Simulation of the Occupational Radiation Dose Caused by Decommissioning Work in PWRs

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A simulation procedure was developed, consisting of a 3D-CAD model, a mathematical method for coordinate transformation, the software MicroShield and an empiric job model, to calculate the occupational exposure for definable jobs near the primary circuit. It was validated for inspection and maintenance jobs in PWRs of the second and third KWU/Siemens generation. This way the aptitude of this tool for the prognosis of radiation exposure was demonstrated. Adhering contaminations within the primary circuit are considered as relevant sources. In this study, the model was extended by PWRs of the so-called Convoy generation, which differ from older plants in the material composition and consequently in the relevant nuclide vectors. Due to the contemporary planned final shut-down of the three Convoy plants (besides others), dismantling work was set into the focus of the simulation. The simulation was conducted and the results compared for Convoy plants and for plants of the older generations two and three. Furthermore, by comparative simulations the question was answered whether full system decontamination in Convoy plants before dismantling leads to benefits that justify this measure.

KEYWORDS: Simulation, decommissioning, occupational dose, modelling

Introduction

The occupational radiation exposure of workers in nuclear power plants with pressurized water reactors is not only determined by the activation and contamination of structural elements of the primary circuit, but also by several additional parameters such as the geometry of shielding, self-shielding of components, deposits of radionuclides, the planning of working tasks within the controlled area or even the behaviour of workers. There are two different sources of actual radiation exposure, either activated systems, structures or components (SSCs) or deposited contamination within the SSCs that was activated in the reactor core and transported with the main coolant. The radiation of directly activated components is only relevant for jobs near the reactor pressure vessel (RPV). In contrast, there are many areas in an NPP where the main share of the occurring dose rates is caused mainly by contamination. Hence, a main share of occupational doses is also directly linked to radiation exposure caused by contamination of components. Thus, it is promising to minimise occupational doses by application of systematic decontamination techniques before the start of dismantling work. The number of parameters influencing the occupational radiation exposure leads to a complex problem which is addressed by a comprehensive generic model. The aim of the model presented is to deliver a quantitative, realistic estimation of the influence of contamination of the primary circuit of PWRs on the occupational doses of workers performing tasks related to decommissioning.

Procedural methods for the simulation of occupational radiation doses

The generic model comprises the following elements that are combined to form a simulation chain:

1. The determination of the relevant representative nuclide vectors,
2. 3D modelling of the PWR primary circuit,
3. Definition of jobs (locations, retention times within 3D model)
4. Dose rate calculations.

A scheme of the stepwise simulation procedure is shown in Figure 1.

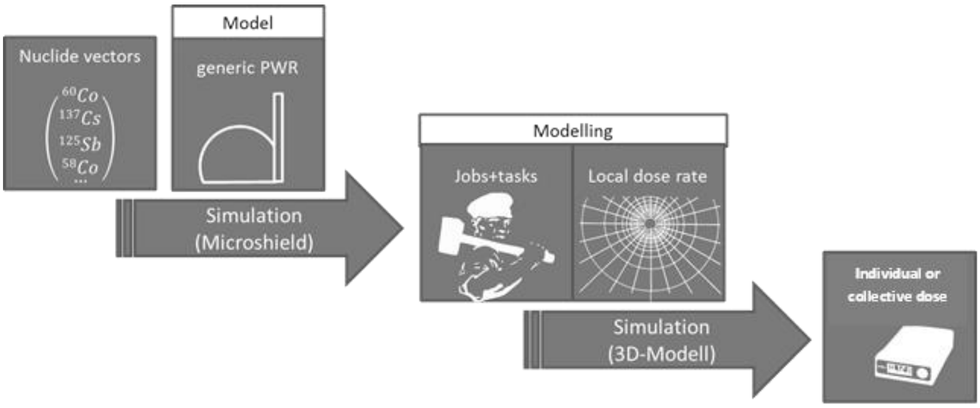

Figure 1 Scheme of the method for simulating job-related doses in nuclear power plants with pressurized water reactors

Part of the first step is the adequate definition of representative nuclide vectors for each PWR generation (KWU/Siemens) for decommissioning. The technical literature of the past three decades was analysed to gather existing knowledge about the formation and deposition of contamination within the primary circuit. Although the important chemical processes at different locations in a PWR are generally well understood, the currently available approaches for the actual modelling of the water chemistry and the transport of radionuclides in the primary circuit usually turn out to be restricted. Several examples can be found in the literature (e.g. 1), 2)), but in most cases the high complexity of chemical and thermodynamic processes within the primary circuit requires a lot of modelling parameters. It is hence difficult to apply these models to simulate the processes such that precise results can be expected only from first principles. Therefore the resulting models tend to be rather specific to individual facilities – thus not generic – and do not lead to general conclusions. In 2) it is deduced that a step back to simpler models might be more successful.
The approach of this work is the deduction of nuclide vectors from

i) A detailed analysis of radionuclide concentrations in the primary coolant in the operational phase including statistics about the incidence of radionuclide concentrations within a certain interval. The outcome of this analysis are PWR-generation-specific normalised nuclide vectors, providing ratios of nuclide concentrations
ii) Reverse simulation from known dose rates at a number of locations in NPPs of each PWR generation, obtained from site visits and gained from regular outage measurement data as available in the ISOE database (for a limited number of locations). The formerly deduced qualitative normalised nuclide vectors are scaled to realistic concentrations.

To determine the relative contributions of the components to the nuclide vectors (i), data of the past 15 years on the concentration of radionuclides dissolved in the primary coolant of German PWRs were analysed, as shown in the histograms in Figure 2 for Convoy type PWRs. For the quantitative determination of nuclide vectors (ii) to describe contamination caused by deposits, only metal oxides are

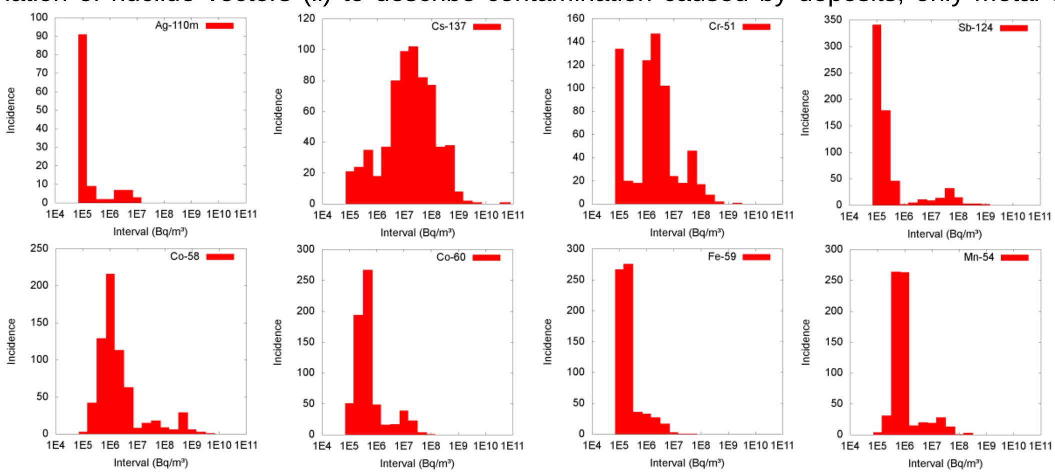

Figure 2 Nuclide incidences for all measurements of the respective nuclides of 4th generation KWU/Siemens PWRs (Convoy)

considered. By using measured data of local dose rates at a number of locations, SSC-specific nuclide vectors were derived by reverse simulation for overall maintenance jobs. Assuming a decay time of five years before decommissioning starts, related nuclide vectors for decommissioning were calculated. Performing a Full System Decontamination (FSD) within the post-operational phase is the normal case in Germany. Hence additional decontamination factors (DF) were applied to the SSC-specific nuclide vectors.
The assumed DFs amount to:

SSC	Gen 2 and 3	Gen 4 (Convoy)
Steam Generator	400	120
Reactor coolant pumps	140	60
Coolant pipes	45	30
Other	215	60

Table 1 SSC- and PWR-generation-specific DFs to simulate the influence of a FSD on the nuclide vectors

DFs for generation 2 and 3 PWRs are mean values of past FSDs. Since no FSD has been performed on Convoy plants so far, assumptions were made instead. The relatively low DFs compared to older plants arise from the knowledge that the stellite content in Convoy plants was low from the beginning of operation and therefore local dose rates are also relatively low. As a consequence, fewer decontamination cycles may be driven in Convoy plants. Although the resulting nuclide vectors are dependent on the individual NPP, it turned out that mainly the Co-60 content has to be adjusted to adapt the nuclide vectors to a specific NPP generation.

The generic 3D model of the primary circuit presented here is based on the analysis of the technical documentation of German nuclear power plants. With the aid of engineering drawings of Siemens/KWU-NPPs with pressurized water reactors of the 1200 MW+ power class, a 3D CAD model was constructed (**Fehler! Verweisquelle konnte nicht gefunden werden.**) with SketchUp (6). This model contains all relevant components from the point of view of radiation protection. With it, the spatial relations during the performance of decommissioning tasks can be well illustrated and investigated. Within this model it can be decided which SSCs act as relevant radiation sources for any working

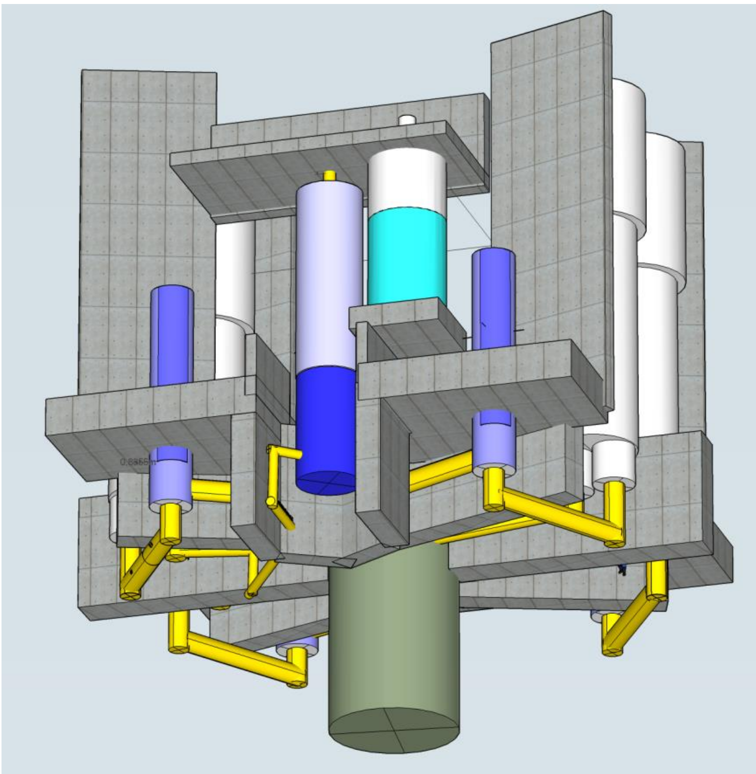

Figure 3 3D CAD model of the primary circuit with shielding walls (Convoy type)

point and in what cases shielding from which components must be considered. The NPP is modelled as several elementary radiation sources (cylinders) and elementary shielding (cylinders and cuboids). Each of these construction elements is defined such that it can be easily fitted to a single MicroShield (4) calculation. Due to geometrical limitations in MicroShield, it was necessary to simplify components within the model to simple geometrical forms, like cylinders (hollow or full). These simplifications followed some rules. The main priority was to keep the radiological impact of a source rather than the outer geometrical dimensions.

Working tasks/jobs are modelled as a combination of retention times and local positions in the surroundings of working areas, so that the average of the occupational doses can be determined. Each job/ working task is broken down into several (usually three) specific local points. Each point is attributed to different dose rates: One point is chosen near to the working object and there is usually a high dose rate. A second point is chosen at some distance from the working object and is attributed to the moving time from a shielded location (where tools and spare parts may be stored). The third point is usually chosen as a shielded point and stands for everything else a common worker has to do in a controlled area, e.g. changing of clothes, pathways, and so on. The geometrical coordinates of relevant local positions are mathematically transformed in such a way that they are suitable as input parameters for the MicroShield software used in the final simulation step (4). Using this, the contribution of any subcomponent and subsystem to the local dose rate is calculated and summarised afterwards.
There are extensive data sets of measured local dose rates, but they are limited to a few working positions (steam generator water chambers and reactor coolant pump outside hot/cold leg) and points in time (overall maintenance and refuelling inspection). Furthermore, data on occupational doses and dose rates as well as about the amount of work are available in the ISOE database mainly for overall maintenance and refuelling inspection tasks. The complete model was benchmarked and optimised by using these data sets, leading to a generic model of a PWR that allows estimating the expected dose rates and collective doses for less documented working tasks, like dismantling work.

Results and discussion

To simulate typical decommissioning-related jobs, the dismantling of a steam generator (Figure 4) and the unmounting and partial disassembling of a reactor coolant pump were selected as representative examples. In contrast to the most maintenance jobs, in the case of decommissioning work, the beginning and end of partial projects may be defined differently for various NPPs. Additionally, the state of the residual plant may be different (e.g. neighbouring SSCs may have already been unmounted or not, leading to different radiological situations) and the dismantling procedure is individually variable. The latter means, for example, that a steam generator may be disassembled in situ or be unmounted in one piece and be disassembled elsewhere. Consequently, the assumed course of action needs to be defined in the job model and the simulation results can only be compared with measured dose values if the assumed and the real procedure match.
The decommissioning job “dismantling of a steam generator” is defined as follows:

- It consists of two parts, one for preparation and one for unmounting
- For the preparation phase we consider: scaffolding, mounting of additional 1 cm lead shielding at the water chambers, removal of insulations, secondary water inside as shielding
- For the unmounting phase we consider: no secondary water as shielding, lead shielding around water chambers in place, cutting of any pipes, mounting of hoist ropes, lifting of the steam generator

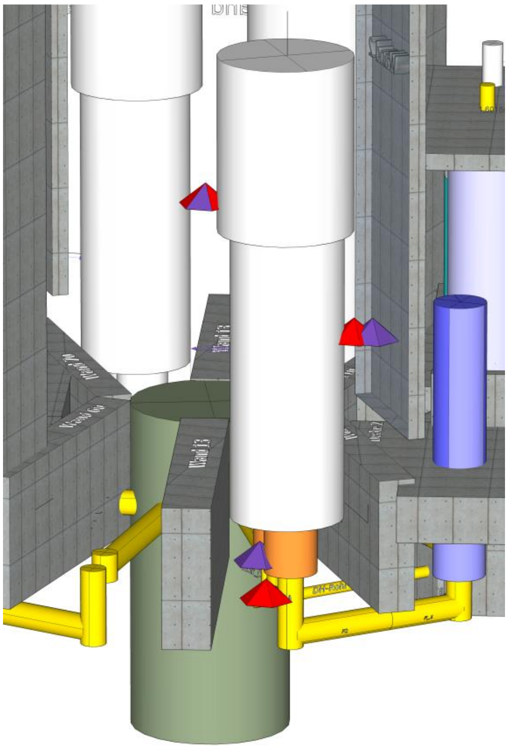

Figure 4 Representative points (tips of pyramids) for dismantling a steam generator

The tips of the purple and red pyramids represent the points of virtual dose rate measurements for the preparation and unmounting phase, respectively.
For the complete dismantling of 4 steam generators, 200 persons and 1000 man*hours are assumed, without differences between plant generations. The latter are differentiated by different nuclide vectors and different material compositions and thicknesses of sources and shielding walls. Full system decontamination was performed in the case of 2nd and 3rd generation PWRs in Germany before their decommissioning started, so that the respective nuclide vectors are chosen accordingly. Since there are no Convoy plants in decommissioning so far and their dose levels are low, it is unclear whether a FSD will be performed during the post-operational phase. Therefore steam generator (SG) dismantling was simulated both with and without a previously performed FSD.
The results of the simulation of SG dismantling are listed in Table 2 and illustrated in Figure 5. The dismantling of SGs without prior FSD in Convoy plants leads to much higher personal doses than in generation 2 plants after FSD. We conclude that the decommissioning of Convoy plants without FSD cannot be justified from an ALARA perspective. The collective doses decrease for dismantling steam generators of generation 2 to 4 PWR by about one order of magnitude.

SG dismantling	Gen. 4 PWR without FSD	Gen. 4 PWR with FSD	Gen. 3 PWR with FSD	Gen. 2 PWR with FSD
Average personal dose (µSv)	2100	18,3	110	205
Job dose rate (µSv/h)	41	0,37	2,2	4,1
Collective dose (mSv)	411	3,7	22	41

Table 2 Results of the simulation of SG dismantling for different KWU/Siemens PWR generations

The decommissioning job “dismantling of reactor coolant pumps (RCP)” is defined as follows:

- the pumps are disassembled on site, the motor is separated from the rest of the pump, the housing is opened and the rotor is unmounted
- preparatory and unmounting work is comprehensively simulated

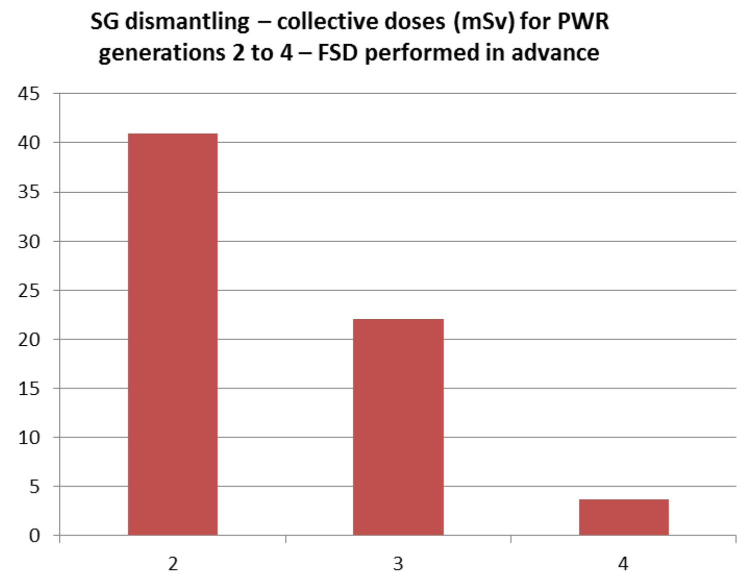

Figure 5 Comparison of the simulated collective doses for SG dismantling in Siemens/KWU PWR of generations 2, 3, and 4

The complete dismantling of 4 pumps is assumed to take 7500 man*h with 40 persons involved. The amount of work is again not differentiated between plant generations. For this, different nuclide vectors and different material compositions and thicknesses of sources and shielding walls are used. Due to the results for SG decommissioning (see above), the nuclide vectors are now chosen with an assumed FSD for all PWR generations.
The results of the simulation of RCP dismantling are listed in Table 3 and illustrated in Figure 6. The estimated collective doses decrease from generation 2 to generation 4 PWR by a factor of about 35.

RCP dismantling	Gen. 4 PWR with FSD	Gen. 3 PWR with FSD	Gen. 2 PWR with FSD
Average personal dose (µSv)	13	171	467
Job dose rate (µSv/h)	0,07	0,9	2,5
Collective dose (mSv)	0,525	6,8	18,7

Table 3 Results of the simulation of SCP dismantling for different KWU/Siemens PWR generations

All of the simulated doses have an underlying uncertainty of about a factor of 2.5 and a factor of 0.5 bounded above and below, respectively. The uncertainty mainly arises from uncertain retention time shares for the representative locations within the exposed area.

Conclusion

In this study, a generic model was developed, consisting of a 3D-CAD model, the software Micro-Shield and an empiric job model, to calculate the occupational exposure for definable jobs at the primary circuit. It was validated for inspection and maintenance jobs in PWRs. This way, the aptitude of this tool for the prognosis of radiation exposure was demonstrated. The model was also extended for newer PWRs of the so-called Convoy generation, which differ from older plants in material composition and consequently in the relevant nuclide vectors. Due to the contemporary planned final shut-

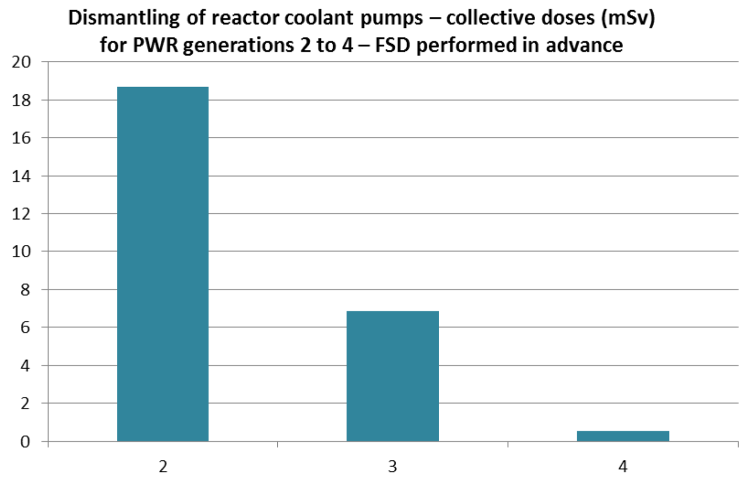

Figure 6 Comparison of the simulated collective doses for SG dismantling in Siemens/KWU PWR of generations 2, 3, and 4

down of the three Convoy plants (besides others), dismantling work was set into the focus of the simulation. The simulation was conducted and the results compared for Convoy plants and for plants of the older generations two and three. Besides this, by comparative simulations it was demonstrated that performing a full system decontamination in Convoy plants before dismantling is beneficial and therefore justified. The determined dose-saving during unmounting work at the steam generators caused by the decontamination is remarkable. Furthermore, the simulation of multiple plant generations reveals a clear decrease in occupational doses for dismantling work at steam generators and reactor coolant pumps by one order of magnitude (for a generation 2 plant compared to a Convoy plant).

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