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CONCEPTUAL SAFETY STUDY FOR PYROPROCESS HOT CELL FACILITY

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ABSTRACT

Pyroprocess technology has been considered as a fuel cycle option to solve the spent fuel accumulation problems in Korea. The Korea Atomic Energy Research Institute has been studying pyroprocess technology, and the conceptual design of an engineering-scale pyroprocess facility, called the Advanced Fuel Cycle (AFC) facility, has been performed on the basis of a 10tHM throughput per year. In this paper, the concept of AFC facility was introduced, and its safety evaluations were performed. For the safety evaluations, anticipated events and accident events were selected, and environmental safety analyses were conducted for the safety of the public and workers. In addition, basic radiation shielding safety analyses and criticality safety analyses were conducted. These preliminary safety studies will be used to specify the concept of safety systems for pyroprocess facilities, and to establish safety design policies and advance a more definite safety designs.

INTRODUCTION

In Korea, pyroprocess technology has been considered as a fuel cycle option to solve the spent fuel accumulation problems. Pyroprocessing is one of the key technologies used to recover actinide elements and long-lived fission products from the spent fuel in LiCl or LiCl-KCl molten salt by an electro-chemical reaction, and it is known that the technology is more advantageous than existing PUREX in terms of nonproliferation. KAERI (Korea Atomic Energy Research Institute) has been developing a pyroprocess technology for the recycling of spent fuels. PRIDE (PyRoprocess Integrated inactive DEmonstration facility) had been developed from 2007 to 2012 as a cold test facility to support integrated pyroprocessing and an equipment demonstration, which is essential to verify the pyroprocess technology [1, 2]. In PRIDE, depleted uranium is used for the process, and the maximum throughput is 10tHM per year. As the next stage of PRIDE, the design requirements of an engineering-scale demonstration facility are being developed, and a conceptual design of the facility is being performed. INL (Idaho National Laboratory) conducted a conceptual design of an AFCF (Advanced Fuel Cycle Facility) and accident analyses for AFCF to support the development of advanced technologies related to safeguards and security, instrumentation, process control and integration, and to provide data on the reliability and scale-up for full-scale separations and fuel fabrication facilities [3-6]. Also, JNC (Japan Nuclear Cycle Development Institute) have proposed the concept of safety systems in pyrochemical reprocessing systems and performed safety evaluations [7].

In this paper, the concept of the AFC (Advanced Fuel Cycle) facility was introduced, and its preliminary safety evaluations were performed. For the safety evaluations, anticipated events and accident events were selected, and environmental safety analyses were conducted for the safety of the public and workers. In addition, basic radiation shielding safety analyses and criticality safety analyses were conducted.

CONCEPTUAL DESIGN OF AFC FACILITY

The AFC facility for the pyroprocess demonstration consists of (a) processing equipment, (b) a hot cell facility, and a building structure to shield and isolate the process equipment, (c) hot cell remote operation equipment for safety operation and maintenance, (d) an argon system to control the inert atmosphere of a process cell, (e) a utility supply facility, (f) material receipt and storage areas for spent fuel, (g) and a waste treatment area and a shipping facility. The main process is composed of the disassembly and rod cutting of a spent fuel assembly, chopping and decladding, voloxidation, electrolytic-reduction, electro-refining, electro-winning, salt purification and recovery, waste form fabrication, off-gas treatment, and so on.

The AFC facility is divided into a main process building and support buildings. The hot cells are contained within 3 stories of a large single 7-story main process building including 1 basement level. The building has a length of 100m, a width of 40m, and a height of 48m, including a 9m high basement. The 1st floor provides space for the process cells, operating area, service area, main entrance area, truck bay, office area, and so on, as shown in Fig. 1. The decontamination cell, a storage room for the waste and process products, an electric room, an argon system, a service area, a utility supply system area, and so on were arranged at the 1st basement level. A maintenance cell, a chemical analysis laboratory, an office area, and a showing area are provided on the 3rd floor, and a HVAC (Heating, Ventilation, Air Conditioning) room was arranged on the 4th – 6th floors. Sectional views of the main process building are shown in Fig. 2, where the overall layout can be seen.

PRELIMINARY SAFETY ANALYSIS

The AFC facility was designed to treat spent fuel and chemically toxic materials, and thus the safety for the public and workers should be protected from the radiological hazards and chemical hazards of facility operation. For successful safety evaluations, the three key elements should be required such as operation and functional requirements for safety SSCs, hazard analysis technique, and safety analysis technique. As a result of a hazard analysis, the design basis accident scenarios are determined, and the initial design concept for safety SSCs should then be changed according to the safety analysis results. This design process can be very iterative, and thus this procedure should be applied in the initial design stage.

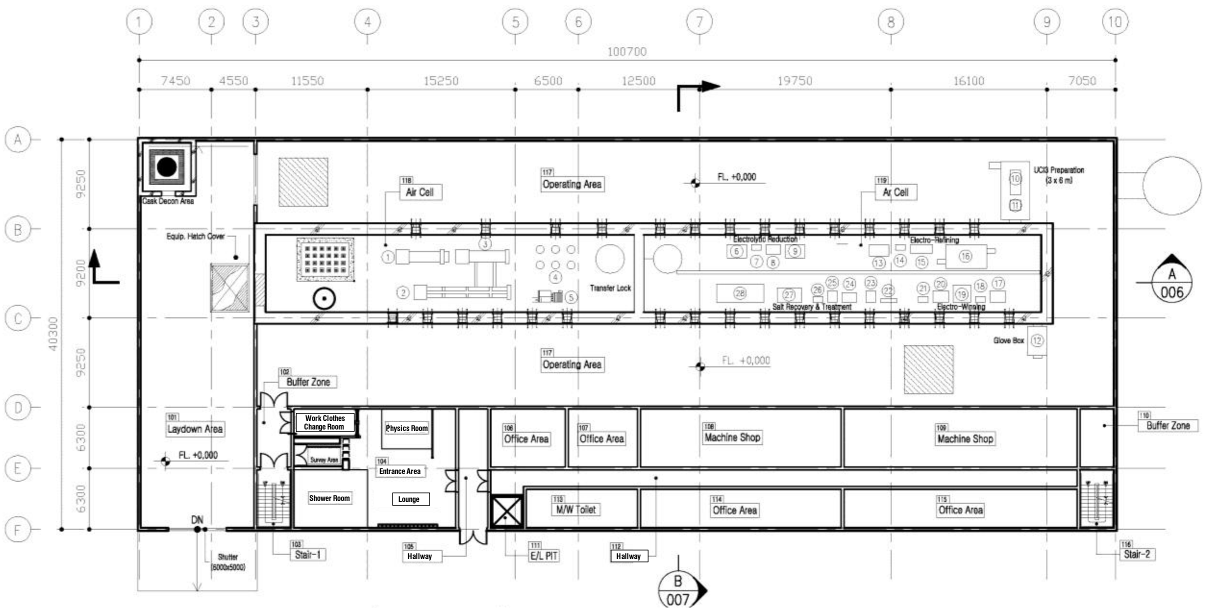
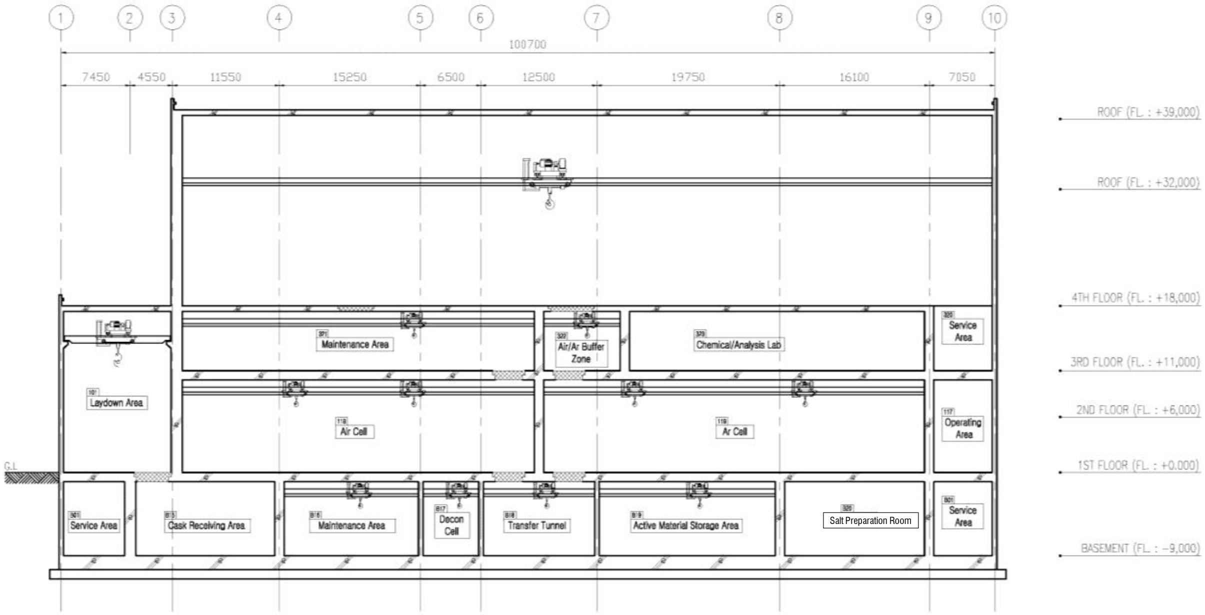
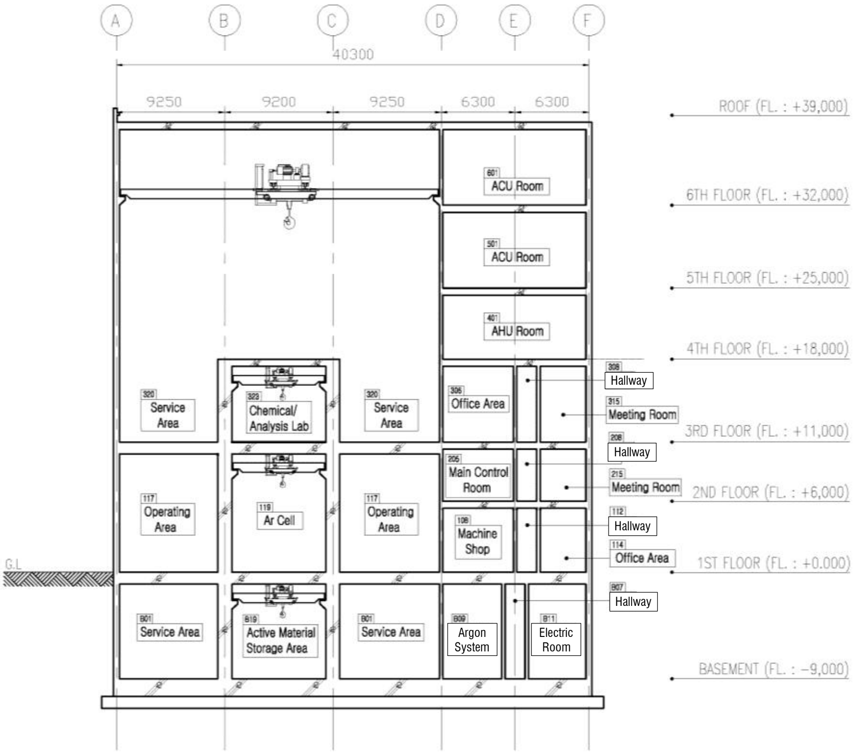


Figure 1. Conceptual design layout of 1st floor



(a) Front section view



(b) Side section view

Figure 2. Sectional view of conceptual design layout

Determination of Accident Scenarios

The hazard analysis is performed to identify and evaluate potential accidents, and to identify bounding accident scenarios (design basis accident scenarios) that require further quantitative development. In addition, the technical safety requirements (TSRs) for defense in depth and the significant safety functions performed by SSCs are established by hazard evaluation results.

Hazard identification was conducted to identify and characterize hazardous materials and energy sources associated with the operations and inventory of the AFC facility. The fundamental hazards affecting the AFC facility can be categorized into process-related hazards, natural hazards, and manmade external hazards, and spent fuel, radioactive materials, toxic materials, and combustibles are included in process-related hazard materials. The hazard identification activities were conducted, and some process-related hazards were identified. However, no external events were identified as a unique hazard. In this study, a preliminary hazard analysis (PHA) was used to evaluate hazards. The results of the PHA serve as the basis for hazard ranking so that bounding accident scenarios can be selected. Hazard ranking is determined by qualitatively assigning frequency and consequence estimates to each hazard or accident scenario developed by the PHA. The hazard frequency is categorized into 5 grades: I, II, III, IV, and V, and the hazard consequence severity is classified into 4 grades: A, B, C, and D [8]. Table 1 shows the representative accident scenarios finally selected by applying PHA and a hazard ranking matrix.

Table 1. Representative hazard evaluation results

Hazard Type	Accident Scenario	Frequency Category	Consequence Category	Risk Ranking
Radiological	Release of radioactive materials due to hot cell fire	III	A	2
Toxic	Release of chlorine gas due to pipe rupture	III	A	2
Toxic	Release of argon gas due to argon supply pipe rupture	III	A	2

Environmental Safety

Most significant processes and operations in the AFC facility take place within the confined hot cell, and both the air and argon in the hot cell would be released through the 2nd stage HEPA filters. Therefore, it is expected that various types of accident conditions may have little effect on the public, workers, and environment. A representative accident was analyzed to verify that the operation of the AFC facility gives no harm to the public, workers, and environment.

The accident analysis was performed for the case of a hot cell fire, which is considered as the greatest accident event influencing on the exposure dose at the site boundary. The hot cell fire scenario is the damage accident of an off-gas treatment equipment in the hot cell by fire, and thus the collected radioactive materials are released into the environment. The key assumptions used for the calculation of radioactive material emission rate are as follows.

(1) 100% of the collected radioactive materials, which is accumulated for 1 year, in the off-gas treatment equipment is released, but only 50% of Xe and Kr, which is accumulated for 6 months, is released because the radioactive materials are retained in the equipment for 6 months.
(2) In-cell filter and ACU (Air Conditioning Unit) do not function due to fire.
(3) All of the radioactive materials are released into the environment within 2 hours.
(4) The final release fraction values are as listed below. These values are for a Hazard Category 2 facility, produced by the U.S. DOE (Department of Energy) [9].
   - Gases (^{3}H, Kr, Xe, Ar, Rn, Cl): 1.0
   - Highly volatile/combustible (P, S, K, I, Na, Br): 0.5
   - Semi-volatile (Se, Hg, Cs, Po, Te, Ru, C): 0.01

The atmospheric dispersion model, PAVAN (Potential Accident Consequence Assessments at Nuclear Power Plants), was used to provide the short-term atmospheric dispersion factors (χ/Q) for an assessment of the consequences of the accident. The following assumptions were used for the calculations.

(1) Effective release height: 0m, ground level height
(2) Meteorology based on 2 year accumulation, which is referred to in preliminary safety analysis

report of Shin-Kori 1 and 2 nuclear power plants
(3) Site boundary location: 560m
(4) Wet and dry depositions of radioactive material are zero for individual receptors
(5) Inhalation and external exposure from a plume
(6) Breathing rate: $3.47 \times 10^{-4} m^3/s$ [10]

The χ/Q values are calculated for 16 sectors at a distance from the AFC facility. The maximum χ/Q at the site boundary is $4.055 \times 10^{-4} s/m^3$ in the NNW sector and this value is used to calculate the dose. The maximally exposed individual (MEI) dose is calculated using conservative assumptions, including the MEI at the site boundary in the NNW direction with along the plume centerline [2].

The effective dose from external exposure and equivalent dose due to the thyroid received by inhalation was calculated and summarized in Table 2. The dose rate limit for unlikely accidents is 250mSv to the whole body, and 3,000mSv of equivalent dose rate to the thyroid, which is embodied in 10CFR100.11 [11]. The ratio of the effective dose to the limit is 2.1% and 21.2% for effective dose due to external exposure and equivalent dose due to the thyroid, respectively, and thus the results show that the design requirement is satisfied.

Table 2. Calculated effective doses

	Effective Does	Equivalent Does for Thyroid
Dose (mSv)	5.2	635
Dose Limit (mSv)	250	3,000
Ratio (%)	2.1	21.2

Radiation Shielding Safety

The AFC facility is dedicated to the mission of the pyroprocessing of spent fuel. The radiation shielding analysis is conducted to determine the thickness of high-density concrete walls, which ensure that radiation doses to the workers from radiation exposures are maintained below the regulatory limits. The dose limits was presented in Table 3 according to adjacent area. The dose limits in the table were determined by considering the maximum dose constraint for workers, 20mSv in a year, as recommended in ICRP-60 and working hour at each area of hot cells.

The following assumptions were used to determine the source term for the shielding analysis.
(1) 10tHM of spent fuels (24 spent fuel assembly), which is the throughput per year, was stored in the temporary spent fuel storage vault.
(2) 5tHM of spent fuels was contained in the head-end or main process cell by considering the process characteristics.

The MCNP-X code was used to evaluate the potential dose from the source term, and the γ and neutron emission rate for the reference fuel were calculated by ORIGEN-ARP of SCALE code Ver. 5.1. Fig. 3 shows the model of temporary spent fuel storage vault for shielding analyses, and 24 (4×6 array) spent fuel assemblies are stored in the 10mm-think steel cask. Fig. 4 shows the analysis model of the head-end or main process cell. In the case of an active material storage area, the shielding walls for the product and waste casks should be additionally installed to meet the dose limits, and thus the design and shielding analysis for the storage area should be performed at the stage of the final design of the AFC facility. It was assumed that the density of concrete, steel, and air is 3.457, 7.870, and 0.001293 g/cm^3, respectively. The shielding walls were modeled in a 1.0m thickness, and a series of shielding analyses were conducted to determine the radiation shielding performance with various detection locations at intervals of 0.1m from the inner surface of the shielding wall.

The results of the calculations are summarized in Table 3, and some of the results were plotted in Fig. 5. The thickness of the side and lower walls, and the upper wall of the spent fuel storage vault are 0.7m and 0.4m, respectively, to meet the dose limits. Also, in the case of the main process cell, a 1.0m side wall and 0.5m upper wall are needed to meet the standard limits.

Table 3. Radiation shielding result; wall thickness satisfied with dose limit

Objective		Dose Limit (mSv/hr)	Wall Thickness (m)
Temporary Spent Fuel Storage Vault	Upper Part	10 (High Radiation Area)	0.4
	Side and Lower Part	0.05 (Service Area)	0.7
Head-end and Main Process Cell	Side Part	0.01 (Operating Area)	1.0
	Upper Part	10 (High Radition Area)	0.5
Active Material Storage Cell	Side Part	0.05 (Service Area)	Not Determined

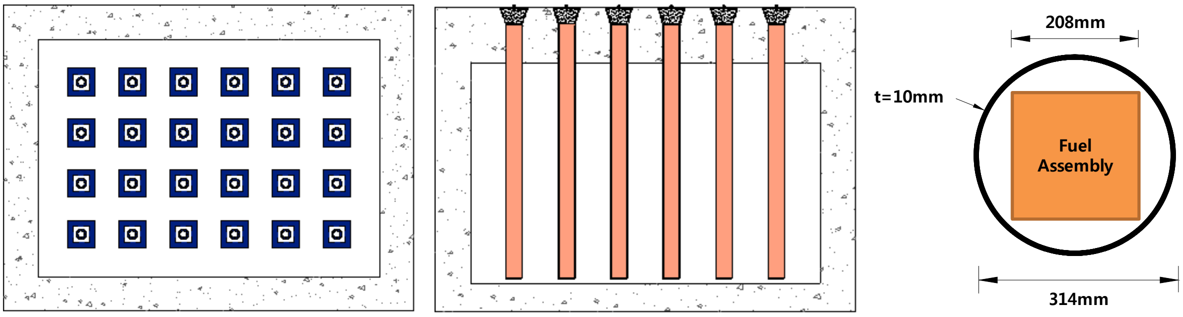


Figure 3. Shielding analysis model of temporary spent fuel storage vault

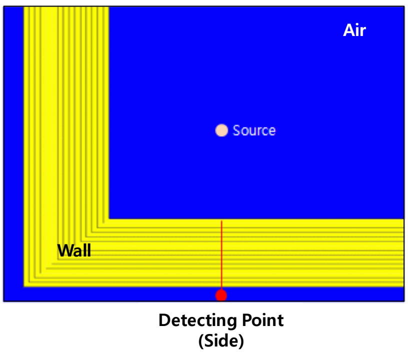


Figure 4. Shielding analysis model

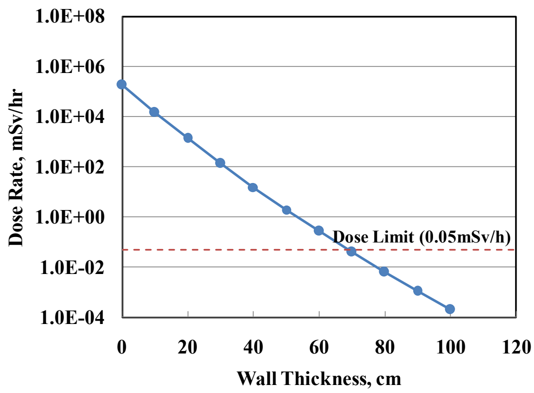


Figure 5. Example of shielding analysis results; Dose rate at side wall of spent fuel storage vault

Criticality Safety

The nature of AFC operations makes a criticality event highly unlikely, however, the AFC facility will process and store fissile materials in sufficient quantity, and thus it is necessary to provide high confidence that criticality cannot occur in the AFC facility under all normal, abnormal, and accident conditions. A maximum value for the effective multiplication factor (K_{eff}) including uncertainty and bias is used to evaluate the criticality safety. The K_{eff} should be less than 0.98 under the condition of the highest anticipated reactivity, assuming optimum moderation as recommended by NUREG-0800, and less than 0.95 under the submerged and water filled condition as recommended in ANSI 57.3-1983. The K_{eff} must include allowance for all relevant uncertainties and tolerances.

Criticality calculations were estimated with the MCNP-X code in a 3D geometry of the TRU metal ingot equipment and storage vaults for the process products shown in Fig. 6 and 7. It was assumed that the minimum critical mass of fissile materials (TRU) is 5.6kg, which is the critical mass of ^{239}Pu, and the operational mass limit of fissile materials was determined as 4.5kg of ^{239}Pu on the assumption that the fissile material is composed of only pure ^{239}Pu and the safety factor is 0.8.

The following assumptions were used for the criticality calculations.

(1) Submerged and water filled conditions

(2) Cylinder shaped container for TRU ingots

The calculation results for the TRU metal ingot casting equipment were presented in Table 4 and 5. It was calculated that the effective multiplication factor of the device would be sub-critical if the plutonium cylinder diameter is below 5.0cm, and the array of the container has little effect on the effective multiplication factor. Table 6 shows the calculated effective multiplication factor by various arrays of a TRU storage container with a diameter of 5cm and a distance of 20cm. In the case of a 3 layer array, the result shows that the TRU storage container slightly exceeded the limit. It is thought that the detailed criticality calculations considering the composition of plutonium and the array of containers should be conducted in the detailed design stage.

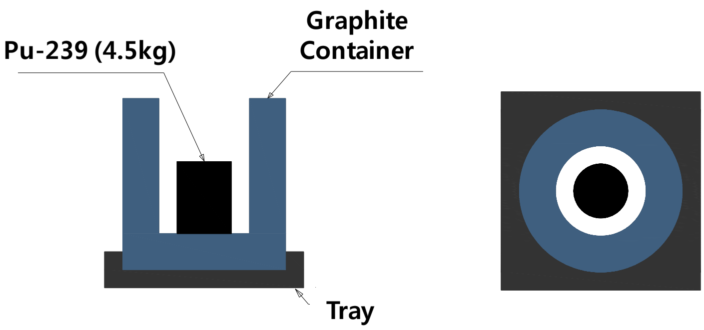


Figure 6. TRU metal ingot equipment

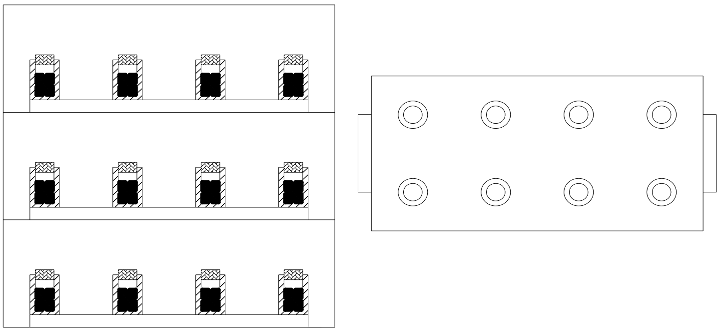


Figure 7. TRU metal ingot storage container

Table 4. Calculated multiplication factor by various diameter of cylinder

Diameter (cm)	Multiplication Factor (K_{eff})
6.0	0.9568±0.0028
5.0	0.9222±0.0028
4.4	0.8929±0.0030
4.0	0.7298±0.0024

Table 5. Calculated multiplication factor by various array of cylinder

Array	Multiplication Factor (K_{eff})
1 X 1	0.8929±0.0030
1 X 2	0.8905±0.0083
1 X 3	0.8938±0.0027

Table 6. Calculated multiplication factor by various array of storage container

Array	Multiplication Factor (K_{eff})
1 Layer 2 X 4	0.9319±0.0031
2 Layer 2 X 4	0.9342±0.0030
3 Layer 2 X 4	0.9353±0.0162

SUMMARY

The development of pyroprocess facilities for an effective management of spent fuel is essential to the long-term success of nuclear energy policy in Korea. In this paper, the conceptual design concept of an engineering-scale pyroprocess facility, Advanced Fuel Cycle (AFC) facility, developed by the Korea Atomic Energy Research Institute, was reviewed, and its preliminary safety evaluations were conducted. The key results are as follows:

(1) As a result of hazard analysis, a hot cell fire scenario was selected as the greatest accident event influencing on the exposure dose at the site boundary, and it was verified that dose rates don't exceed the standard limits.

(2) Radiation shielding analyses were conducted to determine the thickness of hot cell wall assuring of radiation shielding safety.

(3) Criticality calculations were carried out to design the manufacturing equipment and storage container for TRU metal ingots to prevent criticality.

These preliminary safety studies will be used to specify the concept of safety systems for pyroprocess facilities, and to establish safety design policies and advance more definite safety designs.

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