Safeguardability of the Conceptually Designed Korea Advanced Pyroprocess Facility

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1. Introduction

The Korea Advanced Pyroprocess Facility (KAPF) is a conceptual facility for spent PWR fuel management in Korea. Its main function is to produce transuranic metal fuel for a sodium-cooled fast reactor by pyroprocessing spent PWR fuel, thereby reducing the volume of spent PWR fuel and eventually the burden of high level waste disposal. The design concept is to build a module with a throughput of 100 MTHM per year with 70% availability, equivalent to 256 full operating days per year. The standard 17x17 PWR spent fuel assemblies from the Yong-Gwang Units 1 & 2 with an initial enrichment of 4.5wt%, a minimum 10 years of cooling time, and a 45 GWD/MTU with 37.5 MW/MTU average power rate is used as the reference fuel.

2. Material Control and Accountability

Materials accounting is necessary to provide positive confirmation that all material has been properly handled in the KAPF. Therefore, source term analyses were performed to figure out an effective material accounting system, including the gamma, (α,n), spontaneous fission neutron spectra, and fission multiplicity distributions for the reference spent fuel and sample materials in the KAPF, which may be variable across the process. Calculations showed that a curium balance methodology based on neutron coincidence counting is the most feasible nondestructive assay (NDA) for plutonium-bearing material in the KAPF, while NDA based on gamma spectra is the most appropriate for the U-metal product. Fig 1 shows proposed mass balance areas in a pilot-scale KAPF.

3. Safeguardability Assessment

Because nuclear materials processed in the KAPF are contained in many types and forms of matrix, material accountability requires that the material contents of all flows entering and exiting the MBAs and the quantities of nuclear material in the ending inventory be known. The MUF (Material Unaccounted For) is defined as the difference between the measured inventory and what is expected to be in the inventory based on the previous inventory and measured flows into and out of the process. The facility MUF for a given material balance period is a measure of the performance of the facility with respect to its control of the nuclear materials involved. The MUF, as verified by inspection or, alternately, as adjusted on the basis of inspection results, is the key index of performance used by the IAEA in its quantitative assessment of facility performance. Because measurement errors will occur, the actual amount of material measured will differ somewhat from the true value, creating a non-zero MUF. The probability of detecting the loss of a given quantity of material depends upon the uncertainty associated with the determination of the MUF. Achieving the IAEA's goal for Pu, to detect a loss of one significant quantity (SQ)of Pu with 95% detection probability and a 5% false alarm probability, it is required that σ_{MUF} must satisfy $\sigma_{MUF} \leq 8/3.3 = 2.424kg$ for one-sided testing. The one-sided testing means that the facility tests for loss and not for gain of Pu, so the statistical testing is one-sided and the alarm limit is at $1.65\sigma_{MUF}$. The control limit of $1.65\sigma_{MUF}$ is such that an error means that the measured MUF has a 95% probability of being less than $1.65\sigma_{MUF}$, assuming that the true MUF is zero, that all materials have been measured and accounted for, and that all sources of error are used in determining the limit of error.

To investigate whether the safeguards system for the KAPF would meet the IAEA detection goal, the sigma-MUF value was evaluated based on a hypothetical operating scenario. The facility's material control and accountability methods propagate all measurement and sampling uncertainties to give a standard error. As shown in Table 1, the measurement methods used for the material accounting are assumed to have various uncertainties based on the International Target Value (ITV) [1]. The measurement precisions and accuracies reflected in the table by the random and systematic uncertainties, respectively, are values that are expected to be achieved for the analysis of materials of nuclear grade in a hot-cell environment. They include the contributions of all uncertainties occurring after sampling.

With the measurement uncertainties of the safeguards approach and sampling procedures, the uncertainty of MUF (σ_{MUF}) was evaluated as follows:

$$\sigma^2_{ran}(MUF) = \sum_{k=1}^{K}\left[x^2_{kqpt}\left(\sigma^2_{rq..}/n_k m_k + \sigma^2_{r.p.}/r_k m_k + \sigma^2_{r..t}/c_k n_k m_k\right)\right]$$

$$\sigma^2_{sys}(MUF) = \sum_q\left[\sum_{k=1}^{K} A_k x_{kqpt}\right]^2\sigma^2_{sq..} + \sum_p\left[\sum_{k=1}^{K} A_k x_{kqpt}\right]^2\sigma^2_{s.p.} + \sum_t\left[\sum_{k=1}^{K} A_k x_{kqpt}\right]^2\sigma^2_{s..t}$$

$$\sigma^2_{MUF} = \sigma^2_{ran}(MUF) + \sigma^2_{sys}(MUF)$$

$$\sigma^{Pu}_{MUF} = 2.227\ \text{kg} < 2.424\ \text{kg (one-sided testing)}$$

$$\sigma^{U\text{-}235} = 21.22\ \text{kg} < 22.72\ \text{kg (one-sided testing)}$$

Table 1: Measurement Uncertainties for Material Accounting at the KAPF

Sample Matrix and Measurement Method	Uncertainty Component (% Rel. Std. Dev.)			
	Random	System	Sampling	Reference and Notes
DA : U-oxide Spent Fuel	0.2	0.2	0.4	• U & Pu in U-oxide powder by IDMS in hot cell
NDA-3 : Dirty U Powder	2.0	1.0		• Pu mass by HLNC for MOX fuel rod
NDA-1 : Dirty U/TRU Metal	2.0	1.0		• Pu mass by HLNC for MOX fuel rod
NDA-2 : Clean U Metal	8.0	4.0		• ^{235}U mass by AWCC for HEU Metal in hot cell
NDA-1 : Clean TRU Metal	4.0	1.5		• Pu mass by HLNC for FBR MOX in hot cell
NDA-1 : Dirty U/TRU Waste	10.0	5.0		• Pu mass by HLNC for MOX Scrap in hot cell
NDA-1 : Dirty U Waste	10.0	5.0		• ^{235}U mass by AWCC for HEU Metal in hot cell
NDA-1 : Dirty TRU Waste	10.0	5.0		• Pu mass by HLNC for MOX Scrap in hot cell
NDA-2 : Clean U Waste	10.0	5.0		• Pu mass by HLNC for MOX Scrap in hot cell
NDA-1 : Clean TRU Waste	8.0	4.0		• Pu mass by HLNC for FBR MOX in hot cell
Weighing	0.05	0.05		• Electronic Balance

This result suggests that the designed safeguards approach can meet typical IAEA detection goals for campaigns of one month or less for the KAPF with a 100 MTHM/yr throughput.

Since the systematic error of NDA-1 and NDA-2 are the main factors of error propagation in the sigma-MUF evaluations, sensitivity analyses for these systems were conducted for some error ranges. Fig 2 and Fig 3 show the results of sensitivity analyses for TRU and U-metal products, respectively. For the case of Pu MUF, a systematic error of 1.5% was assumed for a conservative situation of poor calibration without good reference TRU-metal samples. Since the gamma intensity of the TRU-metal would be much lower than the feed material, it is very feasible to achieve a good calibration curve with good reference metal samples. In that case, the systematic error of NDA-1 would be less than 1.0 %, and the material balance period could be extended to 2 months, as shown in Fig 2. Similarly, it is very feasible to achieve a systematic error of 2.0% for NDA-2, which is enough for 2 months of the MB period.

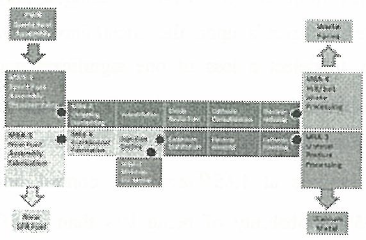

Fig. 1. Proposed mass balance areas in a pilot-scale KAPF

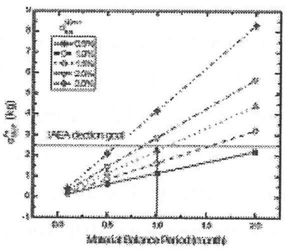

Fig. 2. Sensitivity of sigma-MUF(Pu) for NDA-1

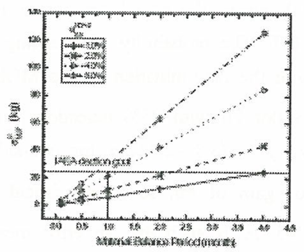

Fig. 3. Sensitivity of sigma-MUF(U) for NDA-2

REFERENCES

[1] H. Aigner et al., *International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials*, STR-327, International Atomic Energy Agency Publication STR-327, Vienna, IAEA, 2001.