CORE LOADING AND BURNUP OPTIMIZATION

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ABSTRACT

The impending worldwide deregulation of the electric power industry has forced nuclear utilities to reassess the way they are doing business: increased competition, pressure on prices and unprecedented market uncertainties are driving nuclear operators to cut costs and to operate more flexibly than before, without adversely affecting safety. Now, efficient planning of the fuel cycle schemes has become essential.

This paper describes an integrated Fuel Cycle Decision Support Technique (FCDST), used as a planning tool for an operator running PWR-plants. This FCDST aims at generating the basic cycle parameters allowing a nuclear operator to define the economically optimal fuel cycle scheme, by considering the best-estimate prevailing and long-term market conditions. It is composed of 4 stages: the first stage aims at optimizing the equilibrium cycle lengths for the different power plants owned by an operator. The second stage consists in optimizing the transition cycles necessary to reach the equilibrium cycles. In a third stage, some selected cycling scenarios are submitted to an in-depth neutronic analysis, in which technical feasibility of core design is guaranteed. The last stage evaluates the generating margin, based on classical valuation methods.

The FCDS Technique has already been proven to be an efficient tool for doing Strategic Core Design for most of the Belgian Nuclear plants.

1. INTRODUCTION

The impending worldwide deregulation of the electric power industry has forced nuclear utilities to reassess the way they are doing business: new generating technologies, legislation issues, increased competition, unprecedented market uncertainties and a greater focus on reducing electricity rates will continue to have profound effects on the industry's structure. The challenge for the operators of nuclear plants is to remain competitive and to meet customer needs against this background.

In this paper we describe an integrated Fuel Cycle Decision Support Technique (FCDST), used as a tool for decision-making regarding fuel cycle strategies involving PWR plants. This FCDST aims at generating the basic cycle parameters allowing a nuclear operator to define the economically optimal fuel cycle scheme. By considering the best-estimate prevailing and long-term market conditions, this FCDS Technique, consisting of a four-phased approach, has already been proven to be an efficient tool for doing Strategic Core Design for some of the Belgian Nuclear plants.

2. DESCRIPTION OF FCDST MODEL

The concept of FCDST is composed of the following four stages:

- First stage : Optimization of the EQUILIBRIUM CYCLE scheme

  This phase aims at optimizing the equilibrium cycle lengths for the different power plants owned by an operator, taking into account the plant-specific technical or legal limitations.

- Second stage : Optimization of the TRANSITION CYCLE

  Once the optimal equilibrium cycle is determined, the 2nd stage consists of defining some possible transition cycling scenarios to reach the reference cycle specified in the 1st stage.

- Third stage : In-depth NEUTRONIC ANALYSIS

  In this 3rd stage, we submit the selected optimal scenario(s) from the 2nd stage to a detailed neutronic calculation, in which, for each cycle, loading patterns are designed that meet current physics and fuel performance design limits, as well as the safety requirements. This 3rd stage guarantees the technical feasibility of the core design.

- Fourth stage : Valuation of GENERATING MARGIN (Earnings from Power Sales-Fuel Cycle Costs)

  Input used for this stage are the Incore Fuel Management parameters that evaluate the benefits (or losses) of a cycling scheme, based on classical valuation methods.

2.1. FIRST STAGE : THE EQUILIBRIUM CYCLE OPTIMIZATION

A semi-empirical correlation between the following 4 parameters defining a specific incore fuel management has been developed. It evaluates the reactivity balance between various batches introduced in the core and is fitted for each of the 4 Belgian PWR plant types (14x14, 2 loops, 8ft ; 15x15, 3 loops, 12ft ; 17x17, 3 loops, 12ft and 17x17, 3 loops, 14ft) :

- Number of fresh assemblies in reload batch

- Average assembly enrichment

- Cycle length, or generated energy
- Stretch-out length

It contains a leakage evaluation module as a function of the fresh fuel batch size and enrichment, that reflects our experience in terms of the feasibility of loading patterns for a given plant and licensing frame.

The relation fits the explicit core calculation very well for Natural Enriched Uranium cores and Enriched Reprocessed Uranium cores even outside the range for which the correlation has been developed (only for Mixed-Oxide cores, the correlation is not fully reliable).

This model allows finding one of the above mentioned 4 variables when the other 3 are known; this makes of it an interesting tool for performing parametric studies on a specific plant as well as on a whole nuclear grid composed of various nuclear power plant types. For instance, charts 1 and 2 show the evolution of the initial UO2-enrichment with cycle length, respectively considering a maximum allowed enrichment of 4.25% and 5.00%, for one of the Belgian NPPs. The breaks in batch size on chart 1 are due to the maximum enrichment limit, whereas on chart 2, they result from the average assembly discharge burnup reaching its design limit (55 GWd/t in our case) well below the enrichment limit. From such a chart, and depending on the required cycle length, we can conclude whether or not it is worth reducing stretch-out length. The impact of the maximum allowed enrichment or maximum assembly discharge burnup can be analyzed and the potential gain of relaxing those limits evaluated.

Consider the following case as an example:

Suppose we opt for an equilibrium cycle of 390 days of operation, without stretch-out. Considering an enrichment limit of 4.25%, the model proposes a reload-batch of 40 fresh assemblies with an average enrichment of 4.20% (see chart 1). A reduction of 4 fresh assemblies, thereby reducing total fuel costs, could be achieved if a systematic 35 EFPD stretch-out policy is applied. It could also be recommended increasing the enrichment limit to 5.00%: in that case, the suggested cycle length would be realized with a reload batch of only 32 fresh assemblies with an average enrichment of 4.8% (see chart 2). The gain of 8 assemblies significantly reduces the total fuel cost.

Chart 1

Evolution of Initial Enrichment vs. cycle length for different stretch-out lengths

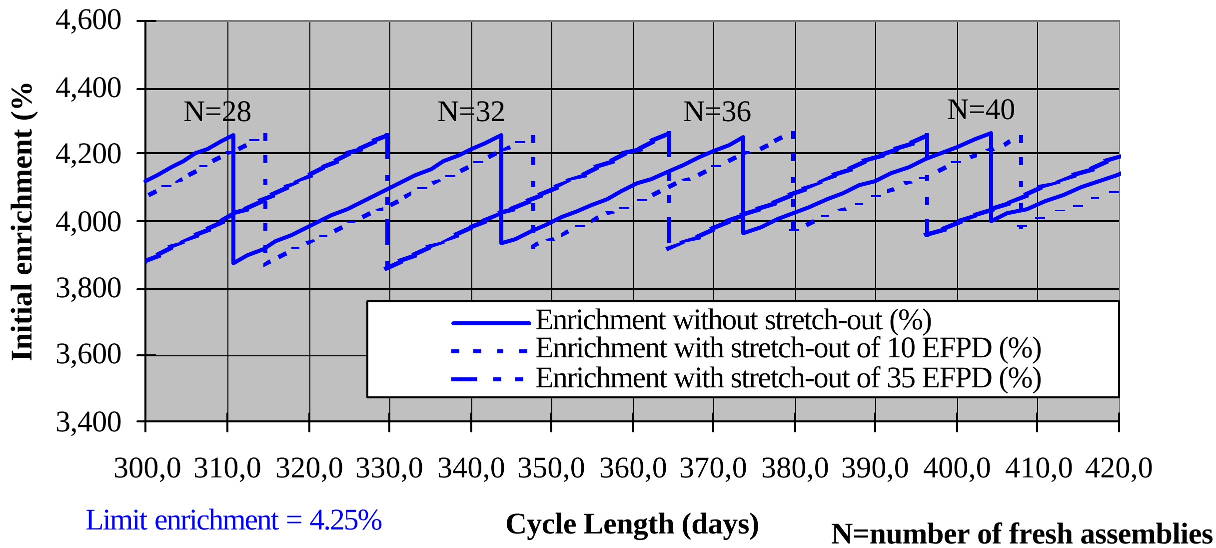
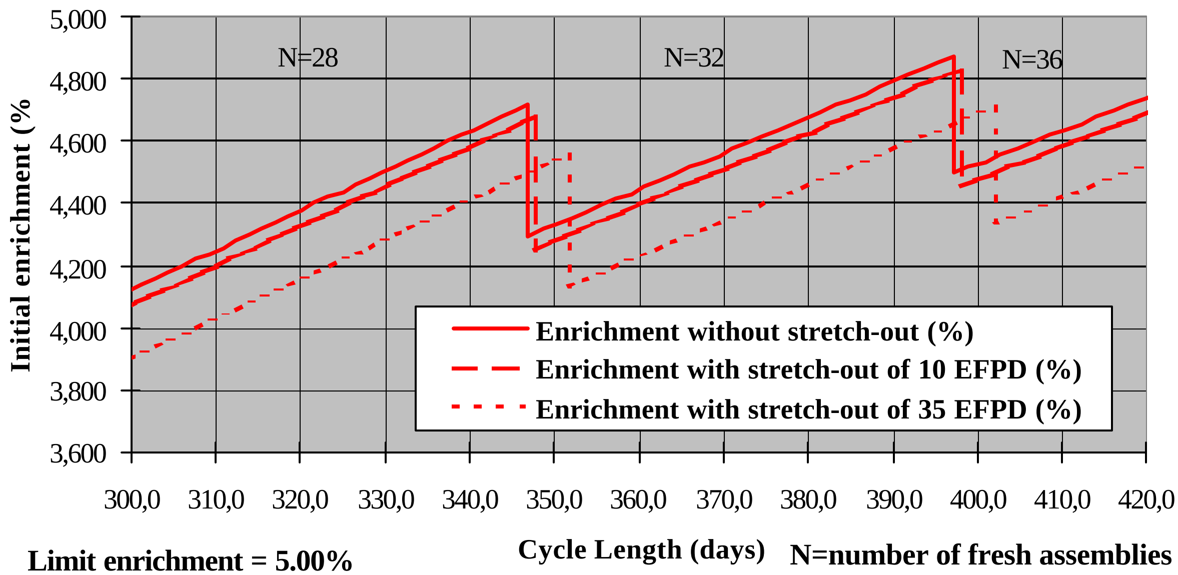


Chart 2

Evolution of Initial Enrichment vs. cycle length for different stretch-out lengths



In Belgium, where 7 nuclear power plants produce 60% of total electricity supply, each of them having their specific characteristics and operating limits, this model has been proven to be very helpful in comparing various fuel management strategies and in guiding strategic decisions.

2.2. SECOND STAGE : THE TRANSITION CYCLE OPTIMIZATION

The transition cycle optimizer is based on a similar reactivity model to the first one, but it additionally allows specifying the different fuel batches in the core: the model contains correlations to simulate the power histories of the fuel assemblies, the neutron leakage flux and the evolution of enrichment with burnup. The performance of these correlations was also analyzed by comparing them with full-core neutronic calculations.

This simple model allows the preliminary exploration of successive cycle analysis. Consider the following two typical cases for which this second stage analysis is used:

- Case 1: Transition to the equilibrium cycle defined in the first stage: Suppose a Utilities strategic optimization (see first stage) resulted in an 18-month equilibrium cycle for one of its nuclear power plants that is currently running a 12-month cycle. The transition cycle optimizer can model different possible cycling schemes very fast from the starting point to the end point, defining for each transition cycle the main characteristics of the reload batch (number of fresh assemblies and average enrichment), given various assumptions on outage planning. It also allows the core design engineer to do some sensitivity analysis quickly, and to prepare his selected optimal input deck for the in-depth neutronic analysis (see third stage).

- Case 2: Consequence of a limited perturbation in one cycle on the following ones. Consider for instance the case of an Operator wanting to increase the U235-enrichment of the reload batch for a future cycle by 0.5%. The optimizer allows working out the extra energy produced by the enrichment increase for that cycle, and also to also evaluating the impact on the following cycles.

Precision of the model being less satisfactory for case 1 as compared to case 2, problems dealing with limited perturbations are more frequently treated with the model, whereas cycle transition analysis using the model is done more on occasion.

Chart 3 shows the comparison of the calculated natural cycle length for a specified nuclear plant. The comparison is between the transition optimizer results and the corresponding explicit in-depth neutronic calculation results for transition to a longer cycle with fresh batch size and enrichment modification (see table 1 for cycling characteristics). In both cases, the same outage planning is considered for the whole transition. Note that this comparison is a severe test for the simplistic model, natural cycle length being a very sensitive parameter. Total cycle length (stretch-out included) is calculated more precisely by the model. We have observed some discrepancies in results within the transition, but the major tendencies are well represented by the simplistic calculations.

Chart 3

Evolution of Natural Cycle Burnup
(Comparison Model-Explicit calculation)

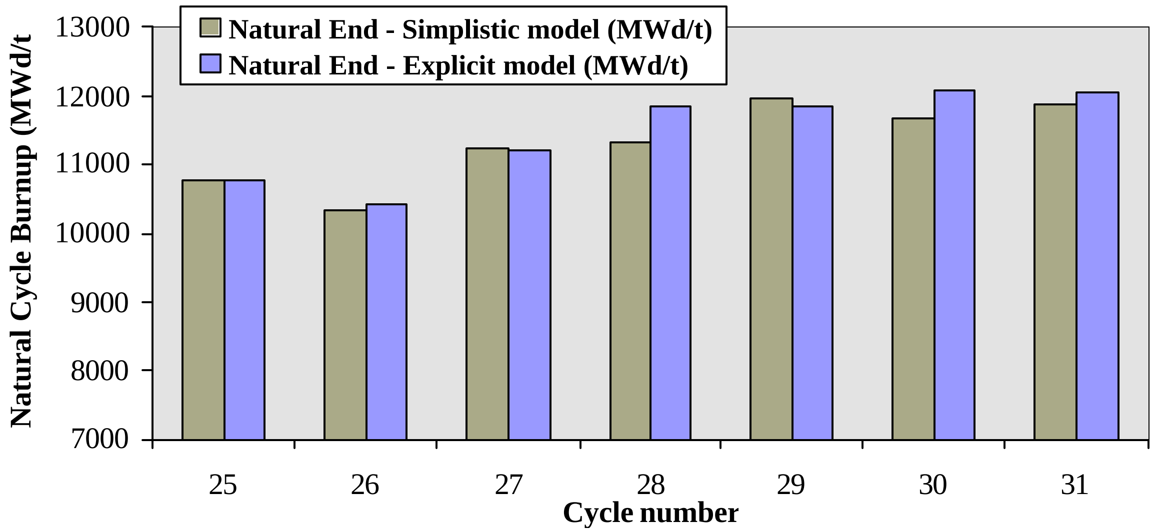


Table 1

Cycle number	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Number of fresh assemblies	32	36	36	32	36	32	32
Enrichment (%)	3.8	3.8	3.8	4.25	3.8	4.15	4.15

2.3. THIRD STAGE : IN-DEPTH NEUTRONIC ANALYSIS

Once a cycling strategy is chosen, it must be submitted to explicit calculation, in which loading patterns are designed, in order to verify the technical feasibility regarding the main limiting physics and fuel performance design limits (F-delta-H, MTC, and shutdown margin) and to confirm the cycle lengths.

This third stage guarantees the neutronic feasibility of the transition cycling scheme. As it boils down to classical neutronic analysis, it is not presented here in detail.

2.4. FOURTH STAGE : VALUATION OF GENERATING MARGIN

In this stage, the FCDST-approach consists in calculating the generating margin, which is defined as the difference between the earnings from power sales, and the marginal costs (fuel cycle costs) for a specific loading strategy. Classical valuation methods, taking into account time-value of money (Discounted Cash Flow , Net Present Value) are used.

Nuclear fuel cycles generally consist of a front-end part including mining, conversion, enrichment and fuel fabrication, and a back-end part including storage, reprocessing and final disposal.

The model uses the most prevailing market data for the cost side (cost of material, enrichment, fabrication, transportation, back-end costs) and the most recent forward curves for electricity rates for the earnings side. By comparing different strategies based on their generating margin, the valuation model also takes into account the energy replacement cost.

3. CONCLUSION : FIELD OF APPLICATION OF THE FCDST

The FCDST is a convenient tool for assisting core design of Utilities in defining the optimal frame in which its nuclear power plants should operate, plant-technical, safety and market conditions having been taken into account.

The following questions, which will be asked more and more often by nuclear plant operators as a result of the changing economic climate in the power industry, can easily and accurately be addressed by the FCDS Technique:

- Do we have to submit our nuclear power plants which are now running 12-month cycles to a power extension program (15 or 18 months), and will the optimal transition to the new reference cycle be cost-effective?
- The national grid Authorities oblige me to lengthen the next cycle of my power plant by 3 weeks. If I have to invest in extra fuel assemblies to reach that goal, will I benefit from the extra earnings from power sales?
- Flexibility issues: how to implement more flexibility in operation of a given nuclear plant?

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