Limited Inventory Startup Core Loading for the NBSR

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INTRODUCTION

The National Bureau of Standards Reactor (NBSR) is located at the National Institute of Standards and Technology (NIST). NBSR is one of the five U.S. high-performance research reactors. It is a 20 MW, heavy water-cooled and moderated tank-type research reactor that has been operational since 1967. The NBSR experienced a fuel failure event during the power increase on February 3, 2021. After extensive cleaning and corrective actions, the NBSR reached criticality again on March 16, 2023.

Post-incident inspections revealed debris on several fuel elements that resided in the core during the incident, which made the reuse of fuel elements from that core loading risky. As such, all the fuel elements from the incident's core loading were deemed unusable and disposed of appropriately. The loss of fuel elements from the incident core disrupted the Original Fuel Management Scheme (OFMS) of the NBSR. OFMS, shown in Figure 1, requires fuel elements at different burnup levels from fresh to 8^{th} cycle elements. However, after the incident, only fresh and 7^{th} cycle fuel elements were available for usage. Many Alternative Fuel Management Schemes (AFMS) are needed to get the NBSR back to its equilibrium core and OFMS as defined in the Final Safety Analysis Report (FSAR). The first AFMS, a new Startup Core Loading (SCL), is a prerequisite to the restart of the NBSR. The introduction of AFMS and the required analysis methodology was documented as part of a License Amendment that was approved by the U.S. Nuclear Regulatory Commission (NRC) [1]. SCL is subject to several limitations, primarily the Technical Specifications (TS), administrative limitations, and existing conditions in the updated FSAR [2]. Nevertheless, the development of the SCL was a challenging task for the restart of the NBSR. This work aims to describe the methodology employed in the development and optimization of the SCL.

METHODOLOGY

The NBSR has a hexagonal grid arrangement of fuel elements in the core, with 30 fuel elements arranged in seven horizontal rows as shown in Figure 1. During normal operations, one fuel cycle of the NBSR would last around 38.5 days. After the cycle, four fuel elements are removed from the core to the spent-fuel storage pool, and four fresh fuel elements are placed in the core. The remaining 26 elements are shuffled within the core according to the OFMS. As shown in Figure 1, a fresh fuel element either completes 7-cycles or 8-cycles, marked as 7-# and 8-#, respectively, where # would be the current cycle number of the specific fuel element.

Since all of the fuel elements from the incident core loading were discarded, only 7^{th} cycle and fresh fuel elements were available to load for the SCL. Although 8^{th} cycle fuel elements were also available, their integral fission density was very close to the TS limitation, making them less attractive for reutilization. It then follows that the SCL must only consist of 7^{th} cycle and fresh fuel elements.

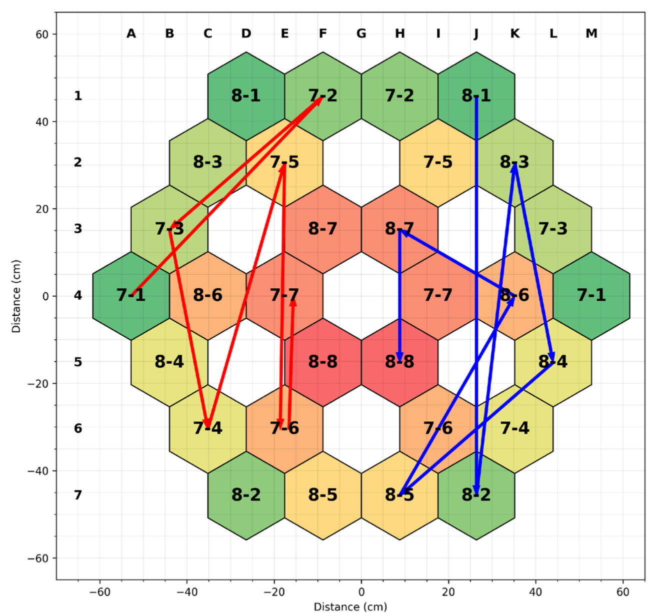

Figure 1. NBSR Original Fuel Management Scheme

In lieu of limitations in the TS and updated FSAR, an AFMS framework that uses MCNP in the backend is developed.

MCNP Model and AFMS Framework

The MCNP model used in this work was originally developed to perform NBSR's Safety Analysis Report calculations. All core structures, cold and thermal beam tubes, and other irradiation structures were well-defined in the MCNP model input. The NBSR has 30 fuel elements that contain highly enriched uranium in U_3O_8-Al dispersed fuel plates. Each element has 2 sets of 17 fuel plates axially separated by a gap that is located between the top and bottom fuel plate sets, which is used as a thermal flux trap for optimal neutron leakage to any of the experiment devices/thimbles. Although the input model contains 60 fuel materials which define all fuel sections separately, this definition does not provide enough fidelity while performing the burnup-related fuel material changes in the axial direction due to the un-evenly distributed flux shape of the fuel plates and radial flux shape variations caused by the high neutron leakage. The model is updated with 720 separate materials to obtain high-fidelity results along the cycle calculation. This updated model is verified against the previous model with criticality safety calculations. Through a License Amendment, the new 720-material model is now included in the updated FSAR.

The burnup runs are performed with MCNP version 6.2 [5] through the use of the BURN card options. Any core loading pattern shall need to be analyzed for each different core configuration by considering the criticality safety and other safety concerns of the NBSR as defined in the updated FSAR and TS. To perform these types of analyses, an engineering analysis framework, shown in Figure 2, is developed. The AFMS Framework performs all nuclear criticality analyses such as excess reactivity, shutdown margins, critical shim angles, and other reaction metrics which are required for assessing the cycle. The framework starts with a core loading pattern which is previously defined by the user. After the core loading parameters are implemented in the MCNP input, the excess reactivity of the cycle is automatically calculated by the framework , the framework then guesstimates the cycle length by using historical operational data. NBSR's operating cycle covers 5 different time intervals and 6 different cycle-state positions including Startup (SU), Beginning of Cycle (BOC), Quarter-2 (Q2), Middle of Cycle (MOC), Quarter-4 (Q4), and End of Cycle (EOC). The first 1.5-day period is SU to simulate the Xe buildup effects in the cycle. Prior to the burnup run, shim calibration routines search for the critical angle of the shim arms for the cycle state. Following the shim critical angle position determination, the cycle state burnup calculation starts with the determined angle, and it is repeated for all cycle states until it reaches EOC. The EOC state is performed to determine the core final criticality condition and the initial guess of the cycle length. If the results are consistent with the calculated cycle results, the EOC is finalized with 10 days of cooling to simulate the maintenance and refueling outage.

All framework uses the core configuration, each assembly's mass composition, and the cycle parameters of the assemblies as inputs.

Core Loading Optimization Methodology

The NBSR inventory has a limited number of 7^{th} cycle elements and the amount of them to be used need to be carefully assessed considering the future fuel cycles required to reach OFMS. Each 7^{th} cycle fuel element has a unique isotope composition because not every past fuel cycle of the NBSR has the same exact operational histories, and the burnups of each 7^{th} cycle elements are various. Moreover, the time that each 7^{th} cycle element stayed in the spent-fuel storage pool; hence the decay of its parasitic fission products is different. Per NRC regulation 10 CFR 73.60, there is a limit for the unirradiated U^{235} amount that a nonpower reactor can

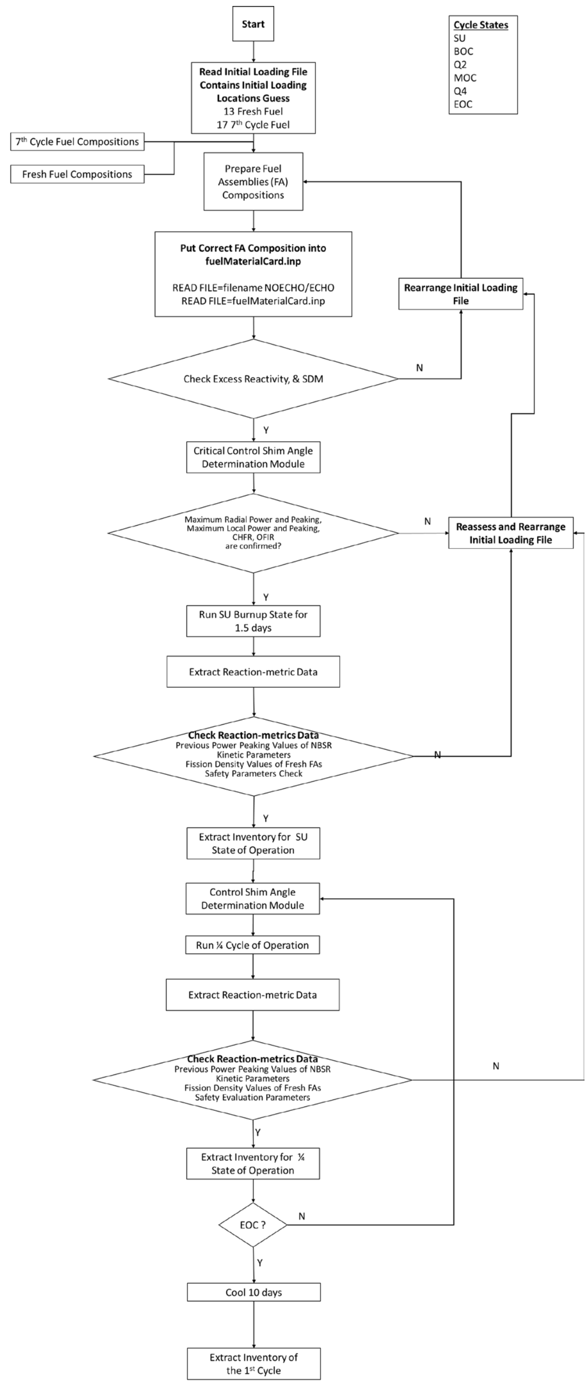

Figure 2. AFMS Framework Basic Flowchart

possess onsite After assessing the availability of 7^{th} cycle elements and the limit of unirradiated U^{235} amount, it is decided to use thirteen fresh fuel elements and seventeen 7^{th} cycle fuel elements for the SCL. Considering that the OFMS is no longer applicable, the total number of possible core loading patterns is $30!/13!$ which is equal to $\sim 3.5 \times 10^{14}$. It is not technically possible to try all possible combinations to find the optimum core. Due to the discrete nature of the isotope compositions of the 7^{th} cycle and fresh fuel elements, the optimization problem becomes a combinatorial optimization. It needs a metaheuristic approach due to the drastic size of the possible solutions.

A metaheuristic is a high-level strategy to solve complex optimization problems, particularly those falling under the class of combinatorial optimization problems where the solution space is discrete but large. It works by efficiently exploring the solution space and providing acceptable but not-guaranteed optimal solutions. Metaheuristics can either be a single-solution or population-based metaheuristics. Single-solution metaheuristics work by iteratively improving a single candidate solution, often incorporating mechanisms to avoid being trapped at local optima. On the other hand, population-based metaheuristics maintain and improve a population of candidate solutions. The diversity within this population aids in exploring the solution space more broadly and helps prevent premature convergence to a suboptimal solution. Our approach for SCL optimization is to utilize a hybrid approach that includes both single-solution and population-based metaheuristics.

To guide the core loading selection, we define utility tables that keep and update the utility of a grid position-fuel assembly pair based on previous iterations. A utility table is a 30 by 30 matrix with rows being grid positions and columns being the available fuel assemblies that can be used in the core loading. The entries of the matrix define the utility of placing a fuel assembly in a specific grid position. At each iteration, the core loading is selected to maximize the utility while ensuring that each grid position is filled, and each fuel assembly is only used once.

This work's approach for the SCL optimization is to maximize the core's excess reactivity while minimizing the maximum power peaking and reducing the heterogeneity of the radial power peaking (RPP) distribution. Available fuel assemblies for the core loading are fresh fuel assemblies with the highest possible U^{235} content and 7^{th} cycle fuel elements within the range of the lowest possible U^{235} content. Therefore, it is not possible to obtain a core loading with RPPs distributed homogeneously due to large differences in fissile materials between neighboring fuel elements. To cope with this limitation, we define a balance parameter that calculates the average deviations of RPPs around an average RPP value to quantify the homogeneity of the RPP distribution. Then the utility function of the core loading assessment can be written as shown below.

$$F = \omega_r(\rho - \rho_t) + \omega_p(\beta - \beta_t) + \omega_b(\gamma - \gamma_t) \qquad (1)$$

Per the relation above, ω is the weight of each contributor, ρ is core excess reactivity, β is the maximum power peaking factor, and γ is the balance parameter. The subscript t defines the target value of each contributor. For a selected core loading, the utility value is calculated with Eq. (1), and the entries of used grid position-fuel assembly pairs in the utility table are updated considering the calculated utility value. It must be noted that the utility value can either be positive to reward the grid position-fuel assembly pair and increase their probability of being selected for future iterations, or it can be negative to penalize the selection of the grid position-fuel assembly pair.

The most important challenge to the SCL optimization problem is the computing cost of running each MCNP simulation. With 80 cores of Intel(R) Xeon(R) Gold 6230 CPU @ 2.10GHz on a computing server, the assessment of any core loading pattern given in Figure 2 takes about 3 to 4 hours. To allow a feasible SCL optimization, a data-driven surrogate of the MCNP model is utilized. The surrogate model is a regression model that takes U^{235} masses at different grid locations as inputs and predicts the ρ, β and γ used in Eq. (1). Therefore, the utility value of any core loading can be calculated very quickly to update the utility table for the next iteration. The steps of generating the utility table, selecting core loading based on the utility table, assessing the core loading, and updating the utility table until desired iteration number is achieved can be considered as a single-solution model.

To diversify the exploration of solution space, we can develop M different single-solution models with their own utility tables and internal iterations. The process of M models completing their iterations is called a generation. At the end of the generation, each model is evaluated and sorted by their fitness. The fitness value is the maximum utility value that a model found with its utility table during its iterations. At the end of the generation, M new utility tables are generated by recombining utility tables of solutions from the previous generation. Solutions with higher fitness values have a higher probability of being selected as parents. The goal of the recombination of utility tables is to use currently known good utility tables to provide a base for further search to find core loadings with higher utility values. For N generations, there are M by N optimal solutions, and the core loading with the highest utility value is proposed as the best core loading. This work uses M and N values equal to 100 and 10, respectively. The framework for the optimization is given in Figure 3.

The performance of the optimization strategy is strongly dependent on the accuracy of the surrogate model. Hence, this work's approach is to continuously improve the surrogate model. To achieve this, the proposed core loadings are predicted with the actual MCNP model, and the results are added to the training dataset of the surrogate model.

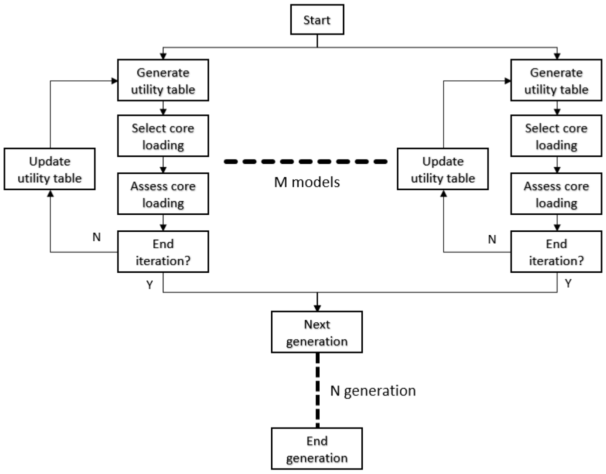

Figure 3. SCL Optimization Framework

The surrogate model is retrained after 5 optimization steps. An ensemble regression model is used to develop the surrogate model where the base estimators are selected from regression models that include linear models, support vector machines, nearest neighbors, tree algorithms, and neural networks. A brute search is applied to try different models with different hyperparameters on the existing training dataset, and the models with lower generalization errors are selected as the base estimators for the ensemble regressor.

RESULTS & CONCLUSION

An Alternative Fuel Management Scheme framework is developed for any NBSR core loadings which deviate from the OFMS that is defined in the updated FSAR. Additionally, an optimization framework for core loading assessment is developed and it is well-coupled with the AFMS framework for the NBSR. The optimization framework uses Machine Learning (ML) algorithms, and it automatically configures the core, tries, and assesses the results internally. The ML has a gradual learning ability from each core configuration trial. By using AFMS and optimization frameworks, the new SCL is determined for the NBSR core as shown in Figure 4.

The SCL depicted in Figure 4, consisting of seventeen 7^{th} cycle elements and thirteen fresh fuel elements (FF) cleared all technical and administrative limitations and has been deemed safe for restarting the NBSR. On March 16, 2023, roughly 2-years and 1-month after the incident, the NBSR was restarted safely and successfully with the SCL shown in Figure 4. The operational measurements show that the measurements and the calculated results with the optimized SCL are in excellent agreement, effectively validating the entire methodology. A framework to evaluate the approach to equilibrium core is currently being developed, and it will be discussed in future works

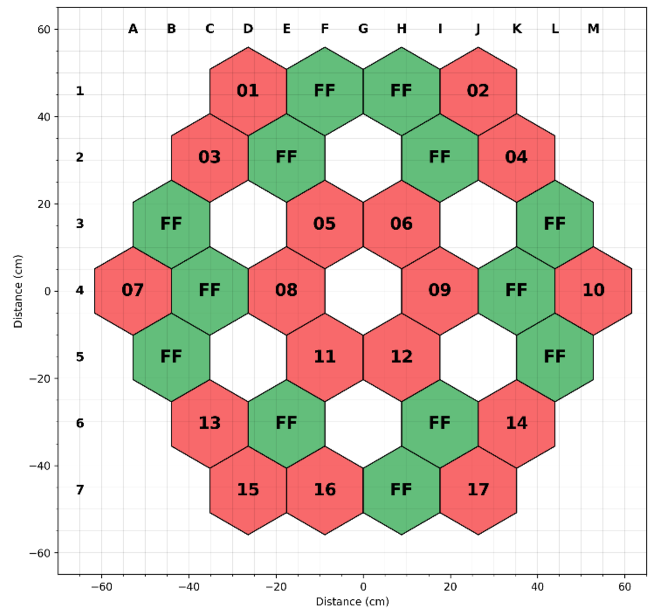

Figure 4. Proposed Core Configuration for the SCL

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