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Logistics optimization code for spent fuel assembly loading into final disposal canisters

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ABSTRACT

The loading of the nuclear Spent Fuel Assemblies (SFAs) produced in Switzerland into disposal canisters for their final emplacement into a deep geological repository has to be planned in advance. To limit the associated cost and the operational time of the corresponding surface facility, an optimization should be applied to the aforementioned problem, since its solution cannot be found analytically. To that end, the National Cooperative for the Disposal of Radioactive Waste (Nagra) developed the logistics optimization code "SIMAN", using the so called Simulated Annealing (SA) method. The objective is to find the best possible loading configuration to minimize the total number of canisters needed. The aims of this study were to finish and analyze the performance of the previous code system and to provide features for extended analysis on the resulting canister loading configurations. Two code revisions were used to simulate different boundary conditions regarding the disposal procedure. Realistic boundary conditions confirmed to add a 10% increase (conservatively) to the total number of disposal canisters needed, compared to the solution for the simplified boundary conditions. In addition, the various reasons and their relative contributions to this increase have been determined and quantified. Finally, an extension to the reference disposal concept has been investigated (so-called "mixed canister") indicating significant potentials for further decrease of the total number of canisters.

1. Introduction

The origins of radioactive waste production in Switzerland stems primarily from the four commercial Nuclear Power Plants (NPPs) of Beznau (2 units), Mühleberg, Gösgen and Leibstadt. In the frame of the waste management concept – approved by the Swiss Federal Council and Parliament – radioactive waste produced in Switzerland will undergo deep geological disposal (SFOE, 2008). To take care of the radioactive waste in Switzerland, the "National Cooperative for the Disposal of Radioactive Waste" (Nagra) was founded in 1972 by the operators of the NPPs and the Swiss Confederation (responsible for radioactive waste from medicine, industry and research).

Nagra has proposed that a deep geological repository is the only method for managing radioactive waste that meets the strict requirements related to long-term safety. Two types of disposal sites have been chosen and are currently further investigated: one for the low and intermediate level waste (L/ILW) and one for the long lived and high level waste (HLW). The largest contribution to the HLW repository concerning the total radiological inventory as well as the sheer volume will come from the approximately 12,000 (depending on the NPP operational scenario assumed) spent fuel assemblies (SFAs) being discharged from the NPPs over their total life span.

The loading of the SFAs produced in Switzerland into disposal canisters (DC) for their final emplacement into a deep geological repository must be planned in advance, to meet the requirements for the development of the geological disposal as well as for guaranteeing sufficient funds for the disposal in the future. The optimization of the DC loading is a complex task which considers different aspects and constraints.

For this purpose, Nagra developed the logistics optimization code "SIMAN", an acronym based on the underlying optimization

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Nomenclature

B/PWR	boiling/pressurized water reactor	NPP	nuclear power plant
BEVA	geological disposal surface facility	SA	simulated annealing
DC	disposal canister	SFA	spent fuel assembly
ff	filling fraction	SIMAN	Nagra's logistic optimization code
H/I/L LW	high/intermediate/low level waste	TSC	transport and storage cask
MOX	mixed oxide fuel	UO_2	uranium oxide fuel
Nagra	Swiss national cooperative for the disposal of radioactive waste	ZWILAG	Swiss interim storage facility

algorithm "Simulated Annealing" (SA). The objective is to find the best possible SFA loading configuration to minimize the total number of canisters needed for their disposal and at the same time to decrease the associated costs for the repository operations. SIMAN is an in-house software which is not yet available for commercial use. Its development was originated from the unique requirements and boundary conditions imposed for the final disposal of the SFAs in Switzerland (Vlassopoulos, 2015). In the past, similar studies have been performed with the use of heuristic algorithms, to provide SFA disposal plans for the case of Finland and Slovenia (Ranta and Cameron, 2012; Zerovnik et al., 2009). A similar but extended approach is currently investigated for the cost minimization of waste management actions in USA, considering also spent fuel allocation strategies (Petersen et al., 2017).

The aims of this study were to debug, complete and extend SIMAN, to analyze its performance and to provide features for extended analysis on the resulting canister loading configurations. In addition, an extension to the reference disposal concept has been investigated.

2. Swiss SFA disposal concept

Nagra's current project prohibits mixing SFAs of different type (from boiling water reactors (BWR) and pressurized water reactors (PWR)) within the same DC. Therefore, both reactor types provide their own respective DC, although they are similar concerning their structure (materials and diameter). A comparison of those canisters is given in Fig. 1. The PWR and BWR canister can maximally include 4 and 9 SFA positions, respectively.

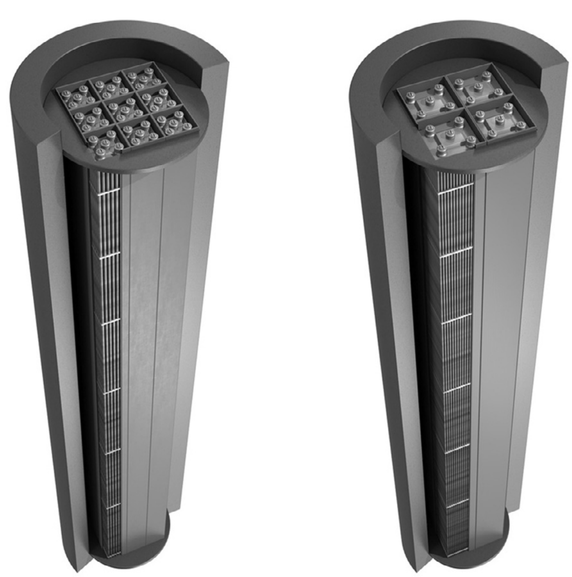

Fig. 1. Cross section of a BWR (left) and PWR (right) final disposal canister (Nagra, 2003).

The process for the disposal of the SFAs can be described as follows; after discharge, the SFAs are stored onsite in wet storage pools, followed by transfer to dry transport/storage casks (TSCs), or external intermediate wet storage pools (wet SFA storage facility in Gösgen). Having decayed sufficiently to lower thermal power the SFAs will be loaded into TSCs and shipped to the central Swiss Interim Storage Facility (ZWILAG) or to a separate interim radioactive waste storage facility in Beznau (ZWIBEZ).

The TSCs will be eventually transferred to a geological disposal surface facility (named "BEVA" – "Brennelement-Verpackungs-Anlage") for the final encapsulation of the SFAs into DC. Following this process, they will be transferred underground to their respective emplacement position within the HLW repository. Each canister will be placed on a bentonite plinth in the disposal tunnel and the entire tunnel will be backfilled with bentonite granulate. Together with the overlying formations, the host rock will form the geological barrier (Johnson et al., 2008).

3. Simulated annealing

SA is a probabilistic metaheuristic algorithm (Dowsland and Thompson, 2012; Aarts and Korst, 1989) which is widely applied in large search space combinatorial optimization problems to approximate the global optimum of a given function. It has successfully been applied in numerous nuclear engineering applications including fuel core loading pattern optimization (Fadaei et al., 2009; Hays and Turinsky, 2011; Zammer et al., 2014).

The method was inspired from the annealing thermal process where a material can reach low energy states after heated past its melting point and slowly cooled down. It was first introduced by Kirkpatrick et al. (1983), where he used the *Metropolis* algorithm (Metropolis et al., 1953) to simulate the evolution of a solid (or a system of atoms) in a heat bath to thermal equilibrium.

SA can be described in a direct analogy to the thermal process. At a certain state i the energy of the system E_i can be calculated as the value of a given objective function. By applying a small perturbation, the system results in a subsequent energy E_j. If $\delta E \leqslant 0$ the move is accepted, otherwise the new state is accepted with a certain probability given by:

$$P(\delta E) = \exp\left(\frac{E_i - E_j}{T}\right) \quad (1)$$

The above is facilitated by generating a random number r from a uniform distribution between 0 and 1. The system is accepted when $r < P(\delta E)$. This is known as the Metropolis algorithm and provides the great advantage of the method escaping local minima by accepting uphill moves. The probability of accepting an uphill step is dependent on the magnitude of the increase of the objective function value and on the current temperature, denoted as T in Eq. (1). In elevated temperatures, the acceptance probability of a worst move is obviously higher, allowing the exploration of a wider search space with the hope of approaching the proximity of the

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