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Line-Balancing Analysis for the Integrated Pyroprocessing Operation

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1. Introduction

The integrated pyroprocessing operation is a key technology for reprocessing spent nuclear fuel, allowing the recovery of uranium and transuranic elements (TRU) while reducing the volume of high-level radioactive waste. This process involves several interconnected unit batch operations, such as decladding, electrolyric reduction, electrorefining, electrowinning and waste treatment. For the system to operate smoothly, it is crucial that each unit batch operation is effectively line-balanced. This study aims to analyze potential bottlenecks in the integrated pyroprocessing operation and derive the optimal number of process equipment to enhance line-balancing and overall efficiency.

2. Modeling

To effectively analyze the complex interactions within the integrated pyroprocessing operation, a Discrete Event System (DES) modeling approach was adopted. This method defines each unit operation task (e.g., the start and end of operations) as an event and simulates the entire process flow by modeling the timing and sequence of these events. This approach enables the identification of bottlenecks and imbalances in processing speeds across various unit processes.

Numerous studies have applied DES modeling and simulation in the field of nuclear energy. Recently, H. Garcia and others utilized the DESM method to analyze the HALEU process in the Fuel Cycle Facility (FCF) hot cell at the Idaho National Laboratory (INL) in the United States [1]. In the past, INL has also developed and used operational analysis models for the FCF hot cell operation [2,3]. Additionally, DES modeling and simulation has been used to develop anomaly detection models using ExtendSim software [4], which has been applied to safeguards analyses [5,6].

In South Korea, the author and others have applied DES modeling and simulation using ExtendSim in the nuclear energy field, with examples including headend process operation analysis [7], repeated batch operation analysis for electrolytic reduction [8], pyroprocessing material flow modeling [9], a material flow evaluation for a 10 tHM/y integrated pyroprocessing system [10], and hold-up material analysis in the headend process [11].

2.1 Scope of Modeling

The scope of the modeling was defined from the headend group process to the electro-recovery group process. Key processes, including decladding, oxidation, mixing, compaction, electrolytic reduction, electro-refining, LCC, TRU drawdown, RE drawdown, and distillation were included. The main operational information for these processes is summarized in Table I, which served as key input data for the modeling.

Table I: Summary of key operational information for the integrated pyroprocessing

Unit process	Number of units (design)	Batch operation time (h)	Batch capacity (kg)
Decladding	2	3	41
Oxidation	2	24	112.5
Mixing	3	7	75
Compaction	3	10	50
Dewaxing/Reduction	2	36	112.5
Sintering	3	72	150
Electrolytic reduction	3	24	50
Cathode Processing	3	48	100
Electro-refining	6	12	50
LCC		28	6 (Cd)
TRU DD		39	6 (Cd)
RE DD		26	6 (Cd)

2.2 Application of DES Modeling

The DES modeling method is particularly effective in simulating the procedural and sequential aspects of operations, as it captures the start and end times, the flow of materials between processes, and the batch processing capacities. This allows for a detailed analysis of each unit operation's impact on the overall system performance.

A critical factor in this modeling is the imbalance in material flow between processes. For example, the decladding process handles 41 kg of material per batch, whereas the oxidation process can handle 112.5 kg per batch. This disparity necessitates additional splitting and combining steps, which can significantly reduce overall process efficiency.

The electrorefining process requires a particularly intricate operational flow due to its dependence on sequential operations. The concept of campaign operations was introduced, where specific processes are performed in sequence after completing a predetermined number of batches. For example, after 20 batches of electrorefining, the process shifts to LCC. This sequential operation is critical for the efficient use of resources and was carefully modeled to ensure that equipment is utilized effectively across multiple processes.

2.3 Key Assumptions and Modeling Limitations

The modeling process was built on the following key assumptions:

· Inter-process Transfer Time: The time required for material transfer between processes was neglected to simplify the model and focus on the core process interactions.

· Splitting and Combining Time: The time required for splitting and combining batches due to capacity differences between processes was also neglected, as these steps are relatively short compared to the overall process flow.

· Equipment Failure and Maintenance: Equipment failures and maintenance activities were not considered, assuming ideal operational conditions to analyze the optimal performance of the system. This introduces a limitation as it does not account for variability in real-world operations.

3. Simulation Analysis

3.1 Design-Based Simulation

The design-based simulation was conducted using the initial operational data for the integrated pyroprocessing system. The simulation analyzed the material flow across the system, considering the batch processing capacities, times, and the number of operational units for each process. The results highlighted significant bottlenecks in certain processes.

As shown in Table II, the reduction, sintering and electrolytic reduction exhibited high utilization rates, while the mixing, compaction, and waste treatment processes had lower utilization rates. This indicates the presence of bottlenecks where certain processes are overloaded, causing material flow delay and reducing the efficiency of the overall system. Such processes are considered as late determining steps in the integrated pyroprocessing.

Table II: Key operational information of the integrated Pyroprocessing

Process	Peak Utilization (Design)	Peak Utilization (Optimum)
Decladding	0.127656	0.255313
Oxidation	0.372083	0.248056
Mixing	0.108511	0.325532
Compaction	0.232523	0.348785
Dewaxing/Reduction	0.557917	0.278958
Sintering	0.557778	0.334667
Electrolytic reduction	0.557778	0.334667
Cathode Processing	0.488056	0.292833
Electro-refining	0.278889	0.278889
Variance	0.030	0.012
Standard deviation	0.174	0.035

3.2 Optimization Simulation

To address the identified bottlenecks and improve line balancing across the processes, an optimization simulation was conducted. The goal of this simulation was to minimize the variance in utilization rates across the different processes and maximize the overall operational efficiency.

The optimization results, shown in Table III, indicate that decreasing the number of operational units in the decladding, mixing and compaction processes, while increasing the number in oxidation, reduction, sintering, electrolytic reduction and cathode processing. It helps alleviate material flow delay issues, thereby enhancing the overall efficiency.

Table III: Comparison of the number of operational units

Process	Design based units	Optimized units	Change of Units
Decladding	2	1	-1
Oxidation	2	3	1
Mixing	3	1	-2
Compaction	3	2	-1
Dewaxing/Reduction	2	4	2
Sintering	3	5	2
Electrolytic reduction	3	5	2
Cathode Processing	3	5	2
total	21	26	5

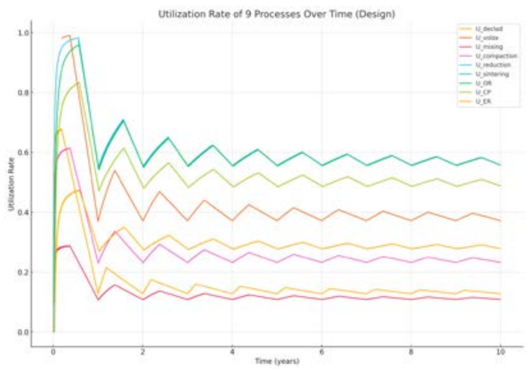

Fig. 2. Utilization of each unit process with designed values

The optimized simulation demonstrated a significant reduction in utilization variance, leading to a more balanced and efficient operation as shown in Figs 2-3. As a result, the system was able to achieve its target of operating for 200 days annually, ensuring a stable and efficient process flow as shown in Fig. 4. These findings provide crucial insights for the future design and operation of the integrated pyroprocessing system, particularly in scaling up to commercial levels.

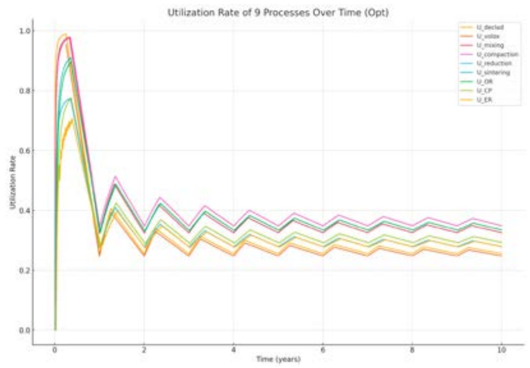

Fig. 3. Utilization of each unit process with optimized values

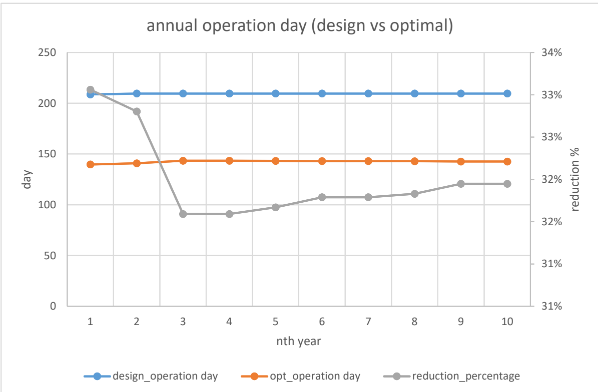

Fig. 4. Annual operational days and reduction rate based on designed and optimized number of operational units.

4. Conclusions

This study conducted a simulation-based analysis to address the line-balancing challenges in the integrated pyroprocessing operation. The results from the design-based simulation revealed that bottlenecks in certain processes, such as reduction, sintering and electrolytic reduction, led to inefficiencies in the overall system. However, through the optimization of process utilization, these bottlenecks were effectively mitigated, resulting in a more balanced and efficient operation. The optimized operational strategy ensures that the system also can meet its target of 200 operating days annually, providing a stable foundation for future scale-up and commercialization efforts.

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