Upgrades on High Reliability Safeguards Model for Material Throughput in Fuel Fabrication

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INTRODUCTION AND MOTIVATION

Pyroprocessing is an electrochemical technology for recycling used fuel to fabricate new metal-type fuels for an advanced reactor concept, such as a sodium fast reactor [1] or to burn long-lived actinides in used fuel to decrease its toxicity for eventual storage. Fuel fabrication is the last sub-process of this technology to manufacture final metal slugs for a new fuel cycle. The development of a high-reliability safeguards approach is imperative for fuel fabrication as it includes special nuclear material (SNM), which contains a substantial amount of Pu [2] and carries the potential diversion risk for use in a fissile explosive. Considering the different material composition of SNM when compared to contemporary fuel, a new quantitative safeguardability assessment was developed using a discrete event simulation (DES) modeling framework [1]. The model was testing if the probability of a false alarm (i.e., Type I error) [3] can be a metric for safeguardability.

The first build of a material throughput model was established for fuel fabrication in a commercial pyroprocessing facility [1]. The baseline design and the equipment design were modeled to determine if the false alarm probability can be used for quantitative safeguardability assessment. By testing if the simulated standard error of the inventory difference (ID) fell below a calculated value from the standard (a mathematical relationship used for safeguards), both designs were concluded to be essentially equivalent in terms of safeguardability. They brought effectively similar system output parameters such as material throughput, number of completed campaigns, and false alarm probability.

There exists substantial upcoming work to develop the model further. Current work now focuses on upgrades on nuclear material accounting (NMA) and operational considerations for safeguardability assessment. It is for integrating proliferation resistance to the facility by establishing a practical safeguards design approach. While the hazard and operation study is being conducted to optimize the model with operational goals [4], this paper addresses its modified logic as the core concept to object-oriented programming, developed to the point of being adjustable in removing and adding different key measurement points (KMPs), as part of facility design. Our motivation, therefore, is to take safeguards-by-design from concept to practical application by developing a design-motivated model to test safeguardability within this context.

BACKGROUND

DES Model Specifications

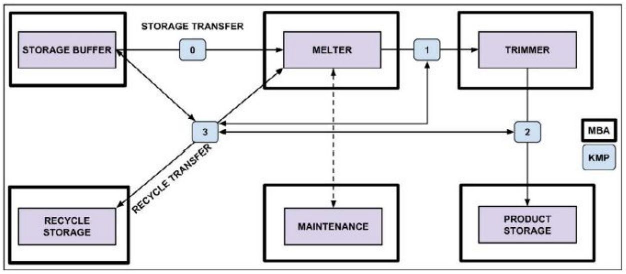

Figure 1. Baseline design of the DES model [1].

The DES model was developed based on the design of the fuel fabrication system (shown in Figure 1). This design, called the baseline design, contains the following vertices: (1) storage buffer, (2) melter, (3) trimmer, (4) product storage, and (5) recycle storage. The model passes the state variable (e.g., material weight) from vertex to vertex in time. We assume there are no changes between these vertices. In reality, the weight measurement is performed through KMPs indicated in Figure 1. The equipment design combines melting and trimming processes and removes KMP2.

Safeguardability Metric

The above two facility designs were tested with the new safeguardability metric. Herein, NMA was implemented at KMPs. The well-known relationship from [3] was used to calculate the standard error of the inventory difference (SEID) (Equation 1).

$$\Phi^{-1}(1-\alpha)+\Phi^{-1}(1-\beta)=\frac{SQ}{\sigma}\,, \tag{1}$$

where α is the false alarm probability, $1-\beta$ is the detection probability, SQ is the significant quantity of SNM, σ is the SEID, and Φ is the Gaussian function.

The simulated SEIDs were within the limit of the calculated SEID value of 2.4 kg for a significant quantity of 8 kg Pu given that α is 0.05 and $1-\beta$ is 0.95. Therefore, the two designs can both be used as a strong and well-established safeguardability evaluation model for the fuel fabrication process to operate safely excluding diversion attacks. We concluded these designs are essentially identical in terms of safeguardability since they produced analogous amounts of material throughput, completed similar numbers of campaigns, and provided comparable false alarm probabilities in the same operation time. The results and the system operation specifications are shown in detail in [1].

Object-Oriented Programming: Inheritance

Although these designs were successfully tested as a high-reliability safeguards metric, upgrades on NMA is critical for producing other distinct facility designs to deliver a more safeguardable model. Ease in adjusting KMP locations for NMA can be obtained by implementing object-oriented principles and developing a 'command and control' module to control material flow in the whole system. Object-oriented programming goes well with this model since fuel fabrication sub-processes are batch-type operations. An object created by a class for each sub-process accepts the batch, acts on it correspondingly, and passes it to the next vertex. Inheritance allows an object or a class to utilize all the properties and behaviors of a parent class [5-7]. A subclass, which is also called a child class, inherits functionality from a parent class.

MODEL STRUCTURAL CHANGES

The facility 'command and control' module, which describes the logic flow of the program run, is developed to create objects and to access classes' attributes and behavior methods. Inheritance is introduced so that all the functionalities from a parent class can be inherited by child classes (e.g., storage buffer, melter, trimmer, product storage, recycle storage, etc).

Removal of Redundant 'Command and Control' Classes

In the current, upgraded version of the code, some discrepancies between the established codes and intended physical operational goals induced removal of several 'command and control' modules previously built. We removed the 'command and control' modules called 'storage unit,' 'fuel fabricator,' and 'final storage unit', which were initially designed to control material flow in specific units. These modules are not practical in changing KMP locations for additional weight measurements or for reducing the total number of material balance areas. Therefore, only one module, which contains the facility 'command and control' class, was kept to control material flow in the whole facility.

The facility component class is inherited by other classes, which can utilize the methods or variables defined in it. This parent class and its major derived classes establish the hierarchical relation, as shown in Figure 2.

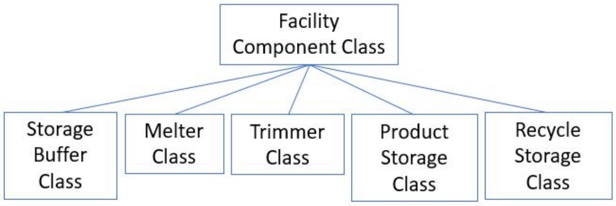

Figure 2. Hierarchical relation between the base class and its derived classes

Besides the child classes mentioned above, the edge transition class and the key measurement point class also inherit functionalities from the facility component class.

CLASS DEVELOPMENT

This paper only addresses the advanced features added to the previous model.

- **Key measurement class:** Two different ID checkup functions are defined. The default function is for KMP1 and KMP2 while the other is for KMP0 and KMP3 under certain conditions. If the measured ID is larger than the expected ID, and the difference between them is above the alarm threshold, then the material weight is measured a total of three times. By taking the average of these data, the new discrepancy between the measured ID and the expected ID is checked again. If it still follows the same condition as the first checkup, the material is moved to recycle storage. If the expected ID is larger than the measured ID, and their difference is above the threshold, an alarm is triggered, and then the material is moved to recycle storage.

- **Facility command class:** It is to command the whole process from batch preparation to material storage. It also utilizes if-else statements and dummy variables to determine whether the material is successfully processed and stored in the product storage or is stored in the recycle storage for further inspection. Moving the heel and the batch temporarily to a recycle storage for the melter inspection is also considered when the melter fails.

RESULTS AND DISCUSSION

The campaigns for fuel fabrication were produced for 250 days. The alarm threshold for each KMP was given as 0.3 kg, and the KMP measurement error (σ_{meas}) was set at 0.1 kg. The melter failure rate (λ) was 1/30 days. Figure 3 describes the relation between the number of false alarms and the operation time. A total of 58 false alarms were triggered during the operation.

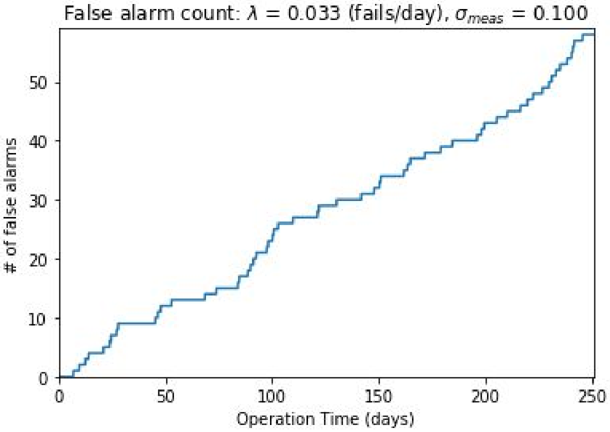

Figure 3. The number of false alarms vs. the operation time (alarm threshold: 0.3 kg)

By modifying the alarm threshold to 0.1 kg, the total number of false alarms increased extraordinarily. More than 200 alarms were inspected, which is shown in Figure 4.

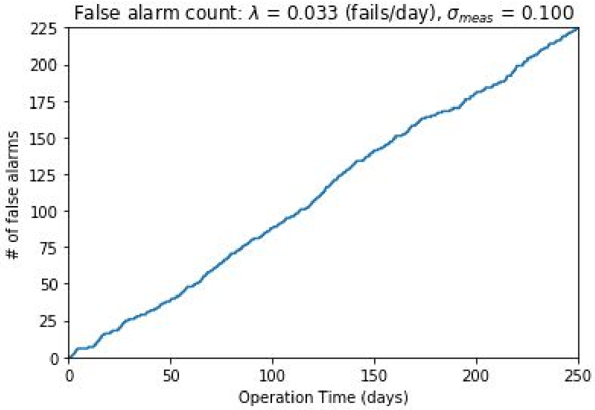

Figure 4. The number of false alarms vs. the operation time (alarm threshold: 0.1 kg)

By increasing the alarm threshold to 0.5 kg, the number of false alarms triggered during 250 days decreased (Figure 5).

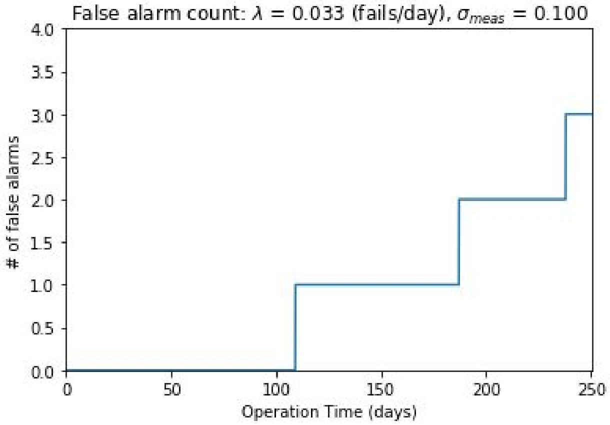

Figure 5. The number of false alarms vs. the operation time (alarm threshold: 0.5 kg)

Therefore, the alarm threshold for each KMP has to be set up appropriately for the facility operation to satisfy its goals while the high reliable safeguards are applied to detect diversion attempts.

While the previous model could not modify KMPs easily, at present, the model is ready to locate new KMPs to test if more safeguardable models can be induced. This offers a flexibility in facility design, allowing different configurations to be tested for safeguardability. Despite the addition of advanced features of ID checkup at each KMP--several ID measurements to increase the accuracy and precision of the data, development of a distinct ID checkup function for each KMP, and the advanced algorithms for raising false alarms--the trends of raising false alarms during 250 days of operation, given different alarm thresholds, are similar to those from the first-build model. Clearly, more false alarms were triggered from the KMPs when a high threshold was given.

CONCLUSION AND UPCOMING WORK

Several 'command and control' modules for specific units were removed, so KMP locations can easily be modified to assess the safeguardability model with different NMA locations. Additionally, we incorporated more accurate ID checkups with thorough weight measurement and intensive algorithms for raising false alarms.

In the future, material balance of measured weights might be performed at the end of a campaign, and it needs to implement new concepts related to system alarms, which are different from false alarms. When moving material from KMP0, KMP1, or KMP2 to KMP3 (which is for storing material in the recycle storage), a robust algorithm for weight discrepancy checkup may be introduced by adopting the Page's test. The sensitivity analysis associated with alarm thresholds and measurement uncertainties is also recommended for further study.

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