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MODELING AND DESIGN OF A RELOAD PWR CORE FOR A 48 MONTH FUEL CYCLE

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Abstract

The objective of this research was to use state-of-the-art nuclear and fuel performance packages to evaluate the feasibility and costs of a 48 calendar month core in existing pressurized water reactor (PWR) designs, considering the full range of practical design and economic considerations. The driving force behind this research is the desire to make nuclear power more economically competitive with fossil fuel options by expanding the scope for achievement of higher capacity factors. Using CASMO/SIMULATE, a core design with fuel enriched to $7^{w}/_{o}$ U^{235} for a single batch loaded, 48-month fuel cycle has been developed. This core achieves an ultra-long cycle length without exceeding current fuel burnup limits. The design uses two different types of burnable poisons. Gadolinium in the form of gadolinium oxide (Gd_2O_3) mixed with the UO_2 of selected pins is used to hold down initial reactivity and to control flux peaking throughout the life of the core. A zirconium di-boride (ZrB_2) integral fuel burnable absorber (IFBA) coating on the Gd_2O_3-UO_2 fuel pellets is added to reduce the critical soluble boron concentration in the reactor coolant to within acceptable limits. Fuel performance issues of concern to this design are also outlined and areas which will require further research are highlighted.

Introduction

Foreword

Incentives to reduce the cost of electricity by increasing reactor capacity factor have motivated increasing operating cycles to 18-24 months. This research, sponsored by the INEL University Research Consortium, examines the currently contemplatable upper limit of 48 months as part of a project of wider scope, which also considers how and whether plants could be operated at power for periods this long[1]. The objective of the task reported here was to establish the feasibility of a 48 calendar month fuel cycle in existing pressurized water reactor (PWR) designs while respecting current fuel burnup limits.

The driving force behind this research is the desire to make nuclear power more economically competitive with fossil fuel options. One of the most effective ways for an operating plant to improve its economic performance is to increase the plant capacity factor, thereby apportioning expenses over a larger amount of electric energy product. Increasing the operating cycle to 48 months offers the opportunity for economic benefit by increasing plant capacity factor and by reducing the number of costly refueling operations that must be performed.

In a scoping study of the 48 calendar month cycle performed by Ayoub and Driscoll, 1995 elementary burnup reactivity models immediately demonstrated that only a single-batch reloading strategy might permit ≥40-month cycles, while respecting current fuel burnup limits[2]. Preliminary economic estimates based on the methods used in this study also showed that a 48 calendar month cycle batch-loaded core has a steady-state fuel cost that is about 3.0 mills/kWhre (~25 million $/year) more expensive than an optimized multi-batch strategy. This deficit would have to be made up from the net benefits of a higher capacity factor (e.g., less replacement energy, fewer refueling outages) levelized over plant lifetime.

Background

In the Ayoub report, the plausibility of a generic 48 month PWR core design was established using the computer code RPM (Reload Power Mapping). RPM is a 1 1/2 group nodal program that characterizes fuel assemblies by their reactivity, linear slope of reactivity as a function of burnup, and burnable poison reactivity at beginning of cycle (BOC). The purpose of the present research was to use state-of-the-art nuclear and fuel performance design packages to evaluate the feasibility of a 48 calendar month core in existing PWR designs, considering the full range of practical design and economic considerations.

It must be emphasized that this research effort is to establish the feasibility of a core design that can be used in *currently operating* PWRs. Accordingly, the following guidelines constrain and focus the scope of the project:

- Core must be able to be retrofit into current designs
- Fuel burnup must be maintained at or below current licensing limits
- A capacity factor of 87% is targeted, in which case a 48 calendar month core requires ~42 effective full power months (EFPM) of operation. A capacity factor of 87% corresponds to likely U.S. industry target goals for the year 2000.
- Single batch loading will be used

The desire to retrofit and the selection of a unibatch reload scheme place severe restraints on the design of the core. The single batch design in particular deprives the fuel manager of much needed flexibility by eliminating the ability to "coddle" highly burned fuel by shuffling high burnup assemblies into areas of low power peaking. However, the single batch reload scheme is essential in order to prevent exceeding current fuel burnup licensing limits.

The single batch, 48-month core design seeks to extend cycle length while maintaining a constraint on discharge burnup. Conventional core designs focus on optimizing fuel utility by maximizing fuel discharge burnup for a given cycle length. Unit cell burnup calculations show that for 7% fuel, end of cycle (EOC) burnup (GWD/MTU) might be slightly improved by making the lattice wetter (i.e., increasing the H/U ratio). However, as the equation below illustrates, cycle length is proportional to the *product* of the mass of fuel in the core and EOC burnup. For a given core thermal power, cycle length depends on the total amount of energy produced by the reactor (in MWD) and not simply on fuel discharge burnup.

$$T_c(EFPD) = \frac{B_c(MWD/MTU) \cdot M(MTU)}{Q(MW)} \quad (1)$$

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where: B_c = Cycle Fuel Burnup (MWD/MTU)
M = Mass of Fuel in the core (MTU)
Q = Core Thermal Power (MW)
T_c = Cycle Length (Effective Full Power Days)

Assuming that current assembly designs have been engineered to contain as much fuel as practicable while meeting thermal-hydraulic constraints, it is therefore not desirable to alter the lattice configuration in order to increase H/U and optimize core discharge burnup. Since achieving a wetter lattice involves removing fuel mass (M) from the core, the above equation shows that this can actually lead to a *decrease* in cycle length. A simple thought experiment also shows that all fuel assemblies should have uniform enrichment, since the EOC poison-free reactivity will be the highest for a core having the highest total residual fissile content. This also argues for reactivity and power shape control using burnable poison. The preceding line of reasoning agrees with the approach taken by ABB/CE in their design of a single-batch-loaded, erbium-poisoned core for the disposition of weapons-grade plutonium[3]. However, while their total time in core was also four years, annual shutdowns were assumed, during which assemblies were to be shuffled in order to adjust assembly discharge isotopics.

PWR Model Description

The plant used in this study is a Westinghouse 4-loop 1150 MW_e Pressurized Water Reactor. The Westinghouse 4-loop PWR was selected as the target plant for this study because of its widespread use and because its high specific power makes it a challenging target for an extended cycle core design. A design strategy which produces an extended cycle core for this type of PWR can be confidently applied to the vast majority of the currently operating plants in the commercial PWR fleet in the United States.

The subject PWR was modeled using the CASMO-3/TABLES-3/SIMULATE-3 reactor analysis suite developed by STUDSVIK NUCLEAR, a division of STUDSVIK AB, Nykoping, Sweden. The codes have been made available to this project through collaboration with STUDSVIK of America, Inc. Assistance in developing detailed models of the Westinghouse 4-Loop PWR has been provided by the Yankee Atomic Electric Company, Bolton, Massachusetts. In this study a two-dimensional model of the core using 1/8 core symmetry was implemented, with each fuel assembly comprising a single radial node.

Core Design Goals

As stated previously, the purpose of this project was to design a reload core for a 48 calendar month fuel cycle in *currently operating* PWR units. Accordingly, the 48-month design will not change any of the core flow paths or internal dimensions. Rather, increased cycle length is accomplished by changing the fuel composition itself and by implementing an innovative assembly loading pattern. Because of this, a complete licensing analysis of the core need not be performed in order to demonstrate technical feasibility. Rather, technical feasibility of a *reload core* may be reasonably demonstrated if certain carefully selected criteria defining the allowable operating envelope of a currently licensed design can be met. The preliminary design goals for the 48-month PWR core are as follows:

- To maintain the Maximum Enthalpy Rise Hot Channel Factor ($F_{\Delta H}$) < 1.65

- To maintain the peak Critical Boron Concentration (CBC) in the reactor coolant <2000 ppm at all times during the operating cycle
- To reduce peak CBC to as close to 1500 ppm as practicable while optimizing the benefits of decreased soluble poison against the expense and drawbacks associated with increased burnable poison, and
- To obtain an operating cycle length of 48 calendar months at a target capacity factor of 87%.

48-Month Core Design

The best-yet design for the 48-month core uses a batch loaded core having fuel assemblies that are uniformly enriched to $7^{w}/_{0}$ U^{235} and which use a combination of $10^{w}/o$ Gd_2O_3 and IFBA (Integral Fuel Burnable Absorbers - a thin film of zirconium di-boride, ZrB_2, applied to the surface of the UO_2 fuel pellets) loaded into selected fuel pins as burnable poisons. The fuel loading pattern of the 48-month core incorporates Gd_2O_3 and IFBA into the same fuel pins in order to take advantage of any shielding effect that the IFBA may have on slowing the burnout rate of the gadolinium, thereby synergistically increasing the effectiveness of both poisons. The radial power peaking in the core is controlled by varying the number of poisoned pins per assembly in order to compensate for the increased reactivity penalty due to leakage as one moves from the center toward the periphery of the core. The current design contains 7 different types of assemblies, with the number of poisoned pins in each assembly varying from 48 in the center of the core to 16 at the core periphery. The pin configuration of a typical assembly is shown in Figure 1.

A 1/8 core model of the 48-month PWR design showing the number of poisoned pins per assembly, maximum $F_{\Delta H}$ at any time in core life, and assembly discharge burnup at EOC is contained in Figure 2. Note that no fuel assemblies attain an assembly-average discharge burnup in excess of the current licensing limit of 60 GWD/MTU.

TABLE 1:

Performance Summary of 48-month Design

	Maximum $F_{\Delta H}$	Peak CBC	Cycle Length at Target CF
Design Goal	1.65	2000 ppm (1500 ppm preferred)	48 Calendar Months
48-Month Core Performance	1.58 @ 28 GWD/MTU	1697 ppm @ 27 GWD/MTU	46.6 Calendar Months

The success of the 48-month core in meeting its design goals is summarized in Table 1. The goals have been met with the exception of the cycle length at the target capacity factor. However, the target cycle length *is* achievable by factoring in a one month coastdown at the end of the cycle. Additionally, at this point the potential effects on core performance associated with switching from a two-dimensional to a three-dimensional model outweigh the magnitude of the "fine-tuning" adjustments required to increase cycle length by a few weeks. Thus, the two-dimensional model demonstrates the technical feasibility of designing a 48-month core for currently operating PWR designs. Plots of CBC and $F_{\Delta H}$ vs. core-average exposure for the 48-month design are shown in Figure 3 and Figure 4 below.

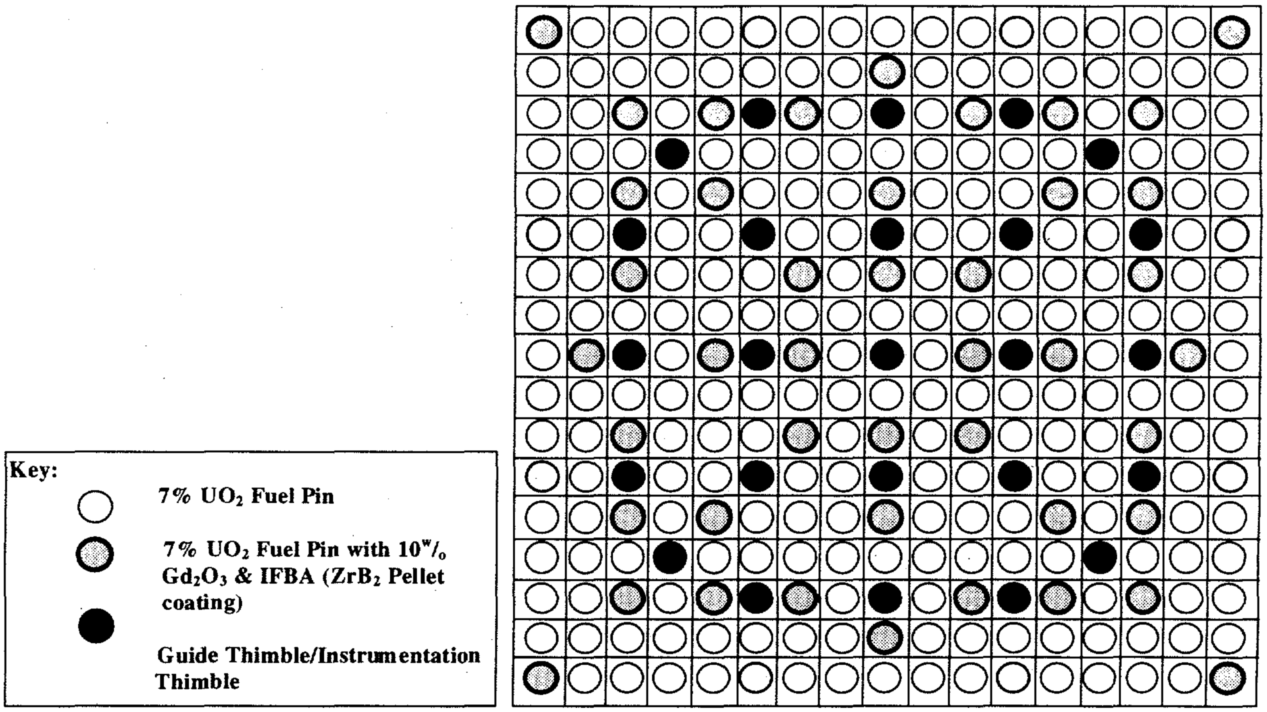

Figure 1
Typical Assembly Design for PWR 48 Month Core (44 Poisoned Pins)

48 1.582 53.985	48 1.577 54.472	44 1.567 55.964	44 1.534 56.490	44 1.446 56.152	44 1.295 54.564	40 1.307 49.604	24 1.317 34.770
	48 1.572 54.859	44 1.536 56.118	44 1.528 56.497	44 1.438 56.058	44 1.286 54.332	40 1.307 49.189	24 1.317 34.307
		44 1.547 56.439	44 1.498 56.439	44 1.398 55.713	44 1.281 53.487	40 1.299 47.599	24 1.303 32.410
			44 1.432 56.069	44 1.320 54.899	44 1.322 51.781	36 1.333 43.635	16 1.250 26.323
				44 1.345 53.118	40 1.382 48.605	24 1.383 36.274	
					32 1.443 42.009	16 1.339 26.202	

Number of Poisoned Pins per Assembly

Peak $F_{\Delta H}$ (Max. During Cycle)

EOC Assembly Burnup (GWD/MTU)

Figure 2
1/8 Core Model of PWR 48-month Design

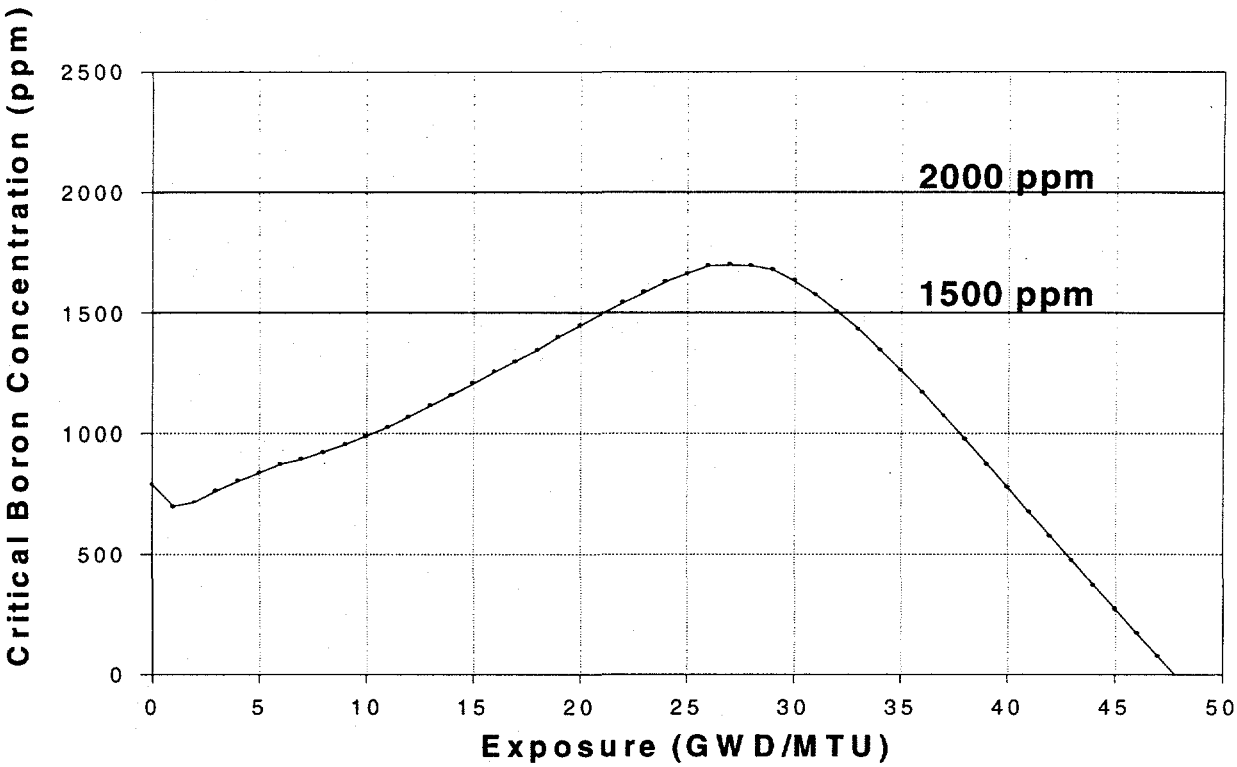

Figure 3
Critical Boron Concentration vs. Core Average Exposure

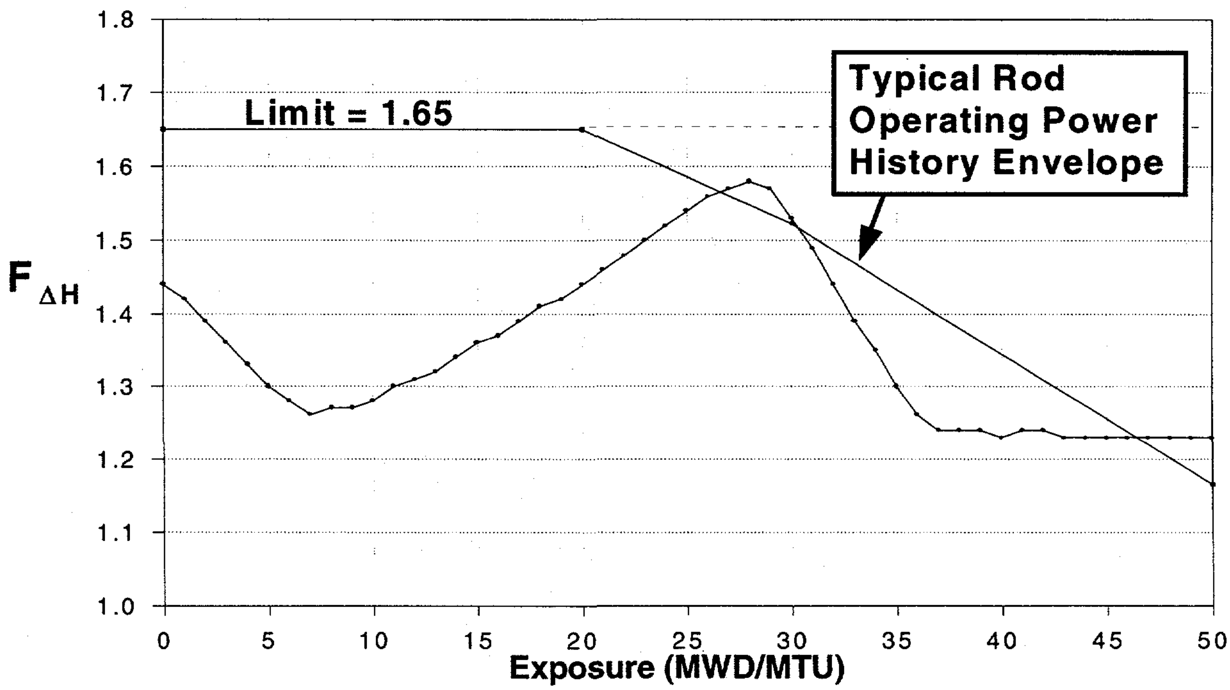

Figure 4
Maximum Enthalpy Rise ($F_{\Delta H}$) vs. Core Average Exposure

Conclusions and Future Work

Neutronic Design

A single-batch reload PWR core has been designed which operates for 4 years (~41 EFPM) using $7^{w}/_{o}$ enriched fuel and a high burnable poison loading ($10^{w}/_{o}$ Gd_2O_3 and 3.09 mg-B^{10}/inch IFBA). This design has been developed by using a two dimensional model and by focusing on a small number of operating design parameters (CBC and $F_{\Delta H}$). Future work for the neutronic design of the core model includes the evaluation of key core characteristics such as Moderator Temperature Coefficient (MTC), Fuel Temperature Coefficient (FTC), control rod worth and shutdown margin. Results to date indicate that the proposed core design can meet requirements in these areas. In order to reduce fuel costs the design will be further modified by replacing the outer rows of fuel pins in the peripheral assemblies with natural uranium pins. This strategy will also reduce pressure vessel fluence, which is higher for the 48-month core than for low leakage cores now in service. Assemblies of this type have been evaluated in the past by Westinghouse[4]. Additionally, a full three dimensional model must be developed in order to evaluate the effects of the axial power shape on the performance of the 48-month core. The three-dimensional model will be used to evaluate the Maximum Hot Channel Peaking Factor (F_Q) within the core. Axial zoning of burnable poisons will be used to reduce excessive axial power peaking and to control axial offset.

Fuel Thermal and Mechanical Performance

Following the completion of the neutronic design, fuel mechanical and thermal performance issues must be addressed. Industry fuel performance experts interviewed indicated that the following issues were of primary concern for the 48-month core design:

- Fission gas release fraction
- Waterside corrosion
- Cladding embrittlement

The presence of high burnup fuel assemblies in areas of greater-than core-average power may lead to fuel performance problems. The effects of increased fission gas pressure, intensified cladding strain, and accelerated Zircaloy waterside corrosion in these assemblies must be carefully quantified. Initial fuel performance goals are to maintain the cladding at less than 1% tensile strain, and preferably less than values characteristic of a reference 3-batch core using similar fuel. This is accomplished by keeping pin internal pressure near or below primary system pressure. Pin internal pressures can be reduced by increasing the size of the fuel pin fission gas plenum, decreasing fuel pin pre-pressurization during manufacture, or by using annular fuel. Fuel Performance analyses will be performed using state-of-the-art fuel performance codes from EPRI (ESCORE) and the Yankee Atomic Electric Company (FROSSTEY-2[5] and ROXE).

Other Issues

In order to complete the design and evaluation of the 48-month PWR reload core, several issues must be investigated further. These issues include:

1. Regulatory problems involved in using 7% enriched fuel:

    - At the current licensing limit of $5^{w}/o$ U^{235}, a batch loaded core will only achieve a cycle length of 36.2 calendar months at the target capacity factor of 87%.

- Key in-plant facilities which will require further analysis include the nuclear storage vault and the spent fuel pool. Costs and methods of ensuring the criticality safety for both of these facilities must be evaluated.
- The transportation of fresh and spent fuel must be addressed.

2. Reactivity control:
   - The hardening of the neutron energy spectrum due to the design's higher fuel enrichment will lower control rod worth by ~20%. This indicates that the current Ag-In-Cd control rods will be replaced by enriched B_4C rods as in proposed Pu burning core designs.
3. Transition cycle
   - The up-front cost penalty of the transition cycle must be reduced. Prematurely discharging the entire 3-batch core after only one cycle sacrifices an estimated $4.5 x 10^7.
4. Economics
   - A refined costing evaluation of all aspects of the 48-month core must be performed.
   - The method of evaluation will be comparison of the 48-month design against a benchmark of a best current practices core (i.e., 3-batch loading with a cycle length of 18-24 months).

In conclusion, the results to date confirm the technical feasibility of devising a highly-rated PWR core which can achieve a 48-month operating cycle. Foreseeable problems can be overcome, but at progressively higher economic penalties. Assessing and minimizing such penalties is a major focus of the near term future effort.

Acknowledgments

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