Decommissioning of Nuclear Facilities

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Contents

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) of 2011, more than 500 reactors and about 275 nuclear fuel cycle facilities have been finally shut down until now.

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. nuclear regulatory supervision, 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 mid-2011, 16 nuclear power plants (power and prototype reactors) have been in different stages of decommissioning in Germany. In 2011, another eight reactors were finally shut down and decommissioning will commence in the next years. The remaining nine plants will be finally shut down in a stepwise process until 2022 due to the amendment of the Atomic Energy Act of July 2011; one plant each by the end of 2015, 2017 and 2019 and another three plants until the end of 2021 and 2022. These plants will also be decommissioned after their final shutdown (▶ Annex, Page 30).

More than 30 research reactors of different size and more than 10 nuclear fuel cycle facilities were finally shut down and were or will be decommissioned. At the site of the Greifswald nuclear power plant (KGR), Europe's largest decommissioning project is being undertaken (▶ Fig. 2).

The map in ▶ Fig. 3 gives an overview of the facilities under decommissioning in Germany in mid-2011, or already dismantled completely. In addition to the power and prototype reactors, these are research reactors and nuclear fuel cycle facilities. Not shown are facilities finally shut down, but not having been granted a decommissioning licence yet.

Fig. 2: Site of the Greifswald nuclear power plant

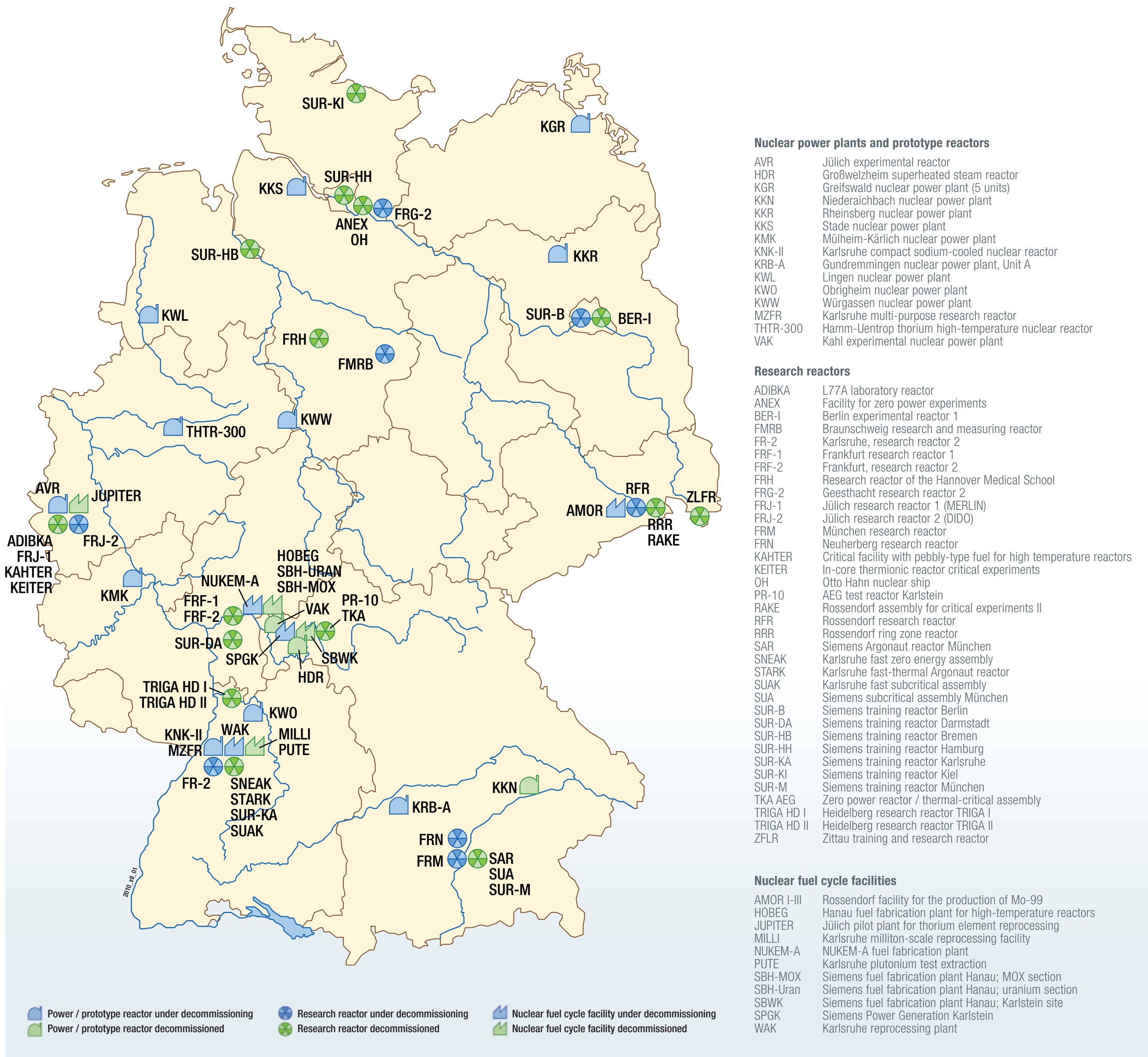


Fig. 3: Nuclear facilities decommissioned and under decommissioning in Germany.
Not shown are facilities finally shut down, but not having been granted a decommissioning licence yet.

In the course of the various decommissioning projects it turns out that each project is actually carried out individually. The course of the project, its financing, the choice of decommissioning strategy and many other conditions strongly depend on the type of facility and on the owner (▶ Financing, Page 28):

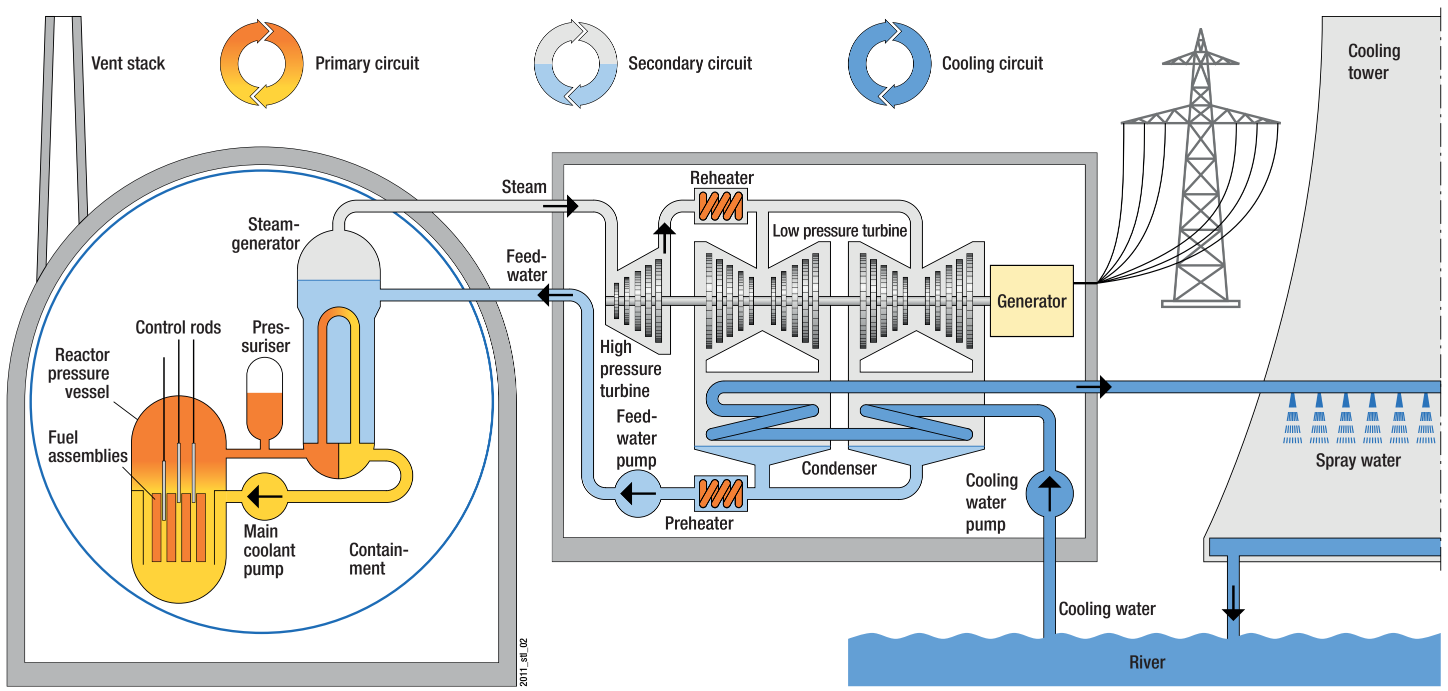
- Power reactors and plants for uranium enrichment and fuel fabrication belong to the power utilities and the companies operating in this sector.
- Research reactors, prototype reactors for electricity production and prototype nuclear fuel cycle facilities are, on the other hand, established at research centres or universities. They are financed publicly. The decommissioning of the Greifswald and Rheinsberg nuclear power plants of the former GDR is financed from the federal budget, just like the decommissioning and remediation of the uranium mining and processing facilities of the »Wismut« in Saxony and Thuringia. The following sections explain the decommissioning processes for different types of facilities.

2.1 Power and prototype reactors

Nuclear power plants (power and prototype reactors) convert the energy content of nuclear fuel (in the so-called fuel assemblies) into electrical energy. In a controlled chain reaction, heat is generated by nuclear fission. This heat is absorbed by a water circuit 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 region, thus helping to cover the unvarying part of daily electricity demand.

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

Fig. 4: Scheme of a pressurised water reactor

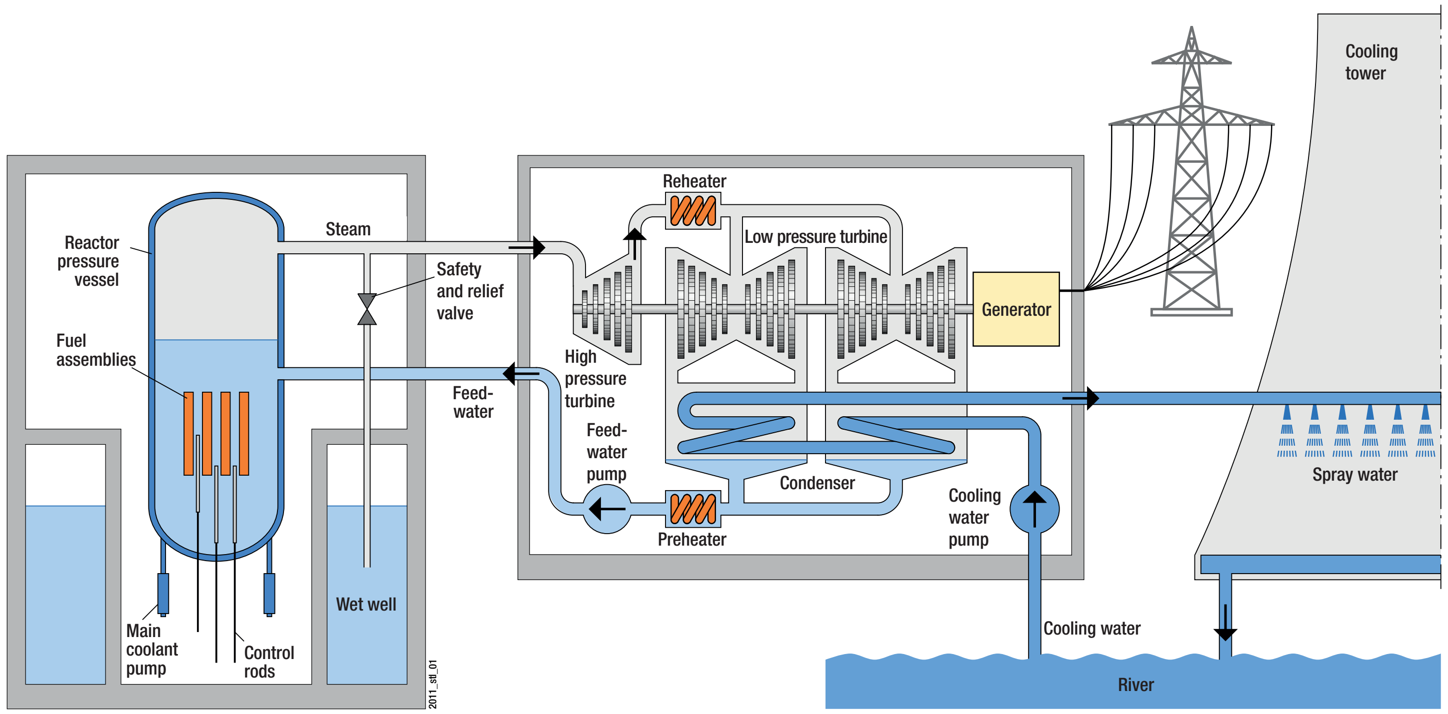


So far, three nuclear power plants have been completely dismantled: the Niederaichbach nuclear power plant (KKN), the Großwelzheim superheated steam reactor (HDR) and the Kahl experimental nuclear power plant (VAK). The first two plants are prototype reactors, whose development was not further pursued. 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 for unrestricted use (▶ Clearance, Page 24).

Experience has shown that decommissioning of a power or prototype reactor will take about 10 to 20 years, while the amount of waste can differ significantly (▶ Residue and waste management, Page 24).

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

Fig. 5: Scheme of a boiling water reactor



2.2 Research reactors

Research reactors, in contrast to power reactors, generally do not serve to generate electricity, but are used for special purposes in research, medicine or in the industrial sector. In particular, the primary purpose is 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 case of a research reactor compared to a nuclear power plant.

Due to the smaller size of research reactors, technical dismantling can be performed within a shorter period (e. g. several months to some years) than for larger power reactors.

Examples of research reactors dismantled or under decommissioning are presented in ▶ Fig. 6 and 7 and in the ▶ Annex.

***Fig. 7**: Control measurements in the reactor cavity of the TRIGA HD II research reactor*

***Fig. 6**: Dismantling of the FRJ-1 research reactor*

2.3 Nuclear fuel cycle facilities

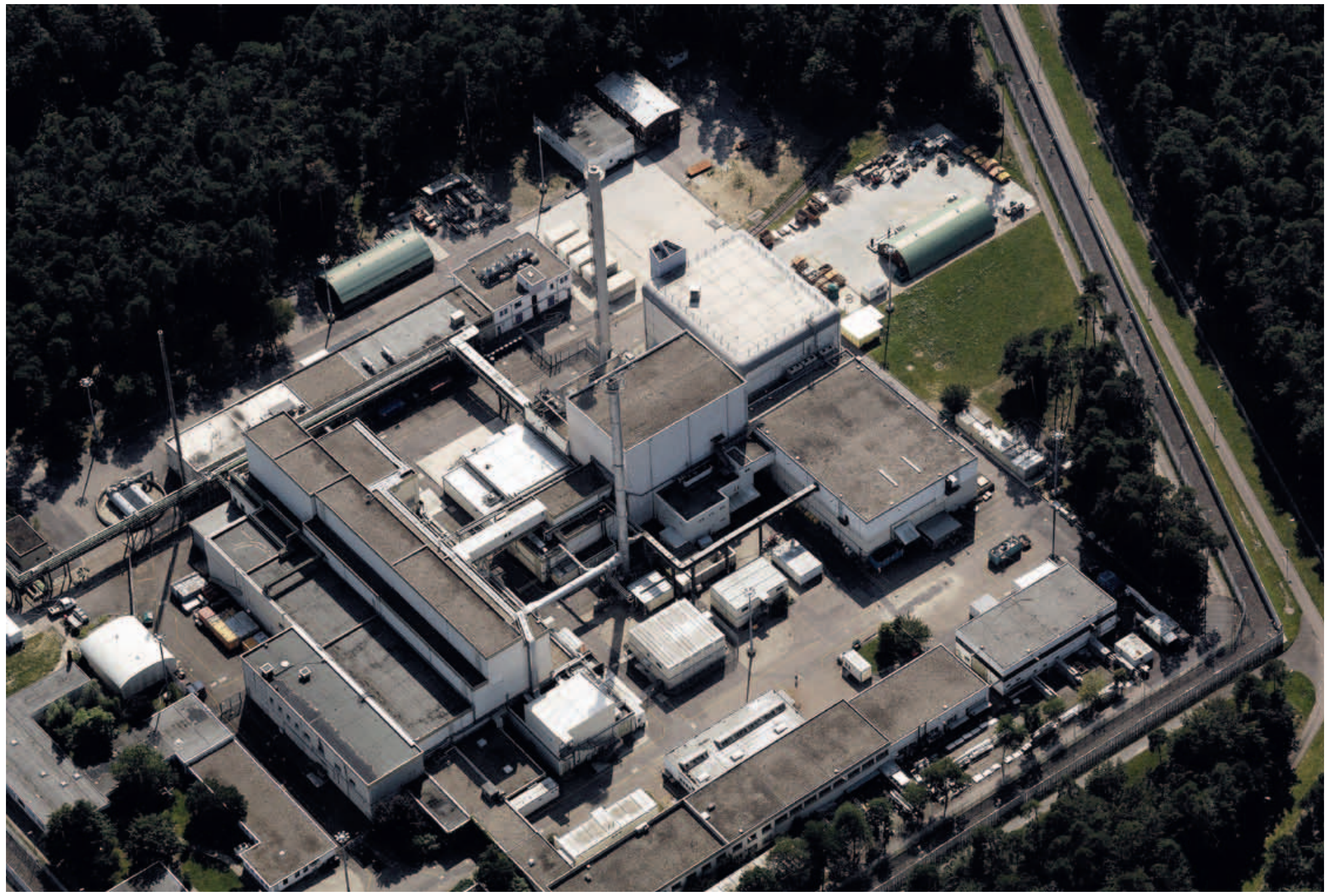
Nuclear fuel cycle facilities are used, for example, for the fabrication or reprocessing of nuclear fuel, or for the conditioning of waste. As shown in the ▶ Annex, there are only a few such facilities in Germany.

At the Hanau site, several fuel fabrication plants were taken out of service in the 1980s and 1990s. At the Forschungszentrum Karlsruhe, the Karlsruhe reprocessing plant (WAK) (▶ Fig. 8) was operated as a pilot plant from 1971 to 1990. Its decommissioning entails particularly complex requirements.

The licensing procedures as well as the duration of decommissioning are comparable with the decommissioning of nuclear power plants (▶ Licensing procedure, Page 15). In the case of the WAK, for example, current estimates are that it will take 25 years from the granting of the first decommissioning licence in the year 1994 until the complete removal of the plant, which is scheduled for 2020.

From a technical point of view, however, the projects differ considerably from the decommissioning of nuclear reactors. This is mainly due to the fact that nuclear fuel cycle facilities 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 methods and for the radiation protection of the personnel.

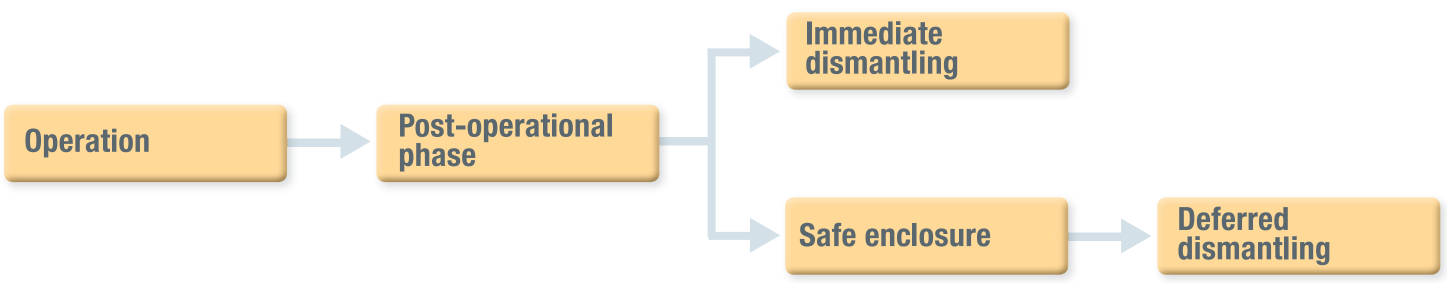
***Fig. 8:** Karlsruhe reprocessing plant (WAK)*



3 Decommissioning strategies

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

Fig. 9: Decommissioning strategies



Common to both is that between final shutdown and start of the actual decommissioning there is the so-called post-operational phase, which may last several years. During this period, the fuel assemblies can be removed, or the operational media and waste can be disposed of as far as covered by the operating licence for the nuclear power plant. At the latest in the post-operational phase, the operator of the facility applies for licensing of decommissioning (▶ Licensing procedure). Only after its granting, the actual decommissioning and dismantling activities may 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 (▶ Radiation protection, Page 18) will be dismantled (▶ Fig. 10). Experience shows that the decommissioning work will at least take a decade.

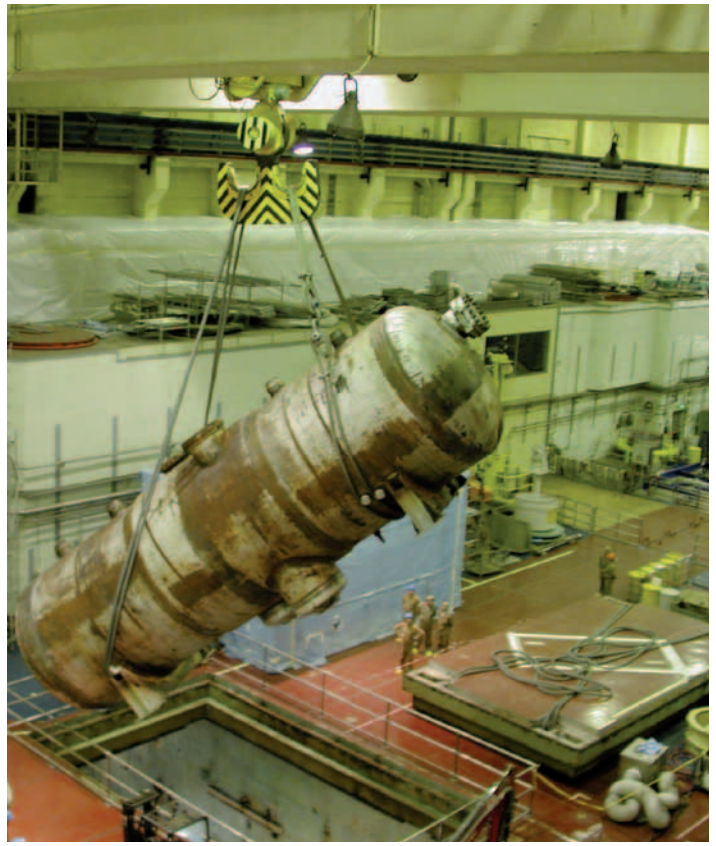


Fig. 10: Removal of a steam generator during immediate dismantling

In the case of the alternative strategy, however, the facility will be dismantled only after a period of safe enclosure, drawing a distinction between three phases:

1. Measures in the facility for the purpose of establishing the safe enclosure,
2. maintaining the facility in safety enclosure (e. g. 30 years) (▶ Fig. 11), and
3. dismantling of the facility.

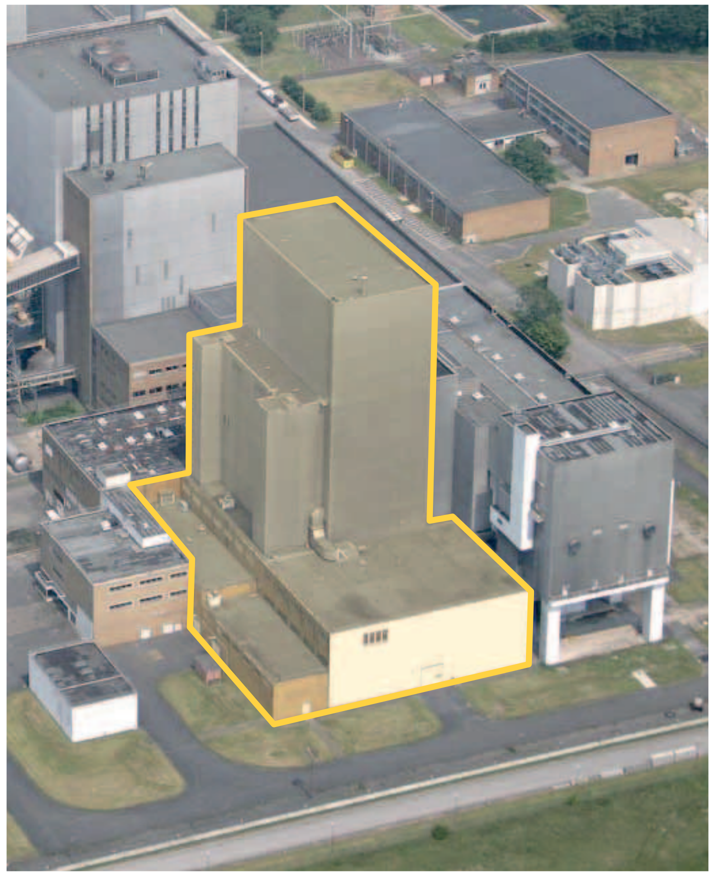


Fig. 11: Safe enclosure of the THTR-300

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

Compared at the international level, it shows that nuclear facilities are usually dismantled immediately. In Germany, there are also only a few facilities in safe enclosure (▶ Annex).

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

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

4 Step-wise dismantling of a nuclear power plant

Using the example of a nuclear power plant it will be shown how nuclear facilities are dismantled. ▶ Fig. 12 - 15 explain the dismantling by means of a simplified section through a nuclear power plant. In each dismantling step, the systems, structures and components highlighted in red will be removed.

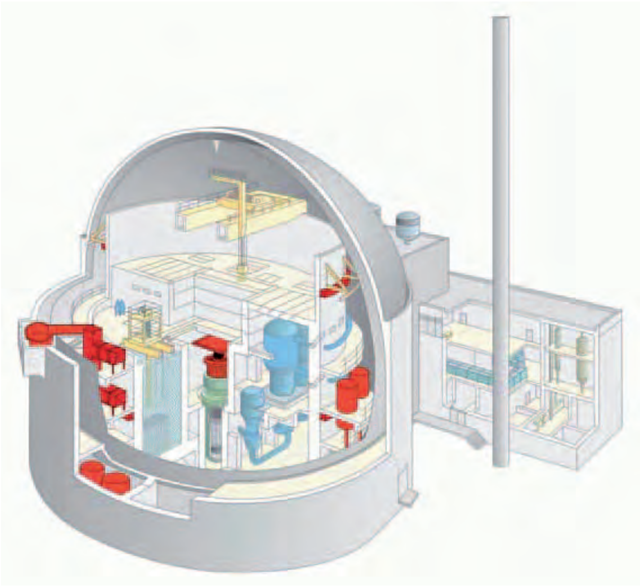


Fig. 12: First, the components no longer needed for dismantling operations are removed.

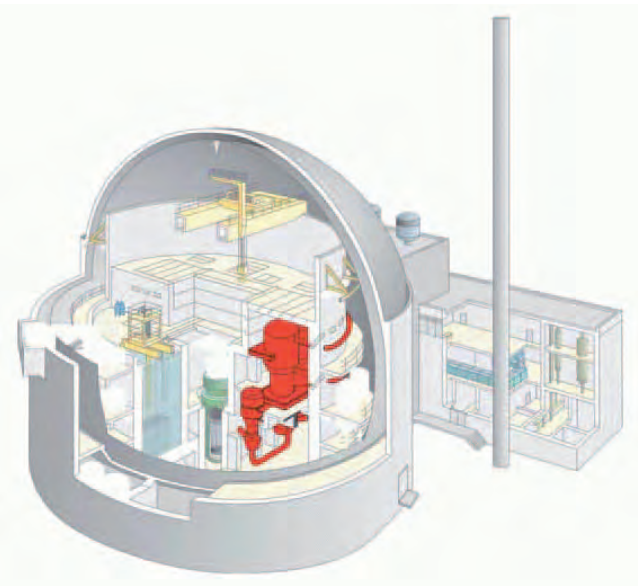


Fig. 13: In the next steps, the higher activated parts, such as steam generators and parts of the primary circuit, are removed.

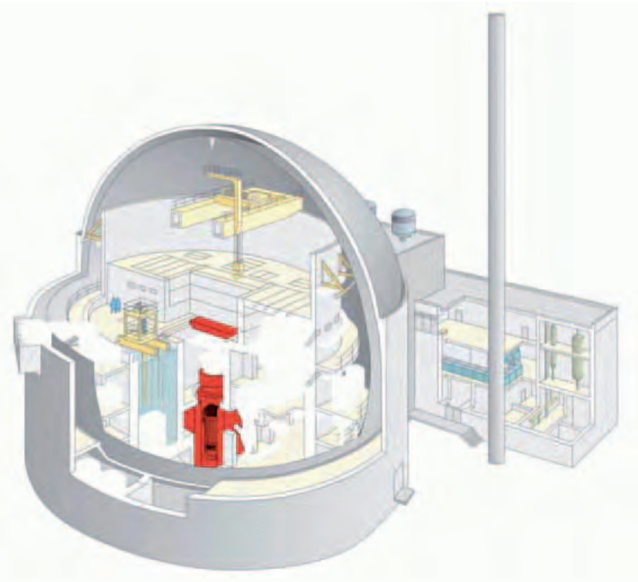


Fig. 14: As a last major component, usually, the highly activated reactor pressure vessel is dismantled.

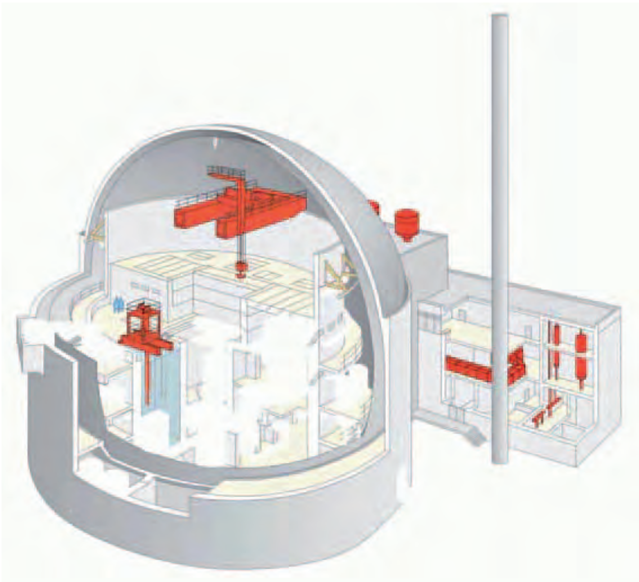


Fig. 15: As a last step, the parts necessary until then, such as cranes and filter systems, are removed.

Before starting the dismantling work, the plant is largely in the same technical condition as during operation. Fuel and operational waste, however, have usually been removed.

In preparation for the decommissioning work, a detailed overview of the radioactive inventory of the plant is prepared. For this purpose, measurements (▶ Fig. 16) are carried out in all areas of the facility, and samples are taken and analysed. After that, the final plan for the dismantling can be prepared. In this phase, it will also be decided on the techniques for decontamination and disassembly (▶ Techniques, Page 20) to be applied.

Fig. 16: Measurement to determine a possible contamination

The dismantling of components usually starts in areas with low contamination and is continued in areas with higher contamination; dismantling is carried out »from the outside to the inside«. In the vacated areas, e. g. parts of the turbine building, devices may then be installed that are necessary to segregate, decontaminate and reprocess the waste and residues.

Practically all removed parts are disassembled into easily manageable pieces and, if necessary, will be decontaminated. Decontamination can take place, depending on the circumstances, before or after disassembly. Each piece is examined for radioactivity. This process will be reviewed by independent experts. Based on the radiological characterisation, it will be decided whether the piece has to be conditioned and handed over as radioactive waste, or whether it can be further treated and cleared (▶ Residue and waste management, Page 24).

Computerised systems ensure continuous tracking of the pieces from the place of their dismantling via the subsequent treatment steps up to their removal from the plant. The overall logistics needed for residue and waste management are substantial and represent a significant cost factor.

Important installations, such as ventilation, power and media supply, are kept in operation or ready to use through all steps of dismantling. These systems are available from the operating phase and their continued operation is necessary. Depending on the requirements, they will be retrofitted.

Finally, work is carried out to dismantle the most contaminated areas and the activated systems and components. These comprise the reactor pressure vessel and its internals, the core beltline region and the adjacent systems and components inside the containment. These dismantling steps are largely carried out by remote control in order to avoid the presence of people in areas of high radiation. Much of the work is also carried out under water, since water is an effective radiation shield. In some cases, major components are removed from the plant for decay storage (▶ Decay storage, Page 26).

The materials arising from this dismantling step are, for the most part, activated. They account for a significant portion of the radioactive waste produced during dismantling (▶ Residue and waste management).

After complete vacation of the building, only residual contamination remains 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). A typical dismantling of a plant takes at least a decade.

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

5 Licensing and supervisory procedures

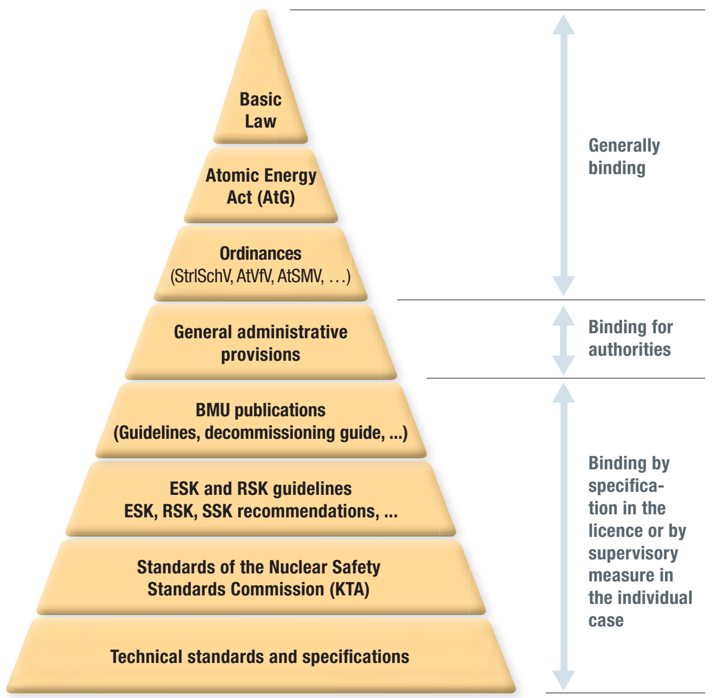


Fig. 18: Regulatory pyramid

5.1 Legal framework

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

The Nuclear Licensing Procedure Ordinance regulates 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 at 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 announcements of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, such as the decommissioning guideline (»Guide to the decommissioning, the safe enclosure and the dismantling of facilities or parts thereof as defined in § 7 of the Atomic Energy Act« as of 26.06.2009), developed by the Federal Environment Ministry (BMU) 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, and licensing and supervision. On 9 September 2010, the ESK adopted guidelines for the decommissioning of nuclear facilities. These guidelines contain technical requirements and thus complement the decommissioning guideline.

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 apply for or grant a partial licence for each step. An example of a process diagram for the decommissioning of a power reactor is presented in ▶ Fig. 19.

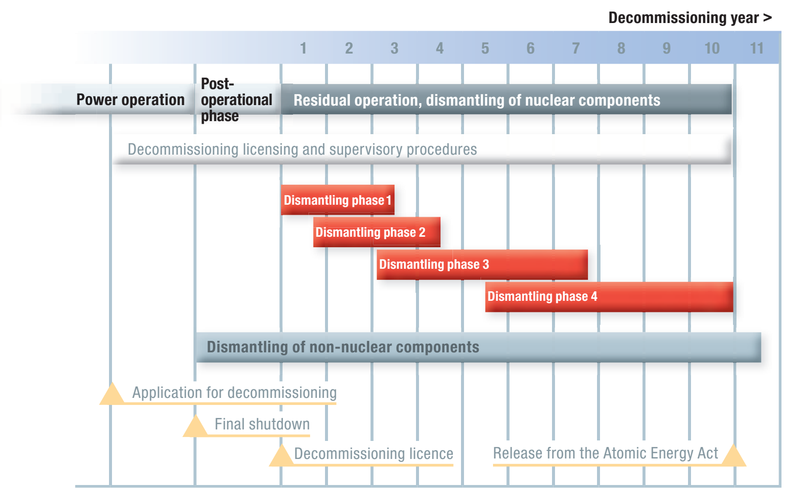


Fig. 19: Example of a process diagram for decommissioning

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 guideline (▶ Legal framework).

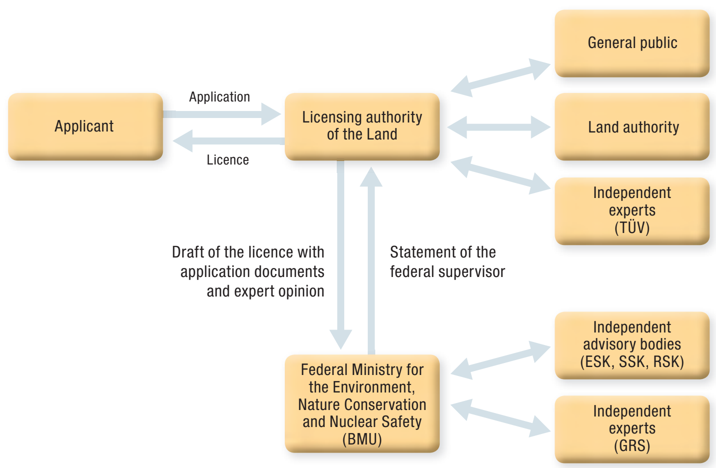


Fig. 20: Parties involved in the licensing procedure

The procedure for granting of a decommissioning licence and the interactions between authorities, independent 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). In this function, they are subject to supervision by the BMU and, according to circumstances, may have to follow the instructions from the Federal Government. In this context, the BMU is advised by the ESK, the RSK and the SSK.
- The competence for granting, cancelling or withdrawing 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.
- The work permitted by the decommissioning licence is supervised by the responsible Länder authorities within the ▶ supervisory procedure.

5.3 Supervisory procedure

Compliance with the requirements for work permitted in the decommissioning licence is supervised by the competent Land authority within the supervisory procedure. It is checked whether the conditions specified for the work and the licensing conditions imposed are complied with. Additional inspections are carried out by independent experts commissioned by the Land authority for assistance. Furthermore, the techniques and methods specified in the licence will be 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 will be monitored throughout the entire dismantling phase by the authorities. 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 will be 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 the operating personnel, the general public and the environment from undue exposure to radiation. This protection has not to be ensured only for all work activities in connection with the decommissioning, but also in case of design basis accidents. Any 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 incident.

The hazard potential is determined by two factors, namely:

1. the radioactive material present in the facility: the »activity inventory« and that particular part of it which, in principle, is available for a 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. The description given here for nuclear power plants applies analogously to research reactors and nuclear fuel cycle facilities.

Fig. 21: Plant-internal transport of irradiated fuel assemblies

Operational phase

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 present elsewhere in the facility. Expressed in the measurement unit for radioactivity, the becquerel, it is about 10^{20} to 10^{21} Bq.

Post-operational phase

With the final shutdown of the nuclear reactor, the plant is pressureless 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.

In particular, if the irradiated fuel assemblies are removed from the facility or stored at the site (▶ Fig. 21), the potential hazard is reduced significantly. This usually happens during the post-operational phase. In this phase, the radioactive operational waste is often removed, too, which also account for a large fraction of the activity inventory.

These measures reduce the radioactive inventory to about one ten-thousandth of its original value (an activity of about only 10^{16} to 10^{17} Bq remains now). The major part of this activity inventory is fixed as activation in the structure materials of the facility 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 components of the facility and surfaces of buildings contributes to the radioactive inventory that remains in the facility. Its activity is about 10^{11} to 10^{12} Bq and is thus again a hundred thousand times lower than the activation.

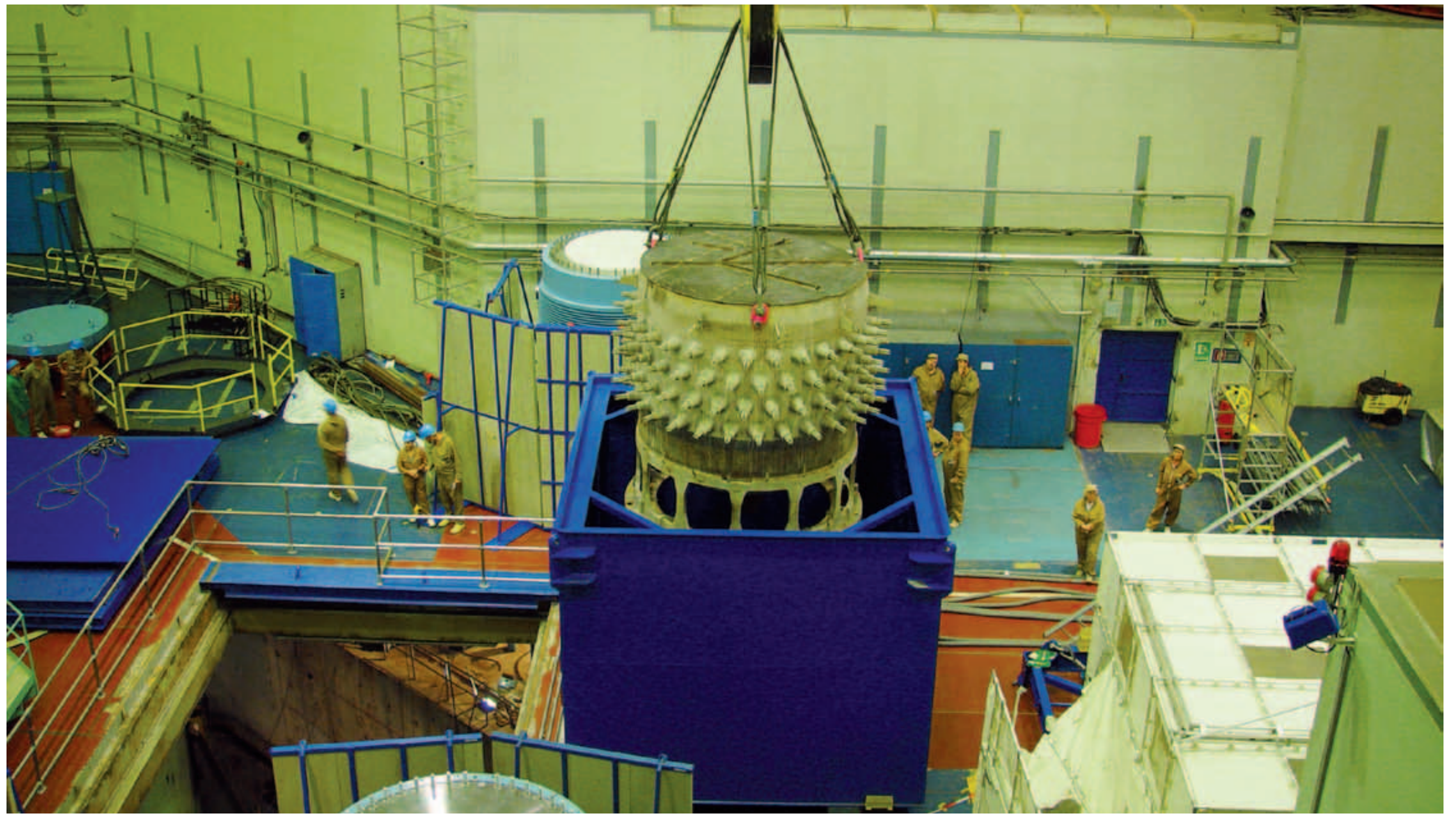
Residual operation and dismantling phase

In the residual operation and dismantling phase, the facility components are removed (▶ Fig. 22). The radioactive inventory of the facilities and their 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 normal material cycle (▶ Clearance). Safety-relevant installations, such as ventilation and fire protection systems, will continue to be operated.

In the course of the dismantling and disassembly work, the fraction of radioactivity available for release may rise temporarily and locally. This may happen, for example, if pipes, vessels, etc., previously closed will be opened. It has to be prevented by radiation protection measures that radioactivity is released during such operations.

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 a 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 personnel, the public and the environment from the hazards of ionising radiation is a central task.

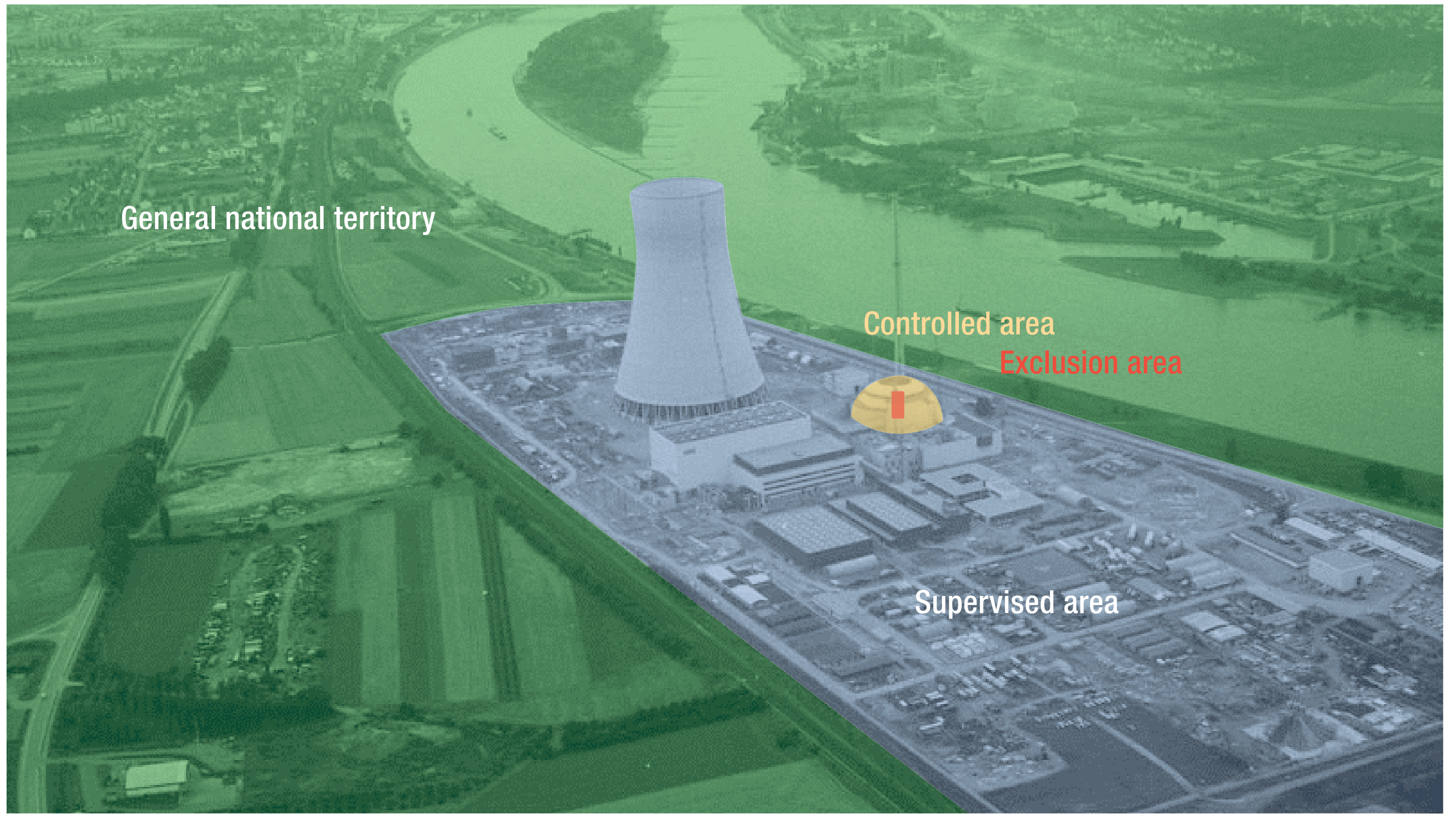
A complex system is constantly monitoring the radiation situation in all rooms and areas of the facilities. Any person operating in the controlled or supervised area of a facility (▶ Fig. 23) carries a personal dosimeter that measures the radiation exposure (dose). Further measures also prevent the uptake of radionuclides into the body. Dose limits for staff are specified in the Radiation Protection Ordinance (▶ Legal framework) and additionally in internal regulations of the facilities. They must not be exceeded. Moreover, the Radiation Protection Ordinance stipulates the avoidance of unnecessary radiation exposure and a dose reduction 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 will be 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 protection measures for staff, such as the duty to wear special protective cloothing, 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 in order to minimise the amount of radioactive substances that may be discharged into the environment in controlled manner amounts within the scope of official authorisation.

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



Since many activities to be 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. Thus, in case of immediate dismantling of the facility (▶ Decommissioning strategies), the existing radiation protection organisation can largely be adopted.

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

6.3 Reportable events

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

The obligation of the operators to report does not end with the shutdown of the facility – even if at that time, the hazard potential (▶ Safety considerations) is much smaller – but remains applicable the entire time 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.

For decommissioning of nuclear facilities, techniques are required for different processes: decontamination techniques, dismantling and disassembly techniques and other techniques, such as for 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 the dismantling work.

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

- Radiation protection aspects, in particular minimisation of the dose of staff,
- adequacy and effectiveness of the technique,
- furthest-possible ▶ clearance of residues and components,
- 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 (▶ Licensing and supervisory procedure).

7.1 Decontamination techniques

Decontamination techniques are used to remove fixed radionuclides (contamination). This improves radiation protection and is an important prerequisite for the utilisation of residual waste. 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.

Systems and rooms will be decontaminated prior to the start of dismantling work to reduce radiation exposure of personnel. This is often done not only by removing the superficially deposited radionuclides, but also a thin layer of the material itself. This way, any radioactivity that has penetrated into cracks or deposited in inaccessible areas is also removed.

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

The cause of the contamination may be due to direct contact with an activity-retaining medium (e. g. primary water). 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.

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 are, e. g. 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 (▶ Fig. 27).

Fig. 25: Chemical decontamination

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

Fig. 27: Sandblast decontamination

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 an area with high exposure to radiation or on highly activated parts, as e. g. in the activated core beltline region, this cannot be done manually on the spot but has to be performed by remote control – often under water (▶ Fig. 28). 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, e. g. 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.

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. 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 commercial ventilation and filter systems.

The most important thermal techniques are:

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

An example of remote-controlled thermal cutting is shown in ▶ Fig. 29.

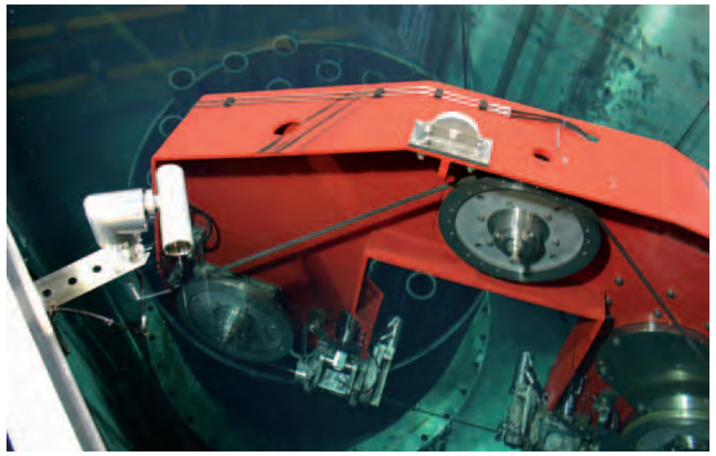


Fig. 28: Underwater cutting of components with a band saw

Fig. 29a: Remote-controlled thermal cutting (control room for remote-controlled work)

Mechanical disassembly techniques generate the kerf by removing material mechanically. In this case, 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 absorbed by filters. Mechanical cutting techniques are used for metals and building structures.

Important mechanical techniques are:

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

Fig. 29b: Remote-controlled thermal cutting (chamber for dry cutting)

7.3 Alternatives to on-site disassembly

Large components like steam generators and reactor pressure vessels are not always disassembled on site, but may be transported as a whole for further processing or for decay storage (▶ Decay storage, Page 26). 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 re-used to a large extent. The residual radioactive waste, which only accounts for a small proportion of the total mass, is returned to Germany.

Fig. 30: Transport of a steam generator to Sweden for melt-down

8 Residue and waste management

One of the most important tasks related 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 these aims (▶ 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.

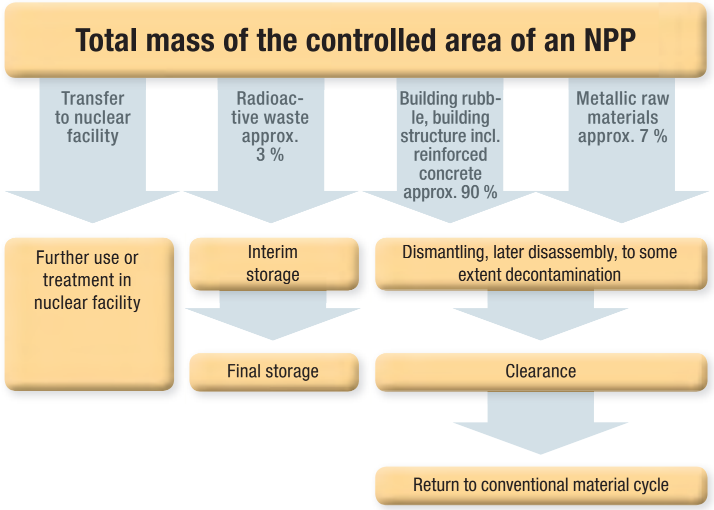


Fig. 31: Radioactive waste and residues

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 has to be put in interim and eventually final storage. As the decision is to be made for each individual piece, the material is usually sorted, as shown in ▶ Fig. 32.

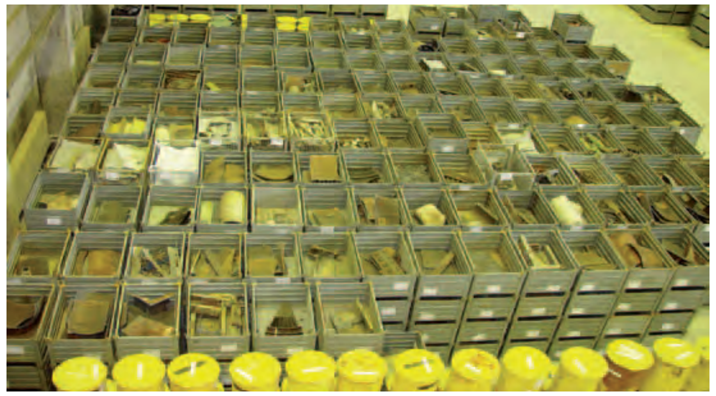


Fig. 32: Boxes with sorted residues for clearance

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 re-used for any purpose. Therefore, the clearance levels (▶ Table 2) for unrestricted clearance are extremely low compared to other options to ensure safety for all conceivable uses of the material.
- In case of »clearance for removal«, the material has to be passed on to a suitable conventional landfill or an incinerator facility. Owing to the waste-related legislation, there are only few material types that qualify for this, e. g. insulating wool, organic material, etc., in low amounts
- Other options of »restricted clearance« exist, e. g. for scrap metal intended for melting down in a conventional steelworks or a foundry, for large amounts of building rubble and excavated soil, for the buildings of the facility, and for the site.

Examples of the clearance values 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 fulfilled.

Nuclide	**Unrestricted**	**Restricted for removal**	**Restricted as scrap metal for melt-down**
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 values for selected radionuclides according to the Radiation Protection Ordinance

Clearance criteria

According to the opinion of international experts (e. g. 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 year. This requirement is stipulated in the Radiation Protection Ordinance and is consistent with the basic radiation protection standards of the EU. Such a dose is equivalent to less than one hundredth of the natural background radiation exposure of the population (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. They were determined by model calculations for about 300 radionuclides and the clearance options described above, and laid down in the Radiation Protection Ordinance.

Procedure for clearance

The clearance procedure is regulated by the authorities during which a number of quality-assurance measures will be performed. The competent nuclear authority verifies whether the steps of the procedure and the measuring methods applied (e. g. ▶ Fig. 33) 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. 33: Measurement for the clearance of waste

▶ Fig. 34 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.

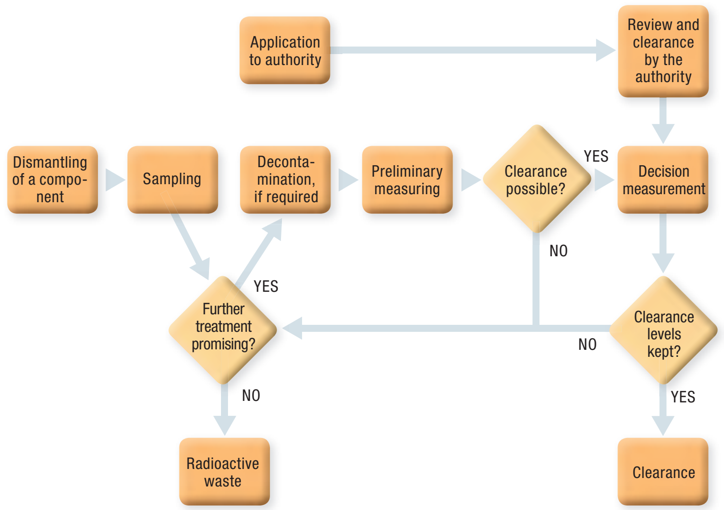


Fig. 34: Decision tree for the clearance of components

Clearance of buildings and soil areas

For the continued use or demolition of buildings of a nuclear facility after dismantling, these are also subject to clearance. Using an appropriate sampling method, the surfaces are checked for contamination (▶ Fig. 35). The methods applied to demonstrate compliance with clearance values require approval by the competent authority.

Fig. 35: Room with markings for determining the surface contamination

If the activity of a surface exceeds the applicable clearance values, one or more decontamination steps will follow. The clearance values for buildings and soil areas are also stipulated in the Radiation Protection Ordinance. If the building is not to be demolished, but continued to be used after decommissioning, the building is subject to unrestricted clearance, requiring the compliance with particularly low clearance values.

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. 36).

Fig. 36: Measurement for clearance of soil areas

8.2 Decay storage

For radioactive material with an activity above the clearance levels even after decontamination, decay storage (▶ Fig. 37) may be taken into consideration. With this approach, the material is stored until the existing activity is reduced sufficiently to reach the clearance levels.

Fig. 37: Decay storage of castings

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, etc.

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) 24,000 years. Radionuclides with much shorter half-lives (in the range of several days down to milliseconds) are insignificant in the context of decay storage.

For structures that have been activated by neutrons (e.g. ▶ Fig. 38), 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.

Fig. 38: Dose rate measurement

Fig. 39: Conditioning of waste (in-drum drying facility)

Fig. 40: Transport casks at the Interim Storage Facility North (ZLN)

8.3 Radioactive waste

All material that arises during dismantling of a nuclear facility and cannot be cleared or passed on to other nuclear facilities is radioactive waste. With respect to the total mass of the controlled area of a nuclear facility, which is about 150,000 tons for a power reactor, the amount of radioactive waste from decommissioning lies within 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 main contribution of radioactive waste from decommissioning originates from nuclear power plants and nuclear fuel cycle facilities. 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 waste in a repository. Until a repository will be available in Germany, conditioning (e.g. in a drum, ▶ Fig. 39) or interim storage are required. Therefore, local interim storage facilities (▶ Fig. 40) are erected during decommissioning of power reactors to accommodate all the radioactive waste from the dismantling of the facilities. Until 2005, the spent fuel assemblies from power reactors could be delivered to reprocessing plants. Since then, they have to be stored in a local interim 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 interim storage facility to a repository.

9 The costs

The costs of decommissioning and dismantling of nuclear facilities and the management of the resulting waste are borne by the owner of the facilities. Owners are:

- the private power utilities for the commercially operated nuclear power plants,
- the operating companies for 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 Greifswald and Rheinsberg being under decommissioning.

9.1 Costs borne by the power utilities

The power utilities finance the decommissioning and dismantling costs from reserves which are built up during the operating time by a surcharge on the price of electricity. This ensures that decommissioning and dismantling of the facilities is financially secured once electricity generation by the nuclear power plants has ceased.

The costs of dismantling of a commercial plant with a pressurised water reactor amount to around € 700 million. Since the design of boiling water reactors requires a larger controlled area, the costs of decommissioning of this reactor type are slightly higher.

According to the power utilities, the total amount of reserves accumulated by the end of 2010 for decommissioning and dismantling of the German nuclear power plants was about € 30 billion.

9.2 Costs borne by the public

In the last decades, the Federal Ministry of Education and Research (or its legal predecessor, 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 € 10-15 billion.

9.3 Total costs

If adding up the costs for all decommissioning projects that have already started and for the decommissioning of the plants still in operation, the resulting economic total costs on the basis of today's estimates lie at around € 50 billion. This sum does not include the costs of disposal of the radioactive waste from the nuclear power plants owned by the power utilities. These costs are distributed among the operators who need to build up reserves for this purpose, and the public sector.

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 2011, more than 50 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 conferences 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. Since 2009, these have been restructured and revised in the long term. This will be achieved by comprehensive developmental and consultation processes carried out by the IAEA member states with the participation of the competent nuclear supervisory authorities.

In addition, the IAEA publishes, as part of its activities to exchange experiences on decommissioning, 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 and thus part of the regulatory assessment. These have to be used by the German operators as a guide.

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. Among the 30 member countries (2011) from Europe, North America and the Asia-Pacific region there is also Germany. Together, the member countries account for approximately 85 % of the global nuclear energy production.

Within the NEA, numerous co-ordination, 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 (»best practices«) and to strengthen co-operation.

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 current state of the art such projects are feasible in a safe manner and in a time frame of about one decade. This finding is of considerable importance for the future decommissioning tasks in Germany: the decommissioning projects for the nuclear power plants and other nuclear facilities can also be carried out safely. What will remain in the end is the radioactive waste from dismantling. This must be disposed of safely.

Future tasks in Germany are the completion of the current decommissioning projects and the decommissioning of the nuclear facilities that are still operating once they have reached the end of their operating life. 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.

12 Annex

12.1 List on decommissioning of nuclear facilities in Germany

In 2011, 16 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. In 2011, another eight reactors were finally shut down and decommissioning will commence in the next years. It is planned to shut down the remaining nine power reactors by 2022.

29 research reactors and seven nuclear fuel cycle facilities have already been dismantled and released from the scope of application of the Atomic Energy Act.

Power and prototype reactors	*Abbrev.*	*Status at the end of 2011*
Jülich experimental reactor	AVR	Decommissioning since 1994
Biblis nuclear power plant, Units A and B	KWB	Shut down since 2011
Brokdorf nuclear power plant	KBR	Shutdown scheduled for 2021
Brunsbüttel nuclear power plant	KKB	Shut down since 2011
Emsland nuclear power plant	KKE	Shutdown scheduled for 2022
Grafenrheinfeld nuclear power plant	KKG	Shutdown scheduled for 2015
Greifswald nuclear power plant, Units 1-5	KGR	Decommissioning since 1995
Grohnde nuclear power plant	KWG	Shutdown scheduled for 2021
Gundremmingen nuclear power plant, Unit A	KRB-A	Decommissioning since 1983
Gundremmingen nuclear power plant, Unit B	KRB-B	Shutdown scheduled for 2017
Gundremmingen nuclear power plant, Unit C	KRB-C	Shutdown scheduled for 2021
Isar nuclear power plant, Unit 1	KKI-1	Shut down since 2011
Isar nuclear power plant, Unit 2	KKI-2	Shutdown scheduled for 2022
Krümmel nuclear power plant	KKK	Shut down since 2011
Lingen nuclear power plant	KWL	Safe enclosure since 1988
Mülheim-Kärlich nuclear power plant	KMK	Decommissioning since 2004
Neckarwestheim nuclear power plant, Unit 1	GKN-1	Shut down since 2011
Neckarwestheim nuclear power plant, Unit 2	GKN-2	Shutdown scheduled for 2022
Obrigheim nuclear power plant	KWO	Decommissioning since 2008
Philippsburg nuclear power plant, Unit 1	KKP-1	Shut down since 2011
Philippsburg nuclear power plant, Unit 2	KKP-2	Shutdown scheduled for 2019
Rheinsberg nuclear power plant	KKR	Decommissioning since 1995
Stade nuclear power plant	KKS	Decommissioning since 2005
Unterweser nuclear power plant	KKU	Shut down since 2011
Würgassen nuclear power plant	KWW	Decommissioning since 1997
Karlsruhe compact sodium-cooled nuclear reactor	KNK-II	Decommissioning since 1993
Karlsruhe multi-purpose research reactor	MZFR	Decommissioning since 1987
Hamm-Uentrop thorium high-temperature nuclear reactor	THTR-300	Safe enclosure since 1997

Research reactors	*Abbrev.*	*Status at the end of 2011*
Karlsruhe, research reactor 2	FR-2	Safe enclosure since 1996
Geesthacht research reactor 1	FRG-1	Shut down since 2010
Geesthacht research reactor 2	FRG-2	Shut down since 1995*
Jülich research reactor 2	FRJ-2	Decommissioning applied for in 2007
München research reactor	FRM	Decommissioning applied for in 1998
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 Berlin	SUR-B	Decommissioning since 2008

Nuclear fuel cycle facilities	*Abbrev.*	*Status at the end of 2011*
Rossendorf facility for the production of Mo-99	AMOR I-III	Decommissioning since 1997
NUKEM-A fuel fabrication plant	NUKEM-A	Decommissioning since 1993
Siemens Power Generation Karlstein	SPGK	Decommissioning since 1993
Karlsruhe vitrification plant	VEK	Shut down since 2010
Karlsruhe reprocessing plant	WAK	Decommissioning since 1993

**FRG-2 has been 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 Outline 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 (▶ 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 atomic 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 until about the year 2012 and that it will be released from the scope of the Atomic Energy Act by that time. The extent of dismantling work (among others ▶ 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 in the so-called Interim Storage Facility North (ZLN) for decay storage (▶ Fig. 42).

Fig. 41: 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, robust manipulator systems are to be preferred.

Stade nuclear power plant

The Stade nuclear power plant was the first purely commercial pressurised water reactor of the Federal Republic of Germany. 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 residual operation within the framework of its dismantling. The steam generators of the Stade nuclear power plant were transported as a whole to Sweden for melt-down. The components non-reusable due to their radioactivity (i. e. the slag and a fraction of the produced castings) are returned to Germany as radioactive waste.

Fig. 42: Decay storage of large components at the Interim Storage Facility North (ZLN)

THTR-300

The 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 – in addition to the Lingen nuclear power plant (KWL) – one of two nuclear power reactors that are currently under safe enclosure. For the Lingen nuclear power plant it was decided to prematurely terminate safe enclosure. Thus, at present, the THTR-300 is the only power reactor for which safe enclosure for a period of 30 years (beginning 1997) is to be realised. 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.

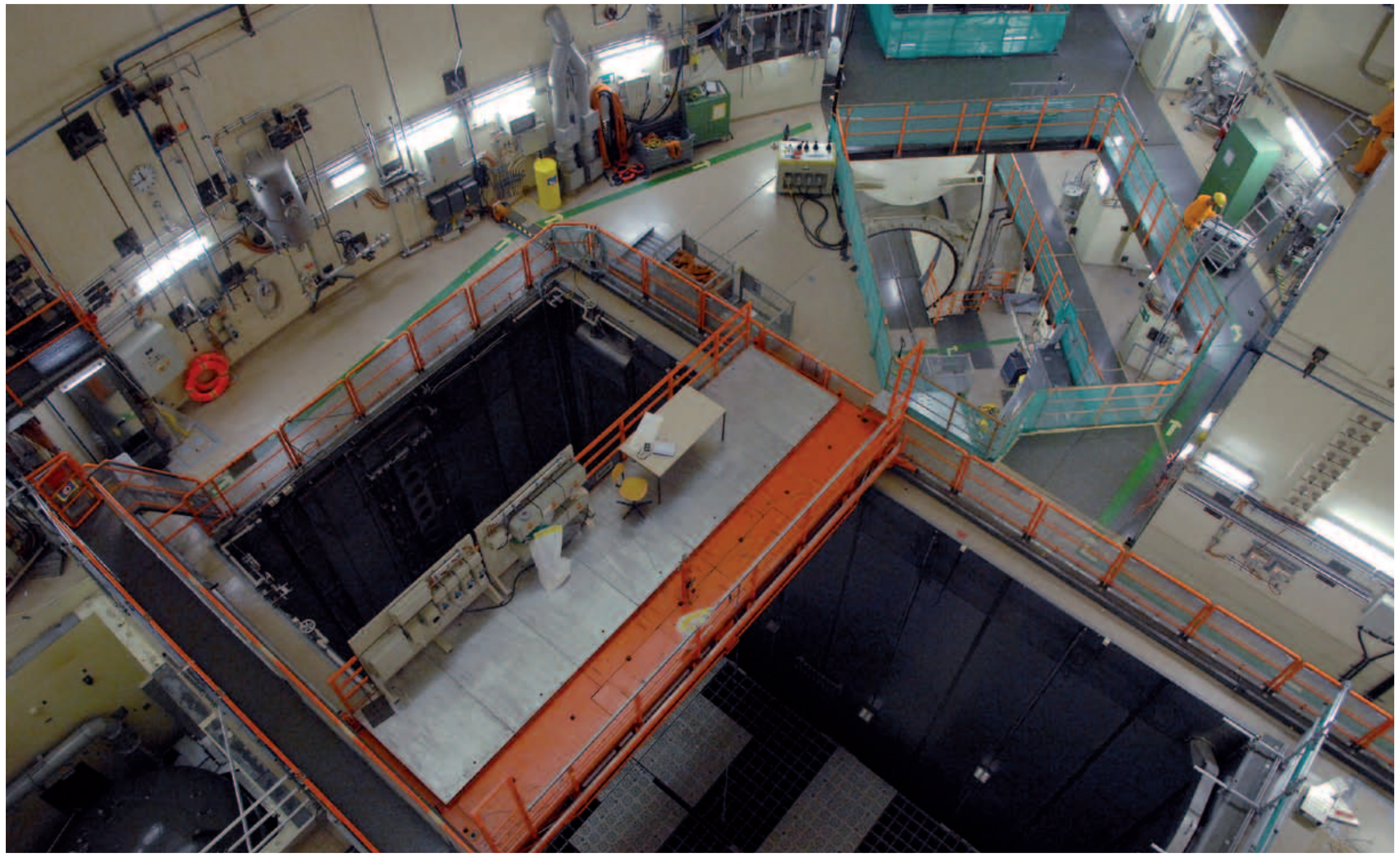
Mülheim-Kärlich nuclear power plant

The Mülheim-Kärlich nuclear power plant (KMK, ▶ Fig. 43) was built between 1975 and 1986 as a 2-loop pressurised water reactor with a capacity of 1,302 MWe and is located approximately 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 to finally decommission the plant within the framework of the nuclear phase-out in Germany planned in 2001. 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 time. In addition, the activity inventory continued to decrease due to the long shutdown period by radioactive decay.

Fig. 43: The empty fuel storage pool of the Mülheim-Kärlich nuclear power plant



FR-2 research reactor in Karlsruhe

The FR-2 – the first German research reactor in Karlsruhe – also marks the beginnings of the Forschungszentrum 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 unit was achieved (▶ Decommissioning strategies). With the exception of the reactor unit, all radioactive components have been removed from the plant. Supporting and auxiliary systems as well as buildings that were no longer of any use have been 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.

Triga HD I and Triga HD II research reactors

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, direct 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
The legal basis for the use of nuclear energy and decommissioning in Germany on which, among others, the Radiation Protection Ordinance 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 positrons). This occurs during a particular radioactive decay (beta decay).

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

BMU
Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

BWR
Boiling water reactor (water-moderated).

Chain reaction
Process in which neutrons generated during the fission of atomic nuclei, in turn, split more atomic nuclei.

Clearance
Administrative act by the nuclear regulatory authority that regulates the release of material, buildings or the site of nuclear facilities from being subject to the Atomic Energy Act.

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
It is said that a nuclear reactor is 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. 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.

ESK
Entsorgungskommission
Nuclear Waste Management Commission
A panel of independent experts that advises the Ministry for the Environment 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.

Interim storage facility
Storage facility (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.

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).

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 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 whose activity cannot be disregarded according to the provision 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 close to the core.

Repository
Storage facility for radioactive waste or spent fuel to be built deep underground. 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 reactor
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.

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

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.

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

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.

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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