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Original Article

Evaluation of the Middle Part of the Nuclear Fuel Cycle

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ABSTRACT

This article describes a comprehensive methodology for the evaluation of the middle part of nuclear fuel cycles. Evaluation of fuel cycles is basically divided into two parts. The first comprises nuclear calculation, i.e., creation of the strategy for nuclear fuel reloading and core design calculations. The second part is the business–economic evaluation of the selected reloading strategy, which can be done either by financial analysis or economic analysis. The financial analysis incorporates the perspectives of a company while the economic analysis can be used primarily by national economists or politicians. This methodology was applied to a case study that is focused on impacts of switching from a 12-month to an 18-month fuel cycle strategy for Water-Water Energetic Reactor (VVER)-1000 reactors.

1. Introduction

Strategic management and decision making in respect of the middle part of nuclear fuel cycles is a very specific problem of power engineering. Although the strategy of nuclear fuel cycles directly influences key issues in nuclear power engineering, i.e., volume of produced electricity and spent nuclear fuel, it can be very inflexible. This can be explained by the fact that switching to a different nuclear fuel cycle strategy always means a substantial impact on the entire operation of a nuclear power plant (NPP).

Therefore we need to carry out a comprehensive analysis [1] of the proposed fuel cycle. Key variables, which influence the particular fuel cycle, are as follows:

- Fuel cycle length (e.g., 12-month fuel cycle or 18-month fuel cycle)
- Number of years the fuel spends in a core (maximum fuel burnup)
- Type of fuel loading pattern (low leakage fuel pattern or high leakage loading pattern)
- Type of fuel used [uranium fuel or mixed oxide (MOX) fuel]

This article focuses on the first variable, i.e., the evaluation of the fuel cycle length.

The major difference between a 12-month and an 18-month nuclear fuel strategy (herein referred to as 12M and 18M) can be seen mainly in the organization of the planned shutdowns for fuel reloading. The 18M cycle

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alternates 18-month-long production periods and shutdown periods (~ 45 days) for fuel reloading. The durations of shutdowns of both strategies are more or less the same. The prolongation of the fuel cycle results in a significant increase of availability of the power plant. 18M fuel cycles require only two refueling outages during a 3-year period instead of three, as is the case with the 12-month fuel cycles. It means that we can save one entire outage (i.e., 45 days) during the 3-year period. Nevertheless, such prolongation influences operation of the entire power plant. Therefore a detailed analysis has to be carried out.

2. Materials and methods

2.1. *Methodology for the evaluation of the middle part of a fuel cycle*

Generally speaking, it is very hard to construct a comprehensive methodology for evaluating the middle part of fuel cycles. However, there are many evaluation procedures that aim to solve separate parts of the problem, such as reload safety evaluation or calculation of costs of interim spent fuel storage Fig. 1.

The evaluation of fuel cycles is basically divided into two parts: the first comprises nuclear calculation, i.e., creation of a strategy for nuclear fuel reloading and core design calculations. Such calculations are crucial for the second part of the evaluation: the business–economic evaluation.

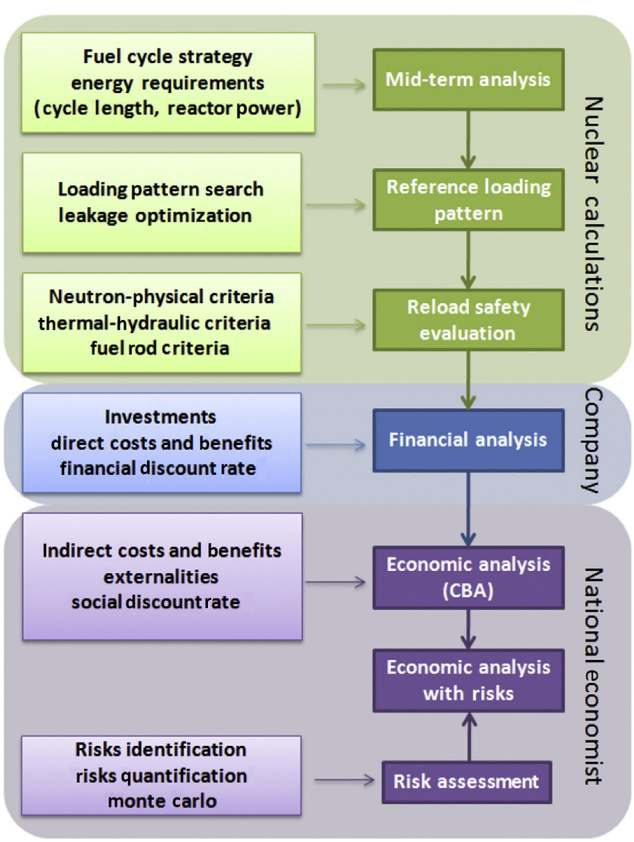

Fig. 1 – Methodology of fuel cycles assessment. CBA, cost-benefit analysis.

The business–economic evaluation must be based on specific nuclear calculations, which are essential as they determine a key input of the evaluation—the fuel costs of the proposed fuel strategy. The output of the nuclear calculations consists of proposed fuel reloads (loading patterns) for each fuel cycle, during which each loading pattern must meet energy requirements for the given power level and also all safety requirements that have to be fulfilled.

2.2. *Nuclear calculations of the fuel strategy*

Core design calculations are a challenging discipline in reactor engineering. Such calculations are reactor specific and therefore cannot be transferred from one power plant to another (especially if they have different reactor types). The fuel requirements also cannot be based on estimations because the core design has too many variables and too many restrictions. The nuclear calculations consist of the following aspects:

- Midterm analysis of reload strategy
- Proposal of a reference loading pattern
- Reload safety evaluation of proposed loading pattern

Midterm analysis of reload strategies comprises calculations of the fuel requirements for several reloads in a row using simple nuclear codes that are based on point kinetics and the linear reactivity model. This analysis aims to optimize the number of fresh fuel assemblies, their enrichment, and neutron leakage from the reactor core over several years (midterm analysis).

The proposal of a reference loading pattern or proposal of transition to a new fuel strategy is based on searching the loading patterns using 3D computational codes. Such outputs are crucial in respect of entire nuclear calculations. They provide detailed knowledge about the behavior of the reactor core during the fuel cycle. The output consists of the proposed fuel loading pattern which must meet energy (cycle length on full power), as well as all safety, requirements such as power distribution, peaking factors, and reactivity feedbacks. These calculations can be extended by cycle optimization, meaning, in particular, searching the low leakage loading patterns that have enhanced neutron and fuel economy.

Each change in the project or operation of an NPP requires safety assessment, especially for such a significant change as the switching of the fuel cycle strategy. The type of the particular safety assessment always depends on the nature of the change. Such calculations are then absolutely crucial for the entire middle part of the fuel cycle. In general, it must be proven that the new fuel strategy meets all safety criteria that come from the safety analysis report. These criteria are divided into three areas:

- Neutron–physical criteria
- Thermal–hydraulic criteria
- Fuel rod criteria

2.3. Business–economic evaluation of fuel strategy

The nuclear calculations are necessary for further evaluations, since they can exclude many promising fuel strategies and provide elementary inputs for further analysis. By contrast, any decision making cannot be carried out only on the basis of nuclear calculations. The decision making must be always based on business–economic evaluations of the proposed reloading strategy. These evaluations can be carried out by several methodologies. The perspective from which we analyze the problem is very important.

If we follow interests of common business entities, i.e., profit-maximizing companies, the financial analysis methodology should be used, but if we follow interests of national economists or politicians, which have to include social and environmental aspects, the economic analysis methodology should be used.

Financial analysis is a basic economic tool for strategic decision making of common business entities. It is focused on the comparison of direct costs and expenses of the project. It uses standard discount rates and calculates the net present value (NPV) of the project or similar indicators.

The methodologies of financial and economic analyses are similar in the basics, but differ significantly in the details. These two views are very important for overall decision making, because priority should not be given only to financial criteria in the nuclear sector.

As power engineering is the core industrial sector of the Czech economy (and other economies), and production of electricity from nuclear resources has a substantial impact on the environment, it would be appropriate [2] to extend the financial analysis to all social and environmental effects.

From the environmental point of view it is necessary that we develop the economics of the back-end part of the fuel cycle [3]. Therefore we should also take into account social costs (externalities) of handling the spent fuel and associated risks.

Financial and economic analyses are generally constructed in the surroundings without risks. However, there are many risks in the real world, which significantly affect decision making. Therefore it is appropriate to also perform a risk analysis. The risks are from the economical point of view. For example the fuel costs, that may fluctuate. Or the spent nuclear fuel: Today no one can precisely calculate the precise costs of back end. In the Czech Republic, we assume the once-through cycle, but there is a probability, that future governments will require the reprocessing of all the spent fuel. There are many risks, that may not be assumed in the financial analysis, but must be evaluated in the risk assessment. The risk analysis plays a substantial role in a fuel cycle assessment. The basic view on risks provides a one-factor-at-a-time analysis, [4] which monitors the impacts of isolated changes of individual factors on selected output. For deeper understanding of the risks (and for their possible elimination) it is more suitable to use the Monte Carlo risk analysis method. An output of such an analysis is the economic NPV (ENPV) of the project in the environment with risks (i.e., ENPV-at risk), or more precisely, its distribution function.

2.4. Case study: transition of Water-Water Energetic Reactor-1000 reactor from 12M to 18M fuel cycles

2.4.1. Nuclear characteristics of 18M cycles

The first step towards decision making has to be an analysis of the nuclear characteristics of 18M cycles. Because of the very sophisticated requirements of the 18M fuel cycle, a new type of nuclear fuel had to be proposed. Standard nuclear fuel (for 12M cycles) does not meet the requirements for power distribution in the core, or other safety requirements. The new type of fuel means optimal fuel pins distribution, optimal use of burnable absorbers and optimal burnable absorber enrichment [for gadolinium (Gd) absorbers]. Fig. 2 illustrates a typical proposal of fuel types for 18M cycles.

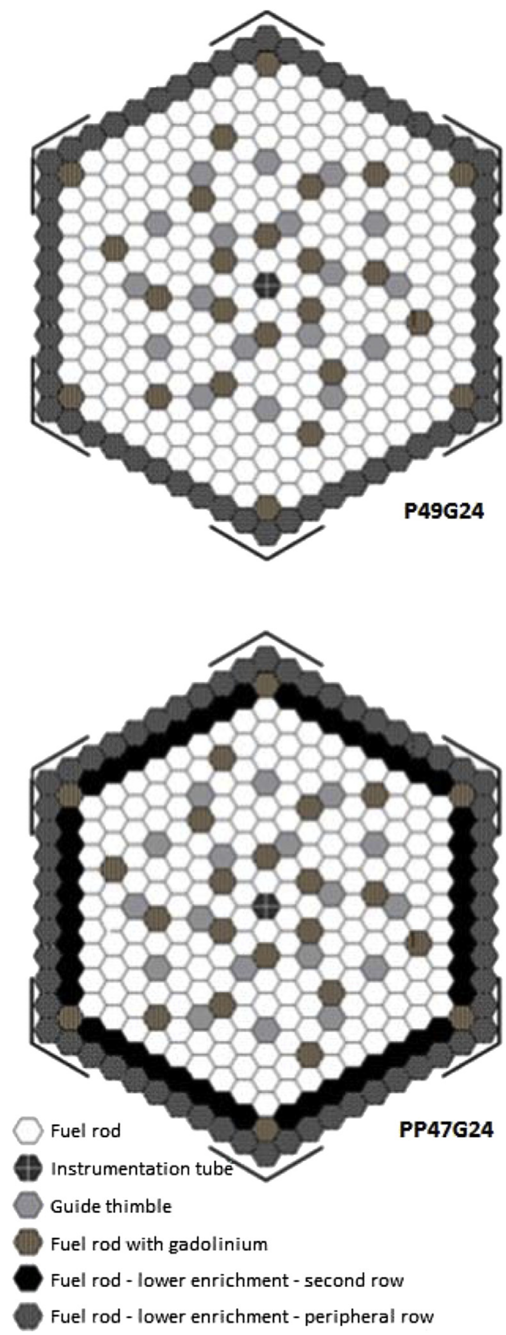

Fig. 2 – Proposal of nuclear fuel for 18-month cycles.

The burnable absorbers play the key role in 18M fuel cycles. Gd as a burnable absorber is sufficient for the 12M cycles but seems insufficient for the 18M cycles. Gd-absorbers in fuel assemblies are used in the form of particular fuel pins (i.e., integral absorbers mixed with uranium dioxide). Gd absorbers very effectively decrease boric acid concentration, but significantly deform the neutron field within the fuel assembly. 18M fuel cycles need a higher amount of burnable absorbers, and that implies problems with power distribution and peaking factors. 18M fuel cycles also imply the increase of Gd enrichment in fuel pins. It is estimated that 8% of Gd enrichment is needed for 18M fuel cycles. A significant improvement could be achieved with combined burnable absorbers. Using Gd-absorbers together with boron-absorbers could provide significant benefits.

It is proven that a low leakage fuel pattern can be achieved for a Water-Water Energetic Reactor (VVER)-1000 core for 18M fuel cycles. The low leakage fuel pattern has significant impact on fuel burnup efficiency and especially on durability of the reactor pressure vessel.

The appropriate type of nuclear fuel can solve most problems of core power distribution. In addition, higher amounts of fresh fuel in the core (e.g., 72 fresh fuel assemblies instead of 42 assemblies; the full VVER-1000 core contains 163 fuel assemblies) implies lower numbers of possible fuel patterns, and finding an optimal pattern can be narrowed to finding *the ring of fire* type of loading pattern (i.e., radial alternating of fresh fuel zones and used fuel zones). The main fuel characteristics of reference cycles for both strategies are compared in Table 1.

2.4.2. *Key economic aspects of 18M fuel cycles*

Basic economic and financial aspects are summarized in Table 2. Economic aspects mean especially social–economic benefits and costs.

Table 1 – Main fuel characteristics.

	12 mo	18 mo
Cycle length (EFPD)	314	490
Number of fresh FAs	40.75[a]	72
Annual fresh FA consumption	40.75	48
Annual spent fuel production	40.75	48
Average fresh FA enrichment (%)	4.04[b]	4.2[c]
Fuel burnup of discharged fuel (GWd/tU)	51	44
Neutron leakage[d]	low	low

EFPD, effective full power day; FAs, fuel assemblies; GWd/tU, gigawatt-days/metric ton of heavy metal of uranium.

[a] To ensure the 4-year fuel cycle with 163 assemblies in the core, 42/42/42/37 must be reloaded every 4 years.

[b] Averaged over all fuel rods (peripheral rods and rods with Gd have lower enrichment) and over axial blankets from natural uranium.

[c] It must be noted the maximum possible fuel enrichment (4.95%) is used in the 18-month reference loading pattern. It corresponds to the central fuel pins of P49G24 fuel type.

[d] A low leakage loading pattern is essential for the protection of the reactor pressure vessel. In both strategies, low leakage is achieved by situating FAs with lowest reactivity on the periphery of the reactor core.

Table 2 – Key economic aspects.

Benefits	Costs
Increase in energy production[a]	Increase in fuel costs[b]
Maintenance savings[c]	Increase in interim storage costs[d]
	Increase in spent fuel production[e]

[a] Decrease in the frequency of outages causes increase in the energy production by approximately 1/3 of outage length per 1 year.

[b] Decrease in the frequency of outages causes decrease in an efficiency of nuclear fuel use by approximately 18%.

[c] Decrease in the frequency of outages causes decrease in maintenance costs during outages.

[d] Decrease in the efficiency of nuclear fuel use tends to increase the consumption of fresh fuel per unit of produced energy and subsequently increase in the costs connected with the interim storage management [5].

[e] Decrease in the efficiency of nuclear fuel use implies increase in the back-end management costs [6].

The financial and economic analyses, which are subsequently solved, always follow from the comparison of 12M and 18M cycles. The evaluation is symmetric and the same approach for the evaluation of both cycles is used. Evaluations are based on additional costs and additional benefits, which follow from the transition to 18M cycles.

2.4.3. *Financial analysis of transition to 18M fuel cycles*

The NPV was calculated for the project, which starts in 2016 and will be in place for the lifetime of the NPP. A 7% discount rate [2] was chosen for purposes of the financial analysis. Major variables in discounted cash flows in the financial analysis were the fuel costs and the energy production benefits, i.e., direct benefits and costs. Results of the financial analysis have a major dependency on market prices of energy.

The financial analysis of the transition to 18M cycles results in NPV = 113 million USD, but the results of the financial analysis can be interpreted as follows:

The total overproduction of approximately 10 TWh of electricity for the entire 18M project lifetime provide NPV = 113 million USD. This overproduction implies the total overproduction of the spent nuclear fuel of 188 additional fuel assemblies, more than 10 fully loaded spent fuel casks. This analysis is performed in the environment without risks and without consideration of social costs.

2.4.4. *Economic analysis of transition to 18M fuel cycles*

An inclusion of indirect and off-market aspects of nuclear energy production was the key approach for the evaluation of the analysis. All cash flows were discounted by the social discount rate, which was 5.5%. An example of such an approach (off-market aspects) is the inclusion of social costs of back-end issues in the economic analysis. The inclusion of social costs of the back-end issues was based on a calculation of the costs of nuclear fuel reprocessing [7,8]. This is only the first approximation of a calculation of real costs of the waste disposal. The fuel reprocessing is not the final solution. The reprocessing solves neither the problem of waste disposal nor the necessity of the final disposal. In the Czech Republic, the

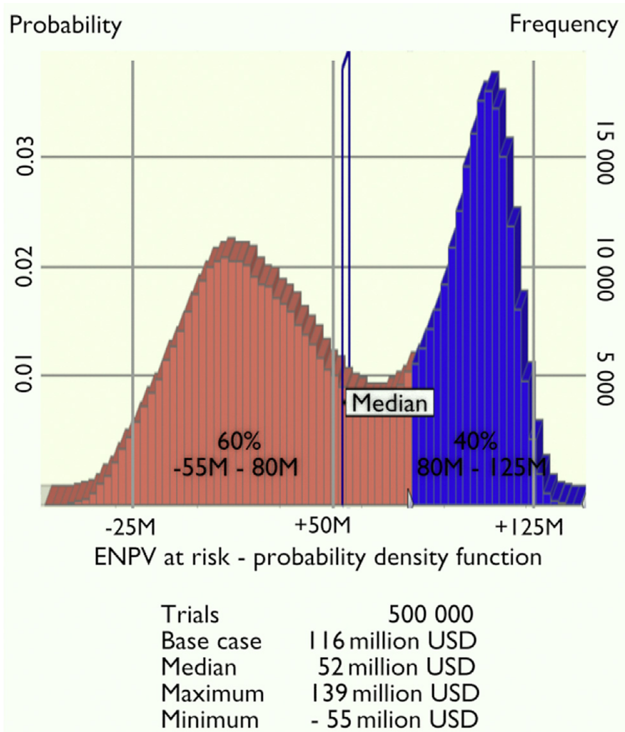

Fig. 3 – The probability density function. Economic NPV (ENPV).

state is responsible for the disposal of radioactive waste, but the nuclear operators in the Czech Republic have to pay all costs connected with the final disposal. At the same time the nuclear operator uses the benefits as a tolerance and approval of the public for disposal of spent nuclear fuel to a deep repository.[1] This approval represents an externality for the public and has to be calculated in the economic analysis. Although the reprocessing of fuel is not its final solution, this concept shows interesting results and is sufficient for this approximation.

The economic analysis results in ENPV = 116 million USD. This value is similar to the value from the financial analysis, but it has a considerably different composition. The high and positive added value is caused by reducing the discount rate and zero tax rate (these are the standards of the methodology of economic analysis). By contrast, there are high social costs of the production of spent nuclear fuel. Although the analysis comprises the difference between 12M and 18M cycles, the impact on the NPV is significant. The social costs of the overproduction of spent nuclear fuel 18M–12M are approximately 5 million USD per year.[2] This item naturally reflects all the economic benefits (e.g., recovered uranium and plutonium) and costs (e.g., costs of disposal of high level waste etc.) of fuel reprocessing. This economic analysis is also carried out in the environment without risks. The most important result of the economic analysis is the volatility of the economic output. It follows that it is necessary to add a risk assessment of the transition to 18M cycles.

2.4.5. *Risk analysis of transition to 18M fuel cycles*

The analysis was carried out by Monte Carlo simulation in the computational software, Crystal Ball. Results of the model confirm the volatility of economic output. The risk analysis revealed also a new type of significant risk. This risk is connected with outage management between 18M cycles. Problems are caused by the higher amount of managed spent fuel casks. Management of spent fuel casks is crucial[3] for length of outage for VVER-1000 NPPs. The final distribution of the ENPV-at risk shows the uncertainty of the positive value of the project.

The risk analysis results in the 40% probability that ENPV will be between 80 million USD and 125 million USD. There is approximately 45% more probability that ENPV will be between zero value and 80 million USD. Approximately 15% probability is for negative value. The probability density function of ENPV-at risk is shown in Fig. 3.

3. Results

3.1. *Results of the case study*

The comparison of 12M cycles and 18M cycles can be carried out according to several criteria:

- Core design criteria
- Economic criteria
- Social criteria

In terms of core design criteria, it can be stated that 18M cycles at VVER-1000 NPPs meet all safety and core design criteria without any problem.

In terms of economic criteria 18M cycles have a mostly positive economic impact, and the project has mostly positive discounted NPVs. It could be stated that the economic value of the project is low in comparison with the economic output of NPP as a whole. Moreover, the risk analysis shows economic risks caused by market uncertainties and possible technical complications.

The social criteria transition to the 18M cycles means the substitution of decrease in the fuel burnup efficiency by the increase in energy production. The question remains as to whether this substitution is socially acceptable at present, given that most technologies are focused on efficiency.

[1] The strategy of once-through fuel cycle was adopted in the Czech Republic. Therefore, two dry cask stores were built on both Czech NPPs and a geological repository is planned.

[2] This evaluation is based on the methodology described in [8]. For this case study the net present cost per kilogram of spent fuel C_{rr} = 1,470 USD/kgHM. The final value of 5 million USD is given by 1,470 USD/kgHM × 3,401 kgHM, which corresponds to the difference in the annual fresh FAs consumption from Table 1.

[3] VVER-1000 NPPs have the spent fuel pool inside the containment building and therefore all fuel handling is on the critical path of refueling outages.

4. Discussion

This article describes a methodology for the evaluation of the middle part of nuclear fuel cycles. This methodology was applied to a case study about the transition of a VVER-1000 reactor from 12M to 18M fuel cycles. It is obvious that such an evaluation must contain nuclear calculations and business–economic evaluations, and thus cannot be carried out separately. Detailed nuclear calculations are necessary for a decision-making process. Nuclear calculations provides an information about the feasibility of certain fuel strategy. There is always a set of fuel cycles that are more economical, but do not meet some reload safety criteria. These fuel cycles must be excluded from further considerations. By contrast, nuclear calculations do not provide any information about benefits or costs. A strategic decision-making process must be carried out on the basis of business–economic evaluations. This article provides two views on how to perform such evaluations. The first approach respects the views of the company which operates the NPP; the second approach respects the views of national economists and politicians who must reflect all social–economic aspects in the assessment.

Conflicts of interest

All authors have no conflicts of interest to declare.

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