SAFE OPERATION OF RESEARCH REACTORS IN GERMANY

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Abstract

In Germany, experience was gained in the field of safe operation of research reactors during the last five decades. In this time, in total 46 research reactors were built and operated safely. Concerning the design, there is, or has been, a very broad range of different types of research reactors. The variety of facilities includes large pool or tank reactors with a thermal power of several tens of megawatt as well as small educational reactors with a negligible thermal power and critical assemblies. At present, 8 research reactors are still in operation. The other facilities are permanently shutdown, in decommissioning or have already been dismantled completely and released from regulatory control. In this paper, four selected facilities still being operated are presented as examples for safe operation of research reactors in Germany, including especially a description of the safety reviews and safety upgrades for the older facilities.

1. INTRODUCTION

The history of civil use of nuclear energy in Germany began in 1955 after the Federal Republic of Germany became a sovereign state and officially renounced the development and possession of nuclear weapons. In October 1957, the “Research Reactor Munich” (FRM) reached criticality as the first nuclear facility in Germany. This may be seen as the starting signal for the development of civil use of nuclear energy in Germany, for both the commercial use for electricity production in nuclear power plants as well as for research reactors.

In 1998, Germany decided the structured phase-out of nuclear energy instead of its promotion. According to the respective amendment of the Atomic Energy Act in 2002, this corresponds specifically to the termination of the use of nuclear energy for the commercial generation of electricity in nuclear power plants, but does not refer to research reactors. The subsequent amendments of the Atomic Energy Act in 2010 and 2011 [1] did not change this situation. Therefore, the safe operation of research reactors still has to be ensured for a longer time in the future.

2. LEGISLATIVE AND REGULATORY FRAMEWORK

In Germany, a comprehensive legislative and regulatory framework had been established to assure the safety of nuclear installations. On top level of this framework, the Atomic Energy Act [1] and its associated ordinances constitute the legal basis and are directly binding to all kind of nuclear installations in a common approach, including research reactors. Below this legal level, these abstract provisions are put in concrete terms by various sublegal nuclear safety regulations. These regulations are mainly developed for nuclear power plants. However, in the regulatory practice, they are applied by analogy or with some interpretation for research reactors, in accordance with the potential hazard of the specific facility by the means of a graded approach. More details may be found in [2].

Within this legislative and regulatory framing, the operator has the prime responsibility for the safe operation of its own nuclear facility. The operation licence for a research reactor is granted unlimited. However, to ensure a safe operation over the entire lifetime of the facility, particularly safety reviews and safety upgrades have to be made continuously. In the German operational and regulatory practice, they may be carried out by different means.

Safety upgrades, which prepare an essential modification of the installation or its operation, require a licence according to Section 7(1) of the Atomic Energy Act [1]. According to Section 7(2), such a licence may only be granted by the competent licensing authority if the license prerequisites are met. This comprises particularly that the necessary precautions against damage have been taken according to the state of the art in science and technology, to be demonstrated by safety analyses of the licensee and reviewed by authorized experts. Safety upgrades, which are not subject to a licensing procedure according to Section 7(1), are carried out within the continuous regulatory supervision pursuant to Section 19 of the Atomic Energy Act. In such cases, they require a prior approval by the regulatory supervisory authority, also based on a respective safety analysis and its review. In addition to the continuous regulatory supervision, periodic safety reviews may be performed. In Germany, they are mandatory for nuclear power plants by Section 19a of the Atomic Energy Act, but not for research reactors. However, they are required for specific facilities like the FRM-II or the BER II, fixed as an obligation in the operation licence or by a provision in the operating manual respectively.

In special circumstances, additional safety reviews may be appropriate. Following the Fukushima accident in March 2011 in Japan, the German Federal Government took immediate action and announced a moratorium for three months concerning nuclear power plants. Within this moratorium, among others, a systematic safety review had been performed by the Reactor Safety Commission (RSK) for all 17 nuclear power plants, especially against severe accident scenarios. The review results were used, among others, as a basis for the phase-out policy in Germany, concerning the use of nuclear energy for the commercial generation of electricity. The Atomic Energy Act was amended accordingly and put into force on 06 August 2011. Recently, such an additional systematic safety review by the RSK concerning severe accidents has also been started for research reactors. It comprises the three larger facilities in Germany still in operation, namely the FRM-II, the BER II and the FRMZ. Up to now, there are no results published.

A further important issue concerning safe operation of research reactors is provided by the operation experience feedback. Within the Nuclear Safety Officer and Reporting Ordinance [3], which also refer to research reactors with a thermal power output larger than 50 kW, the licensees have to report accidents, incidents or other events reportable to safety to the competent supervisory authority. Each reportable event is assigned to one of the individual reporting categories: S (immediate report, without delay), E (quick report, within 24 hours), N (normal report, within 5 days) and V (before initial loading, within 10 days). In addition, the reportable events are also categorized according to the seven levels of the INES scale of the IAEA. Since 1991, when the Ordinance became in force, 245 reportable events occurred in the 16 German research reactors with a thermal power larger than 50 kW. 244 of them were assigned to category N, just one single event in the FRM-II was assigned to category E for a quick report. However, all events have been level zero of the INES scale meaning deviations with no direct safety significance. [4]

3. RESEARCH REACTOR FACILITIES IN GERMANY

In Germany, in total 46 research reactors were built and operated. At present, eight of them are still in operation. Three of these research reactors have a thermal power of more than 50 kW and may be seen as “larger” facilities, particularly with regard to the obligations of the Reporting Ordinance [see Chapter 2]. The remaining five facilities are small training and educational reactors with negligible heat production. All other research reactors are permanently shutdown, in decommissioning or have already been dismantled completely and released from regulatory control. A complete compilation of all research reactors in Germany is presented at the BfS web-site [5].

As examples for the safe operation of research reactor in Germany, four selected facilities will be presented in some more detail. This comprises the three larger facilities which are still in operation, namely the FRM-II, the BER II, the FRMZ, as well as AKR-2 as a representative for the remaining small educational reactors still operated.

3.1. Munich high-flux neutron source in Garching Unit II (FRM-II)

The FRM-II is the largest research reactor still in operation in Germany. It became critical for the first time in March 2004 and started routine operation in April 2005. [6]

The facility is constructed to deliver a high neutron flux for fundamental research and industrial and medical applications as well. A maximum undisturbed thermal neutron flux of $8 \cdot 10^{14}/(cm^2 \cdot s)$ is achieved at a relatively low nominal thermal power of 20 MW. The concept is based on the use of a compact core containing a single cylindrical fuel element installed in the centre of a moderator tank filled with heavy water. Cooling is performed with light water from the reactor pool. The reactor is controlled by means of the central control rod inside the fuel element. To shut it down, an additional, independent system of five shutdown rods is provided in the moderator tank. Each system is individually capable of shutting the reactor down quickly and permanently anytime. The outer walls of the reactor building consist of 1.8 m of reinforced concrete and are designed to withstand the impact of an earthquake or even the impact of a high speed military aircraft, as required particularly in the respective Guidelines of the Reactor Safety Commission for pressurised water reactors. [7]

The compact core consists of a single, cylindrical fuel element. Its inner diameter is 118 mm, its outer diameter 243 mm and its active height is approx. 700 mm. The fuel element with its packaging is approx. 1.3 m high and contains a total of 8.5 kg of highly enriched uranium (HEU) in an uraniumsilicide-aluminium dispersion fuel. It is made up of 113 involuted, curved fuel plates. In order to homogenise the power and fission density, the uranium content in the outer zone of each fuel plate is reduced from 3 g/cm^3 to 1.5 g/cm^3. The average power density amounts to more than 1000 kW/liter. With a burn-up of 1200 MW·d and a cycle length of 60 days, four fuel elements will be required per year. [7]

The FRM-II is operated by the TUM (Technical University Munich) with highly enriched uranium. According to an obligation of the operating licence of 2 May 2003 and an agreement between the Federal Government and the Land Bavaria of 30 May 2003, the reactor core has to be converted to a fuel with a reduced enrichment level of 50 % uranium 235 (MEU) at maximum. Originally it was intended to complete the conversion by the end of year 2010. To comply with this obligation, the operator established already in 2001 an international working group to develop a new high density fuel on the basis of a uranium-molybdenum alloy. However, due to unexpected delays in the international technical-scientific development in the area this requirement could not be complied with. Therefore, the original agreement between the Federal Government and Bavaria of 30 May 2003 was amended on 22 October 2010. Now the plant needs to be converted by 31 December 2018 at the latest. [6]

From 22 October 2010 to 29 October 2011, the facility was undergoing its first long maintenance outage. Up to now, 25 fuel element cycles have been completed. During the inspection of the heavy water circuit, corrosion on a bearing of a security cap has been discovered. The components involved were examined and had to be replaced by new ones, which are designed to be able to withstand the observed corrosion by the heavy water in future [4]. Besides intensive maintenance work in the outage, also several special works have been carried out. One major issue close to the reactor core was the exchange of a beam tube for a positron source. Furthermore, based on a feasibility study for a molybdenum 99 production facility, a so-called thimble in the moderator tank was expanded to install later on an irradiation device. The production facility is designed to provide a major part of the

European supply of molybdenum 99. Start of production is planned for 2014 [8]. For the later operation of the production facility, a separate license according Section 7(1) of the Atomic Energy Act is required, to be granted by the competent licensing authority of the Land Bavaria. Within the licensing procedure all aspects relevant to safety will be evaluated, according to the state of the art in science and technology.

The FRM-II has been operated safely since the beginning of its initial start up. According to the German Nuclear Safety Officer and Reporting Ordinance [3], in total 15 reportable events occurred. With respect to the national reporting categories, one single event was assigned to category E, may having a potential - but no direct - significance to safety. It dealt with a malfunction of a check valve in the primary cooling circuit after shutdown of the reactor in an inservice inspection. In any case, category E demands a quick reporting to the competent supervisory authority within 24 hours instead of a normal reporting within five days. However, this event and all others have been evaluated as level zero of the INES scale meaning deviations with no direct safety significance. [4]

As mentioned in Chapter 2, safety reviews in the sense of a periodic safety review are not mandatory for research reactors in Germany. However, especially for the FRM-II as the newest large research reactor in Germany, a periodic safety review is fixed as an obligation in the operation licence from 2 May 2003. The first safety review has to be submitted to the supervisory authority in 2015, about ten years after the beginning of routine operation in 2005.

The FRM-II is also subject of the additional systematic safety review by the RSK concerning severe accidents, due to the Fukushima accident in March 2011 in Japan [see Chapter 2].

3.2. Berlin Experimental Reactor Unit II (BER II)

The BER II is a pool reactor with fuel elements of the MTR type. The reactor was commissioned on 9 December 1973, and mainly serves pure and applied basic research with beam pipe experiments and generation of radioactive isotopes. During its long time of operation, the facility was continuously upgraded. [6]

Actually, the thermal power is 10 MW and the thermal neutron flux $1.5 \cdot 10^{14}/(cm^2 \cdot s)$. The core consists of 30 MTR fuel elements of uraniumsilicide-aluminium dispersion with low enriched uranium with 20 % uranium 235 (LEU) and is surrounded by graphite reflector elements. [9]

From 1985 to 1991, the plant was largely expanded. The thermal power was doubled from originally 5 MW to 10 MW, and the thermal neutron flux was increased up to $1.5 \cdot 10^{14}/(cm^2 \cdot s)$, which is nearly the ten-fold of the original one. This upgrade and the respective restart of operation were realized within a comprehensive licence procedure according to Section 7 of the Atomic Energy Act. Three partial licences have been granted by the competent licensing authority of the Land Berlin, namely two partial licences for the construction work on 15 August 1985 (first amendment on 29 October 1987) and 26 October 1988 respectively, and a third licence for its operation on 25 March 1991 [6]. Within the licensing procedure, all changes relevant to safety had to be assessed in the light of the state of the art in science and technology. This had been proved carefully by the licensing authority and their authorized experts. The assessment included, among others, the overall safety concept, the reactor core, the installation of a cold neutron source, the core cooling system, the reactor protection system and all auxiliary systems involved. According to the German Nuclear Licensing Procedure Ordinance, also the general public had to be involved, including a public hearing. Furthermore, within the framework of the Federal Oversight, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) was incorporated, with the aim to preserve the uniformity regarding lawfulness and expediency within the Federal Republic. The BMU had no objection concerning the overall licensing procedure executed by the Land Berlin, and also no objection to grant the final operating license in 1991. The decision of the BMU was based, among others, on the recommendations of the Reactor Safety Commission (RSK), which acts as its advisory body and was consulted particularly to technical questions concerning the first partial license [10].

In the following years, the BER II was converted from operation with high-enriched uranium (HEU) to low-enriched uranium with 20 % uranium 235 (LEU). The conversion was mainly to reduce the proliferation risk, but of course, this was also an essential modification of the facility and its operation, and therefore subject to a licensing procedure according to Section 7 of the Atomic Energy Act. Among others, a detailed safety analysis for the comparison of the source terms for a LEU and a HEU core had to be performed, regarding a severe accident caused by a postulated crash of a military aircraft. As result it was found out, that there were no significant differences to the radiological impact on the environment [11]. The licence was granted on 14 June 1994. Following a number of mixed loadings of HEU and LEU a pure LEU core was built up for the first time and commissioned on 7 February 2000 [6].

At the end of 2004, the entire operational instrumentation and control of the BER II was renewed and upgraded to digital technology. This had been approved within the framework of the continuous supervision by the competent supervisory authority. After four months of structural alteration works, the reactor was recommissioned in January 2005.

As already mentioned above in Chapter 2, safety reviews in the sense of a periodic safety review are not mandatory for research reactors in Germany. However, for the BER II a safety review is required every ten years. This was introduced within the licensing procedure for the power upgrade from 5 to 10 MW and is fixed by a provision in the operating manual. The first of such a safety review was completed in September 2004, about 10 ten years after recommissioning with 10 MW. The extent and the details of the total procedure had been coordinated with the supervisory authority. On this basis, the safety review included especially an update of the plant description, an assessment of the operating experience, and a performance of a new accident analysis [12]. The results of the safety analysis have been approved by the supervisory authority. As a main enhancement of safety, improved measures in irradiation devices including the documentation requirements have been implemented.

According to the German Nuclear Safety Officer and Reporting Ordinance, in force since 1991 [3], in total 66 reportable events occurred. All of them have been assigned to category N for normal reporting to the supervisory authority within five days, and level zero of the INES scale meaning deviations with no direct safety significance. [4]

The BER II is also subject of the additional systematic safety review by the RSK concerning severe accidents, due to the Fukushima accident in March 2011 in Japan [see Chapter 2].

3.3 TRIGA Mark II research reactor of the Mainz University (FRMZ)

TRIGA reactors are the most used research reactors around the world and well known. There exist a lot of variations in design, power and operation. The main common feature of all these facilities is the use of homogenous fuel moderator elements with uranium as fuel and zirconium hydride as moderator. This combination provides a prompt negative temperature coefficient. Therefore, TRIGA reactors have a very high level of safety and are very robust in operation, e.g. for being used in pulsed mode.

The FRMZ is such a typical TRIGA reactor of a Mark II type, light-water cooled and moderated in an open pool. It is equipped with about 60 homogeneous fuel moderator elements of low enriched uranium with 20 % uranium 235 and zirconium hydride. The nuclear commissioning was on 3 August 1965. In continuous operation the thermal power is

100 kW_{th} and the thermal neutron flux is $4 \cdot 10^{12}$ $1/cm^2 \cdot s$. Additionally, the reactor can be operated in pulsed operation above 30 ms, with a power peak of 250 MW and a thermal neutron flux of $8 \cdot 10^{15}/(cm^2 \cdot s)$. The total energy release is about 12 MW·s. The plant, operated by the University, is used for basic research in nuclear physics and is especially suitable for examining short-living radionuclides. [6]

In the beginning of the nineties, a large safety upgrade of the reactor systems has been carried out. Of course, it was an essential modification and required a licence according to Section 7 of the Atomic Energy Act, which was granted by the competent licensing authority of the Land Rhineland-Palatinate on 28 July 1992 [6]. The modification comprised, among others, the reconstruction of the primary and secondary circuits, the reconstruction of the condenser between these two circuits as well as the implementation of an own cleaning circuit, hence separated from the primary circuit as before. Furthermore, the cooling tower and several electronic systems for measuring and control purposes have been modified.

The FRMZ is operated safely since it commissioning more than 45 years ago. As an example, not more than 5 reportable events occurred according to the German Nuclear Safety Officer and Reporting Ordinance [3], since it became in force in 1991. All of them have been assigned to category N for normal reporting to the supervisory authority within five days, and level zero of the INES scale meaning deviations with no direct safety significance. [4]

The FRMZ is also subject of the additional systematic safety review by the RSK concerning severe accidents, due to the Fukushima accident in March 2011 in Japan [see Chapter 2].

3.4 Training reactor of the Technical University Dresden (AKR-2)

In the past, in Germany more than a dozen of so called "zero power reactors" have been operated, mainly by universities for education and training of students in all kind of nuclear sciences. Actually, five of these facilities are still in operation, and the AKR-2 will be described in some more detail as an example for the operation of these facilities.

The AKR-2 is a training reactor with a negligible thermal power of two Watt and a maximum thermal neutron flux of about $5 \cdot 10^7/(cm^2 \cdot s)$. This facility is a refurbishment of the former AKR reactor, commissioned in 1978, and was recommissioned in 2005. The reactor core is build up of disk-shaped fuel elements of a homogenous dispersion of polyethylene and low enriched uranium oxide with 20 % uranium 235. In total, the core has a cylindrical form with a diameter of 25 cm and a height of 27.5 cm. The core is surrounded by a graphite reflector. The total mass of the core is 794 g uranium 235, thus just over the critical mass. In detail, the core consists of two separate cylindrical sections with subcritical mass each. In shutdown position, the upper and the lower core sections are separated by 5 cm. For operation, the lower section has to be lifted by a drive mechanism and to be hold up in position by an electromagnetic device. For controlling operation, three cadmium absorber plates are available. They are also designed in such a way that each of them is sufficient to be used as a safety rod to shut down the reactor and keep it subcritical. The reactor needs no cooling at all and has inherent safety features. Therefore, it provides an ideal tool for training and educational purposes, as well as for students in nuclear sciences and staff of the nuclear industry. Furthermore, it is also used for different research projects where high neutron fluxes are not necessary, e.g. development of measuring techniques, radiation spectrometry and bench mark experiments. [13]

The AKR-2 is a complete refurbishment of the former AKR reactor and the most updated training reactor in Germany. Sited in Dresden, the AKR was build and operated within the legislative and regulatory framework of the former GDR (Germany Democratic Republic). In 1989, after approximately ten years of operation, a safety review of all operational and safety systems of the facility and of the reactor administration procedures had been performed, and on this basis the license was renewed unlimited in time. [14]

After the reunification in Germany in 1990, is was determined by a new section 57a introduced in the Atomic Energy Act of the Federal Republic of Germany, that existing licences from the former GDR expires on 30 June 2005, even if they had been granted unlimited. Therefore, a new licence according to section 7 of the Atomic Energy act had to be required to ensure a further operation after this deadline. The licensing procedure was started in 1998. Within the safety review to be performed it was determined that an extensive refurbishment of the facility would be necessary. This referred particularly to the reactor building, the auxiliary technical systems, and the instrumentation and control equipment. On 22 May 2004, the new licence was granted by the competent licensing authority of the Land Saxony, comprising the construction of the new facility as well as of its recommissioning and operation. The reconstruction was carried out in the time from April to December 2004. It included, among others, various construction works at the reactor building, a complete new installation of the electrical systems and the room ventilation, and especially a complete modernization of the entire instrumentation and control system, based on the digital reactor protection, instrumentation and control system TELEPERM. The nuclear design of the reactor itself could remain unchanged, including core, reflector and control rods. On 22 March 2005, the first criticality of the reconstructed facility was reached. [14]

The AKR-2 has a thermal power of not more than 2 Watt. Therefore it is not subject to the German Nuclear Safety Officer and Reporting Ordinance, which refers only to research reactors with a thermal power output larger than 50 kW [3]. Furthermore, with respect to the low potential hazards of this facility, the AKR-2 needs not to be included in the additional systematic safety review of research reactors by the RSK concerning severe accidents, due to the Fukushima accident in March 2011 in Japan [see Chapter 2].

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