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ARTICLE

Impact of Nuclear Fuel Cycle Operation Factor Uncertainty on Nuclear Power Plant Operation

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The robustness of an entire nuclear fuel cycle (NFC) can be assessed through simulations of the operational factors (OFs) of future NFC facilities, combined with mass flow analyses assuming many time series of OFs. In this study, the uncertainty of OF caused by minor troubles, which causes the expansion of the regular maintenance or temporary suspension, was focused on. OF of a reprocessing plant with the uncertainty were predicted by autoregressive moving average model. As a demonstration of the methodology to assess the robustness of an NFC, using the predicted OF data and a NFC simulator, NMB (Nuclear Material Balance) code, the impact of a reprocessing plant OF on a fast reactor OF was quantified. As a results, extra reprocessing capacity or additional plutonium stock induced higher robustness of an NFC.

KEYWORDS: nuclear fuel cycle, operation factor, mass flow analysis, ARMA model, NMB code

I. Introduction

After the accident at Fukushima Daiichi Nuclear Power Plant (NPP), all nuclear reactors in Japan were suspended for necessary safety improvements and repairs. Japan has two primary types of reactors: boiling water reactors (BWR) and pressurized water reactors (PWR). The reactors at Fukushima Daiichi NPP were BWRs; however, all reactors in Japan, regardless of type, were subject to this suspension. Although an increasing number of reactors have been upgraded and resumed their operations, many remain offline, primarily BWRs. This large-scale, long-term suspension of reactors poses a great decline of operation factor (OF) and significant concern for energy security. Additionally, unplanned construction delays at nuclear fuel cycle facilities, such as that of Rokkasho Reprocessing Plant, also cause the concern. At Rokkasho Reprocessing Plant, such delays have hindered domestic reprocessing of spent fuels (SFs) and fabrication of mixed oxide (MOX) fuel. These setbacks cause difficulties in future reactor operations in a nuclear fuel cycle (NFC) reliant on reprocessing, as is the case for fast reactor (FR) cycles utilizing plutonium (Pu).[1,2] Besides these major incidents, even minor troubles can impact NPP operations. While these may not lead to long-term suspension, they affect OF of NPP.

As one of the research of severe accidents of reactors, probabilistic risk assessment (PRA) is being extensively conducted. It is a methodology to quantify the probability of severe accident by evaluating the probability and the impact of breakdown of every system. The methodology was systematically applied for all of the components of a reactor in the U.S. for the first time.[3,4] In Japan, it attracted attention anew and Japanese Atomic Energy Society has revised a standard after the Fukushima accident.[5,6] However, the main scope of PRA studies are severe accidents of NPPs. One of the issues is that not enough research has been conducted on accident tolerance for the entire NFC in a comprehensive manner.

For NPP to play a role of a base load power source, it is necessary to consider an NFC in which the electricity generation, i.e., OF of the reactor, is unlikely to decline even if such accidents occur. Therefore, a methodology to quantify a tolerance of the NFC to the accidents is needed.

A tolerance of an NFC to the effects of operation factor declining events of each facility, such as fuel fabrication plants (FFP), reprocessing plants, and reactors, was called the robustness of the NFC. If the overall power generation or OF of the reactors remains largely unaffected, even when such events occur, the NFC is considered highly robust. In this context, if the degree of the impact of the accidents on reactor OF can be quantified, the robustness of the NFC can be quantitatively assessed by the value of the reactor OF.

Therefore, as one of the NFC robustness studies, this study proposes a methodology to quantify the impact of OF uncertainties in NFC facilities, which is caused by variations in maintenance term and minor troubles, on reactor OF. Using this methodology, the impact of uncertainties in OF of a reprocessing plant (RP) on OF of a FR was analyzed.

II. Nuclear Fuel Cycle Robustness Analysis

1. Methodology and Event Selection

A robustness of an NFC is evaluated under the following steps.

1. Selection of an event that affects the OF of facilities composing an NFC.
2. Modeling a probability distribution of the affected facilities OFs.
3. Calculation of OF distribution of electricity

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generation by NFC simulator with the probability distribution.

NFC simulators are computational tools designed to assess variables such as natural uranium demand, actinide inventory, and waste quantities based on mass flow calculations derived from user-defined inputs, such as annual reactor power and reprocessing rates. Events at NFC facilities impact both the quantity and composition of actinide stock used in nuclear fuel fabrication, influencing risk of fuel shortages and potentially reducing reactor OF. NFC simulators enable a detailed temporal analysis of actinide stock, thereby allowing accurate estimation of reactor power generation over time. Consequently, average reactor OF can be obtained through repeated simulations, with facility OFs generated based on probability distributions.

There are three possible events that affect the robustness of an NFC.

1. Minor trouble
2. Severe accident
3. Construction delay

"Minor trouble" defines unforeseen troubles causing extensions of maintenance terms and a temporary suspension of facilities, but the suspension terms are less than one year. Because of the minor trouble, OFs of NFC facilities are not stable even if a severe accident does not occur. Hence, the OFs are supposed to fluctuate although they have a base value. In this study, the fluctuation was called “uncertainty” for convenience. Troubles in a FFP will propagate to several reactors even if it is minor one. Hence, the minor trouble influences the robustness of an NFC.

“Severe accident” is a large-scale incident like the Fukushima Daiichi NPP accident. In this case, as in Japan, all reactors may require long-term suspensions and improvements to match a new standard established by the authority considering the cause of the accident. In addition to the improvements, the shutdown will be continued yearly due to the need for a restart review by the authority. On the other hand, the suspension terms will change based on reactor type and construction time. New or different reactor concept will have shorter suspension term because they have different improvement scale. Therefore, a combination of several technologies and reactor types leads to a higher robustness of an NFC.

The construction delay of a FFP or a reprocessing plant result in a stoppage of fuel supply. It leads a standstill of nuclear power generation. However, in an NFC employing several reactor types with different fuel concepts at the same time, even if one fuel fabrication stops, others will not be affected. Hence, in this case, the combination of different reactor types and technologies also improves the robustness of the system.

In this study, minor trouble in regular operation was selected as the event. As a demonstration of the methodology, the mean value of OF of FR with a RP of which OF had the uncertainty was analyzed.

2. Operation Factor Model

To quantify the uncertainty of OF, a regression model was employed. Among regression models, one capable of reproducing uncertainty by random number was deemed appropriate. Then, two models were adopted for this study: a simple model comprising a mean value and white noise generated by a random number, and ARMA (Auto Regression Moving Average) model.[7] The ARMA model is expressed in Eq. (1), and it has been well applied in economic and meteorology analysis.[8-11] This is a time series model that reproduces or forecasts time series data using AR and MA terms, which incorporate past data in addition to a mean value and white noise. The AR and MA terms correspond to the first and second terms of Eq. (1), respectively. The optimal model can be identified by specifying the AR and MA orders, which determine the reference points of past data. These orders are selected based on the autocorrelation of the training data.

$$\boldsymbol{y_t} = \sum_{l=1}^{p} \boldsymbol{a_l y_{t-l}} + \sum_{l=1}^{q} \boldsymbol{b_l \theta_{t-l}} + \boldsymbol{c} + \boldsymbol{\theta_t} \tag{1}$$

Where t, time [-]; $\boldsymbol{y_t}$, predicted value at t [-]; p, AR order [-]; q, MA order [-]; l, time lag [-]; θ, white noise [-]; a, b, c, coefficients [-].

In this study, the simple model was regarded as a special case of ARMA model, because ARMA model becomes equivalent to it when the coefficients of the AR and MA terms (a and b) are set to zero. In this case, the mean value corresponds to the parameter c in Eq. (1). As noted above, a OF data of an NFC facility exhibits both a baseline value and fluctuations. Additionally, the OF values may display autocorrelation, as operational disruptions in one year can affect operations in the following year, and regular maintenance schedules impose periodicity specific to the NFC facility. Therefore, the ARMA model was assumed to be appropriate for simulating OF. However, because the amount of actual OF data of reactors or NFC facilities are not sufficient, a better model should be considered when more data becomes available.

The impact of uncertainty was evaluated by repeatedly performing mass flow analyses using an NFC simulator coupled with OF simulated by ARMA model. This approach provided an estimate of the mean reactor OF and enabled quantification of the NFC's robustness.

In this demonstration, the training data of RP OF for ARMA model was derived from actual reprocessing records of Tokai Reprocessing Plant.[12] The plant's capacity was set at 90 tons per year, based on an IAEA database.[13] Reprocessing records were used, excluding periods of start-up, planned shutdown, and years following a fire incident, as these did not represent random fluctuations—start-up and planned shutdown were intentional, and the fire was a major incident extending beyond one year. To determine the AR and MA orders of the model, ACF (Autocorrelation Function) and PACF (Partial Autocorrelation Function) of the training data was investigated. They are generally utilized to determine MA order and AR order, respectively. As a result, all correlation coefficients were within 95% confidence interval, and significant correlations were not in the data at any values of lag. Therefore, the AR and MA orders were set to zero. In other words, a simple model was adopted for this analysis.

Predicted data were generated using the Python statsmodels library.[14] The mean OF was 0.749, with a standard deviation of 0.165. Using this model, RP OF data of 200 years operation were produced 200 times, and mass flow analyses were conducted for each 200-year RP OF data.

3. Mass Flow Analysis and Plant Parameters

Mass flow analysis was performed by NMB code,[15,16] with annual reprocessing amounts derived from the simulated RP OF data and the parameters described later.

The scenario for the analysis was simple, which consisted of a FFP, a FR of 1 GWe, and a RP. To investigate only the effects of the uncertainty of RP OF, the capacity of the FFP was unlimited. In addistion, basic FR OF was set to 100% hypothetically, i.e., if sufficient Pu could be used, the FR was assumed to be operated without any trouble and maintenance. In practice, it is expected that the capacities of FFP and the FR OF would fluctuate similarly to the RP OF, thereby influencing the robustness of the NFC. When RP capacity is low, insufficient Pu is recovered during periods of low RP OF, making it impossible to produce fuel even if the FFP OF is high. This necessitates halting FR, thereby reducing robustness. Similarly, even if the average values of RP OF and FR OF are sufficiently high, a low capacity of the FFP during periods of low FFP OF results in insufficient fuel production, necessitating the stop of FR operation and reducing robustness. Moreover, in this demonstration, because only one FR is introduced, a decrease in FR OF directly equates to a decrease in the robustness. It should be noted that, since the OFs of these facilities mutually influence one another, investigating the actual robustness of the NFC requires considering fluctuations in the operational factors of all facilities. The specification of the FR was referred to a large core concept using MOX fuel with high internal convergence designed in FS (Feasibility Study) project of Japan,[17] and it is listed in **Table 1**. The specifications assumed for the reprocessing plant are shown in **Table 2**.

Table 1 Specification of fast reactor[17]

Item	Value
Thermal power [GW]	2.5
Thermal efficiency [-]	0.4
Batch number [-]	4
Batch length [y]	2.083
Breeding ratio [-]	1.01
Pu inventory of FR core [t]	8.3
Pu consumption [t/batch]	2.07
Out-core period [y]	4

Table 2 Specification of reprocessing plant

Item	Value
Recovery ratio of U and Pu[-]	0.999
Cooling term of spent fuel [y]	3
Time for reprocessing [y]	0.5
Time for fuel fabrication [y]	0.5

4. Base Scenario

The base scenario was defined by a FR of 1 GWe, and a stable RP whose capacity satisfies the minimum requirements. OF of the RP does not fluctuate, and OF of the FR is constant at 1.0.

The reprocessing capacity of the base scenario was based on the annual fuel requirements of the FR, and it was adjusted to sustain the FR OF in the scenario without RP OF fluctuations in advance. The annual fuel requirement amount was 6.75 tons. As an initial Pu inventory, 14 tons of Pu was available in all cases. The composition of the initial Pu was that in an equivalent FR cycle calculated in advance with the same specifications. It is listed in **Table 3**. The amount was just sufficient at any point in the base scenario.

Table 3 Isotopic fraction of initial Pu stock

Nuclide	Isotopic fraction (%)
Pu-238	0.775
Pu-239	58.7
Pu-240	33.1
Pu-241	4.10
Pu-242	3.32

5. RP Capacity in Uncertain Scenario

The amount of Pu available for fuel fabrication significantly impacts the OF of FR. Therefore, in this analysis, parameters were selected to account for the effects on Pu production and initial Pu inventory, which are respectively represented by average reprocessing capacity and additional Pu stock prior to construction of the FR.

The reprocessing capacity was normalized to a range from 1 to 1.3, with 1 corresponding to 6.75 tons described above. Higher reprocessing capacity leads to a higher FR OF due to the increased reprocessing output even at lower RP OF values. The product of the average reprocessing capacity and the predicted RP OF, which was representing the annual available reprocessing amount, was input into the NMB code.

6. Pu Stock in Uncertain Scenario

The additional Pu stock was also normalized, using the amount of Pu consumed in a single fuel batch as a reference, with values ranging from 0 to 1.25, where 1 corresponds to 2.1 tons in addition to 14.0 tons of the base scenario. When the amount of the additional Pu stock are large, Pu shortages can be compensated, resulting in a higher FR OF even at lower RP OF values. In these calculations, the average reprocessing capacity was set to 1 (6.75 tons).

III. Result and Discussion

1. Example of Uncertainty on OF of FR

Figure 1 presents a part of the results of a simulation sampled from 200 simulations using average reprocessing capacities of 1 and an additional Pu stock of 0. For reference, results from the base scenario are also included. The horizontal axis indicates years, beginning from the start of reprocessing operations.

The topmost graph shows the annual available reprocessing amount, which was the product of RP OF and the average reprocessing capacity. Although the results exhibited significant fluctuations, the average value of the orange line was 6.72 tons, with a standard deviation of 1.51.

This outcome demonstrated that the ARMA model's forecast closely matched the stable scenario, where the reprocessing capacity was set at 6.75 tons.

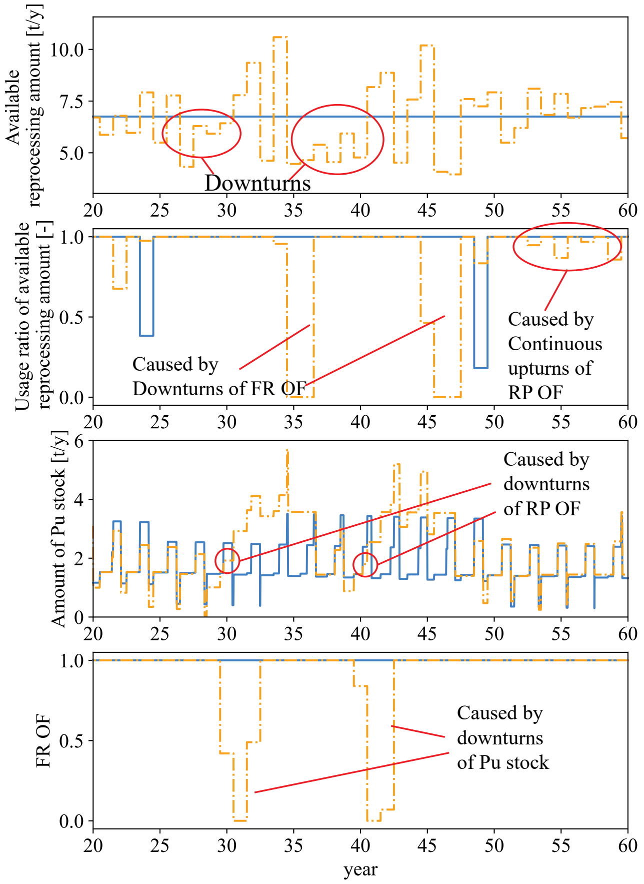

Fig. 1 Temporal change of annual available reprocessing amount, amount of reprocessed spent fuel, and FR OF (Blue solid line : base scenario, orange long dashed dotted line : scenario considering uncertainty of RP OF)

The second graph illustrates the time variation in the usage ratio of the available reprocessing capacity. This ratio represents the annual amount of reprocessed spent fuel relative to the available reprocessing capacity. The third graph shows the time variation in the Pu stock, while the bottom graph presents the FR OF results. These graphs are closely interconnected.

In the base scenarios, the line in the second graph was not flat, despite the RP OF being stable. Specifically, downturns were observed approximately every 25 years. This was attributed to the FR batch length of 2.08 years, which caused a 0.08-year shift in the timing of fuel exchanges. This corresponded to a shift of 0.04-year for every year in the scenario. Consequently, some fuel exchanges did not occur every 25 years, leading to years in which insufficient spent fuel was available for reprocessing.

When considering uncertainty, the second graph exhibited more frequent and varied downturns compared to the base scenario. Smaller downturns were caused by an excess in available reprocessing capacity. For example, in the 55th to 59th years, the topmost graph showed upturns, and the preceding years also exhibited upturns. In these cases, the amount of spent fuel fell short of the reprocessing capacity, preventing the generation of surplus Pu. Larger downturns were linked to FR operational stoppages. In such cases, the bottom graph showed significant downturns occurring just before those in the second graph. During FR stoppages, no spent fuel was discharged, leading to a shortage of spent fuel available for reprocessing.

In the third graph, the line of the base scenario continuously oscillates. These variations arose from the balance between Pu consumption for fuel fabrication (2.1 tons per batch) and Pu generation through reprocessing. The variations appeared to follow a 25-year cycle, consistent with the relation of the FR batch length and the usage ratio of available reprocessing capacity. Under uncertainty, prolonged downturns in RP OF resulted in Pu shortages, causing FR operations to be suspended. For instance, in the 30th, and 40th years, Pu stock levels were lower than those in the base scenario, falling short of the 2.1-ton requirement for fuel fabrication. In contrast, large upturns in Pu stock were observed after FR OF downturns. These upturns occurred when failed fuel exchanges temporarily left Pu from one batch unused.

Hence, FR OF downturns followed Pu stock downturns and preceded stock upturns. In the bottom graph of Fig. 1, the average FR OF value under RP OF uncertainty was 89.3% for this sample. As discussed, even when reprocessing achieved an upturn, the amount of stored spent fuel sometimes failed to meet the reprocessing capacity, resulting in no surplus Pu production. Consequently, despite the average RP OF being 1, FR OF downturns occurred, reducing the overall average OF.

2. Effect of RP Capacity

Figure 2 illustrates the analysis results under varying reprocessing capacities. The line indicates the mean values of FR OFs using simulated data, with error bars representing standard deviations. The results display a curve that asymptotically approaches 100%, with FR OF values remaining below 100% even when the reprocessing capacity exceeds 1. Notably, a reprocessing capacity of at least 1.2 times the annual fuel consumption was necessary to achieve and maintain an FR OF of 95% or higher in this analysis. With high capacity, even though the RP OF has downturn, more Pu can be extracted, and the RP can supply Pu to the fuel fabrication than the case with low capacity.

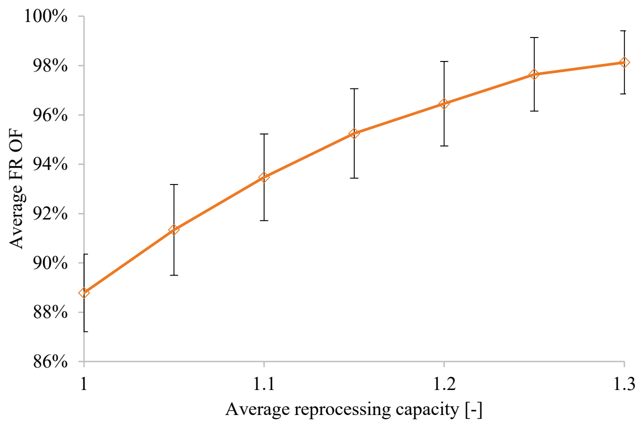

Fig. 2 FR OF and reprocessing capacity (additional Pu stock=0)

3. Effect of Additional Pu Stock

Figure 3 presents the analysis results with varying levels of additional Pu stock with annual capacity of RP of 1.0. In this figure, the line approached 100%. In the scenarios, when RP OF declined, additional Pu was utilized to compensate for the downturn of the RP OF. To maintain a FR OF above 95%, an additional Pu stock of at least 0.5 batch (i.e., 1.05 tons) was required. However, the Pu amount needed to sustain the FR OF varies with the RP OF data and scenario duration.

Including the average reprocessing capacity, these preparations prevented from Pu shortage and maintained the average FR OFs. Consequently, they contributed to the high robustness of the NFC. Enhancing only one of these factors is expected to be effective enough in the point of view of the achievement of a high robustness. However, these improvements also come with drawbacks, such as increased facility construction and operational costs, and heightened concerns regarding nuclear nonproliferation. When considering a robust NFC, it is essential to balance these factors while taking into account costs and social circumstances.

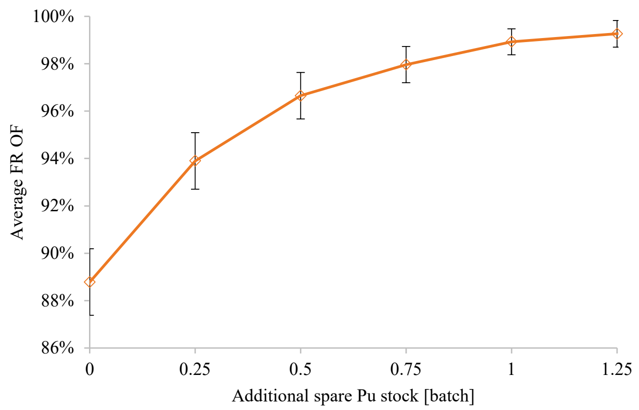

Fig. 3 FR OF and amount of additional Pu stock (annual RP capacity=1)

VI. Conclusion

This study presented a methodology to quantify the impact of uncertainty in the NFC facility's OF on reactor OF, as an example of evaluating the robustness of an NFC. It assessed robustness by simulating NFC facility OF data using ARMA model and performing multiple mass flow analyses with an NFC simulator. As a demonstration of the approach, the effect of uncertainty in RP OF on FR OF was evaluated. The results indicated that the continuous downturns caused by the fluctuations of RP OF declined the average FR OF above 95%. Moreover, to maintain the FR OF, the annual reprocessing capacity should be at least 1.2 times the annual fuel consumption or additional Pu corresponding to 0.5 batch was needed. Thus, this methodology illustrated that the uncertainty of RP OF in a regular operation had impact of the FR OF, and it evaluated quantitatively the robustness of an NFC as the average FR OF. As the next step, we plan to model the probabilities of severe accidents and construction delay using probability distributions. Additionally, we aim to use the developed methodology to evaluate the impact of introduction of multiple reactor concepts on various quantity including robustness, cost, and etc..

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