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Developing and analyzing long-term fuel management strategies for an advanced Small Modular PWR

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HIGHLIGHTS

- Comprehensive introduction and supplementary concepts as a review paper.
- Developing an integrated long-term fuel management strategy for a SMR.
- High reliable 3-D core modeling over fuel pins against the traditional LRM.
- Verifying the expert rules of large PWRs for an advanced small PWR.
- Investigating large numbers of safety parameters coherently.

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ABSTRACT

In this paper, long-term fuel management (FM) strategies are introduced and analyzed for a new advanced Pressurized Light Water Reactor (PWR) type of Small Modular Reactors (SMRs). The FM strategies are developed to be safe and practical for implementation as much as possible. Safety performances, economy of fuel, and Quality Assurance (QA) of periodic equilibrium conditions are chosen as the main goals. Flattening power density distribution over fuel pins is the major method to ensure safety performance; also maximum energy output or permissible discharging burn up indicates economy of fuel fabrication costs. Burn up effects from BOC to EOC have been traced, studied, and highly visualized in both of transport lattice cell calculations and diffusion core calculations. Long-term characteristics are searched to gain periodical equilibrium characteristics. They are fissile changes, neutron spectrum, refueling pattern, fuel cycle length, core excess reactivity, average, and maximum burn up of discharged fuels, radial Power Peaking Factors (PPF), total PPF, radial and axial power distributions, batch effects, and enrichment effects for fine regulations. Traditional linear reactivity model have been successfully simulated and adapted via fine core and burn up calculations. Effects of high burnable neutron poison and soluble boron are analyzed. Different numbers of batches via different refueling patterns have been studied and visualized. Expert rules for large type PWRs have been influenced and well tested throughout accurate equilibrium core calculations.

1. Introduction

Fuel management (FM) includes the placement, movement and discharge of fuels during the plant life. It covers the technical and economic analyses and decisions by which the objective of minimizing the cost of energy production is implemented. The in-core fuel management involves those tasks immediately related to the core stages.

It is mentioned that "Fuel management questions cannot be solved on a once and for all basis. This would be impractical because it would imply (Silvennoinen, 1986)". This complexity of FM implementation can be observed throughout usual optimization studies.

On the other hand, analytical studies of the reactor fuel management present a discussion overall reactor life time including the first, transient, and equilibrium cycles. They had been tried to provide an overall decision making to reduce fuel cost using Linear Reactivity Models (LRMs) and estimations. Although they aren't optimized in different objectives, they can be practical to be used at Nuclear Power Plants (NPPs) (Egan, 1984; Silvennoinen, 1986); but such methods depend on the knowledge and experiences of the expert fuel managers; also they may be severally modified due to safety analyses and redesign process (INRA and IAEA, 2015).

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Nomenclature

Abbreviation or Symbol	Description
B	Number of fuel bundles
BOC	Beginning Of Cycle
CFP	Cold Full Power (a conservative assumption)
E	Energy Exposure (GWD/MT)
E_C	Incremental Energy Exposure (GWD/MT)
E_D	Average Discharge Energy Exposure (GWD/MT)
EOC	End Of Cycle
$EOFPL$	End Of Full Power life
FPD	Full Power Days
HFP	Hot Full Power (operating state)
K_{eff}	Effective Multiplication factor
n	Depletion Batch Index
N	Number of Equal sized Group
R_e	Enrichment free lattice reactivity
R	Total core Reactivity
ρ	Bundle Reactivity
$\frac{\partial \rho}{\partial \varepsilon}$	Bundle enrichment coefficient of reactivity
ε	^{235}U Enrichment

In addition, very different methods have been tried to optimize core management for Material Testing Reactors (MTRs), Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). Generally, these researches study a core configuration, one or a few core cycles as follows:

- Direct Search Algorithms (Naft and Sesonske, 1972; Motoda et al., 1975);
- Linear programming and optimization throughout linear reactivity estimation and reduced core modeling (Okafor and Aldemir, 1988; Suzuki and Kiyose, 1971; Chen et al., 2014);
- Quadratic programming (Tabak, 1968);
- Dynamic programing and optimization (Stout and Robinson, 1973);
- Approximation programming for control rod programming and loading pattern (Motoda, 1972);
- Reverse depletion calculations based on the desired EOC state via one step Haling effect (Downar and Kim, 1986);
- Optimal Control Theory for power flattening (Terney and Williamson, 1982);
- Direct searches of fuel reshuffling using gradient projection method (Ahn and Levine, 1984);
- Knowledge-based heuristic of Artificial Intelligence Techniques or Expert Systems (Galperin and Nissan, 1988; Hedayat, 2016b; Rothleder et al., 1988);
- Monte Carlo integer programming or Simulated Annealing for FM optimization problems (Comes and Turinsky, 1988; Hobson and Turinsky, 1986; Kirkpatrick et al., 1983; Kropaczek and Turinsky, 1991; Parks, 1990; Hedayat, 2014b);
- Core parameter estimation and loading pattern optimization using Artificial Neural Networks (Hedayat et al., 2009a)
- Loading pattern optimization using Genetic Algorithms (Hedayat et al., 2009b; Yamamoto, 1997);
- Minimizing fuel enrichment in the fuel lattice (Francois et al., 2003);
- Using Ant-Q algorithm for FM optimization problems (Machado and Schirru, 2002);
- Using hybrid systems of Artificial Intelligence Techniques for core management and FM optimization problems (Hedayat et al., 2009b; Kim et al., 1993; Yamamoto, 1997).

Nowadays, very novel optimization techniques have been tried for the PWR FM optimization problems especially via population-based techniques as following:

- Using Particle Swarm Optimization (PSO) algorithm (Lin and Hung, 2013);
- Using Artificial Bee Colony (Safarzadeh et al., 2014).

Researches generally influence flattening power distribution and increasing cycle length as the optimization objectives, and Power Peaking Factor (PPF) as the safety limit. The required zone enrichment and zonal arrangement could be noted as the most sensitive control parameters in such applications (Okafor and Aldemir, 1988). They are usually restricted and rely on an independent core configuration instead of consequent core cycles. This kind of research couldn't find a practicable loading pattern that satisfies all of required Operational Limits and Conditions (OLCs), but several loading patterns and concepts can be studied (Chen et al., 2014).

It should be noted that, an integrated optimization pattern are developing to be practical for implementation on the reactor core as cartridge type fuel assemblies (throughout radial and axial loading of different materials and enrichments) for some of new generations of PWRs (Carelli and Ingersoll, 2015). They can be implemented as an independent (one-shot) core reloading pattern.

Usual refueling tasks can be complementary expressed as a multistage decision making. It can be revealed as a stage-wise or multi-cycle decision making (Motoda et al., 1975). Multi-cycle refueling patterns need multi-batch refueling tasks. It can be concluded that, a multi-batch type of refueling tasks gains much more extracted energy output than a single-batch refueling operation (Carelli and Ingersoll, 2015; Egan, 1984). Some studies have been performed according to the multi-cycle or multi-stage decision making process as follows:

- Dynamic programing for a multi-cycle decision making (Wall and Fenech, 1965);
- A multi-cycle optimization using parallel simulated annealing (Kropaczek, 2011);
- Multi-cycle reload design using PSO (Lin and Hung, 2013);
- Developing a long-term fuel management strategy for MTRs (Hedayat, 2014a).

In order to introduce a practical and qualified action plan of refueling tasks, the methodology should consider all of the corresponding Operating Limits and Conditions (OLCs), economic issues especially Return of Investment (ROI) as power generation benefits per the nuclear fuel costs, reactor availability for the fast load following and increasing refueling cycle length, also Quality Assurance (QA) of the program should be identified throughout all of reactor life time (Carelli and Ingersoll, 2015; IAEA, 2006b, 2013).

In this paper, equilibrium refueling tasks for large PWRs have been simulated and studied omitting the transient cycles; and then conceptual analyses will be introduced and tried to gain a practical, accurate, and high reliable methodology for long-term FM strategies as much as possible. It could be noted that, this is a developing and developmental methodology which should be justified and completed throughout several studies to be used in a realistic condition. Usually, accurate core calculations have been performed using the Monte Carlo codes (especially the MCNP code) which are very time-consuming tasks. This research is performed using