# Radiation Protection during Decommissioning of Nuclear Facilities – Experiences and Challenges

**Kaulard, Joerg; Brendebach, Boris**

Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS), mbH,
Schwertnergasse 1, 50667 Cologne, Germany

## Abstract

Decommissioning is the final phase of the life cycle of any nuclear facility. Today more than 450 facilities (nuclear power plants, research reactors) are finally shut down or under decommissioning or for which decommissioning has been already completed all resulting in different technical and radiological end-states. As especially more and more nuclear power plants reach the end of their technical life time and thus will be finally shut down the number of decommissioning projects will increase in the next years. Radiation protection of workers and the public – together with the management of radioactive waste and of spent fuel (if any is available) – is the central challenge during each decommissioning project. Depending on a manifold of influencing parameter, e.g. radiological inventory, complexity of the nuclear facility, decommissioning strategy or approach to structure the project, measure of radiation protection are different and specific for each individual decommissioning project.

Within this contribution to the 13th International Conference of the International Radiation Protection Association an overview on experiences on radiation protection and best practice concluded from past decommissioning projects will be given and an outlook on future challenges in radiation protection during decommissioning will be provided. A special emphasis is laid on the selection of decommissioning techniques, i.e. dismantling and decontamination technique, and on international activities to collect related radiation protection experiences.

**Key Words** Decommissioning; Decommissioning Strategy; Occupational Exposure;

## 1. Introduction

Decommissioning is the final phase in the life cycle of a nuclear facility. Decommissioning aims to transform the nuclear facility into an end state complying with national regulatory requirements, typically on clearance and release of the nuclear facility or its remaining parts and of the site from regulatory control (e.g. [1], [2], [3]). Especially in case of nuclear power plants and large research reactors the transformation process comprises inter alia the decontamination of radioactive contaminated systems and components and full or partial dismantling of the structures, systems and components.

Following international standards decommissioning of a nuclear facility can follow three different decommissioning strategies [4] or combinations of them:

1. immediate dismantling
   "*...strategy by which the equipment, structures and parts of a facility containing radioactive contaminants are removed or decontaminated to a level that permits the facility to be released for unrestricted use, or with restrictions imposed by the regulatory body. In this case decommissioning implementation activities begin shortly after the permanent cessation of operations. This strategy implies prompt completion of the decommissioning project and involves the removal of all radioactive material from the facility to another new or existing licensed facility and its processing for either long term storage or disposal.*"
2. deferred dismantling
   "*...strategy in which parts of a facility containing radioactive contaminants are either processed or placed in such a condition that they can be safely stored and maintained until they can subsequently be decontaminated and/or dismantled to levels that permit the facility to be released for unrestricted use or with restrictions imposed by the regulatory body.*"

3. entombment
   *"...strategy by which radioactive contaminants are encased in a structurally long lived material until radioactivity decays to a level permitting the unrestricted release of the facility, or release with restrictions imposed by the regulatory body."*

The decision on the decommissioning strategy for an individual nuclear facility depends on a variety of parameters which need to be balanced as they are to some extent competitive. Examples on such parameters and on a study related for two research reactors can be found in [5], [6] and [7]. In most countries only immediate dismantling or deferred dismantling are applicable and applied – entombment is a specific strategy which from a technical point of view may be regarded as a near surface disposal option.

The planning of the decommissioning activities, associated by safety assessments (ref. e.g. [8]), has to ensure, that

1. radioactive material is confined, even if step-by-step physical and technical barriers will be removed as the decommissioning will proceed, and
2. the exposure of the personnel and of the public and the environment is limited and kept ALARA.

For decommissioning the same dose limits and radiation protection principles hold as for the operation of a nuclear facility. Practice shows, that – depending on the type of facility and decommissioning strategy – typically the exposure situation during decommissioning is lower than during operation.

Especially in case of nuclear power plants and research reactors decommissioning activities may be already commenced while spent nuclear fuel is still at the facility. In these cases the planning has to consider that nuclear criticality is controlled and prevented at any time and any decay heat can be processed both in a reliable and safe manner.

During planning of the decommissioning activities and concretization of the details of the activities to be performed, several key aspects will require careful consideration, inter alia:

1. continuously changing facility;
2. feasibility and reliability of the decontamination and dismantling techniques to be used;
3. safety during conduct of the activities;
4. radiation protection of the personnel and of the public during conduct of the activities; and
5. management of large quantities of material, especially of radioactive material, radioactive waste, material released from regulatory control (by means of a clearance process).

Not limited to, aspects of safety, radiation protection and management of large quantities of material strongly depend on an appropriate knowledge on the radioactive inventory. For large and complex nuclear facilities such knowledge usually can not be gained in total at the beginning of the decommissioning but must be build up stepwise. In these cases phased approaches for the decommissioning project help to gain the information and support an effective conduct of the decommissioning.

Within this contribution to the 13$^{th}$ International Conference of the International Radiation Protection Association the following aspects are discussed in more detail:

- Occupational exposure during decommissioning, due to the availability of related data this overview is limited to the decommissioning of nuclear power plants (section 2);
- Aspects on daily radiation protection challenges during decommissioning (section 3);
- Experiences from past and current decommissioning projects (section 4); and
- Future Challenges (as part of the conclusions in section 5).

## 2. An overview on occupational exposure during decommissioning of nuclear power plants

The Information System on Occupational Exposures (ISOE), jointly hosted by the International Atomic Energy Agency (IAEA) and OECD Nuclear Energy Agency (NEA), operates the worldwide unique database on occupational exposure in nuclear power plants [9]. Figure 1 presents the average annual collective dose for most of the NPPs worldwide in operation and in cold shut down / under decommissioning. The figure shows that for average data the annual collective dose for nuclear power plants in cold shut down / under decommissioning is since 1990 lower than for nuclear power plants in operation. It is important to notice that the average collective dose for cold shut down / decommissioning depends on the annual contributions from up to 70 units. In addition, depending on their decommissioning schedule the contributions by one NPP can vary significantly; this is true also for NPPs in operation and their changing outage programs, but during operation of NPPs a core set of similar activities can be expected from year to year for one NPP or even a fleet of similar NPPs. Accordingly, no fixed ratio between the average collective dose of NPPs in operation and the average collective dose of NPPs in cold shut down / under decommissioning can be expected.

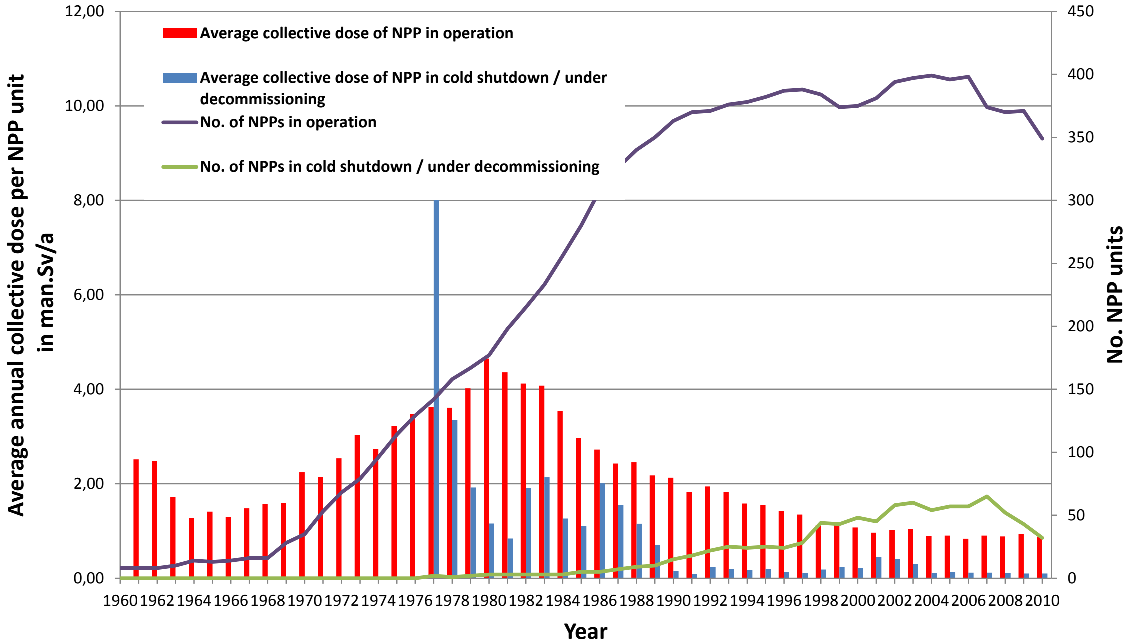



**Figure 1** Average annual collective dose of NPPs worldwide [10]

On a national scale, data from German nuclear power plants under operation and under decommissioning show the same systematic. Figure 2 shows the corresponding data. In addition, Figure 3 shows the annual collective dose for the life time of a German nuclear power plant. The data show inter alia that

(a) the doses during operation are higher than the doses during decommissioning; and

(b) the doses during decommissioning vary strongly, but on a significant lower level than during operation.

The later is a consequence from the changing work program for a NPP under decommissioning. As the exposure – similar to operation – strongly depends on the work activities the contributions will vary. Typically (refer to section 4) the decommissioning work will start in the outer regions of a nuclear power plant, which can be characterized with less dose rates and contaminations and – at the early period of decommissioning – with less handling of radioactive material, the collective doses can be expected to be lower than during the later conduct of the decommissioning activities.

During decommissioning both, utility personnel and contracted personnel are involved in activities. Depending on the work activities the number of contracted personnel can vary significantly. Consistent with the lower average annual collective dose for NPPs in cold shut down / under decommissioning the mean effective dose for the utility personnel and the contracted personnel are generally lower during decommissioning than during operation (see e.g. [11]).

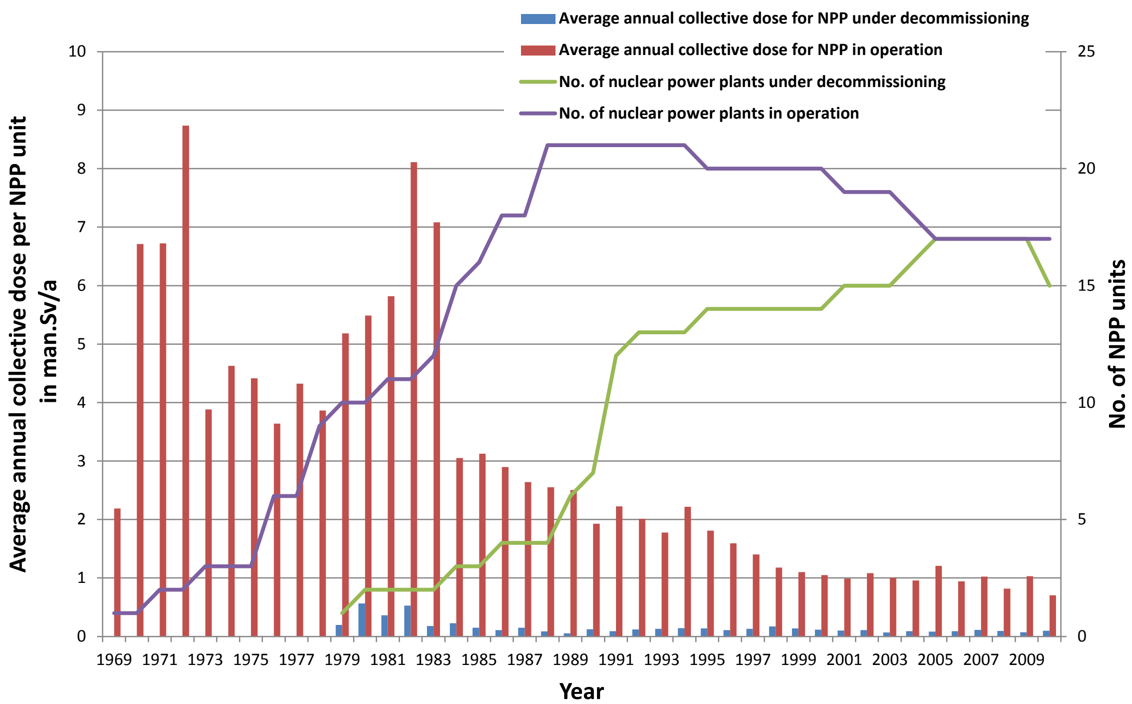



**Figure 2** Average annual collective dose of German NPPs

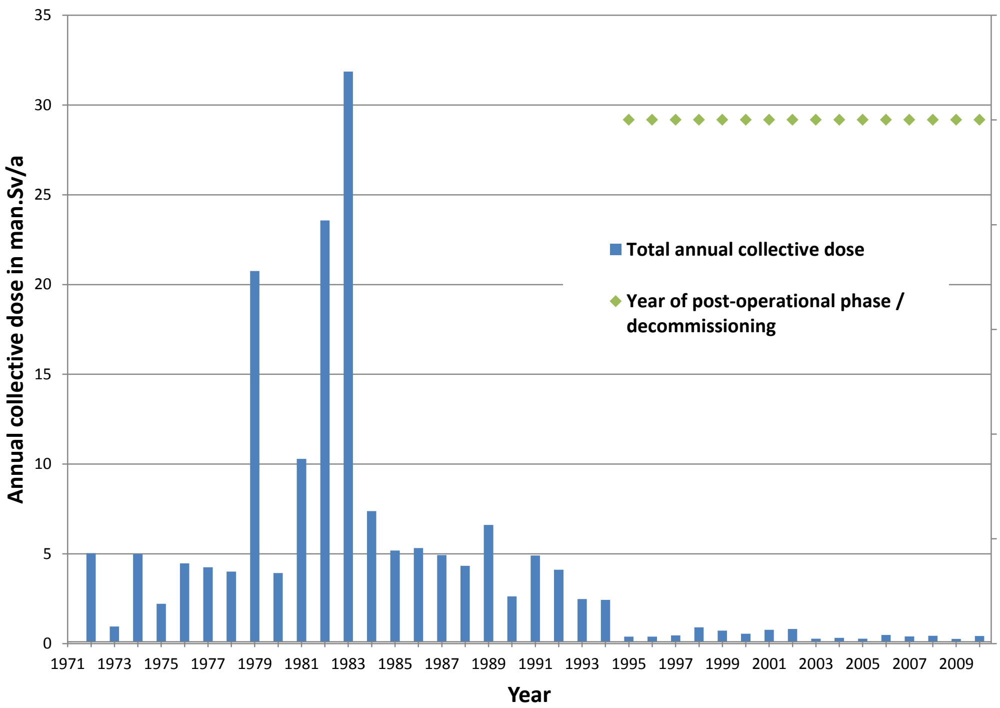



**Figure 3** Annual collective dose of German NPP in operation (until 1994) and in post-operational phase / under decommissioning (since 1995)

## 3. Challenges for radiation protection during decommissioning

In a simplified approach radiation protection during decommissioning might be the same as radiation protection during outage. As during outage, radiation protection during decommissioning has to consider that activities are performed in high dose rates and at work places with contaminations or risk of contamination with radioactive material. As such, the procedures from operation and the protective systems and equipment are appropriate to ensure radiation protection of the workers.

Nevertheless a closer look at the situation reveals that differences exist or aspects gain more importance, e.g.:

- continuous change of the facility due to the decontamination and dismantling activities – systems may not be available anymore, the radiological inventory changes, work instructions requiring adaptations, radiation sources may appear and disappear again;
- increased number of (long-lasting) work activities with interdependencies – high need for coordination of all activities to avoid radiological consequences;
- access to workplaces not accessed during operation and outage – coping with unknown radiological situations;
- need for new or improved cutting and dismantling tools to speedup the decommissioning activities – protective measures need adaptations;
- occurrence of deviations between plans and real situation at the workplace, e.g. due to differences between blueprints and reality, unexpected radioactive material – risk of spontaneous changes of plans without analysis of (safety and radiological) consequences and adaptation of plans and measures;
- high volume of material flow, including flow of radioactive material and activated and contaminated components, through the nuclear facility – storage areas, capacities for handling and processing of radioactive material and to control material entering / leaving the radiation controlled area gain much higher importance;
- depending on the progress of dismantling activities replacement of technical barriers e.g. by administrative barriers – personnel protective equipment becomes more important and human error might have higher impact on safety and radiation protection;
- long-lasting increased number of personnel during all the year in the radiation controlled area – management of the personnel and its equipment is more extensive.

In addition, to avoid radiological consequences an increased need exists to appropriately characterize and continuously monitor the radiological situation (on a high level, but also for the individual work activities), to integrate radiation protection issue early in the planning of decommissioning work, to ensure a high level of training in radiation protection for all personnel involved, to control and maintain work instructions, to appropriately brief personnel, to ensure an ongoing work control, to keep the complexity of activities under control, to control and optimize the material flows and to keep oversight on the nuclear facility and in the work control.

In most cases, procedures from operation of the nuclear facility are used after adaptation to meet the increased needs. Nevertheless experiences show, that the radiological characterization on a level, which is appropriate for a licensing process and for the later work planning, might represent a specific challenge, which can be solved using a multiple phase approach to structure the decommissioning project. This approach will help to solve the problem that areas of a nuclear facility can not be radiological surveyed appropriately at the beginning of a decommissioning project. Experiences show also, that the radiological measurement of a site after completion of a decommissioning project may cause significant problems. This is often due to the fact that reference values for radioactive material not originating from the nuclear facility and which are needed to demonstrate, that clearance levels are met are not available or vary significantly at the site as a result of their deposition processes (e.g. fall-out from nuclear weapon tests or from Chernobyl).

## 4. Experiences from past and current decommissioning projects

Today decommissioning of nuclear facilities is not a novel business anymore. In several countries practical experiences on how to plan and perform a decommissioning project exist, and several international recommendations and collections on experiences and lessons learned are available (e.g. [12] – [19]).

One basic experience is that radiation protection during decommissioning not only depends on the radiological situation and complexity of the nuclear facility but also on a set of strategic decisions made during planning, e.g. on

- the decommissioning strategy;
- multiple phase approach;
- sequence of decommissioning activities;
- conduct of a full system decontamination to minimize contamination of systems and components and to reduce dose rate fields and risks for incorporation;
- cutting of components in-situ or ex-situ, especially on removal of large components;
- pre-selection of decontamination and dismantling techniques;
- waste management concept, especially concerning treatment of radioactive material towards clearance or disposal, and options for logistics;

Some of these strategic decision issues are explained in more detail in the following subsections.

## 4.1 Multiple phase approach for decommissioning projects

Especially in case of large and complex nuclear facilities it is best practice to structure the project in multiple phases. This allows dividing the overall decommissioning project into smaller parts and reducing the complexity as the parts will be conducted mainly in sequence although parallel conduct is possible, too. Following Figure 4 illustrates the multiple phase approach.

Dividing the project into multiple phases allows a stepwise planning, in which gained knowledge from a previous or current phase can be integrated into the planning of the following phases. As such, a multiple phase approach helps to overcome a situation in which an appropriate radiological characterization of the full nuclear facility is not possible for all of its parts at the beginning of the decommissioning project. By dividing the project into multiple phases, work can be started for those phases, for which the radiological characterization is already available while for the remaining phases the radiological characterization can performed although the decommissioning project has been started already. This approach helps reducing delays in the conduct of a project and supports safety and radiation protection as work activities are based on good knowledge of the radiological situation.

It is worth to mention that in many countries the individual phases are subject to individual regulatory approval processes (e.g. licenses).

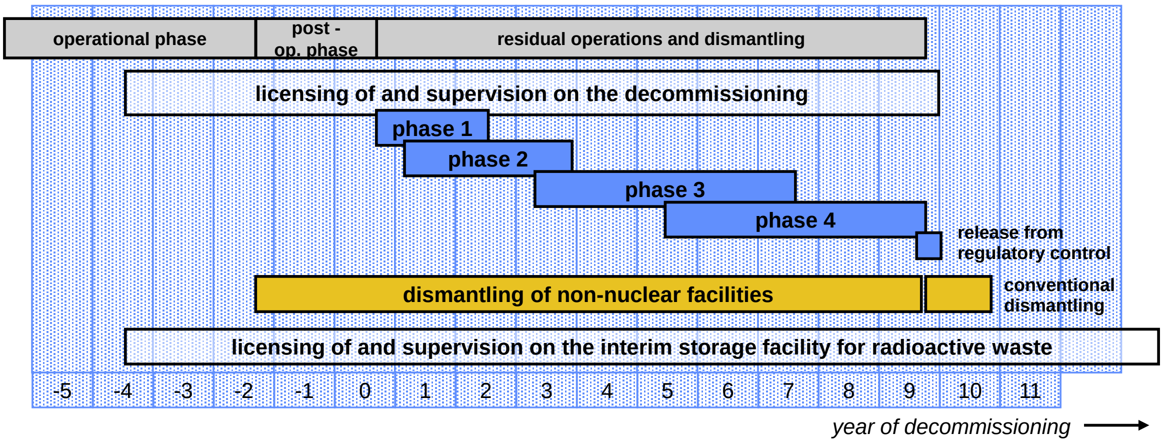
As a matter of fact, typically the radiological characterization will be limited concerning the detail. The detail will be appropriate for an approval process but to less for elaboration of detailed work plan. Accordingly, nowadays it is best practice to conduct more detailed radiological surveys during the planning of the detailed work plans. This information supports a smooth conduct of the decommissioning activity and radiation protection but contributes also to the waste management process, in which a characterization of radioactive waste is mandatory.

## 4.2 Removal of large components

To optimize the schedule of a decommissioning project and to improve the radiological conditions for its cutting, the removal of large components is discussed and applied in recent decommissioning projects [22]. Instead of its in-situ cutting the component is removed for an ex-situ cutting. The concept typically comprises of (a) separation of the component in the nuclear facility (b) closure of any openings and (c) removal of the component from its original position in the nuclear facility.

The (decontamination and) cutting of a removed component can be performed immediately after removal at the nuclear facility or the site, e.g. in a hot shop or dismantling facility, but can be done also outside the site by a service provider. Depending on the radiological inventory of such a component and the techniques applied the decontamination and cutting can result in material ready for release from regulatory control (clearance) and radioactive waste. In an alternative concept, the removed component will be subject to decay storage, lasting several years or decades, to reduce the contamination and / or activation due to physical decay. Such an alternative might increase the fraction of material which can be released from regulatory control but might also allow a manual cutting instead of a remote cutting due to reduction of dose rates after the period of decay storage.

It is worth to notice that the decay storage of an activated component does not necessarily result in lower doses for the personnel involved in the processing of the removed component. In case of an in-situ cutting with remote tools the related collective dose might be less than in case of a manual cutting, where the dose rates allow activities close to the component.

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| ***Post-operational phase*** | Activities for preparation of the decommissioning, including<br>• removal of spent fuel<br>• system decontamination<br>• removal and disposal of radioactive media generated during operation |
| ***Phase 1*** | First dismantling of contaminated components to generate free space for the later dismantling activities, including<br>• equipment airlock and air-recirculation system (modification / replacement)<br>• flooding tanks<br>• external parts of the control rod guide thimbles and drives<br>• accumulator<br>In parallel: set up of infrastructure needed for later dismantling activities |
| ***Phase 2*** | Dismantling of large components, including<br>• pipes and main coolant pumps of the primary coolant loops<br>• steam generators |
| ***Phase 3*** | Dismantling of activated systems and components, including<br>• reactor vessel internals<br>• reactor vessel<br>• biological shielding<br>• concrete cross beams<br>• rack from the former spent fuel pool |
| ***Phase 4*** | Dismantling of remaining systems and components<br>• crane<br>• refuelling platform<br>• ventilation system<br>• water treatment facility |
| ***Release from regulatory control*** | Clearance of the buildings and of the site |
| ***Afterwards*** | Conventional demolition of the buildings |
| ***In parallel*** | Construction and operation of an interims storage facility for radioactive waste generated during decommissioning of the nuclear power plant |

**Figure 4** Example for a multiple phase decommissioning project, based on [20], [21]

## 4.3 Selection process for dismantling and decontamination techniques

After several decades of decommissioning of nuclear facilities, especially of NPPs and research reactors, experiences on a variety of dismantling and decontamination techniques do exist. Numerous publications are available summarizing techniques or providing details on specific techniques, only a few of which are specified in the list of references [23] – [26].

The selection of decontamination and dismantling techniques is one of several decisions made during preparation and conduct of a decommissioning project. As already mentioned earlier, radiation protection aspects are one of the factors considered but not the only one. Other factors, that will be considered are inter alia the needed infrastructure, needed space to operate the technique, time needed for installation / de-installation of a technique, cutting / decontamination capacity, generation of radioactive waste, radiological conditions at the working place, technical requirements set by the system / component to be decontaminated / cut, aspects of safety, costs, dismantling / decontamination strategy. An analysis of the decision making process at several German decommissioning projects showed, that these factors will be considered at different phases of a selection process with different level of detail [25]. From the analysis, a generic and simplified selection process can be deduced which is presented in Figure 5.

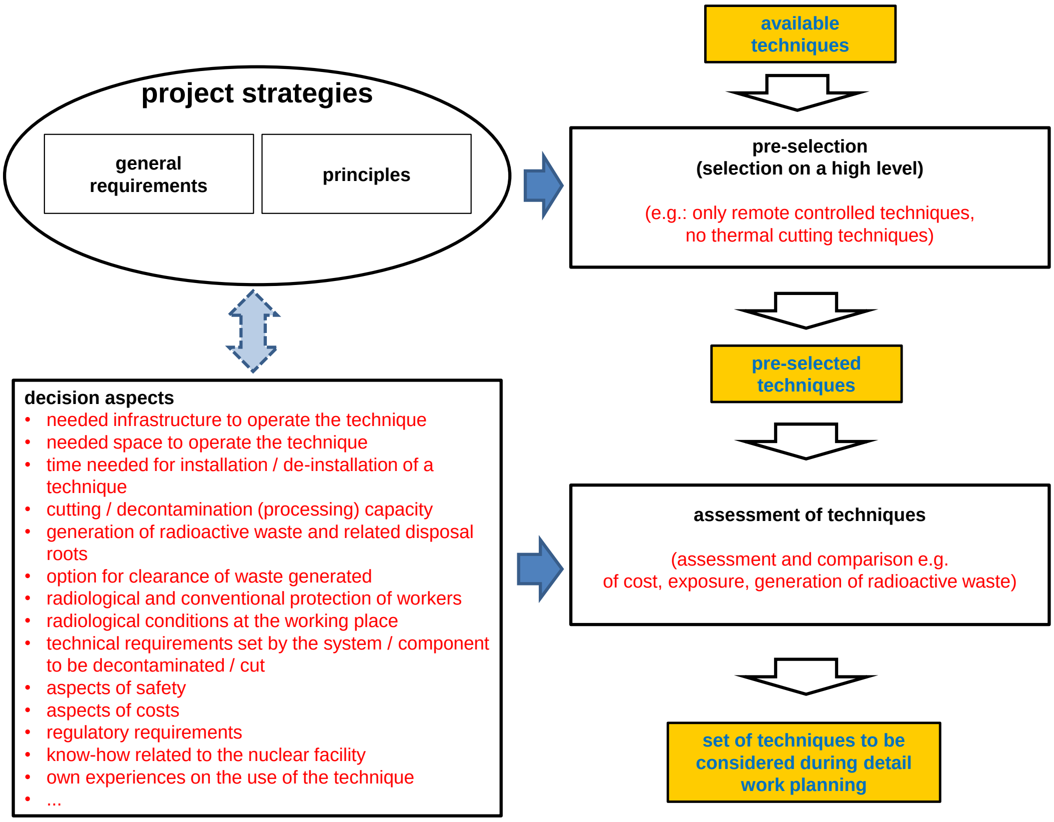


**Figure 5** Generic selection process for decontamination and dismantling techniques [25]

During a first selection step, from a list of all available decontamination and dismantling techniques those are selected, which comply with the project strategies. Project strategies set the general frame for a decommissioning project and consider general requirements (e.g. regulatory requirements and requirements from the type, complexity and inventory of the nuclear facility) and principles (e.g. removal of large components, use of dry cutting techniques only). This first selection step typically takes place at an early stage during the planning for decommissioning and considers decision aspects on an high level. In a second selection step a comparison of the pre-selected techniques is performed considering several aspects to narrow the set of techniques which should be considered during the detailed work planning for a specific work activity. Typically, this assessment is already directed to concrete work activities, but the assessment can be done also for several work activities. During the preparation of the detailed work planning for a specific work activity the technique to be used is selected. While radiation protection aspects are considered at the definition of principles and during the pre-selection process on a high level detailed radiation protection measures are defined within the detailed work planning, considering e.g. PPEs of the workers, measure to implement ALARA etc.

Experience shows that this generic process is quite flexible and a selection of a technique purely for radiation protection reasons is not often the case. As such, typically a set of techniques is available during detailed work planning and ALARA will be performed during that phase of planning.

## 5. Conclusions and future challenges

Since several decades decommissioning of nuclear facilities, especially of nuclear power plants and research reactors, has been performed to dismantle nuclear facilities and to establish final end states, which allow either the release the sited (or remaining buildings, if any) from regulatory control or new practices at the site subject to regulatory control.

Radiation protection is one of the aspects considered during the planning and conduct of decommissioning projects and experience shows that several factors are influencing radiation protection, especially of the workers.

Experience shows, that decommissioning can be conducted safely and reliably based on decommissioning plans taking into account the specific situation of the individual nuclear facility. While today to any technical question either standards solutions are available at the market or can be developed for the specific situation, challenges to any decommissioning project may arise from radiological characterization and radiological survey:

- A radiological characterization needs to be performed at the beginning of a decommissioning project. This is to ensure, that the radioactive hazards of a nuclear facility are known and appropriately considered in the detail work plans. For large and complex nuclear facilities this radiological characterization can not be conducted completely for the full nuclear facility at the beginning of the project. Therefore project strategies as the multiple phase approach are needed to handle such situations.
- After completion of decommissioning radiological surveys need to be performed to demonstrate that the intended final end state has been reached and that this complies with regulatory requirements. Practice shows, that the determination of the reference levels reference values for radioactive material not originating from the nuclear facility and specific to a site are difficult to derive and may impose practical challenges to the operator of the nuclear facility.

Up to now, these challenges have been managed successfully, but an improved experience exchange on how to best perform radiological characterizations and to optimize the radiological surveys might be helpful. This experience exchange could be incorporated into an improved international experience exchange on radiation protection during decommissioning, as e.g. addressed by the Information System on Occupational Exposure (ISOE).

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