The AVR Experimental Reactor – Development, Operation, and Incidents

Final Report of the AVR Expert Group

- Summary -

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Jülich, 26 March 2014

Background and objectives

In 1959, fifteen municipal electric utilities formed the association known as Arbeitsgemeinschaft Versuchsreaktor GmbH (AVR GmbH) with the objective of demonstrating the feasibility and operability of a gas-cooled, graphite-moderated high-temperature reactor. The AVR experimental reactor was constructed in the immediate vicinity of the then Nuclear Research Centre Jülich (KFA) (since 1990: Forschungszentrum Jülich (FZJ) GmbH) and was operated from 1967 until 1988. After AVR had been shut down, "safe enclosure" of the power plant was the next planned step. Plant parts that were no longer required were dismantled and the fuel elements were removed in accordance with the relevant licences. When AVR GmbH was taken over by the state-owned energy company Energiewerke Nord GmbH (EWN) in May 2003, the decommissioning strategy was modified with the aim of completely dismantling the facility in order to use the site for other purposes.

Over the last few years, a discussion has arisen on technical issues related to the AVR, particularly on undetected excessive temperatures in the reactor core as well as the release of high levels of fission products from the spherical fuel elements. Ultimately, FZJ GmbH and AVR GmbH decided to use this debate as an opportunity to ask external experts to review the operating history of the AVR experimental reactor. This expert group comprising chairman Dipl.-Physiker Christian Küppers, deputy head of the Nuclear Engineering & Facility Safety Division at the Institute of Applied Ecology (Öko-Institut e.V.), and members Dipl.-Physiker Lothar Hahn (prior to retirement, scientific-technical director of Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)), a. Pl. Professor Dr.-Ing. Volker Heinzel (prior to retirement, acting head of the Institute for Reactor Safety at Forschungszentrum Karlsruhe), and Dr.-Ing. Leopold Weil (prior to retirement, head of Nuclear Safety at the Federal Office for Radiation Protection (BfS), began work in summer 2011. The expert group was free to choose the issues it investigated in detail. These issues will be discussed below.

A multitude of documents were reviewed by the expert group starting with a compilation of some 200 documents comprising quarterly reports, annual reports, PhD theses, journal articles, and other extensive scientific publications, particularly those by FZJ GmbH. This review led to requests for many of the documents cited within these publications and other documents which included official administrative decisions, memos, and reviewers' reports. Despite this comprehensive review process, it was still impossible to clarify all issues retrospectively.

AVR GmbH and FZJ GmbH actively supported this work by providing relevant documents and information as well as readily participating in various expert discussions with different participants and on different topics. In addition, the expert group met three times with Dr. Rainer Moormann, a former employee of FZJ GmbH and a well-known public critic of the AVR, to discuss numerous technical issues in detail. Without the support of AVR GmbH, FZJ GmbH, and Dr. Rainer Moormann, this work would have been impossible. The expert group would like to thank all of those involved for their support.

During its investigations and the drafting of its final report, the AVR Expert Group was charged with the task of appraising certain aspects of AVR's operating history. When possible deficits could not be checked against formal, codified requirements, each individual case was assessed separately. In this process, the prevailing environment at the time – in some instances, back in the distant past – had to be taken into account in terms of the procedures implemented and the valuation criteria. The requirements stipulated by legal regulations and non-mandatory guidance instruments have changed with time, and they were therefore taken into account in the evaluation in the versions valid at the respective time. On this basis, the aim was an objective evaluation without hiding behind claims that something was "usual" at that particular time.

The members of the expert group jointly compiled a final report as well as this summary. This summary will first briefly outline the technical concept of the AVR reactor. Then, it will discuss the historical background as far as this is helpful for understanding the planning, construction, and operation of the AVR reactor. The subsequent sections will deal with the problems associated with the AVR which the expert group selected as priorities, namely the initially undetected excessive temperatures in the reactor core, the unexpectedly high level of fission products released from the spherical fuel elements, the 1978 steam generator accident, and radiological aspects associated with normal operation and with incidents.

Description of the AVR

The unique features of the AVR reactor concept were:

- the use of the noble gas helium as a coolant,
- uranium-235 and thorium-232 as fuel and fertile material,
- graphite as a moderator material[1], and
- extremely high, previously unattainable coolant temperatures.

It was expected that this type of reactor would also provide a cost-efficient option for smaller power units.

Figure 1 shows a cross section through the 38 m high reactor building, a concrete cylinder. It comprised the gas-tight containment, in which in turn the outer and inner

[1] The moderator material slows down the neutrons released during fission by means of elastic collision processes. These "moderated" neutrons are more likely to split fissile atomic nuclei. Only in this way can a self-sustaining chain reaction be sustained, even for low concentrations of fissile materials.

reactor vessels were installed. The inner reactor vessel enclosed the reactor core, which comprised the pebble bed, carbon brick and graphite structures controlling the gas flow, the reflector, the shutdown rods, and the steam generator. The pebble bed consisted of a total of around 100,000 spherical fuel elements, each with a diameter of 6 cm. These elements had a kernel with a maximum diameter of 5 cm, which contained the coated particles embedded in graphite and coated with pyrolytic carbon and later also with silicon carbide (see Figure 2). The coating was intended to prevent radioactive fission products from being released up to the highest temperatures expected during normal operation and in the case of an accident.

The spherical fuel elements were supplied to the pebble bed from above via five feeder tubes. A central opening in the base allowed them to be removed. Graphite noses protruded from the sides into the pebble bed. They contained bores into each of which one shutdown rod could be inserted. The shutdown rods contained material that absorbed the neutrons and thus stopped the nuclear chain reaction.

The cooling gas flowed through the reactor core from bottom to top. It took up the heat generated in the pebble bed and was heated from approximately 270 °C to between 750 °C and 950 °C depending on the mode of operation. In the steam generator, the hot cooling gas was used to evaporate water and produce steam which was fed into a turbine that drove a generator and produced electricity. The heat output of the reactor was 45 megawatts and the electrical output was 15 megawatts.

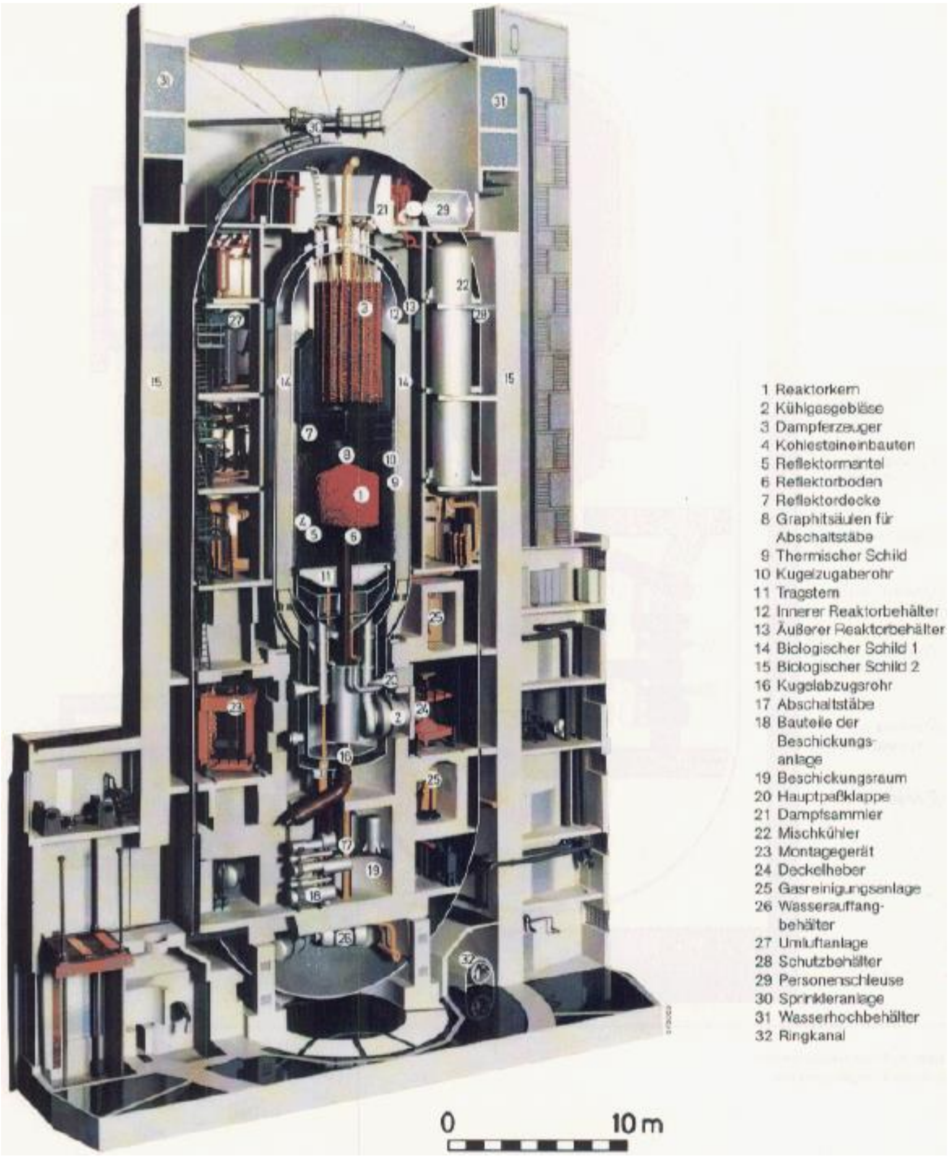

Figure 1: Cross section through the reactor building (Source: AVR GmbH, BBC, HRB GmbH, “Der Kugelhaufenreaktor der Arbeitsgemeinschaft Versuchsreaktor (AVR)”, May 1987)

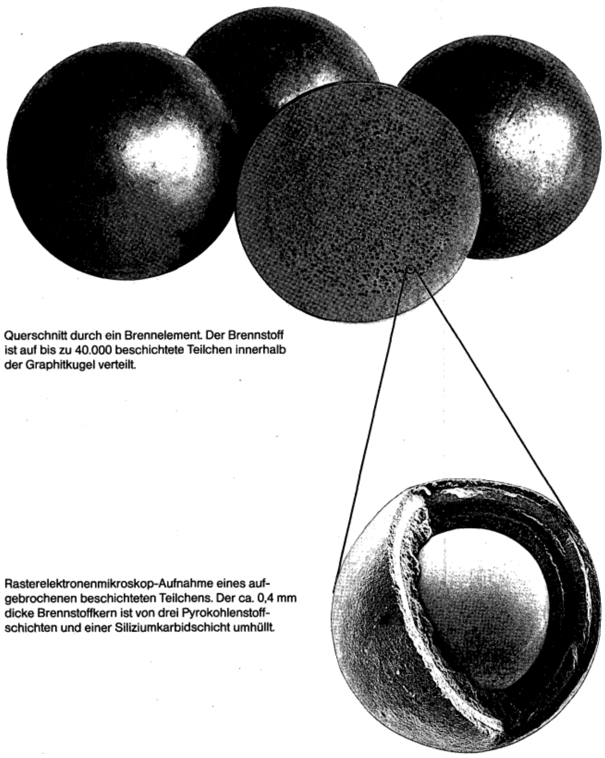

Figure 2: Structure of a spherical fuel element (Source: AVR GmbH, BBC, HRB GmbH, “Der Kugelhaufenreaktor der Arbeitsgemeinschaft Versuchsreaktor (AVR)”, May 1987)

Historical background

German nuclear policy emerged in the 1950s in an atmosphere of great euphoria about providing cheap energy using nuclear reactors and the desire to catch up with the technological advances already made by the nuclear powers at the time – USA, USSR, and UK. In the 1960s, light-water reactors (LWR)[2] were the first reactors constructed in Germany. However, high-temperature reactor (HTR) concepts were also developed early on, and the “pebble bed reactor” as a German invention was the concept that prevailed. It was implemented in the AVR reactor, which began generating electricity in 1967. The HTR concept offered the prospect of using the reactor at sufficiently high temperatures not just to generate electricity but also to provide process heat and for coal conversion. As early as the 1960s, rivalry emerged between the HTR and the “fast breeder”[3] as new reactor lines in addition

[2] Reactors cooled and moderated with water; internationally the most common type of power reactor.

[3] Type of reactor which uses unmoderated (fast) neutrons to produce plutonium in order to re-use this as new fuel. In Germany, development work on this type of reactor was predominantly conducted in the then Karlsruhe Nuclear Research Centre.

to the LWR, reflecting the competitive situation between the research centres in Jülich and Karlsruhe.

The initially pro-nuclear-energy and technology-friendly environment altered considerably in the early 1970s in the face of public opposition. The reactor accident at the Three Mile Island facility on 29 March 1979 made the general public aware of the risks associated with a core melt accident in a LWR. As construction had already begun on most of the 20 large German LWRs, the growing public rejection focused on these projects, while the public protest paid little attention to the implementation of the HTR in the form of the AVR and the THTR-300[4] in Hamm-Uentrop during the 1970s and early 1980s. LWR advocates saw the HTR as an unwelcome competitor whose superior safety features could cast a negative light on the LWR.

At first, it looked as if nuclear energy would hold its own despite public opposition and increasing objections in the political arena. However, the Chernobyl disaster on 26 April 1986 completely shattered confidence in nuclear technology. Considerable effort was invested in emphasizing the safety-related characteristics of the HTR both in politics and the specialist community. The image of the HTR line was technologically damaged by the poor operating results of the THTR-300 and economically by the lack of new commissions.

Nuclear energy in Germany progressively lost its political backing. The AVR was shut down at the end of 1988 and government funding for research and development work on the HTR was withdrawn in 1991. Further German activities after 1991 were mainly limited to activities abroad.

This environment affected the behaviour of HTR advocates. On the one hand, they displayed a sense of superiority, while on the other, they failed to be sufficiently self-critical and underestimated weaknesses of the HTR concept and of specific plants. However, it must be said that there were also a high degree of idealism and personal integrity.

[4] Commercial-scale prototype of a pebble bed reactor with an electrical output of 300 MW; commercially operated for less than a year (June 1987 – September 1988); final decommissioning in 1989.

Temperatures in the primary circuit

The AVR was temporarily operated with temperatures in the core that were excessive compared to the predicted and calculated values without this being noticed. The expert group attempted to identify possible causes for this state of affairs.

In the AVR, it was impossible to directly measure the fuel element temperatures and the temperature distribution in the primary circuit. The temperature distribution in the core and the mean gas outlet temperature were therefore initially only calculated using numerical simulation techniques. It was only possible to measure the temperatures in the core using special monitoring spheres containing melt wires that melted at certain temperatures. However, such monitoring spheres were used from 1970 onwards in three measurement campaigns (in 1970, 1972, and 1986).

Even the first two measurement campaigns (1970 and 1972) revealed certain deviations from the measured values and calculated values of temperatures in the core. In February 1974, the cooling gas outlet temperature was increased to 950 °C in accordance with the relevant licence. From 1972, and particularly in the period 1974–1976, the activity release in the core increased considerably. Memos from 1977 also confirm that there was already evidence at this time of excessive gas and fuel element temperatures, and that the causes were generally believed to be errors in the fuelling strategy, which led to too high a concentration of fissile materials in the outer zone of the core. Furthermore, the authorized value for the mean hot gas temperature was exceeded by 35 °C between 1 January 1976 and 1 May 1976. In the AVR second quarterly report in 1976, this was explained as follows: the failure of several thermocouples meant that the mean hot gas temperature could only be mathematically calculated and that an incorrect relationship was assumed between blower speed and hot gas temperature.

The expert group cannot understand why monitoring spheres were not used for further temperature measurements between 1972 and 1986 despite the fact that numerous relevant boundary conditions had changed. In the third measurement campaign (1986), some of the melt wires melted at the highest melting temperature, namely 1280 °C. The mean gas outlet temperature was subsequently lowered from 950 °C to 810 °C. There are a number of possible causes that could have led to the excessive temperatures measured in 1986. The expert group was unable to identify one mechanism representing the sole cause. It is possible that several causes may have come together. The most likely include bypass[5] coolant flows, errors in fuelling the core, and uncertainties in modelling the flow behaviour of the fuel spheres in the core.

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[5] Bypass flows mean that the coolant takes a path around the core and thus no longer helps to cool it.

The expert group cannot understand why no further safety-related analyses were performed until 1988 after the evaluation of the third monitoring sphere series in 1986. Accident analyses could have been conducted to investigate the impact of elevated temperatures on the controllability of accidents, for example on the formation of water gas after a steam generator accident, particularly since a steam generator accident actually occurred in 1978. It is also unclear why all of the monitoring spheres in the third series were not analysed and why more efforts were not undertaken to identify the causes of the elevated temperatures. An analysis of the bypass flow was first published in 2008.

Primary circuit contamination

In the primary circuit of the AVR, i.e. within the pebble bed and connected systems, relatively high activity concentrations and levels were ascertained for various radionuclides attributable to the release of fission products from the fuel elements. The primary circuit activity in the AVR increased by a factor of 100–1000 for certain radionuclides specifically in the period from 1974 to 1976. Compared to other HTR prototypes or experimental facilities, the primary circuit of the AVR was relatively highly contaminated. The expert group investigated the possible causes of primary circuit contamination and its results are presented below.

The level of fission products released from the fuel elements over time depends on numerous factors, all of which are important for the release mechanisms in different ways. These include the type of fuel element, the fuel element temperature and other physical-technical load parameters to which the fuel element is exposed when it is in the core. These loads in turn depend on where the fuel element was in the core and for how long, which cannot be reliably determined either by measurements or by modelling.

Due to the complex AVR core structure and the simultaneous use of several different types of fuel elements, it was impossible to measure the fission product release behaviour of the individual types of fuel elements in the AVR. Although this could be measured in customized experiments on certain fuel elements or coated particles using special experimental equipment, these irradiation experiments could not be used to derive the total amount of fission products released in the AVR as not enough was known about its complex core structure.

The expert group believes that the causes of the substantive increase in primary circuit contamination in the period from 1974 to 1976 have yet to be clarified despite diverse attempts to explain the situation. To make conclusive statements on the causes, the dependence of fission product release on the relevant factors influencing the types of fuel elements used as well as the conditions to which the fuel elements were exposed in the AVR core must be known. Unfortunately, this is not the case. Things are made more difficult by the potential superimposition of the effects caused by the different types of fuel elements, and the fact that typically six to eight different types of fuel elements were used.

When the substantive increase in primary circuit contamination occurred between 1974 and 1976, a type of fuel element was used that proved to be less robust during operation. The imprecise burnup measurement system meant that fuel elements may have remained in the core for longer than intended. Combined with the licensed increase in the cooling gas outlet temperature, this may have contributed to the further increase in the release of fission products. The majority of relevant publications assume that the release of fission products from HTR fuel elements is strongly dependent on temperature.

The release of fission products from the fuel elements led to high contamination of the primary circuit but not to an unexpected discharge of radioactive substances into the environment. During reactor operation, however, such contaminations increase the radiation exposure of operating personnel working on the primary circuit. With respect to the dismantling of the AVR, the primary circuit contamination caused considerable additional expenditure.

1978 steam generator accident

The ingress of water or steam into the AVR core had to be prevented or at least limited as it could have caused disadvantageous nuclear physics effects or damaged the fuel elements. However, the structural design of the AVR (steam generator above the core) made it theoretically possible that should a leak occur in the steam generator, which was under high pressure compared to the primary circuit, water could escape into the primary circuit. In line with the licensing procedure for the AVR, a steam generator accident was treated as a design basis accident[6].

In mid-May 1978 during AVR operation, the steam generator was damaged, causing a leak that led to an ingress of some 27 m^3 water into the primary circuit. In February 1978, the first of three smaller water ingresses had already occurred, but these leaks led to ingresses of water into the primary circuit that were smaller than a thousandth of this amount of water. The expert group investigated the causes and consequences of the steam generator accident in 1978 as well as the operating crew's reaction to this.

One of the AVR's safety shutdown criteria activated a rapid shutdown mechanism when the cooling gas moisture exceeded a certain value. In the case of the three aforementioned water ingresses, the operating crew had adjusted the measuring range of the moisture measurement so that the reactor's safety shutdown initiation signals were deactivated and the reactor could be restarted. At a gas temperature of

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6 In the case of a design basis accident, certain dose limits must not be exceeded in the surrounding area so that no specific protective measures are therefore necessary.

500 °C, the moisture was then driven out and precipitated into the gas purification system. When the steam generator accident occurred in mid-May 1978 and moisture readings were too high, the crew reacted in the same manner and the measuring range was adjusted even further in order to avoid a fast shutdown. Five days after the onset of the accident, the fragment container[7] was signalling that it was full because of water. Due to the ammonia contained in the water in the fragment container, the operator assumed that the water had not come from a steam generator leak. It was another day before the reactor was shut down because the attempts to dry it out proved unsuccessful. Ultimately, it was discovered that a tube in the steam generator exhibited a leak of between 1 mm^2 and 3 mm^2.

The consequences of the steam generator accident in May 1978 were far less grave than the corresponding design basis accident investigated in the licensing procedure. However, it led to extensive technical improvements to AVR and for planned future plants. The interventions of the personnel in the moisture measurements were censured by the nuclear regulatory authorities because they represented an unauthorized change in the mode of operation.

The steam generator accident gave rise to increased concentrations of radioactive substances in the facility, namely in the water leaked, in the primary gas, and in the live steam. Tritium discharges into the ambient air were considerably higher than during previous operation. A limit for tritium emissions had not yet been set in 1978. However, the amount emitted was three times higher than the limit that was set later.

When the steam generator accident in 1978 was reported to the authorities, it was assigned the lowest reporting category for reportable events ("N": "minor safety-related importance"). The expert group considers this classification to be inappropriate. It concludes that the incident should have been classified at the time at least as an incident with the "potential for significant impact on safety" in category B, if not as a category A incident ("direct impact on safety"). However, the classification made by AVR GmbH was not corrected by the regulatory authorities.

Overall, the expert group established that up until 1988 only 48 events at the AVR were reported – far fewer than for other German nuclear power plants. Other documents detail events at the AVR that were not included in the official lists of reportable events. Examples include the ingress of acid on 7 September 1971, inadvertent criticality on 30 March 1977, damage to the blower on 29 January 1979, and repeated problems with the fuel handling system. Events other than the steam generator accident in 1978 were also classified in a manner that the expert group did not always consider correct.

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[7] The container that collects damaged fuel spheres when the fuels are removed from the core.

Radiological aspects

With respect to the radiological aspects, the expert group concerned itself with adherence to the limits for radionuclide concentrations discharged into the ambient air as defined by the first Radiation Protection Ordinance, with the monitoring of emissions, and with the contamination of soil and groundwater at the AVR.

The first Radiation Protection Ordinance, which was valid until 31 March 1977, limited the maximum permissible concentrations[8] in air and water which could escape from controlled areas. Instead of adhering to the concentration values, it was possible to apply for e.g. annual discharge values[9] if proof was furnished that the dose limits[10] were not exceeded. Yet by the end of the 1970s, AVR GmbH had not applied for such discharge values, although it was otherwise apparently impossible to adhere to the concentration values. This is very difficult to understand from today's point of view, particularly because the licensing authority became aware of these problems at an early stage. However, there are no indications that the dose limits that were valid then or today were ever exceeded in the environment.

Originally, the AVR was only equipped with air monitoring systems for aerosols and noble gases in its exhaust air and in the containment. Tritium discharges were not separately monitored or measured until 1972. The reasons for this are difficult to understand because it had already been established that cooling gas and live steam as well as feed water contained relevant amounts of tritium. It was only in 1980, after the introduction of new requirements in the nuclear rules and regulations, that monitoring also included all important radionuclides. However, it is unlikely that high non-balanced discharges occurred or that the dose limits were exceeded because no indications of this were provided by measurements in various media within the facility.

For structural reasons, concrete chambers were incorporated into the foundations of the AVR reactor building and filled with water in order to prevent the building from lifting in the case of rising groundwater. There was – which is difficult to understand from today's point of view – no monitoring of the activity levels of the water in the concrete chambers and no routine monitoring of the activity in the surrounding soil and groundwater despite the fact that the water in the concrete chambers was in contact with the groundwater. In January 1999, when a measurement was being performed for a different reason, an increased concentration of radioactive sub-

8 The concentration values limited the nuclide-specific activity concentration (in Bq/m^3) in the exhaust air discharged into the environment.

9 Discharge values limit the total activity in the discharged exhaust air for a certain period of time for individual nuclides or nuclide groups, e.g. in Bq per day or Bq per annum.

10 The discharged amount of activity can be used to calculate the dose for individual members of the general public by taking into account mixing in ambient air, deposition behaviour, transfer to the food chain etc. in order to verify adherence to the dose limits.

stances was incidentally determined in the rainwater channel[11] and activity in the AVR's concrete chamber system was subsequently identified as the source. The contamination of the concrete chamber water (and thus also soil and groundwater) was assumed to have been caused by leaks when highly contaminated water was pumped out of the AVR after the steam generator accident in 1978. Furthermore, the investigations in 1999 also indicated that an earlier leakage of contaminated water from a defective underground pipe at a different point on the outer wall of the reactor building had gone unnoticed and apparently caused a local but high strontium-90 contamination of the soil.

About 20 years passed between the suspected cause of contamination of the water in the concrete chambers and its discovery because of a lack of monitoring measures. After the discovery in early 1999, an extensive investigation programme ruled out any possible inadmissible radiation exposure. For the period between 1978 and early 1999, the expert group evaluated the results of groundwater, drinking water, and surface water samples and took the on-site groundwater situation into account with very conservative assumptions, specifically a continuous consumption of drinking water with contamination at a level equivalent to the maximal measured value in a year, and then estimated the dose that could not have been exceeded. Even an extremely conservative estimate of an upper limit for the radiation exposure of the population led to values and risks that were so low that a link between the leukaemia cases in the surrounding area between 1990 and 1992 was deemed impossible. Earlier epidemiological studies came to the conclusion that the observed increase in the number of leukaemia cases should not be considered significant.

Even though it can be assumed that the contamination of soil and groundwater posed no health hazard for the population, this situation made the decommissioning and dismantling of the AVR more difficult. Due to the fact that the site could only be restored after the building had been dismantled, safe enclosure within the original time frame of 20–30 years was no longer possible. As contamination was caused by strontium-90, which is difficult to measure, the effort required for release of the land for re-use, which may involve the removal of part of the soil, was much greater than for other projects dealing with the decommissioning of nuclear power plants in Germany.

Concluding remarks

In its work, the expert group concentrated on a number of priorities, the results and assessments of which were discussed above. Despite the exhaustive evaluation of

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[11] Rainwater that collects on paved areas is fed via the rainwater channel, the main drainage channel, and a pressure pipeline into the discharge channel feeding the tributary known as the Mühlenteich in Krauthausen near Jülich and from there into the river Rur.

the documentation and the discussions with specialists, not all matters associated with these priorities could be resolved.

The lack of in-core measurements, the inconclusive results of measurements with thermocouples, and the systematic underestimation of temperatures in the simulation calculations – particularly with two-dimensional modelling commonly used until 1984 – makes it impossible to draw reliable conclusions on the level, duration, and causes of the elevated temperatures.

Statements on the causes of the heavy primary circuit contamination cannot be substantiated because the dependence of fission product release on relevant factors influencing the types of fuel elements used as well as the conditions to which the fuel elements were exposed while in the AVR core would have to be known. Things are made more difficult by the superimposition of the effects caused by the different types of fuel elements, and the fact that typically six to eight different types of fuel elements were used.

A post-examination programme at the AVR following its shutdown, which could have dealt with these and other open issues, was planned but unfortunately never actually implemented.

The expert group is aware that it could not throw sufficient light on all aspects of the history and the operation of the AVR. However, the group believes that it covered important aspects with its selection of topics and that this final report will help to objectify further discussions.