A Nuclear Material Accounting Simulation Model for Reprocessing Facility

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ABSTRACT

Near Real Time Accounting is an approach of nuclear material accounting for reprocessing facilities. Compared with traditional accounting methods, it requires additional measurement points. A simulation model that integrates both NRTA and traditional method is constructed as a test bed to find cost-effective strategies for implementing NRTA and meeting regulatory requirements. The simulation results show that NRTA is an effective nuclear material accounting method for reprocess plant.

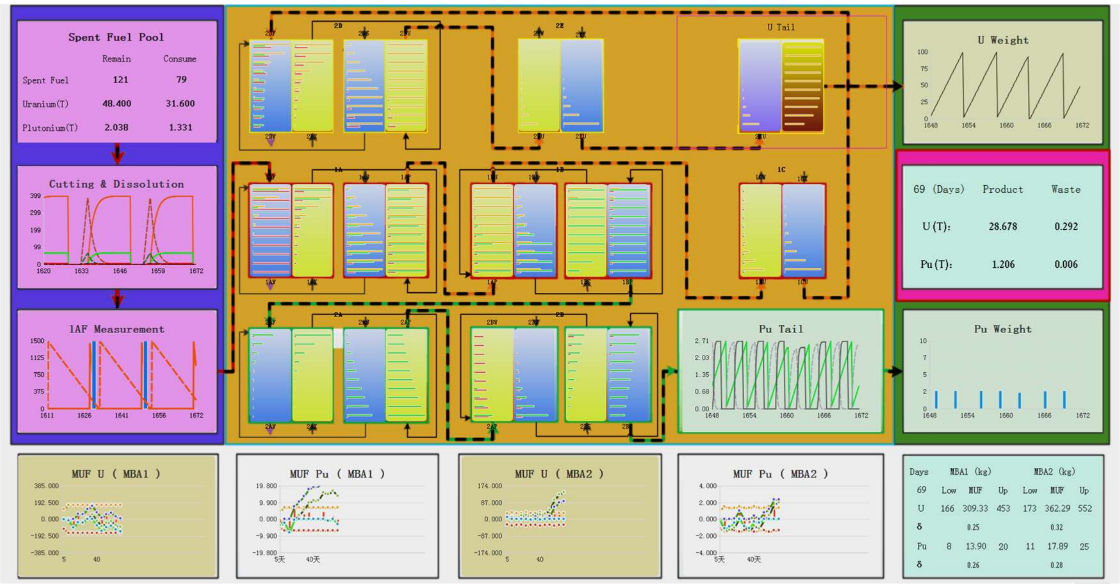
INTRODUCTION

The Nuclear Material Accounting in spent fuel reprocessing plants is crucial for Nuclear Security and Safety, but traditional accounting method face challenges when dealing with large scale processing capabilities [1][2]. A large reprocessing plant with large amount of material flow makes its MUF difficult to stay below material accounting goals [3]. On the other hand, half or one year period PIT is too late to respond to material abnormal scenario. The Near Real Time Accounting is an approach to solve the problems, which calculates the MUF during the reprocessing without disturbing the production process and taking the material in process into consideration [4].

A Nuclear Material Accounting Simulation Model has been developed at China Institute of Atomic Energy, which can serve as the NRTA methodology testing bed to be implemented in the reprocessing facility with the help of the experts from Sandi National Laboratory in the United States. Secondly, it can be used to find the most cost-efficient way to implement measurement instruments so that the MUF precision meets the regulatory requirements. Finally, it is a design tool to implement the philosophy of safeguard by design in the future reprocessing facility development.

MODEL STRUTURE

In order to simulate the PUREX process and demonstrate the inner dynamic extraction process, the Qt programing platform is employed to code the model with C++. The model interface is shown in figure 1. The left 3 blocks on top of blue background are the diagrams of front end, including spent fuel storage, cutting, dissolving and 1AF measurement. The 9 blocks on top of yellow background are inner animation of the PUREX process, comprising extractor of 1A, 1B, 1C, 2A. 2B, 2C, 2D, Uranium and Plutonium tail end. The right 2 blocks on top of green background are the curves of Uranium product and Plutonium product measurement respectively. The bottom 5 blocks are Uranium MUF of MBA1, Plutonium MUF of MBA1, Uranium MUF of MBA2, Plutonium MUF of MBA2 and the traditional MUF evaluation respectively.



Spent Fuel Pool

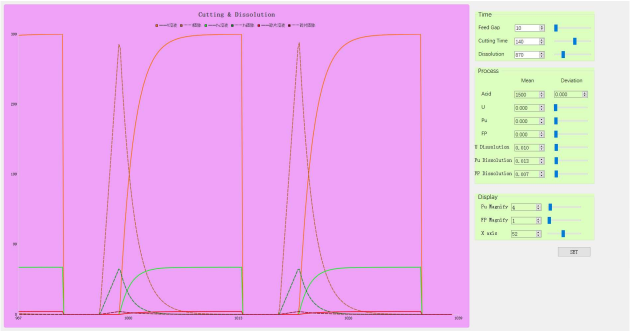
	Remain	Consume
Spent Fuel	121	79
Uranium(T)	48.400	31.600
Plutonium(T)	2.038	1.331

69 (Days)	Product	Waste
U (T):	28.678	0.292
Pu (T):	1.206	0.006

Days	MBA1 (kg)			MBA2 (kg)		
69	Low	MUF	Up	Low	MUF	Up
U	166	309.33	453	173	362.29	552
δ		0.25			0.32	
Pu	8	13.90	20	11	17.89	25
δ		0.26			0.28	

Figure 1 Reprocess Plant Model

Inside the model, a standard C++ template vector is employed to represent the elemental composition of spent fuel. Currently, only three elements (uranium, plutonium and fission products, other elements can be added later) are included. The time step in the model is set to one minute. The spent fuel cutting and dissolving sub-model runs the simulation logic every step as a minute process. The curves inside the block in figure 2 show Uranium, Plutonium and Fission Products dissolving over time respectively (the ratio of Plutonium is enlarged by a factor). The dissolution rate of each composition can be changed separately any time along the simulate.



Time

Feed Gap: 10
Cutting Time: 140
Dissolution: 870

Process

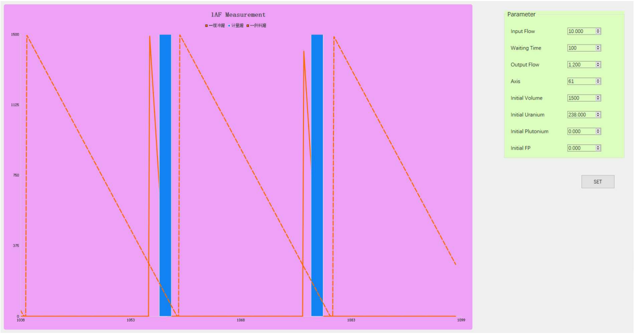
	Mean	Deviation
Acid	1500	0.000
U	0.000	
Pu	0.000	
FP	0.000	
U Dissolution	0.010	
Pu Dissolution	0.013	
FP Dissolution	0.007	

Display

Pu Magnify: 4
FP Magnify: 1
X axis: 52

Figure 2 The Spent Fuel Cutting & Dissolving Sub-model

The curve in figure 3 shows the quantity of the 1AF in feeding tank changing with time and the bar graph indicates every volume measurement of the 1AF.

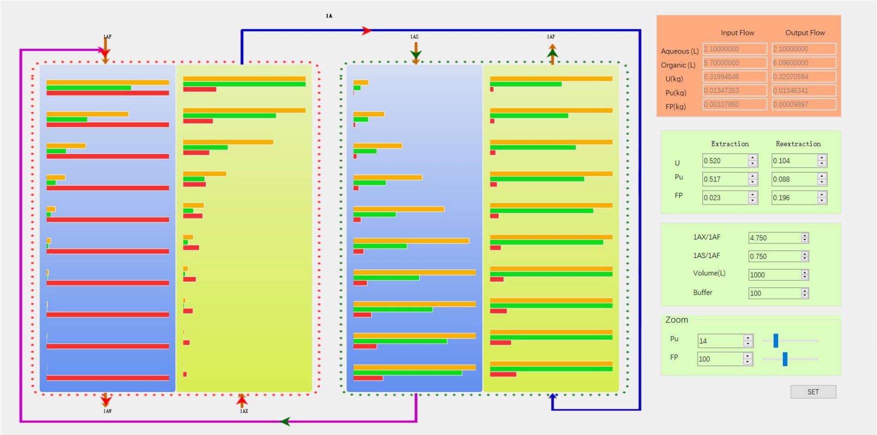


Parameter

Input Flow: 10.000
Waiting Time: 100
Output Flow: 1.200
Axis: 61
Initial Volume: 1500
Initial Uranium: 238.000
Initial Plutonium: 0.000
Initial FP: 0.000

Figure 3 1AF Measurement in Feeding Tank

The 1A sub-model in Figure 4 is the fission product decontamination extractor and re-extractor, including the four columns from left to right representing the aqueous and organic phases in the extractor and that in re-extractor, respectively. The U, Pu and FP are represented in yellow, green and red bar respectively, in which the length stands for the extraction state at each location. When the extraction and re-extraction parameter changed, the bar is changed based on calculation. The other sub-models of PUREX process following the same algorithm.



	Input Flow	Output Flow
Aqueous (L)	2.10000000	2.10000000
Organic (L)	5.70000000	6.09600000
U(kg)	0.31994846	0.32070594
Pu(kg)	0.01347353	0.01346341
FP(kg)	0.00337860	0.00009897

	Extraction	Reextraction
U	0.520	0.104
Pu	0.517	0.088
FP	0.023	0.196

1AX/1AF 4.750
1AS/1AF 0.750
Volume(L) 1000
Buffer 100

Pu 14
FP 100

Figure 4 Fission Product Decontamination Extractor & Re-extractor

MATERIAL ACCOUNTING

Traditionally materials accounting of a reprocessing facility uses uranium and plutonium measurements of the input accounting minus that of product and that in the waste stream. This approach cannot achieve material balance until the flow in the plant stop and flush-out the materials inside the system. This is the reason that the accountability requires periodic plant flush-outs, which not only decrease the production capacity, but also impossible to detect materials lost like leaks in short time.

A reprocessing facility can avoid these problems if the Near Real Time Accountancy can be integrated into the system, which requires additional measurement points with certain precision. With this model, we can calculate lots of parameter combination to find out an optimal design with acceptable accuracy and cost-effectiveness. On the right side of figure 5a there is a list of optional measurement points with adjustable parameter of random and systematic error in PUREX process, while on the left side the red bars indicate the MUF results of each period of material accountancy. The double line above and below the bars are the plus and minus 2σ uncertainty of the current MUF calculated from current measurements uncertainty combinations. With this model operators can get different MUF result from different parameter combinations.

MODEL RESULTS

Assuming that there are 200 spent fuel assemblies ready for reprocessing, each of which contains 400kg uranium, the composition of U, Pu and FP is 95%, 4% and 1%, respectively. The spent fuel dissolution time is set to 24 hours, and only one dissolution tank is used, which causes the plant to take about 200 days to complete the reprocessing and perform the final MUF calculation.

A set of NRTA MUF results (figure 5a) is obtained after the simulation finished. When unselecting all the measurement points except 1AF, uranium and plutonium products and that of waste, traditional accounting results (figure 5b) are calculated, where a large deviation in the material balance occurs at startup due to material building up. The material is released at the end when the system flush-out. While using NRTA (Figure 5a), the deviation is not present because the measurements determine the in-process materials.

Material Accounting

Gap(days) 5

MBA2 (Pu)

☑ MUF ☑ +2σ ☑ -2σ

☑ 累计MUF ☐ page+ ☐ page-

Page Test

K-2P 0.200

Pu Measurements[%]

Points		Random Error	System Error
1AF	☑	0.50	0.20
1AF Volume		0.05	0.10
Pu	☑	0.20	0.10
Pu Weight		0.05	0.05
Waste	☑	10.00	0.00
Waste Volume		1.00	1.00
1AF Feed	☑	5.00	3.00
1A	☑	5.00	3.00
1B	☑	5.00	3.00
1C	☑	5.00	3.00
2D	☑	5.00	3.00
2E	☑	5.00	3.00
2A	☑	5.00	3.00
2B	☑	5.00	3.00
Pu Tail	☑	5.00	3.00
Product We	☑	5.00	3.00

Figure 5a The Near Real Time Accounting Result of Plutunium in MBA2

Material Accounting

Gap(days) 5

MBA2 (Pu)

☑ MUF ☑ +2σ ☑ -2σ

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Page Test

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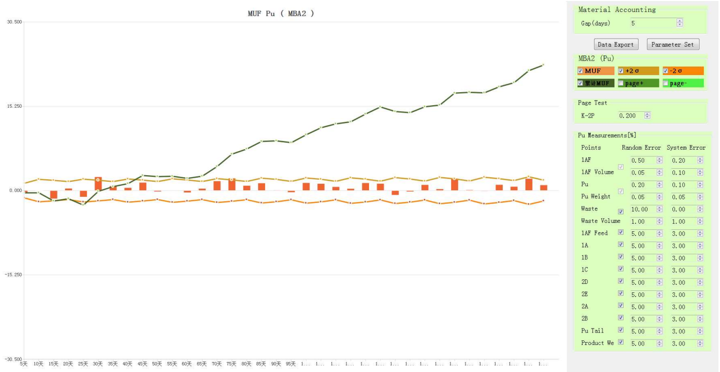
Pu Measurements[%]

Points		Random Error	System Error
1AF	☑	0.50	0.20
1AF Volume		0.05	0.10
Pu	☑	0.20	0.10
Pu Weight		0.05	0.05
Waste	☑	10.00	0.00
Waste Volume		1.00	1.00
1AF Feed	☑	5.00	3.00
1A	☐	5.00	3.00
1B	☐	5.00	3.00
1C	☐	5.00	3.00
2D	☐	5.00	3.00
2E	☐	5.00	3.00
2A	☐	5.00	3.00
2B	☐	5.00	3.00
Pu Tail	☐	5.00	3.00
Product We	☐	5.00	3.00

Figure 5b The Traditional Accounting Result of Plutonium in MBA2

A material diversion scenario (figure 6a) with 0.6% of Pu lost is set to take place at 1000 hours of the simulation, after that the NRTA MUF is biased towards positive value. The green line, the accumulation of the MUFs, rises rapidly indicating that a Pu lost scenario happens. By unselecting all measure points except 1AF, uranium and plutonium products and that of waste, traditional accounting (figure 6b) is shown, where the cumulative line rising slow hardly indicating Pu lost.



Material Accounting

Gap(days) 5

MBA2 (Pu)

☑ MUF ☑ +2σ ☑ -2σ

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Page Test

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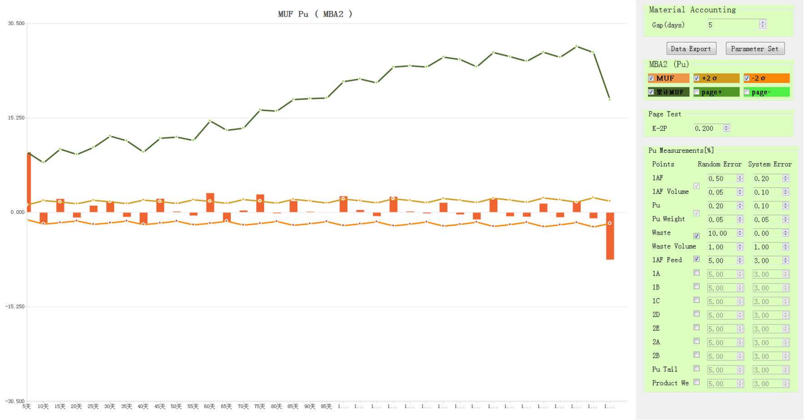
Pu Measurements[%]

Points		Random Error	System Error
1AF	☑	0.50	0.20
1AF Volume		0.05	0.10
Pu	☑	0.20	0.10
Pu Weight		0.05	0.05
Waste	☑	10.00	0.00
Waste Volume		1.00	1.00
1AF Feed	☑	5.00	3.00
1A	☑	5.00	3.00
1B	☑	5.00	3.00
1C	☑	5.00	3.00
2D	☑	5.00	3.00
2E	☑	5.00	3.00
2A	☑	5.00	3.00
2B	☑	5.00	3.00
Pu Tail	☑	5.00	3.00
Product We	☑	5.00	3.00

Figure 6a The NRTA Result of Pu lost taking place at 1000 hours in MBA2



Material Accounting

Gap(days) 5

MBA2 (Pu)

☑ MUF ☑ +2σ ☑ -2σ

☑ 累计MUF ☐ page+ ☐ page-

Page Test

K-2P 0.200

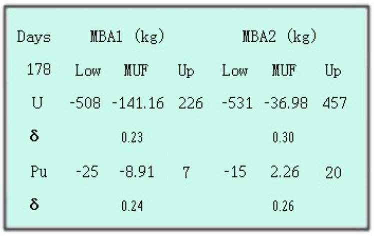
Pu Measurements[%]

Points		Random Error	System Error
1AF	☑	0.50	0.20
1AF Volume		0.05	0.10
Pu	☑	0.20	0.10
Pu Weight		0.05	0.05
Waste	☑	10.00	0.00
Waste Volume		1.00	1.00
1AF Feed	☑	5.00	3.00
1A	☐	5.00	3.00
1B	☐	5.00	3.00
1C	☐	5.00	3.00
2D	☐	5.00	3.00
2E	☐	5.00	3.00
2A	☐	5.00	3.00
2B	☐	5.00	3.00
Pu Tail	☐	5.00	3.00
Product We	☐	5.00	3.00

Figure 6b The Traditional Accounting Result of Pu lost taking place at 1000 hours in MBA2

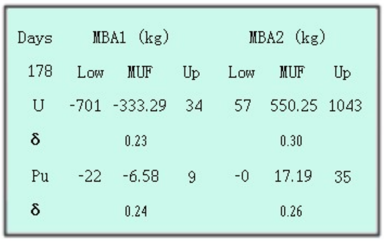
The final MUF calculations of both normal and diversion scenario in the model are shown in figure 7a and 7b respectively. It can be seen that the MUF of Pu in MBA2 (figure 7b) is on the edge of normal and abnormal. Because the Pu loss is so small that it is difficult to judge whether the plant is normal or not, but it is easy to distinguish by NRTA. It is also true for the MUF of U in MBA2 because the quantity of U is much bigger than Pu.

It is also correct for the MUF in MBA1, but considering the high uncertainties measurement of spent fuel, the MUF in MBA1 is not so certain.



Days	MBA1 (kg)			MBA2 (kg)		
178	Low	MUF	Up	Low	MUF	Up
U	-508	-141.16	226	-531	-36.98	457
δ		0.23			0.30	
Pu	-25	-8.91	7	-15	2.26	20
δ		0.24			0.26	

Figure 7a MUF of Normal scenario



Days	MBA1 (kg)			MBA2 (kg)		
178	Low	MUF	Up	Low	MUF	Up
U	-701	-333.29	34	57	550.25	1043
δ		0.23			0.30	
Pu	-22	-6.58	9	-0	17.19	35
δ		0.24			0.26	

Figure 7b MUF of diversion scenario

CONCLUSION

The simulation results show that a material diversion scenario can be detected quickly by NRTA compared with traditional accounting if the internal measurement uncertainty of 1A, 1B and others is under or equal 5%. When the uncertainty raises about 10%, it is hard to detect the diversion scenario.

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