Plant Level Framework for Material Flow in a Nuclear Reprocessing Facility

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Keywords: Plant Level Framework, Spent Nuclear Fuel Reprocessing, Pyroprocess, Mass Balance, Discrete Event Dynamic System.

Abstract: A plant level framework has been developed for a nuclear recycling facility. A plant level model generally consists of multi-tiered models. The bottommost tier is a unit process model regarding electro-chemical phenomenon. The middle tier is an operation model regarding mechanical handling of the process equipment. The topmost tier is a systemic integration in the level of the plant. Even though a unit process model is fundamental to build higher tier models it takes time to make a model with high fidelity. Therefore, a different strategy for a plant level model building is suggested in this study. One of the important issues that nuclear recycling process must consider is dynamic material flow, which could be done with the help of a unit process model. However, from plant level aspect, it can be simply obtained from mass balance sheet rather than understanding of electro-chemical behavior during process time. A plant level framework was suggested to be able to include dynamic material flow even without a unit process model. Thus, a more reliable unit process model can be added later selectively. The characteristic of the current framework was addressed and evaluated for further improvement. The current version of the plant-level-framework could provide many unforeseeable results which are difficult to obtain by intuition. Nevertheless, the next version will include more function to provide various analyses linked with other nuclear related codes.

1 INTRODUCTION

Next generation nuclear fuel cycles require innovative features such as an environmental load reduction, safety, efficient recycling of resources, nuclear proliferation resistance, economics, and so on. From these viewpoints, a pyrometallurgical processing of spent fuel is now considered as one of the most promising options for future nuclear cycles in Korea (Kim, 2006). KAERI has been developing pyroprocess technologies, which could reduce the increasing amount of spent nuclear fuel and dramatically decrease the disposal load, through recycling and destroying toxic waste such as the long-life fission products in spent nuclear fuels (You, 2007).

Pyroprocessing technology has not been fully demonstrated in terms of comercialization and technology maturity. In order to navigate the right direction of pyroprocessing technology development, demonstration in an integrated facility is centainly a tangible solution but is too costly and time consuming to construct a fully integrated facility including all unit process and remote handling equipment. Therefore, technolgoy assessment and breakthrough by modeling and simulation would be preferable. Plant modeling and simulations are now widespread among the manufacturing, semi-conductor, steel and refinery industries. However, they focus on layouts, assembling, automation and remote control of the process flow.

Currently, there is niether commercialized nor integrated pyroprocessing facility around the world. KAERI is constructing an integrated demonstration facility and thus expect to contribute to boost up pyroprocessing technology and step toward realization of spent nuclear fuel recyling. Nevertheless, pyroprocessing technology is confronted by many problems which are awaiting solutions at the moment.

Expected potential benefits of modeling and simulation in the field of nuclear reprocessing system include the following: reduced cost of process and facility development, optimized system designs and reduce risk of material diversion. Actually, modeling and simulation enhance

Jik Lee H., Il Ko W. and Soo Lee H..
Plant Level Framework for Material Flow in a Nuclear Reprocessing Facility.
DOI: 10.5220/0004056703770383
In *Proceedings of the 2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2012), pages 377-383
ISBN: 978-989-8565-20-4

understanding of known systems, provide qualitative and quantitative insights and guidance for experimental work and produce qunatitative results that replace difficult, dangerous or expensive experiments (DePaoli, 2011).

The pyroprocessing contains various unit processes and various types of nuclear materials that flow in and out of those unit processes. It is a batch type process in overall terms, i.e., reciept and shipment of material among unit process, however, unit process itself features continuous chemical or electro-chemical process. Unit process may have a different batch capacity and different processing time. Also, there is feedback of output material on a unit process into a prior unit process. In addition, nuclear elements may take different routes as the process goes on. Due to this complexity, it is difficult to understand the dynamic behaviors of the material flow in the pyroprocess. With this background, this study was undertaken. Simple material flow in the pyroprocess can be easily understood by static mass balance. However, a simple material flow based on the static mass balance cannot give insight into any dynamic behavior of the material flow because it cannot take into account changes according to time and event.

An EXCEL-like software is widely used to establish the static mass balance of the overall process but it is very restrictive to implement a dynamic material flow in the pyroprocess. In this study, a modeling and simulation tool for discrete event dynamic system (DES), ExtendSim was utilized for the plant level framework of a dynamic material flow. The pyroprocess was modeled as DES in this work and then a dynamic material flow was simulated under the framework.

2 R&D STATUS

2.1 The U.S.

Motivated by the challenges and needs in nuclear energy systems that can be addressed bymodeling and simulation, the Office of Nuclear Energy of the U.S. Department of Energy hasarticulated a vision for a Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.NEAMS is aimed toward building on the success of recent programs in advanced scientificcomputing, namely, ASCI and SciDAC, with a focus on very different challenges. Thesechallenges include the need for nuclear energy systems to be licensed by regulators andmoving advanced technologies out of the research environment and into the hands of theengineers who will design, build, and operate the new nuclear energy systems. NEAMS will provide a comprehensive solution and is organized into the following five elements:

- Integrated Performance and Safety Codes (IPSC) end-to-end codes to understand the detailed, integrated performance of new nuclear systems including the following: Nuclear Fuels, Reactor Core & Safety, Separations and Safeguards, Waste Forms and Near-Field Repositories.
- Fundamental Methods and Models
- Verification, Validation, and Uncertainty Quantification
- Capability Transfer Enabling Computational Technologies

Through the NEAMS-IPSC, the U.S. is devoting to develop reprocessing plant level toolkit named RPTk (Reprocessing Plant Toolkit), which uses open source platform to accormodate legarcy codes accross the U.S. (McCaskey, 2011). RPTk implements a data flow architecture that is the source of the system’s extensibility and scalability. Data flows through physicochemical modules sequentially, with each module importing data, evolving it, and exporting the updated data to the next downstream module. This is accomplished through various architectural abstractions designed to give RPTk true plug-and-play capabilities.

2.2 Japan

A decade ago, Japan developed an analysis code (Okamura, 2002) using the object-oriented software ExtendSim for the estimation of material balance for the system design of the pyrochemical reprocessing plants consisting of batch processes. This code can also estimate the radioactivity balance, decay heat balance and holdup, and easily cope with the improvement of the process flow, and so on. The study describes the outline of the code and estimation of the material balance in the oxide electrowining reprocessing system under consideration of the solvent recycling time. Howerver, it is difficult to find out current activity with respect to modeling and simulation spent fuel recyling facility in japan.

2.3 Korea

In order to analyze operational issues in a pyroprocessing head-end facility, discrete event modeling approach was applied (Lee et al., 2009). Also, a code development study on the dynamic material flow in the integrated pyroprocess was carried out (Lee et al., 2011) under the discrete event system environment. This paper addresses the plant level framework in detail including the previous dynamic material flow study.

3 REQUIREMENT

3.1 Nuclear Facility

A nuclear facility deals with radioactive material and the recycling facility can have various types of material since nuclear spent fuel consists of various nuclear fissile elements. Specifically, integrated pyroprocess facility has a lot of unit process equipment, remote handling device and various utility, which need to be appropriately maintained and repaired for machine failure.

Receipt and shipment of nuclear material and remote operation of process equipment are considerately designed in terms of safety and efficiency. Also, safeguards study to prevent nuclear material diversion is critical issue in design stage. Current version of plant level framework does not include safeguards module, but later version will consider including it.

3.2 Facility Code Requirement

Simulation code for pyroprocessing facility is required to have the following features:

1. Modularity

Modularity means re-useable code. Some libraries or blocks can be frequently re-useable within a plant model. For example, dynamic mass balance calculation algorithm is needed to calculate processed quantity in any unit process during simulation.

2. Flexibility

Flexibility means the code can be modifiable in easy way. For example, if more reliable unit process has been built, it can be replaced with old one without many modifications of code. Also, additional function or module could be attached in a way that main framework or top tier model does change minimally or does not change by taking interface with additional module into consideration.

3. Database management

Database management is very important issue in terms of nuclear element management. Recycling facility starts with spent nuclear fuel having many element, which changes its form, radioactivity and amount according to process flow. There are three types of data as follows: input data, output data, and log data. Input data are for example, changeable process conditioning parameters. It influences simulation results. Output data can be simulation results related data, for example, product amount, buffer accumulation and waste generation. Data logging is important to keep and store time dependent information, and see and analyze those after simulation. For example, status of unit process, operation records, resource utilization and all output data can be log data.

4. Interface with other platform code

There exist many legacy codes developed in other software platforms. Specifically, unit process model has been generally generated by using other conventional platform such as C/C++, FORTRAN, and matlab according to modeller's preference. Therefore, integration of different codes could be an issue on plant-level-code development.

5. Reliability enhancement strategy

In order to enhance model and well estimate reality, model validation must be performed with a lot of experimental data. Throughout comparison with various real cases, model could be enhanced. Therefore, validation can be easily carried out by visualization of analysis results.

3.3 Plant-level Code Configuration

Plant-level-model includes all lower models together with various modules. The unit process model is surrounded by unit operation model describing feeding and takeout of material in that process and then material streams among unit process are completed by integrated operation model which can describe the shipment of material.

Also, in the integrated modelling stage, resources such as remote handling device, human, vessel and storage are allocated to unit process according to necessity and withdrawn after the task is finished. All items taken out of and fed into unit process are treated in the unit of batch capacity of unit process. If two sequential unit processes have different batch capacity, the item taken out of the first unit process has to be changed to meet the batch capacity of the next unit process. Material streams indicate where items must flow into and thus connectors and lines must be designed according to material streams.

Discrete event modelling might handle the above issues without difficulty. The plant-level-model also has to include three functions: analysis, database management and visualization. They could be modularized and developed in many ways. For example, DB can be remotely far from ExtendSim and just linked with ExtendSim.

4 PLANT LEVEL MODEL

4.1 3-tiered Modelling Architecture

In order to build plant-level-model, 3-tiered code development architecture was invented in KAERI. The bottom tier is unit process modeling which includes electro-chemical model influencing output chemical composition. The middle tier includes unit and integrated operation model which describes operation behavior such as feeding, transporting and other mechanical operations from unit or integrated process ascpect, resptectively. The top tier is the plant-level-model, which must have various analysis modules, and DB module for SNF and isotope inventory. It also have to show the results, intuitively through well designed visualization module.

4.2 Basic Framework

Without reliable unit process model, it is too difficult to build upper tier model. Currently electrochemical process is not well described by model and must be enhanced further. It is alike wasting time to wait until the reliable unit process model is built. Furthermore, most part of the middle and top tier model can be built without the unit process model. Given feeding material composition and its amount, unit process model presents generally output composition of element after electrochemical reaction. Noticing that expected values of output composition could be set by target values in an equilibrium mass balance sheet, the calculation of dynamic mass balance per batch operation in unit process might be alternative of unit process model. Even though equilibrium mass balance means total input and output mass balance in each unit process at a certain time, it can be broken down by unit of each batch operation capacity of unit process according to each batch time and it can be made to present dynamic mass balance. The current version of plant level framework was tested by using dynamic mass balance calculation algorithm without unit process model. However, the framework could selectively include the unit process model or dynamic mass balance calculation algorithm when the reliable unit process model is prepared.

Figure 1: Three tiered code development architecture.

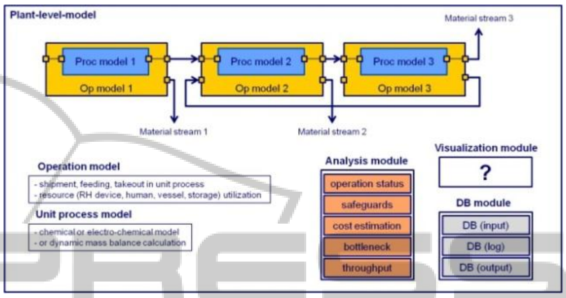

Figure 2: Configuration of plant-level-framework.

4.3 Dynamic Material Flow

Pyroprocess consists of a dozen of unit process and various material streams among them as shown in Figure 3. Material streams in pyroprocess are classified into two categories: nuclear spent fuels and two kinds of salt (LiCl and LiCl-KCl). First feeding material of pyroprocess is spent nuclear fuel from nuclear reactor in the form of assembly and final product is volatile FP (fission product), metal waste, ceramic waste, uranium metal ingot and TRU (transuranium) for fast reactor fuel fabrication. Every time process proceeds to next step, many things (processed mass, buffer accumulation, the number of batch operation, etc.) are changed according to time. In order to capture such dynamic characteristic related to material flow, discrete event based dynamic mass balance calculation (Lee et al., 2011) is needed in case where a target mass balance is set by equilibrium state at a specific instance in time.

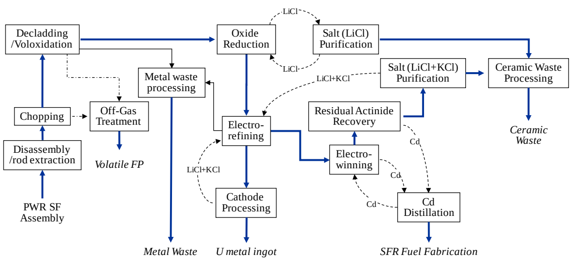

Figure 3: Pyroprocess material streams.

The following equation addresses the processed amount of mass in process P_j given the voloxidation equivalent batch capacity of process P_j and the amount of shipment according to path from process P_i to process P_j.

$$P^{P_j}(e) = \frac{{}^{ve}C_b^{P_j}}{{}^{ve}C_b^{vol}} \frac{C_b^{vol}}{C_e^{vol}} \sum_i N^{P_i \to P_j}(e) \cdot C_e^{P_i \to P_j}$$

where

$P^{P_j}(e)$: the processed amount of mass in process P_j, and it depends on event.

${}^{ve}C_b^{P_j}$: the voloxidation equivalent batch capacity in process P_j, which means the mass of material that the voloxidation process must treat in order to supply the process P_j with feed material for one batch of the process at full capacity.

${}^{ve}C_b^{vol}$: the voloxidation equivalent batch capacity in voloxidation process, i.e., voloxidation batch capacity.

C_b^{vol}: the actual processed mass per batch in the voloxidation process, which is equal or less than ${}^{ve}C_b^{vol}$.

C_e^{vol}: the equilibrium processed mass in the voloxidation process, which is the processed mass by a certain time (generally, one year).

$N^{P_i \to P_j}(e)$: the number of shipment of product from process P_i to process P_j and it depends on event.

$C_e^{P_i \to P_j}$: the equilibrium mass transferred according to path from process P_i to process P_j by a certain time (generally, one year).

In the above equation, the voloxidation equivalent mass is convenient when the operational relationship among process is needed to define. The reference process where equivalent mass is calculated can be randomly selected but the preceding process is preferred.

In the equation, by the law of conservation of mass, the following property can be induced.

$$\sum_i C_e^{P_i \to P_j} = \sum_k C_e^{P_j \to P_k} = C_e^{P_j}$$

$$P^{P_j}(e) = \sum_i P^{P_i \to P_j}(e) = \sum_k P^{P_j \to P_k}(e) + \text{residual}$$

where

$P^{P_i \to P_j}(e)$: the amount of shipment from process P_i to process P_j by a specific instance in time, i.e. by the time when event e happens.

residual: the amount of hold-up remains in the process P_j without leaving for the process P_k.

The above equation means the feeding and leaving amount are the same without hold-up in unit process in equilibrium state and it is the processed amount in that process. However, before the equilibrium state, the processed amount in unit process is equal to a total of feeding material but not equal to a total of leaving material.

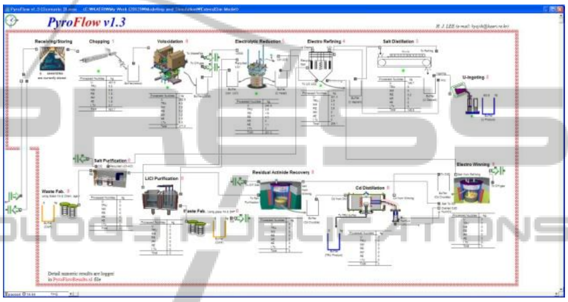

Figure 4: Top window of pyroprocessing plant model.

5 RESULTS AND DISCUSSIONS

5.1 Top Model Design

Figure 4 presents the top model just embrassing operation model and dynamic mass balance calculation algorithm. It shows basic information of material flow by means of visualizaiton through animation which indicates text and picture information changes according to time.

Multi-tiered model architecture might be simply represented on the model by hierarchy. Complex details corresponding to lower tiers could be hidden and on top window only a little information might be displayed. For example, electrolytic reduction process wants U_3O_8 powder and recycled or fresh LiCl salt as feeding material, and pushes output material into temporary buffers every batch operation. Basic information that unit process block includes is input connectors, output connectors, buffer accumulation, processed quantity, the number of batch operation and operation status as shown in Figure 5.

The input and output connectors with names indicate types of the feeding material and output product, respectively. The buffer might be real or imaginary but most pyroprocessing unit is operated in batch type so it is important to have sufficient storage between unit processes to prevent being stuck. The buffer accumulation is animated with the level of tank. The table below the picture icon indicates processed quantity of grouped element which changes dynamically. On the right side of the process name, the number of batch operations is displayed up to now, which is also changed dynamically according to event. The last information of unit process block is operation status, which classified into three kinds: in operation, in breakdown and out of order. The above information is much enough to deliver what happens in the unit process to user during simulation.

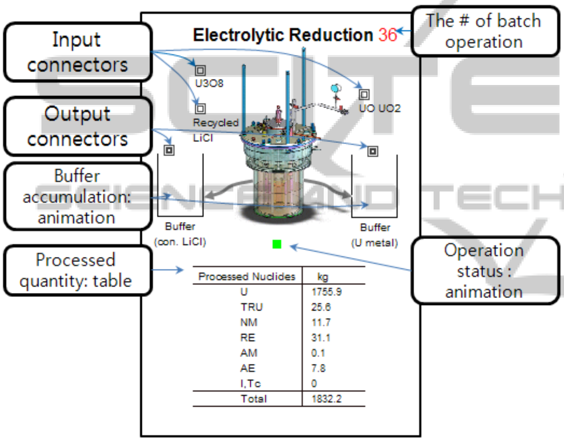

Figure 5: Configuration of unit process block on the plant level top window.

However, detailed numeric results obtained from simulation might be stored in external database management software such as EXCEL, ACCESS and SQL. Specifically, log data describing history statistics for simulation time should be stored in the above mentioned DB SWs. Also, numeric results must be shown in easy ways by using charts and graphs. The more data are generated, the greater care should be devoted to visualization in consideration of what users should look at and how efficiently results could be shown.

5.2 Function of Current Version

For more realistic simulation, it is assumed that unit process is possible to be out of order. Besides, many factors are assumed since real facility has not been developed. Process time, failure rate, batch capacity, the number of equipment and the arrival of spent nuclear fuel are assumed on the basis of experimental experience or achievable goal based on the current level of technology, otherwise, set by design goal.

In the current version of framework, results are exported to EXCEL and displayed on charts in real time since it is fast enough to treat limited data. However, the more data might require more efficient DB management SW other than EXCEL. Figure 6 shows results able to be displayed in the current version. The processed mass of grouped element or total heavy metal of spent fuel is displayed being classified by unit process. The number of batch operations tells us which process is late determining process or bottleneck process during simulation time. The buffer accumulation indicates that the facility has a minimum size of buffer storage to temporarily accommodate product to be sent to the next process. Also, product and waste mean final output in the pyroprocess, which will be sent to metal fuel fabrication facility for recycling and to an interim storage facility for disposal.

The framework will be more modularized in the next version to include much more control function and information and to be simplified in the top window. Also, material flow will be broken down from element level into isotope level, which means over 1,000 isotopes must be tracked according to time and event. In addition, the plant-level framework will be enhanced to be linked with other nuclear related codes for decay heat, isotope composition, criticality and radioactivity calculation if necessary. Regarding DB, restructuring might be needed in order to manage more data at high speed.

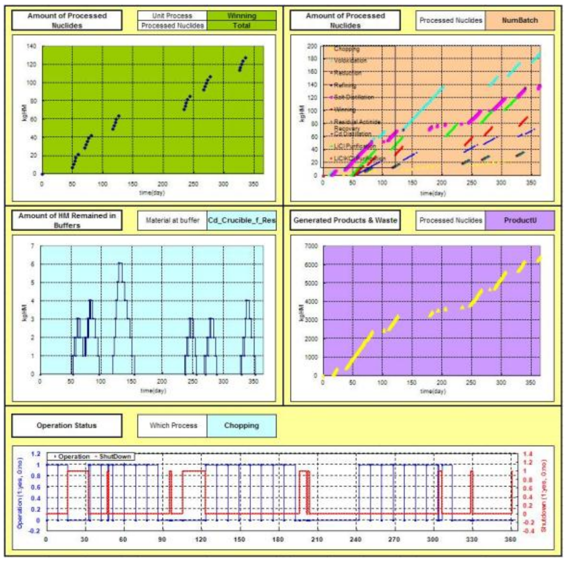

Figure 6: Analysis results able to be obtained from current version of plant level model.

6 CONCLUSIONS

Plant-level framework consisting of 3-tiered model with some functional modules was suggested for pyroprocessing facility. Current version of framework includes basic function for material flow analysis. One of important characteristic in the current version is that dynamic mass balance calculation is possible even without unit process model. It can make us estimate integrated material flow in the pyroprocessing facility. The plant model framework will be improved to satisfy facility code requirement and to provide various analysis linked with nuclear related codes. Modelling and simulation for pyroprocessing facility is expected to save construction cost and reduce design error, finally devote generation of design requirement for engineering scale or commercialized scale facility.

ACKNOWLEDGEMENTS

This work was supported by Nuclear Research & Development Program of National Research Foundation of Korea (NRF) funded by Ministry of Education, Science & Technology (MEST).

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