactor.

The THTR fuel will remain in the intermediate storage until a final disposal site is available, with the repository Gorleben representing a candidate site. In contrast, the graphite and absorber elements, because of their low radioactivity and heat generation, might possibly go to the LAW and MAW repository Konrad [Schröder 1993] which, however, still today has no license to receive any radioactive waste. The fuel spheres – so one option once a final HAW repository has been decided upon – could be repackaged from the CASTOR casks to 400 l waste containers with a capacity of 1500–1800 fuel elements to be disposed in a bore hole field.

The constructive preparation of the configuration of safe enclosure, i.e., the leak-tight confinement of all contaminated and activated plant components (PCRVwith its ~2000 penetrations to be sealed shut, all piping in contact with primary coolant (purification system, fuel handling system, blowers, storage containers with contaminated contents) was achieved in February 1997. All other buildings were taken off the factual scope of the atomic energy act [BASE 2024]. The total mass of the radioactive waste and dismantled plant segments during the establishment of safe enc1osure amounted to 1250 tons. Of these, 739 tons were not radioactive, 428 tons were stored as contaminated waste inside shell of the Safe Enclosure of the THTR plant (incl for example all moderator and absorber spheres), and 83 tons were disposed of as radioactive waste at the central interim storage sites in Gorleben and Morsleben [Raad 1997]. The operation of the safely enclosed plant will last for (at least) 30 years. Beginning of the complete nuclear dismantling is currently planned for 2020 [Dietrich 1995, BASE 2024].

The lessons learned from THTR decommissiong are [Bäumer 1992]:

- Design of an HTR plant should already incorporate aspects of decommissioning;
- Layout of a pebble bed reactor should consider a complete unloading of the core as an operational action;
- During the design of an HTR, activity containing volumes in the plant should be minimized.

4. CONCLUSIONS

In Germany, two high temperature reactors were operated, the AVR test reactor in Jülich and the prototype reactor THTR – 300 in Hamm-Uentrop. Both were shut down, but considerable experience has been gained during their operating periods.

The AVR reactor which was operated over 21 yrs from 1967 until 1988 served the general purpose to demonstrate the characteristic features of an HTR and the particular purpose to test and qualify HTR pebble fuel. In the course of operation, more than 290,000 spherical fuel elements of 15 different types and variants (carbide/oxide, BISO/TRISO, HEU/LEU) were inserted into the core. The continuous measurements of coolant activities over the years has provided profound information on the performance of the various fuel types and particularly allowed the identification of failing coated particles. In combination with comprehensive PIE on selected and randomly discharged fuel element specimens, the poorer-quality fuel charges which were responsible for an extremely high contamination level during their residence time in the core and beyond, could be identified. On the other hand, the measurements also showed the steady improvement of fuel quality, e.g., the lower level of heavy metal contamination of 10^{-5} for the modern TRISO fuel (GLE-3/4) compared to the 10^{-3} level of the older BISO fuel.

The demonstration plant THTR-300 was operated over 423 efpd based on one type of fuel with high-enriched uranium and BISO coated particles. Unlike AVR, the THTR operation was not designed for discharging fuel elements for the purpose of dedicated PIE. The information needed to characterize THTR fuel in terms of spent fuel has been achieved from qualification testing in MTRs and from the fuel element variant GO-THTR tested on a large scale in the AVR.

All fuel from both AVR and THTR has been stored in CASTOR casks (approx. 2000 balls each) and given to interim storage sites. In Germany, the spent HTR fuel treatment of intermediate dry storage before transfer to a deep-mined central nuclear spent fuel repository, is presently the only accepted concept. The total spent fuel from the two German HTRs amounts to approximately 910,000 spheres with 32% being from the AVR and 68% from the THTR-300. Adding up the quantities given in the Tables 3 and 6, the following Table 7 provides the important characteristics of all HTR fuel spheres in Germany [Delley 2014].

TABLE 7. FUEL CHARACTERISTICS OF ALL GERMAN SPENT FUEL SPHERES

	AVR	THTR	Total
# Casks	152	303[(a)]	455
# Fuel spheres	288,200	628,053	916,253
Fuel type	BISO and TRISO	BISO	BISO and TRISO
Total Uranium (g)	547,819	420317	968,136
U-235 (g)	59,443	233,706	293,149
U-233 (g)	25,173	78,886	104,058
Fraction U-235+U-233 (%)	15.4	74.4	41.0
Thorium (g)	1,288,508	6,172,679	7,461,188
Plutonium (g)	6,047	1,034	7,081

(a) Excluding the two CASTOR casks that contain the burnup measurement reactor.

5. REFERENCES

Bäumer R., Dietrich G., THTR commissioning and operating experience. Energy 16 (1991a) No. 1/2 59–70.

Bäumer R., Kalinowski I., Decommissioning concept for the High Temperature Reactor THTR-300. Kerntechnik 56 (1991) No. 6 362-366 (1991b).

Bäumer R., Die Stillegung einer kerntechnischen Anlage: Das Fallbeispiel THTR 300. Presentation, Dortmund, June 12 (1992).

BASE, Status report on the use of nuclear energy in the Federal Republic of Germany 2022. Report BASE-N-01/24, urn:nbn:en: 0221-2024011040868, Federal Office for the Safety of Nuclear Waste Management, Berlin (2024).

Brinkmann U., Duwe R., Engelstädter R., Storch S., Wimmers M., Entsorgung des AVR-Versuchskraftwerks und Untersuchungen an abgebrannten Brennelementen für trockene Zwischenlagerung. Proc Jahrestagung Kerntechnik, Berlin, Deutsches Atomforum, Bonn (1980) 497–500.

Delley A.O., Jones R.H., Moore E.N., Severynse T.F., Feasibility and alternatives for receipt, storage, and processing of HTGR pebble fuel at SRS. Report SRNL-TR-2014-00184, Savannah River National Laboratory (2014).

Dietrich G., Roehl N., Decommissioning of the THTR 300 facility. Proc 4th Hannover decommissioning colloquium and 3. status report decommissioning and dismantling of nuclear plants, Bad Duerkheim, Germany (1995) 109–121.

Dietrich G., Hochtemperatur-Kernkraftwerk GmbH, Hamm, Germany, Personal Communication (2006).

Duwe R., Brinkmann U., Freisetzung gasförmiger Radionuklide aus lagernden HTR-Brennelementen. Proc Jahrestagung Kerntechnik, Munich (1985) 373–76.

JEN, Die Räumung des AVR-Behälterlagers in Jülich – Entsorgung der AVR-Brennelemente. Informational presentation to JEN and FZJ staff, Jülich (2024).

KFA, AVR-Behälterlager – Kurzbeschreibung. Report Research Center Jülich (1988).

Knizia K., Der THTR-300 – Eine vertane Chance? ATW 47 (2002) No. 2, 110–117.

Krumbach H., Duwe R., Rödig M., Handling and behaviour of AVR fuel elements for interim storage. HOTLAB 2004, Halding, Norway, September 2004.

Mank G., Damm G., Modolo G., Wilden A., Pierce R., Maxted M., DeLeon E., Management of spent High Temperature Reactor graphite pebble bed fuel. Proc Int Conf on Research Reactors: Safe Management and Effective Utilization, Vienna (2015) Paper IAEA-CN-231-E.07.

Mank G., Pierce R., Maxted M., Modolo G., Wilden A., Damm G., Innovative digestion and decommissioning of irradiated HTR pebble fuel. ENS European Research Reactor Conference RRFM 22019, Jordan (2019) Presentation RRFMIGORR2019-A0160.

Marnet C., Wimmers M., Birkhold U., Decommissioning of the AVR reactor concept for the total dismantling. Proc IAEA TCM on Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, held at Jülich, 1997, Report IAEA-TECDOC-1043, International Atomic Energy Agency, Vienna (1998) 17–39.

Niephaus D., Referenzkonzept zur direkten Endlagerung von abgebrannten HTR-Brennelementen in CASTOR THTR/AVR Transport- und Lagerbehältern. Report Jül-3734, Research Center Jülich (2000).

Plätzer S., Mielisch M., Unloading of the reactor core and spent fuel management of THTR-300. Proc IAEA TCM on Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, held at Jülich, 1997, Report IAEA-TECDOC-1043, International Atomic Energy Agency, Vienna (1998) 143–150.

Pohl P., AVR decommissioning, achievements and future programme. Proc IAEA TCM on Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, held at Jülich, 1997, Report IAEA-TECDOC-1043, International Atomic Energy Agency, Vienna (1998) 41–53.

Pohl P., Short review of lessons learned from AVR mass fuel testing. HTR-TN International HTR Fuel Seminar, Brussels, Belgium, February 1-2, 2001.

Pohl P., Betrachtung der aufgelaufenen Buchabweichungen nach Abschluss der bisherigen Brennelement- und Brennstoffbuchführung – Eine Geschichte der Brennelementerkennung am AVR. Technical Note E-6509, Arbeitsgemeinschaft Versuchsreaktor, Düsseldorf, Germany (2002).

Raad H., Suchowitz J.M., Qualified waste management for the decommissioning of the THTR-300 NPP. Proc 3rd Int Seminar on Radioactive Waste Products (Radwap'97), Würzburg, Germany, Odoj R. (ed), Research Center Jülich, Report Energy Technology 2 (1997).

Röllig K., et.al., Entsorgung von Hochtemperaturreaktoren. Proc. Status Seminar about Works on High Temperature Reactor Fuel Elements, Graphite, and Disposal, Jülich, Germany, May 18, 1987, FZJ Report Jül-Conf-61, Research Center Jülich, Germany (1987) 109–134.

Schröder G., et.al., Aspekte der Entsorgung des THTR-300. In: Fortschritte in der Energietechnik, Monographien des Forschungszentrums Jülich, Vol. 8 (1993) 301–308.

List of Acronyms

AVR	Arbeitsgemeinschaft Versuchsreaktor
AVR-BL	AVR-Behälterlager – AVR canister store
AVR-TL	AVR-Trockenlager – AVR dry store (for the casks)
BISO	Bi-structural-Isotropic fuel particle coating
BZA	Brennelement-Zwischenlager Ahaus – Fuel element interim store Ahaus
FE	Fuel element
FZJ	Forschungszentrum Jülich – Research Center Jülich (formerly KFA)
GFB	AVR fuel variant, GFB = Gepresst feed breed – Moulded feed breed
GK	AVR fuel variant, GK = Gepresst Karbid – Moulded carbide fuel
GLE	AVR fuel variant, GLE = Gepresst low enriched – Moulded low enriched
GO	AVR fuel variant, GO = Gepresst Oxid – Moulded oxide fuel
HEU	High enriched uranium
KFA	Kernforschungsanlage Jülich – Nuclear Research Center Jülich (today FZJ)
LAW	Low active waste
LEU	Low enriched uranium
MAW	Medium active waste
MTR	Material test reactor
T	AVR fuel variant, T = Tapete – Wallpaper
THTR	Thorium High Temperature Reactor
TRISO	Tri-structural-Isotropic fuel particle coating
UCC	AVR fuel variant, UCC = Union Carbide Co (US manufacturer of first fuel)