# Decommissioning of Nuclear Facilities

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## Contents




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## 1 Introduction

The decommissioning of nuclear facilities is a challenge which the nuclear countries will need to address. According to information of the International Atomic Energy Agency (IAEA) as at August 2017, more than 600 reactors and about 300 nuclear fuel cycle facilities have been finally shut down so far.

After the end of their operational life, nuclear power plants cannot be left to their own. Since they still may pose a hazard, they have to be decommissioned in an orderly manner to protect man and the environment. The term »decommissioning« refers to all measures carried out after granting of a decommissioning licence for a nuclear facility until official supervision, i.e. supervision under nuclear and radiation protection law, is no longer necessary. This usually implies removal of all parts of the building and restoration of the site to its original condition in form of the so-called »green field«, as for example in the case of the Niederaichbach nuclear power plant (▶ Fig. 1).

*Fig. 1: Dismantling of the Niederaichbach nuclear power plant*

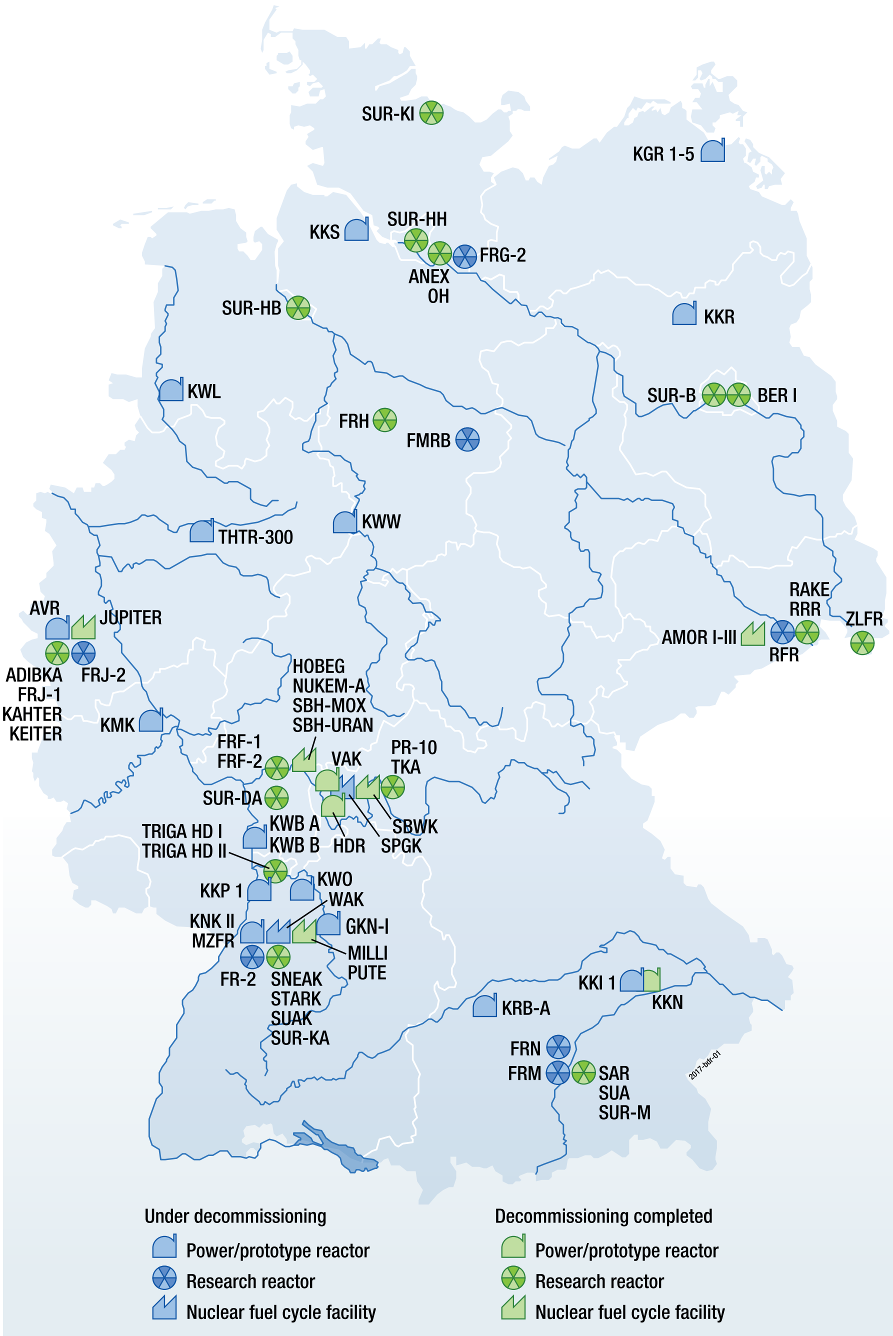
## 2 Overview

In August 2017, 21 nuclear power plants (power and prototype reactors) have been in different stages of decommissioning in Germany. Following the accident at the Fukushima nuclear power plant in Japan and the subsequent decision of the Federal Government to phase out nuclear energy, nine nuclear power plants have been finally shut down so far. From these, five were granted the licence for decommissioning and dismantling in the first half of 2017: the Isar-1 nuclear power plant (KKI 1, decommissioning licence granted on 17 January 2017), the Neckarwestheim nuclear power plant I (GKN I, decommissioning licence granted on 3 February 2017, the nuclear power plants Biblis-A and Biblis-B (KWB A and KWB B, decommissioning licences granted on 30 March 2017) as well as the Philippsburg-1 nuclear power plant (KKP 1, decommissioning licence granted on 7 April 2017). The remaining eight plants, which are currently still in operation, will be finally shut down in a step-by-step process by 2022; one plant each by the end of 2017 and 2019 and another three plants by the end of 2021 and 2022. These plants will also be decommissioned after their final shutdown (▶ Chapter 12.1 List on decommissioning of nuclear facilities in Germany).

Ten research reactors of different sizes were finally shut down in August 2017, six of which have already been in the decommissioning phase. Previously, 29 research reactors and nine facilities of the nuclear fuel cycle had been completely decommissioned in Germany. Two facilities of the nuclear fuel cycle are in the phase of decommissioning. At the site of the Greifswald nuclear power plant (KGR), one of the world's largest decommissioning projects is being carried out (▶ Fig. 2).

The map in ▶ Fig. 3 gives an overview of the facilities under decommissioning in Germany in August 2017 or already completely dismantled. In addition to the power and prototype reactors, these are research reactors and nuclear fuel cycle facilities.

***Fig. 2:*** *Site of the Greifswald nuclear power plant*




**Nuclear power plants and prototype reactors**

| | |
|---|---|
| AVR | Jülich experimental reactor |
| GKN I | Neckarwestheim-I nuclear power plant |
| HDR | Großwelzheim superheated steam reactor |
| KGR 1-5 | Greifswald 1-5 nuclear power plant |
| KKI 1 | Isar-1 nuclear power plant |
| KKN | Niederaichbach nuclear power plant |
| KKP 1 | Philippsburg-1 nuclear power plant |
| KKR | Rheinsberg nuclear power plant |
| KKS | Stade nuclear power plant |
| KMK | Mülheim-Kärlich nuclear power plant |
| KNK II | Karlsruhe compact sodium-cooled nuclear reactor |
| KRB-A | Gundremmingen-A nuclear power plant |
| KWB A | Biblis-A nuclear power plant |
| KWB B | Biblis-B nuclear power plant |
| KWL | Lingen nuclear power plant |
| KWO | Obrigheim nuclear power plant |
| KWW | Würgassen nuclear power plant |
| MZFR | Karlsruhe multi-purpose research reactor |
| THTR-300 | Hamm-Uentrop thorium high temperature nuclear reactor |
| VAK | Kahl experimental nuclear power plant |

**Research reactors**

| | |
|---|---|
| ADIBKA | Burn-up measurement of differential fuel elements with critical assembly Jülich |
| ANEX | Facility for zero power experiments Geesthacht |
| BER I | Berlin experimental reactor 1 |
| FMRB | Braunschweig research and measuring reactor |
| FR-2 | Karlsruhe, research reactor 2 |
| FRF-1 | Frankfurt research reactor 1 |
| FRF-2 | Frankfurt, research reactor 2 |
| FRH | TRIGA research reactor of the Hannover Medical School |
| FRG-2 | Geesthacht-2 research reactor |
| FRJ-1 | Jülich 1 research reactor (MERLIN) |
| FRJ-2 | Jülich 2 research reactor (DIDO) |
| FRM | München research reactor |
| FRN | Neuherberg research reactor |
| KAHTER | Critical facility with pebbly-type fuel for high temperature reactors Jülich |
| KEITER | In-core thermionic reactor critical experiments Jülich |
| OH | Otto Hahn nuclear ship Geesthacht |
| PR-10 | AEG test reactor Karlstein |
| RAKE | Rossendorf assembly for critical experiments |
| RFR | Rossendorf research reactor |
| RRR | Rossendorf ring zone reactor |
| SAR | Siemens Argonaut reactor Garching |
| SNEAK | Karlsruhe fast zero energy assembly |
| STARK | Karlsruhe fast-thermal Argonaut reactor |
| SUAK | Karlsruhe fast subcritical assembly |
| SUA | Siemens subcritical assembly Garching |
| SUR-B | Siemens training reactor Berlin |
| SUR-DA | Siemens training reactor Darmstadt |
| SUR-HB | Siemens training reactor Bremen |
| SUR-HH | Siemens training reactor Hamburg |
| SUR-KA | Siemens training reactor Karlsruhe |
| SUR-KI | Siemens training reactor Kiel |
| SUR-M | Siemens training reactor München at Garching |
| TKA | AEG zero power reactor/thermal-critical assembly Karlstein |
| TRIGA HD I | Heidelberg research reactor TRIGA I |
| TRIGA HD II | Heidelberg research reactor TRIGA II |
| ZLFR | Zittau training and research reactor |

**Nuclear fuel cycle facilities**

| | |
|---|---|
| AMOR I-III | Rossendorf facility for the production of Mo-99 |
| HOBEG | Hanau fuel fabrication plant for high temperature reactors |
| JUPITER | Jülich pilot plant for thorium element reprocessing |
| MILLI | Karlsruhe milliton-scale reprocessing facility |
| NUKEM-A | Hanau NUKEM-A fuel fabrication plant |
| PUTE | Karlsruhe plutonium test extraction |
| SBH-MOX | Siemens fuel fabrication plant Hanau; MOX section |
| SBH-Uran | Siemens fuel fabrication plant Hanau; uranium section |
| SBWK | Siemens fuel fabrication plant Hanau; Karlstein site |
| SPGK | Siemens Power Generation Karlstein |
| WAK | Karlsruhe reprocessing plant |

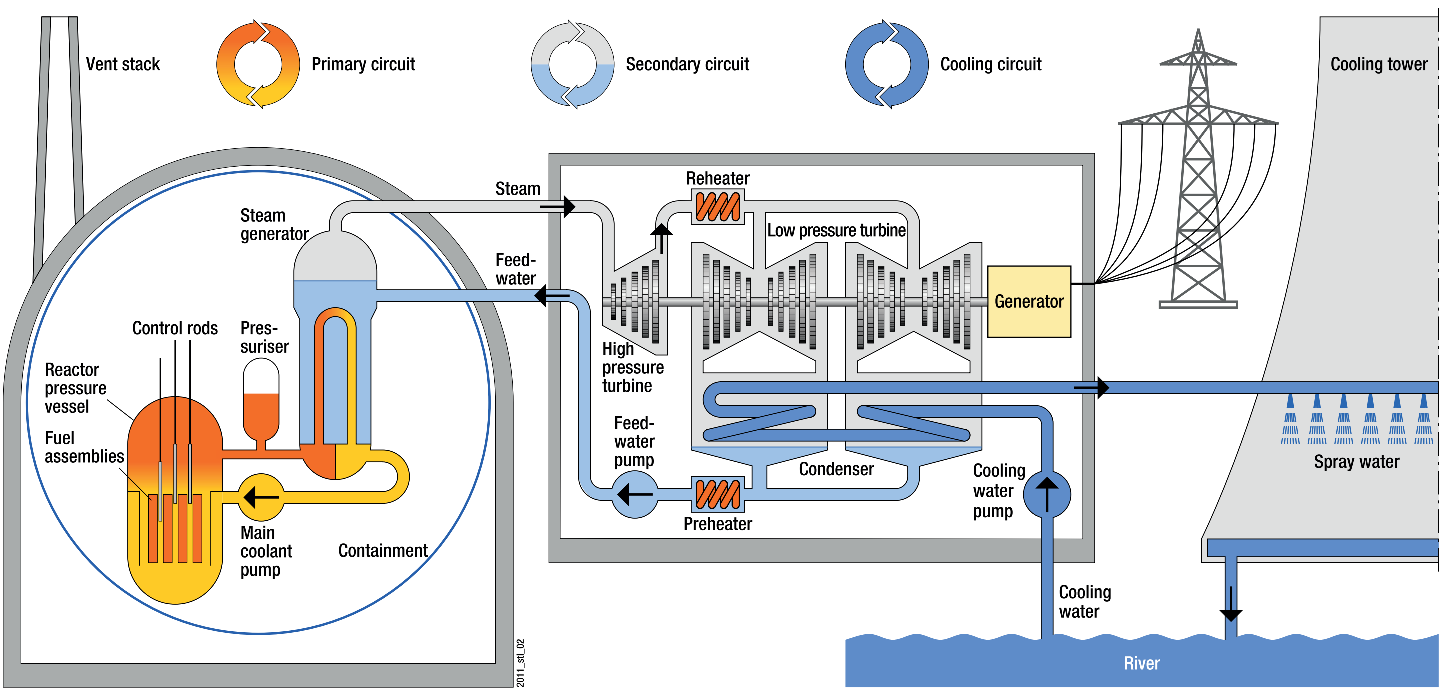
*Fig. 3: Nuclear facilities in Germany under decommissioning or already decommissioned*

## 2.1 Power and prototype reactors

Nuclear power plants (power and prototype reactors) convert the energy content of nuclear fuel into electrical energy (in the so-called fuel assemblies). In a controlled chain reaction, heat is generated by nuclear fission. This heat is absorbed by a water cycle and is converted there into steam that drives turbines. These, in turn, drive generators that produce electricity. Nuclear power plants are mainly used in the base load range, thus helping to cover the unvarying part of daily electricity demand.

In Germany, two different types of nuclear power plants are operated, i.e. boiling water and pressurised water reactors. As shown in ▶ Fig. 4 and 5, both types use water as a coolant, but they differ, among other things, in the design of the cooling circuit.

*Fig. 4: Schematic diagram of a pressurised water reactor*

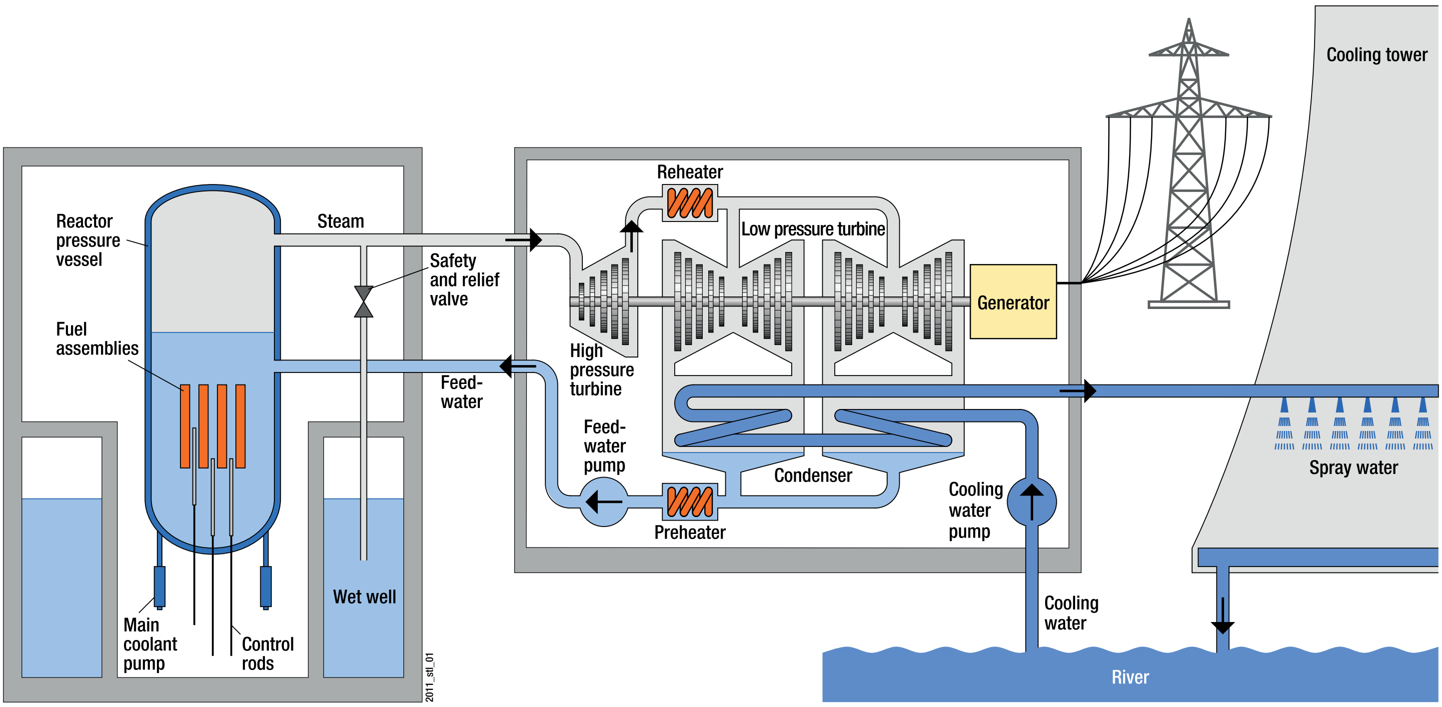


Three nuclear power plants have been completely dismantled so far: the Niederaichbach nuclear power plant (KKN), the Großwelzheim superheated steam reactor (HDR) and the Kahl experimental nuclear power plant (VAK). The first two plants were prototype reactors, whose development was not further pursued. The Kahl experimental nuclear power plant was the first nuclear power plant built in Germany. After 25 years of operation, it was finally shut down in 1985. Parts of the plant and buildings were decontaminated, completely dismantled and the site was cleared in 2010 without restrictions for future use (▶ Chapter 8.1 Clearance).

In the course of the various decommissioning projects it showed that each project is actually carried out individually. Experience has shown that decommissioning of a power or prototype reactor will take about 10 to 20 years.

Several examples of power and prototype reactors decommissioned or under decommissioning are presented in the Annex (▶ Chapter 12.1).

***Fig. 5:*** *Schematic diagram of a boiling water reactor*



## 2.2 Research reactors

In contrast to power reactors, research reactors are generally used for special purposes in research, medicine or in the industrial sector. The main focus here is on the use of neutron radiation produced in the reactor.

Decommissioning takes place according to the same principle as that for a nuclear power plant. The licensing procedure and the techniques to be used for decontamination, disassembly and waste conditioning are very similar. However, the facility size and the radioactive inventory are significantly smaller in the case of a research reactor compared to a nuclear power plant, e.g. there is generally no plant component for electricity generation.

In most cases, a research reactor can therefore be dismantled within a shorter period (between a few months and a few years) than a larger power reactor.

Examples from the dismantling of research reactors are given in ▶ Fig. 6 and 7 (see also list and detailed examples in the Annex (▶ Chapter 12)).

***Fig. 6:*** *View of the reactor block of the FRF research reactor*

***Fig. 7:*** *Dismantling of the FRJ-1 research reactor*

## 2.3 Nuclear fuel cycle facilities

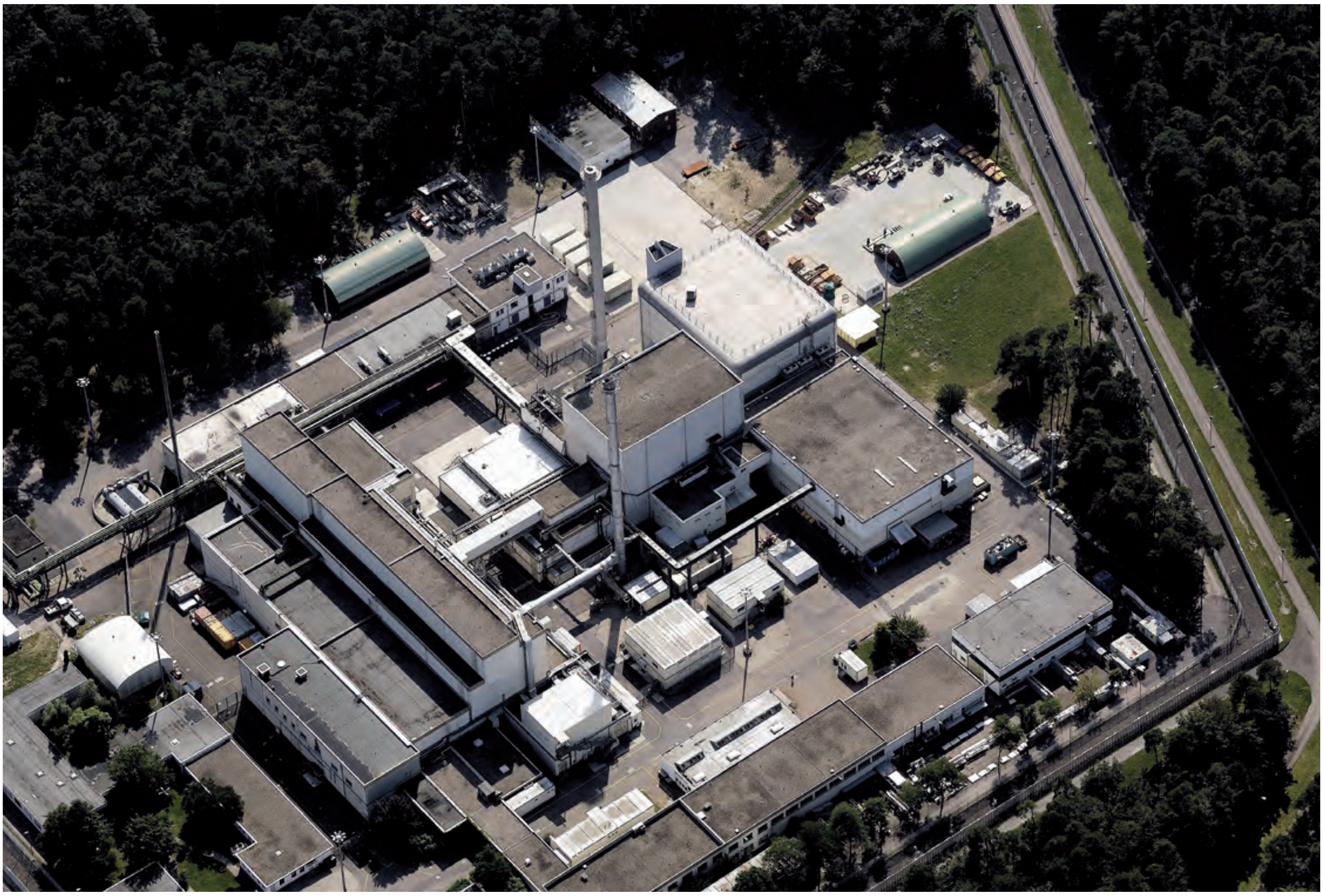
Nuclear fuel cycle facilities are used, for example, for the fabrication or reprocessing of nuclear fuel, or for the conditioning of waste. As shown in the list in the Annex (▶ Chapter 12.1), there are only a few such facilities in Germany.

The licensing procedure and the duration of decommissioning are comparable to the decommissioning of nuclear power plants (▶ Chapter 5.2 Licensing procedure).

From a technical point of view, however, the projects differ significantly from the decommissioning of nuclear power plants. The main reason for this is that facilities of the nuclear fuel cycle are significantly contaminated with uranium and other alpha-emitting radionuclides due to the mechanical and chemical processing of nuclear fuel during their operation. This is why there are different requirements to be met for decontamination and dismantling techniques and for radiation protection of the personnel.

At the Hanau site, several fuel fabrication plants were taken out of service in the 1980s and 1990s. At the former Kernforschungszentrum Karlsruhe (now Karlsruhe Institute of Technology, KIT), the Karlsruhe reprocessing plant (WAK) (▶ Fig. 8) was operated as a pilot plant from 1971 to 1990. Its decommissioning entails particularly complex requirements. So, for example, the dismantling of the WAK is expected to take about 35 years, from the granting of the first decommissioning licence in the year 1994 until complete removal of the plant, which is scheduled for 2030.

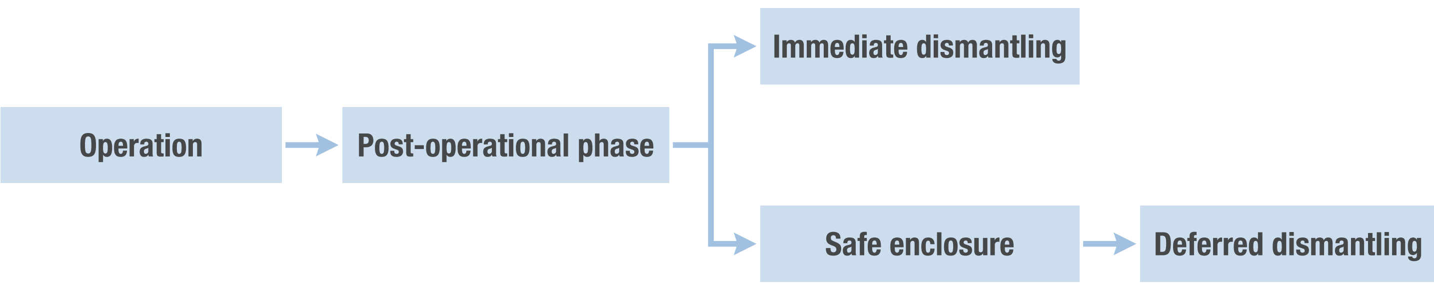
***Fig. 8:*** *Karlsruhe reprocessing plant (WAK)*



## 3 Decommissioning strategies

There are two different strategies according to which decommissioning is generally performed internationally and also in Germany: immediate dismantling or dismantling after safe enclosure (▶ Fig. 9).

***Fig. 9:*** *Decommissioning strategies*




Between final shutdown and start of the actual decommissioning or the period of safe enclosure, there is the so-called post-operational phase, which may last several years. During this period, the fuel assemblies can be removed and the operational media and waste disposed of as far as covered by the operating licence for the nuclear facility. At the latest in the post-operational phase, the operator of the facility applies for licensing of decommissioning (▶ Chapter 5.2 Licensing procedure). Only after granting of the licence, the actual decommissioning and dismantling activities can be started.

In the case of immediate dismantling, the facility will be removed immediately, i.e. immediately after the post-operational phase, all systems and installations of the controlled area (▶ Chapter 6.2 Radiation protection) will be dismantled (▶ Fig. 10).

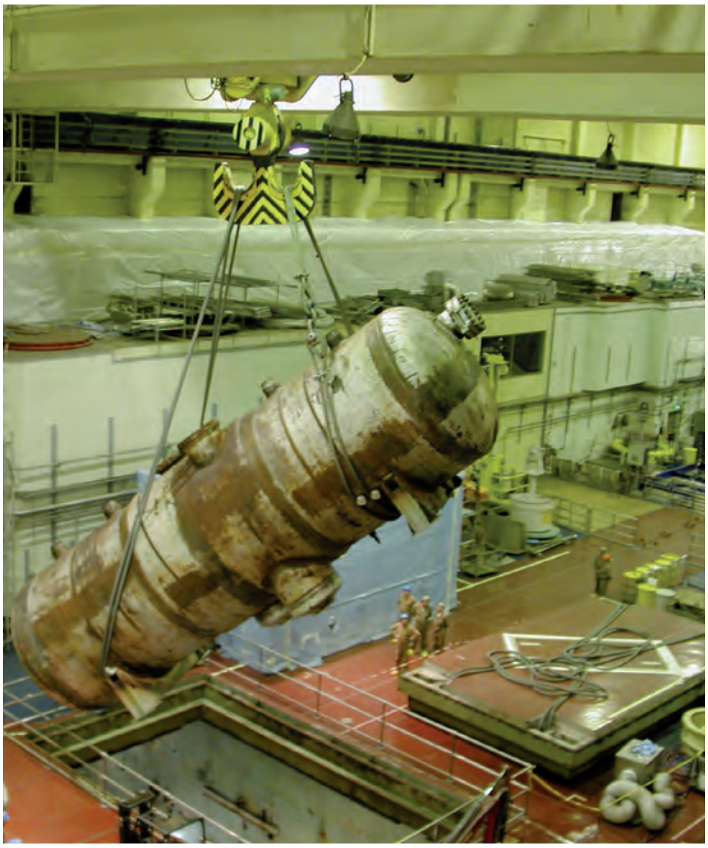


***Fig. 10:*** *Removal of a steam generator during immediate dismantling*

In the case of the alternative strategy, however, the facility will be safely enclosed for a certain period of time (typically a few decades) before dismantling. Here, a distinction is to be made between three phases:

1. Measures in the facility to realise safe enclosure and to transfer the facility to a state with low maintenance requirements (e.g. removal of fuel assemblies and fire loads)
2. Maintaining the facility in safe enclosure over a longer period (e.g. 30 years) (▶ Fig. 11)
3. Dismantling of the facility

*Fig. 11: Building of the THTR-300 (area of safe enclosure blue-coloured)*

Each of the two strategies has its advantages and disadvantages that must be weighed up against each other in the particular case (▶ Table 1). The decision as to which decommissioning strategy will be implemented is taken by the operator of the facility within the scope of entrepreneurial responsibility.

For nuclear power plants, the Act on the Reorganisation of Responsibility in Nuclear Waste Management (Gesetz zur Neuordnung der Verantwortung der kerntechnischen Entsorgung) of 16 June 2017 stipulates that they shall be decommissioned and dismantled immediately. Exceptions may only be authorised by the competent authority in individual cases for plant components as far as this is necessary for reasons of radiation protection.

| | Immediate dismantling | Safe enclosure and deferred dismantling |
|---|---|---|
| Advantages | • Availability of personnel being familiar with the operating history<br>• Mitigation of economic effects for the region<br>• Security of funding<br>• Site may be used again earlier. | • Radioactivity decreases with time (»decay«).<br>• Due to lower radiation exposure during dismantling, dismantling work may be performed with simpler techniques. |
| Disadvantages | • Higher residual radioactivity<br>• Higher radiation exposure may also render dismantling work technically more difficult. | • Measurement efforts for the radiological assessment increase with time.<br>• Knowledge about the facility will get lost.<br>• For dismantling after safe enclosure, new qualified personnel have to be found. |

*Table 1: Comparison of some advantages and disadvantages of both decommissioning strategies*

In Germany, there are only a few facilities in safe enclosure (▶ Chapter 12 Annex). The decommissioning projects currently applied for in Germany are aimed at immediate dismantling.

To some extent, some of the advantages of safe enclosure are exploited directly for immediate dismantling by removal of large components (e.g. steam generator, ▶ Fig. 10) in one piece and temporarily storing them for a certain period of time (▶ Chapter 8.2 Decay storage). Subsequently, disassembly with simpler aids and radiation protection measures is possible. Furthermore, this also reduces radioactive waste.

An international comparison shows that safe enclosure is used for nuclear facilities where the waste management path for parts of the facility has not been clarified yet. This is the case, for example, for nuclear power plants with graphite as moderator (e.g. in England and France). Furthermore, after an accident, safe enclosure is preferred for facilities in order to bring the facility into a safe condition and to start orderly dismantling at a later time. In some cases, the lack of funds required for the dismantling of a facility leads to choosing the strategy of safe enclosure.

## 4 Stepwise dismantling of a nuclear power plant

Using the example of a nuclear power plant it is shown how nuclear facilities are dismantled in principle. ▶ Fig. 12 to 15 illustrate the dismantling by means of a simplified section through a nuclear power plant. In each dismantling step, the structures, systems and components highlighted in red will be removed. The sequence of dismantling shown is one of several different approaches.

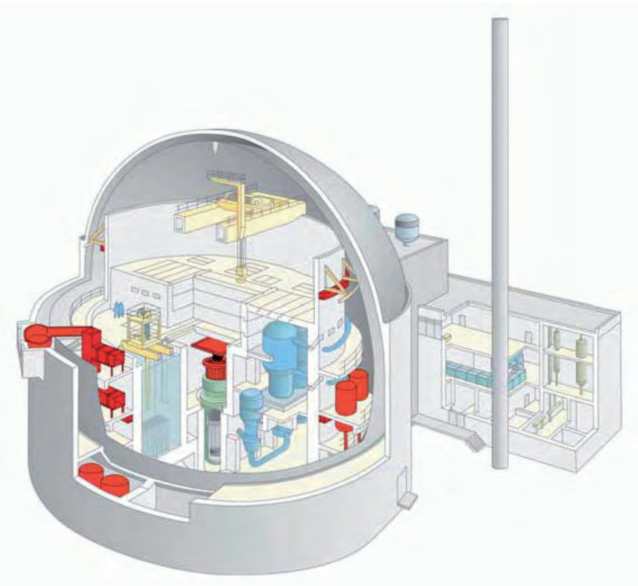


***Fig. 12:*** *In a first step, the components no longer needed for dismantling operations are removed.*

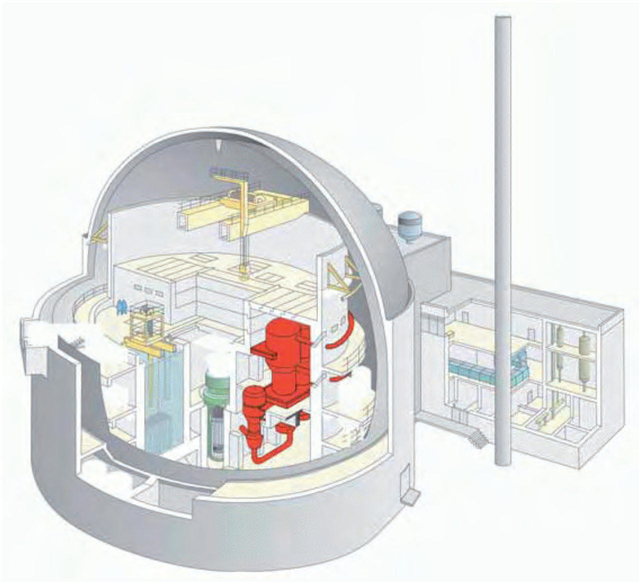


***Fig. 13:*** *In the next steps, the higher activated parts, such as steam generator and parts of the primary circuit, are removed.*

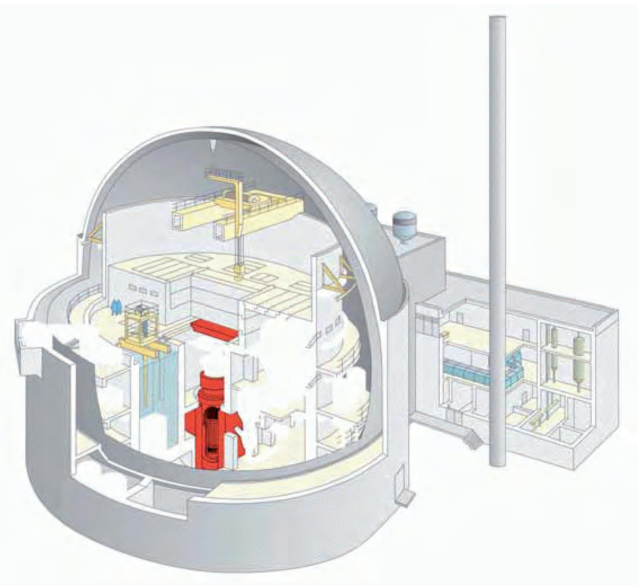


***Fig. 14:*** *As a last major component, usually, the highly activated reactor pressure vessel is dismantled.*

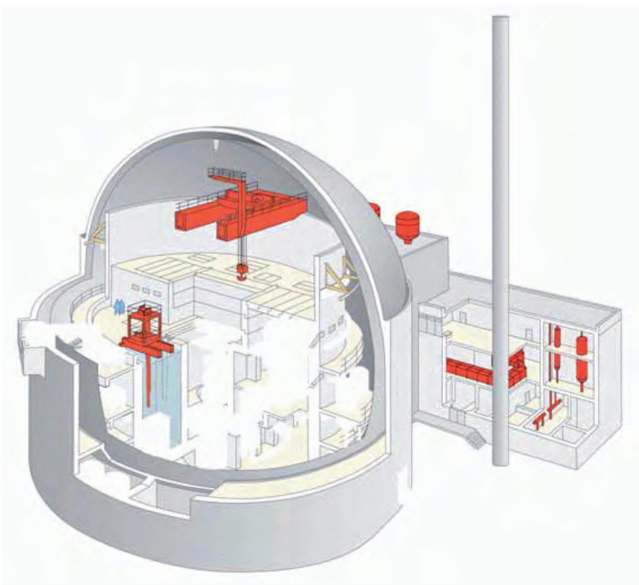


***Fig. 15:*** *As a last step, the parts necessary until then, such as cranes and filter systems, are removed.*

***Fig. 16:*** *Decontamination by sandblasting*

***Fig. 17:*** *Conventional demolition of the outer building shell of the Niederaichbach nuclear power plant*

Before starting dismantling work, the plant is largely in the same technical condition as during operation. However, fuel assemblies have already been removed or are still in the spent fuel pool.

In preparation for the decommissioning work, a detailed overview of the radioactive inventory of the facility is prepared. For this purpose, measurements are carried out in all areas of the facility and samples are taken and analysed. After that, the final plan for dismantling can be prepared. In this phase, it will also be decided on the techniques to be applied for decontamination and disassembly (▶ Chapter 7 Techniques)

The work sequences for dismantling vary according to the different decommissioning projects, where combinations of the variants described below may also be appropriate. One variant provides for first of all removing the components with the highest activation or contamination in order to achieve a significant reduction in the radiation exposure of the dismantling staff for the subsequent dismantling activities. These components include the internals of the reactor pressure vessel, the core beltline region and the immediately adjacent systems and components inside the containment. Plant components with lower or no contamination are subsequently removed. Alternatively, dismantling work can be started reversely in areas with low contamination to subsequently proceed in areas with higher contamination; i.e. dismantling is carried out »from the outside to the inside«. In the vacated areas, e.g. parts of the turbine building, then necessary equipment can be installed for segregation, decontamination and treatment of the waste and residues.

Practically all removed parts are disassembled into easy-to-handle pieces and, if necessary, decontaminated (▶ Fig. 16). In Germany, system decontamination is often carried out during the post-operational phase (▶ Chapter 7.1 Decontamination techniques), which can reduce the internal contamination of a major part of the reactor components by orders of magnitude. Decontamination of individual parts, however, can also take place after disassembly depending on the circumstances.

Components can be disassembled either in the installed state, on site in specially equipped room areas or also externally. In some cases, large components are initially removed from the facility for decay storage (▶ Chapter 8.2 Decay storage) and later disassembled externally.

Each piece is examined for radioactivity. On the basis of this radiological characterisation, it is decided whether the piece must be conditioned and handed over as radioactive waste, or whether it can be further treated and cleared (▶ Chapter 8 Residue and waste management).

The dismantling steps which relate to the reactor pressure vessel and its internals are largely carried out remote-controlled in order to avoid the presence of persons in areas of high radiation exposure. Much of the work is also carried out under water since water is an effective radiation shield. The materials resulting from this dismantling step are, for the most part, activated. They account for a significant portion of radioactive decommissioning waste (▶ Chapter 8 Residue and waste management).

Computerised systems ensure continuous tracking of the pieces, from the place of their dismantling through the subsequent treatment steps to their removal from the facility. Overall, the logistics required for residue and waste treatment are extensive and a significant cost factor.

Important installations, such as ventilation, power and media supply, are required through all steps of dismantling. These systems are either still available from the operating phase and can be used, or new and, where necessary external systems will be installed, which are better adapted to the respective requirements of dismantling. The installation of new and external systems allows earlier dismantling of the systems from the operating phase.

After complete vacation of the building, only residual contamination may remain on the surfaces of the building structures. In the last step, these will be decontaminated and re-examined for remaining contamination. After successful clearance, the building can be released from the scope of application of the Atomic Energy Act and then conventionally used or demolished (▶ Fig. 17).

# 5 Licensing and supervisory procedures
## 5.1 Legal framework

The legal framework for the decommissioning of nuclear facilities results from the Atomic Energy Act (Atomgesetz – AtG). It stipulates that decommissioning is subject to licensing by the competent authority (▶ Chapter 5.2 Licensing procedure).

▶ Fig. 18 shows the hierarchy of the national regulations, including their degree of bindingness, in form of the so-called regulatory pyramid. The Basic Law (Grundgesetz – GG) establishes basic principles and provides that the Federation has the exclusive legislative power for the use of nuclear energy.

For further concretisation of the Atomic Energy Act, several ordinances have been issued. For decommissioning, the Radiation Protection Ordinance (StrlSchV), the Nuclear Licensing Procedure Ordinance (AtVfV) and the Nuclear Safety Officer and Reporting Ordinance (AtSMV) are of particular importance.

The Radiation Protection Ordinance contains the definition of the radiological protection principles and lays down the admissible radiation exposure limits. It also contains provisions for the transport of radioactive substances, the qualification of the personnel, as to when the handling of radioactive material requires surveillance, under what circumstances residual material can be cleared and how radiation protection is to be organised in nuclear facilities. In the course of the implementation of European rules on radiation protection, a Radiation Protection Act (Strahlenschutzgesetz – StrlSchG) was enacted in 2017, which contains superordinate regulations on radiation protection. However, essential parts of the Radiation Protection Act will not enter into force before the end of 2018. Until then, the Radiation Protection Ordinance continues to apply.

The Nuclear Licensing Procedure Ordinance regulates, among other things, the nuclear licensing procedure, the performance of an environmental impact assessment and the involvement of the public (public participation) within the framework of nuclear licensing procedures. Regulations on the reporting criteria for ▶ reportable events in nuclear power plants are included in the Nuclear Safety Officer and Reporting Ordinance.

In addition to laws, ordinances and general administrative provisions, there exists a whole range of nuclear regulations and guidelines of a predominantly technical nature. These become regulatory relevant by being referred to in the nuclear licences. Their task is to describe the state of the art in science and technology. These are recommendations of the Waste Management Commission (ESK), the Reactor Safety Commission (RSK) and the Commission on Radiological Protection (SSK), standards of the Nuclear Safety Standards Commission (KTA) and DIN standards. These also include publications by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), such as the Guide to the decommissioning, the safe enclosure and the dismantling of facilities or parts thereof as defined in § 7 of the Atomic Energy Act (Leitfaden zur Stilllegung, zum sicheren Einschluss und zum Abbau von Anlagen oder Anlagenteilen nach §7 des Atomgesetzes) of 23.06.2016, developed by the BMUB together with the competent licensing and supervisory authorities of the Länder. It includes all relevant aspects of the licensing and supervisory procedure and proposals for the approach to decommissioning and dismantling of nuclear facilities. These proposals concern the application of the non-mandatory guidance instruments, the planning and preparation of decommissioning as well as licensing and supervision. On 16 March 2015, the ESK published the recommendation on guidelines for the decommissioning of nuclear facilities (Leitlinien zur Stilllegung kerntechnischer Anlagen) in its updated version. These guidelines contain technical requirements and thus complement the decommissioning guide.

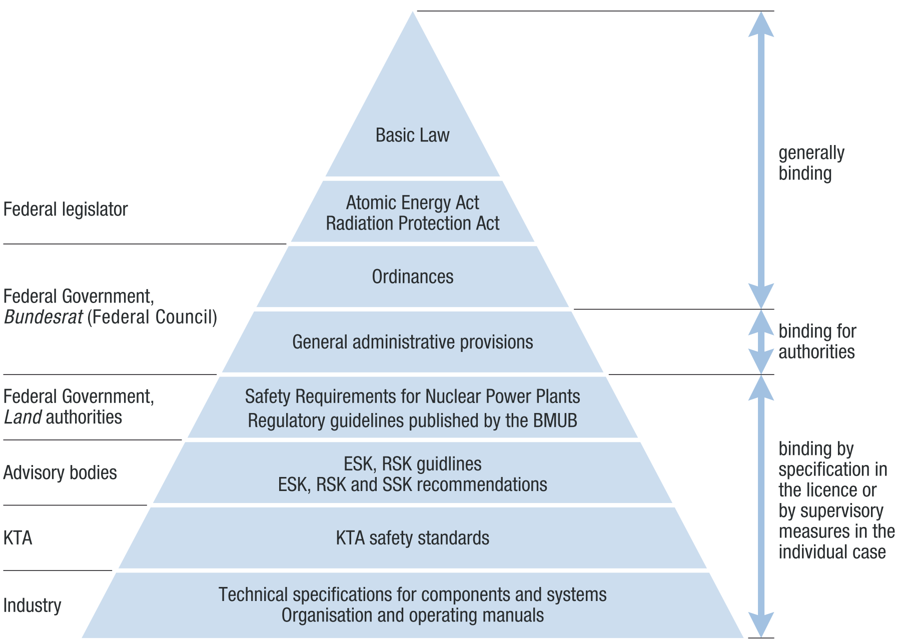



***Fig. 18:*** *Regulatory pyramid*

## 5.2 Licensing procedure

If a nuclear facility whose construction and operation had been licensed according to the Atomic Energy Act is to be decommissioned, then the operator or owner of the facility has to apply for a decommissioning licence. In the case of larger facilities, it may be expedient to divide the licensing procedure into several steps and to make each step the subject of an individual licence. An example of a process diagram for the decommissioning of a power reactor is presented in ▶ Fig. 19.

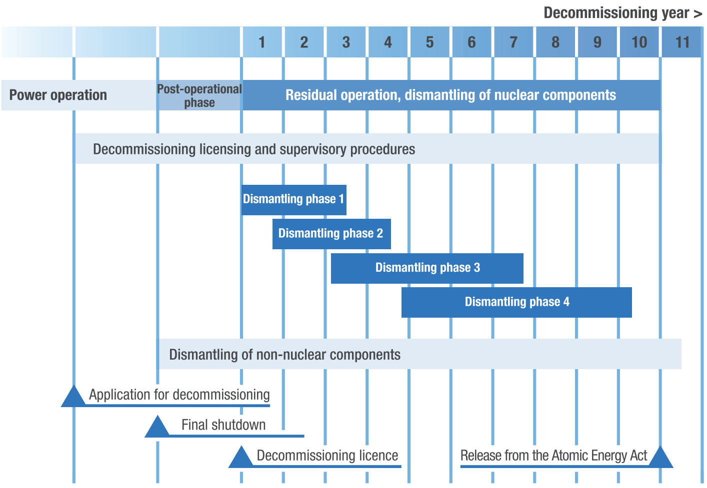



***Fig. 19:*** *Example of a process diagram for decommissioning*

For the licence application, specified documents and information have to be submitted to the competent authority of that Land in which the nuclear facility is located. These have to describe, among other things, the procedure applied for, the planned dismantling measures and associated techniques to be used, the environmental impact and the provisions for radiation protection. Further details are regulated by the Nuclear Licensing Procedure Ordinance and included in the decommissioning guide. (▶ Chapter 5.1 Legal framework).

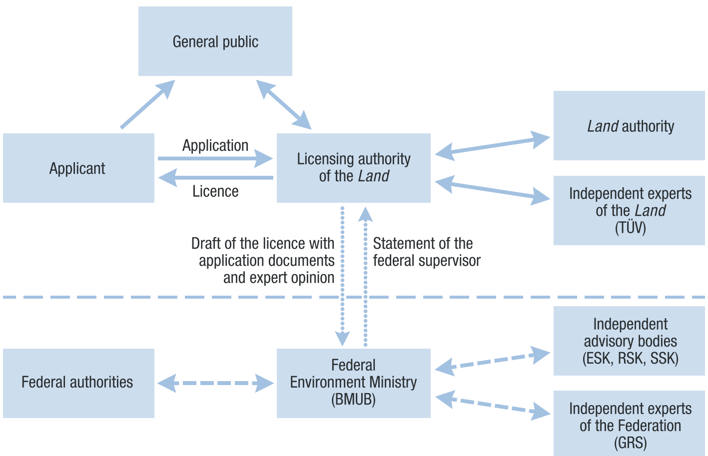



***Fig. 20:*** *Parties involved in the licensing procedure*

The procedure for granting of a decommissioning licence and the interactions between authorities, authorised experts, the general public and other parties involved are presented in ▶ Fig. 20 and briefly explained in the following:

- The Länder are responsible for granting of the licence. Here, they act on federal commission (federal executive administration). They are subject to supervision by the BMUB and, according to circumstances, to its instructions. In this context, the BMUB is advised by the ESK, the RSK and the SSK.
- The responsibility for granting, withdrawal or revocation of a nuclear licence and for nuclear supervision lies with the respective Länder.
- Licence applications are filed, processed and examined at the respective Land authority. The authority makes sure that the public is involved in the licensing procedure and that an environmental impact assessment is carried out where required.
- The work permitted by the decommissioning licence is supervised by the responsible Land authorities within the ▶ supervisory procedure (Chapter 5.3).

## 5.3 Supervisory procedure

Compliance with the work permitted in the decommissioning licence is supervised by the competent Land authority within the supervisory procedure. It is checked whether the conditions for the work specified in the licence and the licensing conditions imposed as well as the legal requirements and requirements according to guidance instruments are complied with. Additional controls are carried out by independent experts commissioned by the Land authority for assistance. Furthermore, the techniques (▶ Chapter 7 Techniques) and methods specified in the licence are finally specified and planned in detail in the course of the supervisory procedure.

The discharge of radioactive substances by a nuclear facility into the environment is monitored by the authorities throughout the entire dismantling phase. For this purpose, measurement stations of the operator are available in the immediate vicinity of the power plant. Furthermore, the discharge of air and water from the facility is monitored by measurements. The corresponding data are transmitted automatically around the clock to the competent supervisory authorities via the remote monitoring system for nuclear reactors (Kernreaktor-Fernüberwachung – KFÜ).

## 6 Safety and radiation protection

Safety during decommissioning and dismantling of nuclear facilities is ensured by a number of technical and administrative measures. The aim is to protect workers, the general public and the environment from undue exposure to radiation. This protection has not only to be ensured for all work activities in connection with decommissioning, but also in case of design basis accidents. Other safety aspects include industrial safety measures for the handling of chemicals, accident prevention, etc., as they are relevant in any industrial plant.

### 6.1 Safety considerations

The potential hazard of a nuclear facility is due to its radioactive inventory and to the fact that a part of this inventory might be released in an accident.

The hazard potential is determined by two factors, namely:

1. the radioactive material present in the facility: the »activity inventory« and the proportion thereof which, in principle, is available for release into the environment and thus for posing a potential hazard to the population: the »activity inventory available for release«, and
2. the probability that such activity is released at all: the probability of occurrence of a design basis accident, for example caused by a fire or leakage.

While the dismantling of the facility progresses, the activity inventory in the facility is reduced until finally, after complete dismantling, no activity inventory is left.

In the following, the development of the hazard potential is described using the example of a nuclear power plant.

During plant operation, the fuel assemblies are located in the reactor pressure vessel and the process of nuclear fission takes place. The activity inventory in the fuel assemblies is 10,000 to 100,000 times higher than the activity inventory elsewhere in the facility. Expressed in the measurement unit for radioactivity, the becquerel, it is about $10^{20}$ to $10^{21}$ Bq.

*Fig. 21: Plant-internal transport of spent fuel*

With the final shutdown of the nuclear reactor, the plant is depressurised at low temperature. Although the process of nuclear fission takes no longer place, cooling of the fuel assemblies has to be continued for some years due to heat generated by the continuing radioactive decay of the fission products.

After removal of the spent fuel from the reactor building and its storage in the on-site storage facility (▶ Fig. 21), the risk potential is significantly reduced. A further significant reduction in the activity inventory can be achieved by removal of the radioactive waste from operation. These measures reduce the radioactive inventory to about one ten thousandth of the original value, so that an activity of about $10^{16}$ to $10^{17}$ Bq remains. For the most part, this activity inventory is fixed as activation in the structure materials of the plant in the core beltline region. At most, it can only be mobilised to a small extent.

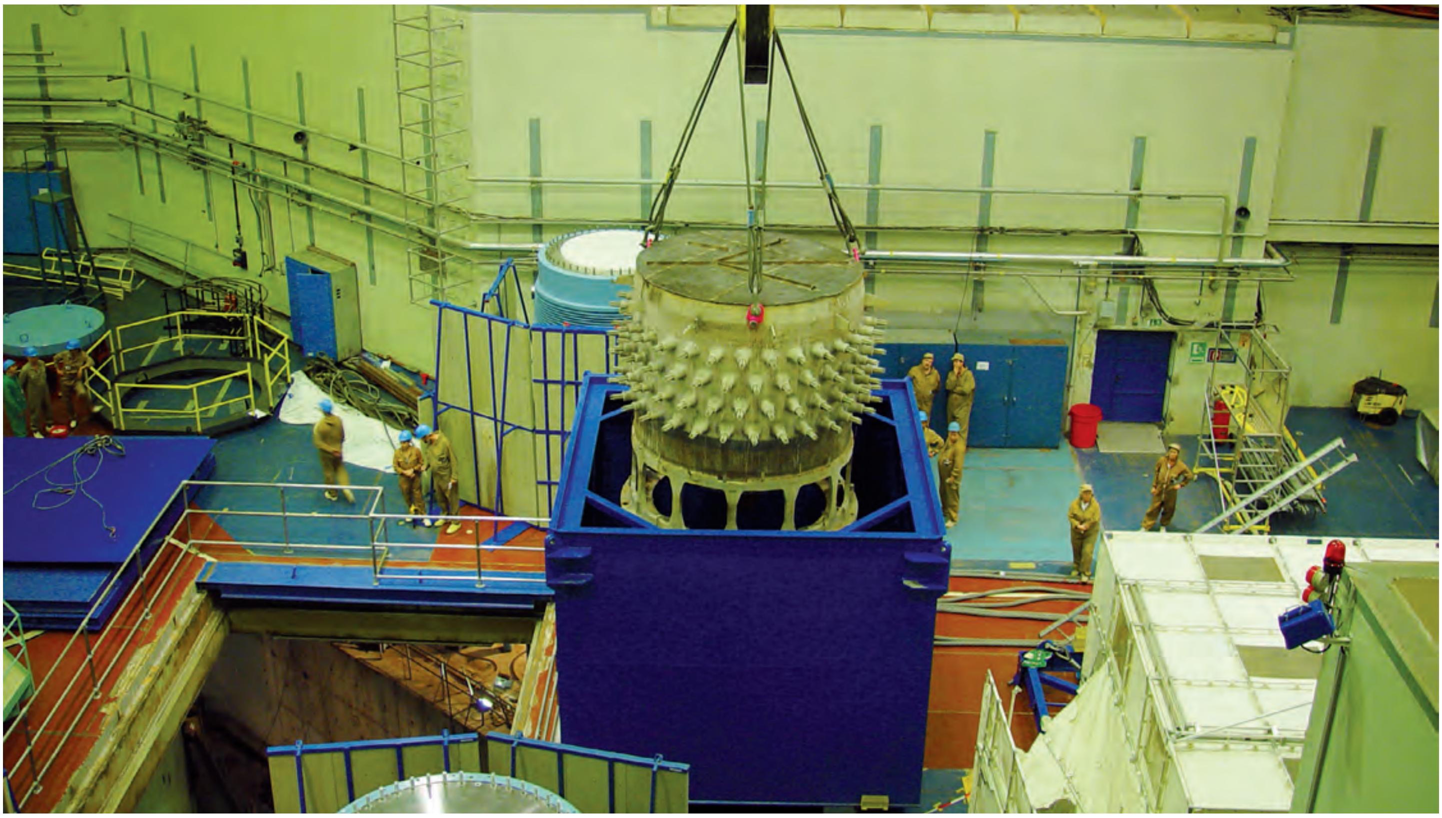
Not only the activation but also the surface contamination on plant components and surfaces of buildings contributes to the radioactive inventory that remains in the facility. The activity of the surface contamination is about $10^{11}$ to $10^{12}$ Bq and is thus again a hundred thousand times lower than the activity due to activation.

In the residual operation and dismantling phase, the plant components are removed (▶ Fig. 22). The radioactive inventory of the plants and plant components can be considerably reduced by decontamination before or after dismantling. A significant portion of the material can be decontaminated to such a degree that it can be officially cleared and returned to the conventional material cycle (▶ Chapter 8.1 Clearance). Safety-relevant installations, such as ventilation and fire protection systems, will continue to be operated or adapted to the changed requirements.

In the course of the dismantling and disassembly work, the releasable portion of radioactivity may rise temporarily and locally. This may happen, for example, if pipes, vessels, etc., previously closed are opened. It must be prevented by radiation protection measures that radioactivity is released during such dismantling measures.

The radioactive inventory that remains in the facility is continuously reduced by progressing decontamination and dismantling until, finally, the facility and the site may be cleared by the authority for another use. In many facilities, radioactive waste is first stored on site in appropriate buildings until an appropriate repository will be available.

***Fig. 22:*** *Removal of a pressuriser*



## 6.2 Radiation protection

Both during operation and during decommissioning and dismantling of a nuclear facility, the protection of workers, the public and the environment from the hazards of ionising radiation is a central task.

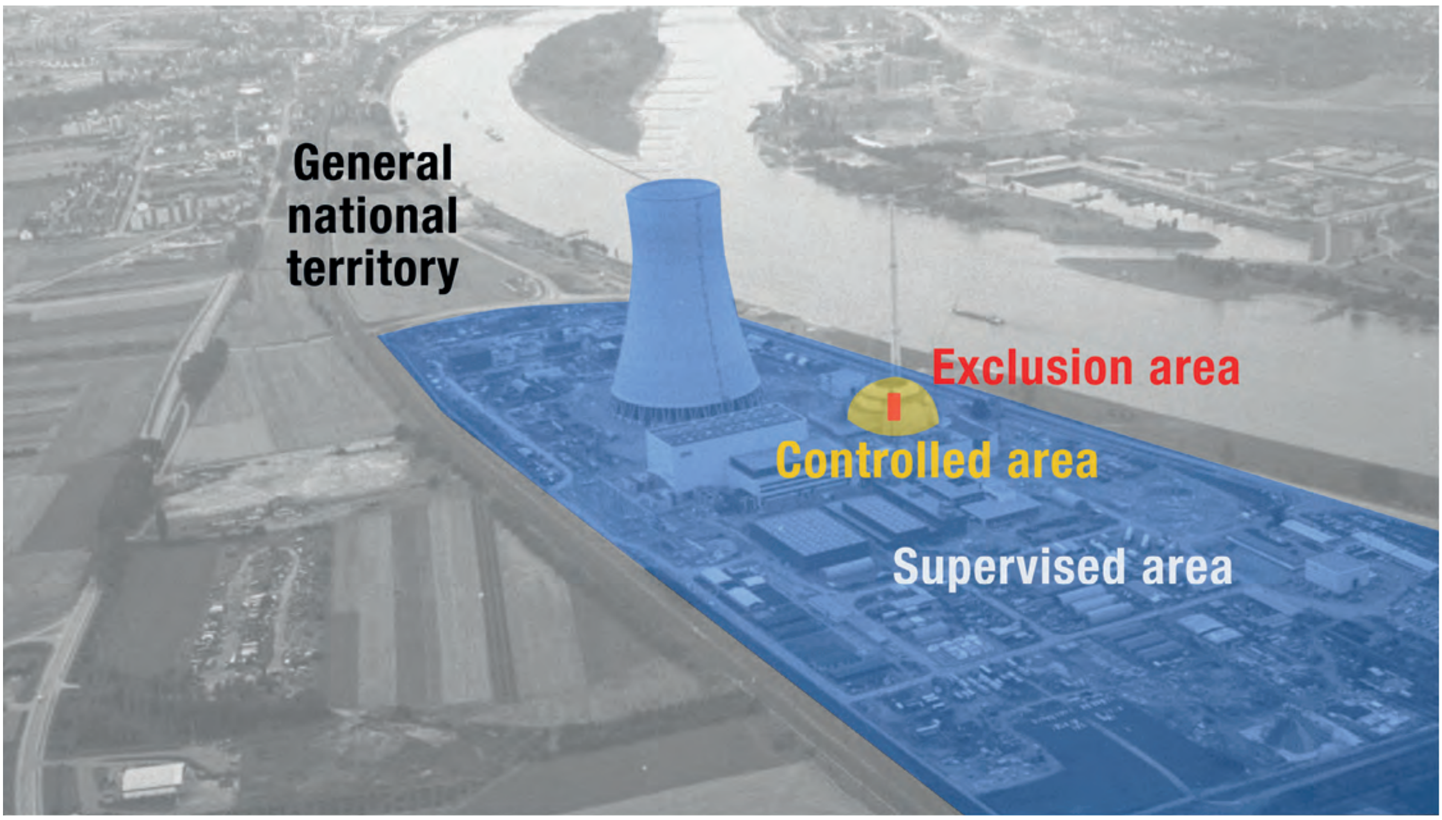
A complex system constantly monitors the radiation situation in all rooms and areas of the facilities. Each person operating in the controlled area of a facility (▶ Fig. 23) carries a personal dosimeter that measures the radiation exposure (dose). Further measures also prevent the intake of radionuclides into the body. Dose limits for workers are laid down in the radiation protection regulations (▶ Chapter 5.1 Legal framework) and are supplemented by dose reference levels in plant regulations. They must not be exceeded. Moreover, avoidance of any unnecessary radiation exposure and dose reduction is mandatory even below the specified limits. In practice, the radiation exposure is generally far below the specified limits as a result of the effective radiation protection measures implemented.

The technically unavoidable discharge of radionuclides with exhaust air and waste water is also monitored carefully. Limits for these discharges are specified in the licences. In practice, these are also far below the specified limits both during the operational and the decommissioning phase.

A variety of technical and administrative radiation protection measures ensures that the radiation protection requirements are met. These include:

- the confinement of the radioactive inventory within systems and rooms in order to prevent any release and dispersion,
- shielding measures to reduce occupational radiation exposure,
- individual protective measures for the personnel, such as the duty to wear special protective clothing, gloves, shoe covers and, if necessary, respirators (▶ Fig. 24),
- training of the external and internal staff,
- a special ventilation system within the facility, and
- filtering of exhaust air and waste water treatment to reduce the amount of radioactive substances that may be discharged into the environment in a controlled manner within the authorised limits.

*Fig. 23: Schematic representation of the radiation protection areas of a nuclear facility*



Since many activities performed during dismantling are similar to those that are necessary for maintenance of the facility, the existing radiation protection knowledge can be used in the dismantling phase. In the case of immediate dismantling of the facility (▶ Chapter 3 Decommissioning strategies), the existing radiation protection organisation can thus be largely adopted, subject to adjustments where appropriate, for example with regard to waste treatment.

*Fig. 24: Full protective clothing during decontamination by high-pressure cleaning*

## 6.3 Reportable events

An event that has or could have an impact on the safety of a nuclear facility must be reported by the operator to the competent supervisory authority. The reporting deadlines vary depending on the type of event and are governed by the Nuclear Safety Officer and Reporting Ordinance (AtSMV, ▶ Chapter 5.1 Legal framework).

The operator's obligation to report such events does not end with the shut-down of the facility, although the hazard potential (▶ Chapter 6.1 Safety considerations) will then be significantly lower. It shall be applicable until activity levels fall below specified limits and, at the request of the operator, exemption from the obligation to report has been approved, or until the facility is completely dismantled and released from the scope of application of nuclear law. Such a reportable event would be e.g. malfunctioning of a fire alarm system detected during a functional test.

# 7 Techniques

For the performance of decommissioning, it is important to have mature and reliable techniques to dismantle and decontaminate components and buildings and to disassemble them into manageable pieces. These techniques must meet the requirements relating to safety, radiation protection and a speedy execution of the project. This is why research centres, universities and also private industry institutions got engaged in the further development of a range of conventional techniques for the decommissioning of nuclear facilities and in the adaptation of these techniques to the specific demands of radiation protection and nuclear safety. Some techniques had to be advanced such that they can also be used by remote control.

Nuclear decommissioning requires a variety of methods of decontamination, dismantling and disassembly as well as of activity measurements and waste conditioning.

The techniques used are chosen by the operator of the facility. One basis for this choice is, among other things, the knowledge about quantity and type of radioactivity of the different components or in the different rooms. For this reason, the contamination level of all systems and rooms is determined and listed in a so-called contamination atlas prior to the start of dismantling work.

For the choice of the individual techniques, the criteria taken into account include:

- radiation protection aspects, in particular reducing the dose of staff,
- adequacy and effectiveness of the technique,
- clearance of residues and components to the largest possible extent,
- reduction of the volume of radioactive waste, and
- spatial boundary conditions.

Selection and application of the techniques are subject to the approval and control by the authority and independent experts (▶ Chapter 5 Licensing and supervisory procedure).

## 7.1 Decontamination techniques

Decontamination techniques are used to remove adherent radionuclides (contamination). This improves radiation protection and is an important prerequisite for the utilisation of residues. Decontamination plays an important role two times during the decommissioning process, namely

1. prior to the start of dismantling work,
2. for cleaning of such dismantled parts intended for clearance.

To reduce radiation exposure of personnel, systems and rooms will be decontaminated prior to the start of dismantling work. This is often done not only by removing the superficially deposited radionuclides, but also a thin layer of the material itself. This way, any radioactive material that has penetrated into cracks or deposited in inaccessible areas is also removed. So, for example, the closed reactor cooling circuit can be decontaminated from the inside before the start of dismantling by pumping various chemicals through the pipe systems and valves. This process is referred to as full system decontamination.

Dismantled parts of a facility are often decontaminated again for their final clearance, i.e. their release from the scope of applicability of the Atomic Energy Act (▶ Chapter 8 Residue and waste management).

The cause of the contamination may be due to direct contact with an activity-containing medium (e.g. primary coolant). Another reason for surface contamination may also be the airborne dispersion of radionuclides within the facility building. In case of superficial contamination, it may be sufficient to brush the material surfaces or to wash them under high pressure. If the contamination has penetrated to a larger depth, part of the surface has to be removed (several micrometres to several millimetres). If all the process parameters have been chosen correctly, the new surface obtained this way is no longer contaminated.

***Fig. 25:*** *Chemical decontamination*

A distinction is generally drawn between mechanical and chemical decontamination methods. Chemical methods work e.g. in a wide range of weak and strong organic and inorganic acids (▶ Fig. 25). Furthermore, highly specialised multi-phase processes are used as well as so-called complexing agents, foams or gels. Relatively simple mechanical methods include brushing and vacuuming. More powerful is high-pressure cleaning with water or steam (▶ Fig. 26). Methods involving surface removal are e.g. grating, scraping, needle-scaling scarification or conventional scarification. These also include various jet-blasting methods with hard abrasive media (abrasives), such as sand or steel balls. Which methods are used depends on the type and penetration depth of the contamination as well as on the contaminated workpiece.

## 7.2 Dismantling and disassembly techniques

Dismantling and disassembly techniques are needed for a wide range of tasks and applications in connection with the dismantling of nuclear facilities. Components must be removed from the plant and disassembled into manageable pieces (subsequent disassembly). This is an important prerequisite for the entire waste and residue management. The spectrum of tasks ranges from the simple detaching of a thin pipe that has never been in contact with radioactive substances, and the dismantling and disassembly of large vessels and thick-walled pipes for radioactive liquids, up to the dismantling of the reactor pressure vessel and its internals.

Another important task is the subsequent disassembly of large components that have already been dismantled, e.g. for the purpose of decontamination or clearance measurement. Apart from various types of metal, concrete components also have to be disassembled, which – as e.g. in the case of the biological shield or some building structures – may contain a large amount of reinforcing steel.

If work has to be carried out in a high radiation field or on highly activated parts, as e.g. in the activated core beltline region, this cannot be done manually on the spot but remotely – often under water (▶ Fig. 27). The water forms an effective shield against the radiation emitted by the materials to be disassembled.

The criteria governing the decision which of the techniques available are best suited are, above all, their safety but also, for example, cutting speed, maximum separable material thickness, or the release of dusts (aerosols).

So this means that disassembly techniques are needed that can be applied in a range of different areas and under different conditions, if necessary even under water. This spectrum of tasks cannot be managed with one single technique. In the following, thermal and mechanical disassembly techniques are described.

***Fig. 26:*** *Decontamination by high-pressure water jet cleaning*

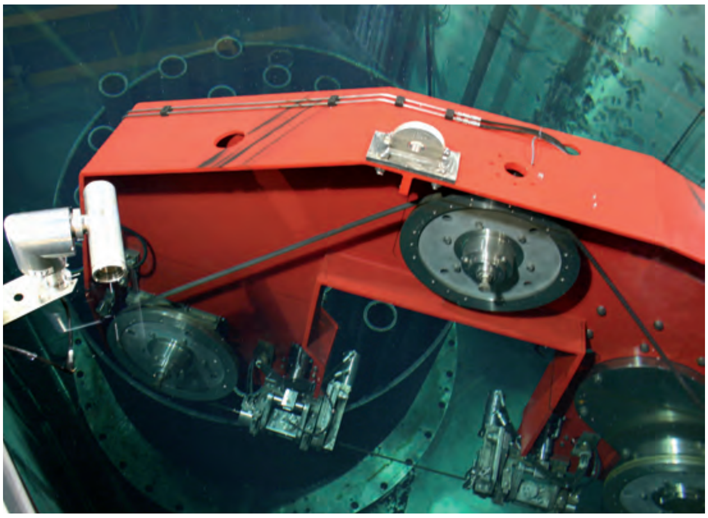


***Fig. 27:*** *Underwater cutting of components with a band saw*

Thermal disassembly techniques melt the material by means of a flame, an electric arc or a laser beam and then blow the molten material from the kerf with a water or gas jet stream or simply by gravitational force. Such techniques are far more frequently used for metals than for concrete or conventional building materials (▶ Fig. 28). Some techniques are suitable for both material types. Thermal cutting in air and under water leads to particulate emissions, so-called aerosols and hydrosols which, however, can be controlled with the help of conventional ventilation and filter systems.

Major thermal techniques are:

- oxyacetylene flame cutting,
- plasma arc cutting,
- electric arc cutting,
- electro discharge machining, and
- laser cutting.

These techniques are generally characterised by high cutting speeds and low restoring forces, making them suitable for remote operation by means of manipulators. An example of remote-controlled thermal cutting is shown in ▶ Fig. 29 a and b.

Mechanical disassembly techniques generate the kerf by removing material mechanically. The material is neither melted nor burnt and no cutting gases are used, either. The chippings and dusts generated during cutting are relatively coarse and can easily be trapped by filters. Mechanical cutting techniques are used for metals and building structures.

Major mechanical techniques are:

- conventional sawing,
- wire sawing,
- milling,
- angle grinding,
- shearing,
- water-abrasive cutting, and
- blasting.

***Fig. 28:*** *Manual use of thermal disassembly techniques*

***Fig. 29a:*** *Control station for remote-controlled work*

***Fig. 29b:*** *Chamber for dry cutting*

## 7.3 Alternatives to on-site disassembly

Large components, such as steam generators and reactor pressure vessels, are not always disassembled on site, but may be transported in one piece for further processing or for decay storage (▶ Chapter 8.2 Decay storage). So, for example, the steam generators of the Stade nuclear power plant (KKS) were shipped to Sweden for further processing after a first decontamination (▶ Fig. 30). There, they were dismantled, further decontaminated and melted down piece by piece. After that, most of the radioactive substances are then contained in the slag, so that the steel can be reused to a large extent. The residual radioactive waste, which only accounts for a small proportion of the total mass, is returned to Germany.

## 8 Residue and waste management

One of the most important tasks relating to the dismantling of nuclear facilities is to cope with the amount of residues and waste arising. Here, the term »residue and waste management« stands for the entirety of all measures that are aimed at the safe, effective and resource-saving handling of the material from nuclear facilities. There are several possibilities to achieve this (▶ Fig. 31):

- If the activity is demonstrably below a certain level, ▶ clearance may be granted. This requires a decision by the authority.
- Prior to clearance or further treatment, ▶ decay storage may take place for activity reduction.
- If the material is to be disposed of as radioactive waste, it has to be conditioned, stored and finally disposed of in a repository.
- A small proportion of the material may be passed on to other nuclear facilities for further use.

*Fig. 30: Transport of a steam generator to Sweden for meltdown*

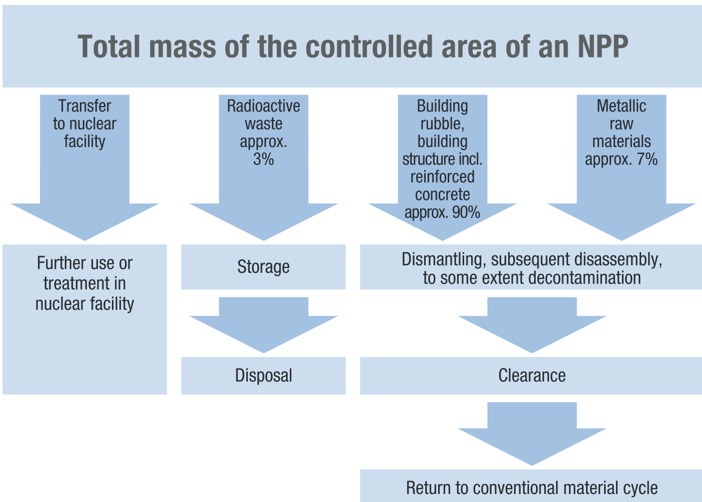



*Fig. 31: Radioactive waste and residues*

The total masses generated at the sites of nuclear power plants in Germany differ according to the type of power plant (pressurised or boiling water reactor). However, the masses of the controlled area, i.e. the area in which radioactive substances can be handled during power plant operation, amount to 200,000 Mg for most or the power plants.

The 200,000 Mg of the controlled area of a nuclear power plant can be cleared to a large extent (about 97%) (▶ Chapter 8.1 Clearance). In case of optimised dismantling, only about 3% of the mass of the controlled area is radioactive waste and must be emplaced in a disposal facility (▶ Fig. 32).

## 8.1 Clearance

Only a small proportion of all the material in a nuclear facility has ever come into contact with radioactive substances. Of these, the largest part can, in turn, be freed from adhering radionuclides by decontamination measures.

Material whose activity is demonstrably below a certain level and below the clearance levels specified in the Radiation Protection Ordinance may be cleared on the basis of a decision by the authority and will thus be released from supervision under radiation protection law. The material that remains, however, is considered as radioactive waste and must be placed in storage and eventually be disposed of. As the decision is to be made for each individual piece, the material is usually sorted, as shown in ▶ Fig. 33.

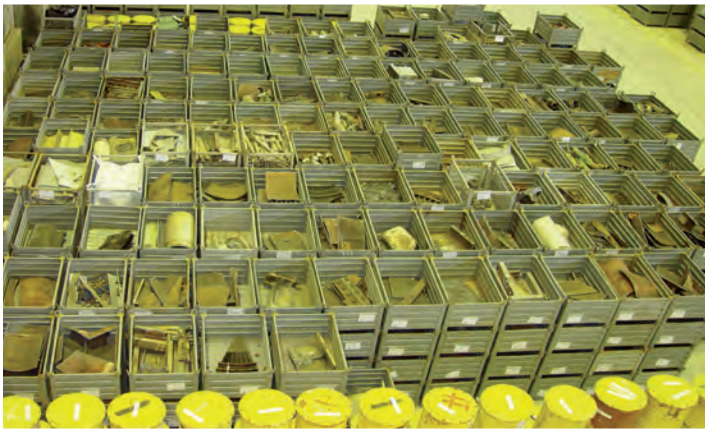


*Fig. 33: Boxes with sorted residues for clearance*

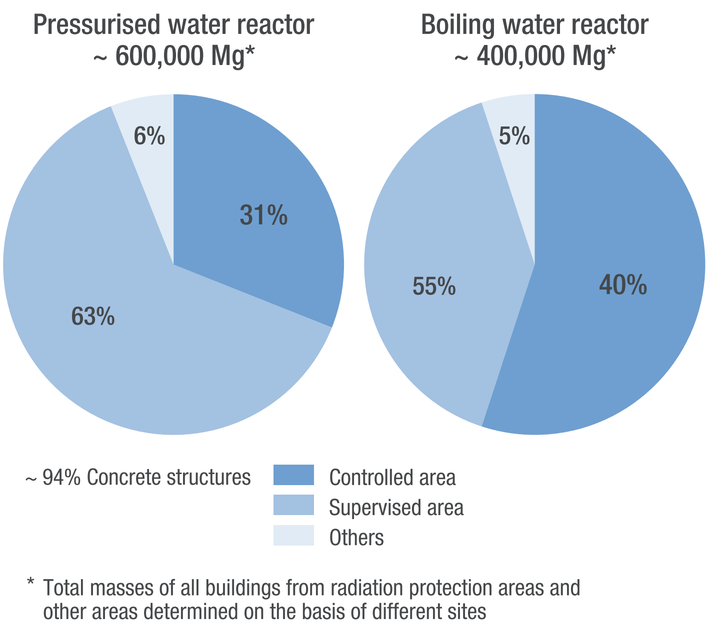



*Fig. 32: Total masses from the dismantling of nuclear power plants (according to the ESK)*

## Clearance options

There are several clearance options that are defined by the Radiation Protection Ordinance:

- After »unrestricted clearance«, the material is no longer radioactive in terms of the Atomic Energy Act and may be reused for any purpose. Therefore, the clearance levels (▶ Table 2) for unrestricted clearance are significantly lower compared to other options to ensure safety for all conceivable uses of the material.
- In the case of »clearance for removal«, the material must be delivered to a suitable conventional landfill or an incinerator facility and disposed of there in a specific way.
- Other options exist, e.g. for scrap metal intended for melting down in a conventional steelworks or a foundry, for large amounts of building rubble, for the buildings of the facility and for the site.

Examples of the clearance levels specified for the different options are listed in ▶ Table 2. The clearance levels have all been derived such that the clearance criteria described in the following are reliably met.

## Clearance criteria

According to international expert opinion (e.g. of the International Commission on Radiological Protection – ICRP), release from supervision under radiation protection law can be justified if, as a result, the additional dose occurring for a member of the public will not exceed a value in the range of 10 µSv per calendar year. This requirement is stipulated in the Radiation Protection Ordinance and is consistent with the basic radiation protection standards of the EU (EURATOM). Such a dose is 200 times lower than the dose from natural background radiation exposure of the population over the same period (e.g. by cosmic radiation and naturally occurring radioactivity). Based on this consideration, the clearance levels have been developed such that the allowable dose cannot be exceeded, even under worst case assumptions.

| Nuclide | **Unrestricted** | **For removal** | **As scrap metal for meltdown** |
|---|---|---|---|
| Fe-55 | 200 Bq/g | 10,000 Bq/g | 10,000 Bq/g |
| Cs-137 | 0.5 Bq/g | 10 Bq/g | 0.6 Bq/g |
| Pu-241 | 2 Bq/g | 100 Bq/g | 10 Bq/g |
| Am-241 | 0.05 Bq/g | 1 Bq/g | 0.3 Bq/g |

***Table 2:*** *Clearance levels for selected radionuclides according to the Radiation Protection Ordinance*

*Fig. 34: Measurement for clearance*


*Fig. 36: Room with markings to determine surface contamination*

## Procedure for clearance

The clearance procedure is regulated by the authorities during which a number of quality assurance measures are provided for. The competent nuclear authority verifies whether the steps of the procedure and the measuring methods applied (e.g. ▶ Fig. 34) are appropriate for the clearance procedure. This way, the authority ensures, if necessary with the assistance of independent experts, that the material to be cleared meets the applicable clearance criteria.

▶ Fig. 35 gives an overview of the overall process of the clearance procedure, whose individual steps are shown using the example of a dismantled component of the facility.

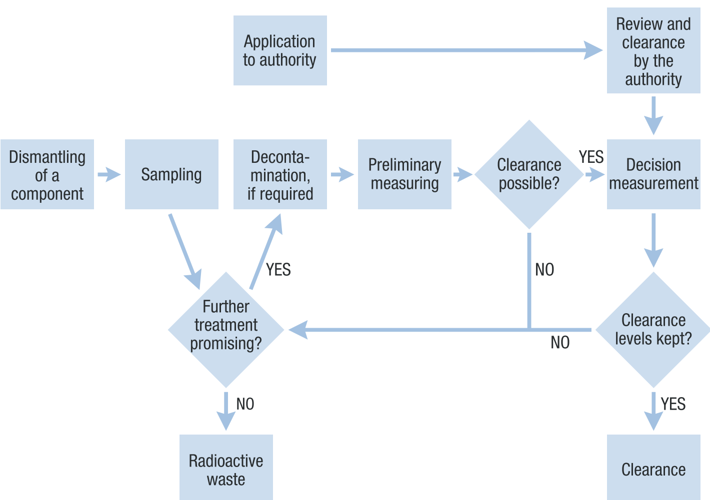



*Fig. 35: Decision tree for the clearance of components*

## Clearance of buildings and soil areas

For the continued use or demolition of buildings of a nuclear facility after dismantling, these must be subjected to clearance. The surfaces are checked for contamination (▶ Fig. 36). The methods applied to demonstrate compliance with clearance levels require approval by the competent authority.

If the activity of a surface exceeds the applicable clearance levels, one or more decontamination steps will follow. The clearance levels for buildings and soil areas are also stipulated in the Radiation Protection Ordinance.

The soil areas at the site of a nuclear facility will also be checked for contamination during dismantling of the facility and cleared by the competent authority (e.g. ▶ Fig. 37).

## 8.2 Decay storage

For radioactive material whose activity is still above the clearance levels even after decontamination measures, mostly due to activation, decay storage (▶ Fig. 38) can be considered. With this approach, the material is stored until the activity level falls below the clearance levels.

Here, the fact is used that after a specific time span (half-life), half of the atomic nuclei of a radionuclide have decayed and thus activity is halved, too. After another half-life, activity is halved again and so on.

The half-life is specific for each radionuclide and may vary for different radionuclides by many orders of magnitude. So, the half-life of e.g. cobalt-60 (Co-60) is 5.3 years, for caesium-137 (Cs-137) 30 years and for plutonium-239 (Pu-239) about 24,000 years. Radionuclides with much shorter half-lives (several days down to milliseconds) are insignificant in the context of decay storage.

***Fig. 37:*** *Measurement for clearance of soil areas*


***Fig. 38:*** *Decay storage of castings*

For structures activated by neutrons (e.g. ▶ Fig. 39), the radionuclides are distributed over the volume and cannot be removed by decontamination. In this case, decay storage is used prior to processing to significantly reduce the radiation exposure of personnel. In particular, large components like steam generators and reactor pressure vessels are sometimes stored over several years or decades prior to further disassembly and processing. Many such large components are currently stored in the storage facility Zwischenlager Nord (ZLN) near Greifswald (▶ Fig. 40).

***Fig. 39:*** *Dose rate measurement*

***Fig. 40:*** *Decay storage of large components in the storage facility Zwischenlager Nord (ZLN)*

***Fig. 41:*** *Conditioning of waste (in-drum drying facility)*

## 8.3 Radioactive waste

All material that is generated during dismantling of a nuclear facility and cannot be cleared or delivered to other nuclear facilities is radioactive waste. With respect to the total mass of the controlled area of a nuclear facility, which is about 200,000 Mg for a power reactor, the amount of radioactive waste from decommissioning is in the range of a few percent. The dominant nuclides in nuclear reactors are relatively short-lived beta/gamma emitters, such as cobalt-60 and caesium-137. In the case of nuclear fuel cycle facilities, there are also long-lived radionuclides, which are particularly radiotoxic due to their alpha activity.

The largest amount of radioactive waste originates from the decommissioning of nuclear power plants and facilities of the nuclear fuel cycle. Much lower amounts originate from the decommissioning of research reactors and other nuclear research facilities.

Radioactive waste must be isolated from the biosphere for long periods of time. This can be achieved by disposal of the radioactive waste in a repository. Until a repository will be available in Germany, conditioning (e.g. in a drum, ▶ Fig. 41) or storage are required. Therefore, local storage facilities (▶ Fig. 42) are established during decommissioning of power reactors to accommodate all the radioactive waste from the dismantling of the facilities. Until 2005, the spent fuel from power reactors could be delivered to reprocessing plants. Since then, they have to be stored in a local storage facility. Thus, the final clearance of the site not only depends on the complete dismantling of the facility, but also on when the waste can be transferred from the storage facility to a repository.

***Fig. 42:*** *Emplacement of a transport cask with spent fuel in the Brunsbüttel storage facility*

# 9 Costs

According to § 9a(1) of the Atomic Energy Act, the operators of facilities in which nuclear fuel is handled have to ensure (among other parties responsible for waste management) that any residual radioactive material is utilised without detrimental effects or disposed of as radioactive waste (direct disposal). This obligation can be transferred to a third party commissioned with storage management by the Federation, as defined in § 2(1), first sentence of the Waste Management Transfer Act (Entsorgungsübergangsgesetz). This is based on the principle that the costs of decommissioning and waste management must ultimately be paid by the waste producers:

- for the commercially operated nuclear power plants, these are their operators, i.e. the private power utility companies behind them (see also ▶ Chapter 9.1),
- the operating companies for the respective nuclear fuel cycle facilities, and
- the public authorities for nuclear facilities in the research sector (research reactors, facilities in the research centres, at universities, etc.), for prototype reactors and for the nuclear power plants of the former GDR in Greifswald and Rheinsberg being under decommissioning.

## 9.1 Costs of commercially operated nuclear power plants

The German Bundestag passed the Act on the Reorganisation of Responsibility in Nuclear Waste Management (Gesetz zur Neuordnung der Verantwortung in der kerntechnischen Entsorgung), which entered into force on 16 June 2017. Based on the recommendations of the Commission to Review the Financing for the Phase-out of Nuclear Energy (KFK), which has been set up for this purpose, it regulates, among other things, the transfer of responsibility for the storage and disposal of radioactive waste from the use of nuclear energy to the state. The electric power utilities have paid approx. 24.1 billion euros into a public fund. The electric power utilities continue to be directly responsible for decommissioning, dismantling and appropriate conditioning of the radioactive waste.

## 9.2 Costs borne by the public

In the last decades, the Federal Ministry of Education and Research (or the ministry previously competent for research, respectively) initiated the establishment of research and prototype facilities. Decommissioning and dismantling of the nuclear facilities set up within this framework are financed to the largest part from public funds of the Federation and the Länder.

The total costs to be financed by public funding will amount to approximately 10 to 15 billion euros.

# 10 International provisions

In addition to the national laws and regulations, EU-wide regulations and recommendations have to be considered as well as the recommendations and publications by international bodies, such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP). Furthermore, the obligations under the »Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management« have to be fulfilled.

## 10.1 Convention on spent fuel and nuclear waste management

By 2016, more than 70 states have acceded to the »Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste«, which was adopted in 1997. The Convention also covers the decommissioning, safe enclosure and dismantling of nuclear facilities. Review meetings of the Contracting Parties to examine the extent to which the objectives of the Joint Convention have been fulfilled are usually held every three years.

## 10.2 IAEA

The International Atomic Energy Agency (IAEA) publishes standards within the framework of the »IAEA Safety Standards Series« relating to safety during the decommissioning of nuclear facilities. This involves comprehensive developmental and consultation processes carried out by the IAEA member states with the participation of the competent nuclear supervisory authorities.

As part of its activities to exchange experiences on decommissioning, the IAEA also publishes a number of documents that reflect the extensive experience in the decommissioning of nuclear facilities. These documents are therefore part of the international state of the art in science and technology.

## 10.3 OECD/NEA

The Nuclear Energy Agency (NEA) is an institution within the international Organisation for Economic Co-operation and Development (OECD), based in Paris. The aim of the NEA is to promote a peaceful, safe, environmentally friendly and economical use of nuclear energy. Germany is one of the 31 member countries (as at 2016) from Europe, North America and the Asia-Pacific region. Together, the member countries account for approximately 85% of the global nuclear energy production. Within the NEA, numerous coordination, information, review and research activities are carried out, among others on decommissioning.

## 10.4 EU

In compliance with the EURATOM Treaty, comprehensive data are to be submitted at the EU level in the context of the decommissioning of nuclear reactors and reprocessing plants on the facility and its surrounding area, on planned and unplanned discharges of radioactive substances, the removal of radioactive waste from the facility as well as on emergency plans and environmental monitoring. These data are to be communicated via the competent federal ministry if possible one year, but at least six months before granting an authorisation for the discharge of radioactive substances.

## 10.5 WENRA

The Western European Nuclear Regulators' Association (WENRA) is an independent organisation that is composed of representatives of nuclear regulatory authorities of the countries of Europe. The main objectives are to develop a common approach to nuclear safety and regulatory practice, particularly within the EU, to enhance nuclear safety in national responsibility as well as to develop a network of chief nuclear safety regulators in Europe to promote experience exchange and to strengthen cooperation.

For further development of nuclear safety, the Working Group on Waste and Decommissioning (WGWD) of WENRA has developed specific requirement catalogues for decommissioning and waste management with the so-called safety reference levels. The WENRA members committed themselves to implement the respective safety reference levels in the national rules and regulations to the extent they are not already included.

## 11 Summary and outlook

The experience gained in Germany and abroad with the complete dismantling of nuclear facilities of various types and sizes down to the »green field« shows that with the currently available technologies such projects can be carried out safely and within a time frame of about ten to twenty years. This finding is of considerable importance for the future decommissioning tasks in Germany: the decommissioning of nuclear power plants and other nuclear facilities still in operation can also be carried out safely. What will remain in the end is the radioactive waste from dismantling. This waste must be disposed of safely.

Future tasks in Germany from the point of view of decommissioning are the completion of the current decommissioning projects and the decommissioning of the nuclear facilities still in operation once they have reached the end of their operating lives. With the amendment of the Atomic Energy Act of July 2011, the remaining facilities will be finally shut down in a stepwise process until 2022, so that further nuclear power plant units will be decommissioned in the next few years. A list of facilities that are currently under decommissioning is included in the ▶ Annex (Chapter 12.1).

## 12 Annex

### 12.1 List on decommissioning of nuclear facilities in Germany

In August 2017, 21 power and prototype reactors have been in different stages of decommissioning in Germany. In addition, the Niederaichbach nuclear power plant (KKN), the Großwelzheim superheated steam reactor (HDR) and the Kahl experimental nuclear power plant (VAK) have already been completely dismantled. At the plants in Würgassen (KWW), Gundremmingen-A (KRB-A) and the multi-purpose research reactor (MZFR) near Karlsruhe, nuclear decommissioning has largely or entirely been completed.

In 2011, eight power reactors were finally shut down, followed by the Grafenrheinfeld nuclear power plant (KKG) in 2015. For these nine shut down nuclear power plants, applications for decommissioning and dismantling were filed. Of these plants, the Isar-1 nuclear power plant (KKI 1) was granted a licence for decommissioning and dismantling on 17 January 2017, the Neckarwestheim I nuclear power plant (GKN I) on 3 February 2017, the nuclear power plants Biblis-A (KWB A) and Biblis-B (KWB B) on 30 March 2017 and the Philippsburg-1 nuclear power plant (KKP 1) on 7 April 2017. It is planned to finally shut down the remaining eight power reactors by the end of 2022.

29 research reactors and nine nuclear fuel cycle facilities have already been dismantled, some of which were released from the scope of application of the Atomic Energy Act.

| Nuclear power plants (power and prototype reactors) | *Abbr.* | *as at April 2017* |
|---|---|---|
| Jülich experimental reactor | AVR | Decommissioning since 1994 |
| Biblis-A nuclear power plant | KWB A | Decommissioning since 2017 |
| Biblis-B nuclear power plant | KWB B | Decommissioning since 2017 |
| Brokdorf nuclear power plant | KBR | Shutdown scheduled for 2021 |
| Brunsbüttel nuclear power plant | KKB | Decommissioning applied for in 2012 |
| Emsland nuclear power plant | KKE | Shutdown scheduled for 2022, decommissioning applied for in 2016 |
| Grafenrheinfeld nuclear power plant | KKG | Decommissioning applied for in 2014 |
| Greifswald nuclear power plant, 1-5 | KGR 1-5 | Decommissioning since 1995 |
| Grohnde nuclear power plant | KWG | Shutdown scheduled for 2021 |
| Gundremmingen-A nuclear power plant | KRB-A | Decommissioning since 1983 |
| Gundremmingen-B nuclear power plant | KRB-II B | Shutdown scheduled for 2017, decommissioning applied for in 2014 |
| Gundremmingen-C nuclear power plant | KRB-II C | Shutdown scheduled for 2021 |
| Isar-1 nuclear power plant | KKI 1 | Decommissioning since 2017 |
| Isar-2 nuclear power plant | KKI 2 | Shutdown scheduled for 2022 |
| Krümmel nuclear power plant | KKK | Decommissioning applied for in 2015 |
| Lingen nuclear power plant | KWL | Safe enclosure since 1988, dismantling since 2015 |
| Mülheim-Kärlich nuclear power plant | KMK | Decommissioning since 2004 |
| Neckarwestheim-I nuclear power plant | GKN I | Decommissioning since 2017 |
| Neckarwestheim-II nuclear power plant | GKN II | Shutdown scheduled for 2022, decommissioning applied for in 2016 |
| Obrigheim nuclear power plant | KWO | Decommissioning since 2008 |
| Philippsburg-1 nuclear power plant | KKP 1 | Decommissioning since 2017 |
| Philippsburg-2 nuclear power plant | KKP 2 | Shutdown scheduled for 2019, decommissioning applied for in 2016 |
| Rheinsberg nuclear power plant | KKR | Decommissioning since 1995 |
| Stade nuclear power plant | KKS | Decommissioning since 2005 |
| Unterweser nuclear power plant | KKU | Decommissioning applied for in 2012 |
| Würgassen nuclear power plant | KWW | Decommissioning since 1997 |
| Compact sodium-cooled nuclear reactor | KNK II | Decommissioning since 1993 |
| Multi-purpose research reactor | MZFR | Decommissioning since 1987 |
| Thorium high temperature nuclear reactor | THTR-300 | Safe enclosure since 1997 |

| Research reactors | *Abbr.* | *as at March 2017* |
|---|---|---|
| Berlin experimental reactor II | BER-II | Shutdown scheduled for 2019 |
| Research reactor 2 Karlsruhe | FR-2 | Safe enclosure since 1996 |
| Geesthacht-1 research reactor | FRG-1 | Decommissioning applied for in 2013 |
| Geesthacht-2 research reactor | FRG-2 | Decommissioning applied for in 2013[1] |
| Jülich 2 research reactor | FRJ-2 | Decommissioning since 2012 |
| München research reactor | FRM | Decommissioning since 2014 |
| Neuherberg research reactor | FRN | Safe enclosure since 1984 |
| Rossendorf research reactor | RFR | Decommissioning since 1998 |
| Siemens training reactor Aachen | SUR-AA | Decommissioning applied for in 2010 |
| Siemens training reactor Hannover | SUR-H | Decommissioning applied for in 2013 |
| Braunschweig research and measuring reactor | FMRB | Decommissioning since 2001, except for the storage facility, released from the scope of application of the AtG |

| Nuclear fuel cycle facilities | *Abbr.* | *as at February 2017* |
|---|---|---|
| Siemens Power Generation Karlstein | SPGK | Decommissioning since 1993 |
| Karlsruhe reprocessing plant with vitrification facility (VEK) | WAK | Decommissioning since 1993 |

*[1]FRG-2 was shut down and partially dismantled. Since it is a part of a common facility with FRG-1, formally, only common decommissioning will be possible.*

## 12.2 Brief descriptions of selected decommissioning projects

### Kahl experimental nuclear power plant

The Kahl experimental nuclear power plant (VAK) was the first nuclear power plant in Germany. Although it was a pilot plant, it had already been ordered, built and operated commercially. It had a boiling water reactor with a capacity of only 16 MWe (megawatt electrical; for comparison: the Biblis nuclear power plant commissioned in 1974 had already more than 1,200 MWe). After 25 years of operation, it was finally shut down in 1985 after it had fulfilled its scientific and economic tasks. Decommissioning began in 1988 and was completed in 2010. For this plant, immediate dismantling without prior safe enclosure was realised (▶ Chapter 3 Decommissioning strategies).

### Greifswald nuclear power plant

Originally, the nuclear power plant site at Greifswald (KGR) on the Baltic Sea was intended to accommodate eight nuclear power plant units with Soviet-designed pressurised water reactors, each having a capacity of 440 MWe. In 1989, units 1 to 4 were in operation (commissioning between 1974 and 1979) and Unit 5 was in the commissioning phase, while units 6 to 8 were still under construction. The individual units of the nuclear power plant were finally shut down at the end of 1989 and in the course of 1990. To operate the nuclear reactors in compliance with federal German nuclear law, comprehensive backfitting measures would have been necessary.

The first decommissioning licence was granted in 1995. The decommissioning concept provides that the overall plant will be dismantled and released from the scope of the Atomic Energy Act. The extent of dismantling work (i.a. ▶ Fig. 41) and the resulting amount of waste and residual material make the decommissioning of the Greifswald nuclear power plant the largest project of its kind world-wide. The steam generators and reactor pressure vessels are stored in the so-called storage facility Zwischenlager Nord (ZLN) for decay (Fig. 40).

*Fig. 43: Turbine building of the Greifswald nuclear power plant after removal of the generators*

## Niederaichbach nuclear power plant

The Niederaichbach nuclear power plant (KKN) was operated from 1972 to 1974. For economic and technical reasons, it was finally shut down in 1974. A remarkable feature of the dismantling of the KKN was the use of a manipulator for the dismantling of the reactor pressure vessel and its internals. This complex and tailor-made system for KKN was able to carry various tools, had a high degree of automation and was very flexible in its application. Experience has taught, however, that often simpler and robust manipulator systems are to be preferred.

## Obrigheim nuclear power plant

The Obrigheim nuclear power plant (KWO) was the first to be shut down in the framework of the so-called »Atomkonsens«, i.e. nuclear consensus, of 2000. It was finally shut down in 2005 after more than 36 years of power operation. A full system decontamination in the year 2007 reduced the radiation level by a factor of 600 on average, so that the employees involved in dismantling are less exposed. After granting of the first decommissioning and dismantling licence, dismantling started in 2008. The fourth and final decommissioning licence was applied for in 2015, so that once it will have been granted, all systems and plant components are included in the licences and the plant can be completely dismantled. Dismantling is expected to be completed by 2023.

***Fig. 44:*** *Control station for the remote-controlled disassembly in the Obrigheim nuclear power plant (KWO)*

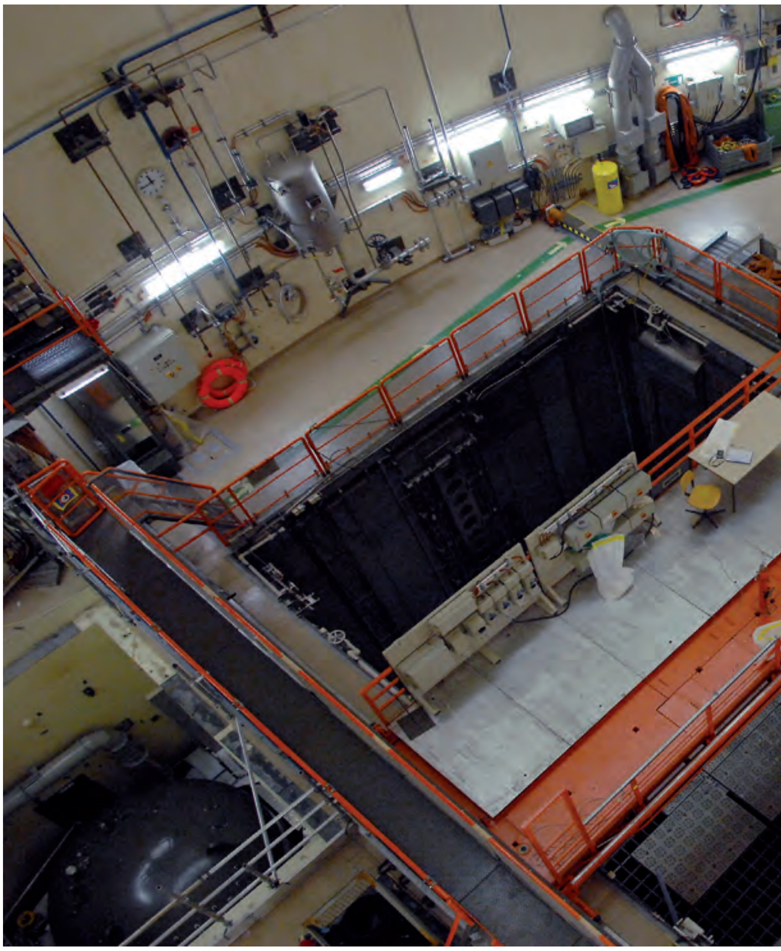
## Stade nuclear power plant

The Stade nuclear power plant was the first commercial pressurised water reactor in the Federal Republic of Germany only used for commercial purposes. After 31 years of operation, the plant was finally shut down in November 2003 for economic reasons. Until granting of the decommissioning licence in September 2005, the plant was operated in a post-operational phase subsequent to power operation and since then has been in the phase of dismantling. The steam generators of the Stade nuclear power plant were transported in one piece to Sweden for meltdown. The components non-reusable due to their radioactivity (i.e. the slag and a part of the produced castings) are returned to Germany as radioactive waste.

## Mülheim-Kärlich nuclear power plant

The Mülheim-Kärlich nuclear power plant (KMK, ▶ Fig. 45) was built between 1975 and 1986 as a 2-loop pressurised water reactor with a capacity of 1,302 MWe and is located around 10 kilometres northwest of the city of Koblenz. In August 1987, commercial operation of the plant started. After only one year of operation, the plant was taken out of service for legal reasons. After a long legal dispute that followed, it was decided in the framework of the so-called »Atomkonsens«, i.e. nuclear consensus, of 2000 to shut down the nuclear power plant. The decommissioning licence for the first phase of dismantling was granted in 2004 and since then, dismantling of the plant has been continued. The fuel assemblies were already removed in 2002 during the post-operational phase. The activation of structures in the core beltline region and thus also the radioactive inventory was less than in comparable plants due to the short operating life. In addition, the activity inventory continued to decrease by radioactive decay due to the long shutdown period.

***Fig. 45:*** *The empty fuel storage pool of the Mülheim-Kärlich nuclear power plant*

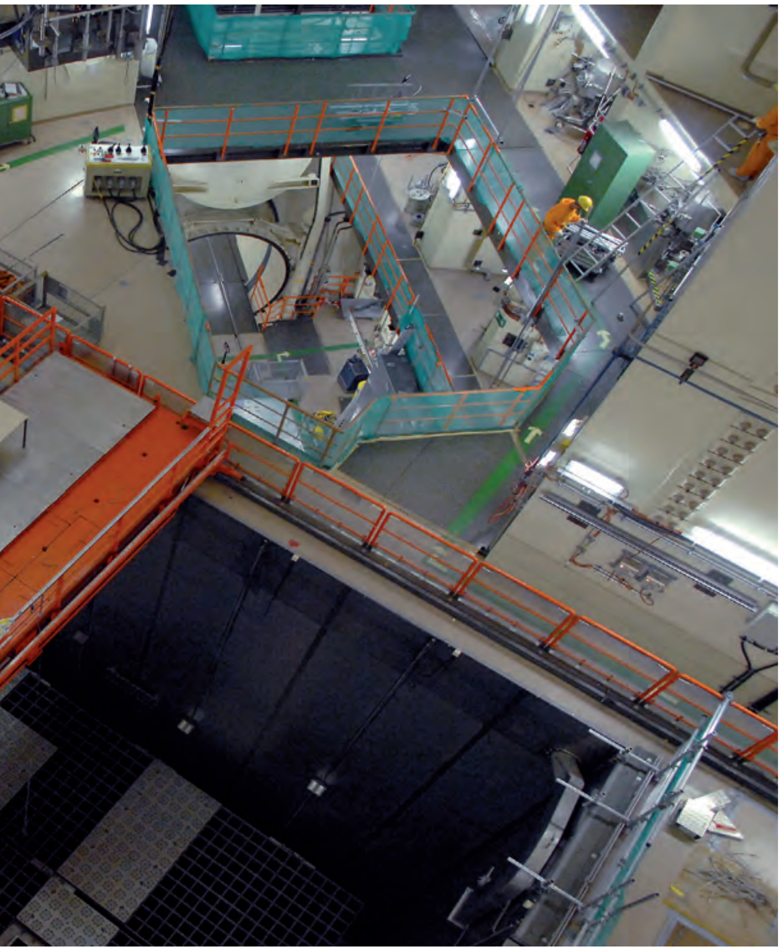


## Biblis nuclear power plant, units A and B

The nuclear power plant Biblis Unit A (KWB A) started power operation in 1975 and Biblis Unit B (KWB B) in 1977. The power plant reached an electrical output of 1,225 MWe (gross). Both units share various social and ancillary buildings at the site. With the Thirteenth Act Amending the Atomic Energy Act adopted on 06.08.2011 in the wake of the events in Fukushima, the plant lost its authorisation for power operation. Both units filed an application for decommissioning and dismantling in August 2012. Until granting of the first decommissioning and dismantling licence on 30.03.2017, the two units had been in the so-called post-operational phase. In this phase, activities were already carried out which were covered by the operating licence but had a positive influence on decommissioning and dismantling. So, for example, primary system decontamination was carried out. KWB A has been free of nuclear fuel since the end of 2016. For the KWB B, this is to be reached by the end of 2017. The respective first decommissioning and dismantling licences include the dismantling of the reactor pressure vessel internals, the dismantling of systems and equipment no longer required and a large number of components (e.g. steam generators, primary coolant pumps, etc.). In the further course of dismantling of KWB A and KWB B, at least one additional licence is planned, which will then cover the dismantling of the reactor pressure vessel, the biological shield and other installations.

## Thorium high temperature reactor

The Thorium high temperature reactor (THTR-300) was a gas-cooled high temperature reactor with a capacity of 300 MWe in Hamm-Uentrop. It first went into operation in autumn 1983 and was finally shut down in 1988. The THTR-300 is the only power reactor that is currently under safe enclosure. Since the facility is located on the territory of a major power plant site which has to be supervised anyway, the cost of maintaining safe enclosure of the THTR-300 is relatively small.



## Würgassen nuclear power plant

As the first large-scale commercial boiling water reactor plant in the Federal Republic of Germany with a gross electrical output of 670 MWe, the Würgassen nuclear power plant (KWW) fed electricity into the public grid for the first time on 18.12.1971 after almost four years of construction. It was a boiling water reactor pilot plant with direct steam injection from the reactor into the turbine, as it was later realised several times in Germany in a modified form. After detection of cracks in the core shroud and the core grid plates, which would have required extensive replacement and retrofitting of the core internals, the decommissioning decision was made on 29.05.1995 for economic reasons. The work for dismantling of the plant in the reactor building, turbine building and the adjacent components in the controlled area was completed in 2014. According to current plans, the reactor building and the turbine building will be demolished only after evacuation of the storage facilities.

## Jülich experimental reactor AVR

With the gas-cooled high temperature reactor, which fed electricity into the public grid for the first time in 1967, the concept of a pebble bed reactor was implemented for the first time worldwide. During the 21 years of power operation, numerous research objectives were achieved for the new reactor technology. At the end of 1988, the experimental nuclear power plant was shut down and transferred into safe enclosure before the licence for dismantling was granted in 2009. A milestone in the dismantling process was the removal and transport of the reactor vessel in one piece. For this purpose, a material lock with a crane system was built adjacent to the reactor building so that the reactor building could be removed until it was possible to lift the reactor vessel. The vessel was filled with porous lightweight concrete to bind radioactive substances in the interior and to stabilise the structures of the vessel. After lifting out of the building, the 2,000-tonne reactor vessel was turned horizontally in the material lock in order to transport it to the specially constructed on-site storage facility of the Forschungszentrum Jülich in May 2015. It is planned to disassemble the vessel after about 60 years, when the radioactivity inside will have decayed significantly. In the meantime, the remaining components and the reactor building can be completely removed.

*__Fig. 46:__ Transport of the AVR reactor vessel from the reactor building to the storage facility*

## Research reactor 2

The research reactor 2 (FR-2) marks the beginnings of the Kernforschungszentrum Karlsruhe. The facility had a thermal rating of 50 MW and served as a neutron source for various physical experiments. At the beginning of the 1980s, however, the reactor no longer met the demands of the scientists working with it and was therefore taken out of service in 1981. Between 1982 and 1986, the fuel assemblies and the coolant were removed and the experimental loops were dismantled. In 1993, further dismantling and decontamination work was begun. On 20.11.1996, the decommissioning of the FR-2 came to a temporary end when the safe enclosure of the reactor block was achieved (▶ Chapter 3 Decommissioning strategies). With the exception of the reactor block, all radioactive components were removed from the plant. Supporting and auxiliary systems as well as buildings that were no longer of any use were dismantled. The vacated building ground has been recultivated. The reactor building is freely accessible, except for the area of the enclosed reactor core, and today accommodates an exhibition on the development of nuclear energy and nuclear research that is open to the public.


## Frankfurt research reactor

The Frankfurt research reactor (FRF-1) was commissioned in 1957 by the Johann Wolfgang Goethe University, Frankfurt. The nuclear fuel was an aqueous uranyl sulphate solution. Due to technical problems, the reactor was shut down in 1968. The new FRF-2, a TRIGA reactor, was installed 1973 to 1977, but never went into operation. Decommissioning was ordered in 1980. The licence for the dismantling of the facility was granted at the end of 2004. The dismantling activities took place from March 2005 to August 2006. The facility was released from the scope of application of the Atomic Energy Act by decision of 31.10.2006. A tunnel-shaped access into the reactor block made of heavy concrete was created by means of a hydraulic chisel. The graphite inside the block was withdrawn manually using telescopic tools and all other attachments were lifted by crane. After removal of the steel pipes by means of core drilling, the activated structure could be disassembled from the inside. This was done by extending the tunnel, combining the use of concrete drill and wire saw. Subsequently, the dismantling of the other systems took place. The radioactive waste is delivered to the Land collecting facility in Hesse and the clearance measurement of residues takes place in the VKTA, Rossendorf.

## Research reactor TRIGA Heidelberg (TRIGA HD I and TRIGA HD II)

The TRIGA HD I research reactor was located at the site of the German Cancer Research Center (DKFZ) in Heidelberg and was operated by the Institute of Nuclear Medicine. It primarily served to generate short-lived radionuclides for medical purposes and further analyses in the context of cancer research. The reactor went into operation in August 1966 and was shut down in March 1977 due to the construction of a second research reactor (TRIGA HD II). The newer research reactor of the same type, the TRIGA HD II, started operation in the following year and was shut down in November 1999 after 21 years of operation because it was no longer needed due to new research priorities. Between 1980 and 2006, the TRIGA HD I was in a phase of safe enclosure (▶ Decommissioning strategies) and was completely dismantled in 2006. For the TRIGA HD II, immediate dismantling was completed in 2005.

## 13 Glossary

**Activation**
Process where by irradiation, for example with neutrons from a nuclear reactor in operation, some substances become radioactive themselves. The resulting radionuclides are distributed over the volume of material and are therefore practically not removable.

**Activity**
Number of decaying nuclei per unit time for a radioactive substance (▶ Becquerel).

**Alpha radiation**
Particle radiation consisting of helium nuclei. This occurs during a particular radioactive decay (alpha decay). In case of external irradiation, alpha emitters are relatively harmless to humans, but when incorporated (e.g. by inhalation) they have a higher radiotoxicity than beta or gamma emitters.

**Atomic Energy Act**
(Atomgesetz – AtG)
The legal basis for the use of nuclear energy and decommissioning in Germany on which, among others, the Radiation Protection Ordinance (StrlSchV) is based upon.

**Becquerel (Bq)**
Unit for the activity of a radioactive substance. 1 Bq (becquerel) is equivalent to 1 decay per second.

**Beta radiation**
Particle radiation consisting of electrons (or their antiparticles, the posi trons). This occurs during a particular radioactive decay (beta decay).

**Biological shield**
Thick-walled concrete structure (about 2 m) surrounding the reactor pressure vessel and shielding neutron radiation and gamma radiation.

**BMUB**
(Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit)
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

**BWR**
Boiling water reactor (water-moderated)

**Chain reaction**
Self-sustaining process in which neutrons generated during the fission of one generation of atomic nuclei cause the fission of at least an equal number of nuclei of the succeeding generation.

**Clearance**
Administrative act which effects the release of radioactive substances and any movable goods, buildings, soil areas, facilities or parts thereof which are activated or contaminated by radioactive substances and which originate from practices from the scope of application of the Atomic Energy Act and ordinances based thereon and decisions of administrative authorities for the use, utilisation, disposal, possession or their transfer to a third party as non-radioactive substances.

**Conditioning**
Treatment and packaging of radioactive waste and spent fuel suitable for disposal.

**Containment**
Thick-walled (some cm), mostly spherical metal body with several 10 m in diameter that prevents leakage of radioactive substances as an additional technical barrier.

**Contamination**
As used here: adhesion of radioactive substances.

**Controlled area**
Spatially separated area of radiation protection in which persons may be exposed to an annual dose of more than 6 mSv. The controlled area may only be entered to perform certain work activities. The controlled area is usually surrounded by a supervised area.

**Conversion**
Conversion of the intermediate products of the uranium ore into a condition required for enrichment.

**Coolant**
Medium in nuclear reactors (in light water reactors: water) that removes the heat generated during the chain reaction from the reactor core. This heat content is then used to generate electricity.

**Criticality/critical**
A nuclear reactor is regarded as critical when the same number of neutrons is generated by nuclear fission as necessary for the continued maintenance of the chain reaction. Criticality is therefore defined as the normal operating condition of a nuclear reactor.

**Decommissioning**
All measures carried out after granting of a decommissioning licence for a nuclear facility until official, i.e. nuclear regulatory supervision is no longer necessary.

**Decontamination**
Complete or partial removal of contamination, e.g. by washing, use of chemical solvents or grinding.

**DIN**
(Deutsches Institut für Normung e. V.)
German Institute for Standardization

**Dose**
The radiation emitted during the decay of radioactive substances produces a specific effect while being absorbed in material or tissue, which is quantified using the term dose. The dose is measured in sievert (Sv).

**Dose limits**
Maximum limit values for doses that are specified in the Radiation Protection Ordinance (StrlSchV). For radiation protection monitored personnel (persons who are exposed to increased radiation in nuclear facilities), the limit is 20 mSv per year.

**Dosimeter**
Instrument for measuring the dose (radiation exposure). Depending on the measuring task, dosimeters have different properties and functions.

**Enrichment**
Process in which the fraction of the uranium-235 nuclide in the nuclear fuel is increased compared to the natural content. This is necessary in order to use the nuclear fuel in light water reactors.

**Entsorgungskommission (ESK)**
Nuclear Waste Management Commission
A panel of independent experts that advises the Federal Environment Ministry on issues relating to the management of radioactive waste.

**Exclusion area**
Spatially separated area of radiation protection in which persons may receive a dose of 3 mSv per hour. Entry is only permitted in certain circumstances for a short time.

**Fuel**
▶ Nuclear fuel

**Fuel assembly**
Part of the nuclear reactor that contains the nuclear fuel.

**Gamma radiation**
Electromagnetic radiation which occurs during certain radioactive decays. Gamma radiation has a relatively large range and is therefore the main source of danger in case of external irradiation, while in case of incorporation (e.g. by inhalation) alpha radiation is more harmful.

**Half-life**
Time span during which half of the radionuclide will have decayed. The half-life is specific for each radionuclide.

**Immediate dismantling**
Decommissioning strategy where a nuclear plant will be immediately dismantled without prior safe enclosure following the post-operational phase.

**KTA safety standards**
Safety standards for the construction and operation of nuclear facilities. These are developed by the Nuclear Safety Standards Commission (Kerntechnischer Ausschuss – KTA), a panel of independent experts.

**Licensing procedure**
Procedure for granting a licence or partial licence according to the Nuclear Licensing Procedure Ordinance (AtVfV).

**Light water reactor**
Collective term for pressurised water and boiling water reactors.

**MW**
Megawatt, a unit to measure the output of nuclear reactors. For nuclear power plants, the electrical power (MWe, megawatt electrical) is given, for nuclear reactors without electricity generation the thermal power (MWth, megawatt thermal).

**Neutron**
Electrically neutral particle that is part of an atomic nucleus and is released during nuclear fission. Neutrons are required for the fission of atomic nuclei in a nuclear reactor.

**Nuclear energy**
Technology for large-scale conversion of energy from nuclear fission into electricity.

**Nuclear facility**
Collective term for nuclear power plants, research reactors and nuclear fuel cycle facilities.

**Nuclear fission**
Process in which neutrons split an atomic nucleus into several fragments with the release of energy.

**Nuclear fuel**
Fissile material whose energy content in a nuclear power plant is converted into electrical energy.

**Nuclear fuel cycle**
Term referring to all steps and processes that serve the supply of nuclear fuel and the management of waste.

**Nuclear fuel cycle facilities**
Facilities serving the supply of nuclear fuel and the management of waste, such as production and reprocessing of nuclear fuel or conditioning of waste.

**Nuclear power plant**
Thermal power plant for generating electric power with a nuclear reactor.

**Nuclear reactor**
Installation in which controlled nuclear fission takes place continuously in a chain reaction.

**Post-operational phase**
Transitional period between the final shutdown of a nuclear power plant and the granting and utilisation of the decommissioning licence. The preparatory work for dismantling must be covered by the operating licence still in force.

**Power reactor**
Nuclear reactor solely used to generate electricity. Compared to research reactors, power reactors have a significantly higher performance.

**Prototype reactor**
Nuclear reactor with which a particular design has been realised for the first time. Prototype reactors are smaller than typical power reactors.

**PWR**
Pressurised water reactor (water-cooled)

**Radiation protection**
Protection of man and the environment from the harmful effects of ionising radiation emitted, among other things, by radioactive substances.

**Radiation Protection Ordinance**
(Strahlenschutzverordnung – StrlSchV)
Legal ordinance that regulates principles and requirements for preventive and protective measures for the protection of man and the environment from the harmful effects of ionising radiation.

**Radioactive substance**
Any material containing one or more radionuclides the activity of which cannot be disregarded according to the provisions of the Atomic Energy Act.

**Radionuclide**
Specific nuclide (type of atom) that decays spontaneously without external influence under emission of radiation.

**Radiotoxicity/radiotoxic**
Harmful effect of a substance due to its radioactivity.

**Reactor core**
Part of a nuclear reactor containing the nuclear fuel and in which the controlled chain reaction takes place.

**Reactor pressure vessel**
Thick-walled metal body (about 20 cm) safely enclosing the reactor core and other internals in the core beltline region.

**Reaktor-Sicherheitskommission (RSK)**
Reactor Safety Commission
A panel of independent experts that advises the Federal Environment Ministry on issues relating to reactor safety.

**Repositories**
Disposal facilities for radioactive waste or spent fuel to be built deep beneath the earth's surface. The objective is a reliable isolation from the biosphere for very long periods of time.

**Reprocessing**
Procedure in order to extract unused fissile material from »spent« material, i.e. fuel assemblies used in a nuclear power plant fuel. The highly radioactive »spent« part is conditioned for disposal.

**Research reactors**
Nuclear reactors in research centres, universities, hospitals or in industry. They are used for research and medical purposes and in the industrial sector. In contrast to power reactors, research reactors do not generate electricity.

**Safe enclosure**
Decommissioning strategy where a nuclear facility will be safely enclosed for a certain period of time (typically 30 years) prior to dismantling to achieve a lower radiation exposure of workers during dismantling.

**Steam generator**
Component to produce steam, which is used in a pressurised water reactor to transfer the heat from the reactor core (primary circuit) to the secondary circuit, which feeds the generator turbine.

**Storage facilities**
Facilities (central or at the site of the plant producing the waste) where conditioned waste packages are stored for a transitional period until they can be disposed of in a suitable repository.

**Strahlenschutzkommission (SSK)**
Commission on Radiological Protection
A panel of independent experts that advises the Federal Environment Ministry on issues relating to radiation protection.

**Supervised area**
Spatially separated area of radiation protection in which persons may be exposed to an annual dose of more than 1 mSv. Often, the entire power plant site is designated as a supervised area.

**Supervisory procedure**
Supervision of compliance with all provisions of the Atomic Energy Act, the related legal ordinances and the regulations of the licensing decisions for the construction, operation and decommissioning of nuclear facilities by the nuclear regulatory authority.

**Sv**
Sievert, unit to measure the radiation dose (1 Sv = 1000 mSv). In Germany the natural radiation exposure for the population is in the range of 1 to 6 mSv per year with an average value of 2.4 mSv per year.

**Uranium enrichment**
▶ Enrichment

**Uranium ore mining and uranium ore processing**
First, uranium ore has to be extracted in mines (just like other metal ores). The uranium is separated in several steps in the processing plants.

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