Research Article

A Methodology for Optimizing the Management of Spent Fuel of Nuclear Power Plants Using Dry Storage Casks

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The management of spent nuclear fuel assemblies of nuclear reactors is a priority subject among member states of the International Atomic Energy Agency. For the majority of these countries, the destination of such fuel assemblies is a decision that is yet to be made and the “wait-and-see” policy is thus adopted by them. In this case, the irradiated fuel is stored in on-site spent fuel pools until the power plant is decommissioned or, when there is no more racking space in the pool, they are stored in intermediate storage facilities, which can be another pool or dry storage systems, until the final decision is made. The objective of this study is to propose a methodology that, using optimization algorithms, determines the ideal time for removal of the fuel assemblies from the spent fuel pool and to place them into dry casks for intermediate storage. In this scenario, the methodology allows for the optimal dimensioning of the designed spent fuel pools and the casks’ characteristics, thus reducing the final costs for purchasing new Nuclear Power Plants (NPP), as the size and safety features of the pool could be reduced and dry casks, that would be needed anyway after the decommissioning of the plant, could be purchased with optimal costs. To demonstrate the steps involved in the proposed methodology, an example is given, one which uses the Monte Carlo N-Particle code (MCNP) to calculate the shielding requirements for a simplified model of a concrete dry cask. From the given example, it is possible to see that, using real-life data, the proposed methodology can become a valuable tool to help making nuclear energy a more attractive choice costwise.

1. Introduction

In 2018 there were a total of 451 nuclear reactors in operational conditions (i.e., connected to the electrical grid of their countries) in the world. These reactors made up a total of 0.391 TW of installed electrical power. That year, these reactors utilized 65014 tons of uranium. In 2015, 2.44 trillions of kWh was generated by thermonuclear sources, which equals about 11.5% of all electrical energy produced that year [1].

Depending on the operator’s decision, the spent fuel discharged from a nuclear reactor goes through one of the possible management strategies listed below [2].

(i) Once-through cycle, when the fuel is sent to be disposed in a repository.

(ii) Closed cycle, when the fuel is reprocessed and reused in a nuclear reactor.

(iii) The “wait-and-see” policy, when the fuel is stored indefinitely and the decision on either reprocessing or disposal is made at a later moment.

Any one of these strategies demands that the spent fuel is stored for an initial period of time.

Högsetius [3] argued that it is possible to consider the exportation of spent fuel to countries that detain reprocessing technology as a fourth possible policy. In general, the reprocessed fuel returns to its origin country after the operation.

Högsetius also identifies five factors that can influence the decision of a country to opt for one of these policies. They are: military ambitions and nonproliferation, technological culture, political culture and civil society, geological conditions and energy policy [3].

A new approach that is also being considered is the Advanced Fuel Cycle [4], which is considered to be a closed cycle strategy whose goal is to use chemical separation
technologies to remove the constituents of the spent fuel that contribute the most to its decay heat generated and volume, such as separating pure uranium that can be reprocessed or disposed as low-level waste and separating cesium and strontium, removing the short-term heat load.

The three main objectives of pool storage of spent fuel are cooling the fuel assemblies, shielding the workers, and the public from radiation emitted from the fission products present in the fuel and to avoid criticality accidents. A typical spent fuel pool has a depth of approximately 12 m and an area of 12 m x 12 m. The walls are usually built out of reinforced concrete with 1.2 m to 2.4 m thickness. The inside walls of the pool are lined with stainless steel [5].

Dry casks were first used in 1986 at the Surry power plant as a temporary solution until a permanent destination was defined. However, no permanent solution was ever put in practice by the majority of operators [6].

The storage of spent fuel in dry casks has the same basic safety objectives as storage in pools. However, for dry casks, these objectives must be fulfilled without the use of water and mechanical devices. Cooling must be achieved passively, through air and the structural materials that are used to construct the cask. Shielding is also achieved by the choice of materials that make up the cask which may be lead, concrete and/or steel, to attenuate gamma photons, and metals or boron impregnated resins to attenuate neutrons. The criticality control is achieved by the arrangement of the fuel assemblies inside the cask and by racking baskets that contain boron in their structure to absorb neutrons and maintain the geometry of the fuel [5].

The decision begins with the choice of purpose of the container, i.e., storage only or storage and transport. The main difference between the two options is the fuel temperature allowable for transport casks, as it needs to be considerably lower so that the materials that are used comply with weight and dimension requirements of available means of transport [7].

The crucial technical parameters for a licensed dry cask design are majorly defined by the characteristics of the fuel to be stored or transported, especially its physical dimensions, initial enrichment, burnup, and the initial cooling time after the plant operation, which determines the heat generation rate at the beginning of storage or transport [5].

A plan for the management of spent fuel that is elaborated efficiently can result in the design of a spent fuel pool that occupies a smaller area than one that is designed to store for undetermined time the fuel from the whole life span of a nuclear power plant.

The aim of the study presented in this paper is to propose a methodology to optimize the time to remove fuel elements from the initial storage spent fuel pools at reactor sites, taking into account the refueling schedule of the power plant, the isotopic concentrations in the fuel at the time of its removal from the pool (i.e., the source term) and its storage costs. In consequence, it is possible to determine the most efficient dimensions for the spent fuel pool and the optimal design features of an intermediate storage system, assuming that, during the design stage of a new plant, it has been determined that, sometime in its lifetime, the spent fuel will be moved to an intermediate facility that employs dry storage casks. The proposed methodology is therefore intended for countries that have chosen dry casks as solution for interim storage of spent fuel and does not consider interim storage in pools. It is assumed that regulatory requirements, such as the mechanical limits of the casks and the spent fuel pool, are to be addressed by the designer after the initial dimensioning optimization is fulfilled, which is the goal of the proposed methodology.

Spencer et al. [8] developed a methodology to optimize the loading configurations of fuel assemblies in dry casks that minimize the number of casks to be employed, their heat load and the time at which they meet transportation requirements. That study, however, does not intend to optimize, in terms of cost, the design features of either the spent fuel pool nor of those the dry casks.

Figure 1 presents a general description diagram of the methodology proposed in this paper.

2. Materials and Methods: Steps Required for the Application of the Methodology

The steps required for the application of the methodology are listed below. They do not necessarily have to be followed in this exact order.

1. Definition of the operation scenario of the NPP.
2. Definition of the type and average characteristics of the fuel assembly to be used in the NPP.
3. Simulation of the NPP’s operation using reactor physics codes.
4. Definition of the type of dry cask to be employed for the intermediate storage of spent fuel.
5. Modeling of the storage costs for the spent fuel pool, in relation to the number of fuel assemblies to be stored in it and modeling of the storage costs for the chosen dry cask, considering the number of fuel assemblies to be stored in it and the parameters of the spent fuel at the time it is removed from the spent fuel pool.
6. Establishment of the dose rate limits at the points of interest for the installation licensing.
7. Establishment of the temperature limits of the structural materials that compose the dry casks.
8. Market research of the costs involved in the construction of the spent fuel pool and the dry casks.
9. Application of the obtained models and input data to an optimization algorithm.

Figure 2 presents a flow diagram of all the steps involved and the following sections describe them in further detail.

2.1. Operation Scenario. At this step, the main characteristics of the NPP must be defined. They are the number of units operating at the NPP, type of reactor, i.e., Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), etc., reactor power, duration of the refueling cycle, number of fuel
2.2. Fuel Assembly Parameters. It must be observed that inside a nuclear reactor there are fuel assemblies with different characteristics, arranged in such a manner to allow for the correct and efficient operation of the plant. At each refueling, this arrangement is altered and as such, it is difficult to predict, at the design stage of the plant, the parameters of all the fuel assemblies that will need to be stored. This methodology uses as input data the parameters of a typical fuel assembly that is usually employed with the chosen reactor type and the hypothesis of equilibrium [9] is adopted.

The fuel assembly parameters that must be known are the number of fuel rods per assembly, assembly pitch, assembly height, initial \( \text{U}_2\) mass, initial enrichment and burnup.

2.3. Simulation of the NPP’s Operation. It is necessary that a simulation of the operation of the plant is carried out, using reactor physics codes. This simulation provides information on the isotopic concentrations and residual heat present in the irradiated fuel. It is also necessary to simulate how the isotopic concentrations change and the decay heat decreases during the time the spent fuel is stored in the pool.

2.4. Choice of Dry Cask Type. At this stage, the type and characteristics of the dry casks to be employed must be
defined. They are: purpose (i.e., storage or storage and transport); capacity (i.e., number of fuel assemblies that can be stored in it); materials used for shielding; and heat removal capacity.

2.5. Modeling of Storage Costs. It is necessary to obtain a function that describes the costs involved in the management of spent fuel, which is a function of the initial storage time of the fuel in the spent fuel pool. A fraction of the cost is independent of the time the fuel stays in the pool, such as personnel and machinery involved in the transference of the fuel to the dry casks and the costs for the construction of the dry casks that are not dependent on the parameters of the spent fuel assemblies.

As such, it is possible to define

\[ C_{\text{total}}(t) = C_{\text{sfp}}(t) + N_{\text{cask}} C_{\text{cask}}(t) + C_{\text{const}} \]  

(1)

\[ C(t) = C_{\text{sfp}}(t) + N_{\text{cask}} C_{\text{cask}}(t) \]  

(2)

where \( t \) is the initial cooling time, i.e., the time the spent fuel assemblies are stored in the at-reactor spent fuel pool; \( C_{\text{total}}(t) \) is the total costs of management of spent fuel; \( C_{\text{sfp}}(t) \) is the costs of storage in the spent fuel pool that are function of \( t \); \( N_{\text{cask}} \) is the number of casks that will be needed to store all the fuel assemblies from the NPP’s life span; \( C_{\text{cask}}(t) \) is the cost of storage in one dry cask that is a function of \( t \); \( C_{\text{const}} \) is the fraction of the cost of storage that is not a function of \( t \), and \( C(t) \) is the total costs of the fuel storage which is a function of \( t \). Costs from racking space in the pool as a margin for emergencies can be considered as part of \( C_{\text{const}} \), as this does not depend on the initial cooling time.

Figure 3 presents a sketch of the expected behavior of the contributions to the spent fuel storage costs.

For the spent fuel pool model, the defining parameter is the maximum number of fuel assemblies that are to be stored in it simultaneously. The costs associated with the heat removal and shielding of the radiation from the spent fuel are all lumped into a single value \( C_{\text{cask}} \) that represents the cost of storage per fuel assembly in the pool.

The number of fuel assemblies stored simultaneously in the pool depends on the rate of removal of fuel assemblies from the reactor, in accordance with the refueling schedule of the NPP, and the rate of removal of fuel elements from the pool, after the initial cooling period. Figure 4 presents the flow of fuel assemblies in and out of an at-reactor spent fuel pool that may be shared by the \( n \) units of a NPP.

\[ C_{\text{sfp}}(t) = C_{\text{FA}} \max[N(t, T)] \]  

(3)

where \( N(t, T) \) is the number of fuel assemblies in the pool at time \( T \) from the beginning of the NPP operation and in function of the initial cooling time \( t \) and \( \max[N(t, T)] \) is the maximum value of \( N(t, T) \) during the life span of the NPP. \( N(t, T) \) is thus defined as

\[ N(t, T) = \int_{T_0}^{T} N_{\text{in}}(t, T) dT - \int_{T_0}^{T} N_{\text{out}}(t, T) dT \]  

(4)

where \( N_{\text{in}}(T) \) is the number of fuel assemblies that are placed in the pool at time \( T \) from the beginning of the NPP operation and \( N_{\text{out}}(t, T) \) is the number of fuel assemblies that are removed from the pool at time \( T \) and in function of the initial cooling time \( t \).

As stated earlier, the outflow of fuel assemblies from the pool depends on the time they stay in it for initial cooling. However, in this optimization problem, the cost of the dry casks is also dependent of the initial cooling time. The pricing of the dry casks is related to the characteristics of the fuel assemblies that are to be stored in them. The main parameters to be taken into consideration are the number of assemblies to be stored in a single cask, the decay heat and the activity of the fission products still present in the fuel at the time of transference to the casks [11]. These last two parameters are functions of \( t \).

The main radiation sources that should be considered for the shielding design of a dry storage unit are primary gamma rays emitted from fission products and actinides, gamma rays from Cobalt-60 in the fuel assemblies’ structural materials, secondary gamma rays from the radiative capture of neutrons by cask materials, neutrons from subcritical and spontaneous fission and neutrons emitted from \((\alpha, n)\) reaction of fissionable material [6].

Chen et al. [12] made an accuracy and computational efficiency comparison of dose rate calculations for a spent fuel storage cask using the MCNP and SAS4 (Shielding Analysis Sequence 4) computer simulation codes, whose
main differences are the cross-section libraries and the imbedded variance reduction techniques MCNP has. In this comparison, MCNP’s overall performance was better, although SAS4 was more efficient when the only concern was the dose rate measured at the side of the cask.

Gao et al. [6] used MAVRIC (Monaco with Automated Variation Reduction using Importance Calculations) to compare the dose rate distributions, with high level of detail, of a TN-32 cask, designed by Transnuclear [13], with two geometry models and two cross-section datasets. The study concludes that primary gamma rays contribute to $\sim 91\%$ of the total dose rate at the side surfaces of the cask and to $\sim 99\%$ at the top surface.

It is assumed for this study that measures for maintaining the subcriticality are guaranteed by the geometry of the positioning of the fuel assemblies inside the casks and by the use of boron in the spacing baskets inside the casks. The costs that result from these measures are not considered in this analysis, though they will be considered in future studies, as optimal positioning of the fuel assemblies in the casks might contribute to reducing the costs of boron used in the spacing brackets.

2.6. Dose Rate Limits. The dose rate limits to be respected by the dry cask design are those that are established by the regulatory agencies of each country. These limits will establish the minimal shielding capacity that the cask designer must demonstrate.

In the United States, these limits are established in accordance with 10 CRF part 72 [14]. However, as observed in NUREG 1536 [15], the federal regulation does not impose specific dose rate limits for individual dry casks, as acceptable dose rates depend on various factors, such as the geometry of the dry casks array, time the workers need to stay in the vicinity of the casks and the proximity to areas usually inhabited by workers. In previous evaluations, in the light of 10 CFR part 72 [14], US NRC has accepted dose rates ranging from 0.2 mSv/h to 4 mSv/h. NUREG 1536 [15] also states that the dose rates must be calculated at a distances of 1 m from points such as the surface of the cask and the air vents, as these dose rates typically contribute to the exposure of the workers.

2.7. Temperature Limits. The temperature limits of the materials that compose the selected dry casks, as well as their heat removal capacities, define the maximum decay heat allowed for the fuel assemblies to be stored in them.

Li et al. [16] presented a thermal analysis of a vertical storage dry cask containing 32 fuel assemblies with a total decay heat load of 34 kW using the ANSYS/FLUENT code. Several configurations of cannister fill gas, internal pressure and basket material were studied in order to determine peak cladding temperature and cannister surface temperatures. For this study, the dry cask was modeled after the HI-STORM 100 system by HOLTEC International [17].

2.8. Market Research. To obtain results with economic relevance, it is necessary that a market research is carried out in order to estimate the costs of storage per fuel element in the spent fuel pool and the costs for the acquisition of the dry casks with the minimal parameters to guarantee the integrity of the fuel assemblies stored in them and that the minimal shielding capacity that must be fulfilled.

The change of unit costs over time was not considered in this analysis, though it might be the subject of future studies with the contribution of specialists in the economics field.

2.9. Optimization. The final step is the coding of an optimization algorithm, using all the data gathered up to this point, to obtain the optimal time to remove the fuel assemblies from the spent fuel pool and transfer them to the dry casks. The fuel assemblies’ parameters, the NPP operational data, and the values obtained from the market research are used as input data to the problem. The function that models the sum of spent fuel pool and dry casks costs is used as a fitness or objective function to be minimized. The temperature and dose rate limits are used as restrictions for the algorithm.

3. Example of Application

3.1. Hypothetical NPP. To demonstrate the methodology, it is necessary to establish a hypothetical model of a NPP that will operate in accordance with the premises adopted for this study. This NPP will be referred to as the Hypothetical NPP or the HNPP.

The HNPP is comprised of one reactor unit of the PWR type, whose electrical power is 640 MW. Its main parameters are as follows:

(i) Number of fuel assemblies: 121.
(ii) Number of fuel rods per assembly: 235.
(iii) Fuel assembly pitch: 19.82 cm.
(iv) Fuel assembly height: 4 m.
(v) Initial $\text{UO}_2$ mass per Fuel Assembly: 0.47 MTU.
(vi) Average refueling enrichment: 4.0%.
(vii) Average Maximum Burnup: 55000 MWd/t.
(viii) Refueling frequency: 12 months.
(ix) Fraction of the core that is removed after refueling: $\sim 33\%$.

It is established that the HNPP will operate for 60 years, will only be shut down for refueling and that it will operate at its nominal power during its whole life span.

The following simplifications will be adopted for the HNPP operation:

(i) From the first operational cycle, it is considered that the core is at equilibrium.
(ii) At each refueling, the new core will have the same configuration as the one before it.
(iii) All the fuel assemblies that are going to be stored have the same isotopic concentrations and decay heat. In this case the average parameters were adopted, in view of the available data.
(iv) Only normal operation will be considered. Accidental scenarios are not studied.
Considering that the reactor core has 121 fuel assemblies and that approximately one-third of them is removed during a refueling outage and assuming that ~1% of these assemblies fail and must remain in the spent fuel pool, we can assess that 40 fuel assemblies will be removed at each refueling operation. For this reason, a dry cask design that can store 24 fuel assemblies was chosen, similar to the one made available by HOLTEC with their HI-STORM 100 system [17], and two of them (with 20 fuel assemblies each) will be needed for each refueling operation.

As the life span of the HNPP is 60 years, refueling is carried out every 12 months, and in the last year of operation the whole fuel will be removed from the reactor core, the total number of dry casks that will need to be purchased is

$$N_{\text{cask}} = 124$$

The failed fuel assemblies will not be considered in the example, as they require special analysis before disposal.

3.2. Dry Cask Selection. A single purpose cask design, i.e., storage only, was selected for this example. The simplified model of the cask comprises an internal cylindrical canister which holds up to 24 fuel assemblies arranged in baskets where 20 assemblies will be stored.

An outer concrete cylinder provides shielding from the radiation within. Two concrete lids, at the top and at the bottom provide shielding from the radiation that may come from those directions.

Air ducts in between the two cylinders allow for the passive removal of decay heat from the fuel. Boron injected traps placed in the air ducts ensure that no radiation flows through the air inlets at the bottom of the cask and the outlets at the top of the cask.

3.3. Spent Fuel Data. For this example, the fuel data was obtained from NUREG 7227—“US Commercial Spent Nuclear Fuel Assembly Characteristics: 1968–2013” [10]. This document provides a compilation of fuel assemblies from BWR and PWR reactors arranged by various burnup, initial enrichment and initial cooling time values. In this document, with data obtained from the GC-859 database, simulations were carried out using the ORIGEN code and information such as decay heat, isotopic concentrations and activity were presented.

The document presents these values for initial cooling times of 5 hours, 1 day, 90 days, 1 year, 5 years, 10 years, 100 years and 200 years, for three PWR and three BWR groups arranged in accordance with the year the fuel assemblies were removed from their respective reactors. This arrangement coincidentally places the assemblies in groups with roughly similar median initial enrichment and burnup values [10].

From the PWR-3 group, where the HNPP reactor parameters fall, the isotopic concentrations and activity data were obtained. The values that occur in between the available initial cooling times were interpolated.

3.4. Cost Modeling. The model that represents the costs of the spent fuel pool is used as described in Section 2.6. The model that represents the costs of the dry casks is described as follows.

Figure 5 shows the model for the thickness of the materials used for the shielding of radiation.

The bundle of 20 fuel assemblies that make up the source inside the cask are then approximated to a cylinder, as described by Figure 6 and Equations (6) and (7). The approximation considers the 24 available slots for fuel assemblies inside the cask, even though 4 of them are left unused. For this example, as the approximation considers a homogeneous cylindrical source, it does not matter which slots remain empty. The empty slots may contribute to optimizing the shielding capacity of the cask and must be considered in a more accurate model of the source.
\[ r^2 = (3L_{FA})^2 + L_{FA}^2 \]  
\[ V_S = \pi r^2 h_{FA} \]

where

\( r \) is radius of the cylinder that approximates the geometry of the source.

\( L_{FA} \) is length of the side of the fuel assembly.

\( h_{FA} \) is height of the fuel assembly.

\( V_S \) is source volume.

From the values defined in Section 3.1,

\[ r = 60.71 \text{ cm} \]  
\[ V_S = 46.324 \text{ m}^3 \]

Considering that the mass of \( \text{UO}_2 \) in one fuel assembly is 0.47 MTU, for the whole source term, the mass of \( \text{UO}_2 \) in a single cask is 9.4 MTU.

The cost of the whole array of dry casks, as considered in this example, is then defined as

\[ C_{cask} = C_c N_{cask} \left[ \pi (r + L_c)^2 (h_{FA} + 2L_c) - V_S \right] \]  

\[ \text{Relative Error} \]

| Concrete thickness (cm) | Dose per decay at the source (pSv) | Relative Error |
|-------------------------|------------------------------------|----------------|
| 10                      | 5.36E-08                           | 0.0109         |
| 20                      | 2.18E-10                           | 0.0495         |
| 30                      | 6.36E-13                           | 0.0712         |
| 40                      | 1.86E-16                           | 0.1721         |
| 50                      | 1.90E-19                           | 0.1095         |
3.5. Decay Heat Removal. The calculation of the heat removal capacity of dry casks is usually done using Computational Fluid Dynamics (CFD) codes. The purpose of such studies is to determine the behavior of the materials chosen and verify if they fulfill the cooling requirements [19]. For the present example, heat removal analysis was not carried out, and it is assumed that the temperature limits of the materials are always respected. In a real case, these limits would be used as boundaries for the optimization algorithm.

3.6. Market Research. For this example, a market research was not done. Instead, the values for the storage per fuel assembly in the spent fuel pool and for the unit volume of concrete used in the dry casks were varied and the algorithm was run several times. This was carried out as part of the sensitivity analysis presented in Section 4.

3.7. Optimization Algorithm. For the example, the final step of the methodology, which is the optimization algorithm execution, was done using the “Global Optimization” toolbox available in MATLAB® [20]. The chosen method was the Genetic Algorithm.

Genetic algorithms are inspired by the evolutionist theory, in which the stronger individuals have a better chance to pass on their genes through reproduction. Natural selection dictates which individuals’ characteristics in one generation survive to the next. The two basic operators that create new solutions from the previous generation’s solutions are crossover, in which two individuals’ genes are combined to form new individuals; and mutation, that introduces diversity to the population and avoids premature convergence to an optimal solution that may not be the global one. The suitability of an individual solution to an objective function, called fitness, determines the probability that it survives to the next generation [21].

Functions to calculate the costs of the dry cask and the spent fuel pool, as well as for calculating the dose rates measured at the point located at 1 meter from cask surface location were coded. The fitness function to be minimized was defined as equal to the sum of the dry cask and pool costs and the dose rate function was used as a constraint for the algorithm.

4. Results and Discussion

To evaluate the behavior of the optimization algorithm, as well as the effects of changes in the input parameters of the problem on the algorithm’s output, a simple sensitivity analysis was carried out. For this, the values for dose rate limits and unit prices for the storage per fuel assembly at the pool and cubic meter of concrete were varied in relation to each other.

Table 4 presents the sensitivity analysis for the Cesium-137 fraction of the source obtained from the Genetic Algorithm for a dose rate limit of 0.2 mSv/h and for a dose rate limit of 4 mSv/h. The unit prices are measured in Monetary Units (M.U.) and are displayed within a range where changes to the results could be observable. The parameters of the scenario and the simplifications made during the development of the example defined the range where these changes could be observable.

Analyzing the results, it is noticeable that, for the algorithm to work in a range where changes in the result can be observed, the value of a cubic meter of concrete must be high in relation to the storage cost of a fuel assembly in the pool. This is a consequence to the simplification of the dry cask model used for this example, as in a real design, there are other characteristics that depend on parameters of the spent fuel that vary with the initial cooling time, such as materials for neutron shielding and passive decay heat removal features.

Secondly, it is observed that the example scenario is much more sensible to changes in concrete shielding thickness than it is to changes in initial cooling time, for example, an increase of 1 mm to shielding thickness has a larger impact on the measured dose rate than an increase of 12 months in initial cooling time. This can be explained by the choice of only using Cesium-137 as the source for this example, as this isotope has a long half-life (approximately 30 years), and changes in its activity are more noticeable at short term. Also, the higher the dose rate limit is, the smaller is the increment or decrease in shielding thickness necessary to compensate for changes in initial cooling time.

To observe how the algorithm behaves when a more diverse source term is present, a second sensitivity analysis was carried out using a source with the decay characteristics of Cesium-137 (i.e., one photon with energy of 0.6617 MeV) and the activity at various initial cooling times for the whole spent fuel isotopic composition obtained from (USNRC, 2015) [10]. This adaptation of the source does not have any means the objective of representing the actual source inside a dry cask, but it is useful as a tool to evaluate the sensitivity of the optimization algorithm, as it has a steeper decrease curve than the source comprised solely of Cesium-137. Table 5 presents the activity values for different cooling times of this adapted source.

Table 6 presents the sensitivity analysis of the Genetic Algorithm using the adapted source for both 0.2 mSv/h and 4 mSv/h dose rate limits, once again presented at unit costs of fuel assembly and concrete unit costs intervals where changes in the algorithm output can be observed.

As can be observed, using the adapted source with a steeper activity decrease allowed for more noticeable changes in the results, i.e., longer initial cooling times allowed for larger decreases in shielding thickness in comparison to the Cesium-137 only source.

It also possible assess that the fitness function has many local minima that correspond to the points where the dose rate at the detector is closest to, but not greater than, the normative dose rate limit. What determines if one minimum is better than another is the relation between unit costs for spent fuel cost per fuel assembly and cubic meter of concrete.

Further data, such as dose rate at 1 m from the surface of the cask and minimal capacity needed for the spent fuel pool can then be obtained for the optimal values of a given scenario of dose rate limit, choice of source and unit costs for fuel assembly storage in the pool and cubic meter of concrete. For example, using the adapted source, the 4 mSv/h dose rate limit and unit costs of 25 M.U. for storage of fuel assemblies...
Table 4: Sensitivity analysis for the optimization algorithm using Cesium-137 as the source.

| Dose Rate Limit | Concrete cost per m³ (M.U.) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) |
|-----------------|-------------------------------|--------------------------|------------------------|--------------------------|------------------------|--------------------------|------------------------|
| 0.2 mSv/h       |                               |                          |                        |                          |                        |                          |                        |
| 100             |                               |                          |                        |                          |                        |                          |                        |
| Optimal Time    | Concrete Thickness            | Optimal Time             | Concrete Thickness     | Optimal Time             | Concrete Thickness     | Optimal Time             | Concrete Thickness     |
| (months)        | (mm)                          | (months)                 | (mm)                   | (months)                 | (mm)                   | (months)                 | (mm)                   |
| 1               | 13                            | 299.660                  | 720                    | 298.034                  | 720                    | 298.034                  | 720                    |
| 10              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| Pool cost per   |                               |                          |                        |                          |                        |                          |                        |
| stored Fuel     |                               |                          |                        |                          |                        |                          |                        |
| 20              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| 25              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| 26              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| 27              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| 28              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| 30              | 13                            | 299.660                  | 13                     | 299.660                  | 13                     | 299.660                  | 13                     |
| Dose Rate Limit |                               |                          |                        |                          |                        |                          |                        |
| 4 mSv/h         |                               |                          |                        |                          |                        |                          |                        |
| 100             |                               |                          |                        |                          |                        |                          |                        |
| Optimal Time    | Concrete Thickness            | Optimal Time             | Concrete Thickness     | Optimal Time             | Concrete Thickness     | Optimal Time             | Concrete Thickness     |
| (months)        | (mm)                          | (months)                 | (mm)                   | (months)                 | (mm)                   | (months)                 | (mm)                   |
| 1               | 720                           | 253.115                  | 720                    | 255.115                  | 720                    | 255.115                  | 720                    |
| 10              | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| Pool cost per   |                               |                          |                        |                          |                        |                          |                        |
| stored Fuel     |                               |                          |                        |                          |                        |                          |                        |
| 20              | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| 50              | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| 100             | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| Assembly        |                               |                          |                        |                          |                        |                          |                        |
| (M.U.)          |                               |                          |                        |                          |                        |                          |                        |
| 250             | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| 750             | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
| 1000            | 13                            | 287.635                  | 13                     | 287.635                  | 13                     | 287.635                  | 13                     |
Table 5: Activity for all the isotopes in the spent fuel (adapted from [10]).

| Initial Cooling Time | Activity per MTU (Ci/MTU) |
|----------------------|---------------------------|
| 5 hours              | 7.53E+07                  |
| 1 day                | 5.61E+07                  |
| 90 days              | 7.79E+06                  |
| 1 year               | 2.98E+06                  |
| 5 years              | 8.02E+05                  |
| 10 years             | 5.56E+05                  |
| 50 years             | 1.81E+05                  |
| 100 years            | 5.81E+04                  |
| 200 years            | 1.15E+04                  |

The results obtained from the example show that, following the steps established by the methodology, the user can obtain the desired information, which is the optimal time, in relation to overall cost, to remove the spent fuel assemblies from the spent fuel pool and move them to dry casks as well as several data of great value for the designer of a new NPP.

5. Conclusions

This study had the purpose to establish a methodology for the optimization of the management of spent nuclear fuel assemblies. Some simplifications were necessary in order to present the example given, allowing for the development of the methodology utilizing the available resources.

It is not the intention of the authors that the results obtained from the presented example are directly applied to the design of an installation, but rather, to demonstrate the steps necessary for the application of the proposed methodology, with real data and more detailed models, to allow for the reduction of the initial investment of purchasing a new plant.

5.1. Limitation of the Study. Many uncertainties exist before the operation of a nuclear power plant. Political and financial decisions, as well as unforeseen events, such as accidents that alter the public perception of the use of nuclear energy, may result in the change of the fuel management policy adopted by any nation. Problems such as the lack of resources to acquire dry casks during the operation of the plant may cause the capacity of the spent fuel pool to be compromised, which in turn may demand that the plant is shut down until the problem is resolved. In the same manner, technological development may make dry cask design and manufacturing cheaper, making them more advantageous options than they were during the application of the methodology at the design stages of the power plant. The proposed methodology cannot foresee such issues and further studies might be needed to include an approach to address them.

The methodology also only deals with a scenario where a country opts for using dry casks as a solution for interim storage and does not apply to those countries that may choose to store their spent fuel in independent pools, limiting the scope of its application.

The adoption of the core Equilibrium Hypothesis might also limit the application of the proposed methodology as variations in the core configuration during the life span of the NPP can impair the results obtained by the optimization process. Further studies focused on this issue might also benefit and improve the methodology.

Further investigations include the refinement of the shielding and source models, including activated structural materials, decay heat analysis, and a detailed market research, with the contribution of specialists in the economic field, to obtain realistic values for the unit prices of the shielding materials and spent fuel pool construction, including their variation with time.

6. List of Symbols and Acronyms

BWR: Boiling Water Reactor.
Table 6: Sensitivity analysis for the optimization algorithm using the adapted source.

| Dose Rate Limit 0.2 mSv/h | Concrete cost per m$^3$ (M.U.) | 100 | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) |
|---------------------------|-------------------------------|-----|--------------------------|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|
| Pool cost per stored Fuel Assembly (M.U.) | 25 | 121 | 343.877 | 433 | 300.000 | 720 | 299.709 | 720 | 299.709 |
| 50 | 61 | 360.956 | 433 | 300.000 | 433 | 300.000 | 433 | 300.000 |
| 75 | 61 | 360.955 | 433 | 300.000 | 433 | 300.000 | 433 | 300.000 |
| 100 | 13 | 389.405 | 433 | 300.000 | 13 | 389.405 | 121 | 343.877 |
| 500 | 13 | 389.405 | 61 | 360.956 | 13 | 389.405 | 121 | 343.877 |
| 1000 | 13 | 389.405 | 13 | 389.405 | 13 | 389.405 | 121 | 343.877 |

| Dose Rate Limit 4 mSv/h | Concrete cost per m$^3$ (M.U.) | 100 | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) | Optimal Time (months) | Concrete Thickness (mm) |
|---------------------------|-------------------------------|-----|--------------------------|-----------------------|------------------------|-----------------------|------------------------|-----------------------|------------------------|
| Pool cost per stored Fuel Assembly (M.U.) | 1 | 720 | 288.610 | 720 | 288.610 | 720 | 288.610 | 720 | 288.610 |
| 10 | 13 | 299.670 | 720 | 288.610 | 720 | 288.610 | 720 | 288.610 |
| 50 | 13 | 299.670 | 13 | 299.670 | 13 | 299.670 | 720 | 288.610 |
| 75 | 13 | 299.670 | 13 | 299.670 | 720 | 290.050 | 720 | 288.610 |
| 90 | 13 | 299.670 | 13 | 299.670 | 613 | 290.050 | 121 | 297.002 |
| 100 | 13 | 299.670 | 13 | 299.670 | 61 | 298.003 | 121 | 297.002 |
| 250 | 13 | 299.670 | 13 | 299.670 | 13 | 299.670 | 13 | 299.670 |
| 200 | 13 | 299.670 | 13 | 299.670 | 13 | 299.670 | 13 | 299.670 |
Table 7: Optimal result data for a given set of example parameters with 4 mSv/h as the dose rate limit.

| Source                      | Adapted   |
|-----------------------------|-----------|
| Dose Rate Limit             | 4 mSv/h   |
| Cubic Meter of Concrete Unit Cost | 5000 M.U. |
| Storage Cost per Fuel Assembly in the Pool | 90 M.U. |
| Optimal Initial Cooling Time | 121 months |
| Optimal Shielding Thickness | 297.002 mm |
| Spent Fuel Pool Minimal Capacity | 400 Fuel Assemblies |
| Spent Fuel Pool Cost        | 3600 M.U. |
| Dose Rate at 1 m from Cask Surface | 4 mSv/h |
| Concrete Volume for Whole Cask Array | 11.15 m³ |
| Cost of Whole Cask Array    | 6.9126 x 10⁶ M.U. |
| Cost per Fuel Assembly Stored Dry | 2787.33 M.U. |

Table 8: Optimal result data for a given set of example parameters with 0.2 mSv/h as the dose rate limit.

| Source                      | Adapted   |
|-----------------------------|-----------|
| Dose Rate Limit             | 0.2 mSv/h |
| Cubic Meter of Concrete Unit Cost | 5000 M.U. |
| Storage Cost per Fuel Assembly in the Pool | 90 M.U. |
| Optimal Initial Cooling Time | 433 months |
| Optimal Shielding Thickness | 300.000 mm |
| Spent Fuel Pool Minimal Capacity | 1440 Fuel Assemblies |
| Spent Fuel Pool Cost        | 129,600 M.U. |
| Dose Rate at 1 m from Cask Surface | 0.2 mSv/h |
| Concrete Volume for Whole Cask Array | 11.24 m³ |
| Cost of Whole Cask Array    | 6.9703 x 10⁶ M.U. |
| Cost per Fuel Assembly Stored Dry | 2810.60 M.U. |

$C(t)$: costs of management of spent fuel that depend on the initial cooling time $t$.

$C_c$: cost per unit volume of concrete.

$C_{cont}$: costs that do not depend on the initial cooling time $t$.

$C_{EA}$: cost of storage per fuel assembly in the pool.

CFR: Code of Federal Regulations.

$C_{cask}(t)$: cost of one dry cask that is dependent on $t$.

$C_{dp}(t)$: cost of spent fuel pool that is dependent on $t$.

$C_{total}(t)$: total cost of management of spent fuel.

$h_{EA}$: height of a fuel assembly.

HNPP: Hypothetical Nuclear Power Plant.

$L_c$: concrete shielding thickness.

$L_{EA}$: length of the side of a fuel assembly.

M.U.: Monetary Units.

MAVRIC: Monaco with Automated Variation Reduction using Importance Calculations.

max[$N(t, T)$]: number of fuel assemblies in the pool at time $T$ in function of $t$.

MCNP: Monte Carlo N-Particle.

MTU: Metric Ton of Uranium.

$N_{cask}$: total number of dry casks.

$N_{in}(t)$: number of fuel assemblies that are placed in the pool at time $T$.

$N_{out}(t)$: number of fuel assemblies that are removed from the pool at time $T$ and in function of $t$.

NPP: Nuclear Power Plant.

NUREG: United States Nuclear Regulatory Commission Regulation.

PWR: Pressurized Water Reactor.

SAS4: Shielding Analysis Sequence 4.

$t$: initial spent fuel cooling time.

$T$: time from the beginning of the power plant operation.

$UO_2$: Uranium Dioxide.

US NRC: Unite States Nuclear Regulatory Commission.

$V_s$: volume of the source.

Data Availability

The MCNP simulated radiation dose data used to support the findings of this study are included within the article. The Spent Nuclear Fuel Assemblies Characteristics data supporting this study are from previously reported studies and datasets, which have been cited. The processed data are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.
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