〈Technical Note〉

DESIGN AND CONSTRUCTION OF AN ADVANCED SPENT FUEL CONDITIONING PROCESS FACILITY (ACPF)

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KAERI has worked on the development of an advanced spent fuel conditioning process (ACP) since 1997. A hot cell facility, termed the ACPF, has also been developed. The ACPF consists of two air-sealed hot cells. The results of a safety analysis as part of the license procurement process stipulated by the Korean Government showed that the facility was designed safely. After its construction, an integrated performance test was performed. The results of this test confirmed that the facility satisfies the design requirements.

KEYWORDS : Spent Fuel, Conditioning, Hot Cell, Safety Analysis

1. INTRODUCTION

Spent fuel is a type of highly radioactive waste and is detrimental to the environment if discarded improperly. The disposal or interim storage of spent fuel typically involves use of an isolated area. For countries with a high population density, such as Korea, it is not easy to find sites for the disposal or interim storage of spent fuel. Therefore, treatment and reduction of the volume of spent fuel provide many advantages with regard to disposal and interim storage. Furthermore, spent fuel can prove to be a valuable asset if effectively treated and recycled. KAERI has focused on a project entitled "The Development of an Advanced Spent Fuel Conditioning Process (ACP)" and has developed and demonstrated an advanced spent fuel management process in a laboratory setting (see Fig. 1).[1-4] This technology involves the electrolytic reduction of uranium oxide in a high-temperature LiCl-Li_2O molten salt bath.

2. DESIGN OF THE ACPF

For the demonstration of the ACP, several hot cells, in which spent fuel can be treated safely, are necessary. However, KAERI does not have access to the type of

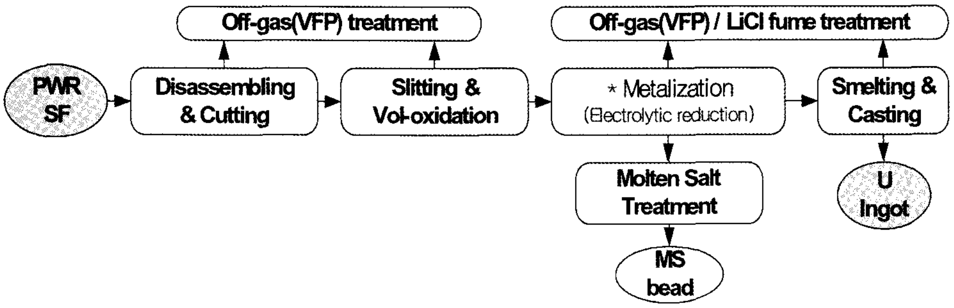

Fig. 1. Process Block Diagram for the ACP

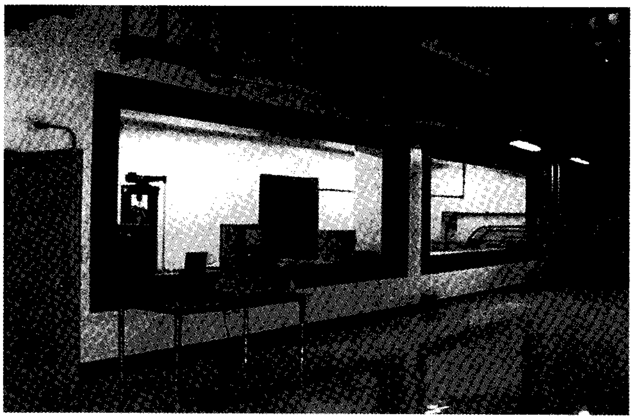

Fig. 2. The Future Cell Line in the IMEF before Refurbishment

Table 1. Radioactivity Source Terms of the ACPF

Materials	Radioactivity Level (Ci)
1 Batch of Spent Fuel (20 kg-HM)*	9,930
4 Batches of Uranium Ingots (80 kg-HM)	14,740
4 Batches of H-3, Kr-85 (fission gases)	560
2 Batches of Waste Molten Salt	12,220
Total	37,450

* 3.5 wt% enrichment, 43,000 MWd/MtU burnup, 10-year cooling time

Table 2. The Design Requirements of the ACPF

Items	Requirements
Type of Hot Cell	· α-γ seal with air environment
Shield Design	· Operation area: 0.01 mSv/h · Maintenance area: 0.15 mSv/h [Korean regulation guide: 1 mSv/week]
Shield Reinforcement	· Opening parts on front wall: Heavy concrete, 90 cm · Heavy concrete, 80-cm wall: Steel plate, 4 cm
Differential Pressure	· -27~-37 mmAq
Air Exchange Rate	· 20 times/h
Manipulation Device	· Seal type: master-slave manipulator (9~12 kg) · Telescopic manipulator (~15 kg) · In-cell crane (~1 ton)
Shielding Windows	· Double seal in frame connectors, cover glass, hot cell liner · Cover on hot and cold sides

cells required for an ACP demonstration. Hence, KAERI decided to use the future cell line, located on the basement floor of the IMEF (Irradiated Material Examination Facility). This line was originally constructed with a rear wall and two sidewalls so that a hot cell facility could be installed and used in the future. Refurbishing of the Future Cell Line required a number of modifications, including the creation of shielded windows and manipulators in the front wall, the installation of an intercell crane, the construction of intercell doors and a rear door, and the implementation of a Padirac cask adaptor. In addition to the ACP hot cell design, the safety analyses and evaluations from the previous IMEF undertaking were reanalyzed and reevaluated to ensure the safe integration of the ACP facility (ACPF) within the IMEF.[5] The original inner dimensions of the future cell line were 11 m in length × 2 m in depth × 4.55 m in height. Fig. 2 shows the future cell line before modification began. The IMEF was originally designed for post-irradiation examinations of fuel and structural materials that are irradiated in a material test reactor (HANARO) in KAERI.

2.1 Source Terms and Design Requirements for the ACP Demonstration

The maximum radioactivity retained in the ACP hot cells and the design bases of the hot cell containment were determined. This data is shown in Tables 1 and 2.

2.2 Facility Layouts

The ACPF (see Figs. 3 and 4) consists of two hot cells: one for the actual process and the other for the maintenance of the process and the handling equipment. This hot cell line, like the other hot cell lines in the IMEF, was designed to minimize any radiation exposure and avoid contamination of the personnel. In the IMEF, the working areas are divided into four zones (green, blue, amber, and red) for protection from radiation. The green zone, an area that is always free of radiation, includes the offices, a meeting room, and the clean section of the changing room. The blue zone, usually a radiation-free area, includes the corridor and the hot cell working area. The amber zone, which is usually referred to as the intervention or service area, is the rear area of the facility. This area is normally a radiation-free zone, but contamination may occur during maintenance of the hot cells. The red zone is normally a contaminated zone, such as the interior of a hot cell.

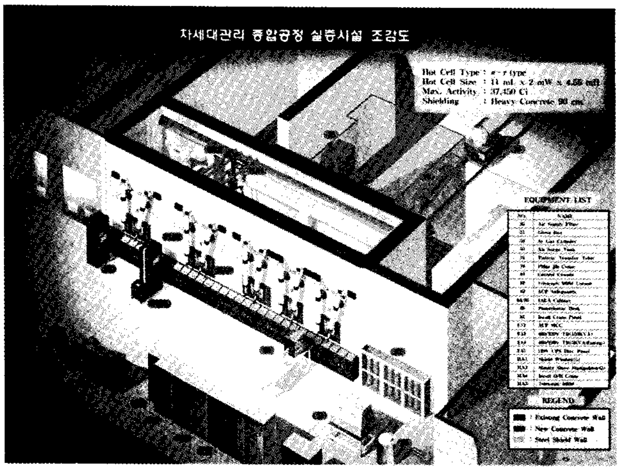

Fig. 3. An Overall View of the ACPF

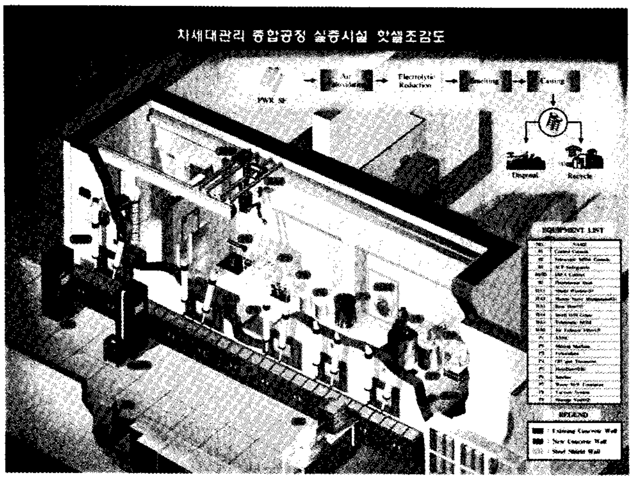

Fig. 4. A Cutoff View of the ACPF

3. SAFETY ANALYSES OF THE ACPF

3.1 Process Safety

ACP electrochemical processes treat high-level radioactive materials and chemically toxic materials in hot cells. Process safety should be considered for safe operation. There are four types of hazards that may be associated with the ACP:[6]

1) Risk of radiation produced by radioactive materials
2) Chemical risk produced by radioactive materials
3) Plant conditions that affect the safety of the radioactive materials and thus present an increased radiation risk to a worker. For example, such conditions might produce a fire or an explosion and thereby cause a release of radioactive materials or result in unsafe conditions.

Table 3. Process Safety Requirements

Classify	Requirements
General Considerations	- Hazard evaluation and designed to prevent various failures - Designed to ensure that primary failures do not progress to severe failures - Double monitoring and control of important process parameters - Proper pressure balance between the process equipment and the off-gas trapping system
Considerations Due to Process Characteristics	- α-γ sealed hot cells - Designed to prevent leakage and release of U_3O_8 powder from the process reactor - Designed to trap volatile fission products and LiCl fumes - Designed to prevent clogging of the off-gas line (pressure build-up: monitoring and control of pressure)

Table 4. Process Source Terms that Bring about Radioactive Materials Release

Process	Source Terms
Voloxidation (RT*: 500 °C)	Release of the total quantity of gas forms fission products such as Kr, Xe, I, and H
Metallization (RT: 650 °C)	1% release of volatile fission products such as Ru, Tc, Mo, Se, and Rb
Smelting (RT: 1,400 °C)	Release of the total quantity of volatile fission products such as Ru, Tc, Mo, Se, and Rb except for the fission products remaining in the molten salt and semi-volatile fission products such as Cs, Cd, Sb, and C
Waste Salt Treatment (RT: 650 °C)	No release of fission products

*RT: Reaction Temperature

4) Plant conditions that result in an occupational risk but do not affect the safety of the radioactive materials. For example, there might be exposure to chemically toxic materials and other hazards. A chemical explosion in a hot cell may release radioactive materials, just as a radioactive environment may make it more difficult to respond to a hazardous chemical spill or leak.

The process safety requirements in place to prevent these hazards should be considered when designing an ACPF. The process safety requirements established for the safe operation of the ACPF are described in Table 3. General considerations for process safety include a

Table 5. Fault Analyses for each Process

Process	Fault Type	Cause	Effects	Design Consideration
Voloxidation	- Pressure build-up	- Air PIC malfunction - Sintered filterclogging	- SF powder leakage - Hot cell contamination	- Dual pressure control system - Back flushing system for filter - Manual control for emergencies - Air shut-off at high pressure
	- Temperature build-up	- TE/TIC malfunction	- Powder partial sintering - Powder discharge interruption	- Dual temperature control system - Electrically powered shut-off at high temperatures
Metallization	- Pressure build-up	- Ar PIC malfunction - Off-gas line clogging	- LiCl fume leakage - Hot cell contamination	- Dual pressure control system - Manual control for emergencies - Ar shut-off at high pressure
	- Temperature build-up or temperature below the melting temperature	- TE/TIC malfunction - Failure of a heating furnace	- LiCl vapor pressure build-up - LiCl fume leakage - Hot cell contamination - Solidification of LiCl molten salt	- Dual temperature control system - Electric power shut-off at high temperatures - Cold trap for emergencies - Easy replacement of heating element
Smelting	- Failure to maintain an inert atmosphere	- Failure of the Ar supply - Failure of the vacuum system	- Oxidation of SF metal (out of specification) - Smelting temperature increase	- Dual Ar supply system - Dual vacuum system
Waste Molten Salt Treatment	- Pressure build-up	- Ar PIC Malfuncti - on - Off-gas line clogging	- LiCl fume leakage - Hot cell Contamination	- Dual pressure control system - Manual control for emergences - Ar shut-off at high pressure
	- Tempera-ture build-up	- TE/TIC malfuncti-on	- LiCl vapor pressure build-up - LiCl fume leakage - Hot cell contamination	- Dual temperature control system - Electric power shut-off at high temperatures - Cold trap for emergencies
	- Failure of Molten Salt Transfer	- TE/TIC malfunctio-n - Failure of a line heater - Failure of The vacuum system	- Solidifying of LiCl molten salt and clogging in the transfer line	- Dual temperature control system - Dual vacuum system

Process	Fault Type	Cause	Effects	Design Consideration
Off-gas Treatment	- Interruption of off-gas exhaust	- Failure of a vacuum system - Off-gas line or absorber clogging	- Pressure build up in the process reactors - Increase of the differential pressure in the off-gas absorber	- Dual vacuum system - Dual pressure control system - Differential pressure monitoring system
Utility	- Interruption of Ar supply	- Trouble in the Ar supply system	- Lack of inert atmosphere in the process reactor - Increasing reactor surface temperature	- Dual Ar supply system - Dual Ar control system
	- Interruption of normal electrical power	- Trouble in the electric power supply system	- Failure of the off-gas system and pressure build-up in the process reactors	- Emergency power for the vacuum pump in the off-gas system - UPS of control system for safe emergency shut-down of the process operation

hazard evaluation, prevention of a secondary failures, a double-check system, and a pressure balance between the process equipment and the off-gas trapping system. To maintain these general considerations, the requirements due to the process characteristics described in this table should be considered. Table 4 shows the source terms under which a radioactive material release from each process may be induced.

Table 5 shows detailed fault analyses for each process within the ACP, satisfying the general process requirements. The main fault types are classified as a pressure build-up, a temperature build-up, failure to maintain an inert atmosphere, interruption of normal electric power, failure of the off-gas trapping system, and failure during a molten salt transfer.

3.2 Radiation Shielding Safety

The working area in the front of the hot cells was designed to minimize radiation exposure. Table 6 shows the reinforcement material used and the thickness of each wall. Both the material used and the thickness of the walls were determined by an analysis that verified the design criteria of 0.01 mSv/h for the operational area and 0.15 mSv/h for the maintenance area of the ACPF. It is also important to note that the source terms of the material being handled were carefully considered in the design of the shielding material. Both neutrons from the spent fuel and the gamma source spectra were considered when analyzing the radiation safety of the facility. The photon and neutron spectra from the ACP radiation sources are shown in Figs. 5 and 6, respectively. The gamma intensities were calculated using the ORIGEN-2 code and the neutron intensity was calculated using the SOURCES code.

Table 6. Reinforcement Thickness of the Future Hot Cell Line

Location	Reinforcement Method
Front Wall	Heavy Concrete, 90 cm
Rear Wall	Heavy Concrete, 80 cm + Steel, 4 cm
Side Walls	Heavy Concrete, 80 cm + Steel, 4 cm
Inter Cell Wall	Heavy Concrete, 70 cm

In terms of cost and structural performance, heavy concrete was selected as the basic shielding material for the wall. Steel plates with a thickness of 4 cm were chosen as the reinforced shielding material for the side and rear walls due to space restrictions.

3.3 Criticality Safety

ACP hot cells treat spent fuels with an initial enrichment of 3.5 wt%, a burnup of 43,000 MWd/MtU,

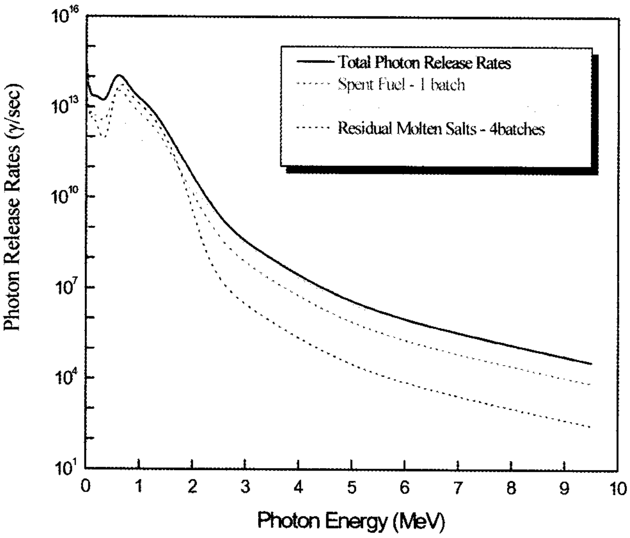

Fig. 5. Photon Spectra of the ACP Sources

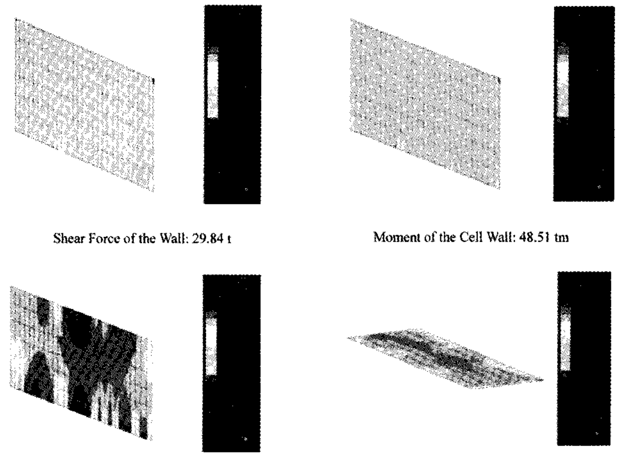

Fig. 7. Maximum Forces and Moments of the ACPF Walls

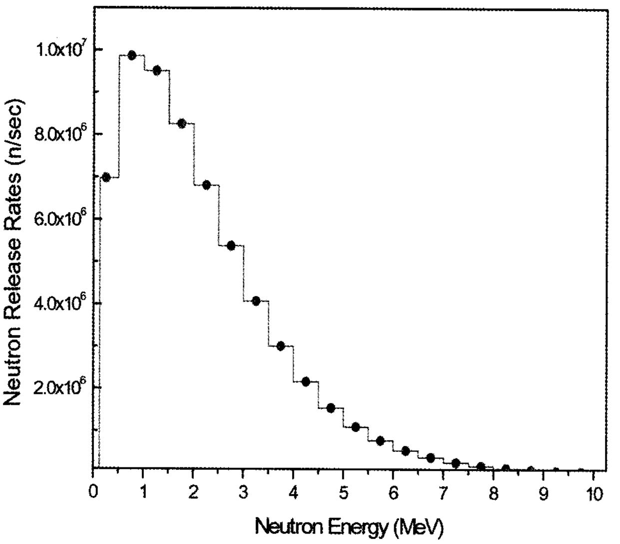

Fig. 6. Neutron Spectrum of the ACP Sources

and a 10-year cooling time. The size of one batch is 20 kg of spent fuel, and the storage vault has a maximum capacity of 4 metal ingots. The ACP is a dry process, requiring no water supply into the hot cells. However, a criticality safety analysis was performed in a water condition. If the criticality safety can be confirmed by a maximum handling limitation of the process material and conservative calculations, the criticality design for the ACP hot cells can be disregarded NUREC-0800 (Standard Review Plan) recommends that an effective multiplication factor of the spent fuel should have a value lower than 0.95 under water conditions. The criticality safety of 100 kg of spent fuel (initial enrichment: 3.5 wt%; burnup: 20 GWd/MtU; cooling time: 10 years) was analyzed for a homogenized, spherical, and fully reflected condition surrounded on all sides by 30 cm of water. The results showed that the maximum Keff value is 0.912. The calculations were performed using the SCALE 4.4a code and the KENO V.a code in conjunction with the ENDF 44-group Cross Section Library. The results, therefore, confirmed that the ACP is reliable with regard to its criticality safety, even under the worst accident conditions. The criticality safety for each ACP was also calculated and evaluated for the worst accident conditions, but no process exceeded the sub-critical limit value.

3.4 Structural Safety

Seismic analyses of the entire IMEF building block, including the ACP hot cells, were performed to verify the integrity of the hot cell structure against a Design Basis Earthquake (DBE) and an Operating Basis Earthquake (OBE). For the seismic analyses, the SAP2000 code was used and the ACPF was modeled using 3D FEM. The response spectrum curve of the IMEF (or HANARO, USNRC Reg. Guide 1.60 & CANS-N 298 3, M 81) was used for the horizontal component, while that of the ASCE (Structural Analysis and Design of Nuclear Plant Facilities) was used for the vertical component. Fig. 7 shows the maximum forces and the moments for the ACPF walls. The total displacements of the IMEF building, including the ACP hot cells, were calculated as 22.9 mm (horizontally) and 10.0 mm (vertically). The horizontal displacements of the HANARO and the RIPF buildings, which are in contact with the IMEF building, are 4.9 mm and 7.9 mm, respectively. The seismic gaps between the IMEF and the two buildings are 50 mm. Thus, the

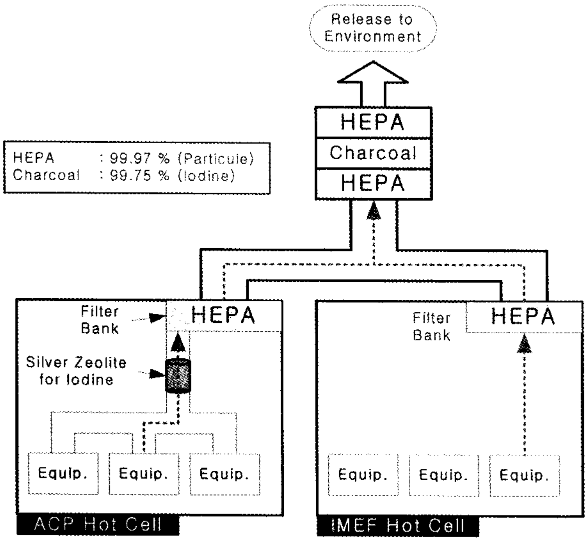

Fig. 8. Off-gas Filtration System of the ACP Hot Cells

Table 7. Results of the Analyses of the Environmental Effects of the ACPF

[Under normal operating conditions]

Item	Regulation	Evaluation Result	%
Gamma Absorption in the Air (mGy)	1.0E-1	4.43E-4	0.44
Beta Absorption in the Air (mGy)	2.0E-1	5.02E-2	25.11
Effective Dose (mSv)	5.0E-2	6.12E-4	0.10
Skin-equivalent Dose (mSv)	1.5E-1	3.5E-2	23.30
Organ-equivalent Dose (mSv)	1.5E-1	6.43E-3	4.30 (Child, Thyroid)

[Under accident conditions]

Item		Radiation Dose (Sv)		
		Effective Dose (External)	Effective Dose (Internal)	Organ-equivalent Dose (Thyroid)
Regulation	10CFR100.11	0.25	0.25	3.0
	IMEF Facility Standard	2.5E-3	2.5E-3	3.0E-2
In-cell Fire Accident Case		3.77E-5	4.76E-4	1.65E-3

seismic analyses of the IMEF building show that all of the buildings are safeguarded against seismic accidents because the total horizontal displacements of 14.9 mm (with the HANARO building) and 17.9 mm (with the RIPF building) are less than the seismic gaps.

3.5 Environmental Safety

The ACP hot cells are α-γ sealed. The ACPF ventilation system was designed to ensure air flow from the clean areas to the more radioactive areas. A maximum pressure differential of –37 mmAq is maintained between the interior of a hot cell and the intervention area (or the hot cell rear service area). Air changes at a rate of 20 times/h are recommended for the control of the hot cell environment. Fig. 8 shows the off-gas filtration concepts of the ACP equipment, and Table 7 shows the evaluation results of the environmental effects of the radioactive materials released from the ACP hot cells.

4. CONSTRUCTION OF THE ACPF

The existing front wall of the IMEF future cell line, as shown in Fig. 2, was removed by a diamond-cutting saw and rebuilt with heavy concrete. The rear wall was fixed by attaching metal plates for radiation shielding. Shielding windows, alpha-gamma-type manipulators, and penetration tubes for the insertion of electrical cables were installed in the front wall. The hot cells inside the walls were lined with stainless steel plates to form an air seal and for easy decontamination. An in-cell crane with a capacity of one ton and a telescopic manipulator with a capacity of 15 kg were also installed for the handling and repair of process equipment and materials. Fig. 9 shows an overall view of the ACPF working area after the

Fig. 9. Overall View of the ACPF Working Area

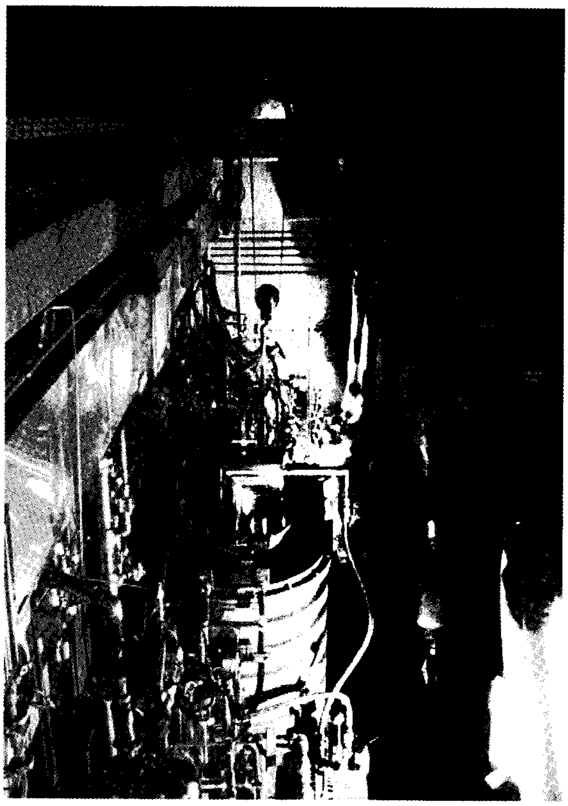

Fig. 10. A View of the Interior of the ACP Hot Cell

modifications were complete. Fig. 10 also shows an inside view of the ACP hot cell after the installation of all of the ACP equipment.

5. FINAL PERFORMANCE TESTS OF THE ACPF

After the completion of safety performance tests of the integrity of the ACPF, including a uniformity test of the radiation shielded walls, the final integrated process tests were performed using unirradiated UO_2 pellets and simulated spent fuel mixed with major fission product elements in unirradiated UO_2. These inactive tests will be continuously performed in the future for optimization of the ACP until it is confirmed that active tests using spent fuels are possible.

6. SUMMARY

KAERI has been developing an advanced spent fuel conditioning process (ACP), which is a reduction process for uranium oxide nuclear fuel that utilizes an electrolytic reduction method in a high-temperature $LiCl$-Li_2O molten salt bath. The ACPF consists of one laboratory-scale cell line and associated auxiliary facilities. The hot cell line consists of two air-sealed hot cells and related hot cell equipment. Analyses and evaluation of the process, the degree of protection from radiation, the structural integrity, the criticality safety, and the environmental safety were performed. The results show that the ACPF is well designed and meets all safety requirements. Integrated performance tests using unirradiated and simulated fuel materials were also carried out, with successful results.

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