Illustration of Nagra's AMAC Approach to the PWR Kori-1 Based on Experience from its Detailed Application to Swiss NPPs

Ben Volmert [a*], Valentyn Bykov [a], Dorde Petrovic [a], John Kickhofel [b], Natalia Amosova[b], Jong Hyun Kim [c], Cheon Whee Cho [c]
[a]*National Cooperative for the Disposal of Radioactive Waste (NAGRA), Hardstrasse 73, 5430 Wettingen, Switzerland*
[b]*Apollo+ Nuclear, Weineggstrasse 7, 8008 Zurich, Switzerland*
[c]*ACT, 1434, Yuseong-daero Yuseong-gu, Daejeon, Republic of Korea*
[*]*Corresponding author: ben.volmert@nagra.ch*

1. Introduction

Over the last 15 years, the *National Cooperative for the Disposal of Radioactive Waste* (NAGRA) has developed a methodology to characterize the activation of nuclear power plant (NPP) components and building structures caused by neutron irradiation. This so-called *Advanced Methodology for Activation Characterization* (AMAC) [1] has been successfully applied and validated to determine the radioactive waste volumes and their activity classification for the future decommissioning of all four Swiss commercial NPPs [2-5], the research reactor of Basel, Switzerland [6], as well as the largest German NPP, Gundremmingen (KGG) [7].

The results of AMAC serve on the one hand as input for the periodic Swiss decommissioning and disposal cost studies, providing a basis for the determination of the financial requirements for the decommissioning and disposal funds, and on the other hand to help the utilities owning the NPPs to prepare and plan for the decommissioning.

The main results of AMAC consist of a detailed three-dimensional neutron flux and activation distribution mapping of the NPP building structures, the reactor pressure vessel (RPV) and its internal components, as well as a segmentation strategy and packaging concept based on given container specifications for the arising decommissioning waste streams.

In this paper, the illustrative application of AMAC to the South Korean Westinghouse-designed pressurized water reactor (PWR) of Kori unit 1 (Kori-1) is presented which was retired in summer 2017.

2. Methods and Results

The AMAC methodology involves several major steps, which are summarized in Fig. 1.

The current work is seen as a preliminary project, called *Phase A*. This work utilizes strictly publicly available data related to Kori-1 geometry and operational power history. For this reason, the results are described as illustrative and should not be misconstrued as quantitatively or qualitatively accurate. This work has been performed in the following subsequent steps.

First, a simplified Kori-1 MCNP [8] model (called *Kori-1(A)*), based on publicly available data, was created and used for the simulation of the neutron propagation within the NPP. The result of these calculations is the neutron flux distribution throughout the Kori-1(A) MCNP model.

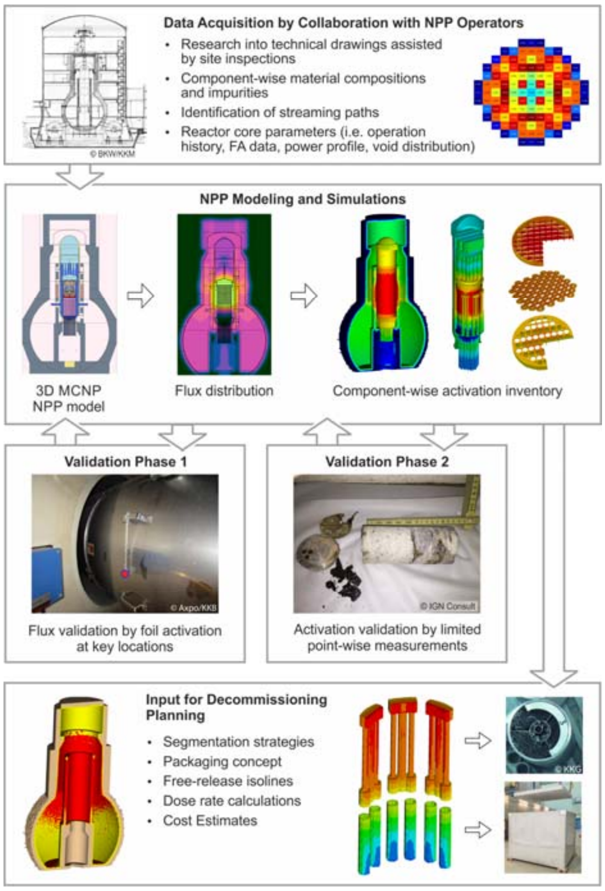

Fig. 1. Scheme of the Advanced Methodology for Activation Characterization (AMAC)

Next, the component-average key-nuclide reaction rates for the reactor internals and the RPV were calculated. For the adjacent building structures, like the biological shield, the reactor pit floor and the pool area above the RPV, corresponding mesh tallies with high spatial resolution are chosen. By using the Bateman equation and the operational power history of Kori-1, the corresponding key-nuclide specific activities for selected decay times after shutdown of the NPP were derived. An activation depth profile for the biological shield wall and the reactor pit floor was determined by comparing the activity distribution of Eu-152 (the key-nuclide for concrete activation) against a free release activity limit of 0.1 Bq/g (see Fig. 2).

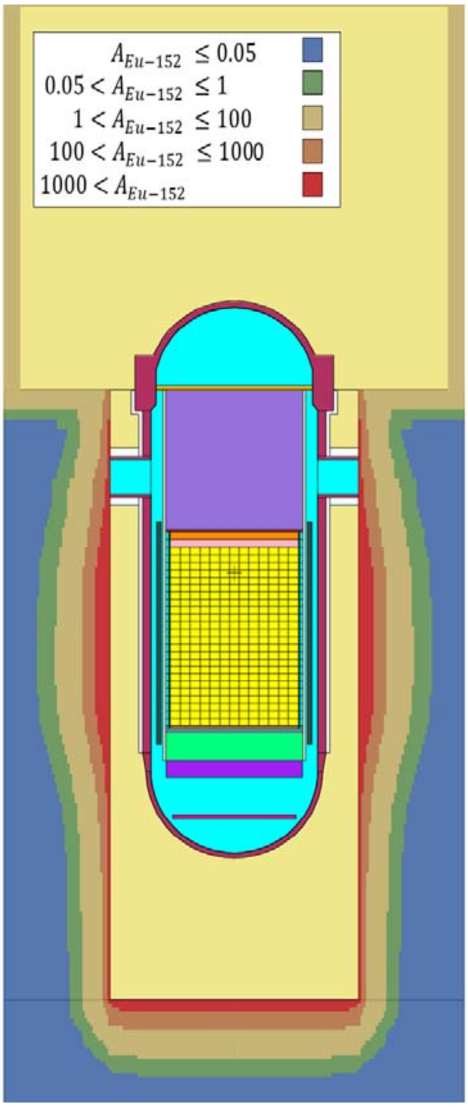

Fig. 2. Eu-152 activity distribution [Bq/g] for concrete structures of Kori-1(A) (13 y decay)

In the third step, the component-averaged key-nuclide inventories for the Kori-1(A) was used to scale the component-wise AMAC results from the Swiss PWR Beznau (KKB) [4], a Westinghouse-designed two-loop PWR similar to Kori-1. An example of the resulting activity distribution for the lower core support plate is shown in Fig. 3.

Through this analogy, it is possible to illustrate the activation distribution for all Kori-1 components with high resolution and to prepare the results for the subsequent estimation of decommissioning waste volumes and activities, as well as for the development of a corresponding segmentation strategy including an initial packaging concept.

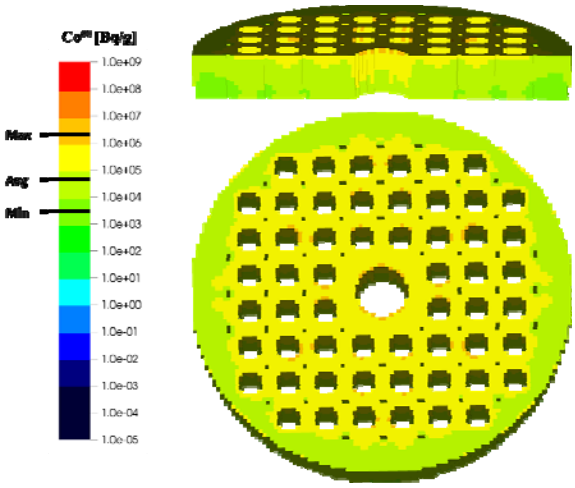

Fig. 3. Illustrative specific Co-60 activity distribution in the lower core support plate, based on Kori-1(A) activation calculation and Beznau detailed geometry and AMAC results (10 y decay)

In the final section of the work, the differences between this simplified Kori-1(A) model approach and a complete characterization of Kori-1 (*Phase B*) using AMAC based on detailed data provided by the NPP owner, are discussed and evaluated.

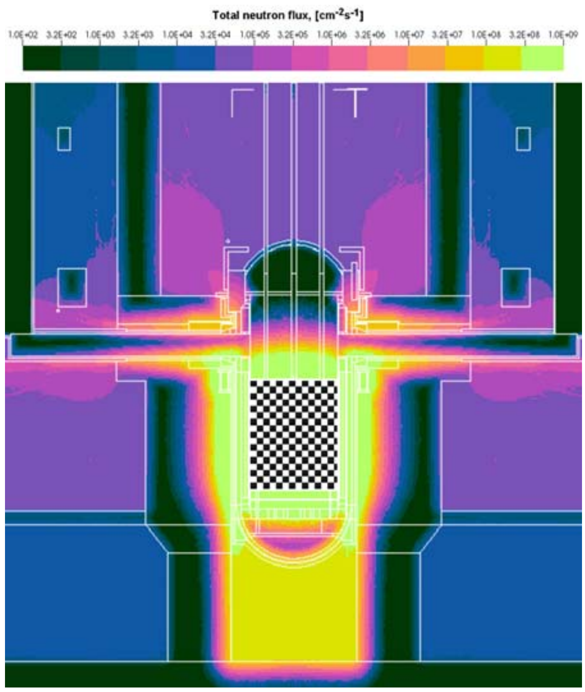

Fig. 4. Total neutron flux distribution for the NPP Beznau [4] (legend ends at 1.0E+09)

This discussion and evaluation are based on the application of AMAC to the Swiss PWR Beznau. Fig. 4 shows the total neutron flux distribution for KKB [4], illustrating the specific radiation propagation character-istics of the neutron streaming through main cooling pipe and other ventilation/access penetrations. Fig. 5

presents the resulting complex activity distribution within and on the outside surfaces of the KKB biological shield induced by the neutron streaming [1].

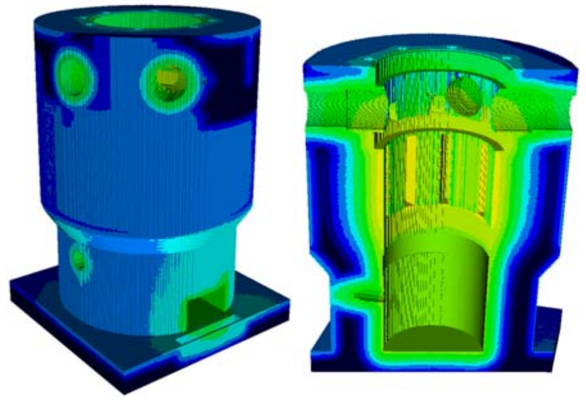

Fig. 5. Realistic activation distribution pattern for the wall and floor of the NPP Beznau biological shield [1]

Neutron streaming effects through openings in the biological shield and into the reactor pool area cannot be adequately quantified by the simplified Kori-1(A) MCNP simulation. As such, the results presented in this work – particularly for internals further away from the active core, as well as the activated concrete volumes – represent an estimate and should be interpreted with reasonable caution.

2.1 AMAC Code Interactions

The software used as part of AMAC represents the state of the art in neutron transport and activation. AMAC focuses on automation, minimizing the human input as much as possible, in order to reduce the engineering time and reduce the incidence of human errors. Fig. 6 shows an overview of the corresponding code interactions within the AMAC sequence.

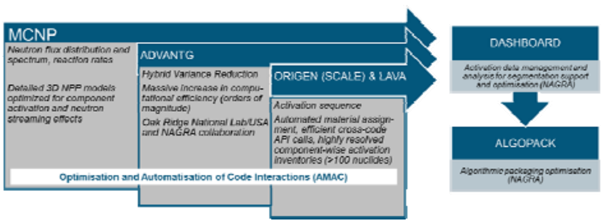

Fig. 6. Overview of code interactions within AMAC

In order to efficiently obtain neutron flux maps, it is necessary to extensively apply variance reduction (VR) techniques [9], so that the MCNP runs can be effectively optimized for specific regions and components of interest. In this respect, the *Automated Variance Reduction Generator* (ADVANTG) package [10], a hybrid VR code developed at the Oak Ridge National Laboratory (ORNL), has been implemented in AMAC.

The assignment of materials for activation calculations is automated in AMAC through the use of a ray-tracing module called LAVA, originally developed for ADVANTG, which automatically calculates the material mixtures in each of the 10^5-10^7 cells of the corresponding mesh representing individual reactor components.

For activation calculations, AMAC utilizes a High-Performance Computing version of ORIGEN [11], which is fully parallelized, thus allowing dozens of cells to be activated at the same time. This HPI version also features an *Application Programming Interface* (API), which enables the assignment of activation jobs and extraction of output without the need to write any input or output files. This further speeds-up the interfacing between individual codes in the AMAC sequence.

2.2 AMAC Validation

The validation approach chosen for the past AMAC projects was the foil activation method since all Swiss NPPs and the German KGG were still in operation while their validation was in progress. The foils are distributed within the NPP building at key locations during a plant outage and are irradiated during the subsequent reactor cycle before being retrieved and sent to a laboratory for analysis. This validation method is augmented by additional point-wise chemical and radiological samples on some removed or exchanged irradiated reactor components or concrete drillings. The chemical sampling is important to reveal the concentrations of key impurities (e.g. cobalt and europium) in the main materials (i.e. various steel types and concrete).

The foil radiation method is obviously no longer possible for the shutdown NPP Kori-1, but a corresponding radiological sampling of selected components and building structures is recommended for validation purposes.

2.3 Packaging Concept Development with ALGOPACK

The detailed information about the activation distribution of Kori-1 components was subsequently used to develop an optimized packaging concept based on intelligent segmentation.

The waste containers of different types needed to package the activated Kori-1 components are, for the purpose of this work, chosen in accordance with Swiss and international regulations. They are based on the Swiss concept for NPP decommissioning waste management and the existing licensing of the container types and variants therein. The Swiss concept includes large reinforced concrete containers (LC-86, LC-84 and LC-84-Plus) for concrete and steel waste streams of low to medium activity and MOSAIK®-II [12] casks for highly activated reactor components. Extra shielding can be provided by the LC-84-Plus and MOSAIK®-II.

The option to replace the Swiss LC-containers by the *16 Pack South Korean Radioactive Waste Container* (16 Pack SKRWC) is also investigated (albeit recognizing that extra shielding is required).

The optimization of the packaging concept is accomplished by using ALGOPACK [1], an internal code of the AMAC sequence. ALGOPACK is a software developed by NAGRA to find the optimum packaging concept and ensure efficient component segmentation. It analyzes the activation distribution data provided by AMAC, loads the available waste container limits as constraints, and interprets the resulting optimization task as a two-dimensional vector bin packing problem with variable bin sizes (see Fig. 7). Further discussion on the mathematics behind the algorithm can be found in [9].

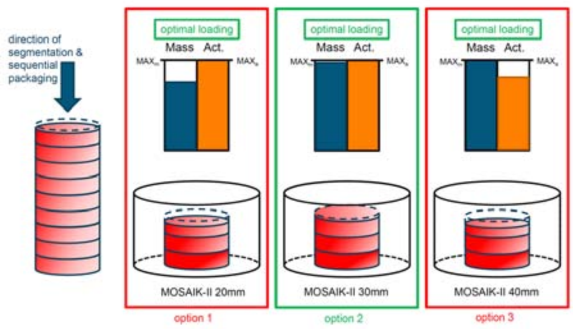

Fig. 7. Evaluation of different waste container loading options by the NAGRA optimization code ALGOPACK

Table 1 lists the resulting total container balance for the packaging concept of Kori-1(A) for RPV, internal components and activated building structures. Optionally, the replacement of Swiss LC containers with the *16 Pack SKRWC* is evaluated.

Table 1: Summary of packaging concept for Kori-1(A) (10 y / 13 y decay for internals and RPV / building structures)

Origin of waste stream	Cask type	total
Building structures (reinforced concrete)	LC-86 (Concrete)	271
RPV and internal reactor components	LC-84	26
RPV and internal reactor components	LC-84-Plus	19
Option: usage of Koreran 16 Pack instead LC-8x	16 Pack container	277
RPV and internal reactor components	MOSAIK-II	307

3. Conclusions

The present joint work performed by Swiss and South Korean organizations represents a showcase – or proof of concept – for applying AMAC to South Korea's commercial nuclear power plant fleet which utilized publicly available plant data.

The results achieved are presented and are supported by the existing experience from applying AMAC to Swiss and German NPPs. The results in this work are also used for a first approximation of the activated waste volumes for Kori-1 and the associated packaging concept.

Differences between the model built as a part of this work and a more realistic component and building structure layout normally used when applying AMAC to an NPP are to be expected and will influence the results. In this context, the continuation of the work based on detailed data and information supported by the owner of the Kori-1 NPP, Korean Hydro and Nuclear Power (KHNP), is strongly recommended. This will allow the creation of a realistic and detailed Kori-1 MCNP model by implementing all necessary streaming configurations.

Finally, the application of AMAC is expected to lead to significant cost savings by enabling efficient decommissioning project planning and execution, reducing the number of expensive waste containers and by significantly reducing the number of radiological measurements to be taken.

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