SAFEGUARDABILITY ASSESSMENT ON PILOT-SCALE ADVANCED SPENT FUEL CONDITIONIG FACILITY

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1. Introduction

In South Korea, approximately 6,000 metric tons of spent nuclear fuel from commercial reactor operations have been accumulated, and there is the expectation that more than 30,000 metric tons, three times the present storage capacity, will be accumulated by the end of 2040 [1]. To resolve these challenges in spent fuel management, the Korea Atomic Energy Research Institute (KAERI) has been developing a dry processing technology called the Advanced Spent Fuel Conditioning Process (ACP). This is an electrometallurgical treatment technique that converts oxide-type spent fuel into a metallic form. The goal of the ACP study is to convert and recover more than 99% of the actinide elements into a metallic form to minimize the volume and heat load of spent fuel, thus lightening the burden of final disposal in terms of disposal size, safety, and economics.

In the framework of R&D collaboration for ACP safeguards, Los Alamos National Laboratory (LANL) and KAERI conducted a joint study that addresses the safeguardability of the ACP technology through analysis of material flow and the development of a proper safeguards system that meets the International Atomic Energy Agency's (IAEA's) comprehensive safeguards objective. The sub-processes and material flow of the pilot-scale ACP facility were analyzed, and subsequently, the relevant material balance area (MBA) and key measurement point (KMP) were designed for material accounting. The uncertainties in material accounting were also estimated with international target values, and design requirements for the material accounting systems were derived.

2. Intrinsic features of the ACP

ACP technology is based on the pyro-chemical process that was designed in the 1960s and 1970s. In the referenced lithium reduction process, which consists of six major sub-processes (see Figure 1), the oxide fuel elements are chopped into segments and are voloxidized, and the resultant oxide powder is loaded into a porous magnesia basket. The basket is charged into a vessel in which the fuel is reduced with lithium dissolved in molten LiCl at 650℃. Some fission products with high heat load, such as cesium and strontium, are dissolved in lithium chloride molten salt and separated from the spent fuel product [2].

Recently, KAERI proposed a modified concept of lithium reduction to simplify the reference technology and to increase the proliferation resistance (PR) of the process. Electrolytic reduction (ER) technology is known as a more efficient concept for spent fuel conditioning. In the ER process, the lithium recovery (electro-winning) step is conducted at the uranium oxide cathode simultaneously with the reduction of oxide fuel to metal. Consequently, the lithium recovery process is no longer needed and the possibility of separating actinides is inherently ruled out.

The success of the ACP depends on a number of factors. One key factor is PR and the manner in which it addresses the issue of proliferation. The existing "open" or "once through" LWR fuel cycle is relatively proliferation resistant compared with closed cycles. Any closed fuel cycle is likely to present an increase in proliferation concerns, and bulk-handling operations are a perfect diversion location because of the availability of the material and reliance upon materials accounting for detection [3].

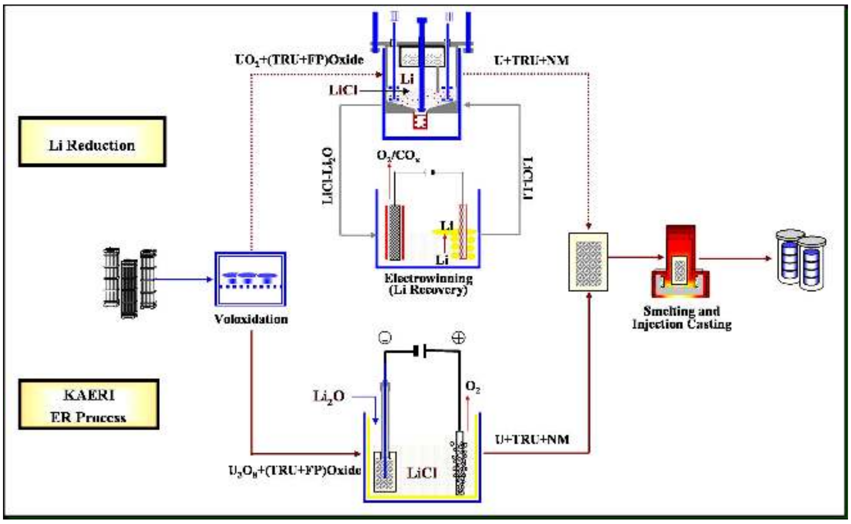

Figure 1 Flow Diagram of Electrolytic Lithium Reduction Process

Not all nuclear facilities, however, are equally susceptible to proliferation, nor are they all equally easy to safeguard. Intrinsic factors influence both the attractiveness of materials/facilities to proliferators and their safeguardability. The inherent attributes of the ACP that make this fuel cycle unattractive for proliferation compared with conventional fuel reprocessing and plutonium recycling technologies include the following:

- The processes used for the ACP do not produce a pure or partially pure plutonium product. Because of the chemistry of the ER process, no fissile material can be separated in pure form. Plutonium is co-deposited together with minor actinides and some fission products [4].
- The decay heat and radioactivity of the ACP product are about 25% of those of the initial spent-fuel feed to the ACP. As shown in Figure 2, the presence of some fission products leads to a high dose rate of radiation arising from the process materials. The IAEA estimated that all materials above 1 Sv/hr at 1 m are highly radioactive and self-protecting [5].
- The reconstitution options require a highly remote operation in canyons of highly shielded cells. It is difficult to gain undetected access to these cells in order to modify hardware or install new

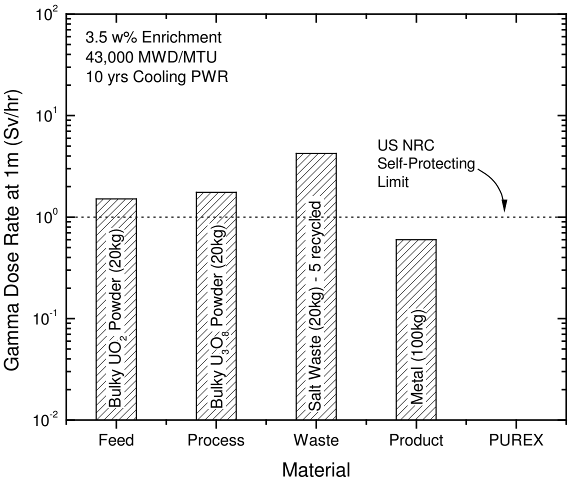

Figure 2 Self-Protection of ACP Materials by Fission Products

processes, and the complexity of these operations with highly radioactive materials precludes manual operation. Therefore, the process must be highly automated with inherent abilities to track and log in-cell operations included in the design.

According to the PR evaluation methodology proposed by the IAEA, these inherent features of the ACP result in strong intrinsic barriers to proliferation [6].

3. Material control and accountability

To measure the extrinsic barrier, a pilot-scale ACP facility with a capacity of 30 MTHM/year was designed for safeguardability assessment. The facility stands alone physically (operationally) and is administratively isolated from reactors and interim spent fuel storage facilities. The main process of the facility is the ER concept, which has no need for the lithium recovery system. The facility availability is assumed to be 60%, which is equivalent to 219 full operating calendar days per year. The process consists mainly of three parts: a spent fuel handling area (spent fuel disassembling and rod extraction); a main hot cell (decladding, reduction, smelting, casting, etc.); and a U-metal handling area (loading metal rods into storage cask and temporary storage). The referenced spent fuel used in the facility is Korean Yong-Gwang Unit 1&2 PWR's standard 17×17 assemblies with a minimum of 10 years cooling time after 43,000 MWd/MTU of final burnup.

3.1 Material accounting system

Lacking specific design information for the pilot-scale ACP facility, features such as the MBA definition, material flow pattern, KMPs, and inventories on material balance closing were designed for the conceptual facility. Many assumptions necessary to calculate the detection sensitivity of the materials accounting system were also made. The ACP fuel conditioning facility was designed to contain two MBAs [7]. The operations of MBA-A are based on individual item counts because the composition is not varied and items are only broken into other discrete items. Therefore, the material accountancy in the MBA-A is similar to that in any storage area.

Figure 3 identifies MBA-B boundaries, KMPs, and locations of inventories at material balance closing. It is assumed for this analysis that the facility closes material balances once every three months or once after every 54 days of operation. It is also assumed that the present IAEA detection goals for spent LWR fuels would be applied to materials within the ACP facility. Nuclear material contents for material balance were calculated on the basis of the reference fuel and the material contents at each step. In MBA-B, the facility operator conducts material accounting based on certain declared values for feed materials; destructive chemical analyses for mixed oxides and metal ingots; and NDA measurements for U-metals, recyclable scraps, and disposable waste streams. Isotopic analysis for ACP materials with respect to mass distribution, total dose rate, and neutron production rate support the concept of a curium-monitoring method if the amount of Pu relative to Cm is verified continuously at all stages of the process [8].

Because the size, shape, and chemical form of nuclear material would be changed in the ACP, a more sophisticated material accountancy method is required. Two types of material balance concepts are employed: batch closeout, which is the inventory difference for a single process, and material accountancy, which is the inventory difference in a specified time interval over several critical zones. The batch closeouts have two different steps based on available information. First, a mass balance is performed based on the total weights of the materials that enter and leave a piece of equipment during a batch. This balance must meet a specified accuracy, or operations are halted to investigate possible sources of error. The check provides the assurance that operations proceed as planned and the inventory difference from the measured weights lies within expected limits. After analytical chemistry results are received, a second batch closeout is performed to check expected and measured compositions. The expected masses and compositions of new items are based on operational models and prior experience. This two-step closeout provides the best data for every item in the MBA-B, provides a model of discrete accountable items distributed in space and time, and constitutes a complete historical record [9].

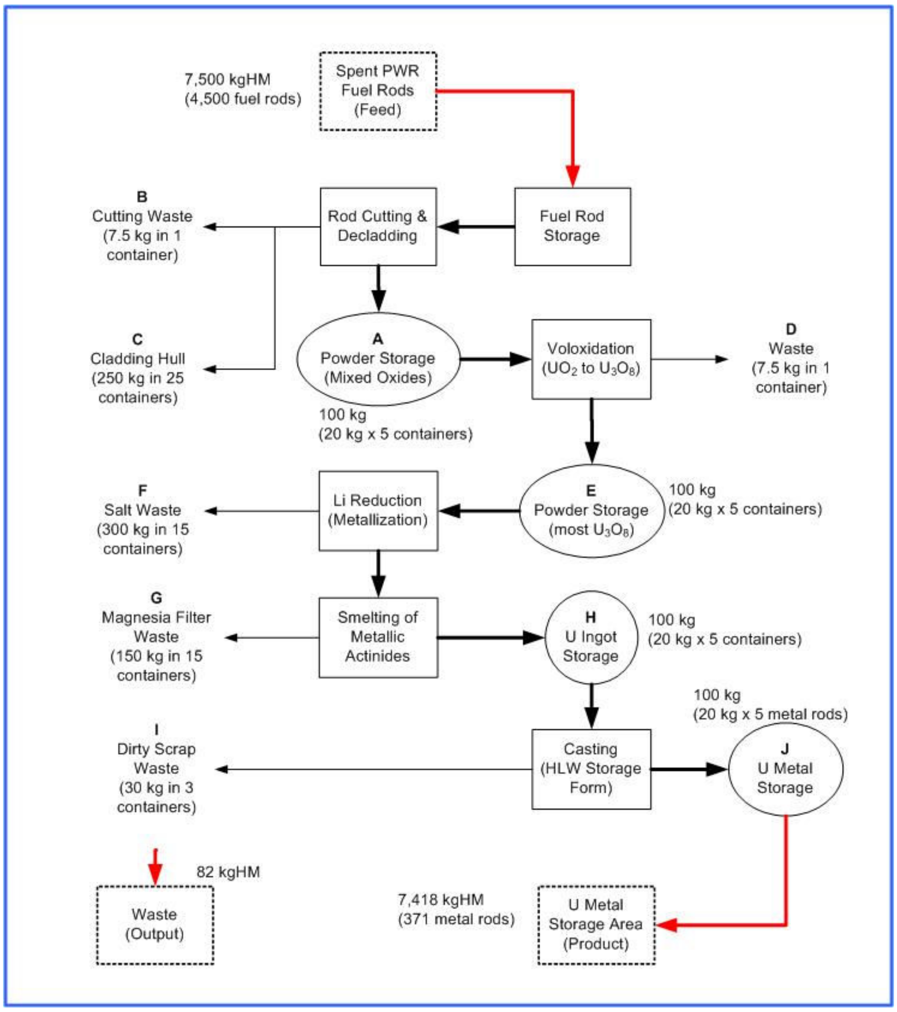

Figure 3   Material Inventory at MBA-B of Conceptual ACP Facility

IAEA verification would employ attributes and variables measurements, preferably NDA measurements. The facility closes material balances once every three months and plans to have the IAEA inspections coincide with this schedule for plant shutdown, cleanout, and material balance closing. The large inventories of feed materials and products (MBA-A and KMP-J) are maintained as "items" for inventory purposes and are stored in separate storage locations. Performing the cleanout operation before material balance closing recovers almost the entire residual process holdup, and therefore, inventory of plutonium as process holdup is negligible.

3.2 Uncertainty assessment

To investigate whether the ACP facility would meet the IAEA detection goal, the limit of error in the material unaccounted for (MUF, LEMUF) value was determined on the basis of a hypothetical operating scenario [10]. Because of insufficient detailed information for the ACP facility to treat these issues at this time, assumptions regarding measurement procedures on the part of the facility and inspectorate were introduced.

Inventory for the bulk-handing area was assumed as shown in Figure 3. Table 1 summarizes the characteristics of 23 strata identified in the ACP facility. The ACP includes one bulk measurement method, three material type determinations, and four analytical methods. It is important from the standpoint of facility accounting that all items in inventory be associated with measured values. Such measured values should be obtained in a way compatible with efficient operation. The destructive assay

(DA) measurements for plutonium concentration are made on a batch basis. It is unnecessary, time consuming, and costly to obtain a sample from each individual container of powder. Instead, samples are drawn from containers deemed representative of other containers in a batch.

The facility's material control and accountability methods propagate all measurement and sampling uncertainties to give a standard error. As shown in Table 2, the measurement methods used for material accounting are assumed to have various uncertainties based on the ITV 2000 [11]. The measurement precisions and accuracies reflected in the table by the random and systematic uncertainties, respectively, are values that must be achieved for the analysis of nuclear grade materials in a hot-cell environment. They include the contributions of all uncertainties occurring after sampling. Using these assumptions and uncertainty values, the result for the uncertainty of MUF (σ_{MUF}) was estimated as 1.881 kg of elemental plutonium, assuming no data falsification. The corresponding limit of error value for MUF is 3.761 kg of plutonium. This result suggests that it could be possible to meet typical IAEA detection goals for campaigns of three months or fewer.

It has been noted that the primary role of inspection from an accounting viewpoint is to install confidence in the reported MUF and its variance. In performing this function, the so-called D-statistic, or the difference statistic, is of prime importance. The quantity D is an estimate of this bias in the facility MUF. In actuality, it estimates a relative bias between the facility and the inspection agency, which is interpreted as a bias in the facility MUF when the assumption is made that the agency inspection measurements are unbiased. In practice, the value of D will not equal zero because of measurement errors on the parts of the facility (for declared values) and the inspectorate (for verification values). In most cases, σ_D greatly exceeds σ_{MUF} because the inspectorate's accounting is based on poorer quality measurements (e.g. NDA vs. DA) of fewer items. It is necessary to compare D to a limit, based on propagation of the uncertainties involved, to evaluate the possibility of data falsification.

For the D-statistic estimation in the ACP facility, it was assumed that only one type of NDA measurement per item is used for verification accounting, with no destructive samples and no attributes measurements. In the case of the inspection plan developed for the conceptual ACP facility, σ_D was estimated as 3.175 kg of plutonium. Thus, σ_D is roughly 3.57 % of the total plutonium handled during MB period. The largest single contributor to σ_D involves PWR powder measurement. From the D-statistic results, it could be concluded that the sensitivity of the verification for the conceptual ACP facility is very good because the inspection plan affords adequate protection against gross falsification and σ_D small relative to 1 significant quantity (SQ) of plutonium (= 8 kg).

4. Conclusion

Table 1 Characteristics of the ACP Strata for Material Accounting at ACP Facility

Stratum	KMP	Material Form	Total Element (kg)	Total Pu (kg)	Accounting Method
1	1	Spent Fuel Feed (most UO_2)	7500.00	88.875	DA + Weight
2	2	U-Metal Product (TRU+MA)	7440.00	88.164	NDA
3	3	Waste Output	60.00	0.711	NDA
4,14	A	Mixed Oxides Storage (most UO_2)	100.00	1.185	DA + Weight
5,15	B	Cutting Waste (for 1 MB period)	7.50	0.089	NDA
6,16	C	Cladding Hull Materials (for 5 batches)	0.50	0.006	NDA
7,17	D	Disposable Waste & Dirty Power Residues (accumulated for 1 MB period, most U_3O_8)	7.50	0.089	NDA
8,18	E	Mixed Oxides (most U_3O_8)	100.00	1.185	NDA
9,19	F	Salt Waste (accumulated for 5 batches)	1.00	0.012	NDA
10,20	G	Magnesia Filter Waste (for 1 MB period)	7.50	0.089	NDA
11,21	H	Uranium Ingot (for batch closeout)	100.00	1.185	DA + Weight
12,22	I	Dirty Metal Scrap (for 1 MB period)	15.00	0.178	NDA
13,23	J	Uranium Metal Rods (for batch closeout)	100.00	1.185	NDA

Table 2 Measurement Uncertainties for Material Accounting at ACP Facility

Sample Matrix & Measurement Method	Uncertainty Component (% Rel. Std. Dev.)			
	Random	System	Sampling	Reference & Notes
DA : Spent Fuel Powder	0.2	0.2	10.0	• U & Pu by IDMS at Hot Cell
NDA : Spent Fuel Powder	4	2		• Pu mass by HLNC for MOX
NDA : Hulls & Wastes	10	5		• Pu mass by HLNC for MOX Scrap
DA : U-Metal	0.2	0.2	10.0	• U & Pu by IDMS at Hot Cell
NDA : Dirty Scrap	10	5		• Pu mass by HLNC for MOX Scrap
NDA : U-Metal	4	2		• Pu mass by HLNC for MOX
Weight	0.05	0.05		• Electronic Balance

As a result of the preliminary study on the safeguardability of a pilot-scale ACP facility, our conceptualization of facility features and material flows across the ACP facility lead us to conclude that a safeguards system could be designed to meet the IAEA's detection goals and to provide an independent verification scheme. During and following the selection of an ACP option for engineering demonstration, parallel efforts will be directed at developing systems for material accounting, measurements, containment and surveillance (C&S), and verification of the flow and inventories of materials at the ACP facility. As we get information on measurements and verification approaches that are more reliable, these data and calculations can be modified.

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