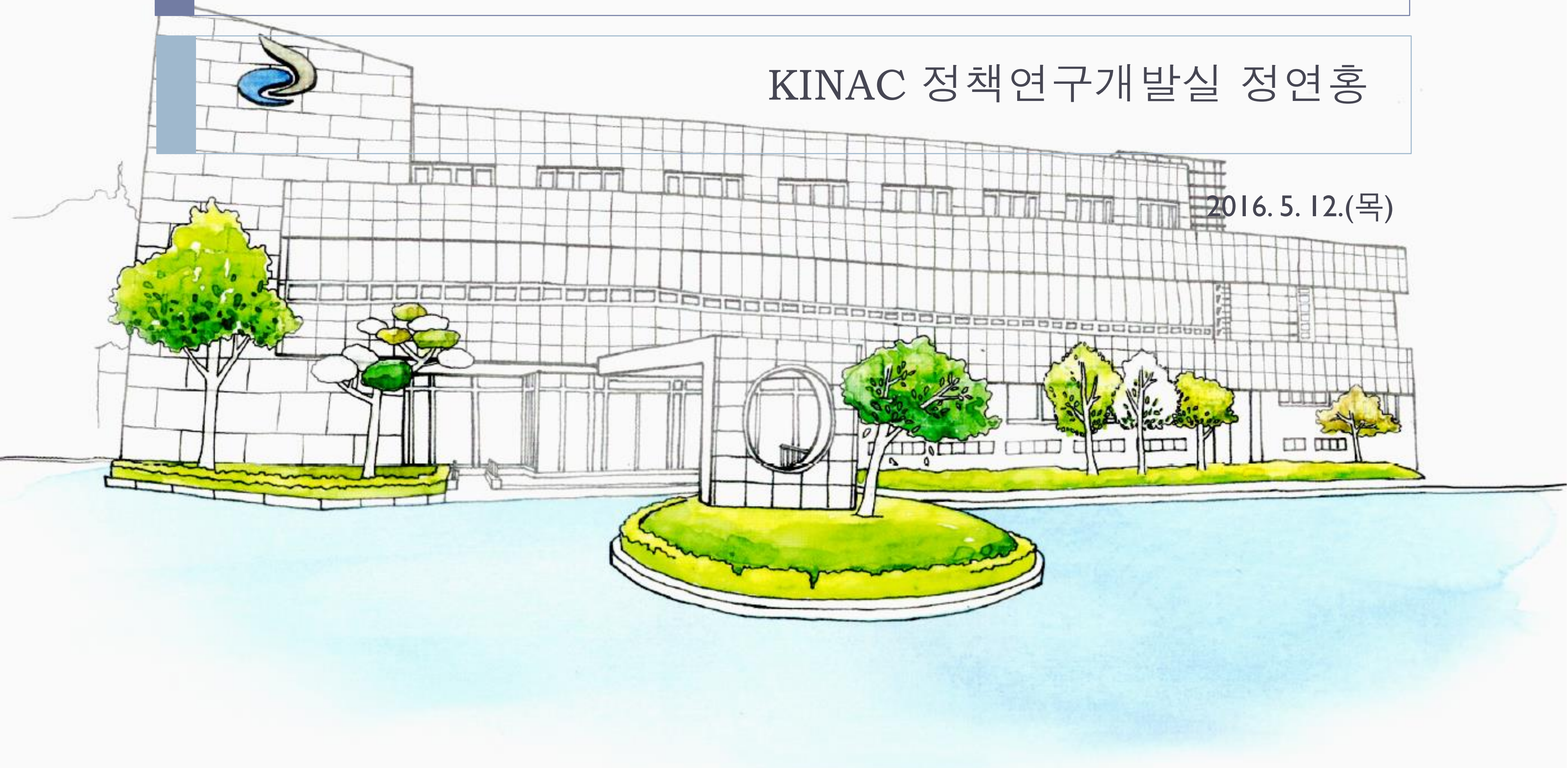
Calculation of MUF for the Pyro-processing Facility

KINAC 정책연구개발실 정연홍

2016. 5. 12.(목)



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1 연구 배경

연구 개요

- 민감 핵주기 기술 개발
  - 국내에서 후행핵주기 기술 대안 중 하나로 건식재처리기술 개발을 추진 중
  - Pu과 같은 특수핵물질(Special Nuclear Materials) 처리 시설
- 핵비확산성 보증 (IAEA 안전조치 적용)
  - 설계정보서
  - **핵물질 계량관리**
  - 현장검증
  - 격납감시

연구 개요

- 핵물질 계량관리
  - 지정된 구역 내 핵물질의 양 및 변화량을 확인하기 위해 수행하는 활동
  - MBA 구분, MBA 별 핵물질 양에 대한 기록 유지
  - PIT 기간 내 물질수지를 확정하고 MUF 계산
  - 계산된 MUF량과 허용 오차를 확인

- 규제 시스템 구축을 위한 핵확산에 대한 정량적 평가
  - **미계량핵물질(MUF) : 핵물질 계량관리의 유효성 검증**
  - 핵물질매력도(FOM) : 공정 내 취약지점 분석/검증

미계량핵물질(Material Unaccounted For)

- 물질수지구역(Material Balance Area, MBA)에서의 물질 재고의 오차 및 계량 오차량

$$MUF = (PB + X - Y) - PE$$

Where,

PB : the beginning physical inventory

X : the sum of increases to inventory

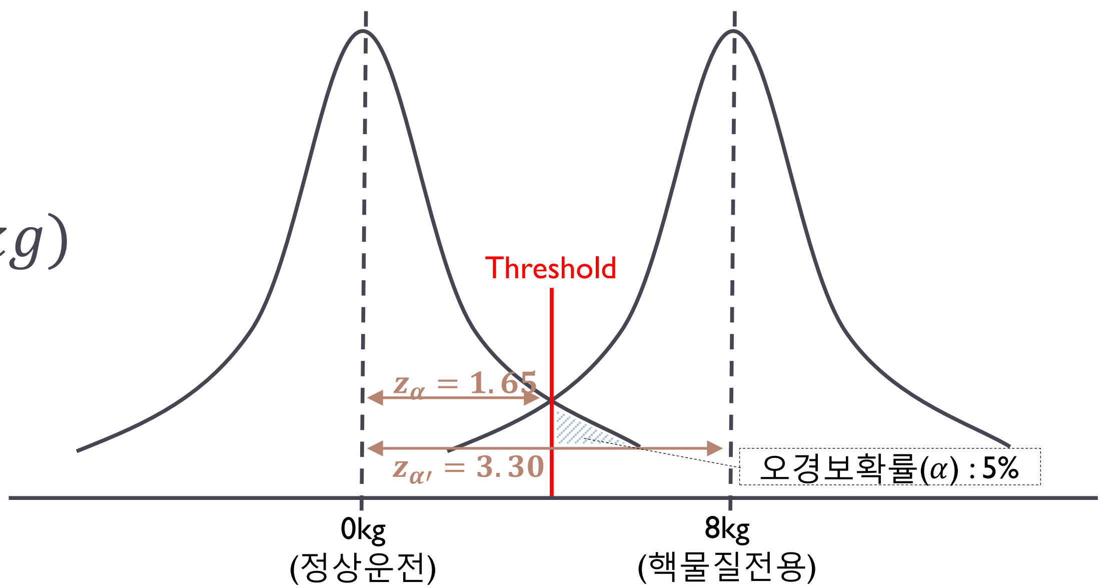
Y : the sum of decreases to inventory

PE : the ending physical inventory

물질수지평가 (MUF 불확도)

- 벌크 시설에서는 <u>**측정오차**</u>, <u>**공정오차**</u>, 측정에서의 오류, 측정되지 않은 손실, 기록에서의 오류 등으로 MUF에서 불확도가 필연적으로 발생

- 통계적 가설검정
  - 탐지확률 95%
  - $3.3\sigma_{MUF} \leq 1SQ(8kg)$



물질수지평가 (MUF 불확도)

- 오차(Error)의 종류
  - Random Error(σ_r) : 동일한 측정 조건하에서 생기는 오차
  - Systematic Error(σ_s) : 측정기기의 부정확성, 측정방법의 차이 등에서 발생하는 오차
- 오차 발생 요인들
  - Bulk(σ^b) : 측정에서 발생하는 오차
  - Sampling(σ^s) : 표본 추출에서 발생하는 오차
  - Analytic(σ^a) : 분석에서 발생하는 오차
- 오차전파(Error Propagation)를 통해 대표 오차 산정
  - $\sigma_{MUF}{}^2 = \sum_{i=1}^{k} M_{O_i}{}^2 \left(\frac{\delta_{O_{ri}}{}^2}{n_{O_i}} + \delta_{O_{si}}{}^2 \right)$

* IAEA TECDOC-261, IAEA Safeguards Technical Manual, IAEA, Vienna, 1982

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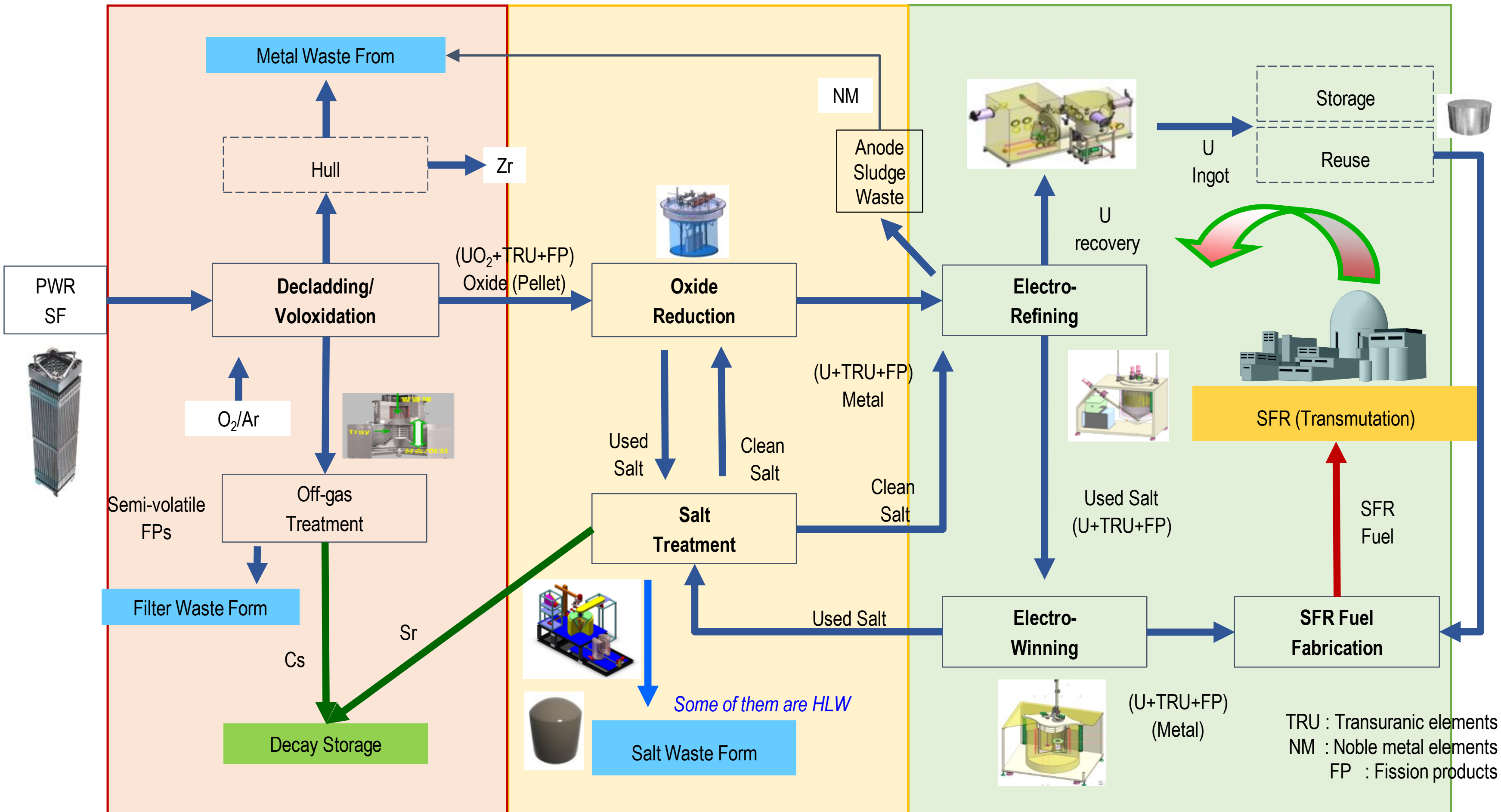
주요 내용

Facility Information (Pyro-processing facility)

Pyroprocessing Flow : KAPF

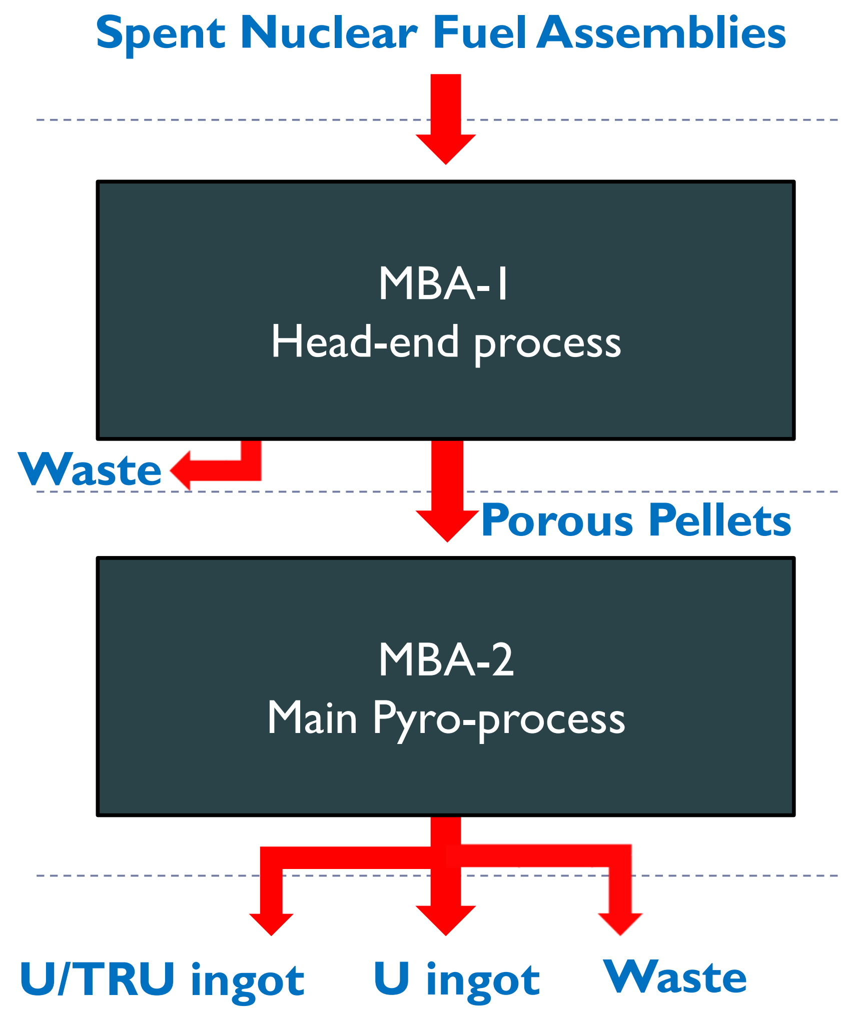


Seong Won Park, ANS, 2013.

Facility Information (MBA, KMP)

MBA	FKMP and IKMP (Material Form)		Accounting [a)]	Add. Analysis [b)]	Requirement [c)]
MBA1 SF Receipt, Storage Head-end Process Cell	Flow KMP-1	Input Flow (SFA)	ID, Item Count	Rad. Meas.[†]	Remotely Verification Capability
	Flow KMP-2	Output Flow (Porous Pellets)	Weighing	DA/NDA	Sample Taking/Transfer
		Output Flow (Head-end Wastes)	NDA	DA	Sample Taking/Transfer
	KMP-A	SF Assembly Storage Area	ID, Item Count	Rad. Meas.[†]	Remotely Verification Capability
	KMP-B	Before De-cladding (SF rods)	ID, Item Count	Rad. Meas.[†]	Remotely Verification Capability
	KMP-C	After Mixing (SF powder)	DA	NDA	Sample Taking/Transfer
	KMP-D	Other materials in the cell[*]	Weighing, DA, NDA	DA	Sample Taking/Transfer
MBA2 Main Pyro-processing Cell	Flow KMP-1	Input Flow (Porous Pellets)	Weighing	DA/NDA	Sample Taking/Transfer
	Flow KMP-2	Output Flow (U/TRU Products)	DA	NDA	Sample Taking/Transfer
		Output Flow (U Products)	NDA	DA	Sample Taking/Transfer
		Output Flow (Main process Wastes)	NDA	DA	Sample Taking/Transfer
	KMP-A	Before E-Reduction (Porous Pellets)	Weighing	DA/NDA	Sample Taking/Transfer
	KMP-B	Electro-Refining (Salt)	DA	NDA[‡]	Sample Taking/Transfer
	KMP-C	Other materials in the cell[*]	Weighing, DA, NDA	DA	Sample Taking/Transfer
MBA3 Storage	Flow KMP-1	Input Flow (U/TRU, U Products, Wastes)	ID, Item Count	NDA	Remotely Verification Capability
	Flow KMP-2	Output Flow (U/TRU, U Products, Wastes)	ID, Item Count	NDA	Remotely Verification Capability
	KMP-A	U/TRU Products	IID, Item Count	NDA	Transferring Storage Casks
	KMP-B	U Products	ID, Item Count	NDA	Transferring Storage Casks
	KMP-C	Wastes	ID, Item Count	NDA	Transferring Storage Casks

a) DA always combining weighing: * SNM in samples in analysis laboratory, UCl3, SNM from anode sludge, scraps, etc.
b) Additional NDA measurement for IAEA verification and/or NRTA: † IAEA verification tools such as PDET, Slab detector, ‡ Including additional measurement for NRTA beside for inspector verification
c) Requirements for sample taking and transferring always includes weighing requirement
d) Waste storage area can be the separated MBA from the product storage MBA, but simply assumed one MAB for all products and wastes as there are no significant differences in the conceptual design phase.

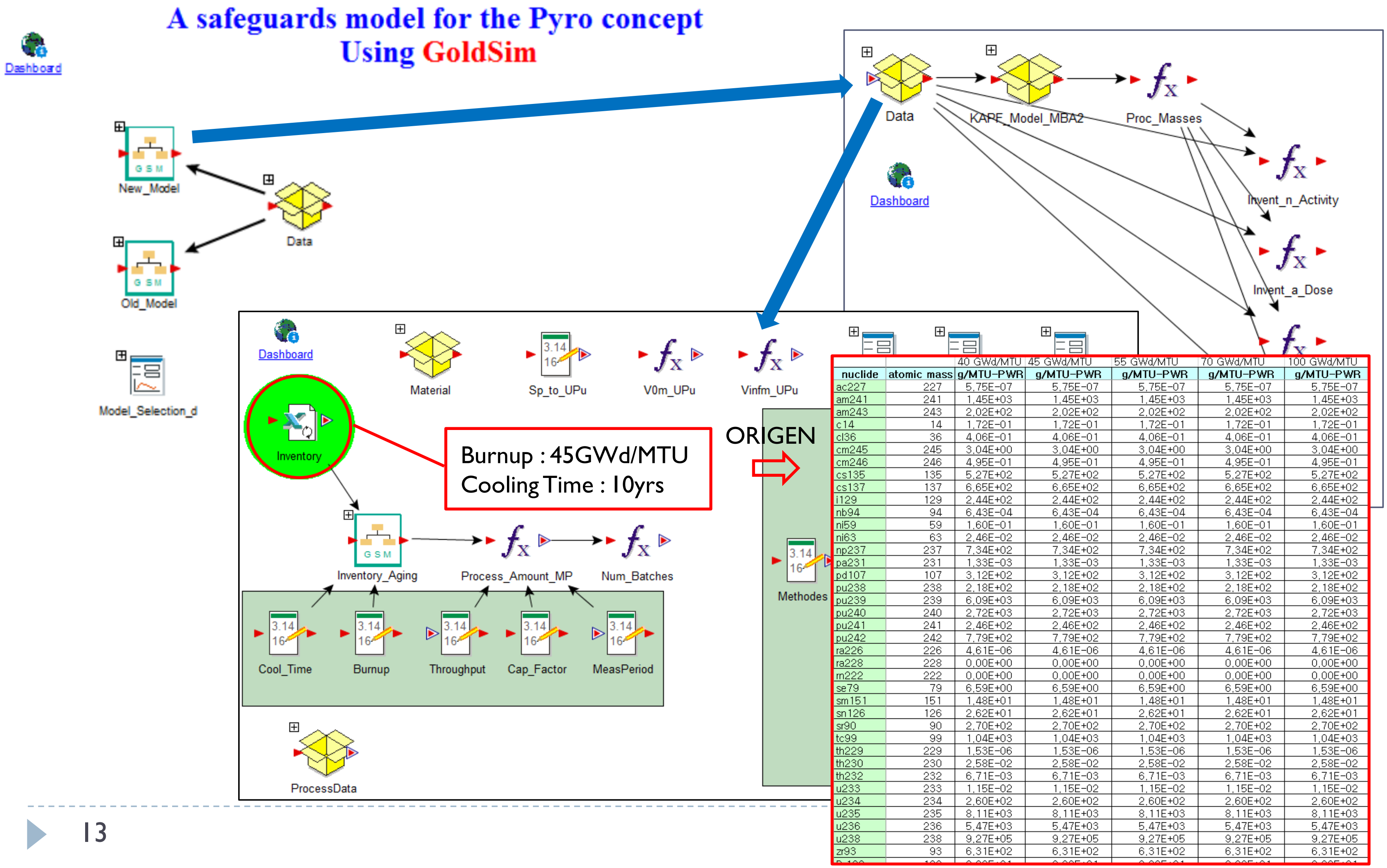


Facility Information (Measurement Method, Uncertainty)

Material Form	Measurement Method (Equipment)	Uncertainty					
		Bulk		Sampling		Analytic	
		δ_r^b	δ_s^b	δ_r^s	δ_s^s	δ_r^a	δ_s^a
SF assemblies	Item count	0.05	0.05	-	-	-	-
SF rods	Item count	0.05	0.05	-	-	-	-
SF oxide powder (homogeneous)	U-NDA M1 & M3	0.05	0.05	1.0	0.5	1.2	3.8~8.3
	DA	0.05	0.05	1.0	0.5	0.6	0.3
U metal ingot	U-NDA M2 (U)	-	-	-	-	1.8	5.0
	U-NDA M1 (Pu)	-	-	-	-	1.2	5.0~9.0
	DA (U, Pu)	0.05	0.05	0.05	0.05	0.5	0.2
U/TRU metal ingot	Fission chamber (Pu)	-	-	-	-	0.029	4.9~8.9
	U-NDA M3 (U)	-	-	-	-	1.8	5.0
	DA (U, Pu)	0.05	0.05	0.2	0.2	0.5	0.2
UO or UO_2 powder (recycle)	U-NDA M2	-	-	-	-	1.8	5.0
UCl_3 pellets	U-NDA M2	-	-	-	-	1.8	5.0
U+ LiCl+ KCl	U-NDA M2	0.05	0.05	10	5.0	1.8	5.0
U+ TRU+ LiCl+ KCl (refining)	Fission chamber	-	-	-	-	8.0	10.0
Hull and other wastes	Waste PNC + Cm ratio	0.05	0.05	10	5.0	6.0	10.0
Reducer salt waste (SF salt) ER/EW salt waste (TRU salt)	Waste PNC + Cm ratio	0.05	0.05	10	5.0	8.0	10.0
Reducer cathode (SF metal)	Waste PNC + Cm ratio	0.05	0.05	10	5.0	8.0	10.0
Refiner cathode (U metal)	Waste ANC	0.05	0.05	10	5.0	8.0	10.0
Cadmium cathode (TRU metal)	Waste PNC + Cm ratio	0.05	0.05	10	5.0	8.0	10.0

* H. Aigner, R. Binner, E. Kuhn, International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials, IAEA, Vienna, Austria

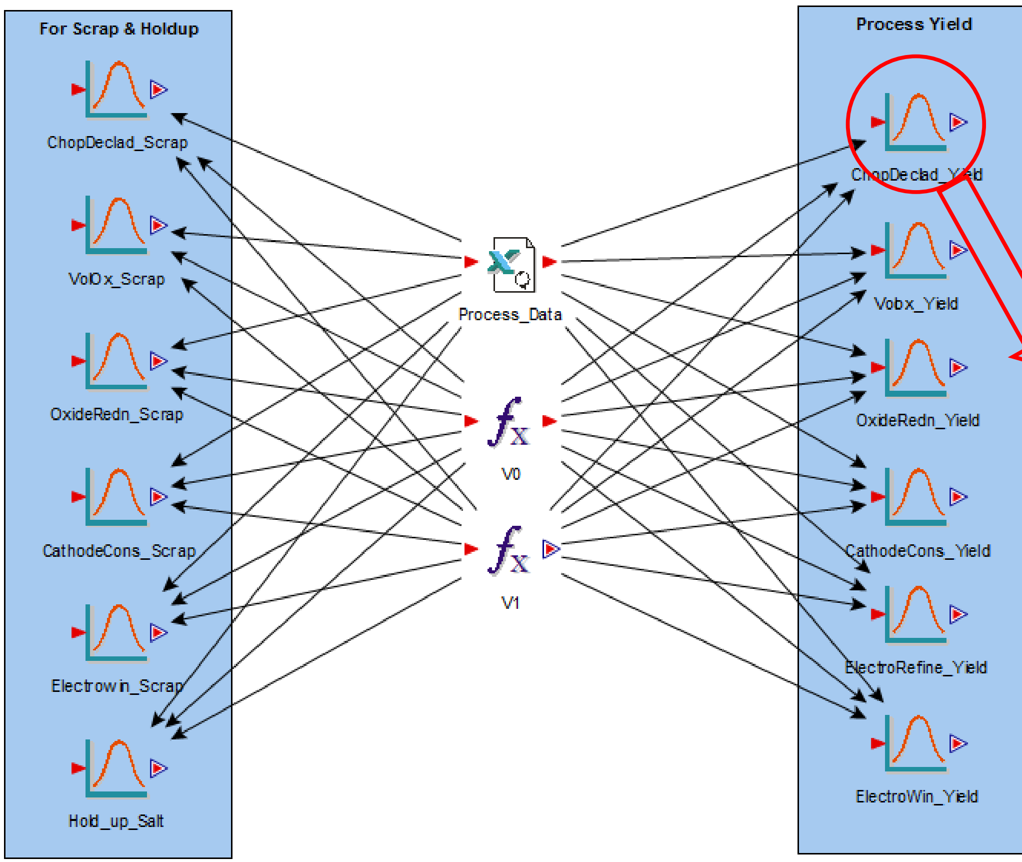
Model Data

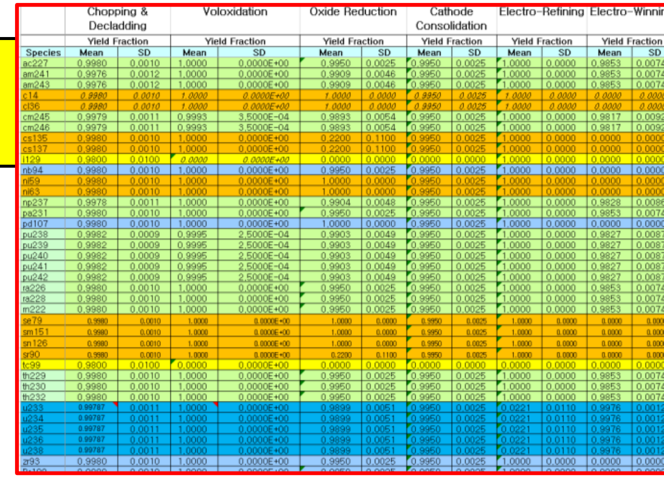


		40 GWd/MTU	45 GWd/MTU	55 GWd/MTU	70 GWd/MTU	100 GWd/MTU
nuclide	atomic mass	g/MTU-PWR	g/MTU-PWR	g/MTU-PWR	g/MTU-PWR	g/MTU-PWR
ac227	227	5,75E-07	5,75E-07	5,75E-07	5,75E-07	5,75E-07
am241	241	1,45E+03	1,45E+03	1,45E+03	1,45E+03	1,45E+03
am243	243	2,02E+02	2,02E+02	2,02E+02	2,02E+02	2,02E+02
c14	14	1,72E-01	1,72E-01	1,72E-01	1,72E-01	1,72E-01
cl36	36	4,06E-01	4,06E-01	4,06E-01	4,06E-01	4,06E-01
cm245	245	3,04E+00	3,04E+00	3,04E+00	3,04E+00	3,04E+00
cm246	246	4,95E-01	4,95E-01	4,95E-01	4,95E-01	4,95E-01
cs135	135	5,27E+02	5,27E+02	5,27E+02	5,27E+02	5,27E+02
cs137	137	6,65E+02	6,65E+02	6,65E+02	6,65E+02	6,65E+02
i129	129	2,44E+02	2,44E+02	2,44E+02	2,44E+02	2,44E+02
nb94	94	6,43E-04	6,43E-04	6,43E-04	6,43E-04	6,43E-04
ni59	59	1,60E-01	1,60E-01	1,60E-01	1,60E-01	1,60E-01
ni63	63	2,46E-02	2,46E-02	2,46E-02	2,46E-02	2,46E-02
np237	237	7,34E+02	7,34E+02	7,34E+02	7,34E+02	7,34E+02
pa231	231	1,33E-03	1,33E-03	1,33E-03	1,33E-03	1,33E-03
pd107	107	3,12E+02	3,12E+02	3,12E+02	3,12E+02	3,12E+02
pu238	238	2,18E+02	2,18E+02	2,18E+02	2,18E+02	2,18E+02
pu239	239	6,09E+03	6,09E+03	6,09E+03	6,09E+03	6,09E+03
pu240	240	2,72E+03	2,72E+03	2,72E+03	2,72E+03	2,72E+03
pu241	241	2,46E+02	2,46E+02	2,46E+02	2,46E+02	2,46E+02
pu242	242	7,79E+02	7,79E+02	7,79E+02	7,79E+02	7,79E+02
ra226	226	4,61E-06	4,61E-06	4,61E-06	4,61E-06	4,61E-06
ra228	228	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
rn222	222	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
se79	79	6,59E+00	6,59E+00	6,59E+00	6,59E+00	6,59E+00
sm151	151	1,48E+01	1,48E+01	1,48E+01	1,48E+01	1,48E+01
sn126	126	2,62E+01	2,62E+01	2,62E+01	2,62E+01	2,62E+01
sr90	90	2,70E+02	2,70E+02	2,70E+02	2,70E+02	2,70E+02
tc99	99	1,04E+03	1,04E+03	1,04E+03	1,04E+03	1,04E+03
th229	229	1,53E-06	1,53E-06	1,53E-06	1,53E-06	1,53E-06
th230	230	2,58E-02	2,58E-02	2,58E-02	2,58E-02	2,58E-02
th232	232	6,71E-03	6,71E-03	6,71E-03	6,71E-03	6,71E-03
u233	233	1,15E-02	1,15E-02	1,15E-02	1,15E-02	1,15E-02
u234	234	2,60E+02	2,60E+02	2,60E+02	2,60E+02	2,60E+02
u235	235	8,11E+03	8,11E+03	8,11E+03	8,11E+03	8,11E+03
u236	236	5,47E+03	5,47E+03	5,47E+03	5,47E+03	5,47E+03
u238	238	9,27E+05	9,27E+05	9,27E+05	9,27E+05	9,27E+05
zr93	93	6,31E+02	6,31E+02	6,31E+02	6,31E+02	6,31E+02

Process Yield Fraction

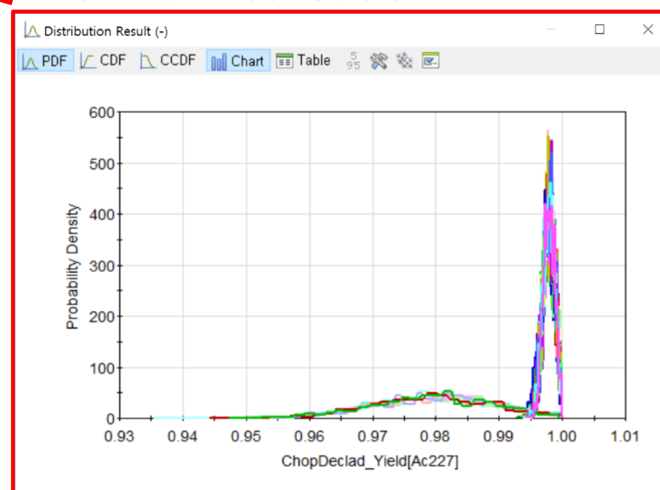
Sample Yield Factors for each Process Station, over the Measuring Period



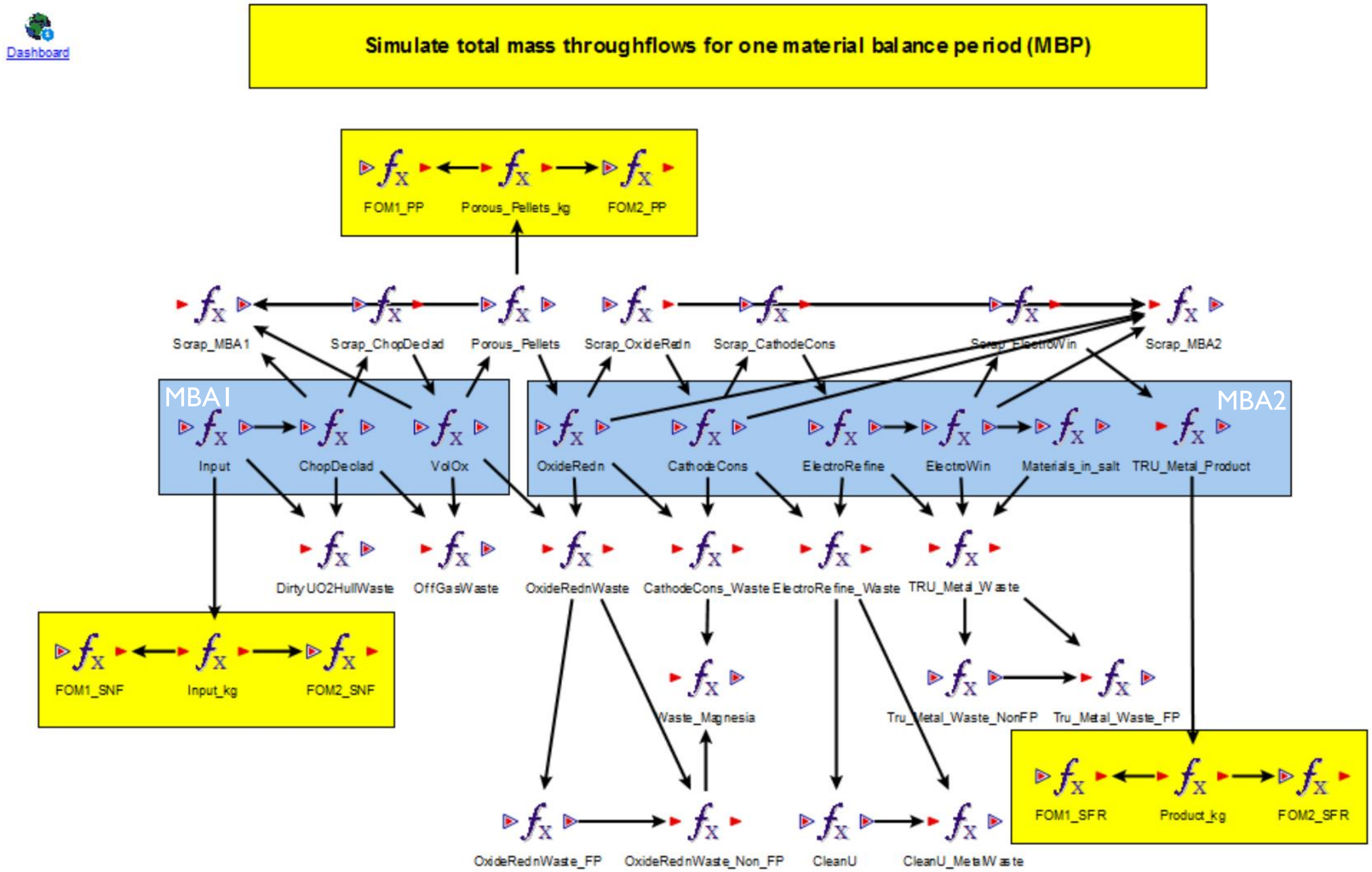


	Chopping & Decladding		Voloxidation		Oxide Reduction		Cathode Consolidation		Electro-Refining		Electro-Winning	
	Yield Fraction		Yield Fraction		Yield Fraction		Yield Fraction		Yield Fraction		Yield Fraction	
Species	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
ac227	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
am241	0,9976	0,0012	1,0000	0,0000E+00	0,9909	0,0046	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
am243	0,9976	0,0012	1,0000	0,0000E+00	0,9909	0,0046	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
c14	0.9980	0.0010	1.0000	0.0000E+00	1.0000	0.0000	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
cl36	0.9980	0.0010	1.0000	0.0000E+00	1.0000	0.0000	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
cm245	0,9979	0,0011	0,9993	3,5000E-04	0,9893	0,0054	0,9950	0,0025	1,0000	0,0000	0,9817	0,0092
cm246	0,9979	0,0011	0,9993	3,5000E-04	0,9893	0,0054	0,9950	0,0025	1,0000	0,0000	0,9817	0,0092
cs135	0,9980	0,0010	1,0000	0,0000E+00	0,2200	0,1100	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
cs137	0,9980	0,0010	1,0000	0,0000E+00	0,2200	0,1100	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
i129	0,9800	0,0100	0.0000	0.0000E+00	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000	0,0000	0,0000
nb94	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
ni59	0,9980	0,0010	1,0000	0,0000E+00	1,0000	0,0000	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
ni63	0,9980	0,0010	1,0000	0,0000E+00	1,0000	0,0000	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
np237	0,9978	0,0011	1,0000	0,0000E+00	0,9904	0,0048	0,9950	0,0025	1,0000	0,0000	0,9828	0,0086
pa231	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
pd107	0,9980	0,0010	1,0000	0,0000E+00	1,0000	0,0000	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000
pu238	0,9982	0,0009	0,9995	2,5000E-04	0,9903	0,0049	0,9950	0,0025	1,0000	0,0000	0,9827	0,0087
pu239	0,9982	0,0009	0,9995	2,5000E-04	0,9903	0,0049	0,9950	0,0025	1,0000	0,0000	0,9827	0,0087
pu240	0,9982	0,0009	0,9995	2,5000E-04	0,9903	0,0049	0,9950	0,0025	1,0000	0,0000	0,9827	0,0087
pu241	0,9982	0,0009	0,9995	2,5000E-04	0,9903	0,0049	0,9950	0,0025	1,0000	0,0000	0,9827	0,0087
pu242	0,9982	0,0009	0,9995	2,5000E-04	0,9903	0,0049	0,9950	0,0025	1,0000	0,0000	0,9827	0,0087
ra226	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
ra228	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
rn222	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
se79	0.9980	0.0010	1.0000	0.0000E+00	1.0000	0.0000	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
sm151	0.9980	0.0010	1.0000	0.0000E+00	1.0000	0.0000	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
sn126	0.9980	0.0010	1.0000	0.0000E+00	1.0000	0.0000	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
sr90	0.9980	0.0010	1.0000	0.0000E+00	0.2200	0.1100	0.9950	0.0025	1.0000	0.0000	0.0000	0.0000
tc99	0,9800	0,0100	0,0000	0,0000E+00	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
th229	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
th230	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
th232	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,9853	0,0074
u233	0.99787	0,0011	1,0000	0,0000E+00	0,9899	0,0051	0,9950	0,0025	0,0221	0,0110	0,9976	0,0012
u234	0.99787	0,0011	1,0000	0,0000E+00	0,9899	0,0051	0,9950	0,0025	0,0221	0,0110	0,9976	0,0012
u235	0.99787	0,0011	1,0000	0,0000E+00	0,9899	0,0051	0,9950	0,0025	0,0221	0,0110	0,9976	0,0012
u236	0.99787	0,0011	1,0000	0,0000E+00	0,9899	0,0051	0,9950	0,0025	0,0221	0,0110	0,9976	0,0012
u238	0.99787	0,0011	1,0000	0,0000E+00	0,9899	0,0051	0,9950	0,0025	0,0221	0,0110	0,9976	0,0012
zr93	0,9980	0,0010	1,0000	0,0000E+00	0,9950	0,0025	0,9950	0,0025	1,0000	0,0000	0,0000	0,0000

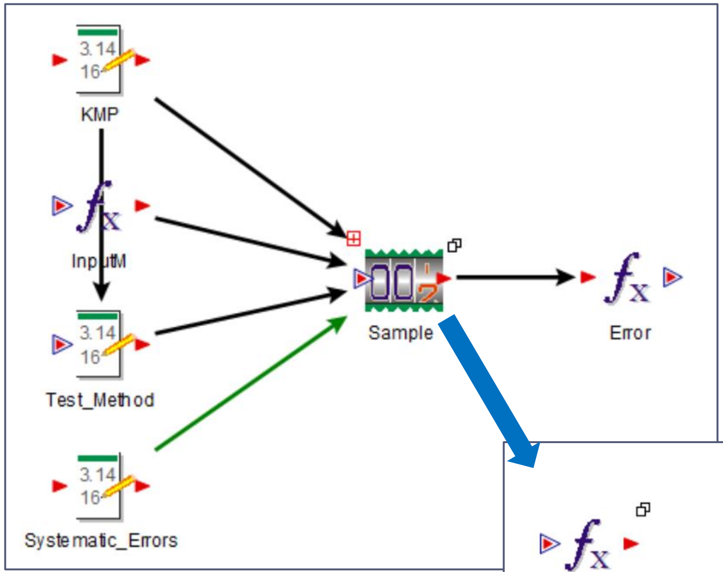
Normal Distribution



Total mass flow simulation

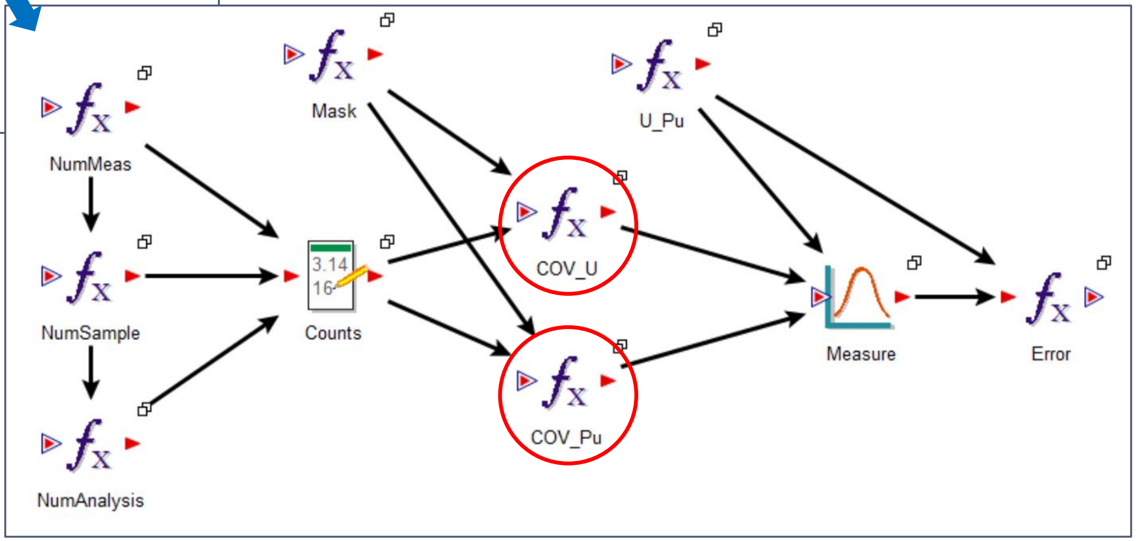


Error Calculation in each KMP

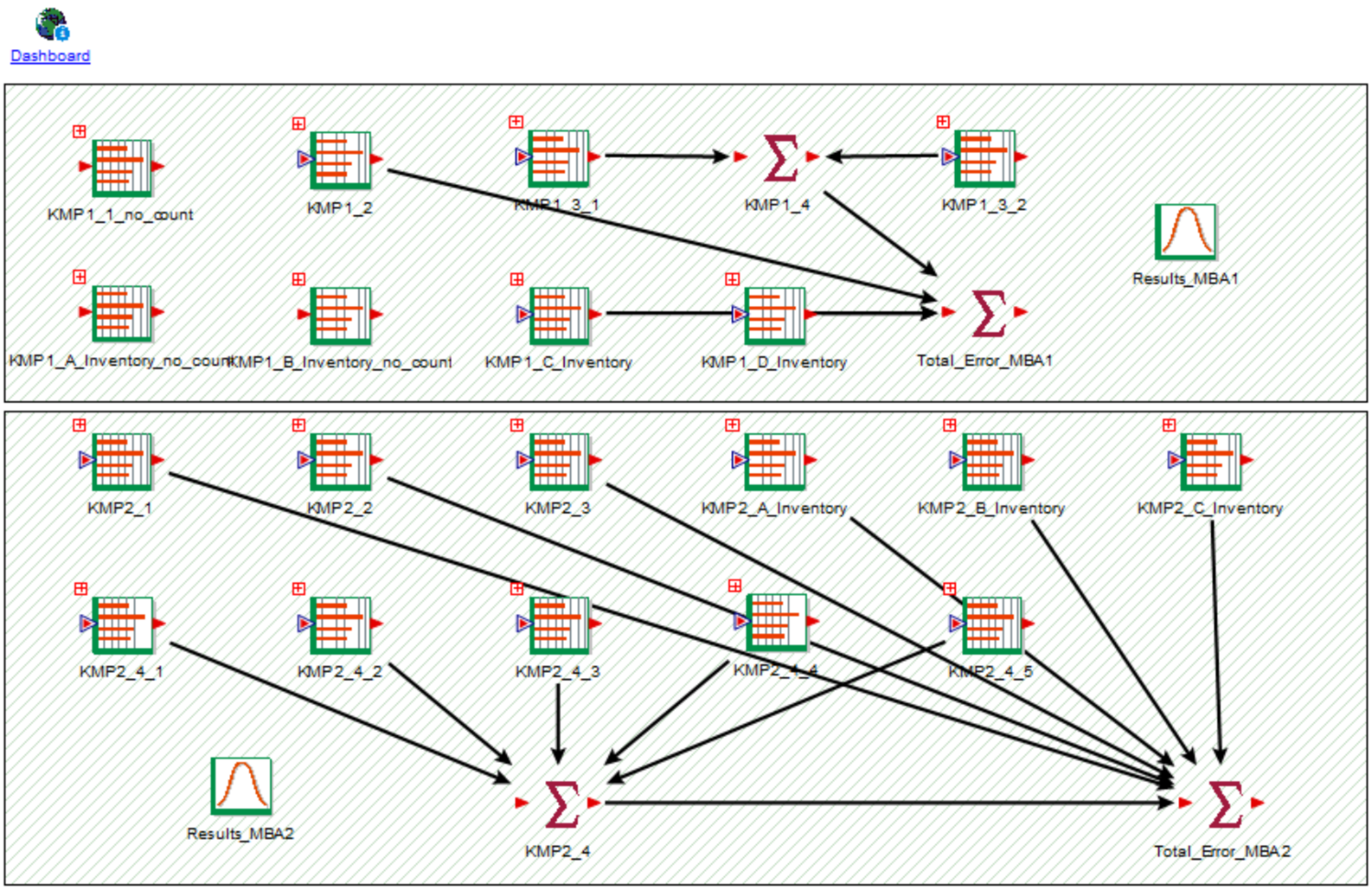


Gauss Error Propagation

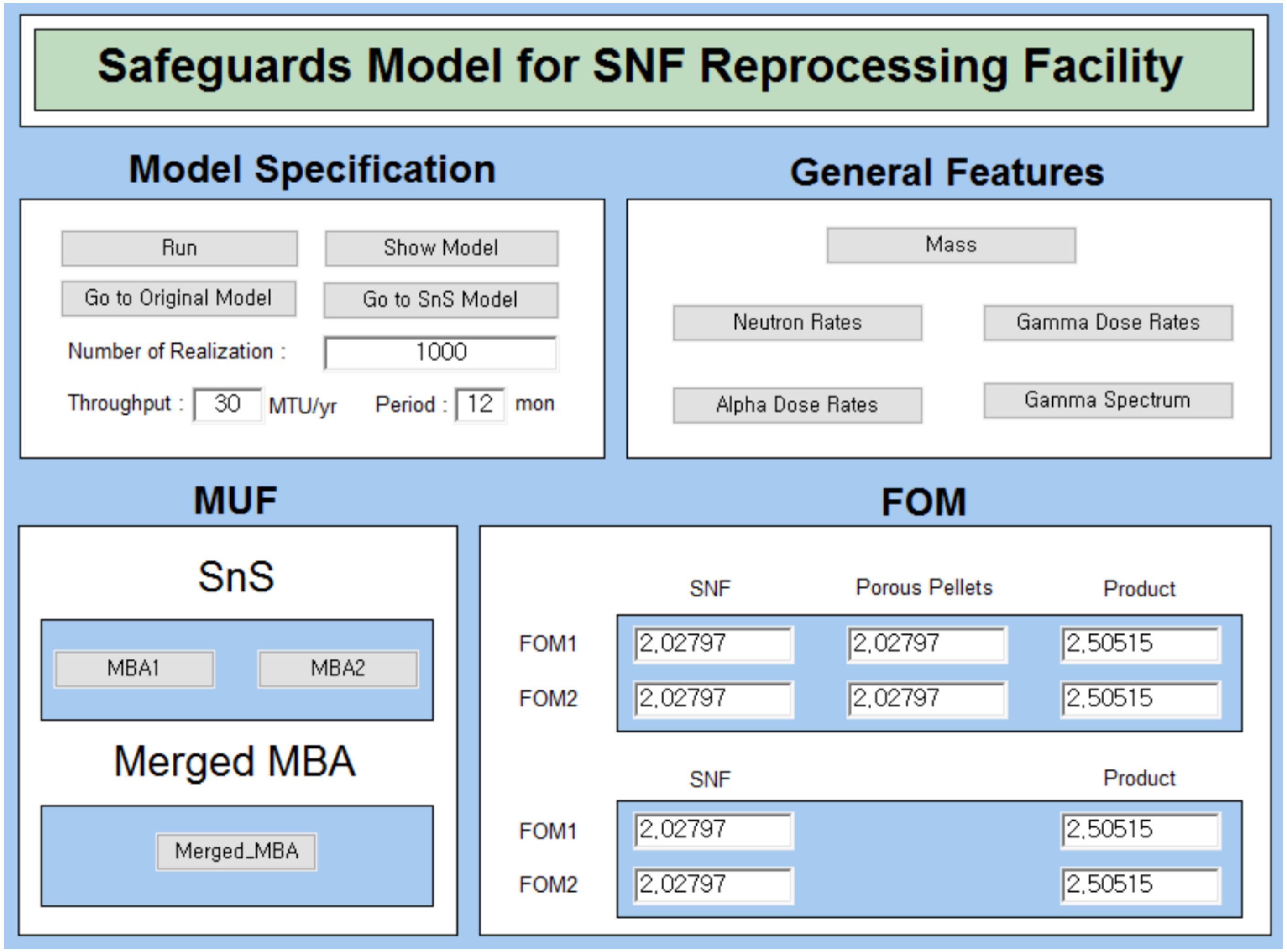
$$\sigma_{MUF}^2 = \sum_{i=1}^{k} M_{O_i}^{\ 2}\left(\frac{\delta_{O_{ri}}^{\ 2}}{n_{O_i}} + \delta_{O_{si}}^{\ 2}\right)$$



KMPs Information



Main Dashboard



Sampling/Uncertainty Data Input

Sampling Data

For each test type, enter the size of the item or container (in kg of waste), the fraction of items that are tested, and the number of U/Pu tests done on each tested item.

	TestContSize [kg]	TestFraction [%]	TestCount	Methodes
MBA1_KMP2	20	75	3	1
MBA1_KMP3_A	20	75	3	8
MBA1_KMP3_B	20	75	3	8
MBA1_KMPC	20	75	3	1
MBA1_KMPD	20	75	3	1
MBA2_KMP1	20	75	3	1
MBA2_KMP2	20	75	3	5
MBA2_KMP3	20	75	3	3
MBA2_KMP4_A	20	75	3	10
MBA2_KMP4_B	20	75	3	10
MBA2_KMP4_C	20	75	3	3
MBA2_KMP4_D	20	75	3	5
MBA2_KMP4_E	20	75	3	5
MBA2_KMPA	20	75	3	1
MBA2_KMPB	20	75	3	7
MBA2_KMPC	20	75	3	1

For U235, for each test type, enter the random and systematic test standard error values for weighing, sampling, and testing.

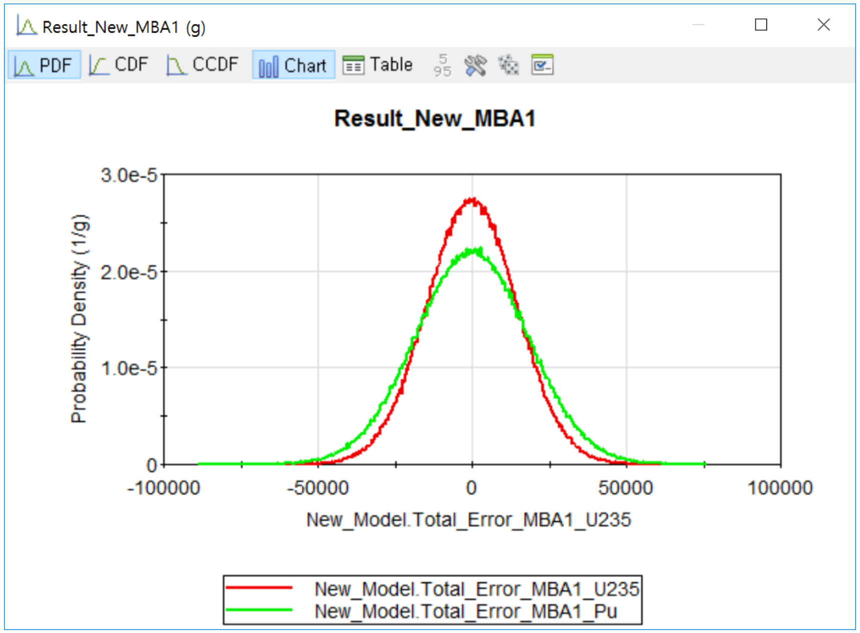
[%]	R_Weighing	R_Sampling	R_Tests	S_Weighing	S_Sampling	S_Tests
1	0.05	1.0	1.2	0.05	0.5	6.0
2	0.05	1.0	0.6	0.05	0.5	0.3
3	0	0	1.8	0	0	5.0
4	0.05	0.05	0.5	0.05	0.05	0.2
5	0	0	1.8	0	0	5.0
6	0.05	0.2	0.5	0.05	0.2	0.2
7	0.05	10	1.8	0.05	5.0	5.0
8	0.05	10	6.0	0.05	5.0	10
9	0.05	10	8.0	0.05	5.0	10
10	0.05	10	8.0	0.05	5.0	10
11	0.05	0.4	8	0.05	0.4	4

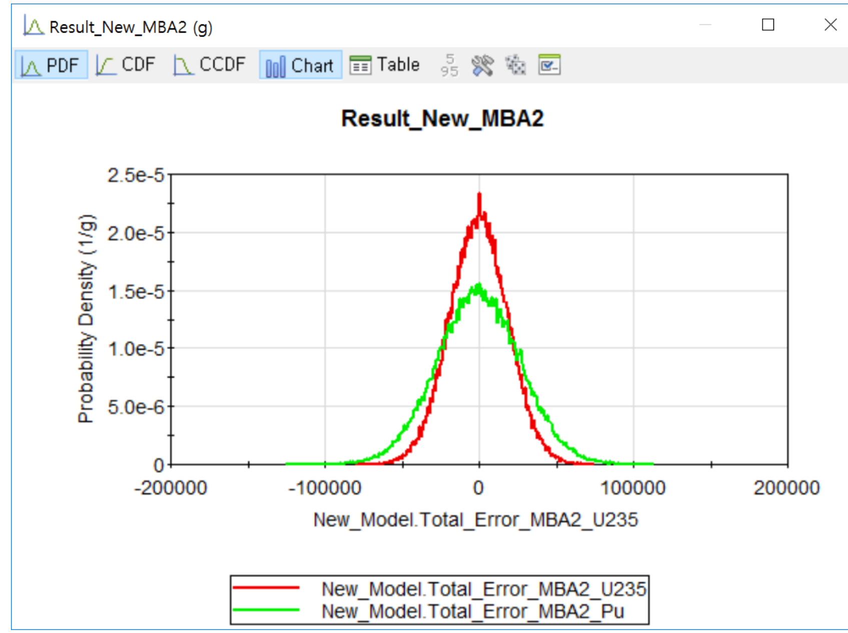
For Pu, for each test type, enter the random and systematic test standard error values for weighing, sampling, and testing.

[%]	R_Weighing	R_Sampling	R_Tests	S_Weighing	S_Sampling	S_Tests
1	0.05	1.0	1.2	1.	0.5	6.0
2	0.05	1.0	0.6	0.05	0.5	0.3
3	0	0	1.2	0	0	7.0
4	0.05	0.05	0.5	0.05	0.05	0.2
5	0	0	0.029	0	0	6.9
6	0.05	0.4	10	0.05	0.4	5
7	0.05	10	1.8	0.05	5.0	5.0
8	0.05	10	6.0	0.05	5.0	10
9	0.05	10	8.0	0.05	5.0	10
10	0.05	10	8.0	0.05	5.0	10
11	0.05	0.4	8	0.05	0.4	4

3 주요 결과

각 MBA 별 σ_{MUF}

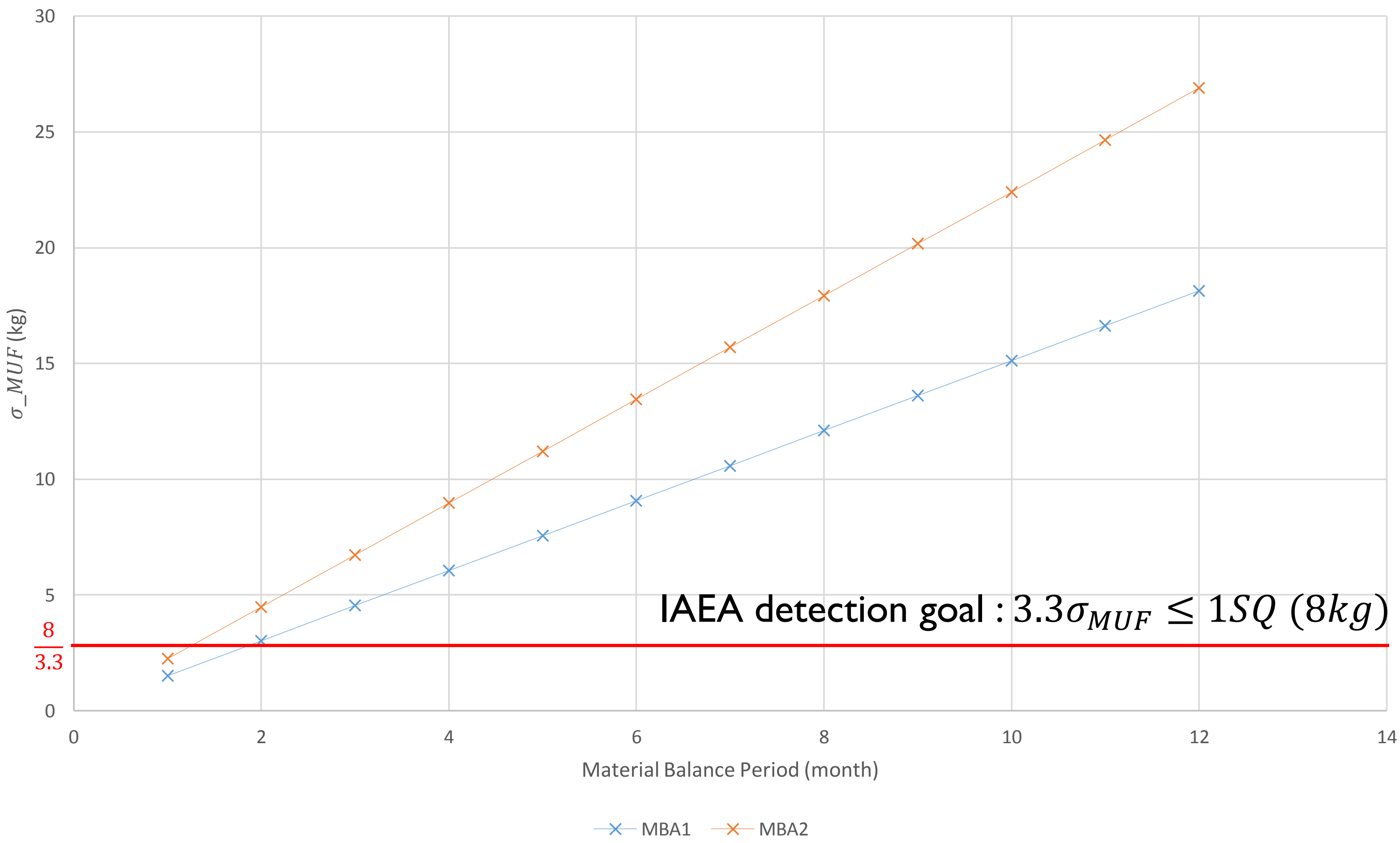




Total Error (U235)	
MBA-1	14,624 g
MBA-2	18,756 g

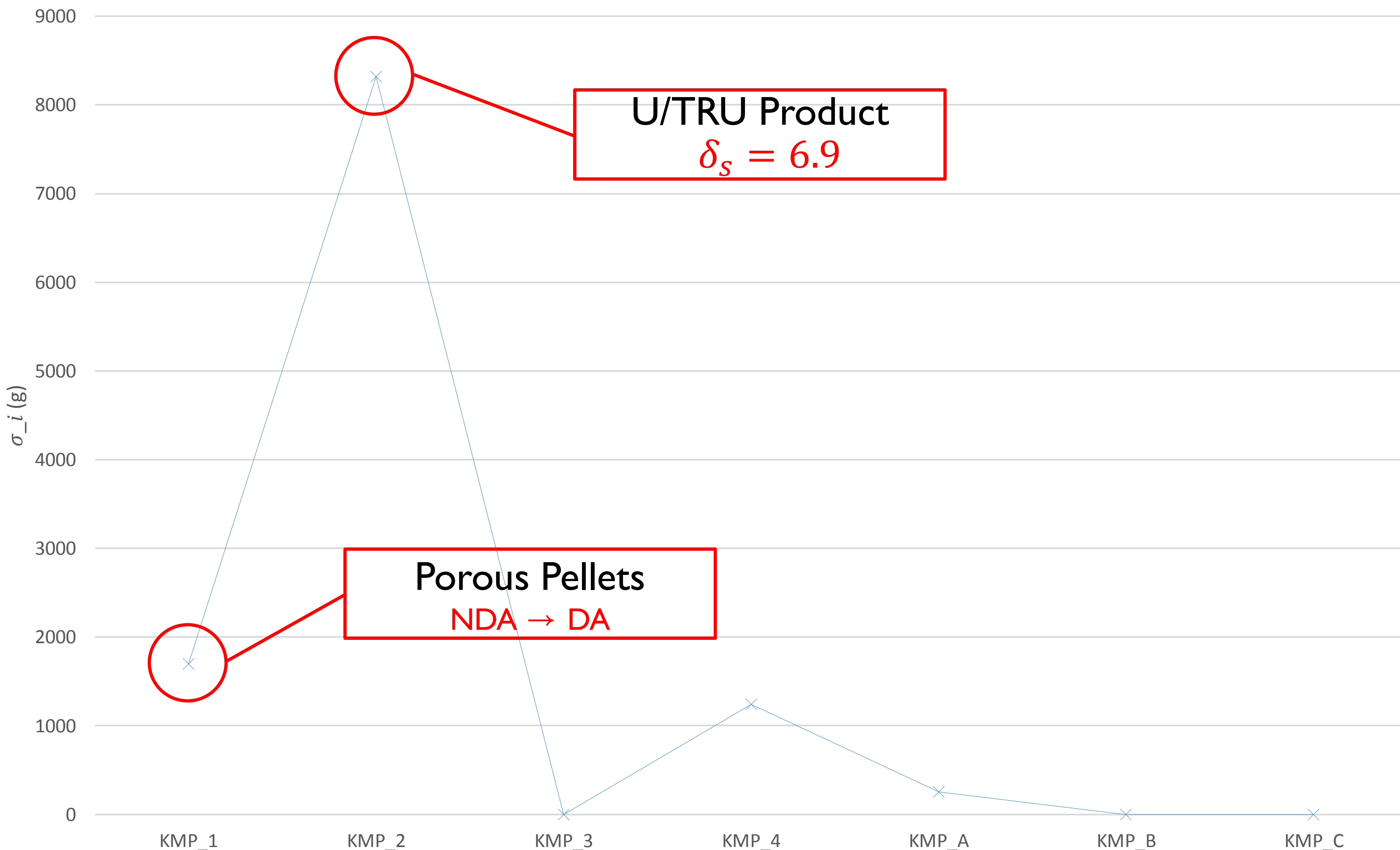
Total Error (Pu)	
MBA-1	18,142 g
MBA-2	26,893 g

Pu의 MBP 별 σ_{MUF}

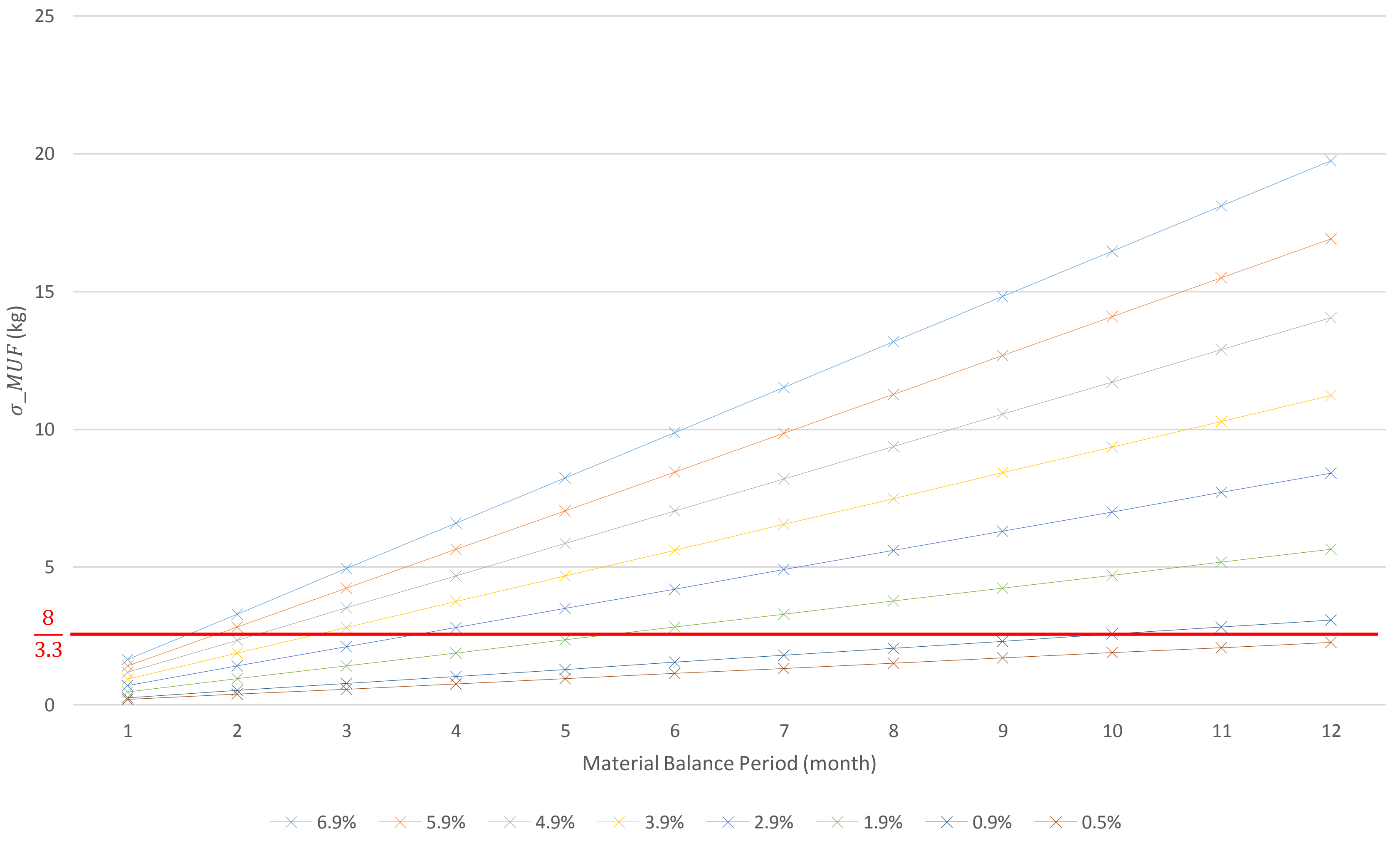


* Scott DeMuth (LANL), Proliferation Risk Assessment for Large Facilities with Simulation and Modeling, Global 2011 Chiba, Japan December 11-16, 2011

MBA2의 KMP별 기여도



δ_s에 따른 σ_{MUF}의 민감도



결론

- 30 MTU/yr 규모의 재처리 시설에서의 MUF 불확도가 높아 detection goal을 달성하기 어려움
- 이를 달성하기 위해서는 MBP를 줄이거나 MUF 불확도에 미치는 영향이 높은 U/TRU product에서의 계통 오차(systematic error)를 0.5% 이하로 줄여야 함
- 가정이 많고 입력값에 대한 검증이 필요
- 벌크시설에 대한 신뢰할 수 있는 공정정보, 계측정보, 물질수지정보가 주어진다면 합리적인 MUF 불확도 및 공정/계측에 대한 성능목표치 추정 가능

감사합니다

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