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Developing a practical optimization of the refueling program for ordinary research reactors using a modified simulated annealing method

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ABSTRACT

Each core configuration of a research reactor can be optimized to provide particular or general multi-purpose irradiating conditions; specially, it includes refueling cycle length and irradiating neutron fluxes if a core management is limited to a refueling task. Each practical core or fuel management operation needs providing all of related Operational Limits and safety Conditions (OLCs). In this paper refueling cycle length and maximum irradiating thermal neutron flux are chosen as the optimizing objectives; also OLCs including total Power Peaking Factor, Shutdown Margin, Reactivity Safety Factor (RSF), and maximum permissible core excess reactivity are influenced as optimizing constraints. All parameters have been calculated accurately and benchmarked against operational parameters of a 5 MW MTR. Primary 2-D annealing process is following up to a secondary re-annealing in fine 3-D calculations. This expands global search space while the required time is reduced. Safety margins are introduced by stepwise penalty functions instead of a direct rejecting method. Results are very promising, required iterations are decreased; safety faults are automatically removed, and final results are gained near touch the infeasible frontier formed by safety margins. Refueling cycle length is significantly increased, averaged and maximum irradiating neutron fluxes are enhanced while selected OLCs are passed.

1. Introduction

Research reactors are necessary tools for nuclear energy development and evolution. A significant number of operating research reactors have become multi-purpose facilities producing radioisotopes, material studies, performing neutron radiography, semiconductor doping and neutron activation analysis for a wide range of users while continuing their traditional role in education and training (IAEA, 1999; IAEA, 2007a, b).

Refueling program or the in-core fuel management is defined as the placement, movement and discharge of fuel assemblies. Each time the reactor becomes subcritical, a decision is required to which fuel elements should be discharged, reshuffled, and replaced by fresh fuel elements (IAEA, 2008b). It must provide desired operational irradiating conditions; also Operational Limits and safety Conditions must be taken into account and influenced (IAEA, 2008 a, b, c). There are two general approaches for the core management of a research reactor:

- Introducing an equilibrium core or periodic refueling chains chosen for a long operating time (Hedayat, 2014; Villarino and Padilla, 2011).
- Optimization of each core configuration independently to provide different desired conditions during the reactor operation (Hedayat et al., 2009b);

Ordinary research reactors usually have been used a partial out-in refueling operation. Such periodic fuel management strategy can be scheduled for particular and determined irradiating tasks due to general characteristic of each reactor type. Since fuel elements remain in the core until they extracted, an overall decision can be made sequentially for refueling process and final discharging. It introduces an equilibrium core via periodic refueling pattern as a long-term fuel management strategy for research reactors (Hedayat, 2014; Villarino and Padilla, 2011). Providing periodic irradiating conditions, high safety margins (conservative approaches), quality assurance for specific irradiating tasks, and simple refueling tasks are the most important keys of this method.

The second method can be useful when each operating core is chosen and arranged, independently; it can be optimized to

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improve refueling cycle length, neutron fluxes at irradiating locations, irradiating volume, and safety margins to install experimental devices.

(Mazrou and Hamadouche, 2006) optimized the K_{eff} and PPF for the 10 MW IAEA core benchmark model (IAEA, 1980; IAEA, 1992) using a simulated annealing algorithm; they used feed-forward Artificial Neural Networks (ANNs) to speed up optimization process. Hedayat et al., 2009a, b) optimized the 10 MW IAEA core benchmark model via a multi-objective optimization process using a hybrid artificial intelligence algorithm, too. It was composed of a fast and elitist multi-objective genetic algorithm (GA) and a fast learned and fitness function evaluating system based on the cascade feed forward ANNs (Hedayat et al., 2009a, b).

Advanced multipurpose research reactors uses additional safety features such as secondary shutdown systems, burnable poisons, high and distributed uranium loading for core management; while ordinary light water reactors without additional safety features (IAEA, 2006, 2008a) uses an out-in partial refueling operation to gain safety margins conservatively. Although ANNs can estimate core parameters very fast, in order to plan a practical core management it is better to calculate all corresponding parameters accurately. Main optimizing objectives are operating and irradiating performances; safety margins must be passed as optimizing constraints; also solution space (criterion space) must be mapped in the domain of the feasible area in the decision space; in the other words, the refueling plan can be operable using available core assemblies and providing core OLCs.

In this paper, refueling cycle length and maximum thermal neutron flux over fixed positions of irradiating boxes are considered as the optimizing objectives. On the other hand, safety margins including total Power Peaking Factor (PPF), Shutdown Margin, Reactivity Safety Factor (RSF), and core excess reactivity during 30% extraction of the all control rods (introducing an operating safety margin for maximum permissible excess reactivity) are impacted during optimization process. All parameters have been calculated accurately and benchmarked against operating parameters of a 5 MW Material Testing Research Reactor (MTR). Global search space is expanded and optimization time is reduced using stepwise calculations both in core dimensions and influencing safety margins.

2. Core management and fuel handling at research reactors

Core management and fuel handling are the two of the various important activities to be performed by the operating organization of each research reactor according to the safety principles (IAEA, 2006). It states that: “The most harmful consequences arising from facilities and activities have come from the loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or other source of radiation.”

Core management refers to those activities that are associated with the fuel assemblies, management of core components and reactivity control; activities that should be performed in order to allow optimum reactor core operation and reactor utilization for experiments, without compromising the limits imposed by the design safety considerations relating to the fuel assemblies and the reactor as a whole (Hedayat et al., 2009b; Hedayat, 2014; IAEA, 2008b).

Fuel handling refers to the movement, storage and control of fresh and irradiated fuel, whether manually or by means of automated systems (IAEA, 2008b). It can be defined as refueling chains (AEOI, 2009; Hedayat, 2014). Each fuel handling process or storage task must ensure following terms (IAEA, 2008a):

- Provide the possibility of shutdown and heat removal in all operational states and in design basis accidents;
- Provide negative feedback of reactivity;
- Provide desired neutron fluxes via moderation and control;
- Minimize radiation exposure;
- Prevent an inadvertent criticality;
- Limit any rise in fuel temperature;
- Provide safe storage of fresh and irradiated fuel; and
- Prevent mechanical or corrosive damage to the fuel.

In addition, advanced multi-purpose research reactors have been optimized in core design and elements to improve fuel economy and provide high effective and qualified neutron fluxes within high safety margins using high density fuels, distributed uranium loading, burnable poisons, and optimized reflector and core design (Hedayat et al., 2009b; AEOI, 2005a, b; IAEA, 2007a, b; IAEA, 2008a; Raina et al., 2006; Villarino and Doval, 2011; Villarino and Padilla, 2011).

2.1. Safety criteria for a standard nuclear fuel management

For a research reactor to be operated safely, the Operational Limits and Conditions (OLCs) must be taken into account and influenced in design. These limits on operating parameters and requirements should be developed in the evaluation of the design safety as a set of OLCs. They normally includes: safety limits and safety system settings on relevant variables and parameters of the reactor; limiting conditions on equipment and operational characteristics of the reactor; surveillance requirements; and administrative requirements. This set should satisfy the basic requirements for the OLCs according to the basic and general requirements. A complete set of OLCs and operating procedures must be established to achieve the defense in depth phenomena (IAEA, 2006; IAEA, 2008c).

The following list of operational parameters and equipment should be considered and included in establishing limiting conditions for a safe operation of the core. These limiting conditions for safe operation may be operational constraints or administrative limitations imposed on each of the selected items. They have contributed to a standard nuclear fuel management program as following (IAEA, 2008 b, c):

- Fuel and FEs and assemblies: uranium enrichment; uranium content; materials used; geometry; burn-up limits; fuel failure criteria; inspection and testing of fresh fuel and in-service elements and assemblies.
- Fuel handling: capability to unload and store core components; requirements for fuel movements.
- Reactor core configuration: permissible internal or peripheral cavities; maximum and minimum number of FEs; reflection conditions; number of control elements, including fuel followers; mixed cores; permissible configurations; requirements for determining new configurations; reactor power; average and peak FE power; maximum fuel and cladding temperatures allowed; departure from nucleate boiling ratio and flow instability;
- Reactivity and reactivity control systems: maximum excess reactivity; minimum shutdown margin during operation and fuel movement; reactivity for control mechanisms; increases in reactivity via control mechanisms, experiments, and FEs; total reactivity of all experiments; maximum reactivity of specific types of experiment; reactivity for backup shutdown systems; reactivity balance; type and number of control rods.
- Auxiliary systems and equipment: cranes; emergency systems.

Usually, terms of limiting conditions for a safe operation must be included directly in a fuel management program of an operating