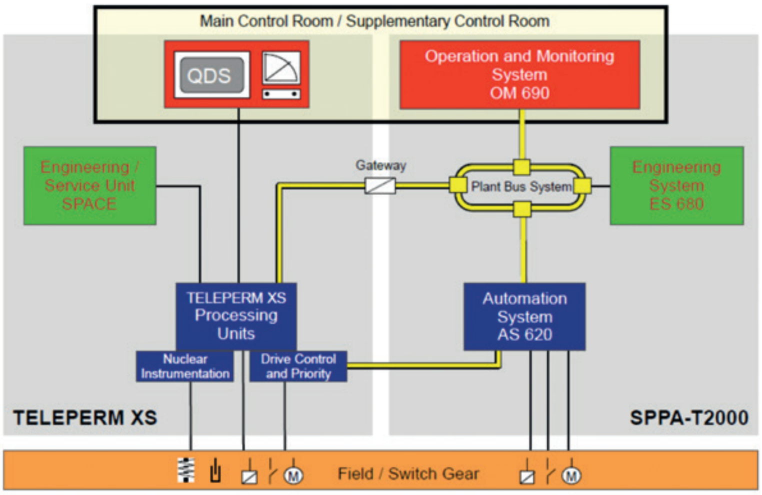

| **Abb. 18.**
Übersichtsbild zum digitalen Leittechnikkonzept von AREVA & SIEMENS.

Überarbeitete Fassung eines Vortrags, gehalten auf dem

Revised version of a paper presented at the

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bestimmt, d.h. die Verkürzung der Revisionszeiten macht keinen Sinn, wenn der Einkaufspreis für Elektroenergie kleiner ist als die Stromerzeugungskosten im Kraftwerk, so wie es häufig im Sommer in Deutschland und deren Nachbarschaft, wie der Schweiz, verstärkt der Fall ist.

In Bezug auf Post-*Fukushima*-Produkte erhält *AREVA* aufgrund der Behördenforderung viele Nachfragen aus den Ländern, wo es diesbezüglichen Nachrüstbedarf gibt. Das sind Japan, Spanien, Belgien aber auch China, Russland, Ukraine, Taiwan und Korea. Frankreich setzt aktuell auf Flottenmodernisierungen. Schweden und die Schweiz haben zwar einige größere Modernisierungsprojekte geplant (z.B. in *Forsmark* oder *Gösgen*), gehen diese aber meist schrittweise an. *AREVA* unterstützt dabei in den ersten Planungsphasen.

Allerdings zeigt die Erfahrung, dass in Summe ein Betreiber in der Krise über zehn Jahre mehr Geld ausgibt, wenn er immer nur improvisiert, anstatt einmal mit einer umfassenden Modernisierung die Grundlagen für einen langfristig sicheren Betrieb zu legen.

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Nuclear Power Plants: Safe and Efficient Decommissioning

Helmut Huger and Richard Woodcock

1. Introduction Project experience and independent expertise are the key factors for success when decommissioning and dismantling nuclear facilities. Time and again, unforeseen events lead to delays and it becomes necessary to make planning or scheduling changes during implementation. The reasons for such changes may be safety related, legal or political. Authorities, operators and service providers then have to analyse and solve a large number of interdisciplinary tasks reliably and sometimes under severe time pressure. In practice this is made more difficult if, for example, the documentation for the plant or project sequences are incomplete, laws and regulations are open to different interpretations, or there is a lack of qualified staff with experience of handling these problems. Bottlenecks occur here in particular, both in countries which are only just embarking on decommissioning and also in countries which already have nuclear expertise and the necessary infrastructures.

More than 400 nuclear power plants, research reactors and pilot plants have already been retired from operation worldwide. Some of these have already been fully dismantled (*World Nuclear Association WNA*, London, status: March 2014). An equal number are still operating (*International Atomic Energy Agency IAEA*, Vienna, status: March 2014). While the majority of facilities are decommissioned and dismantled at the planned end of their operating period, cases of premature decommissioning and dismantling due to technical, economic or political developments also have to be included in the considerations. As a result, the transformation of the German energy market between 2015 and 2030 will lead to a peak in decommissioning which could bring with it considerable bottlenecks both for the authorities and also for operators and service providers. Demand is also growing, however, in other countries. In view of this, it is even more vital to prepare projects in good time and with care.

Weighing strategies, monitoring phases

The decision regarding the optimum decommissioning option should ideally be taken in the planning phase of a nuclear facility and should take into account any resulting measures during its construction. This is not always guaranteed, particularly in the case of existing facilities. Three high level decommissioning strategies are used worldwide and combinations of these are used on a case-by-case basis. (see also **Figure 1**)

Immediate dismantling enables the site to be reused at the earliest possible opportunity. However, the work is technologically demanding because some components have to be dismantled by means of remote handling due to the radiation fields prevailing immediately after the end of operation. As experience has shown, the individual process steps extend over a period of approximately ten years. This period varies depending on the reactor type and decommissioning planning. As decommissioning follows on immediately from the post-operational phase, there are still sufficient numbers of qualified staff, who are familiar with the facility, available for this task. As a result, valuable knowledge of special operating conditions and the history and behaviour of components can be incorporated in the decommissioning project. At the same time, continued employment minimises the social and economic consequences for the operating staff and the region. However, a solution for interim storage or treatment or final disposal of the higher activity wastes produced must be in place or taken care of externally.

Safe enclosure with deferred dismantling uses the natural decay of radioactivity over a period of several decades. At this point the radiation exposure within the nuclear plant has decreased to such an extent that, on one hand, the volume of radioactive residual materials has reduced while on the other hand, the expense for the dismantling work is lower and any improved technologies developed in the meantime can also be utilised. Added to this, the investments for dismantling occur later. Unlike immediate dismantling, however, it is mostly no longer possible to fall back on staff who were familiar with the facility during its commercial operation period. In this case, the metrological requirements for the radiological assessment are higher than for immediate dismantling. Further challenges relate to ageing of the facility's existing infrastructure which is necessary for dismantling, and also in part to the non-availability of appropriate spare parts or to the lack of components of adequate quality.

Entombment involves the permanent safe containment of the facility on site. High active fuels are removed in advance. Low active components are gathered together in one area of the plant, embedded in concrete and left there. The process has the least risks for health and safety and sometimes cost benefits but does not solve the facility's waste management problem for a foreseeable period. Longterm monitoring is also necessary. Entombment is not legally permissible in all countries.

Interdisciplinary challenges

In addition to enormous technical, logistical and organisational challenges, decommissioning also includes a large number of financial, legal and political aspects which depend not least on social developments. A sound overall option stands out in that it is both technically and commercially feasible and also suitable for licensing. It is not just the facility itself that has to be converted and made accessible so that the components can be dismantled and transported off-site. It is also necessary to realign the whole operational organisation towards a new corporate purpose and also to obtain the employees for this. One of the difficulties that has to be overcome in this period is the change of mindset of the workforce from one of looking after plant and equipment (in the operational phase) to preparing to dismantle and remove (in the decommissioning phases). Close cooperation between the authorities and all those concerned is essential in terms of project management and quality management. This applies particularly where there may be different points of view or where differences arise between the project partners. Overall, time is an important factor here. Every delay causes additional costs. This incurs not only staff costs but also sometimes cost-intensive safety precautions and periodic inspections.

IMMEDIATE DISMANTLING	SAFE ENCLOSURE AND DEFERRED DISMANTLING
ADVANTAGES	
▪ Employees familiar with the facility and its operating history are available	▪ Technically simplified dismantling due to lower radiation exposure
▪ Mitigation of social consequences for the employees	▪ Radioactivity decreases over time
▪ Mitigation of economic consequences for the region	▪ Lower volume of radioactive residual materials
▪ Site usable earlier for other purposes	
DISADVANTAGES	
▪ Higher radioactivity still present	▪ New qualified staff required for decommissioning
▪ Technically complex dismantling due to higher radiation exposure	▪ Metrological effort and expense for radiological assessment increases with time
▪ Solution for interim storage or treatment or disposal of higher activity wastes must be in place.	▪ Availability of spare parts and components made more difficult to some extent

Fig. 1.
Decommissioning options with advantages and disadvantages (Source: TÜV SÜD AG).

2. Forward planning

Just like construction and operation, decommissioning also requires a licence. After shutting the plant down and until the first decommissioning licence is received, a nuclear power plant is considered to be in the post operational phase. In the meantime, the plant continues to be subject to the valid operating licence. During this time, measures for decommissioning can be planned and prepared:

- unloading of the fuel assemblies
- and their transfer to interim storage,
- adaptation of written operational regulations
- and reversible isolation and shutting down of systems which are no longer necessary from a safety related and operational point of view.

Basically, no changes can be made in the post-operational phase that are incompatible with the operating licence and its conditions. Thus it is not permissible to dismantle components that are necessary for safe operation of the power plant. Measures which signify the ultimate end of commercial operation require a decommissioning licence.

Selection of the decommissioning option

A first step in decommissioning planning is deciding on the right decommissioning option: immediate dismantling, safe enclosure with subsequent dismantling or entombment. The decommissioning option determines the general dismantling of the plant and further detailed planning.

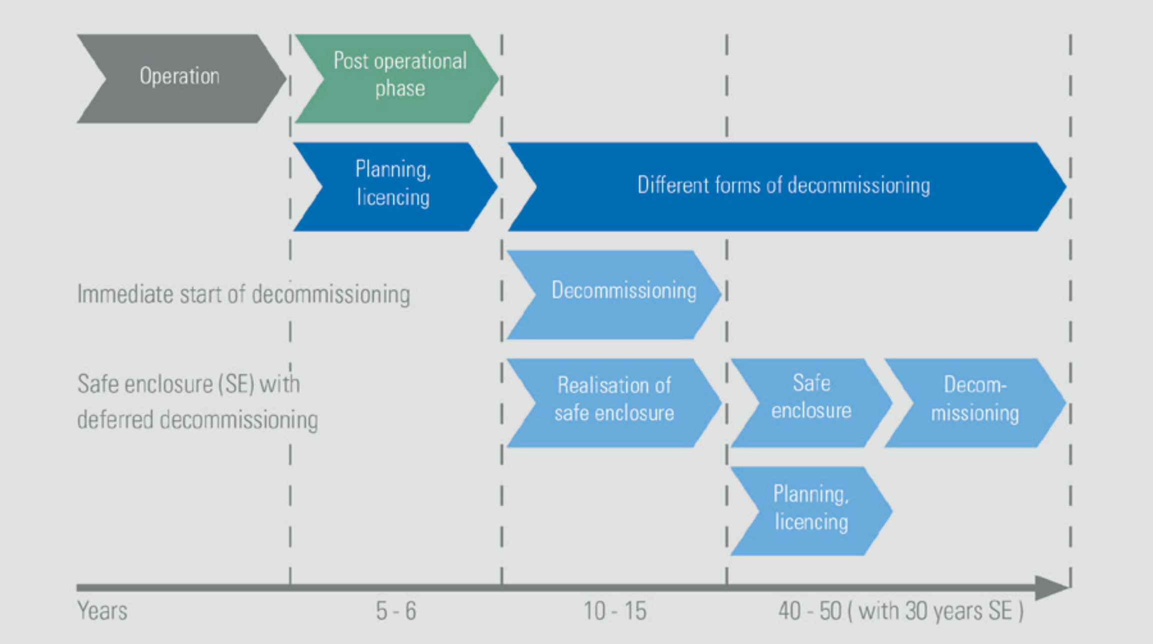

Fig. 2.
Different forms of decommissioning (Source: TÜV SÜD AG).

This includes, for example, incident analysis, aspects of radiological protection, dealing with residual materials arising, but also fire protection and ultimate withdrawal from the plant **(Figure 2)**.

A series of basic radiological, legal, ecological and economic conditions are taken into account when assessing the decommissioning options. The top priority is complying with nuclear safety targets in respect of safety, health and the environment. To do this, it is necessary to plan the chronological sequence of decommissioning carefully, to consider possible incidents, to make allowance for interdependencies and particularly to investigate radiological aspects of components with a high dose rate. Basically, the individual decommissioning steps must not make future measures more difficult or impossible. Experience gained from previous decommissioning projects is particularly valuable here.

In practice, it is not only radiological aspects and the type of power plant that should be considered in the technical assessment of the decommissioning options. Routes for residual material streams, the availability of an interim storage facility or final repository and sufficient space, e.g. for the use of remotely controllable systems, must all be taken into consideration. This also applies to the equipment for dismantling and conditioning components, and to decontamination areas. Independent experts appreciate the need for the right characterisation and that adequate front end definition is undertaken for a decommissioning and waste management project. They deploy a number of tools to facilitate this such as Data Quality Objective (DQO) process, Process Wiring Diagrams (PWD), Technical Baseline Underpinning Research and Development (TBuRD).

Measures during the post-operational phase

First of all the radiological, physical and chemical actual condition of the plant is determined in preparation for decommissioning. For this purpose, measurements are taken in all areas of the plant and samples are taken and evaluated. This provides a detailed overview of the radioactive and non-radioactive waste inventory. It is essential for the further planning of decommissioning and for selecting the best possible techniques for decontaminating, conditioning, dismantling and transporting the components. By removing the fuel assemblies and thoroughly decontaminating the reactor coolant system and other systems, it is possible in many cases to remove over 90 or up to 99 percent of the activity inventory which considerably simplifies the further course of decommissioning.

During the subsequent decontamination of components, both chemical processes as well as sandblasting, high pressure water jet cleaning, milling and dismantling techniques are used. In the dismantling processes, the focus is on large components such as the steam generator, reactor pressure vessel with internals, concrete slab, large concrete casks and the reinforced concrete cylinder (biological shield). Remotely controlled techniques have proven effective in practice. They include mechanical and also thermal processes, such as oxy-acetylene cutting and plasma cutting.

Radioactive residual materials and waste originating from the operating period can be removed in the post-operational phase. To this end, the waste properties and quantities are first assessed to determine optimised treatment routes for each of the different types of waste. The aim is to reduce both the quantity and also the volume as far as possible. Depending on the type of waste, the conditioning processes of pressing, burning, drying and cementing can be used or they can also be used in combination. It may be necessary to construct new infrastructures in order to condition and store waste on site. In addition to equipment for processing, conditioning and decontaminating, this may include measuring rooms, workshops and stores for conventional materials.

It is essential to understand the physical, chemical and radiological aspects of the waste that will be produced, the challenges that these will pose and the subsequent wasteroute requirements. This means that underpinning work, to ensure routes that are compliant with regulation and legislation are in place, is understood and planned appropriately.

As important parameters change, it is necessary to reclassify systems for the post-operational phase according to the safety analysis. This is where experts determine and assess possible events which might occur during the post-operational phase according to their safety risk. The investigation includes both systems which are necessary for operation and for maintaining safety and also those which no longer have any operational significance. Reclassification has an impact on the reporting process, classification of the change project and the scheduling of periodic inspections and maintenance procedures. Safety related classification of the system must be constantly updated beyond the post-operational phase and also during decommissioning.

Changed organisational processes

Basic requirements for organisation continue to exist even during the post-operational phase and decommissioning. Although postoperation mainly requires no change to the organisational structure, it does require a change in expertise. As a result, simulator training is dropped and there are fewer technical requirements for knowledge of systems and incidents. At the same time, there are changes to specific requirements for the operating regulations.

Organisational changes are also added during commissioning. In practice it has proven effective to create separate departments for residual operation, decommissioning and monitoring. Central operations units covering units and sites can also be useful, e.g. for monitoring. Basically, interfaces and responsibilities must be clearly defined between residual operation, the systemic areas and dismantling or waste management. Shifts in tasks and duties are unavoidable during post-operation and decommissioning. For example, the area "core design" is scrapped while areas for dismantling and waste management are built from scratch. After the fuel assemblies are removed from the plant, the focus generally shifts to decommissioning. This requirements for radiological protection, site security and quality management still continue to apply.

Country-specific licensing procedures

The basic legal conditions for the decommissioning of nuclear facilities differ throughout the world. There is normally a multistage hierarchy of national regulations and regulatory application and approval processes. These include higher level constitutional laws, Atomic Energy Acts and generally binding ordinances as well as administrative regulations for authorities, notices and announcements by ministries and nuclear regulations and guidelines.

Application and approval processes which differ from country to country also arise from the various basic nuclear conditions. However, they all have in common the orientation towards internationally recognised safety targets, such as the safety of people and the environment. For this it is necessary to demand extensive evidence, e.g. in the form of safety and accident analyses as well as studies on fire and radiological protection. Profound knowledge of the national regulations and approval processes is essential so that decommissioning applications can be processed and granted speedily and efficiently.

3. Integrated implementation

From the outside in or from the inside out

It is possible to decommission from the outside in or from the inside out. In the first case, professionals initially dismantle plant sections in the non-contaminated or low activity area. Following this, they dismantle components with higher activity, e.g. pipes and fittings, and finally also activated parts such as reactor internals and reactor pressure vessel together with concrete shielding. The remaining operating systems are then dismantled. Decontamination and release measurement for clearance of the remaining building envelopes take place when the building is empty. After this the buildings can be released for conventional use or for demolition of the buildings and reclamation of the power plant site.

In the second case, dismantling starts with the highly contaminated components inside the plant and progresses towards low active and uncontaminated plant sections. Both approaches have advantages and disadvantages. And any decision should always be made taking the individual parameters into account. The construction method and position of the components in the plant in addition to basic external conditions are important.

In safe enclosure, contaminated components are first dismantled outside the planned enclosure area in order to minimise the so-called controlled area which is surrounded by a monitored area. Different permissible radiation doses are defined for both areas. System interfaces are sealed off while activated structural components remain in the installed position. These are the reactor internals, the reactor pressure vessel and the concrete shielding

Around five years should be scheduled to establish safe enclosure. The duration of the enclosure is usually 30 years. It is necessary to continue operating vital systems such as ventilation and monitoring equipment during the enclosure period. The enclosed power plant also has to be monitored for the entire period. In the meantime, an application can be made for the decommissioning permit to dismantle the remainder of the plant. A period of approximately ten more years can then be assumed for complete decommissioning. The process runs similarly to immediate dismantling, although it is sometimes necessary to establish other infrastructures or to upgrade those existing.

Meshed decommissioning phases

The masses arising depending on the type of power plant which vary between 150,000 and 250,000 Mg (one megagram equates to one metric ton) present significant logistical challenges. Many nuclear power plants

Preparing for Decommissioning

- Recycle and remove radioactive residual materials arising from the operating period
- Decontaminate plants and systems (e.g. reactor coolant system)
- Reversibly isolate and take out of service safety related systems no longer required for operation
- Adapt written operational regulations
- Unload fuel assemblies and transfer to the interim storage facility
- Record the actual condition of the plant

were not originally designed to transfer such volumes of material out of the buildings. The following measures, among others, are necessary to enable safe dismantling and efficient transportation:

- Create transport routes and interim storage areas,
- Construct lifting systems, infrastructure equipment and conditioning centres,
- Identify release measurement areas and
- Provide storage facilities.

Last but not least, decommissioning is divided into phases in terms of logistical planning and project management. The transition between the individual phases is not always clear in practice because to some extent they mesh with each other. To counter any project delays at a later stage, it is advisable to have decommissioning monitored by external experts who have interdisciplinary experience. In close collaboration with the client, they are able to closely monitor the project with an overview of the project subsections which also prevents any interface problems. This also includes reliably coordinating communication between authorities, operators and service providers. Experience also shows that the volume of residual materials arising changes dynamically over the course of decommissioning. The material streams have to be planned carefully in advance to minimise follow-up work and additional expenses. This may also require new buildings to create storage capacities.

Adapted safety concept

The safety concept for a plant must be reassessed during the transition from commercial operation to the post-operational phase and decommissioning. This is partly necessary due to the changed operating parameters and partly because of the possible consequences for people and the environment which can still be caused by events during decommissioning phase even if the plant is already free of fuels.

There is a need to analyse and carefully assess possible events which could arise during the postoperational phase in order to minimise any risks. These include internal hazard like

- mechanical impact and load crash,
- In-plant leaks and flooding,
- Thermal and chemical impacts,
- Failure of safety-related systems (including ventilation and fire protection)

Or external events such as

- earthquakes or subsidence damage (natural) or
- aircraft crashes (man-made)

The nature and scope of the protective measures required are usually determined by the applicable regulations and are specified in detail by the relevant licensing authority. This means considering the potential extent of losses on a case by case basis. It includes studying the probable sequence of events and calculating the possible activity released and any radiation exposure.

Although basic requirements for fire protection and ventilation exist even during decommissioning, they do, however, shift from safe operation of the reactor towards the protection of people. As a result, there are frequently greater numbers of staff on site during dismantling work which must be considered not least with regard to escape and rescue routes. At the same time, as fire loads, such as oils and cables, are progressively removed, the fire fighting sections can be lifted and fire detectors and extinguishing equipment can be taken out of service. However, decommissioning may also require the installation of new fire detectors and extinguishing systems.

The requirements for fire protection apply equally to ventilation in that the range of potential incidents is identical to that during commercial operation but the potential risks differ due to the changed parameters. The main task of ventilation for the enclosure of radioactive materials also continues during decommissioning. The supporting function, e.g. for convection cooling and heat removal, decreases significantly towards the end of commercial operation. As is the case with fire protection, the requirements for ventilation pass over to the use of conventional regulations as decommissioning progresses, e.g. for plant areas where there is no longer any need to hold back radioactivity.

It is also necessary to reassess transport technology, electrical engineering, control and instrumentation and structural engineering within the context of plant safety. Experts for structural design, soil and seismology analyse impacts on structures, including load crashes, flooding, jet forces, temperature and pressure loads, floods and aircraft crashes. Delays, particularly at critical interfaces, such as between structural and plant engineering, can be prevented by carefully coordinating consultation processes between operators and authorities.

In the specifications for radiological protection and waste management, it is necessary, depending on the country, to comply with various laws which are in turn embedded in international regulations. These include recommendations by the *IAEA*, the *International Commission on Radiological Protection (ICRP)* and the *Nuclear Energy Agency (NEA)* or the European "Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste".

4. Conclusion

Decommissioning and dismantling of nuclear facilities are complex large-scale projects with enormous interdisciplinary challenges and often high project risks – particularly with regard to unforeseen additional expenditure in time or budget. In addition to technical and logistical aspects, which have to be carefully coordinated, this mainly concerns extensive legal requirements and processes for licensing. These requirements differ from country to country and are sometimes open to different interpretations.

Independent experts understand the challenges of decommissioning due to their experience in delivering complex projects worldwide. They provide impartial expertise in the areas of assessment, testing, inspection, licensing, certification and training. As many years of experience have shown, interdisciplinary expertise and knowledge of local laws, regulations and authorities are crucial factors for successful multi-project management when decommissioning and dismantling nuclear facilities. In this case, the close cooperation of authorities, operators and their service providers is a fundamental requirement.

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